Report No. FAA-RD-78-157

REVIEW OF AIRWORTHINESS STANDARDS FOR CERTIFICATION OF HELICOPTERS FOR INSTRUMENT FLIGHT RULES (IFR) OPERATION

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February 1979

FINAL REPORT

Document is available to the U.S. public through
the National Technical Information Service,
Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

ERRATA

REPORT NUMBER: FAA-RD-78-157 DATED: FEBRUARY 1979

Review of Airworthiness Standards for Certification of Helicopters for Instrument Flight Rules (IFR) Operation

PAGE 4-113: In Figure 4-36 (Labeling on graph)

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PAGE 4-115: In Figure 4-37 (Labeling on graph on right side)

$\zeta =$ 0.2 should read $= 0.11$

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RELEASE DATE: APRIL 24, 1979

Technical Report Documentation Page

1. Report No. (18) FAA-RD (19) 78-157	2. Government Accession No.	3. Recipient's Catalog No. (11)
4. Title and Subtitle (6) Review of Airworthiness Standards for Certification of Helicopters for Instrument Flight Rules (IFR) Operation,		5. Report Date Feb[redacted] [redacted]79
		6. Performing Organization Code SSED/FSD
7. Author(s) (10) J. J. Traybar, D. L. Green [redacted] A. G. DeLucien		8. Performing Organization Report No. (14) PAR-007-79
9. Performing Organization Name and Address PACER Systems, Inc. (Suite 510) 1755 S. Jefferson Davis Highway Arlington, VA 22202		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. (15) DOT-FA77WA-3966
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, D.C. 20591		13. Type of Report and Period Covered (9) Final Report, Apr[redacted] [redacted]77 [redacted] Jun[redacted] [redacted]78
		14. Sponsoring Agency Code FAA/ARD-530
15. Supplementary Notes (12) 247p.		

16. Abstract

This report reviews the Airworthiness Standards for Certification of Helicopters for Instrument Flight Rules Operation. It specifically reviews the Interim Criteria, Federal Aviation Regulations, Advisory Circulars and other pertinent documents associated with the certification of Helicopters for Instrument Flight. A review of current technology, existing data applicable to IFR helicopter operation and certification procedures is accomplished. Identification of specific airworthiness requirements for helicopters operating in IFR conditions is studied and special attention is given to aircrew manning configurations, pilot flight-control workloads, helicopter trim, static stability, dynamic stability, handling qualities, analysis of time history data and documentation procedures, augmentation systems, autopilots and a review of certain flight test techniques. An analysis was made of the numerous helicopters recently certified for IFR flight in order to establish the various systems utilized including avionics systems, display systems and autopilot type systems. Special emphasis was centered on the study of the most critical IFR flight phases depicted by high workload cruise conditions and marginal stability conditions due aft c.g. conditions, descent, and high climb rate conditions during IFR approaches and missed approaches for Category I procedures.

17. Key Words HELICOPTER: AIRWORTHINESS STANDARDS FOR IFR CERTIFICATION, CRITERIA, HANDLING QUALITIES, STABILITY AND CONTROL		18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) UNCLASSIFIED	20. Security Classif. (of this page) UNCLASSIFIED	21. No. of Pages 252	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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PREFACE

The study described in this report was sponsored by the Systems Research and Development Service (SRDS), Federal Aviation Administration, U.S. Department of Transportation under Contract Number DOT-FA77WA-3966. Mr. Thomas C. West (ARD-530) served as technical monitor and engineer for the Systems Research and Development Service.

The authors wish to express their appreciation to the Aerospatiale Helicopter Corporation, Atlantic Aviation Corporation/Agusta Division, Bell Helicopter Textron, Boeing Vertol Company, Sikorsky Aircraft Company, Sperry Flight Systems, Jet Fleet Corporation, Petroleum Helicopters Incorporated and to the other organizations, agencies and operators for their willing assistance, data, candid comments and cooperation for this research. Special thanks must be made to those companies that released technical information and data on IFR helicopters and systems.

Recognition is also given to the branches and sections of the Federal Aviation Administration; namely, the Aircraft Flight Safety Branch of SRDS (ARD-530), the Southwest Regional Headquarters at Fort Worth, Texas (ASW), the Aircraft Handling Qualities Section, Flight Test Branch (AFS-160) of Flight Standards Service, and the Northeast Regional Headquarters at Boston, Massachusetts (ANE), for their timely briefings and cooperation.

Special appreciation and gratitude is given to Messrs. J. Shapley (ASW-216) and T. C. West (ARD-530) for their valuable time, vital assistance, painstaking reviews and helpful comments during the entire course of the study.

Additionally, the authors specifically wish to thank Messrs. R. J. Tapscott (NASA-Langley), S. J. Craig (Systems Technology, Inc., Hawthorne, California), T. A. Dukes (Princeton University) and R. Scharpf (Eustis Directorate, Virginia) for their suggestions, interpretations and guidance regarding aircraft handling qualities criteria and flight systems requirements.

Finally, heartfelt appreciation is extended to Mrs. Lori Perkowski and Ms. Anne Smoot for the many long hours of typing and retyping of this report and to Mr. Stephen W. Jordan for his careful editing and review of the final text. The special thanks of the authors cannot be adequately expressed.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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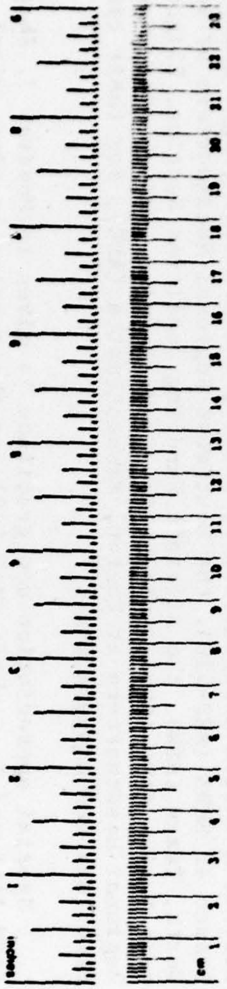
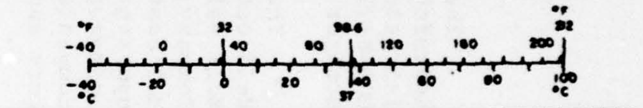
*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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ABBREVIATIONS

AC	Advisory Circular
A/C	Aircraft
ADF	Automatic Direction Finder
ADI	Attitude Director Indicator
AFCS	Automated Flight Control System
AGL	Above Ground Level
AIM	Airman's Information Manual
AMC	Aircrew Manning Configuration
AP	Autopilot
ARU	Attitude Retention Unit
ASR	Airport Surveillance Radar
ASW	Anti-Submarine Warfare
ATC	Air Traffic Control
BC	Back Course
CAT	Category
COMM	Communication
CRT	Cathode Ray Tube
DF	Direction Finder
DH	Decision Height
DME	UHF Standard (TACAN Compatible) Distance Measuring Equipment
FAA	Federal Aviation Administration
FAC	Final Approach Course
FAF	Final Approach Fix
FAR	Federal Aviation Regulations
FD	Flight Director
FM	Fan Marker
FSS	Flight Service Station
GNS	Global Navigation System
GS	Glideslope
IAF	Initial Approach Fix
IF	Intermediate Approach Fix
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
IMLS	Interim Microwave Landing System
ITO	Instrument Takeoff
LF	Low Frequency
LOC	Localizer
LOM	Compass Locator at Outer Marker ILS
MAP	Missed Approach Point
MDA	Minimum Descent Altitude
MLS	Microwave Landing System
MM	Middle Marker (ILS)
MSL	Mean Sea Level
NAV	Navigation

NDB	Non-Directional Radio Beacon
NM	Nautical Miles
NPH	Non-Precision (Approach) Helicopter
OM	Outer Marker (ILS)
PAR	Precision Approach Radar
PIC	Pilot-in-Command
RNAV	Area Navigation
RVR	Runway Visual Range
SAS	Stability Augmentation System
SCAS	Stability and Control Augmentation System
SFAR	Special Federal Aviation Regulation
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
STC	Supplemental Type Certificate
SVFR	Special Visual Flight Rules
TACAN	UHF Navigational Facility Omni-Directional Course and Distance Information
TC	Type Certification
TCA	Terminal Control Area
TERPS	Terminal Instrument Procedures
UHF	Ultra High Frequency
VASI	Visual Approach Slope Indicator
VFR	Visual Flight Rules
VHF	Very High Frequency
VLF	Very Low Frequency
VMC	Visual Meteorological Conditions
VOR	VHF Omni-Directional Radio Range
VORTAC	Combined VOR and TACAN System
VOT	a VOR Receiver Testing Facility

FAR PART I SPEED DEFINITIONS

V_A	Design maneuvering speed.
V_C	Design cruising speed.
V_D	Design diving speed.
V_H	Maximum speed in level flight with maximum continuous power.
V_{NE}	Never-exceed speed.
V_X	Speed for best angle of climb.
V_Y	Speed for best rate of climb.

LIST OF SYMBOLS

$C_{1/2}$	Cycles to one-half amplitude, ND
C_2	Cycles to double amplitude, ND
$d\,\delta/du$	Derivative notation for stick position variation with speed
e	Logarithmic constant, $e = 2.71828$
g	Acceleration due to gravity, ($32.2\ ft/sec^2$)
j	Notation for square root of minus one
M	Pitching moment, ft/lb
M_u	Velocity stability derivative, rate of change and pitching moment divided by moment of inertia with velocity
M_w	Angle of attack stability derivative, rate of change of pitching moment divided by moment of inertia with angle of attack
n	Normal acceleration or normal load factor (measured at the c.g.)
ND	NOSE DOWN or Non-Dimensional
NU	NOSE UP
n/α	The steady-state normal acceleration change per unit change in angle of attack for an incremental elevator deflection at constant speed
s	Laplace transfer complex variable, ($s = \sigma + j\,\omega$)
t	Time, sec
t/T_n	Non-dimensional time, ND
T_n	Period based on undamped natural frequency ($T_n = 2\pi/\omega_n$) Figure D-3
T_P	Period of oscillation, sec
$T_{1/2}$	Time to one-half amplitude, sec

LIST OF SYMBOLS (cont'd)

T_2	Time to double amplitude, sec
T_{63}	First order time constant, sec
u	Horizontal perturbation velocity, sec
U_o	Trim flight velocity, knots or ft/sec
V_h	Horizontal velocity, knots
V_v	Vertical velocity, knots or ft/min
w	Vertical perturbation velocity
Z_w	Stability derivative, rate of change of Z force divided by mass with vertical perturbation velocity
Z_u	Stability derivative, rate of change of Z force divided by mass with horizontal perturbation velocity
α	Angle of attack, deg or rad, ($\alpha \doteq w/U_o$)
γ	Flight path angle, deg, ($\gamma = \theta - \alpha$)
δ	Control deflection, deg
ζ	Damping ratio, ND, (The ratio of the damping that exists in a second order system to the critical damping)
θ	Pitch angle, deg or rad
π	Approximate value equal to 3.14159
σ	Real part of s
ω	Imaginary part of s
ω_n	Natural frequency, rad/sec or cyc/sec
ω_{nd}	Damped frequency, rad/sec or cyc/sec

SECTION 1

INTRODUCTION

The helicopter was originally developed to fill a very specific need; namely, to accomplish tasks which could only be achieved by hovering, taking-off vertically, or landing vertically. The first practical helicopters were severely limited by inadequate power available, engine reliability, range, stability, etc. In short, the early helicopter, like the early airplane, was a very fragile vehicle.

The late 1950s and early 1960s, witnessed the introduction of the turbo-shaft engine, improved rotor design, and the broader use of advanced materials and equipment for the helicopter. Thus, a more modern helicopter evolved and came into being with improved hydraulic systems, flight control systems, gyro-referenced stability/control augmentation systems, large attitude indicators, radar altimeters, and systems to automatically maintain a constant rotor speed. The U.S. Navy and Sikorsky Aircraft Co. were early pioneers in this development process. The Anti-Submarine Warfare (ASW) mission provided the incentive. The all-weather ASW mission requirement first produced the Sikorsky SH-34J in the late 1950s and subsequently, the Sikorsky SH-3A in the early 1960s. Both of these aircraft could be easily flown IFR, and when all systems worked properly, it was possible to conduct essentially automatic approaches to 20 to 40-foot hovers over the water. This was done with a two-pilot aircrew even under near "zero-zero" conditions at night over the constant, "flat-plane" of the sea.

Although a considerable amount of the early IFR helicopter utilization and technology had its origin in the military, there were some early civil entries as well. Notably, the Cessna Aircraft Company developed the CH-1 helicopter and in 1958 requested an IFR certification. This aircraft was followed by the Vertol BV-107, similarly developed in the early 1960s. The Sikorsky S-61L/N, a derivative of the SH-3A, was also a very successful pioneer civil IFR certification, (Reference 1).

Because of the accomplishments of the Sikorsky S-61L/N, it must be considered one of the most successful early entries into the area of civil IFR certification and operations (Reference 2). The considerable success and lessons learned from this aircraft program are quite significant and should not be forgotten. During the six years of scheduled IFR passenger-carrying operations that were conducted in the Los Angeles area between 1965 and 1972, many innovative and lasting milestones for IFR helicopter operations were achieved. Los Angeles Airways (LAA) received approval in June 1950 to operate four S-51 helicopters. These aircraft were unstabilized and had only a bungee-type force trim system. LAA began implementing a comprehensive instrument program with a stabilized (AFCS equipped) S-61 as early as 1961. Two instrument rated pilots were used for these operations and in April 1965, the first IFR scheduled passenger flights were conducted. "Helicopter-only" instrument approaches and departures were used together with some innovations that included an early type of "point-in-space" concept. Although this IFR activity represented a specialized operation, it was located in a high-density area and it was concluded that"...instrument operations definitely increased completion factors while decreasing the pilot workload", (Reference 2). Some additional generalized results of that operation as stated in Reference 2 are: "...pilot's attitude toward instrument flying was excellent; that it was safer, more productive and increased their professional value; enroute times did not increase significantly and in fact, they declined in many instances; it often took longer to fly a trip Special VFR than it did IFR, the ATC people were excellent and imaginative". The entire operation and experience had a major impact on the development of Chapter 11 in the Terminal Instrument Procedures (TERPS) conference in May 1970.

Since those first requests, the FAA has continued to certify helicopters for IFR operations by allowing manufacturers to demonstrate compliance with certain airplane-type FAA requirements or by demonstrating "equivalent safety" (Reference 3). Initial use was made of mechanical and electro-mechanical-hydraulic stability augmentors (of the type that usually provided additional angular damping and sometimes "lagged-rate" type augmentation) to aid in satisfying some of the handling qualities requirements. Interim Criteria for IFR certification of helicopters (Reference 4) were developed (with certain material drawn from and/or emulating various sections of the already existing Military Specification for helicopters, MIL-H-8501A., Reference 5), and have been in use throughout the 1970s.

The intervening years have seen the BH-212, SA-330, S-58T and SA-341, A-109, BO-105, and SA-360 helicopters certified for U.S. civil IFR use. In addition, it should be noted that the FAA amended FAR Part 61, Certification: Pilots and Flight Instructors, (to permit cost effective instrument training in non IFR-certified helicopters) and issued a Special FAR (SFAR) 29. The SFAR 29 authorized evaluation of special helicopter IFR routings in remote operations. This SFAR was extended for three years, to allow more operators an opportunity to participate, and apparently will continue to be extended and "in-force" for the near future.

Many recent certification programs have centered on adapting in-service helicopters to IFR requirements via the use of Supplemental

Type Certification (STC); however, helicopter manufacturers are now striving to have the IFR capability designed into future helicopters. This change in approach should impact 1978-1979 programs such as the Bell 222 and Sikorsky S-76. In addition, many aircraft and avionics manufacturers are expected to strive for single-pilot certifications. This suggests that most new helicopter programs will involve concomitant IFR certification during the initial Type Certification (TC). The fact is, there will be more and more applications for IFR STCs and initial IFR Type Certification for helicopters.

The anticipated or projected growth in IFR applications has several explanations. First, many commercial operators are being pressed by their customers for a near 100% mission availability, almost regardless of weather conditions. A second reason involves the rapid increase in the number of government and corporate operators. Many of these operators desire all-weather capability and are not quickly deterred by equipment costs. Next, many IFR-rated helicopter pilots from the military have been absorbed into civil aviation. The reservoir of trained pilots has made it possible for operators to economically field IFR-qualified crews. This evolving need for a general IFR helicopter capability has caused a fourth factor to develop, the availability of new helicopter avionics. The avionics industry has responded with a wide range of equipment that has made it possible to expand the capabilities of civil helicopter operators. This potential for increased capability has in turn added emphasis to the apparent need for many helicopters to be certified for IFR operations.

As opposed to many general aviation and small air-taxi airplane owner/operators, the helicopter owner/operator is frequently forced by necessity to utilize his helicopter to a fuller extent because of its relatively high purchase price and direct operating costs. If the cost per flight hour becomes too great, the customers will seek other ways to satisfy their transportation requirements. The pressure for minimum costs and maximum utilization is passed quickly to the manufacturer. Operating costs can be reduced by minimizing crew (one-pilot vs two-pilots) and minimizing system complexity (initial purchase costs and possible maintenance costs). Concurrently, with a decrease in operating cost, everyone on the industry side strongly desires to maximize the certified IFR capability of their vehicles. Ideally, helicopter manufacturers would like to offer a "basic" vehicle (with satisfactory stability and control), single-pilot crew manning (for the smaller vehicles), basic display/navigation/communication systems, and have the FAA certify the helicopter for a maximum of IFR utility.

Free enterprise, on the other hand, has offered relief to what would (for some aircraft) otherwise be an unacceptable state of affairs. Electronic system manufacturers variously offer such things as radar, flight directors, autopilots, navigation couplers, approach couplers, augmentation systems, Automatic Flight Control Systems (AFCS) and computer driven Cathode Ray Tube (CRT) displays linked to flight and navigation sensors. Military and civil experience has demonstrated that when state-of-the-art technology is applied to almost any helicopter in adequate layers, that helicopter can be made abundantly capable of IFR operations for all varying mission objectives and crew manning levels.

The FAA is in the mandated position of making the final assessment as to what combination of crew, helicopter and equipment are safe for various operations and the different combinations of environmental factors. This position of final recourse requires superior judgment, analysis, and rating on the part of the certification team yet there is no obvious alternative which can provide a higher level of consumer safety.

In this study, a review is made of Interim Criteria (Appendix A), the most pertinent FAR, Advisory Circulars and other regulatory supportive material. Subjects that relate to handling qualities, certification procedures, and IFR operations of helicopters are reviewed and addressed for the purposes of providing data and information that is of value to the FAA in updating the appropriate documents. The objective of this effort is to provide a basis for increasing the level of safety of helicopters operating under IFR conditions through the definition of requirements based on current and valid state-of-the-art data.

The study includes identification of specific operational and airworthiness requirements for helicopters flying in Instrument Meteorological Conditions and accomplishing approaches to the Category II minimums. Consideration is given to the appropriate present and near-future navigation aids, their cockpit displays, the needs and effects of autopilots, flight directors, instrument displays, pilot workload and ATC interaction. A review of ongoing programs, current technology, and existing data applicable to IFR helicopter operations and certification has been made. Data searches were conducted and survey trips and telephone conferences were made with helicopter manufacturers, research organizations and agencies, helicopter instrument flight instruction schools, military instrument flight units and avionics manufacturers. During the course of the data collection, acquisition, and review, efforts were made to isolate those data judged valid and useful for developing new or modifying current regulations and requirements pertaining to IFR certification of helicopters.

This report is divided into five sections and Appendices. The Introductory section is followed by four sections presenting various information, data and results on operations, certification, and analytical efforts and conclusions. Section 2 provides a review and definition of operational objectives. Section 3 covers a variety of topics under the general headings of certification considerations and technology review. It includes subject areas such as helicopters currently certified, use of SAS, autopilot systems, critical IFR flight phases, minimum aircrew manning considerations, documentation goals, pilot workload, envelope tailoring, displays, etc. Section 4 contains a summary of all the efforts associated with the collection and analysis of IFR related helicopter data. It combines the flight test data obtained from reviews of civil and military helicopter reports, simulator and flight research findings, criteria statements from the Interim Criteria, FAR and criteria data established by earlier military and civil flying qualities requirement documents. Section 5 contains the conclusionary findings. The Appendices cover the Interim Criteria, Handling Qualities definitions, Complex plane mapping techniques, the Divergence Criterion, and a reference on engine power loss.

SECTION 2

REVIEW AND DEFINITION OF OPERATIONAL OBJECTIVES

There are a great number of helicopter flight conditions and related sets of operational and environmental factors which impact them. However, the unique capabilities which enable rotary wing aircraft to undertake specialized missions are evidenced more under VMC than under IMC. It is also apparent that once penetration into IMC occurs, the actual conduct of any mission will be essentially the same for all helicopters, regardless of objective.

Composite Helicopter IFR Flight Profile

Following a review of FAA documentation, operational objectives were defined in terms of a Composite Helicopter IFR Flight Profile (Figures 2-1 through 2-4). It included all possible events and occurrences of a routine nature that helicopter pilots might encounter during flight under IMC. The Profile was divided into flight phases to be relatively consistent with the current procedures embodied in Reference 6 (MIL-F-8785B) and Reference 7 (MIL-F-83300). The events and flight phases were determined through a study of FARs and AIM Part I. One possible condition of a routine nature was not included - the Profile Descent - because it is an airplane-only condition, applying to turbojets and turboprops weighing 12,500 pounds or greater.

Selection of an appropriate instrument approach to conclude the Composite Profile was based on using that approach representing the highest level of workload -- because certification requirements call for evaluating a helicopter in its most critical environment. Non-precision approaches using terminal navaids, off-airport/heliport navaids, or a point-in-space were excluded because they are normally less demanding than the precision ILS approach. Radar Approaches, both precision and non-precision GCAs, provide verbal cues from a controller in addition to visual cues for the pilot from his instruments, but because they offer similar workload when compared to the final approach segment of an ILS and are seldom encountered in civil operations, were not included. The precision approach of the Composite Profile is considered to include the Missed Approach phase, because that possibility always exists as a continuation of the approach phase.

The Approach/Missed Approach portion of helicopter IFR flights is generally regarded within the industry as the most critical from the pilot's standpoint. Even so, there are pilots who contend that the enroute portion of such flights can generate a total workload level as demanding as that experienced in the approach segments. This is because

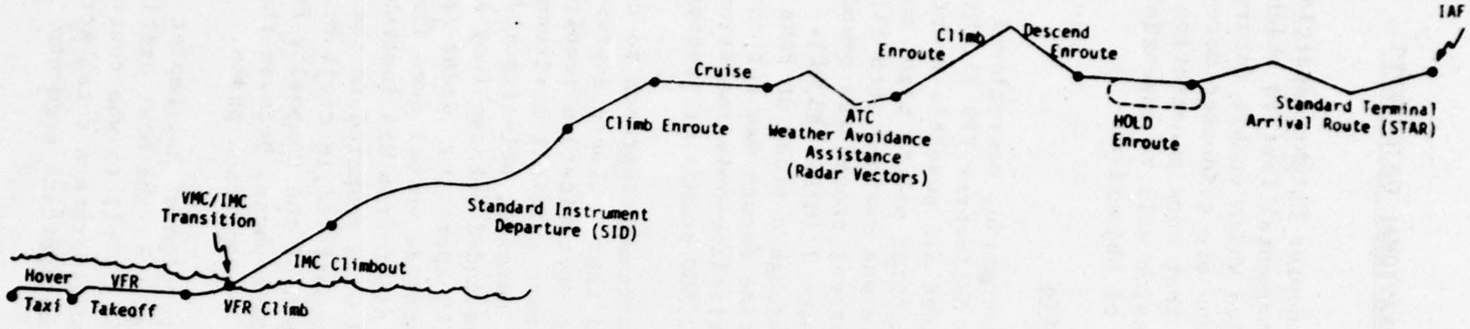


Figure 2-1. Composite Helicopter IFR Flight Profile. (Departure and Enroute)

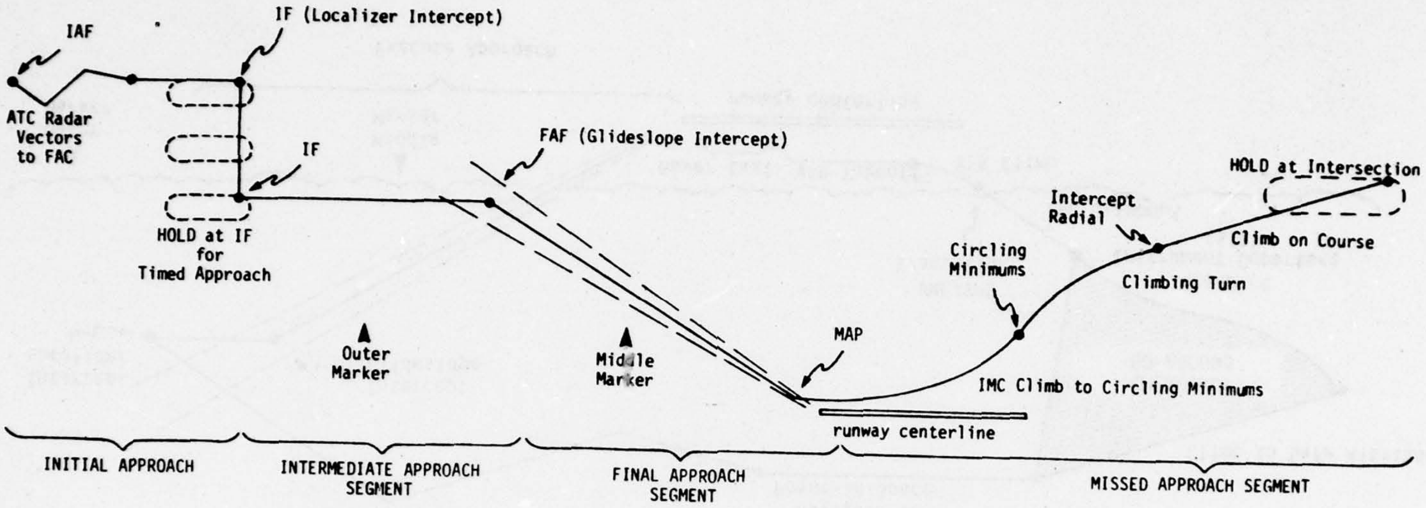


Figure 2-2. Composite Helicopter IFR Flight Profile (Approach and Missed Approach)

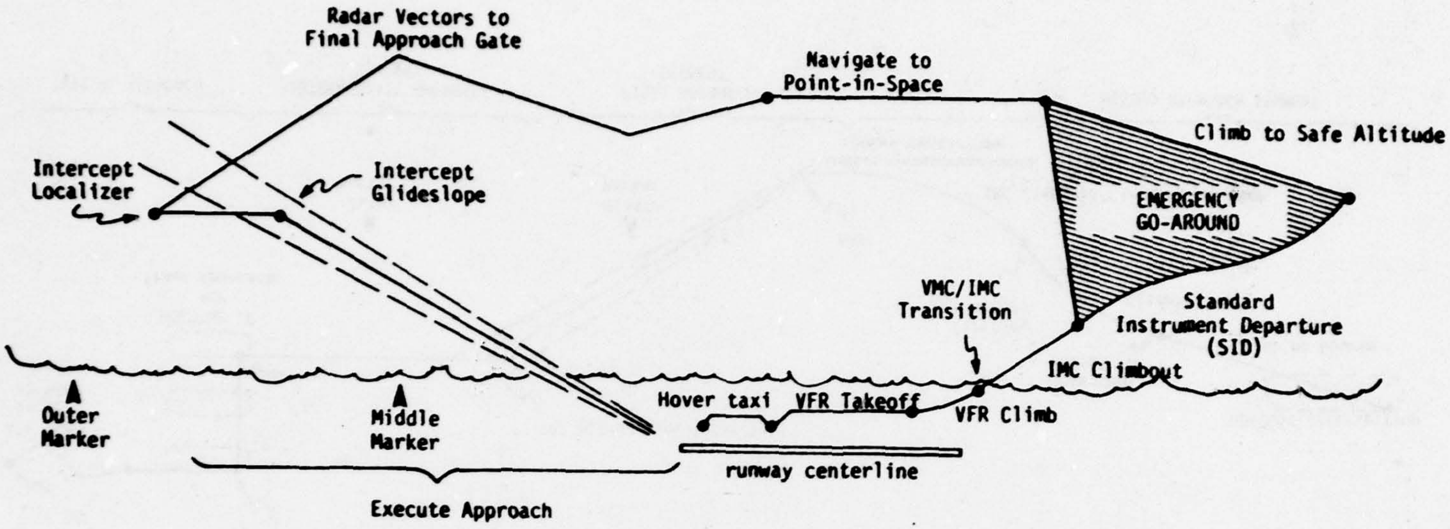


Figure 2-3. Composite Helicopter IFR Flight Profile.
(Emergency Go-Around/Precautionary Return-to-Landing)

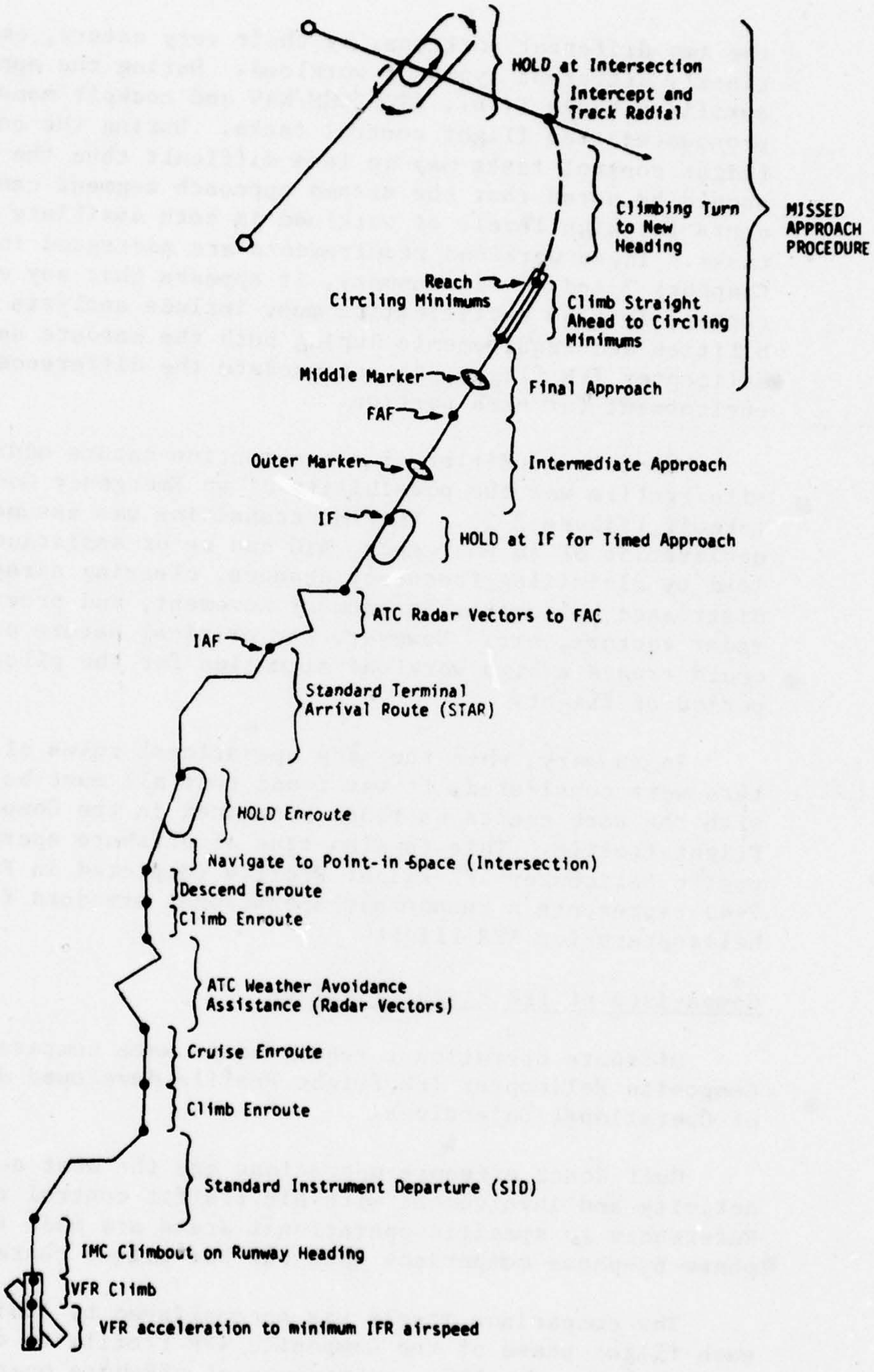


Figure 2-4. Composite Helicopter IFR Flight Profile. (Plan View)

the two different portions, by their very nature, emphasize two distinctly different types of workload. During the approach segment, auxiliary tasks (i.e., ATC/COMM/NAV and cockpit management) are less pronounced than flight control tasks. During the enroute portion, flight control tasks may be less difficult than the auxiliary tasks. It should be noted that the missed approach segment can generate requirements for high levels of workload in both auxiliary <u>and</u> flight control tasks. These workload requirements are addressed in more detail in Chapters 3 and 4. In summary, it appears that any evaluation of helicopters for IFR certification must include analysis of the total capabilities and requirements during both the enroute and terminal phases of helicopter IFR flight, to accommodate the differences in operational environment for each portion.

The only condition of a non-routine nature addressed in the Composite Profile was the possibility of an Emergency Go-Around after takeoff (Figure 2-3). VMC/IMC transition was assumed complete. After declaration of an emergency, ATC can be of assistance to reduce workload by minimizing frequency changes, clearing airspace to allow the distressed helicopter freedom of movement, and providing navigational radar vectors, etc. However, the critical nature of the emergency could create a high workload situation for the pilot during the remaining period of flight.

In summary, when the many operational roles of civilian helicopters were considered, it was found that all must be prepared to contend with the same events as those contained in the Composite Helicopter IFR Flight Profile. This is also true of offshore operations. The Composite Helicopter IFR Flight Profile (depicted in Figures 2-1 through 2-4) represents a reasonable operational standard for certification of helicopters for IFR flight.

Comparison of IFR Flight Profiles

Offshore operational requirements were compared against the Composite Helicopter IFR Flight Profile developed during the definition of Operational Objectives.

Gulf Coast offshore operations are the most developed in terms of activity and involvement with air traffic control requirements. References to specific operational areas are made throughout the phase-by-phase comparison when one has unique characteristics.

The comparison itself was accomplished by individually reviewing each flight phase of the Composite IFR Profile to determine if it was applicable to the IFR requirements of offshore operations. Each flight phase is addressed below. The impact of takeoff minima is addressed separately.

The helicopter community did not unanimously agree that all missions have essentially the same requirements when operating under IMC. Some felt that the offshore IFR mission was a special case in itself. Review of the offshore IFR profile revealed that it is, in fact, no different than the Composite Profile. Although it appeared to be a special case, when weather conditions created low ceilings and limited visibility, the pilots had to be prepared to contend with virtually all the same requirements as other IFR operators, even those in high-density areas such as the Northeast Corridor.

With the exception of flight separation spacing brought about by limited range communications, navigation, and radar flight following, the ATC requirements that can be expected for operators in the offshore environment are the same as those for any onshore environment, where one can encounter all the events described in the Composite Profile detailed earlier.

The offshore profile differs significantly in terms of outbound or inbound flights. The most demanding ATC requirements occur when helicopters return to shore from the rigs. Here they can be faced with much the same tasks as in a high-density area (in terms of ATC requirements) but often without a high volume of traffic. Outbound there is limited similarity to the Composite Profile. Major profiles are shown in Figures 2-5, 2-6 and 2-7 for Gulf Coast Operations.

Comparison by Flight Phase

The details of the comparison of offshore operations against the Composite Profile by flight phase follows.

Takeoffs by helicopters for IFR operations are under visual conditions (i.e., with visual reference to the ground and at airspeeds to preclude collision with obstacles and other aircraft). This applies to both Part 135 and Part 91 operators, regardless of minimums. Not addressed in the comparison was the military Instrument Takeoff (ITO) as practiced by a number of military organizations since it is more of a tactical (non-civil) departure, which consists of near vertical takeoff into overcast conditions. The transition in airspeed from zero knots at liftoff to 70-80 knots climb speed is done completely on instruments with the initial climbout IMC when ceilings are zero-zero. This is taught (and practiced under the hood) but rarely used. Few military aviators experience the need to use the ITO when filing IFR. Typically they execute a departure similar to civilian operations - a VFR takeoff and transition to IMC after achieving minimum airspeeds that are comfortable for the VMC/IMC transition.

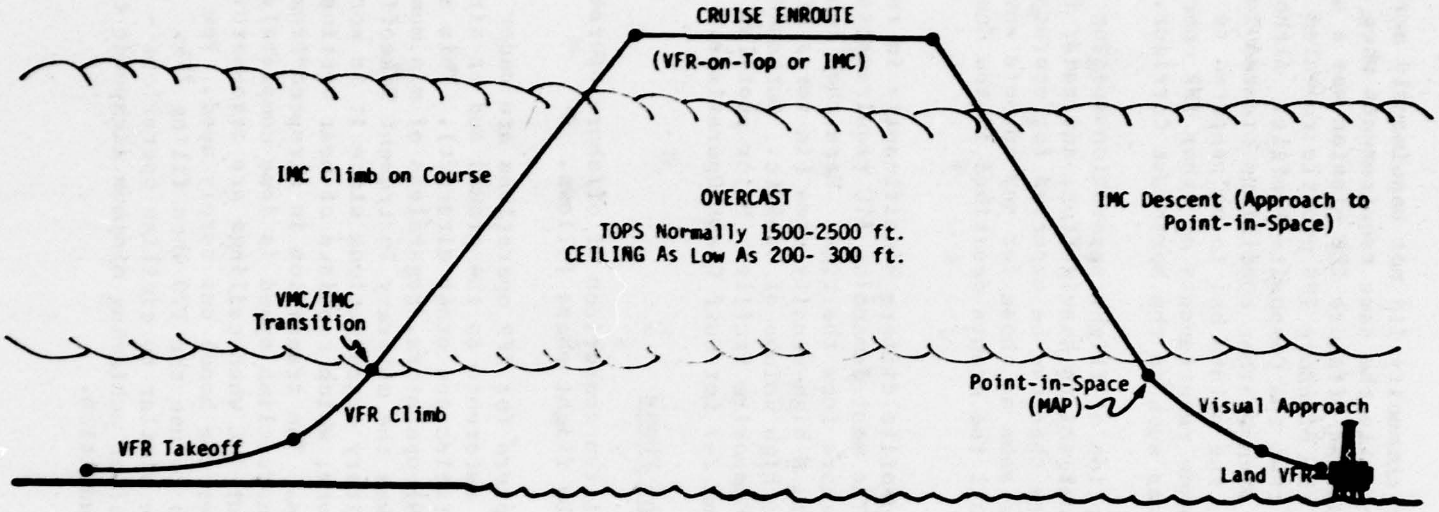


Figure 2-5. Gulf Coast Offshore IFR Flight Profile.
(Outbound, Year-Round)

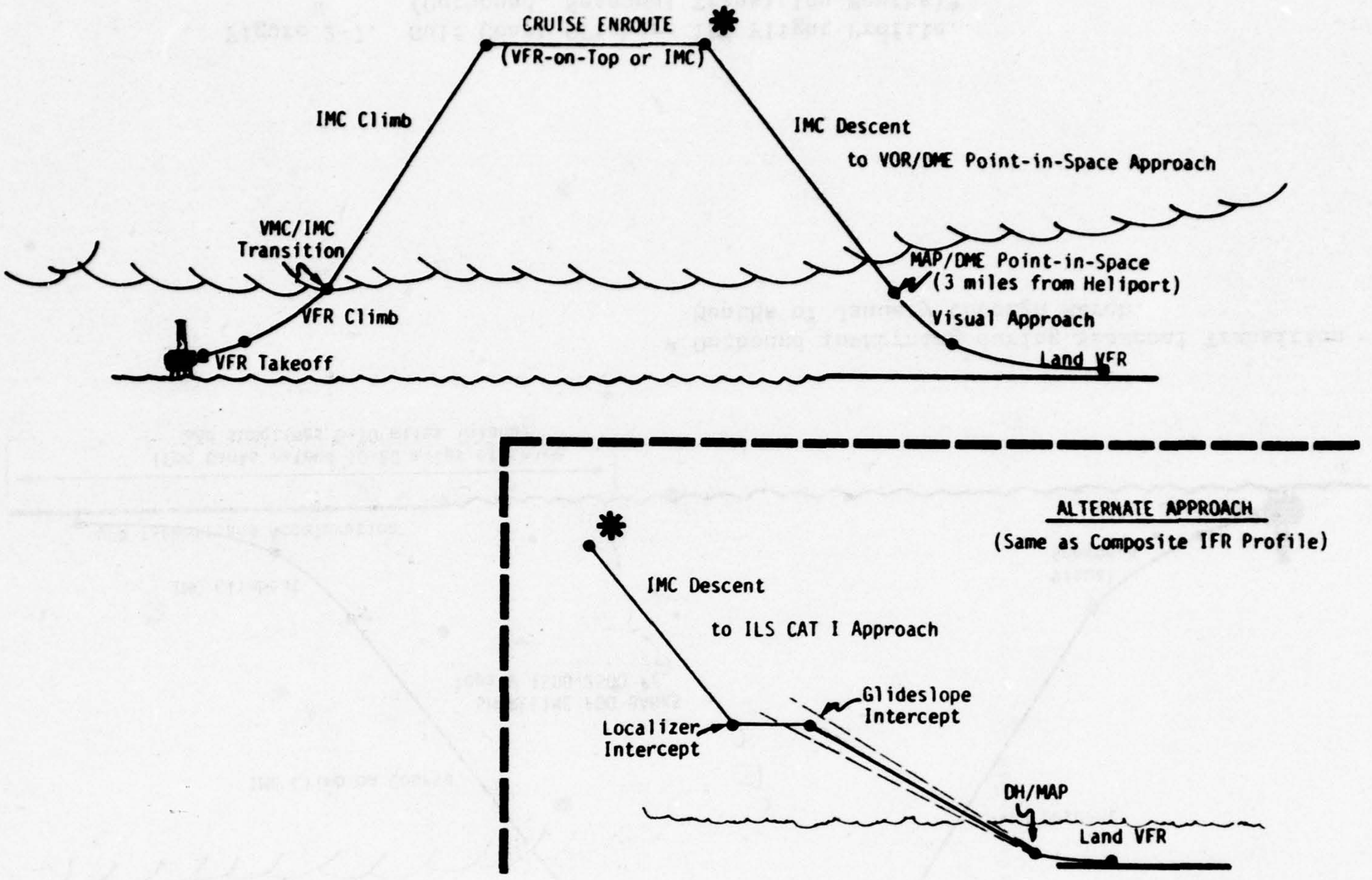
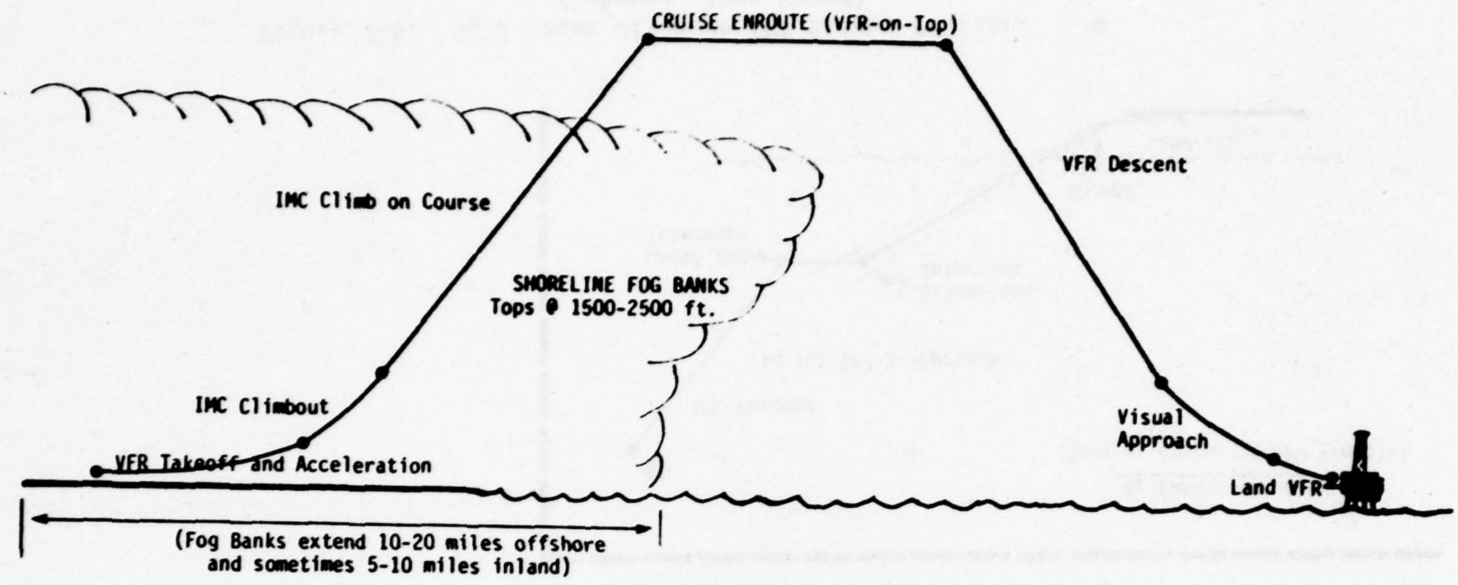


Figure 2-6. Gulf Coast Offshore IFR Flight Profile.
(Inbound, Year-Round)



* Outbound in Morning during Seasonal Transition Months of January through March.

Figure 2-7. Gulf Coast Offshore IFR Flight Profile. (Outbound, Seasonal Transition Months)*

Standard Instrument Departures are applicable on those occasions where departure is from an airfield (such as New Orleans International) on an IFR day when required by ATC for separation purposes. Normally, takeoff will be under VMC conditions with penetration into IMC at approximately 200-300 ft. above ground level. Climb enroute and VMC/IMC transition typically occur at about the same time.

Climb, Cruise, and Descent Enroute are as delineated in the Composite Profile.

ATC Weather Avoidance Assist (Radar Vectors) are available within approximately 50 miles of the coast and vectors around weather are not unusual. Farther out in the vicinity of rigs, shore-based radar coverage is not normally available.

Hold Enroute. Outbound flights normally do not encounter holding requirements. Inbound this becomes a common occurrence when returning with low ceilings requiring a precision approach to a major airport.

Standard Terminal Arrival Route (STAR). Inbound flights, especially when anticipating precision approaches to major airports, are likely candidates for use of STARs. As the Atlantic offshore region develops, this could become a normal occurrence because of the high volume of onshore traffic already in existence in the area.

ATC Radar Vector to Final Approach Course (FAC) are a distinct possibility for inbound offshore flights (again to precision approaches at major airports). This practice is common in West Coast operations (Santa Barbara Channel) for outbound flights (radar vectors to rigs are considered equivalent to vectors to FAC). The distances from shore radar installations to where rigs are located on the Gulf and East Coast preclude this becoming common practice for outbound flights in those areas.

Hold at Approach Fix for Timed Approach. Outbound this rarely, if ever, occurs. Inbound this is quite possible.

Final Approach Phase. Comparison of the various possible approaches is discussed separately.

General. Offshore operations require different approach procedures for outbound and inbound flights. Since precision aids are not yet in existence on the rigs themselves, outbound flights terminate with non-precision approaches (typically, VFL/OMEGA with airborne radar). For inbound flights the complete spectrum of approaches is possible. According to offshore pilots, ILS is considered to be the most demanding approach from a workload standpoint.

Outbound Final Approach Phase. Flight plans are filed to an offshore grid approximately 2.8 miles square, in which the destination rig is located. The outbound flight is conducted to a point-in-space determined with VLF/Omega navigation equipment, and that point-in-space becomes the missed approach point.

The approach itself is typically conducted using VLF/Omega during descent to the missed approach point-in-space. Weather radar, operated in ground mapping mode, is used as a backup for obstruction clearance and to help identify rig location more precisely.

Weather minimums set by FAA are 600 - 1 without radar and 300 - 1 with radar. At least one offshore operator expressed a desire for reducing minimums with radar to 200 - 1/2. The approach with radar is the most complex and was used for the comparison. Typical approach profile follows:

> VLF/Omega equipment provides azimuth and distance readouts to the filed point-in-space. The pilot begins his descent to arrive at minimum altitude upon reaching the point-in-space, using the weather radar in the ground mapping mode. Approximate distance to the rig can be determined by using the range rings on the radar screen.
>
> At approximately 2 miles from the rig, during descent to minimums, the pilot turns 15 degrees away from the rig to the downwind side. This allows the helicopter additional separation from the rig because of the wind advantage. The target rig is painted on the radar screen throughout the approach.
>
> Upon reaching the bottom of the overcast, the helicopter transitions to VMC and continues the approach. The copilot, in the left seat, establishes visual contact with the rig while the pilot continues to fly the approach heading (15 degrees downwind). Abeam of the rig, the copilot takes the controls and turns toward the rig, which provides an into-the-wind heading for a visual approach.

Inbound Final Approach Phase. Return flights inbound offer the full range of possible approaches. There are three approaches most commonly used during offshore operations:

- VOR/DME approach is typically used at heliports along the shoreline, and at alternate airports that do not have ILS approaches.

- VOR/DME to Point-in-Space approach is used at heliports that have high towers or other nearby obstructions. In a Gulf Coast example of this case, a point-in-space is used which is 3 miles from the heliport and is the missed approach point (MAP). At the MAP, if under VMC, the pilot continues the flight VFR underneath and maintains VFR separation from obstructions.

- Cat-I ILS approaches are used into a major airport when ceilings are encountered that make VOR/DME approaches unusable.

Offshore pilots consider both types of VOR/DME approaches to be less demanding than the precision requirements of an ILS. The Point-in-Space approach was identified by them as the most comfortable from the pilot's standpoint because of the assurance of obstruction clearance from both towers and other structures in the vicinity of airports and heliports since the last three miles of the approach are conducted VMC with no airspeed requirements.

Impact of Takeoff Minima on Offshore Flight Profiles. There are two categories of offshore operators: Part 91 and Part 135. Each has to comply with different takeoff minima. Part 135 operators have both ceiling and visibility minima, while Part 91 operators can effectively take off under zero-zero conditions. Part 91 governs companies operating offshore which own and operate their own helicopter fleets. Part 135 governs the air taxi/charter operators who contract out to companies, providing commercial services.

Part 91 operators need comply only with visibility requirements, and not ceiling. Presently, all helicopters engaged in offshore operations are in the two-engine or less category and thus require only one statute mile visibility for takeoff under IMC. However, by requesting a Special VFR (SVFR) clearance, they may commence the flight without any visibility or ceiling requirements. SVFR requires only that the pilot have sufficient visibility (pilot-determined) to avoid collision with obstacles or other aircraft. Technically, SVFR flight may be conducted with weather reported zero-zero at the departure point. The options open to the pilot after SVFR departure are: conduct the whole flight VFR; or, pick up an IFR clearance after takeoff, changing from VFR to IFR enroute.

Part 135 operators have an additional requirement for an alternate airport within one hour flying time at normal cruise if weather conditions are below the authorized IFR landing minima for the point of departure. These requirements can be changed by FAA issued Operational Specifications (Op Specs). For example, the Op Specs of one Part 135 operator prescribe takeoff minima of 300 - 1/2, or landing minima for point of departure, whichever is greater except that when taking off from an airport with an ILS approach the operator may use the lower ILS minima.

Landing Minima for ILS Approaches

Advisory Circular 97-1 details the visibility and Decision Height (DH) requirements for the various categories of Instrument Landing System approaches:

> "GENERAL INFORMATION. All-weather instrument approach operations are divided into categories corresponding to different standards of instrumentation in the aircraft and on the ground. For each category, there is a minimum value of specified Runway Visual Range (RVR) below which operations are not permitted. The following table identifies the categories and LOWEST minima associated with each:
>
> | Category | Visibility (RVR) |
> |---|---|
> | Nonprecision | 2400 feet |
> | Category I | 1800 feet - (DH = 200 feet) |
> | Category II | 1200 feet - (DH = 100 feet) |
> | Category IIIA | 700 feet - (DH None prescribed) |
> | Category IIIB | 150 feet - (DH None prescribed) |
> | Category IIIC | 0 feet - (DH None prescribed)" |

Perspective on Helicopter ILS Approaches

It must be made clear from the beginning that, when weather conditions are not too severe, a CAT I ILS approach to a runway, in currently IFR certified helicopters flown at their minimum approved approach speeds, is not overly difficult. This is true at the more ideal flight envelope parameters and configurations both for single pilot operations with all systems working, and when there are two pilots in the cockpit. There are two distinct advantages in this situation of the helicopter over fixed wing. First, at its typically lower approach speed, there is an extra moment or two (compared to airplanes) after breakout for pilots to transition to a VMC approach and landing. Second, there is no requirement to effect a virtually immediate touchdown near the runway threshold.

SECTION 3

CERTIFICATION CONSIDERATIONS AND TECHNOLOGY REVIEW

INTRODUCTION

The study took into consideration the appropriate current and near-future helicopter automatic stabilization systems, stability augmentation systems, cockpit displays, flight directors, navigation aids and navigation coupler systems. The results of this effort were used to define the combinations of equipment which in turn define the configuration that should logically be considered when establishing workload levels for the critical flight phases (defined as a result of studying profiles such as those depicted in Section 2). Equipment combinations and related characteristics were analyzed in context with two very different IFR air traffic and electronic situations. The high density air traffic situation was considered as well as operation in the lower density offshore environment. Also, two of the higher workload flight phases were considered to apply: the instrument approach phases and the IMC cruise-enroute phases, where the auxiliary task levels are high.

A general discussion and listing of some of the specific helicopters that have been certified for IFR is given together with a short review of the applicable stability and control augmentation systems and automatic stabilization equipment utilized. Aircrew manning configurations are defined and documentation of helicopter configuration and modes of operation are detailed. The importance of pilot workload (especially for single-pilot manning levels) is discussed. Also, general topics such as envelope tailoring, the display/control systems/workload trade off, decreased IFR visibility minima for helicopter approaches, computer simulation for dynamic responses and the need for a radar altimeter for autorotations under IMC.

SPECIFIC HELICOPTERS CERTIFIED FOR IFR FLIGHT

The flight manuals, IFR supplements and other pertinent information on the helicopters listed below were reviewed to determine the IFR equipment needed, manning requirements and other certification facts.

HELICOPTER		MINIMUM IFR CREW
AEROSPATIALE	GAZELLE SA-341G	1 PILOT
AEROSPATIALE	DAUPHIN SA-360C	1 PILOT
AEROSPATIALE	PUMA SA-330J	2 PILOT
AUGUSTA	A-109A	1 PILOT
BELL	212 TWIN	2 PILOT
BOEING/BOELKOW	BO-105C	1 PILOT
SIKORSKY	S-61N	2 PILOT
SIKORSKY	S-58T	2 PILOT
SPERRY/BELL	212 TWIN	1 PILOT

In reading the various Helicopter handbooks, IFR Supplements and other pertinent data in order to determine what was certified and what was the intent of each item under such headings as GENERAL, LIMITATIONS, OPERATIONS-NORMAL PROCEDURES, EMERGENCY PROCEDURES and REQUIRED PLACARDS, etc., some interpretation of meaning was occasionally required; however, in most cases the information was explicit. The following information and interpretations, as determined from the available data are offered on the helicopter IFR certifications, systems and aircrew manning requirements.

Of the nine helicopter/IFR systems listed above, five are certified for single pilot and four (usually the larger/heavier aircraft) are certified for dual pilot IFR flight. All the aircraft are twin engined except the Gazelle SA-341G and the Dauphin SA-360C. Numerous avionics and flight systems companies have been responsible for the installation of the components required for IFR flight in the aircraft. If the helicopter was not designed from inception as an IFR aircraft and the additional equipment and new components were assembled as "add-ons" to obtain IFR certification for a VFR vehicle, the general rule seemed to be "change the basic design of the VFR vehicle as little as possible while providing maximum beneficial handling qualities changes with the add-on equipment." This usually meant providing only the needed equipment and new systems (commensurate with assurance of reliability/redundancy requirements and compliance with the Interim Criteria) in order to keep the costs down and still provide a readily certifiable, safe IFR aircraft. This was especially true when multiple systems had to be considered for installation (e.g., Duplex and Triplex SAS and Autopilot Systems). Also, almost all the single piloted IFR helicopters require the ATTITUDE-HOLD mode of the basic autopilot to be turned on and available during IFR flight. This was determined by reading and interpreting the intent of the information contained in the handbooks and IFR supplements.

For the BELL 212 Twin aircraft there are two different certifications, a single-piloted one designated SPERRY/BELL 212 and a dual-piloted one designated BELL 212. The BELL 212 incorporated a BELL Automatic Flight Control System (AFCS) that was comprised of a SCAS system and an Attitude Retention Unit, ARU (an outer loop attitude-hold system). The SCAS used in this aircraft adjusts the pilot's control sensitivity and augments the angular damping of the helicopter through the use of electronic rate gyro signal feedbacks. The BELL 212 also utilizes a mechanical stabilizer bar (as does the SPERRY/BELL 212) to provide inputs for pitch and roll angular damping (lagged-rate damping). The bar is a strictly mechanical system that provides a limited amount of artificial stability.

A few general statements should be made about the yaw axis control of some of these helicopters with regard to their installed systems. If augmentation actuators exist in the yaw axis, it is usually in the form of yaw rate dampers. In some systems, the augmentation is of the type frequently referred to as lagged-rate feedback for the low speed flight regime. For the higher speeds, some of the lagged-rate augmentation is washed-out and a force/coordinated-turn feature is provided so that pilots can more easily coordinate their turns. For the yaw axis, this amounts to getting rid of some of the yaw damping and yaw angle stiffness so that directional control sensitivity stays relatively high at the higher speeds. This is especially true if the helicopter has a large vertical tail that provides additional damping to "stiffen the system" at these higher speeds. Some coordinated-turn systems make use of a lateral accelerometer that measures slips and skids and provides correcting control motions to eliminate them. If a heading-hold feature is utilized, the yaw actuator responds to the gyro commands in order to hold heading. If actuators exist in the pitch and roll channels only, then heading-hold is accomplished by the roll actuator and the pilot manually controls the anti-torque pedals to provide coordinated flight.

STABILITY AND CONTROL AUGMENTATION SYSTEMS AND AUTOMATIC STABILIZATION EQUIPMENT

General

The recent advent of numerous IFR certifications of helicopters has brought forth a myriad of new and sometimes novel stability and control augmentation systems, automatic stabilization systems and avionics equipment. Introduction of the use of state-of-the-art flight instruments, updated avionics, and a new variety of augmentation and autopilot systems has aided in providing certification approval for single-pilot IFR helicopters. Recent vehicle design improvements and the use of auxiliary tail surfaces have improved the inherent stability and control characteristics of basic helicopters in cruise flight. The improved basic machine, the addition of artificial augmentation and control systems, state-of-the-art displays and avionics and the use of autopilot-type stabilization systems all have provided the means to conduct IFR helicopter flight operations for slower speed instrument approaches as well as cruise speed flight. The high speed end of the VFR flight envelope is sometimes reduced for IFR flight and the slow speed end used for instrument approach purposes is constrained to minimum IFR airspeeds ranging from 40 to 70 knots. Instrument flight at slower speeds and hover is still prohibited for such reasons as stability and trim problems, lack of adequate displays, need for additional air data instrumentation, and the requirement for new navigation/approach systems that will provide glide slopes steeper then three degrees. However, even with today's helicopter systems and certifications, a pilot flying an ILS type approach at about 40 knots (presuming he desires to limit his maximum rate of descent to about 500 feet per minute) could fly down a glide slope of almost 8 degrees if the precision approach aid existed today (Figure 3-1). The subject areas of stability and control, automatic stabilization equipment, IFR flight operations, and other systems used for approaches in terminal areas are well covered in the literature (References 8 through 21).

Utility of Stability Augmentation and Automatic Stability Equipment

A significant element that distinguishes present IFR certified helicopters from existing VFR-only vehicles (as far as handling qualities; e.g., dynamic stability and control, and workload etc., are concerned) is the addition of attitude gyro packages. Attitude gyros provide the means to obtain greatly improved stability and control and flying qualities as well as allowing for implementation of autopilot type devices that are frequently used to reduce workload. Through the use of attitude and attitude rate information, the response of the aircraft to gusts may be greatly diminished by introducing enhanced

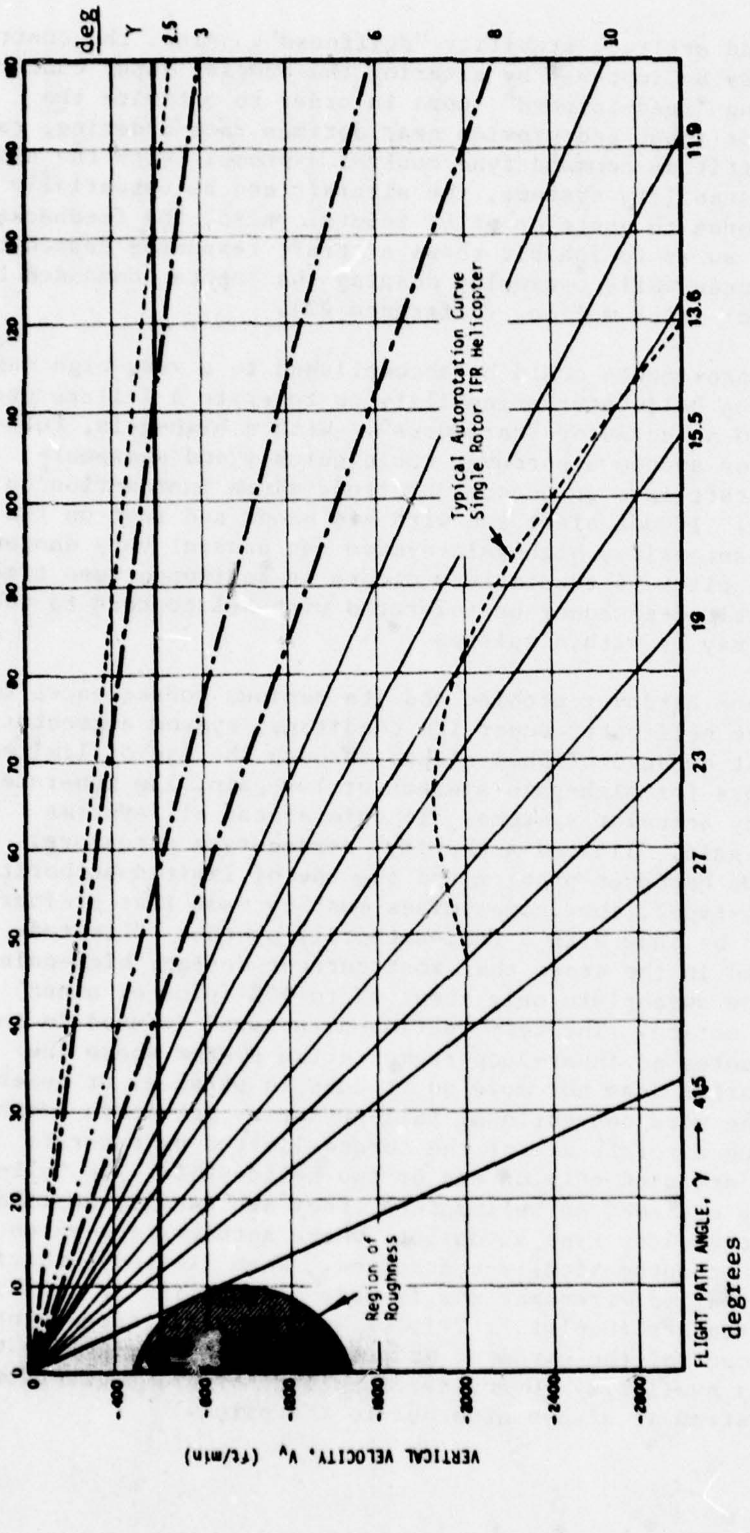


Figure 3-1. Relationship of Typical Autorotation Curve to Flight Path Angle Plots.

angular damping and attitude stability "stiffness". Also, the control system features may be improved by altering the damping input characteristics and using "feed-forward" loops in order to optimize the response to a pilot input and provide near optimum rate ordering, rate command, and/or attitude command type control systems. With the aid of these artificial stability systems, the aircraft can be essentially decoupled in response to gusts or pilot inputs. Also, the feedbacks may be programmed so as to inhibit those aircraft responses caused by external disturbances while optimally shaping the inputs commanded by the pilot's control stick motion, (Reference 22).

All these improvements could be accomplished to a very high degree were it not for the helicopter's inability to tolerate a failure condition referred to as actuator "hardovers". With a high-gain, full-authority, actuator system a hardover could quickly and unexpectedly put the aircraft into an unusual attitude given inattention on the part of the pilot. If not alert and with his hands and feet on the controls, a full-authority, high-gain system can present very dangerous situations to the pilot if the failure occurs at an inopportune time. Severe unusual attitudes cannot be tolerated with helicopters to the degree that they may be with airplanes.

Because of the hardover problem and its serious consequences to the control of the helicopter under IFR conditons, system augmentation or automation must be accomplished either through the use of limited authority actuators for high-gain systems or low-gain, low run-rates for full-authority actuator systems. To date almost all systems make use of high-gain, "limited-authority" series-type actuators. As a result of the hardover problem and the use of limited-authority actuators (series-type), some compromises must be made that ordinarily would not have to be made with a full-authority system. "Limited-authority" is used in the sense that most current design, high-gain actuators move the swashplate only about 5% to 15% (plus or minus) of its full control motion. The term "series-actuators" is used in the sense that it denotes an inner-loop augmentation system where the pilot's control stick does not move as it does in parallel or outer-loop systems. The more conventional full-authority actuators commonly used on fixed wing aircraft are of the torque-limited or run-rate limited type and are used only on one or two helicopters. If full-authority systems are used on helicopters, they are usually applied to attitude-hold, outer-loop type autopilots where actuator run-rates are strongly limited or automatically controlled. When limited-authority actuators are installed, frequent use is made of doubling or tripling the number of actuators (Duplex or Triplex Systems with independent transducers) to control the hardover problem while increasing the total control authority available. Override capability of all augmentation and autopilot systems is always afforded to the pilot.

All currently certified IFR helicopters have control systems that are fully powered using irreversible control system devices. These "boost" systems essentially isolate the rotor blade vibratory forces and motions from the pilot and also provide him with relatively low control forces. There are no "sensible" feedback forces applied to the pilot's controls by the swashplate or rotor blade pitch horns anyway (i.e., no forces similar to those normally provided by conventional control surfaces on classic airplanes), and therefore simple systems such as spring cartridges or capsules are usually incorporated with the pilot's controls to provide him with a constant spring force gradient. There is a capability for the pilot to reposition that "null-point of the gradient" as control position trim requirements dictate. A typical system schematic for an artificial augmentation/automatic flight control system is shown in Figure 3-2.

Definition of Stability Augmentation and Automatic Stabilization Equipment

Many forms of Stability Augmentation Systems and Automatic Stabilization Equipment have been utilized to improve the basic handling qualities of helicopters by enhancing, modifying, and improving the angular damping, control and maneuvering response, stability, and long-term trim as well as providing workload relief for the pilot. The various systems take many forms and some of the more common definitions and attributes are given below. Two primary feedback quantities are utilized for the basic functions of these systems. They are attitude and attitude rate. For the more sophisticated coupled operations, radio position signals (ILS, VOR etc.), radio-rate signals, barometric signals, radar signals (radar altimeter), airspeed data, accelerations, heading etc., may be added to the basic function of the automatic stabilization equipment. Only the most basic types and functions of Stability Augmentation Systems (SAS) and Automatic Stabilization Systems will be discussed here. They are:

- Stability Augmentation Systems, (SAS)
  Rate-SAS
  Attitude-SAS
- Stability and Control Augmentation Systems, (SCAS)
  Rate-SCAS
  Attitude-SCAS
- Lagged-Rate Stabilization
  Young's Stabilizer Bar (Bell-Bar)
- Automatic Stabilization Equipment, (ASE)
  Attitude-Hold mode of an Autopilot
  (ATTITUDE-HOLD/AP).

The following definitions and system descriptions are used in this report.

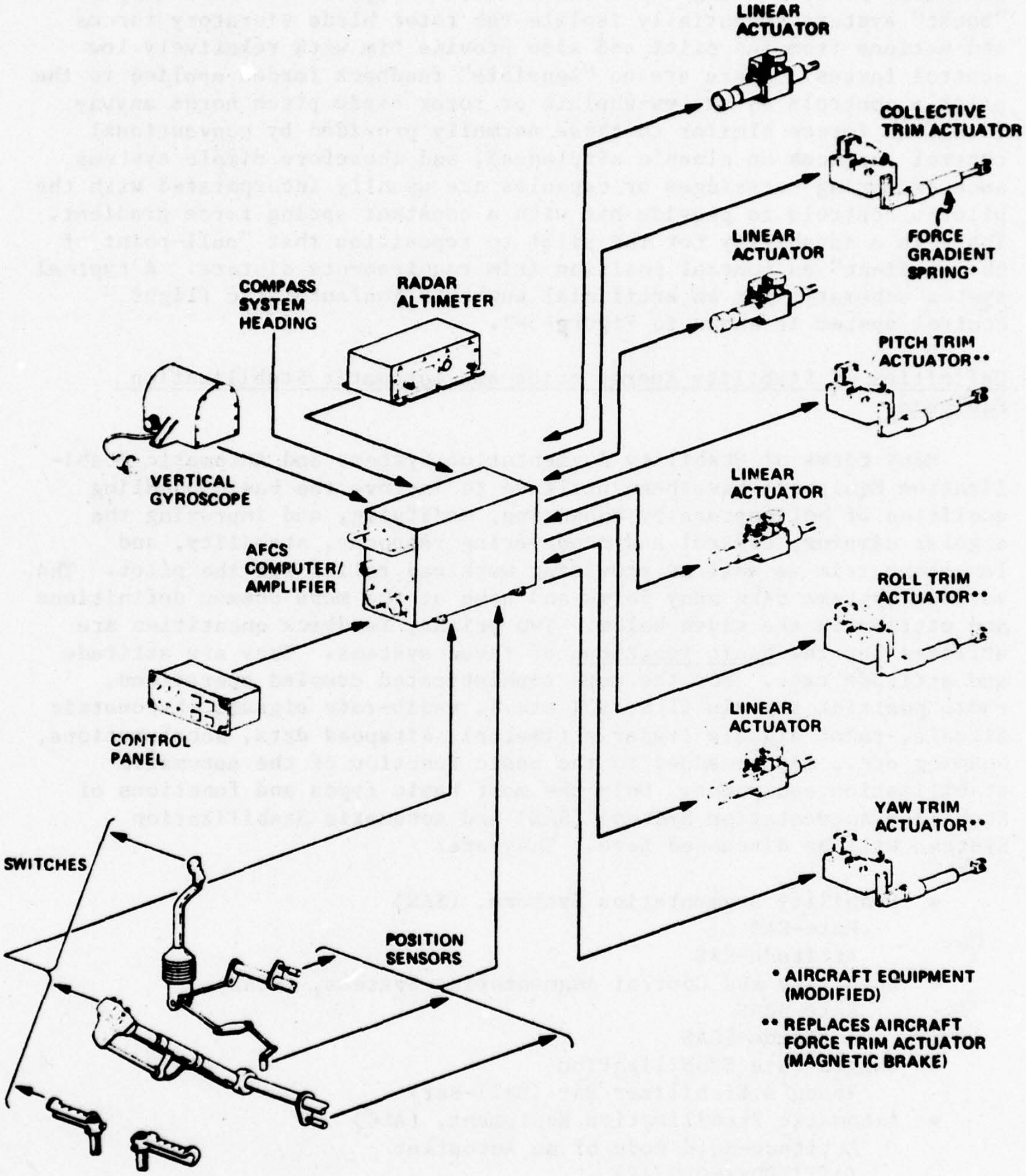


Figure 3-2. Schematic of a Typical Augmentation/Automatic Flight Control System (Reference 13).

Rate-SAS is any system that enhances or supplements the inherent angular damping of an aircraft. The hardware of the system may comprise electrical, mechanical, and fluidic devices and components. Rate signals (or derived rate) are used as feedback quantities. The systems produce an enhanced moment-opposing motion that is proportional to aircraft angular rates. When systems can be approximated as being first-order, the characteristic time required to achieve 63% of the final steady state angular velocity (following a step input) is of importance in characterizing the system.

Attitude-SAS is any system that enhances or supplements the stability and the damping of the basic aircraft. Attitude-SAS in this report always implies that both Attitude and Attitude Rate signals are used as feedback quantities. An attitude (vertical) gyro type system is required. With relation to the aircraft, a new or "synthetic" aircraft stability derivative is created and provides an attitude "stiffness" or stability with respect to the horizontal flight path. Of course, the aircraft can provide stability only with respect to the velocity vector so that use of this "new" stability derivative is an extremely important addition to the system and is essentially the foundation for single-pilot IFR flight in helicopters. Since many basic helicopters represent low damped systems in vital portions of their flight envelope, the use of attitude rate with attitude feedback is also very important. Use of just attitude signals or rate signals alone usually cannot optimize the stability of the aircraft for all conditions of the flight envelope. Both SAS and SCAS systems are considered fly-through, pilot-in-the-loop, hands-on type systems. When attitude signals are used in these systems they are usually "washed-out" or "leaked-off" in the short term and thus tend to provide an attitude type response in the very short term and a rate type response in the longer term.

Rate-SCAS is any system that enhances, modifies or supplements the angular damping and control system response of the aircraft. Use of the term SCAS normally implies that "feed-forward" loops are utilized and pilot's control motion is sensed. In these systems, the augmentation actuators will move either with the pilot's control input or against it in order to establish or maintain a pitch (roll) rate that is proportional to his input. In other words, the pilot's pitch and roll control sensitivity may be adjusted in terms of his input. With these systems, it is most important to note that if a gust upsets the aircraft and the pilot did not move his controls (as sensed by the control motion or position sensors attached to his stick), the augmentation actuators will be utilized to suppress or attenuate the effects of the gust. In addition to the enhancement of the control system, Rate-SCAS implies that rate feedbacks are also used to modify the angular damping of the vehicle (Reference 22). An important aspect of these systems must be noted. Use of the term SCAS normally implies that both the aircraft and its augmentation actuators will respond totally differently depending on whether the input is caused by the pilot's control motions or by an external disturbance. When the input is a control motion by the pilot, the SCAS system will sense the stick motion and the actuators will not immediately start to provide additional damping but will usually (depending on the model and the programming) initially enhance his control quickness (in effect, increase the stick gearing). Then the actuator motion will reverse and provide the damping to approximate a rate-ordering type control system. When the input is caused by an external disturbance, the SCAS system will sense that the input was not the pilot's control motion and the actuators will immediately attempt to suppress or attenuate the upset. The important item to note here is that the actuator motion, in this gust case, is usually relatively larger and it is not uncommon for limited-authority type actuators to saturate during these circumstances. Regardless of input, saturation of actuator motion provides the pilot with a non-linear control and motion characteristic for the aircraft.

Attitude-SCAS is any system that enhances, modifies or supplements the stability, angular damping, and control system response. Attitude-SCAS in this report always implies that both Attitude and Attitude Rate signals are used as feedback quantities. The characteristics of the Attitude-SCAS system can be determined by what has already been said above under Attitude-SAS and Rate-SCAS.

Lagged-Rate Stabilization is any system that uses rate and lagged-rate signals as feedback quantities. This characteristic is usually provided electronically when only rate gyro type signals are available. Also, another widely used system that offers lagged-rate stabilization is Young's Stabilizer-Bar (Bell-Bar, Hiller-Bar). The effects and use of these devices are widely documented in literature. Generally speaking, the stabilizer bar devices provide what has been called a mixture of rate damping and attitude stability for a certain frequency range. However, "true" attitude signals (as provided by a vertical gyro) are required to obtain the most beneficial effects over the speed range. The greatest benefits of the mechanical bar generally are obtained at hover and slow forward speeds. It normally provides only a modicum of the attitude stability and increased damping required for good handling qualities for IFR flight over the applicable speed ranges and should never be expected to completely overcome dynamic instabilities caused by divergences.

The Attitude-Hold Mode of an Autopilot (ATTITUDE-HOLD/AP) is the most basic function provided by Autopilots or Automatic Stabilization Equipment. ATTITUDE-HOLD/AP systems imply basic autopilot functions that will maintain aircraft pitch, roll, and yaw (heading) long-term attitude automatically, for pilot-out-of-the-loop, hands-off type operation. As stated in many manuals, "The system will, without pilot intervention, hold whatever pitch and roll attitude the pilot places on the helicopter". However, when these systems are used in helicopters, and depending on the mechanization and method of operation, they are considered by many pilots also to be fly-through, pilot-in-the-loop and hands-on operation. This dichotomy in viewpoint is easily understandable because of the way many of these ATTITUDE-HOLD/AP systems are used during IFR flight in helicopters. Regardless of whether the autopilot system is an inner-loop type (where the control stick does not move) or an outer-loop type, the pilot is always able to easily cancel the attitude-hold feedback loop (integral of attitude) and fly the aircraft himself. This is usually done by exerting pressure on the control (force or position sensors on the controls) or typically through use of the Force Trim Release (FTR) button located on the pilot's cyclic stick. This must be accomplished since either the autopilot <u>or</u> the pilot can be controlling the aircraft <u>at any instant</u> in the Attitude-Hold mode of operation. The FTR button provides the pilot with the capability of manually positioning the cyclic for desired pitch and roll corrections and to establish new pitch and roll reference attitudes for the autopilot when in the ATTITUDE-HOLD MODE. Without the FTR button, the pilot would have to override or overpower the actuators in order to make any desired attitude changes when in the ATTITUDE-HOLD mode of operation. (This ATTITUDE HOLD/AP operating technique is just the opposite of typical SAS or SCAS systems operation. The SAS or SCAS systems are designed and meant to be used as fly-through devices for the pilot where <u>both</u> he <u>and</u> the augmentation actuators are (each) always simultaneously and jointly providing their own <u>unique</u> inputs to the control system for swash plate control motion.) As an emergency procedure, the pilot can always override or overpower (by clutches or control authority) the autopilot inputs (or any augmentation inputs) without disabling the attitude-hold feedback loop.

During precision flight (with the ATTITUDE-HOLD/AP System engaged) where the pilot may be injecting control motions as frequently as one input every second or two, he will be actively interrupting the attitude-hold feedback loop on a moment by moment basis and placing a new reference attitude on the autopilot as frequently as he wishes. On many installations he can also enter the loop by operating various knobs and wheels that provide bias inputs for new attitudes or headings.

If, according to the FAA certification, the ATTITUDE-HOLD mode of operation <u>is</u> required to be "enabled" for the duration of the IFR flight (mandatory), the pilot may not permanently turn off the autopilot (ATTITUDE-HOLD function) during any portion of the flight. Should he choose to keep the Force Trim Release (FTR -- a momentary switch) button depressed all the time (say during an ILS approach when he is closely controlling the helicopter with frequent control inputs), he will effectively be disabling the ATTITUDE-HOLD mode for the longer term. Keeping the FTR button depressed all the time removes the spring gradient forces from the controls. This is a piloting technique that is highly desired (and cherished) by a large segment of helicopter pilots for the conditions where frequent, "delicate" control motions are required. Such activity is often required for precision ILS or precision hovering with a sling load.

The ATTITUDE-HOLD/AP system has been used in many single-pilot IFR aircraft and is a required equipment that is mandatory for IFR flight in most certified single-pilot helicopters. It is frequently installed to provide the single-pilot with flight control workload relief in order that he may accomplish the necessary auxiliary tasks required for IFR flights within the National Airspace System. Although the ATTITUDE-HOLD/AP system provides a degree of flight control workload relief for the pilot, it may not provide it long term. In classic airplanes, "attitude-hold" more nearly implies an autopilot function in that it usually tends to hold heading, altitude and airspeed to some tolerable degree for an acceptable length of time. In helicopters, depending on the specific characteristics of each vehicle, attitude-hold may provide none of these heading/altitude/airspeed-hold features long term. In order to achieve "real" autopilot-type functions in a helicopter, it is usually necessary to actually provide the air data (such as altitude and airspeed) and heading data as feedback information and close the loops. When these data are provided as additional information to a Flight Director System/Computer and the autopilot coupled to it, it is frequently referred to by pilots as "coupled-autopilot" or "coupler" operation and implies pilot "out-of-the-loop", automatic/hands-off flight path control. If the pilot does not choose to disconnect this system, he may get into the loop only to the extent of operating trim wheels, buttons, knobs or switches as inputs to the autopilot system (pilot "flying-by-the-knobs" operation). Also, if information from installed radio navigation and approach systems (VOR, ILS, etc.) is provided to the flight computer and autopilot such that automatic guidance, tracking and flight path steering are available, it is frequently referred to as a fully coupled autopilot. This also is considered pilot out-of-the-loop, hands-off, "flying-by-the-knobs, switches and buttons" operation.

THE CRITICAL IFR FLIGHT PHASES

IFR Scenarios

The following IFR scenarios were selected as the most pertinent and relevant to the IFR certification process for helicopters. In this analysis, the mission is to satisfactorily complete a safe IFR flight within the National Airspace System using a helicopter. Special emphasis is placed on two flight phases (and the associated flight subphases). They are:

- The Approach/Missed Approach Flight Phases for Category I type operations.
- The Enroute Flight Phases where high density/high ATC activity conditions exist and require high workload, auxiliary task achievement on the part of the pilot.

The Approach/Missed Approach Flight Phases for Category I type operations are generally high workload flight control situations for the pilot. They encompass all the flight subphases connected with approaches and missed approaches in the high-density terminal area. They include the letdown, normally associated with the initial approach segment, terminal area holding, identifying approach fixes, localizer/glide slope capture and tracking, missed approach procedures, and all the necessary auxiliary tasks such as communication, navigation, ATC interaction, chart handling, and chart reading, etc., (Figure 2-2). When a single-pilot is flying the helicopter, he may subordinate all possible auxiliary tasks in order to concentrate on the flight control task to achieve maximum tracking performance while on final approach (or the missed approach).

The Enroute Flight Phases, where high density, high ATC activities and other auxiliary tasks may impose a high workload on the single-pilot, are also of importance. Normally, for enroute phases of helicopter flight, the pilot must direct more effort toward the auxiliary tasks of flight planning, ATC interaction, cruise control, navigation and general management of the flight. It would appear logical to expect that under conditions of high auxiliary task loading, the pilot may desire to reduce the amount of effort he is using for the flight control task. If, in this cruise phase, the auxiliary task workload is high and the flight control workload also remains relatively high (e.g., because of turbulence), the enroute flight phase can also become critical and perhaps most critical relative to certification.

The primary factors of importance during these flight phases are the specifics which detail flight conditions, configurations and definition of flight envelope parameters. In this study, the flight condition, envelope, and configuration for the approach is always assumed to be dictated by the IFR Flight Manual and IFR Supplement (carried in the aircraft) under the IFR certification subsections labeled GENERAL, LIMITATIONS, OPERATIONS - NORMAL PROCEDURES, EMERGENCY PROCEDURES and REQUIRED PLACARDS, ETC. For the approach flight sub-phase, the minimum approved approach airspeeds are utilized, minimum crew is as stated (except where special consideration warrants discussion of other aircrew manning levels) and CAT I, CAT II - ILS precision approach operations are implied. As a special note, with the appropriate flight envelope considered (IFR envelope, if different than VFR envelope) and since it is within the purview of the examiner to certify, this report will normally consider that the certification includes the most critical IFR case. The critical case is exemplified by the most critical approved approach airspeeds, most critical c.g. conditions, most critical gross weights, most critical aircrew manning configuration and most critical descent and climb conditions for the enroute, approach, and missed approach flight phases. For example, this report emphasizes verification type flight tests for certification of the "worst condition" approved; such as, a missed approach at low altitude (CAT I), low air-speed, most aft c.g., light gross weight, and high climb rate (high power). This case would always be flight tested and closely examined. While these conditions may seem unduly harsh, they appear to be in keeping with the charge to the examiner to certify the most critical cases of the aircraft. This definition of a critical flight phase (or phases) serves to frame the pilot's task in the perspective needed for this analysis. The approach permits the study analyst to use handling qualities and workload level judgments in a way which basically parallel the approach followed by FAA pilots in their determination of the "minimum-acceptable" helicopter for IFR certification.

Additional Factors and Discussion

The definition of PERFORMANCE (in Appendix B) is adhered to in this report and it is presumed, that on the approach subphase detailed above, the pilot always strives to accomplish the task with a certain finite precision. For example, the precision expected could be similar to the performance limits presented as guideline values in Advisory Circular 61-64 (Part 61 Revised), Flight Test Guide for Helicopter Instrument Pilots.

SPECIAL CONDITIONS (Appendix B) of weather, aircraft environment, and pilot stress are included in the scenario of the approach described earlier. In this report, a critical condition is presumed, and it consists of approaches conducted under Category I ILS conditions. The prevailing weather conditions are not ideal. For example, the approach could be conducted at night in a steady but moderate rain. The wind, 15 knots gusting to 25, is aligned 45 degrees to the right of the approach heading and occasionally shifts to 90 degrees in a gust. Due to the low ceiling, visibility, and general weather, and commensurate with CAT I type ILS approaches, a missed approach with flight to an alternate is considered a probability. In addition, the case where the weather falls to near zero-zero is of some interest also. This last situation is particularly important in considering a single pilot, CAT I or CAT II approach with no passengers (and no copilot). In this case, the lone pilot must split his scan between his instruments and the outside during the critical moments when approaching the Decision Height.

Admittedly, these scenarios are critical and stringent ones, but it is felt that the charge of the certifying agency is to examine the so called "worst cases" as the most important case from the "level of safety required" standpoint and the "minimum acceptable" aircraft definition. It avoids basing the certification on information associated with narrow selections of favorable flight envelope parameters and limited special conditions. It should be kept in mind that if an applicant for IFR certification voluntarily elects to reduce the size of the IFR envelope as compared to the VFR envelope, the aircraft is accordingly documented and certified.

Military IFR Helicopter Operations

With regard to the scenarios portrayed herein and used as a base point for this study, a great deal has been heard or related about IFR military flying in certain helicopters using two-pilot aircrew manning levels. These apparently *extensive two-pilot* IFR operations are reportedly conducted easily and successfully on a routine basis. Although this is apparently the case, this information is somewhat discounted as being of significant aid here in defining a "minimum acceptable" IFR aircraft in keeping with a required "level of safety" for a number of reasons. Of the accounts rendered, no easily obtainable, well documented information could be traced for many of the types of data of interest for this report, such as the extent of envelope tailoring (either inadvertent or dictated); gross weights in effect; center of gravity positions; rates of climb and descent utilized; whether or not full power climbs were employed at critical gross weights; the degree of interaction with ATC; competence and skill levels of aircrews; whether the flights were actually IMC or simulated (hooded) flight; weather conditions; and tracking performances achieved for specific flight phases or subphases. As an example and with regard to the last few items listed above; it is always helpful to know if the IFR flight operations involved just "punching up and down" through stratus layers, a hooded GCA to a long runway, or an actual IMC, CAT-I, ILS precision night approach with crosswinds, turbulence, rain, obscurations and minimum IFR airspeeds. Generally, when several interviews were made, the military pilots revealed that they (two pilots) normally flew the more ideal speeds and flight envelope parameters and usually avoided the extremes of climb rate, aft c.g., etc. In the few cases where military helicopters could be found with ILS receivers on board (usually VIP Squadrons), it appeared that actual IFR flights and low approaches were usually targeted for or conducted at the more optimum flight conditions, flight envelope parameters, and special conditions of weather.

This general mode of operation was also found at civilian helicopter instrument training type schools. There may be two lessons here, but they may not be that easy to document or apply. One lesson is that for some helicopters, the IFR envelopes can be much smaller than the VFR envelopes. A second lesson is that reduced flight envelopes will yield a very acceptable level of productivity. This latter point may be particularly true when the amount of time actually spent in the IFR mission is calculated.

The Impact of Special Conditions of the Critical Case of Offshore IFR Operations

Offshore IFR operations are reviewed again here to examine the possible effects that SPECIAL CONDITIONS of weather and environment have on these IFR flights. Sketches of three possible weather and flight profiles for activities between the main bases on land and the oil rigs in the Gulf are shown in Section 2.

The case of interest here, for the Critical IFR Scenario SPECIAL CONDITIONS is portrayed in Figure 2-6 under the label Alternate Approach. In this case, a returning inbound flight must make a full ILS, CAT I type approach to New Orleans, Lafayette, etc., because of inability to complete a VOR/DME approach due to low minima. Because the home base is fogged-in, an approach must be made to the closest ILS equipped airport with weather good enough for the CAT I approach. Therefore, the Gulf Coast instrument pilot is occasionally forced into a high-density ATC/COMM/NAV environment complete with all the flight planning, holding enroute, flying in heavily controlled airspace and maneuvering with other airplane traffic in order to complete his CAT I approach. In effect, this indicates that they too may encounter the identical situations that commonly prevail at any high density airport. Also, this will be true probably to a greater degree for the Atlantic offshore operations where the weather, relatively speaking, will be worse and the amount of controlled airspace and traffic will be greater. Therefore, offshore helicopter IFR operations still fall within the scenario used for this report; namely, precision approach, CAT I - ILS, high density ATC/COMM/NAV environment. Surely the need for special routes, procedures and "helicopter-only" approach techniques will increase. Some FAA approved "helicopter-only" approach procedures exist but these will probably be updated to permit lower minima and accomodate advanced avionics and other newer navigation equipment such as MLS, Omega, LORAN C, RNAV and NAVSTAR/GPS when they become available.

AIRCREW MANNING CONFIGURATIONS AND OPERATIONS FOR SINGLE-PILOTED HELICOPTERS

General

Some single-pilot certified aircraft have alternate aircrew manning configurations for IFR flight when certain systems or equipment are inoperable. Generally speaking, if certain major systems or parts of systems required for single-pilot IFR are inoperable, options are available to fly the aircraft IFR legally. For example, on one single-pilot IFR vehicle, if the SAS-Autopilot systems are totally inoperable, the helicopter still may be flown legally and routinely on repeated IFR flights as long as a second, fully-rated pilot occupies the copilot's fully equipped flight station. On another single-pilot IFR helicopter that is equipped with dual SAS-Autopilot systems, if one of the two SAS-Autopilot systems is inoperative, "IFR flight may be initiated for the purpose of ferry to repair facility providing an IFR qualified second-in-command occupies the co-pilot's station and the aircraft is fitted with dual controls and dual flight instruments."

Minimum Aircrew Manning Levels

Although initially there were some minimum aircrew manning level variations for helicopters certified for IFR flight, the possible minimum aircrew manning levels appeared to have settled down to the obvious two types currently in use:

- One-Pilot
- Two-Pilot

The ONE-PILOT minimum aircrew manning level is currently being utilized for helicopters that have some type of pilot's aid or augmentation on board. The augmentation or aid usually takes the form of improving the dynamic stability and control of the helicopter and/or providing pilot workload relief in the form of an autopilot with an ATTITUDE-HOLD function. Although improvements in dynamic stability and control cannot always be directly related to improvements in flying qualities, it is safe to say that if the dynamics are improved to the point where they compare with well-behaved "classic" airplane dynamic stability and control, then the improved helicopter should be able to be flown single-pilot IFR as well as a single-pilot IFR airplane. Since it is becoming more apparent that some recent single-piloted IFR capable airplanes do not have "good" IFR handling qualities (Reference 23), the word "classic" refers to those airplanes that have well-behaved, favorable short period and long period mode characteristics and generally favorable handling qualities. For the classic airplane, the short period mode is optimally damped and the long period mode is well-behaved, stable and the airplane is easy to trim long term.

If augmentation systems are provided that make the helicopter match the handling qualities of the "classic" airplane, then apparently single-pilot IFR flight in a helicopter would "match" that of single-pilot IFR flight in a classic airplane. In order to achieve this to an optimal degree, the artificial means installed in the helicopter may comprise fly-by-wire or fly-by-light logic schemes, high-gain and low-gain, full-authority and limited-authority, series and parallel systems and actuators, programs and logic to decouple the helicopter controls and responses. The "means" might require automatic failure diagnosis, monitoring, and correction systems that would allow the single-piloted helicopter to operate IFR with a high level of reliability and safety. With these optimal systems, improved transducers, and displays, the single piloted helicopter can probably operate IFR over the full VFR flight envelope (including slow speed flight and hover).

Most single-pilot IFR helicopter systems recently certified use limited authority actuators, tailored flight envelopes, minimum slow speeds, restricted IFR climb rates, and workload relief systems obtained from the ATTITUDE-HOLD function of an autopilot. When an ATTITUDE-HOLD function of an autopilot is required as part of the approved IFR equipment for single-pilot IFR operation, it appears that the required flying qualities of the helicopter can be quite different fundamentally. Depending on the helicopter, two cases are possible.

When the aircraft is being actively maneuvered by the pilot (ATTITUDE-HOLD loop of autopilot disabled so that the pilot may control the aircraft), he may be operating a vehicle that has either of the below characteristics:

- Basic helicopter - No artificial augmentation of any kind installed on vehicle. No Rate or Attitude SAS or SCAS installed. Vehicle will probably have fixed or movable tail surfaces and may have a mechanical stabilizer-bar type device. The control system type will be characterized as Rate-type or Acceleration-type depending on the inherent angular damping of the basic vehicle (as characterized by the first-order time-constants). If no mechanical "decoupling boxes" are installed, helicopter control and response will be highly coupled.

  If the basic aircraft is too difficult for the single-pilot to control or attend to because of IFR flight conditions, workload, and other circumstances, he can always fall back to the ATTITUDE-HOLD mode of the Autopilot whenever he chooses. It will attempt to hold a selected attitude within the capability of its actuators and system design. Note, that for this case, either the Autopilot (in ATTITUDE-HOLD mode) controls the basic aircraft in attitude <u>or</u> the pilot controls the basic aircraft in attitude. Regardless of how frequent or momentary the pilot's inputs may be, only one of these two entities controls the attitude of the helicopter at the same instant.

- Augmented Helicopter - Artificial augmentation of some kind installed, (e.g., Rate or Attitude SAS or SCAS) and operating full time. This provides the pilot with an aircraft that has enhanced stability and control and flying qualities while he maneuvers the helicopter. Since most current systems use attitude feedback, the control and response of the helicopter will give an attitude stiffness characteristic over the very short term and a rate-ordering or rate-command type characteristic over the longer term. Because it probably uses limited authority actuators, it cannot assure these qualities over a full envelope spectrum or for all flight and turbulence conditions so that, although he has a fairly good system, the single-pilot may still need the ATTITUDE-HOLD function of an Autopilot for workload relief. In the SCAS mode of operation, the aircraft control and response coupling effects and responses to gusts will be very much reduced.

When single-pilot IFR certification is requested for a given aircraft, the vehicle is judged as presented. If the display includes a Flight Director System (for performance enhancement or whatever reason) and it is certified along with the rest of the required equipment and displays, it too can become a required item for approved IFR flight. This has been documented in some Flight Manuals for IFR certifications as:

"Operable Flight Director System required for normal IFR operations".

One helicopter is also certified for Category II Approaches for single-pilot. Although the flight manual has to be interpreted on several points, the following requirements are stipulated:

1. Fully coupled/automatic autopilot type approach is mandatory; the autopilot is coupled to radio/NAV signals (ILS) and approach (pitch & roll axis) is being flown by autopilot while pilot is responsible for collective adjustments and anti-torque pedal inputs. The single pilot is a monitor/manager of the automatic approach and he is required to monitor raw data to assure proper operation of the system and crosscheck ILS information to guarantee approach quality.

2. Pilot-in-command must be CAT II qualified.

3. CAT II Approach Speeds are 70 K(min) - 130 K(max).

4. For any loss of system or function revert to CAT I requirements.

5. All full autopilot systems must be functioning before take-off. Also required are a Radar Altimeter, two VHF/NAV receivers and primary heading information.

The TWO-PILOT certifications may be either augmented or unaugmented and utilize an autopilot or not. Two-pilot IFR certifications have been approved under both circumstances depending on the flying qualities of the basic aircraft. The configuration requires two fully qualified IFR helicopter pilots at two fully-equipped flight stations (controls, displays, avionics, and aircraft systems).

During the last few years one other minimum aircrew configuration, for a small single-pilot IFR certification, involved the use of a copilot (seated at the copilot's station but without separate controls, displays or systems) if certain pre-specified systems and/or equipment were inoperable. This aircrew manning level was an isolated case and it appears to be of little consequence at this time.

DOCUMENTATION OF HELICOPTER CONFIGURATIONS AND MODES OF OPERATION

Possible Configurations to be Documented

In order to complete IFR certification, the helicopter stability and control characteristics must be documented and the Interim Criteria applied. This documentation normally takes the form of a series of graphs and time histories. Considering the wide variety of configurations that have been or are being proposed, some initial decisions typically are made regarding what configurations require extensive documentation in order to satisfy the intent of the Interim Criteria. At least three configurations are candidates for documentation for the single-pilot case:

1. The automatically controlled (pilot-out-of-the-loop) vehicle.
2. The manually maneuvered (pilot-in-the-loop) vehicle.
3. The failure-mode (first failure-continue to fly) vehicle.

Another way of listing the same three configurations may be:

1. <u>The vehicle dynamics</u> as controlled by the AUTOPILOT/ATTITUDE-HOLD mode of operation.

2. <u>The vehicle dynamics</u> that the pilot sees when he has disabled the ATTITUDE-HOLD/AUTOPILOT mode of operation in order for him to manually maneuver the aircraft to a new attitude and trim position or to do routine IFR maneuvering and tracking before re-engaging the ATTITUDE-HOLD function of the Autopilot. The dynamics representing this vehicle could be that of the "basic" helicopter if the inherent characteristic were good enough to pass the requirements of the Interim Criteria (or obtain an equivalence). For this case, the pilot would probably have the ATTITUDE-HOLD mode of the Autopilot as a workload relief system and the basic aircraft as the maneuvering or pilot-in-the-loop system.

   Another more typical variation of this second configuration is where the vehicle dynamics are those that the pilot sees when he has again momentarily disabled the ATTITUDE-HOLD mode of the Autopilot in order to manually fly the aircraft but now has an augmented system to fly. This augmented system is usually provided by Rate or Attitude SAS or SCAS.

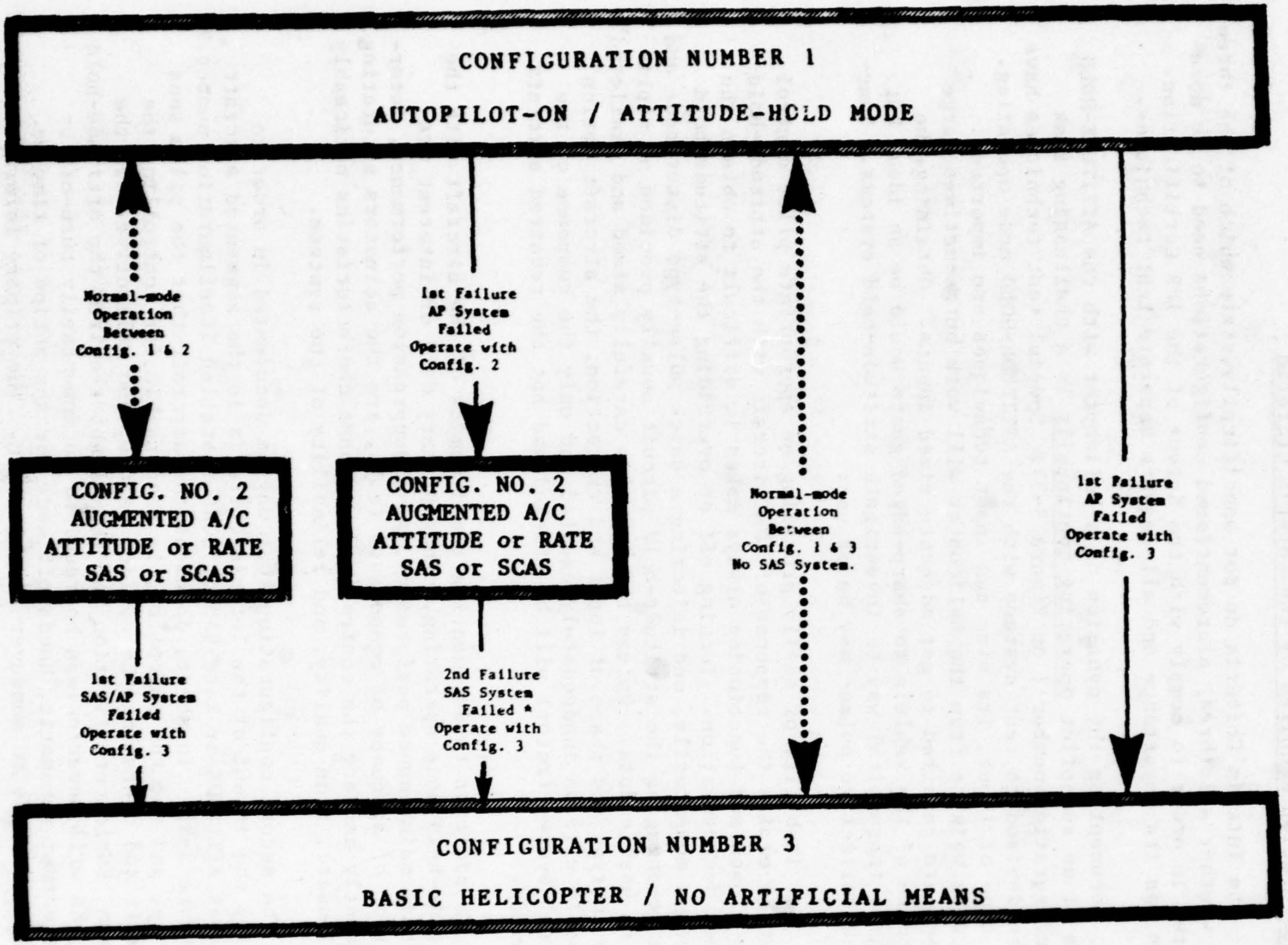
   In many single-pilot IFR certifications, the ATTITUDE-HOLD/AUTOPILOT mode of operation is mandatory for the entire IFR flight. It cannot be turned off for legal IFR flight. However, it must be intermittently and frequently disabled in order for the pilot to manually maneuver the aircraft as he pleases or is required by the dictates of IFR flight maneuvering. Disabling the ATTITUDE-HOLD is easily accomplished on every installation (e.g., depressing the Force Trim Release, FTR momentary, button on the pilot's cyclic control stick).

3. The vehicle dynamics that the pilot sees when he is forced to maneuver in the failure mode of operation. This is normally considered here as that first-failure which allows the pilot to continue to fly after failure and complete the IFR mission without declaring an emergency. In many cases this could be the basic vehicle.

One viewpoint of the various documentation configurations together with their normal operational and transitional/failure possibilities is shown in Figure 3-3. In a general way, the amount of system change or degradation between systems can be seen. The figure applies to most single-pilot certifications where the ATTITUDE-HOLD/AUTOPILOT method of operation is mandatory for the entire duration of the IFR flight. It may or may not apply to two-pilot certifications depending on what is offered to be certified. An approved two-pilot IFR certification using the basic helicopter already exists. This two-pilot IFR certified vehicle is not required to have any SAS systems, Autopilot Systems, Flight Director systems etc., installed and therefore the criticality of its failure modes, system degradation, and failure transitions may be reduced considerably.

Defining the various failure modes is a complicated subject given the large variety and matrix of possibilities that exist. It is possible for a helicopter (especially the single-pilot vehicles) to contain systems and items such as:

- Simplex, Duplex, Triplex actuators (up to a total of three actuators per axis)
- Three axes of augmentation
- Simplex, Duplex, Triplex vertical gyro sources. (up to three complete gyro packages for a Triplex system)
- Primary, Secondary, Battery-Only Electrical Systems
- Boost Systems (sometimes primary and secondary and failure modes)
- Single and Multiple Autopilot, Augmentation, Avionics, Control Computers, Amplifiers, and Control Panels, etc.



* On many systems when SAS fails, AP inoperative.

Figure 3-3. Typical Operational Configurations for Single-Pilot Helicopters.

Documentation Required by the Interim Criteria

The Interim Criteria do not specifically state which of the three (or whether all three) aforementioned configurations need to be documented in order to comply with the intent of the IFR Certification. Each has its importance and all require separate test techniques.

Documenting the dynamics of a helicopter with the ATTITUDE-HOLD mode of an autopilot operating continually is a challenging task (Configuration number 1 on Figure 3-3). Special test techniques have to be devised to test systems with the ATTITUDE-HOLD mode operating. The type of input, its size and input techniques are important. Dropping weights from the helicopter will work but sometimes large masses are required to get adequate sized inputs. Obtaining the response of the vehicle to sharp-edged gusts would be an ideal but perhaps impractical way to investigate attitude-hold systems. Sometimes collective pulses may be of use.

The inability of easily providing an appropriate pilot control input to excite the response of the aircraft with the attitude-hold loop closed and functioning always makes it difficult to obtain the proper documentation. Turning off or overriding the attitude-hold function momentarily, and injecting a quick pulse-type disturbance and then re-engaging the attitude-hold circuit usually provides no applicable, usable data. Unless the input is carefully sized and "tailored" both in type and phase of input and extraction, the aircraft motion probably will be inadequately excited and only the response of the control system (rotor) will be checked and not the required aircraft dynamics.

In addition to documenting the dynamics of the aircraft with the attitude-hold mode operating, other primary data of interest are attitude maintenance performance, gust suppression performance, determination of adequacy of components (e.g., are the actuators saturating frequently and are the control and response characteristics noticeably non-linear), ride quality, and reliability of the systems.

The second configuration that may be documented in order to satisfy the intent of the Interim Criteria is the augmented aircraft that has ATTITUDE or Rate SAS or SCAS installed (Configuration number 2 on Figure 3-3). In short, document the aircraft that the pilot sees when he, and not the autopilot, is responsible for controlling the aircraft and operating the cyclic, pedals, and collective. If the minimum basic certification for IFR flight requires the attitude-hold mode, he will nevertheless be required to momentarily turn-off or disable that automatic, hands-off mode for the period of time he chooses or needs to maneuver the aircraft. The primary information to be obtained would probably center on items like short and long term response characteristics or period, damping ratio (cycles to half amplitude) and/or first-order time constant. Other characteristics such as cross-coupling effects, gust response and attenuation, and ability to trim the aircraft quickly, easily, and accurately are also of importance. The documented dynamics of this vehicle could then be properly assessed and compared to the criteria.

The third configuration that may be documented in order to satisfy the intent of the Interim Criteria is the "basic" vehicle (Configuration number 3 in Figure 3-3). Whether this represents the failure-mode or normal-mode configuration depends on the system originally offered (and probably the inherent stability of the helicopter). The primary information is approximately the same as that required for the previous (second) configuration. If this configuration (or any other configuration) represents the failure-mode of flight, it is important to determine in some quantitative way, the amount of system degradation, (dynamics, cross-coupling, handling qualities) that occurs compared to the normal-state flight condition. Handling qualities degradation due to first-failure should not be so great as to compormise the safe completion of IFR flight and require the pilot to declare an emergency.

With respect to the three configurations discussed; ATTITUDE-HOLD/AP mode (pilot out-of-the-loop), maneuvering mode (pilot in-the-loop) and "basic" mode (or failure-state mode, continue flight after failure), it appears that at least the maneuvering-mode with the pilot-in-the-loop and the failure-state mode should be documented and analyzed with respect to the requirements associated with dynamic stability as stated in the Interim Criteria. The maneuvering mode needs analysis simply because it is the mode the pilot must fly IFR. Similarly, the failure-state mode needs to be studied because it reveals the system the pilot will have to fly and quantifies, to some degree, what the so called "relative degradation factor" of the pilot/vehicle system will be in case of failure. An investigation of the failure-state mode, at the most critical flight conditions, will fully define the character and stability of the aircraft and diminish the chances of surprising the pilot with a situation that may degrade to an emergency condition. Should it appear that the ATTITUDE-HOLD/AP mode dynamics seem marginal, they too will have to be documented to see if they meet the minimum requirements of the Interim Criteria.

With fully-coupled automatic tracking modes using radio signals and other transducers where all the sophisticated coupling is utilized (together with autotrim and automatic coupling to the collective), the pilot is very far removed from handling the aircraft (he is flying by the knobs, trim wheels, and buttons) and is relatively far out-of-the-loop. He is performing as a monitor/manager of a system, and the inherent dynamics of the vehicle and its associated handling qualities

no longer need be of prime concern to him as long as he is operating in this manner in a non-failed state mode. Some helicopter pilots do not choose or like fully-coupled flying because it removes them too far from the actual flight control task. It restricts them in maintaining proficiency and keeps them from easily injecting their "learned processes" and experience into the IFR approach. Airline captains (and other pilots flying fully automated/augmented approaches) face a similar dilemma. If they are given the option, airline captains would sooner manually fly a CAT II, flight director approach rather than a fully automated, coupled "managerial/monitored" type approach. The reason is obvious. In case of coupler system failure, they are interested in knowing how much degradation in approach flying qualities will appear and they always want to learn how proficient or capable they will be when handling the now less stabilized aircraft in the environmental and weather conditions as they exist at the time of the CAT II approach. At least, the degradation should not be so severe that he cannot easily abort the CAT II approach, successfully execute a missed approach, and revert to a higher minima approach category at another airport.

PILOT WORKLOAD AND THE IFR CERTIFICATION PROCESS

Introduction

As the result of interviews with industry and FAA pilots and engineers, it became apparent that many of the persons interviewed felt that some workload rating system should be developed and incorporated into the FAA IFR certification process. Yet some felt very strongly that there was no place in the FAA certification process for anything resembling a Pilot Rating Scale. They felt that the examiner is only required to make a PASS/FAIL judgement and no relative rating is needed. This issue, while considered sensitive, must also be addressed for two very important reasons. The most significant reason involves the paramount importance placed upon the FAA pilot's flight evaluation of performance/workload and other handling qualities --- within the certification process. Second, all flight research in handling qualities (e.g., workload and performance in a flying task) has historically always involved assigning pilot ratings to quantified engineering definitions of the pilot/vehicle system being evaluated. If the FAA is ever going to match past, present, or future flight research results to the rule making process, it should define which NASA Pilot Rating equates to an acceptable civil pilot/ aircraft system. The definition of acceptable is equated to an aircraft which will yield a level of flight safety while being flown IFR by a pilot.

Pilot Workload and the FAR and Interim Criteria

The subject of pilot workload in airplanes is addressed in FAR Part 25, Airworthiness Standards: Transport Category Airplanes under section 25.1523, minimum flight crew and is excerpted as:

> "The minimum flight crew must be established so that it is sufficient for safe operation, considering -
>
> (a) the workload on individual crewmembers; ..."

More pertinently, the subject of pilot workload in rotorcraft is addressed in FAR Part 27, Airworthiness Standards: Normal Category Rotorcraft; and FAR Part 29, Airworthiness Standards: Transport Category Rotorcraft; under Subpart G, Operating Limitations and Information, sections 27.1523 and 29.1523. The wordings are identical to that in 25.1523 and as shown excerpted above. The last few phrases of the last paragraph (j) of the Interim Criteria seem to be the most pertinent regarding the subject area of workload, namely:

"(j) IFR Flight. The rotorcraft must be flown in the air traffic control system under actual IFR day and night conditions for a period of at least five hours. The items evaluated during this period include:

> (1) Ability to operate the rotorcraft satisfactorily under IFR conditions in the air traffic control system without undue pilot fatigue or exceptional pilot skill or alertness.
>
> (5) In-flight IFR workload demands on the minimum required flight crew.
>
> (6) Handling of the rotorcraft in rough air turbulence."

Other sections of FAR 27 and 29 address the workload issue more indirectly and with special regard to failures. One example of this is given under FAR 27 and 29, Subpart B, Flight Characteristics, Section 27.141 subparagraph (b) excerpted as:

"(b) Be able to maintain any required flight condition and make a smooth transition from any flight condition to any other flight condition without exceptional piloting skill, alertness, or strength, and without danger of exceeding the limit load factor under any operating condition probable for the type, including -

> (1) Sudden failure of one engine, for multi-engine rotorcraft meeting transport category A engine isolation requirements; and
>
> (2) Sudden, complete power failure, for other rotorcraft; and

(c) Have any additional characteristics required for night or instrument operation, if certification for those kinds of operation is requested."

The above items appear to be the most pertinent parts of the FAR and Interim Criteria which address aircrew IFR workload level requirements. Because of the apparent importance of workload level determination in the certification procedures and requirements, it appears that the subject area is both incompletely defined and inadequately described. Moreover, the Interim Criteria do not relate or formalize how each different workload increment associated with -

- different minimum aircrew level (one or two-pilots)
- different certification objectives (CAT-I or CAT-II)
- different augmentation, autopilot, control systems

- different display and avionics systems
- low and high-density ATC traffic situations

impacts on or facilitates an effective approach to the total judgment of workload/performance in the IFR certification process of helicopters.

The judgment is especially acute for single-pilot IFR certifications where there is the strongest interplay between the handling qualities factors of the vehicle (stability and control, displays, tasks, performance, augmentation systems, avionics, etc.) and the workload capability required by the pilot in order to participate in auxiliary tasks. One acceptable methodology could be that if certain handling qualities factors (statics, dynamics, displays, etc.) are good enough and meet certifiable minimums (or equivalences are granted), then all that is additionally needed is an ATTITUDE-HOLD/AUTOPILOT to ameliorate the pilot's workload problem with auxiliary tasks. Presumably, as the aircraft handling qualities factors (statics, dynamics, control systems, displays, etc.) improve, the need for an ATTITUDE-HOLD/AUTOPILOT will diminish for single-pilot certifications. However, there is a very distinct trade off between the basic design of the helicopter versus installation of augmentation and autopilot systems in economic terms. Given the many different designs and configurations, it is probable that each will offer separate solutions.

The pilot workload level determination currently being used is producing helicopters that are clearly safe to fly IFR as far as workload rating is concerned but the process could be aided by some specific structure and more precisely stated or illustrated certification objectives. The workload level rating systems or procedures seem to be relatively informal in nature. It is suggested by some that present procedures seem to work adequately among the different examiners (and regions) as long as all the participants recognize and maintain some common norms and/or ground rules and coordinate the procedures amongst themselves on a timely basis. In fact, numerous different helicopters have been successfully IFR certified by different examiners in different regions by determining that the pilot's IFR workload level (in addition to compliance achieved or equivalence granted regarding the other items in the Interim Criteria) was acceptable.

The methodology of utilizing and applying a set of criteria to a system in which there is a pilot in the loop, and the need to determine acceptable handling qualities and workload level using formalized pilot opinion rating scales is a difficult task, but not a new one. The rating method of judging acceptability of and compliance with criteria has been used by many agencies including the FAA for many years. In its own way, the granting of "equivalent safety" by the FAA on, for

example, a detailed engineering numerical specification of a Standard that is not met, is a rating judgment. The use of a coordinated, formalized and structured rating scale would greatly aid the current system. Efforts should be initiated on the implementation and use of a formal rating system. A typical rating system and definitions on workload, performance, handling qualities, etc., is given in Appendix B.

ENVELOPE TAILORING

When the V_{NE} of a given aircraft is 150 knots for VFR flight but is reduced to 120 knots for IFR flight, the flight envelope is said to have been "tailored". When work on this study was initiated, the airframe manufacturers appeared to oppose the idea of tailoring the flight envelope downward to lesser speeds than VFR in order to achieve an IFR certification. The main concern expressed by candidate applicants involved the loss of productivity and operational efficiency. The concern for this loss appeared to be centered around the desire to maintain an adequate competitive position rather than the maintenance of helicopter versus airplane productivity in an altruistic sense. However, in the final stages of this study, the FAA and the industry attitudes appeared to have generally migrated toward acceptance of Envelope Tailoring as an acceptable method of facilitating the IFR certification of a new helicopter configuration.

Envelope tailoring can be used in two ways. First, the IFR envelope can be constrained for normal operations. Second, the envelope can be constrained after a failure occurs to facilitate workload reduction, for continued flight. Obviously there are limits to what can be done in either of the two basic applications of envelope tailoring. Primarily, the tailored envelope must represent an envelope which is large enough to insure that useful, economical operations can be conducted. In tailoring an envelope for the post failure case, the post-failure V_{NE} limit should not be allowed to produce a significant reduction in the still-air cruise range. Typically, the variation of specific range with airspeed is fairly flat for helicopters near and below V_{NE}. Thus, it may be possible to achieve large reductions in V_{NE} without any appreciable reduction in range. Of course, the trip time will become much longer but that should be of less importance. One might suppose that a 5% reduction in cruise range would be acceptable for the post failure case. This is probably a range reduction that the crew could accept for continued non-emergency, IFR flight and still adhere to fuel reserve requirements.

When evaluating the advisability of applying for or allowing a tailored envelope for post failure operations, the analyst must be aware of the fact that this is exactly what pilots do on their own. If the aircraft flight control task (or accumulative workload) is too difficult, (or the accumulative workload is too high), the pilot will slow the aircraft down to achieve a reduction in pilot workload. Typically a pilot will endure a high workload (IFR) situation only if the result produced by slowing down is worse than the probable consequence of maintaining speed. That is, a pilot would prefer to endure the high workload situation in preference to slowing to a cruise speed which will result in fuel exhaustion prior to reaching the desired landing field. This is particularly true when flying over open seas or mountainous terrain.

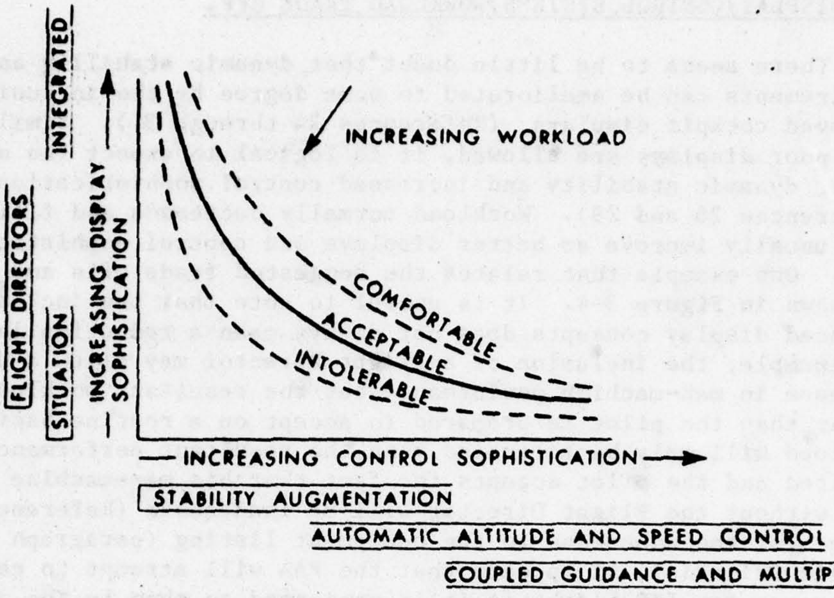
Sometimes the term envelope tailoring is also applied to c.g. ranges. The c.g. range for IFR flight may be reduced to less than the VFR range. Also, limitations are sometimes put on maximum climb rates allowed for IFR flight. Minimum IFR flight speeds are always specified.

THE DISPLAY/CONTROL SYSTEMS/WORKLOAD TRADE OFF.

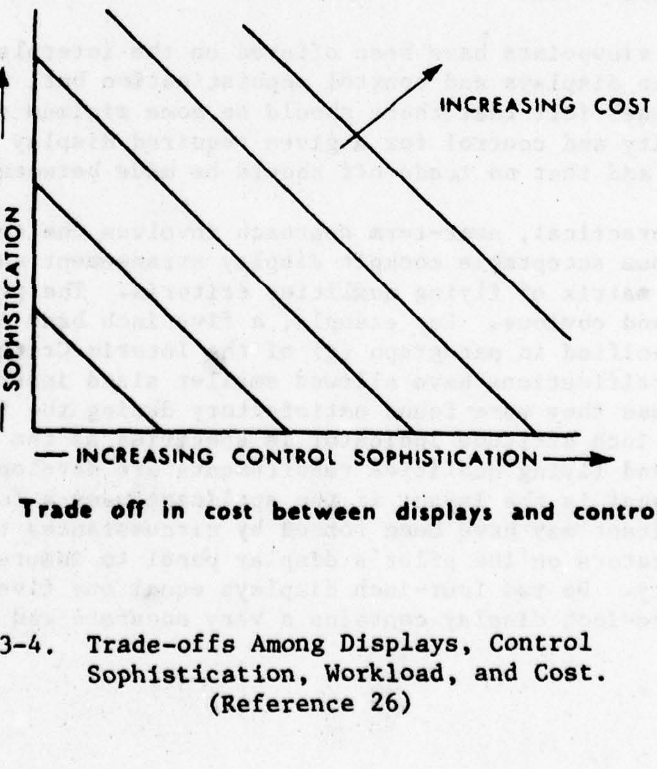
There seems to be little doubt that dynamic stability and control requirements can be ameliorated to some degree by the inclusion of improved cockpit displays, (References 24 through 31). Similarly, if very poor displays are allowed, it is logical to expect the need for better dynamic stability and increased control sophistication technology, (References 26 and 29). Workload normally decreases and flying qualities usually improve as better displays and control sophistication are used. One example that relates the suggested trade offs and techniques is shown in Figure 3-4. It is useful to note that the inclusion of advanced display concepts does not always mean a reduction in workload. For example, the inclusion of a Flight Director may allow a dramatic increase in man-machine performance but the resultant workload may be higher than the pilot is prepared to accept on a routine basis. The workload will only be tolerated when the resultant performance is required and the pilot accepts the fact that his man-machine performance without the Flight Director will be inadequate (Reference 30). Except for the adherence to the equipment listing (paragraph g of the Interim Criteria), it appears that the FAA will attempt to certify a helicopter for IFR flight as it is presented to them by the applicant, and this includes the display. For example, if it is presented with a Flight Director System and the examiner utilizes it (or feels it is a needed addition) for IFR flight in this helicopter (from a performance/workload standpoint), it will be listed in the Rotorcraft Flight Manual as a required item.

Many viewpoints have been offered on the interplay and/or trade off between displays and control sophistication but, in general, most FAA personnel felt that there should be some minimum acceptable level of stability and control for a given required display system and aircraft, and that no trade off should be made between the two.

The practical, near-term approach involves the determination of some minimum acceptable cockpit display arrangement and establishing a predicted matrix of flying qualities criteria. The problems are numerous and obvious. For example, a five inch bank and pitch indicator is specified in paragraph (g) of the Interim Criteria yet most recent certifications have allowed smaller sized instruments to be used because they were found satisfactory during the flight evaluation. If a five inch attitude indicator is specified as the baseline (or minimum) and flying qualities requirements are developed around this display, what is the impact if the applicant uses a four inch indicator? This applicant may have been forced by circumstances to use two attitude indicators on the pilot's display panel to insure display system reliability. Do two four-inch displays equal one five-inch display? If the five-inch display contains a very accurate and large, easily



Trade off between display and control sophistication



Trade off in cost between displays and controls

Figure 3-4. Trade-offs Among Displays, Control Sophistication, Workload, and Cost. (Reference 26) readable, roll attitude indication, can it be considered to compensate for some reduction in lateral/directional stability requirements? Although there is no methodology or system of credits within the certification process as it now stands, these questions are typical of the kind that are not easily resolved using much of the current literature.

Finally, although considerable effort has and is being expended in programs (as noted in the References listed above and in other research work) to define the Display/Control/Workload trade offs, most of this work does not relate to the combinations which appear most pertinent to Civil IFR helicopter operations. Also, it would appear that good pilot displays in helicopters are very important after failure of the stability/control augmentation system or autopilot system.

In summary, additional flight simulation efforts should concentrate on determining:

(1) the minimum display configuration
(2) the trade off of good, current display systems against poorer flying qualities (those often associated with first-failures).

RADAR ALTIMETER AND AUTOROTATION UNDER IMC

One point that should be addressed at least briefly in this report is the engine failure emergency condition for single engine helicopters (and perhaps others) during IMC flight. Coping with emergency autorotative descents during IFR flight, when low ceilings and visibilities prevail, is a general problem, but, it should be addressed because the following conditions and characteristics are possible:

1. Single-pilot/Single-engine operations

2. Low enough ceilings and sufficiently poor visibility in the emergency landing area so as to preclude visual contact with the ground, at 150 feet above ground level or higher.

3. As the only crew member, the pilot must fly a steady-state autorotative descent on his cockpit instruments while simultaneously "looking-out" for VFR contact near the base of the ceiling or obscuration in order to effectively transition to VMC and land. He is also anticipating a possible requirement for immediate deceleration, flare and cushion to an unfavorable landing area when achieving VMC.

4. Visibility and ceiling in the predicted or emergency landing area are poor enough that the pilot needs accurate flight information (airspeed, vertical rate, altitude, etc.) in order to have a good chance at a successful flare and landing.

This condition is of interest here from the standpoint of safety and is discussed in several reports, studies and certain military handbooks (References 32 and 33). Essentially, they recommended that practiced and learned IFR autorotation procedures be accomplished for this special case and note that a radar altimeter is always required for an accurate measure of height above the ground. Also, if flights are generally conducted with the hand frequently removed from the collective, then this consequence should be considered and the appropriate delay times must be applied.

Engine failure during IFR flight for a single engine aircraft of any type is an extreme emergency under any circumstances. However, there is at least one difference between airplanes and helicopters as far as the handling of vertical rate of descent is concerned. In an airplane, a wide variety of vertical descents and even extended shallow glides with relatively low rates of descent are possible (when the ground is near or visible and excess airspeed is being dissipated). With the helicopter, less leeway in IFR autorotative descents is possible and higher vertical descent rates must be maintained as compared to many airplanes. An autorotation curve showing descent rates that are typical for a class of single rotor IFR helicopters is plotted on Figure 3-1. Even at the best speed for minimum rate of descent (68 knots), the vertical rate is still almost 2,000 feet per minute. For a single pilot on a night IFR flight presented with an emergency autorotation with low ceilings and faced with high rates of descent, the inclusion of a radar altimeter would be of great aid for this very difficult situation.

Whether dual piloted aircraft, where the copilot can aid the pilot by looking out for visual conditions (and perhaps turn on landing lights at night in time for the deceleration), need the same treatment is not clear. Usually, from the instrumentation standpoint, if it is a larger vehicle it will probably have a radar altimeter already installed as part of the original instrumentation package of the aircraft.

The need for a radar altimeter should be addressed from a safety standpoint, at least for the special case detailed above, where the flight operation does not have multi-engine protection and/or a copilot to aid during the final critical moments of the autorotation. (See Appendix C for general criteria on engine power loss in helicopters. This referenced work was completed in 1973 and offered as a user guide for a possible updated version of MIL-H-8501).

COMPUTER SIMULATION FOR DYNAMIC RESPONSES

One should expect that a manufacturer can propose to use a computer program to produce many of the required dynamic responses and static stability characteristics of an aircraft proposed for certification. If an applicant selects to provide computer data in lieu of flight test data, the FAA could and should ask for more data than would normally be developed via actual flight test. The data should be presented in the same format in which it would have been presented had it been acquired in flight. Specifically, time histories of aircraft response should be developed from control inputs modeled after actual pilot inputs. That is, pure or "ideal" square pulses, doublets or steps should not be employed.

Next the FAA and manufacturer should agree on the loadings and flight conditions which present the least stable cases. The FAA would then fly these points and collect actual in-flight data. This data and the computer simulation data should be compared for the same test points. If the two agree in an equal or conservative way, the results would confirm the computer program and suggest that all of the appropriate and applicable computer data should be accepted for the purpose of the certifications. (The data are equal if the disagreement is randomly an increment more stable or less stable. If the computer data are consistent in their disagreement with the flight test data, the result should be an understatement of desirable qualities and not an understatement of bad qualities.)

DECREASED IFR VISIBILITY MINIMA FOR HELICOPTERS

Changes in Federal Aviation Regulations permit decreased visibility minima for IFR approaches with helicopters (FAR PART 97). This allows a helicopter pilot to conduct operations with the published visibility minima reduced to one-half their value (but to not less than one-quarter mile) for all instrument approaches. This change will have impact on any published visibility approach minima that are greater than one-half mile since they can be reduced by half. The most notable effect of this change appears to be on non-precision type approaches such as exemplified by those that are normally made using VOR/DME facilities. For example, for a specific VOR/DME straight-in approach such as published for a Laramie, Wyoming Airport, the published minima has been listed as 288 feet and 1 mile. For an IFR helicopter approach, this means that the published minima for a non-precision, VOR/DME straight-in landing would be changed to 288 feet and one-half mile. To date, it has been difficult to determine whether different aircrew manning levels were considered (namely, single-pilot IFR helicopter certifications versus dual pilot) when this change was approved. During the information surveys, initial observations seemed to indicate that dual piloted U.S. Army helicopter operations were the prime consideration when this rule change was weighed and implemented. Later, it was determined that not all FAA personnel agreed with the premise that the change was based on dual pilot operations only. Apparently, the rule change applies to single piloted IFR approaches as well as dual pilot. The impetus for making the change probably was the recognition of the unique and versatile capabilities of rotary wing aircraft to safely conduct wide ranging "stall-free" maneuvers and rapid decelerations to slow speed and hover when flying VFR. The fact is that we are dealing with "post breakout" situations beneath the ceiling (and chances are, in an environment of somewhat reduced visibility but still VFR flight) where the pilots can employ these capabilities to full advantage. During "break-out" and when visual underneath, the second pilot serves a very vital function as a second set of eyes that provides important aid to the handling pilot as he maneuvers, decelerates or sideslips into position for landing.

The U.S. Army appears to be using the newly allowed minima in this way since they require two qualified pilots in helicopters for IFR operations. However, a check with one Marine Corps helicopter unit (involved in extensive IFR airways flying) indicates that the USMC does not use the changed minima even though all IFR flights are conducted with two pilots. Recent contact with a civilian instrument flight school for Helicopter Pilots, indicates that it is teaching its students to utilize the allowed reduced visibility minima.

SECTION 4

CRITERIA ANALYSIS

INTRODUCTION

This section presents a summary of all of the efforts associated with the collection and analysis of IFR related helicopter data. In effect this section combines the flight test data obtained from reviews of civil and military helicopter reports, simulator and flight research findings, criteria statements from the Interim Criteria and criteria data established by earlier military and civil flying qualities requirement documents.

Data on Civil Helicopters

Pursuant to this report, a considerable amount of flight data and information were acquired on IFR certified civil helicopters. The owners of this data were invariably concerned about the possibility of public release. Manufacturers were especially concerned with respect to any commentaries which might be attached to their own data. In appreciation of this sensitivity, the authors have neither reprinted nor identified any civil flight data which was used in the body of the report. Even military data were of considerable concern because they could eventually be linked to a civil or military related court action. All data used in this report are accurate in the sense that they are presented, but none are a one-for-one representation of any actual plot/graphic.

A General Review of the Interim Criteria

The primary purpose of this study was to review an informal "Interim Criteria for Helicopter IFR Certification". This review was to be conducted in context with past experience, the existing operational environment and the current methods used by the various FAA regions to certify helicopters for IFR operations. The central issue to be resolved involved the validity of the "Interim Criteria". One of the early findings of the study involved the discovery of numerous versions of this "Interim Criteria" document. The version furnished as the basis for this effort is presented as Appendix A. It appears that minor variations of this criteria have been evolved within the numerous FAA Regions. A few variations have been excerpted and are included in Appendix A to better depict the versions in current use by the industry.

The original "Interim Criteria" were generated by FAA pilots in the early 1960s as an informal document. These criteria were evolved from the then existing version of MIL-H-8501 and other, then existing, airplane type flying qualities requirements. They were requirements which the FAA felt were responsible for adequate airplane IFR capability. In any case, these criteria have been used in one form or another in conjunction with other FAR (e.g., FAR 27 and FAR 29) to certify all of the IFR helicopters currently operating in the USA.

Typically, the FAA includes a version of the Interim Criteria for compliance as a part of the application for certification. The applicant is then required to demonstrate the fact that the subject vehicle will meet the "Interim Criteria" as the primary basis for IFR certification. The Interim Criteria have thus accumulated the weight of precedent. Precedent is typically an immensely important factor in the FAA certification of all aircraft, fixed or rotary wing.

This study determined that certain segments of industry feel the criteria are unnecessarily demanding while others feel the criteria are inadequate or incomplete. The first group desires relief while the extremist in the second group might dictate a bible of stringent flying qualities requirements. In responding, the FAA must first and foremost insure that the aircraft is safe. In the process of insuring this safety the FAA can only dictate those stability and control and flying qualities characteristics which are necessary to achieve or provide a level of safety. This is a key constraint and all FAA Flight Standards personnel are keenly aware of this fact. Any Flying Qualities Criteria must then be limited in "scope" and in "required quality" so as to yield the maximum allowable relief in design requirement, consonant with satisfactory flight safety determined in context with the anticipated operational objectives.

Applicability of Interim Criteria

One point that should be made clear at the outset involves applicability of certain sections of the current Interim Criteria. For example, the section detailing the requirements for oscillatory dynamics are identical to those stated in MIL-H-8501A, the helicopter specification.

In the Dynamics Section of this report, the aircrew manning levels implied for the data obtained in the IFR Sections of 8501A are discussed. It is reasoned in this section that the dynamic stability requirements of 8501A (and the Interim Criteria) were determined for two-pilot manning levels for IFR flight in helicopters.

During the survey trip and contacts, there was repeated emphasis of the fact that the IFR minimum requirements developed for precision instrument flight under 8501A applied to two-pilot manning levels (i.e. an <u>unloaded</u> pilot only had to acccomplish the flight control task while a copilot accomplished all auxiliary tasks. Therefore, if Sections of the Interim Criteria contain items that are based on, or specifically determined for use with, two-pilot manning levels (and no criteria are given specifically for one-pilot manning levels), then the Current Interim Criteria should be construed to be applicable only to two-pilot IFR Certifications.

This is stated here with full recognition of the fact that other paragraphs in the Interim Criteria do properly allude to different aircrew manning levels or minimum required aircrew (one-pilot or two-pilot). However, these are for requirements pertaining to items such as artificial stability, operating information and limitations, and workload (e.g., paragraph j5, "...In-flight IFR workload demands on the minimum required flight crew...").

Design Criteria vs Demonstration Criteria

The importance of distinguishing between "design criteria" and "demonstration criteria" is a vital aspect of the certification process. The FAA cannot establish design criteria per se, but the FAA can establish performance or demonstration criteria and functional criteria. The flying qualities criteria should then be "demonstration criteria and functional criteria." With this firmly in mind, the FAA pilots and engineers need a set of criteria for a matrix of helicopter flying qualities. Among other considerations, the demonstration criteria must account for various input control configurations and various data acquisition systems. These criteria must also take into account test methods and data analysis methods.

Performance criteria which do not include specific reference to test technique and analysis method are of little or no use. The current Interim Criteria do not include the type of guidelines required to avoid conflict. If the Interim Criteria are rewritten into a standard, FAA pilots and engineers as well as industry pilots and engineers should be provided with a well formulated set of data acquisition and data analysis guidelines. (It should be noted that testing to MIL-H-8501A and MIL-F-8785B is supported by test manuals developed as informal standards over the years.)

Equivalency

When a helicopter does not meet the letter of some requirement (of the Interim Criteria), the FAA can grant a certification based upon equivalent safety. That is, if the criteria requires a yaw control force gradient, and none exists, the FAA can determine via flight evaluation that the alternative approach (one with no force gradient) *exhibits an equivalent* level of safety. Frequently, the more specific the criteria are and the more diverse advanced control systems become, the more often the applicant must ask for certification based upon equivalence.

What is equivalence? When reading the criteria in Appendix A (and the FAR), one notes the absence of a clear statement of objective, or functional need. For example, what is the intent of the longitudinal static stability requirement?

Does the demonstration of positive static stability assure the FAA that the aircraft is safe? No. What the static stability criteria statement does, is provide the FAA with one way to explain a dynamic stability problem or a trimability problem, etc., but positive statics do not in themselves insure good flying qualities. So how then does the applicant demonstrate equivalent safety? It appears that the applicant cannot do this directly. The applicant and the FAA must first discuss and agree as to the intent of the criteria (functional requirement). The applicant must next provide a characteristic which is felt to provide equivalence. Finally, the FAA must fly, test, analyze, obtain a consensus and agree with the applicant. If the intent of each criteria were clearly stated, i.e., "to provide hands off speed maintenance in moderate turbulence", the ability to demonstrate functional equivalence would be greatly facilitated. Each and every performance criteria should be structured so as to relate to one or more functional requirements. Typically some of this can be accomplished in introductory criteria statements within an FAR, but more definitive statements of intent should be developed and included in a flight test and analysis guide.

A substantial segment of FAA personnel feel that new criteria should contain as few as possible of the general, blanket type requirements statments. They feel that any new criteria should adequately portray the intent of the requirement, be complete enough in coverage, and sufficiently specific in engineering and flight test terms so that few, if any, "equivalent safety" requests need be made when a particular design has to meet the criteria. New criteria should strive for this goal.

Inconclusive Data Comparisons to the Criteria

Flight test data are acquired by the applicant and the FAA and retained by the FAA to support the approval of an IFR certification. FAA pilots essentially spot check the data provided by the applicant. In some cases, extensive FAA flight test operations are required to assure the FAA that proper margins of safety are present. As a rule of thumb, it appears that the industry expects that the FAA flight test program will be most extensive for aircraft with the smallest margins of safety.

In any case, the data submitted by the applicant in support of the certification request, and the data acquired by the FAA pilots-engineers, is retained for aircraft which have been judged acceptable.

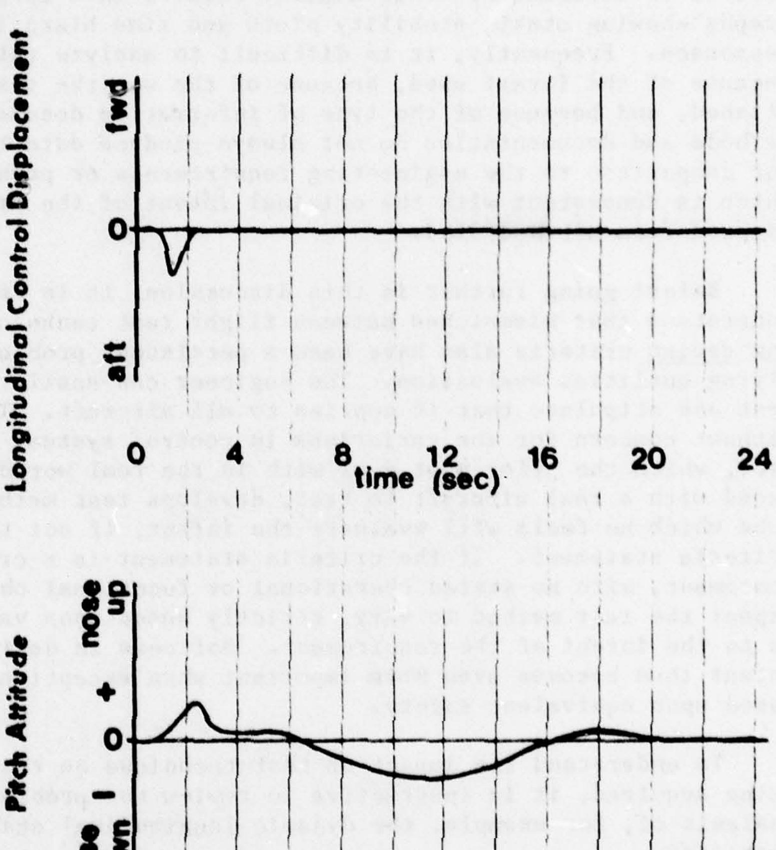
For those aircraft where some section of the Interim Criteria (or FAR) is not met, the applicant is notified and the data are kept on file to await further action. This usually takes the form of listing of the item, the reason re-evaluation is needed and the changes documented.

Nevertheless, before the IFR certification of the helicopter can be completed, the stability requirements detailed in the Interim Criteria have to be documented. This usually results in a large number of graphs showing static stability plots and time histories of dynamic responses. Frequently, it is difficult to analyze this data. This is because of the format used, because of the way the tests were accomplished, and because of the type of information documented. Some test methods and documentation do not always produce data that are suitable for comparison to the engineering requirements or presented in a way which is consistent with the original intent of the criteria (as adapted from MIL-H-8501A).

Before going further in this discussion, it is very important to understand that mismatches between flight test techniques and engineering design criteria also have been a persistent problem in military flying qualities evaluation. The engineer can easily write a requirement and stipulate that it applies to all aircraft. This is often done without concern for the variations in control system, trim system, etc., which the pilot must deal with in the real world. The pilot, faced with a real aircraft to test, develops test methods and techniques which he feels will evaluate the intent, if not the letter of a criteria statement. If the criteria statement is a cryptic engineering statement, with no stated operational or functional objective, one can expect the test method to vary, strictly based upon variance of opinions as to the intent of the requirement. Softness in definition of intent thus becomes even more important when exceptions are allowed based upon equivalent safety.

To understand the impact of test technique on the data currently being acquired, it is instructive to review the problems found in analysis of, for example, the dynamic longitudinal stability time histories.

Certain of the long period dynamic data acquired for IFR certification and printed in TIRs cannot easily be compared to the requirements of the Interim Criteria. For a large segment of the responses, pulse type inputs were used to excite the long period. Usually the test pilot tries to return the control to the original trim position accurately and on many occasions "control-jigs" are used to aid the pilot. Ideally, an input and response would appear as in Figure 4-1. Unfortunately, less than ideal inputs, unintentionally but commonly, occur (Figure 4-2). For example, after the pulse was complete, the longitu-



LONG PERIOD FOLLOWING PULSE OF LONG CONTROL WITH CONTROL RETURNED TO TRIM

Figure 4-1. Accurate Pulse Input Response Data.

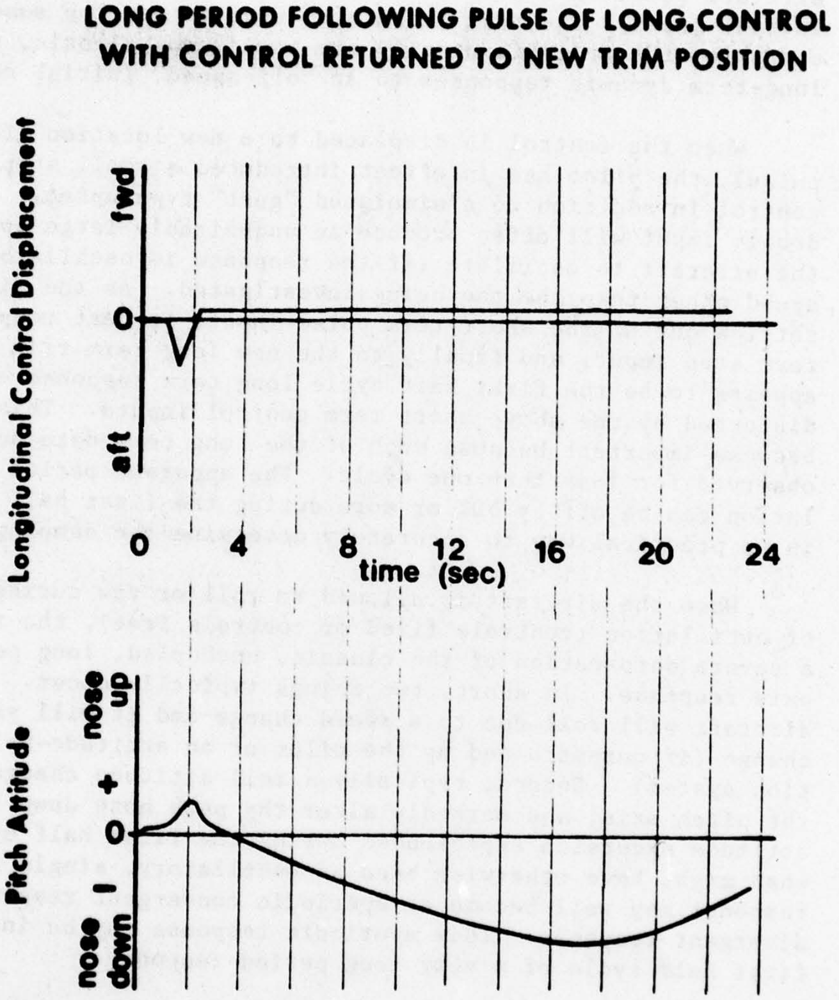


Figure 4-2. Erroneous Response Data for a Pulse Input Investigation.

dinal control could have been inadvertently displaced forward following aft pulses, or, aft following forward pulses. This displacement would result in a pitch rate command, or speed change command, being applied during the subsidence to the short period pulse. Additionally, the aircraft could have been allowed to roll and/or yaw following the initial input. The test techniques used to develop some of the requirements for the Criteria usually are based upon classic, uncoupled long-term dynamic responses to an "off-speed" initial condition.

When the control is displaced to a new location (following a pulse), the pilot has in effect introduced a small step input of control in addition to a simulated "gust" type upset. This type of double input will often produce an undesirably large upset and cause the aircraft to oscillate (if the response is oscillatory) about a speed other than the one being investigated. As the aircraft response settles out of the short term pulse input, it next responds to a short term step input, and finally to the new long term trim condition. What appears to be the first half cycle long term response can be grossly distorted by the above short term control inputs. This distortion becomes important because much of the long term data acquired is observed for less than one cycle. The apparent period of the oscillation can be off by 50% or more during the first half cycle and there is no practical way to accurately determine the damping ratio.

When the aircraft is allowed to roll or yaw during a long period of oscillation (controls fixed or controls free), the result is normally a severe deformation of the classic, uncoupled, long period, single axis response. In short, two things typically occur. First, the aircraft will roll due to a speed change and it will yaw due to a speed change (if unrestrained by the pilot or an attitude-hold type augmentation system). Second, typically a roll attitude change will couple into the pitch axis, and markedly alter the peak nose down (or nose up) attitude excursion experienced during the first half cycle. Additionally what might have otherwise been an oscillatory, single axis, long period response may well become an aperiodic convergent response or an aperiodic divergent response. This aperiodic response may be interpreted as the first half cycle of a very long period response.

If most of the data were collected in the above fashion, it would appear that adequate comparison with the intent of the requirements of the Interim Criteria are difficult to achieve. Given the great expense of flight testing, new and updated test techniques should be designed and established.

TRIM AND STATIC STABILITY

The Interim Criteria

"The current Interim Criteria address the subject of trim and static stability as follows:

(a) Trim. It must be possible to trim the longitudinal, lateral, and directional control forces to zero in steady flight at all approved IFR airspeeds, power, and configurations appropriate to the type. This must be accomplished by a recentering button or conventional trim controls. The trim device may not introduce any undesirable discontinuities in the force gradients, and its operation must be such as to provide gradual trimming without abrupt changes in the force or position. At these trim conditions, the control must exhibit positive self-centering characteristics. If it is necessary to turn the trim controls to operate, the direction of rotation must be such as to produce similar rotation of the rotorcraft about an axis parallel to the axis of the particular control.

Cockpit control free-play may not be excessive on the lateral and longitudinal axis. Motions of the control from the trim position, which result in no control surface response, may not cause objectionable handling characteristics, nor in any case exceed ±2 percent of total control travel.

(b) Static longitudinal control force stability. The helicopter must, at all forward speeds and at all trim and power conditions specified in this paragraph, possess positive static longitudinal control force stability with respect to speed. The slope of the control force versus airspeed curve must indicate that any significant change in airspeed is clearly perceptible to the pilot through a resulting change in stick force. Minimum perceptibility is interpreted to mean 1 pound per 6 knots speed change, excluding control friction. When the control force is slowly released with the rotorcraft at any airspeed within the applicable range specified in this paragraph, the airspeed must return to the specified trim speed ±5 percent or 5 knots, whichever is greater.

The tests specified in subparagraphs (1), (2), (3), and (4) of this paragraph must be conducted at the critical weight and c.g., with the landing gear retracted (if retractable). Static longitudinal control force stability must be shown as follows:

(1) Climb. The stick force curve must have a stable slope over an airspeed range from 20 knots above to 20 knots below the trim speed with -

(i) Maximum continuous power; and

(ii) The rotorcraft trimmed at the best rate of climb speed or the minimum approved IFR airspeed, whichever is greater.

(2) Cruise. The stick force curve must have a stable slope over an airspeed range from 0.7 to 1.1 times V_H or V_{NE} whichever is lower, with -

(i) Level flight power at 0.9 times V_H or V_{NE}, whichever is lower; and

(ii) The rotorcraft trimmed for level flight at 0.9 times V_H or V_{NE}, whichever is lower.

(3) Slow cruise. The stick force curve must have a stable slope over an airspeed range from .90 times minimum approved IFR airspeed to 1.30 times minimum approved IFR airspeed, with -

(i) Level flight power at 1.10 times minimum approved IFR airspeed; and

(ii) The rotorcraft trimmed for level flight at 1.10 times minimum approved IFR airspeed.

(4) Letdown at 500 feet per minute (ft./min.). The stick force curve must have a positive slope over an airspeed range from 20 knots above to 20 knots below the recommended approach speed with landing gear extended and retracted, if applicable, with -

(i) Power required to maintain 500 ft./min. letdown at recommended approach speed; and

(ii) The rotorcraft trimmed at the recommended approach speed.

(c) Lateral and directional static stability. For climbs of 1000 ft./min. or maximum continuous power climb, whichever is less, and for rates of descent of 1000 ft./min., at all approved IFR airspeed.

(1) In straight steady sideslip -

(i) At angles of sideslip up to 15 degrees, either side, the lateral and directional control movements and forces must increase in the stable direction and must be substantially proportional to the angle of sideslip as it is increased;

(ii) At angles of sideslip above 15 degrees, either side, up to the angle at which full directional control is employed or up to the maximum sideslip angle appropriate to the rotorcraft type, whichever is less, the directional control pedal forces may not reverse, and increased control deflection, if available, must produce increased angles of steady sideslip;

(iii) Sufficient bank must accompany steady sideslipping to indicate clearly any departure from steady unyawed flight;

(iv) There may not be any undesirable discontinuities in lateral or directional force gradients; and

(v) There may not be any undesirably high breakout forces for the lateral and directional controls.

(2) The directional static stability, as shown by the tendency to recover from a skid with directional controls free, must be positive, with the landing gear retracted (if retractable).

(3) The lateral static stability, as shown by the tendency to recover to level attitude from a sideslip with the lateral controls free, must be positive with landing gear retracted (if retractable).

The Federal Aviation Regulations (FAR)

Federal Aviation Regulations, PART 27 and 29 Airworthiness Standards: Normal Category Rotorcraft (maximum weights of 6,000 pounds or less) and Transport Category Rotorcraft respectively address the subject as follows:

27.161 and 29.161 Trim Control

The trim control -

(a) Must trim any steady longitudinal and lateral control forces to zero in level flight at any appropriate speed; and

(b) May not introduce any undesirable discontinuities in control force gradients.

27.171 and 29.171 Stability: General

The rotorcraft must be able to be flown, without undue pilot fatigue or strain, in any normal maneuver for a period of time as long as that expected in normal operation. At least three landings and takeoffs must be made during this demonstration.

27.173 and 29.173 Static Longitudinal Stability

(a) The longitudinal cyclic control must be designed so that, with the throttle and collective pitch held constant, during the maneuvers specified in 27.175 a rearward movement of the control is necessary to obtain a speed less than the trim speed, and a forward movement of the control is necessary to obtain a speed more than the trim speed -

(1) For power-on operations over the full range of altitude and rotor r.p.m. for which certification is requested; and

(2) For power-off operations, over the range of altitude and rotor r.p.m. for which certification is requested that is attainable with the controls rigged in accordance with the approved rigging instructions and tolerances.

(b) The stick position versus speed curve may have a negative slope within the speed range specified for the maneuver in 29.175(d) if the necessary negative stick travel does not exceed 1 inch measured at the top of the pilot's normal hand position.

27.175 and 29.175 Demonstration of Static Longitudinal Stability

(a) Climb. Static longitudinal stability must be shown in the climb condition at speeds from 0.85 V_Y to 1.2 V_Y, with -
(1) Critical weight;
(2) Critical center of gravity;
(3) Maximum continuous power;
(4) The landing gear retracted; and
(5) The rotorcraft trimmed at V_Y.

(b) Cruise. Static longitudinal stability must be shown in the cruise condition at speeds from 0.7 V_H or 0.7 V_{NE}, whichever is less, to 1.1 V_H or 1.1 V_{NE}, whichever is less, with -

(1) Critical weight;
(2) Critical center of gravity;
(3) Power for level flight at 0.9 V_H or 0.9 V_{NE}, whichever is less;
(4) The landing gear retracted; and
(5) The rotorcraft trimmed at 0.9 V_H or 0.9 V_{NE}, whichever is less.

(c) Autorotation. Static longitudinal stability must be shown in autorotation throughout the speed range for which certification is requested, with -
(1) Critical weight;
(2) Critical center of gravity;

(3) Power off;

(4) The landing gear (i) retracted and (ii) extended; and

(5) The rotorcraft trimmed at the speed for minimum rate of descent.

(d) Hovering. For helicopters in the hovering condition -

(1) The longitudinal cyclic control must operate with the sense and direction of motion prescribed in 27.173; and

(2) The stick position curve must have a stable slope, between the maximum approved rearward airspeed and a forward airspeed of 17 knots with -

(i) Critical weight;

(ii) Critical center of gravity;

(iii) Power required to maintain an approximately constant height in ground effect;

(iv) The landing gear extended; and

(v) The helicopter trimmed for hovering.

GENERAL COMMENTS ON TRIM AND STATIC STABILITY REQUIREMENTS

Trim, General

The paragraph (a) on Trim in the Interim Criteria neglects to cover or comment on trimming of the collective control forces. It discusses longitudinal, lateral and directional control forces and states that it must be possible to trim these forces to zero by use of a recentering button or conventional trim control. The criteria relate that the trim device may not introduce any undesirable discontinuities in the force gradient and its operation must be such as to provide gradual trimming without abrupt changes in face or position. It does not specifically address how the many Force Trim Release (FTR) buttons of current helicopters function. For example, the FTR type recentering button usually removes the force gradients from all axes simultaneously. This would appear to be unfavorable in high speed, IFR cruise flight when the pilot, wanting to make an adjustment to roll trim, activates the force trim release system and loses all longitudinal force cueing instantaneously (Reference 34). For IFR flight, the use of continuous trim systems and for separate axis force trim release systems should be reappraised and re-addressed more carefully. Also, some aircraft do not have trim systems available on all axes. There is a general need for more data and research on the requirements for suitable trim systems on IFR helicopters.

Trim Requirements for an IFR Certified Helicopter

It is possible to place the directional control so as to achieve zero force without a trim system. The S-58T was certified for IFR operations without a yaw trim system. Also, the aircraft incorporates a yaw pedal damper which resists the pilots attempts to move a pedal as a function of pedal rate. It seems fairly obvious from reviewing the flight procedures involved in flying the S-58T (and H-34J) that no yaw pedal force gradient or force zeroing capability is required. This apparent lack of need for a force gradient is explained by several characteristics. First, a single rotor helicopter typically requires the pilot to move the pedals every time the collective (power) is moved. The S-58T yaw control (and H-34J) has roughly a 6 pound friction band. This friction is low enough to be acceptable yet high enough to hold the pedals in place (there is no force feedback because the yaw control incorporates an irreversible hydraulic servo system). The need to continuously move the directional controls in response to yaw trim changes is easier to accomplish without a yaw trim system. Most systems use a "force trim release button" which will zero all forces at once. This can cause the longitudinal and lateral control forces to zero any time the pilot attempts to zero the pedal force. It would appear that given the option, the pedal force trim system should be separate from the longitudinal and lateral control system. Next to having two separate trim release buttons, it would appear that the S-58T yaw force arrangement is superior to the arrangement provided for in the Interim Criteria.

Carrying this discussion further, consider the lack of desirability associated with a stick trim release system which zeroes the longitudinal and lateral forces with a single depression of the trim switch. The typical single rotor helicopter is normally so aerodynamically coupled that it is impossible to change the forward speed (even collective fixed) without inducing a small out of trim condition in the yaw and lateral control. Consider the case where the pilot desires to use the longitudinal control force as a cue of an offspeed condition (an indication of apparent positive longitudinal static stability). Any time the pilot tries to trim the aircraft into lateral-directional trim, he will zero the longitudinal stick centering force cue. It would appear to be much more desirable to have a suitable friction trim system in yaw. In addition, there is the distinct possibility that a friction system in roll (with a roll control rate damper attached to the control linkage or the equivalent) would be perferable to a single stick trim release button. This is especially true if a prime element of an aircraft's IFR capability involved its stable longitudinal force characteristic.

The strongest argument against eliminating a control centering force system involves the control location maintenance function (hands-off). The pilot needs to release the controls to accomplish other cockpit duties and the natural vibration of the helicopter will often cause a control to move if friction alone is used. Or, if the friction is set high enough, it is too high to permit accurate and quick (small) control inputs for short term gust suppression.

Now if the yaw control is decoupled from the collective we have a much different yaw trim requirement. The more the yaw is decoupled (as viewed by the pilot) from the collective and speed changes, the more desirable becomes a yaw force trim system with a centering feature.

Similarly, the more stable the pitch and roll characteristics become the more useful and desirable becomes a control centering force trim system. But, the proper design may change from the instantaneous trim button version to the beeper trim type. This bi-directional trim system is typically not tied to the yaw control system and the longitudinal and lateral trim systems operate independently as well (S-61, H-3, H-2, H-46, H-47, H-1N etc.).

The augmented aircraft are more easily treated than the less augmented designs but, in general, it appears that it may be possible to obtain better IFR flying qualities in some aircraft with no yaw force trim system. Additionally, it may be desirable to have only a longitudinal force trim system.

In summary, if the static-longitudinal force characteristic is important to the IFR suitability of the helicopter, then the longitudinal force should not drop to zero when the yaw, roll or collective trim button is operated. If this is not the case, the argument for longitudinal static stability (as applied to control force characteristics) may be significantly weakened because the force characteristic is hardly ever really available in operational flight.

General Comments on Interim Criteria Static Longitudinal Control Stability

The requirement for the aircraft to return to the original trim speed is a very demanding requirement and should be an adequate demonstration of "speed trimability". The ability to trim on speed and return to speed is one of the more basic functions the FAA can attempt to establish. Static longitudinal stability is just one of the ingredients required to achieve speed trimability and speed maintenance.

Measurement of the classic, longitudinal, static stability is really needed for, or in support of, an aircraft that does not meet the requirements in the dynamic long period sense or in its ability to be trimmed sense. The control displacements associated with the command of longitudinal speed changes and "collective (power) to pitch" trim changes are generally much larger than the motions associated with sensing speed changes as a result of a static stability dependent longitudinal force cue. These longitudinal control displacements are required to push the nose over (or pull it up) in conjunction with collective displacements and they are very non-airplane. Pilots have required light control forces in force feel systems because of these non-airplane control techniques and because of other conflicting hover control tasks. The conclusion one can draw from past experience is simple, when the aircraft is unaugmented or lightly augmented, the control force characteristics need to be relatively light. If the "1 pound per 6 knot" force characteristic of the Interim Criteria were observed, the correct trim spring could easily result in a 10 pound per inch gradient. This gradient is in direct conflict with conventional practice, which sizes the longitudinal control force more like 0.3 lb/inch.

In one FAA flight program, a test was conducted against the "1 lb per 6 kt" requirement to specifically determine comparative suitability. Figure 4-3 presents the results of this evaluation in a somewhat sanitized presentation of the flight test data. Two spring gradient levels were evaluated. The high force gradient was documented for two trim speeds while the acceptable gradient was documented for only one trim speed. It would appear that past experience has clearly shown that a force characteristic which provides positive stick centering and does not drop to zero (in the friction band) will yield satisfactory results.

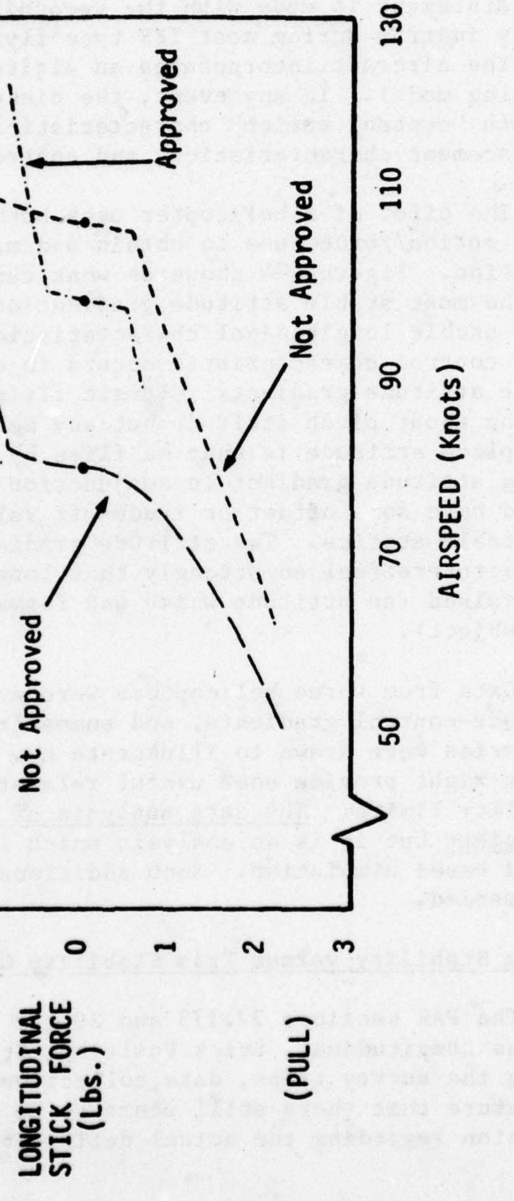


Figure 4-3. Results of Stick Force Gradient Test.

The Importance of Pitch Attitude versus Trim Stability Characteristics

Figure 4-4 illustrates the way pitch attitude and longitudinal control position normally vary over the typical speed range of a medium size single rotor helicopter. The aircraft is in trim at each point, so the data does not directly relate to classic, longitudinal static stability. The longitudinal control position trim stability data are possibly even more important because they relate more exactly to the characteristic through which the pilot flies under IFR conditions. This statement is made with the recognition that the aircraft is very nearly in trim during most IFR type flying. This is even more correct when the aircraft incorporates an altitude-hold mode (or glide-slope tracking mode). In any event, the discussion to follow applies equally to both "control motion" characteristics, static stability control displacement characteristics, and control force static characteristics.

The pilot of a helicopter uses both pitch attitude and the longitudinal motion/force cues to obtain and maintain a trimmed airspeed condition. Figure 4-4 shows us what can typically be expected. That is, the most stable attitude gradient occurs in conjunction with the least stable longitudinal characteristic, and the most stable longitudinal control characteristic occurs in conjunction with the least stable attitude gradient. Classic flying qualities research says nothing about pitch attitude but any helicopter pilot will tell you that pitch attitude is what he flies by, IFR. It would appear that a strong attitude gradient in conjunction with a good attitude indicator should have some offset or trade-off value when considering the need for stable statics. The attitude gradient can also explain why some manufacturers feel so strongly that longitudinal static stability is over valued (an attitude which was forwarded in various interviews on the subject).

Data from three helicopters were evaluated with respect to their attitude-control gradients, and summarized in Figure 4-5. In addition, boundaries were drawn to illustrate how such an interdependent set of limits might provide some useful relaxation of the longitudinal static stability limits. The data analysis of this characteristic is obviously incomplete but it is an analysis which lends itself well to flight and ground based simulation. Such additional simulation is highly recommended.

Static Stability versus Trim Stability Curves

The FAR sections 27.173 and 29.173 require that the helicopter possess Longitudinal, Stick Position, Static Stability. It was found during the survey trips, data collection efforts, and in certain literature that there still seems to be some continuing difficulty or confusion regarding the actual definition of Static (Control or Stick

(Single Rotor Helicopter Under 12,000 pounds)

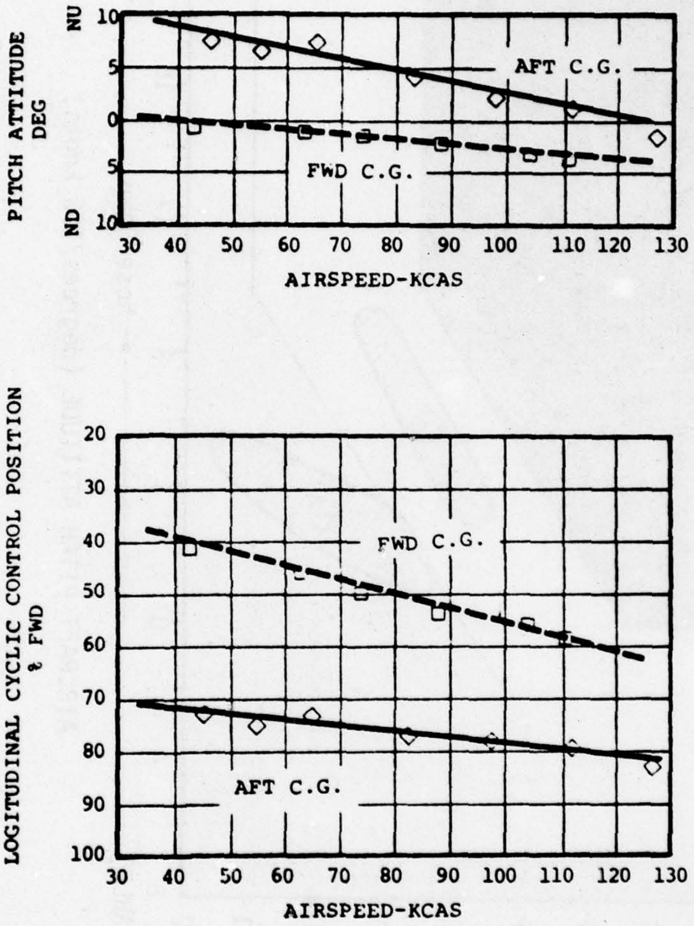


Figure 4-4. Example of Longitudinal Control Position and Pitch Attitude for Trimmed Level Flight.

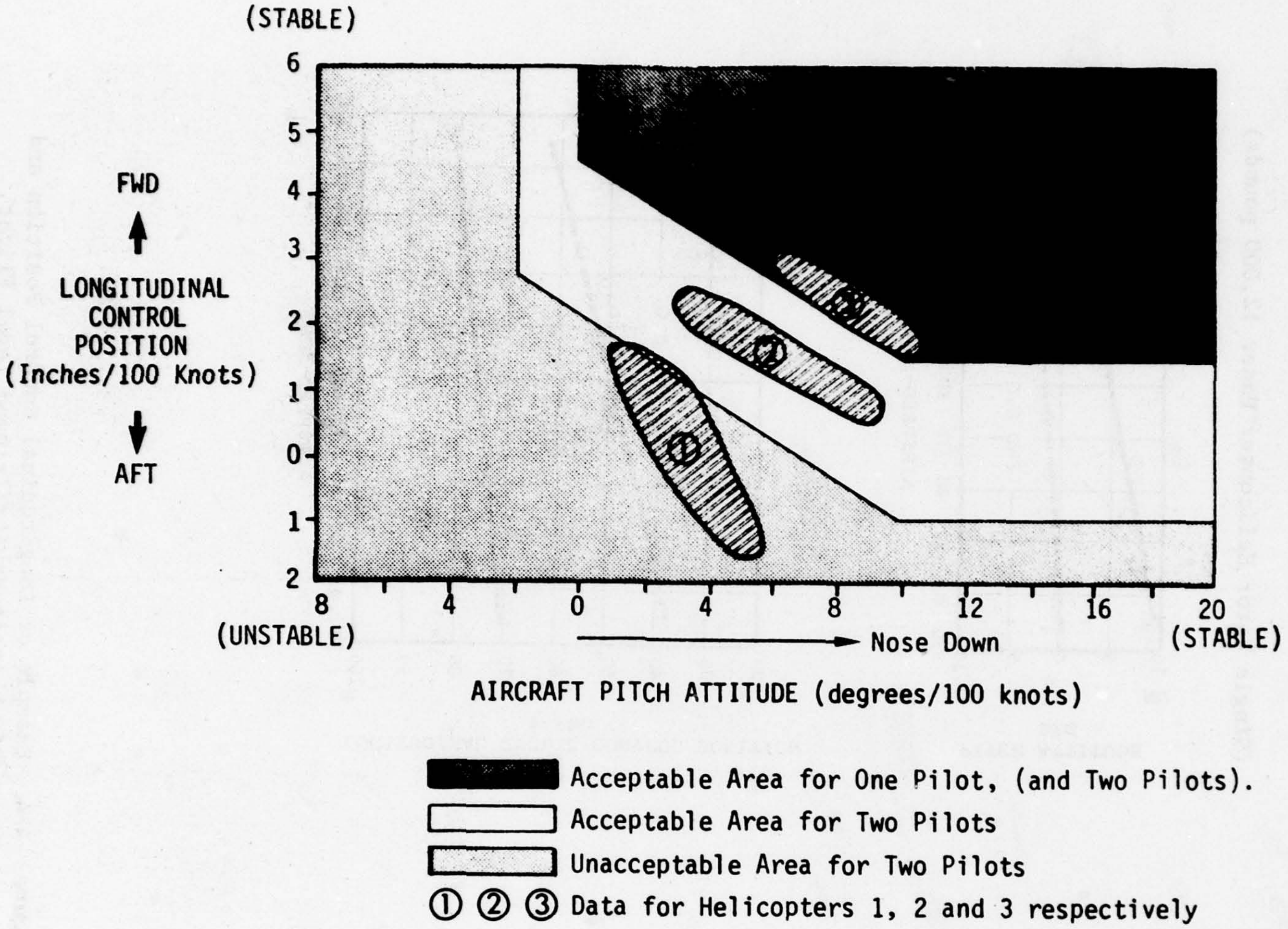


Figure 4-5. Typical Data Showing Allowable Combinations of Longitudinal Trim Gradient and Aircraft Pitch Attitude.

Position) Stability as compared to Trim Stability curves (Reference 35). The FAR states that data is to be obtained with the throttle and collective pitch held constant. References 35 and 36 both state that there are a variety of stability curves that may be plotted that are of interest. However, the FAR intend, by their wording, that the classic static (stick position) stability with the "constant-power" constraint be determined and is required to be positive (stable). As Reference 35 states it, "... the change in stick position for a unit change in speed about a trim condition; i.e., it is the ratio of change in (control position) to a change in (velocity) about a trim point (the initial trim velocity) for all other controls remaining fixed. This is not to be confused with the slope of the curve connecting the level flight trim points of stick position versus velocity." Bramwell (Reference 37) discusses static (control position) stability in relation to the (E) coefficient of the quartic and states "... Consider a helicopter changing from one trimmed speed to another, the collective pitch remaining fixed. For small changes of speed from level flight, the resulting angle of climb or descent will be quite small corresponding to the gliding flight of classical fixed wing stability theory." Curtiss (Reference 36) also relates the static (stick position) stability to the sign of the constant term (the E coefficient, the non s term) in the characteristic equation. He states that "The sign of this term will normally indicate whether one of the modes of motion of the aircraft is a pure divergence or not. This term is equal to:

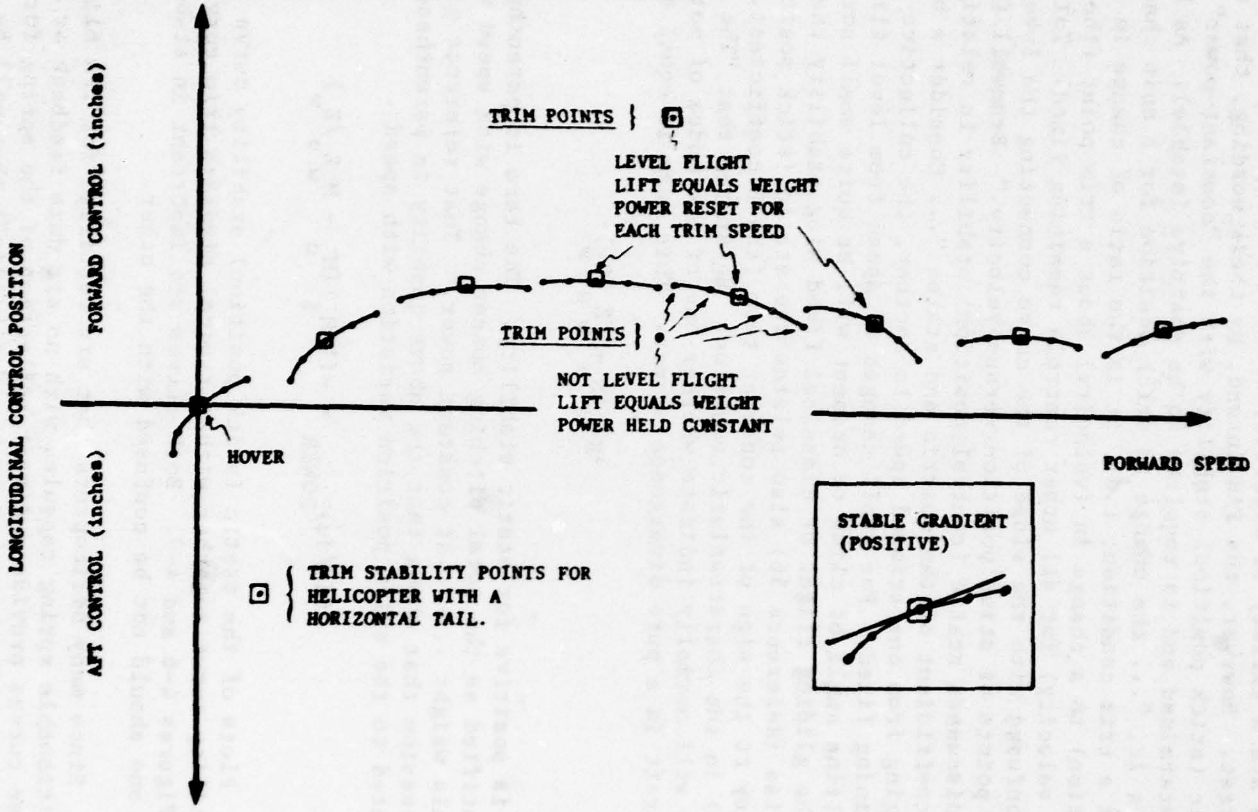
$$-gZ_w(M_u - M_w Z_u/Z_w)$$

and is positive for static stability. The term in parentheses can be identified as the total pitching moment change with speed when lift equals weight ... ...at constant power." That reference gives the expression that shows that the above quantity in parentheses is directly related to the stick position variation with speed

$$(d\delta/du)_{POWER} = -(1/M_\delta)(M_u - M_w Z_u/Z_w)$$

Plots of the static (stick position) stability curve and the trim stability curve together with a typical airplane trim curve, are shown in Figures 4-6 and 4-7. Both curves are important in stability analyses but one should not be confused with the other.

Since many helicopters that are certified for IFR flight use pilot positionable spring capsules with no air data feedback or intelligence, these curves provide a direct reflection of the spring forces (and the so-called apparent static force "stability") that will be noted by the



NOTE: LOCAL SLOPES OF THE CURVES (OBTAINED AT CONSTANT POWER) TAKEN AT THE LEVEL FLIGHT TRIM POINTS REPRESENT STATIC (STICK POSITION) STABILITY

Figure 4-6. Static Stability Curves (Stick Position).

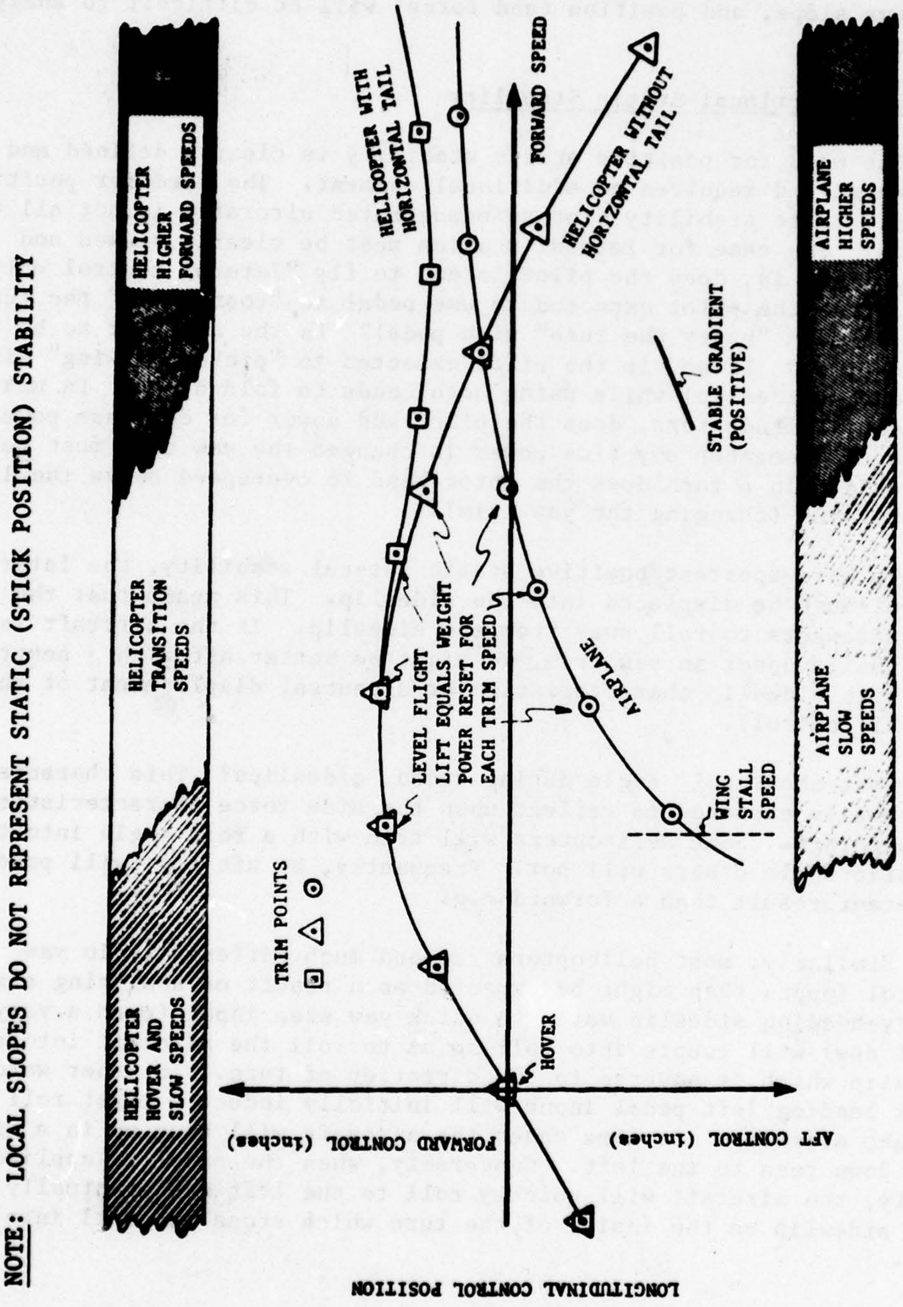


Figure 4-7. Trim Stability Curves

pilot. If the static (stick position) stability is negative, the force stability will probably be noted as negative. It is worth noting that for a certain speed range the curves may be very flat or have a slightly negative slope, and position (and force) will be difficult to analyze or document.

Lateral/Directional Static Stability

The need for positive static stability is clearly defined and documented and requires no additional comment. The need for positive lateral static stability (for an unaugmented aircraft) is not all that obvious. The case for lateral statics must be clearly viewed and flown. That is, does the pilot intend to fly "lateral control only" turns or is the pilot expected to use pedal to "coordinate" the turn, or maybe even "hurry the turn" with pedal? Is the aircraft to be flown single-pilot? If so, is the pilot expected to "pick up a wing" with the pedal (sideslip) while using both hands to fold a map? In making a constant altitude turn, does the pilot add power (or decrease power) in the turn? Remember any time power is changed the yaw trim must be corrected. In a turn does the rotor tend to overspeed above the level flight value (changing the yaw trim)?

To have apparent positive static lateral stability, the lateral control must be displaced into the sideslip. This means that the aircraft wants to roll away from the sideslip. If the aircraft is continually upset in yaw trim, we might be better off with a neutral roll with sideslip characteristic (or a neutral displacement of the lateral control).

What about roll angle during steady sideslips? This characteristic is normally expected to reflect upon the side force characteristic of the aircraft. Some helicopters will trim with a roll angle into the sideslip while others will not. Frequently, an aft c.g. will produce a different result than a forward c.g.

Similarly, most helicopters respond much differently to yaw control inputs than might be expected as a result of analyzing classic steady-heading sideslip data. A quick yaw step input (even a very small one) will couple into roll so as to roll the aircraft into a sideslip which is adverse to the direction of turn. In other words, a quick leading left pedal input will initially induce a right roll into a right sideslip. In some cases the aircraft will hang up in a right wing down turn to the left. Conversely, when the pedal is applied slowly, the aircraft will quickly roll to the left and eventually build up a sideslip on the inside of the turn which stops the roll into the turn.

The Interim Criteria require lateral static stability. No data can be found which suggests an IFR related control problem because of neutral or even slightly unstable, apparent lateral static stability as reflected in the requirements of the Interim Criteria. Experience would suggest that there may be dynamic problems associated with entry into autorotative flight when the aircraft has a strong tendency to roll into an adverse bank due to rapid pedal inputs. Some dynamic test associated with entry into autorotation may well be the way to determine the acceptability of the lateral roll attitude and roll control characteristic. If the test pilot can hold the pedals fixed, rapidly decrease the collective and produce a roll to the right with full left lateral control in, a real problem exists. An additional test to determine the acceptability of an unstable lateral control characteristic would involve measuring the instability (e.g., 1/4 inch in the roll control at say 15 degrees of sideslip). Having determined the control instability, zero the sideslip and record the time to roll an increment of 15 or 30 degrees roll angle. If the time to reach either limit is very long (say 60 seconds) and the roll rate was decreasing at 30 degrees, one could assume a certain degree of equivalent safety had been demonstrated.

There is every reason to expect that there is some trade-off in acceptability between bank angle (wing down into a steady heading sideslip) and lateral control displacement. It might be possible to explain the acceptability of otherwise unstable characteristics by the use of a chart much like that in Figure 4-5. That is, a stable bank angle characteristic could allow for the acceptance of a mildly unstable lateral static control characteristic.

DYNAMIC STABILITY, GENERAL

Before delving into the subject area and the particulars of the dynamic stability required for the helicopter to fly IFR, it is helpful to discuss two pertinent topics. The first topic discusses the differences and relationships between "dynamic stability" and "flying qualities" so that the terms may be applied properly and the distinctions noted. The second topic discusses the types of dynamic behavior typical of current "basic" and "augmented" IFR certified helicopters and attempts to compare them, where possible, to airplane-type dynamics, terms, and analyses.

Flying Qualities versus Dynamic Stability

The subject of flying qualities deals with the evaluation of the complete pilot/aircraft system whereas dynamic stability concentrates primarily on the study of the time history behavior of the aircraft alone. For pilot/aircraft systems that are required to comply with a given set of standards, level of safety and satisfactory workload/performance; pilot opinion and rating scales provide the most accurate and efficient method of assuring a suitable assessment of the acceptability of a complete pilot/aircraft system used for a specified task. Studies using pilot opinion and ratings in the evaluation of aircraft flying qualities have been accomplished by numerous agencies. In fact, many of the bases for the IFR dynamic stability boundaries detailed in MIL. SPEC. H-8501A (and emulated by the current Interim Criteria) were established by the use of pilot opinion flight experiments accomplished at NASA-Langley. Also, in its own way, the granting or determination of "equivalent safety" by the FAA for stability requirements could be construed as a pilot opinion rating of flying qualities.

The usual definition for flying qualities, frequently stated from Reference 38, is: "Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role." Note that the definition includes many subject areas of the pilot/aircraft system such as workload, display sophistication, tracking performance, and task to mention a few. Unfortunately, with so many variables and the special characteristics of helicopters, the subject of helicopter IFR handling qualities becomes a very complicated one. Consider, for example, the characterization of the pilot/aircraft system for a helicopter, high performance IFR precision ILS to an obscured landing area in the presence of external disturbances such as atmospheric turbulence. In a general way, the pilot/aircraft system and the task can be diagrammed as shown in Figure 4-8. For an ILS approach, the

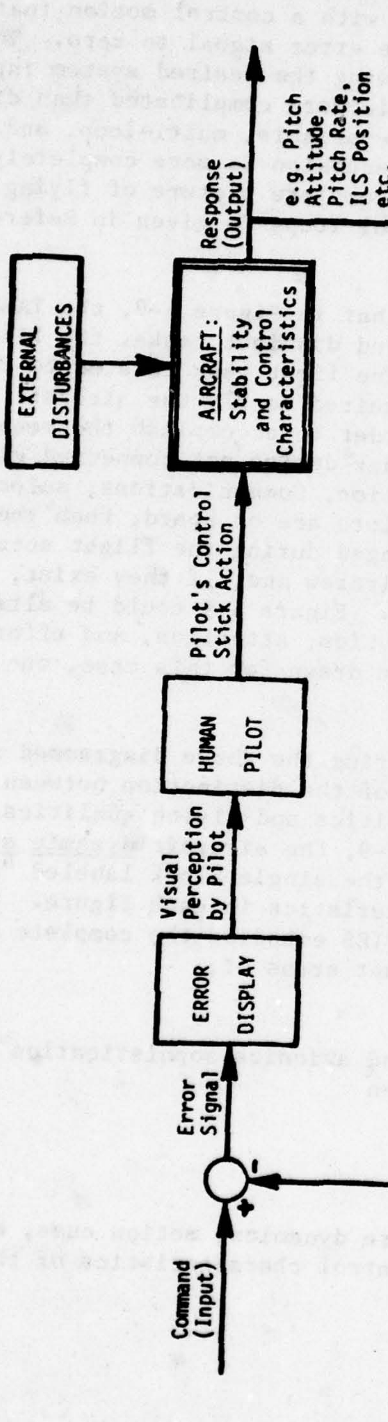


Figure 4-8. Typical Pilot/Aircraft System Diagram

input command is the ILS beam centerline or null position. The error signal, sensed by the instrumentation, will be visually displayed to the pilot causing him to react with a control motion that will move the aircraft and tend to reduce the error signal to zero. Then the aircraft output will be precisely following the desired system input command. Of course the complete system is more complicated than diagrammed in the figure since it is a multi-variable, multi-loop, and multi-degree-of-freedom problem. The above discussion is more completely related in Reference 14 and another more complete picture of flying qualities factors versus the pilot control loops is given in Reference 38 and shown in Figure 4-9.

It is important to note that in Figure 4-9, the TASK input to the pilot comprises two separate and distinct tasks, the Flight Control Task and the Auxilary Task. The first task relates to that part of pilot effort and attention required to fly the aircraft by maintaining attitude and maneuvering in order to accomplish the required tracking. The second task covers all other duties not connected directly with flight control such as Navigation, Communications, selection of systems etc. (Appendix B). If two pilots are on board, then the tasks are divided, shared, and interchanged during the flight according to the personal preferences of the aircrew and, if they exist, the dictates of cockpit procedures guidelines. Figure 4-9 could be altered accordingly to reflect this division of duties, attention, and effort and two separate loop systems could be drawn for this case, one for the pilot and one for the copilot.

The main reason for offering the above diagrammed descriptions is to provide a clearer picture of the distinction between aircraft dynamic stability characterisitics and flying qualities. In the diagrams of Figures 4-8 and 4-9, the aircraft dynamic stability characteristics involve only the single block labeled "AIRCRAFT" Stability and Control Characteristics in each figure. Whereas, the subject area of FLYING QUALITIES embodies the complete diagrams with all the collateral or attendant areas of;

- task
- instrument display and avionics sophistication
- aircraft configuration
- pilot stress
- workload
- tracking performance
- environment
- failure modes, failure dynamics, motion cues, etc. as well as the stability and control characteristics of the aircraft itself,

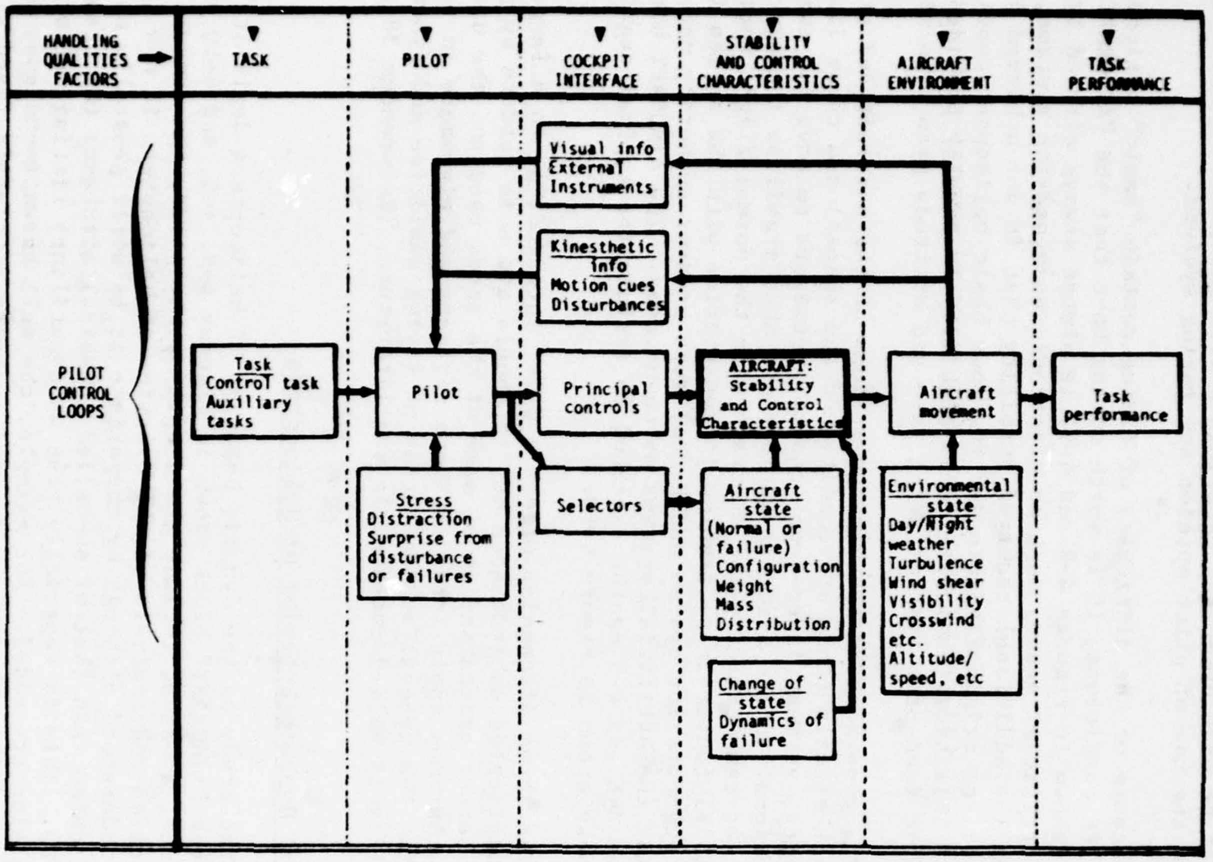


Figure 4-9. Handling Qualities Factors versus Control Loops
(Reference 38)

the dynamic characteristics of the aircraft can be determined by documenting and analyzing the time histories of the vehicle responses alone. However, the flying qualities assessment of the complete system can best be made by actual experiments with the pilot in-the-loop and through the use of pilot opinion and rating systems.

Because of the difficulty of flying certain "basic" helicopters under IFR conditions, it is worth noting here that the "AIRCRAFT" block (shown in Figures 4-8 and 4-9) is almost always altered by using artificial means, such as electronic augmentation systems, to provide the additional required stability that is not achieved inherently or not originally intended for some basic helicopter configurations. This additional artificial stability is usually provided by automatic feed-back systems using rate and attitude gyro type signals.

The gyro sensors measure the motions of the aircraft and provide feedback signals (that are conditioned and shaped) and cause limited-authority, series (inner-loop) control actuators to move the swashplate proportional to the aircraft motions and thus stabilize the aircraft. The pilot can still fly the aircraft with the normal flight controls in a parallel (outer-loop) fashion in conjunction with the series (inner-loop) augmentation system and he has much greater authority and can override the artificial systems as he chooses. The AIRCRAFT block of Figures 4-8 and 4-9 can be sketched to include the typical augmentation feedbacks shown in Figure 4-10.

The above discussion offers a brief introduction to a large and complicated subject area but it should aid some readers by providing a better understanding of some of the terms used and the distinctions that may apply later in these sections and elsewhere in the report. The general subject areas of flying qualities and dynamic stability is well documented in the literature, (References 38 through 68).

Typical Dynamic Behavior of Helicopters

The study of the dynamic behavior of helicopters deals strictly with the "AIRCRAFT" block shown in Figures 4-8, 4-9, and 4-10 and does not, as such, include the displays, the pilot, the task, etc. The prediction and analysis of the dynamics of helicopters is now quite well understood although by comparison it is still generally more complicated than that of so-called classical airplanes (References 69 and 70). This is especially true when auxiliary lifting surfaces and propulsion are added. For example, the well known techniques of longitudinal stability and control analyses of classic fixed-wing airplanes permits dividing the longitudinal motion into two quadratic

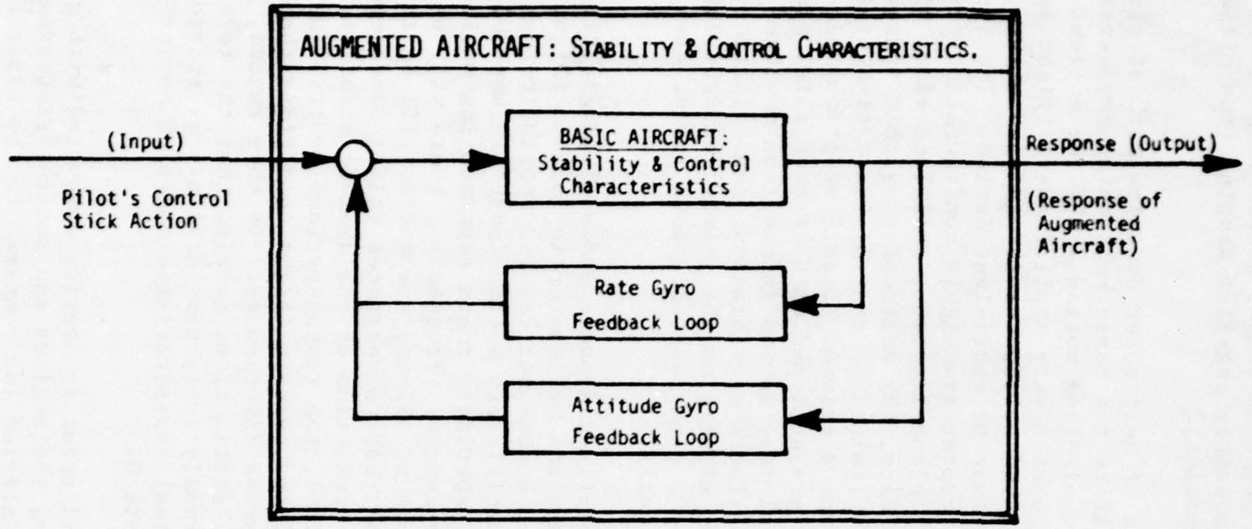


Figure 4-10. Diagram of Typical Aircraft System with Augmentation Loops

type motions that are quite well understood and whose physical interpretation is relatively simple. Characteristic airplanes modes, for stick-fixed longitudinal responses, are normally two oscillations; one of relatively short period (e.g. one to four seconds) with quite heavy damping and the other of longer period (e.g. 30 to 40 seconds) with very little or possibly negative damping (the classic airplane phugoid or long period motion).

Comparisons of helicopter dynamics with airplane dynamics are very difficult since the basic helicopter may never exhibit or approximate the classic airplane motions. If the motions are similar, they will occur only over a very small forward flight speed range and then probably only if the helicopter is equipped with an appropriate horizontal tailplane or equivalent device. The important modes of motion of a helicopter are highly configuration oriented and very sensitive to tailplane location, tailplane size, hinge offset, c.g. location, etc. Also, for helicopter dynamic response studies, discussion is normally limited to control-fixed time history responses (after a disturbance from a trimmed flight condition) since currently certified vehicles are equipped with irreversible, power-boosted control systems. Control-free motion information on these helicopters usually centers on the effects of vibration, control friction, spring, mass, and acceleration effects on the pilots' control levers, preload, slop, "sticktion", dead-zone, breakout force, etc. -- subjects of control system quality.

The control-fixed dynamic modes of longitudinal motion of a "basic" (unaugmented) helicopter in forward flight are typically characterized by a non-oscillatory, aperiodic-type, short term motion and either an oscillatory motion (possibly unstable) or additional combinations of aperiodic roots representing motions classed as divergences or convergences. Frequently, there will be no recognizable oscillatory roots at all and the motion will be totally characterized by apparent real root convergences and/or divergences. To further complicate the prediction of the dynamic stability (and comparisons to airplane dynamics), the responses (and control inputs) may be strongly coupled. Also, for certain flight conditions the responses may entail rapid and dangerous divergences. In this regard, it is important to note a specific distinction, namely, that the terms DIVERGENCE and CONVERGENCE normally imply non-oscillatory, aperiodic motions (Reference 71). Typical characteristic modes of motion and nomenclature are shown in Appendix D.

If the helicopter is heavily augmented with artificial means and has a tailplane, the motions and control responses in forward flight are completely altered (as compared to the basic helicopter or classical airplane) and artificially shaped to various degrees depending on many factors such as augmentation system type, actuator control authority, tailplane size, location and gearing to flight controls, c.g. range and flight envelope, etc. With these features and configuration variations, identification and prediction of the entire character of the motion may be quite difficult and greatly altered and no easily usable relationships for long or short period motion comparisons to the basic helicopter (or airplane) exist. In these systems, familiar long and short period motions are masked or washed-out and, practically speaking, no longer of interest for this case. Analysis of the stick-fixed motions of helicopters with sophisticated stability augmentation and automatic stabilization systems frequently turns into an analysis of autopilot performance, ride quality, actuator performance or saturation, etc., and bears only a remote resemblance to the prediction and determination of minimum dynamic stability criteria and requirements of the helicopter for IFR certification. Failure modes are still of interest especially in the determination or documentation of the degree of dynamic stability degradation and/or increase in pilot workload that occurs and evaluation of whether the vehicle can still be flown to complete the mission or if it is now strictly a dangerous emergency mode of flight.

The comments made above apply only to general helicopter dynamic stability and they set the scene and provide a brief insight into the complicated character of helicopter dynamics. As related, helicopter dynamics generally are considerably different then classical airplane dynamics and the wide variety of configurations and systems utilized only tends to complicate the pilot/vehicle systems further. However, the discussion offered above does frame, in a very general way, the range of dynamics that are possible and should provide a better insight to the important aspects of the remarks made later in these sections.

DYNAMIC STABILITY, FEDERAL AVIATION REGULATIONS

Current FAR

The current Federal Aviation Regulations, FAR, Parts 27 and 29, Airworthiness Standards: Normal Category and Transport Category Rotorcraft, replace Parts 6 and 7 of the Civil Air Regulations. They were published as a notice of proposed rule making in 1964. Dynamic stability requirements are not given in quantitative form but are addressed indirectly in various sections. In Parts 27 and 29 under FLIGHT CHARACTERISTICS, Sections 27.141, 27.143, and 27.171 appear to be the parts most related to the general dynamic behavior associated with helicopters. These sections read, in part, as:

" 27.141 General.

The rotorcraft must -

(b) Be able to maintain any required flight condition and make a smooth transition from any flight condition to any other flight condition without exceptional piloting skill, alertness, or strength, and without danger of exceeding the limit load factor under any operating condition probable for the type, including -

(1) Sudden failure of one engine, for multiengine rotorcraft meeting transport category A engine isolation requirements of Part 29 of this chapter; and

(2) Sudden, complete power failure, for other rotorcraft; and

(c) Have any additional characteristic required for night or instrument operation, if certification for those kinds of operation is requested.

27.143 Controllability and maneuverability.

(a) The rotorcraft must be safely controllable and maneuverable -

(1) During steady flight; and

(2) During any maneuver appropriate to the type, including -

(i) Takeoff

(ii) Climb, etc. ...

(b) The margin of cyclic control must allow satisfactory roll and pitch control at V_{NE} with -

(1) Critical weight;

(2) Critical center of gravity;

(3) Critical rotor r.p.m.; and

(4) Power on and power off.

(c) A wind velocity of not less than 17 knots must be established in which the rotorcraft can be operated without loss of control on or near the ground in any maneuver appropriate to the type (such as crosswind takeoffs, sideward flight, and rearward flight), with -

(1) Critical weight;
(2) Critical center of gravity; and
(3) Critical rotor r.p.m.

(d) The rotorcraft, after (1) failure of one engine in the case of multiengine rotorcraft that meet transport category A engine isolation requirements, or (2) complete engine failure in the case of other rotorcraft, must be controllable over the range of speeds and altitudes for which certification is requested when such power failure occurs with maximum continuous power and critical weight. No corrective action time delay for any condition following power failure may be less than -

(i) For the cruise condition, one second, or normal pilot reaction time (whichever is greater); and
(ii) For any other condition, normal pilot reaction time.

27.171 Stability: General.

The rotorcraft must be able to be flown without undue pilot fatigue or strain, in any normal maneuver for a period of time as long as that expected in normal operation. At least three landings and takeoffs must be made during this demonstration."

General Comments on FAR Dynamics

The sections pertaining to general dynamic behavior in Part 29 are essentially identical in content. The other sections in Parts 27 and 29 under FLIGHT CHARACTERISTICS deal mostly with other areas such as trim and static stability. Most of the sections discussed in Parts 27 and 29 relate to VFR type flight conditions, however, paragraph (c) of Section 27.141 specifically mentions the words "night or instrument operations".

The requirements on dynamic stability (and workload/performance) are alluded to in the FAR in numerous, broad, general phrases such as:

- "Be able to maintain any required flight condition ...
- ... make a smooth transition ...
- ... without exceptional piloting skill, alertness, or strength ...
- ... without danger of exceeding limit load factors under any operating condition ...
- ... must be safely controllable and maneuverable ...

- ... can be operated without loss of control on or near the ground in any maneuver appropriate ...
- ... must be controllable over the range of speeds and altitudes for which certification is requested ...
- ... must be able to be flown without undue pilot fatigue or strain in any normal maneuver for a period of time as long as expected in normal operation."

It would appear that for the dynamic stability (and workload/performance) requirements specified in the FAR, compliance would be adjudged mainly from a flying qualities point of view using the pilot opinions and ratings of the examiner.

DYNAMIC STABILITY, INTERIM CRITERIA

Interim Criteria, Statements of Paragraph (d)

The current Interim Criteria directly addresses the subject of helicopter IFR dynamic stability under paragraph (d). Excerpting that portion from the Criteria (Appendix A, Version 1) it reads:

"(d) Longitudinal-lateral-directional dynamic stability. Longitudinal-lateral-directional oscillations with controls fixed following a single disturbance in smooth air must exhibit the following characteristics:

(1) Any oscillation having a period of less than five seconds must damp to one-half amplitude in not more than one cycle. There may not be any tendency for small amplitude oscillations to persist.

(2) Any oscillation having a period of from 5 to 10 seconds must damp to one-half amplitude in not more than two cycles. There may not be any tendency for undamped small oscillations to persist.

(3) Any oscillation having a period greater than 10 seconds but less than 20 seconds must be at least lightly damped.

(4) Any oscillation having a period of 20 seconds or more may not achieve double amplitude in less than 20 seconds."

General Comments on Interim Criteria Dynamics

Some general comments or initial observations are offered on the above Interim Criteria dynamic stability statements of paragraph (d) regarding completeness, scope of applicability, utility, and importance in IFR certification procedures, namely:

A. The requirement appears to be a general and blanket specification on longitudinal, lateral, and directional dynamic stability and makes no additional distinctions or impositions on the different axes of motion.

B. They address only oscillations and apparently exclude or neglect the very common, important non-oscillatory dynamics of helicopters; real roots appear to be eliminated from consideration.

C. If the real axis is addressed in the criteria above, then depending on interpretation of statement (4), aperiodic, non-oscillatory divergences with times to double amplitude as low as 20 seconds are allowed and meet the Interim Criteria.

D. As far as helicopter oscillatory motions are concerned, the four statements are properly drafted but address only a limited aspect of the subject area of dynamic stability. For example, when these same statements were first drafted in early versions of the MIL. SPEC. they represented a concentration on a single longitudinal mode of motion which at the time appeared to be of interest primarily for the hover/slow speed spectrum of operations of earlier vintage tail-less, essentially unaugmented helicopters. (However, in general, some very useful, widely applicable data were obtained during the many simulated slow speed IFR approaches performed for these experiments, References 42 and 56.) In those earlier days, many dynamicists were obsessed (and perhaps rightly so, depending on the tasks of importance at that time) with the hover/slow speed longitudinal dynamic characteristics of helicopters. The requirements on longitudinal oscillatory dynamics were added (almost as an adjunct) to 8501A, at that time, to address primarily the longer term motions present at hover and slow forward speeds and were not meant to cover the short term dynamics requirements. The statements of paragraph (d) of the Interim Criteria are insufficient in themselves and fail to portray the necessary or adequate dynamic stability and control requirements for acceptable, safe IFR flight in helicopters for the applicable IFR speed ranges.

E. The dynamic stability criteria do not distinguish between requirements needed for short term dynamics versus long term dynamics and cover them both for all axes with the blanket specification.

F. Certain other significant dynamic stability and control criteria important to the achievement of an acceptable rating of IFR handling qualities commensurate with the attainment of a required level of safety are not included. For example, the criteria appear incomplete as far as special or additional needed stability criteria such as the "concave downward" requirement, specification of minimum allowable short period frequencies, minimum damping and control power, etc.

Related Issues on Interim Criteria Dynamics

The lettered-item comments listed above tend to apply quite directly to the Interim Criteria dynamic stability statements of paragraph (d). They will be referred to and discussed in greater detail throughout this section. However, some additional items not mentioned, or less directly implied, but related to the dynamic criteria of (d) are listed below. A few items may appear to be slightly afield from the dynamic criteria but it is felt they are generally related and need to be mentioned here. They will be referred to in other sections of this report and are discussed to some degree in a general way below. Additional related comments on the Interim Criteria dynamic stability are:

G. The dynamic stability criteria make no specific mention, allowances or distinction in required levels of dynamic stability versus minimum acceptable aircrew manning level (one-pilot IFR operation versus two-pilot IFR operation).

H. It appears that these Criteria are not readily applied to certification of highly-augmented, sophisticated control system helicopters. Many of the currently certified, highly augmented, helicopters far exceed the above oscillatory requirements and the need for expensive documentation flights and determination of the precise dynamics (to determine if it meets the minimums of the Interim Criteria) is probably a moot exercise in many cases. Therefore, it could be reasoned that the dynamics part of the Criteria does not provide much guidance (or plays very little part) in the IFR certification procedure and determination of minimum dynamic requirements and level of safety of these helicopters.

I. The IFR dynamic criteria, as stated in paragraph (d) above, provide no guidance as to the influence on certification of high-quality, greatly sophisticated display systems for the pilot. Under paragraph (g) <u>Equipment for IFR Operations</u> of the Interim Criteria, Item 2 reads, in part:

> "(2) The following are required instruments:
>
> (i) Non-tumbling gyroscopic bank and pitch-indicator with a five-inch diameter unless smaller instruments are found satisfactory during flight evaluation.
>
> (ii) Gyroscopic direction indicator with a five-inch diameter unless smaller instruments are found to be satisfactory during flight evaluation.
>
> (iii) Rate of climb (vertical speed) indicator (no lag type)."

The above listed equipment are required in addition to the basic equipment. Nowhere in the Criteria is there an indication that allowances will be made or credit given for sophisticated pilot instrument-display systems (like 3-cue flight directors or contact-analog type displays, etc.) versus degree of dynamic stability and control sophistication. In the opinion of most examiners, this is a proper, well established and correct position and they believe that a minimum level of IFR dynamic stability must be achieved independent of the degree of the pilot's IFR display sophistication. This position is not disputed here now but some experimentalists (and pilots) suggest that a trade-off between display sophistication, dynamic stability, and control enhancement is logical and proper (References 26 and 28). One example portraying the suggested trade-off technique is shown in Section 3 under the title DISPLAY/CONTROL SYSTEM/WORKLOAD TRADE OFF.

The importance (or proper applicability and use) of the dynamic stability criteria in certification procedures may be difficult to judge when helicopters far exceed (or just barely meet) the current Interim Criteria when other factors intercede. For example, there is a chance or probability that these aircraft could ultimately pass or fail IFR certification on the basis of the installed display and not on the quality of their dynamics alone. An aircraft that far exceeds the minimum dynamics may be offered with a "basic" display while another aircraft that just barely meets the minimum dynamic criteria may be offered with a highly sophisticated, contact-analog, flight-director display (Reference 30). They both meet the minimum dynamic criteria but each aircraft may ultimately pass or fail IFR certification because the examiner will be required to make the certification judgement on flying qualities factors such as pilot workload, tracking performance etc.; factors that are strongly dependent on the IFR flight instrument display sophistication.

Consequently, these factors can render the current minimum dynamic stability criteria of questionable importance in the actual certification process for some vehicles. For these cases, the quality of the dynamics alone may play a minor role in certification since frequently the onus appears to be put on the examiner when he is forced to make the proper certification judgement on the strict basis of flying qualities. This entails judging certain flying qualities items and may tend to minimize the role of the precise, documented dynamics of the vehicle in the certification process. For the circumstances of certifications of this type, the flying qualities judgement may well prevail over some doubtful dynamic behavior.

Interim Criteria, Failure State Dynamics

J. Paragraph (d) does not offer any specific options as to degree of dynamic stability and control required for failure mode operation. This is especially important in the determination of the amount of degradation in dynamic stability allowed in a specific failure mode which still permits the pilot to continue the flight without declaring an emergency condition.

Paragraphs (e) and (f) of the criteria address reliability of artificial means and failure mode operation, they read:

"(e) Artificial stability. If the basic rotorcraft utilizes artificial means to meet the stability requirements in paragraphs (b), (c), and (d) of this Appendix, the reliability of artificial means must be substantiated.

(1) An artificial means may be used without a backup or standby means provided the rotorcraft -

(i) With the means inoperative, has all of the flight characteristics specified in Subpart (B) of this Part and, in addition, has positive lateral, longitudinal, and directional stick position stability and is free from tendencies towards excessively rapid or dangerous divergence.

(ii) Can be flown IFR without undue difficulty by the minimum crew with the means inoperative for a length of time equivalent to the useable fuel supply of the helicopter, but in any event not less than one hour. If usable fuel capacity of the helicopter is increased after certification, the requirement of this subparagraph must be met with the new fuel capacity, or else the length of time established with the previous fuel supply must be applied (either in the flight manual or on a placard) as an operating limitation.

(2) If the conditions of subparagraph (1) of this paragraph are not met, an equivalent backup or standby artificial means must be provided. Careful consideration must be given to the manner (e.g., automatic or manual switching) in which the backup or standby means is activated when the primary artificial means fails or malfunctions.

(f) Controllability. Throughout the approved IFR airspeed range there may not be dangerous divergence and uncontrollable tendencies following a sudden failure or malfunction of the artificial stabilization means or following the failure of a powerplant.

> The control authority of an automatic stabilization device may not be of such magnitude that in case of failure of the device, insufficient control remains with the pilot for maneuvering in both normal and emergency conditions."

The opening paragraph (e) of the Criteria, "If the basic rotorcraft utilizes artificial means to meet the stability requirements", seems to imply that "means" are expected to be installed only to resolve stability deficiencies. It does not address or fails to take note of the fact that certain single-pilot certifications appear to require augmentation functions and automatic stabilization features (such as the attitude-hold function of an autopilot) to resolve flying qualities factors such as workload/performance/trimmability requirements as much as the dynamic stability of the aircraft. The IFR certified helicopter may pass all the dynamic stability requirements of the Interim Criteria but can still be required to have "artificial means" strictly from a workload/performance standpoint. If the Interim Criteria are intended to cover this case also, then the opening paragraph (e) should include this intention. For example, the underlined words added in this Report to paragraph (e) shown below could read:

> "(e) Artificial Stability. If the basic rotorcraft utilizes artificial means to meet <u>the workload requirements and/or</u> the stability requirements in paragraphs (b), (c), and (d) of this Appendix, the reliability of artificial means must be substantiated."

Also, paragraph (e,1) of the Criteria specifically addresses flight with the augmentation means completely inoperative and requires "... positive static stick position stability and that the dynamical motions be "free from tendencies toward excessively rapid or dangerous divergence". Although it is not clearly stated here, it is presumed that the word "divergence" is meant to include oscillations as well as aperiodic behavior. Paragraph (e,1,i) "... with the means inoperative ..." appears to retain the requirements for static stick position stability while the requirements of paragraph (d) for dynamic stability appear to be modified or replaced with "... the rotorcraft ... is free from tendencies towards excessively rapid or dangerous divergence". Because of the absence of quantitative values for this failed-state operation, the evaluation of those tendencies again becomes a flying qualities judgment. Paragraph (e,1,ii) also addresses flying qualities issues such as the workload/performance of the minimum crew to continue failed-state flight from a fuel supply/endurance standpoint. Paragraph (f) deals with aircraft controllability and again is largely a flying qualities judgment of failure-dynamics, aircraft dynamics, actuator authority, and flight control power during failed-state operation caused by the artificial means, power plants, (and boost systems, etc.).

Test Procedures of Interim Criteria Dynamics

Flight test data on the stability of the aircraft are acquired, recorded, and retained by the FAA and the Contractor in the IFR certification process. The test techniques to be utilized to obtain the proper dynamics data for comparisons to the criteria are not adequately stated. Under paragraph (d), the first sentence states that the oscillations shall be obtained "... with controls fixed following a single disturbance in smooth air ...". Version 3 of the Interim Criteria (Appendix A) contains the following note under dynamic stability paragraph (d):

> "Note: Dynamic stability shall be tested by pilot inputs to the appropriate control system; the inputs shall be sudden pulse type inputs with immediate release. Inputs shall be of at least one inch deflection at the cyclic control stick grip and/or appropriate rudder pedal deflections."

Specific mention is not made regarding whether the dynamics tests shall be done using limited degree-of-freedom techniques (e.g., longitudinal motion only) and/or full six degree-of-freedom techniques (complete longitudinal and lateral/directional coupled motion). Also, no mention is made regarding the need for separate measurement of short term dynamics versus long term dynamics. The importance of the proper test techniques to assure accurate, applicable information for the data comparisons to the Interim Criteria cannot be over-emphasized. This subject area is discussed to a greater extent in other sections of the report.

At the end of Version 1 of the Interim Criteria, a short explanatory note was attached which stated in part:

"Explanation. The current provisions of paragraph (c) of (FAR) 29.141 require that rotorcraft have flight characteristics required for instrument operation if certification for such operation is requested. However, there are no standards concerning the necessary flight test procedures. The proposal would add such standards."

Importance of Aircrew Manning Level and Workload/Performance to Dynamics

The subjects of minimum required flight crew and workload/performance and their relation to dynamic stability and flying qualities are mentioned in several places in the criteria, namely under paragraphs:

"(e,ii) Artificial Stability. ... can be flown IFR without undue difficulty by the minimum crew with the means inoperative for a length of time equivalent ...".

"(i) Operating Information and Limitations. The pertinent information and limitations necessary for proper and safe operation of the rotorcraft under the instrument flight conditions for which approval is sought must be presented to the minimum required flight crew in the form of suitable placards or in the rotorcraft flight manual or both. A minimum approved IFR airspeed must be based on the technical merits of the rotorcraft characteristics."

"(j) IFR Flight. The rotorcraft must be flown in the air traffic control system under actual IFR day and night conditions for a period of at least five hours. The items evaluated during this period must include:

(1) Ability to operate the rotorcraft satisfactorily under IFR conditions in the air traffic control system without undue pilot fatigue or exceptional pilot skill or alertness.

(3) Pilot visibility in precipitation during low approaches.

(5) In-flight IFR workload demands on the minimum required flight crew.

(6) Handling of the rotorcraft in rough air turbulence."

Unfortunately, there are no stated requirements in the present standard that differentiate the minimum dynamic stability requirements for one-pilot versus two-pilot certifications. The same problem exists on delineating the acceptable level of workload for different aircrew manning levels. For example, it would appear that for a single-pilot certification, primary emphasis in the criteria is placed on the assessment of an acceptable pilot workload level for a given standard of performance and safety with minimum dynamic stability of the aircraft playing a secondary role (since the aircraft will probably already have a sophisticated augmentation and automatic stability system). For a two-pilot certification, where the total workload can be divided and inter-changed between pilots, primary emphasis appears to be placed on ascertaining that the aircraft met a two-pilot level of minimum dynamic stability with total pilot workload assessment, a secondary factor. However, if the Pilot-in-Command flight-control workload assessment indicates that the pilot is not handling the vehicle well enough to assure an acceptable level of safety and performance, the two-pilot certification will fail regardless of whether or not the aircraft meets the minimum dynamic stability criteria.

A more realistic example of one aspect of the interplay among aircraft dynamics, augmentation systems, and pilot workload assessment and the roles they play in an IFR certification is discussed below.

This example is taken from a review of information on an existing new helicopter that has already been certified for IFR flight in two configurations (single-pilot IFR and dual-pilot IFR). The needed information is most accurately and freely drawn from the Rotorcraft Flight Manual, RFM, and its IFR supplement (and probably is the only readily available, accurate source since information from other sources is frequently restricted or of limited access). The example aircraft is a single-rotor, single-engine helicopter that carries about 12 persons.

According to the FLIGHT MANUAL, for certified single-pilot IFR operation, Stability Augmentation Systems/Autopilot Systems (SAS/AP Systems) are required to be installed and operating. For certified two-pilot IFR operation (using the same aircraft) the Stability Augmentation Systems/Autopilot Systems (SAS/AP Systems) are not required and therefore need not be installed for this configuration. Two important items of interest, as gleaned from the FLIGHT MANUAL for this aircraft, should be noted for this example. First, that the SAS/AP systems used on this aircraft contain, as a standard feature of the autopilot, an ATTITUDE-HOLD function. As a general rule, for recent single-pilot approvals, these helicopter autopilots contain as their most basic feature an ATTITUDE-HOLD function and for most certifications require that this system be on and operating for IFR flight. Similarly, single-pilot IFR flight with SAS only (ATTITUDE-HOLD function of the autopilots inoperative) is not a legally approved IFR flight configuration and may be used as an emergency mode of IFR flight only. Second, for this same helicopter, in the event that the SAS/AP Systems are totally inoperative, this single-pilot certified aircraft may still be flown legally, on routine and regular IFR flights, provided that "an IFR qualified second-in-command (pilot) occupies the copilot's (flight) station and the aircraft is fitted with appropriate dual controls and instruments." This is not an alternate, one time-restricted use, IFR approval (where the aircraft can be flown IFR this way only to a maintenance facility for the needed SAS/autopilot repairs) but a fully FAA approved, normal mode, IFR configuration in keeping with that previously set by the two-pilot IFR approval of this aircraft (SAS/AP system not required).

It is important to note that the basic helicopter, with no augmentation system of any kind installed, apparently meets the minimum required dynamics as set forth in the current Interim Criteria (or at least has been granted an "equivalence" on the dynamics) and can be legally flown IFR with two pilots. For all single-pilot approvals to date, some type of augmentation system (SAS or SCAS) and/or automatic stabilization equipment (ATTITUDE-HOLD/AP) is installed. These augmentation systems and/or autopilot systems are needed to resolve stability and control criteria and/or pilot workload/performance requirements. Thus, the importance of the assessment of pilot workload/performance factors in the helicopter IFR certification process cannot be overemphasized.

DYNAMIC STABILITY, HELICOPTER MIL. SPEC. 8501A

Analysis and Comparison Techniques

The subject areas discussed earlier in this section were offered to provide a short review of the many factors, related issues, and special circumstances that come to bear or are involved in the interpretation and application of the stability requirements for IFR certification of helicopters. The most pertinent part of the Interim Criteria dynamic stability is stated in paragraph (d) of that document (Appendix A). It was noted earlier, with regard to the comments on completeness, scope, utility and importance of the paragraph, that the requirement appears to be a general, blanket specification on longitudinal, lateral and directional dynamic stability of helicopters. The dynamics requirement addresses only oscillations and excludes or neglects non-oscillatory dynamics. The oscillation criteria are related in terms of the length of the period of the oscillation and the number of cycles allowed for the oscillation to damp to half amplitude. They also permit dynamic instabilities for oscillations having periods of 20 seconds or greater but state that they may not achieve double amplitude in less than 20 seconds.

In order to facilitate the analysis and comparison of these requirements with other applicable data, it is convenient to plot the dynamic criteria on the complex plane. It is important that a fundamental knowledge of mapping procedures and the type of information displayed on the complex plane be reasonably well understood before delving into a study of this dynamic stability criteria. Appendix D provides a brief, simple insight into plotting procedures, information displayed, expressions and notations utilized and offers some general values of parameters that are of use in this study. Readers who are not familiar with some of the basic information contained on the complex plane may find it beneficial (for understanding other parts of this report) to peruse Appendix D in order to become more acquainted with certain aspects of the complex plane and stability comparisons.

The Interim Criteria Oscillation Boundary

The dynamic stability requirements of the Interim Criteria may be easily plotted on the complex plane (Figures 4-11 and 12). The second figure is an expansion of the area close to the origin on the first figure. For convenience, the figures have multiple labeling on the vertical and horizontal axes in order to improve their facility for different readers. The most common parameters used in this study are the length of the period of the oscillation (T_P), the time required for the oscillation to damp to half amplitude ($T_{\frac{1}{2}}$), the damping ratio

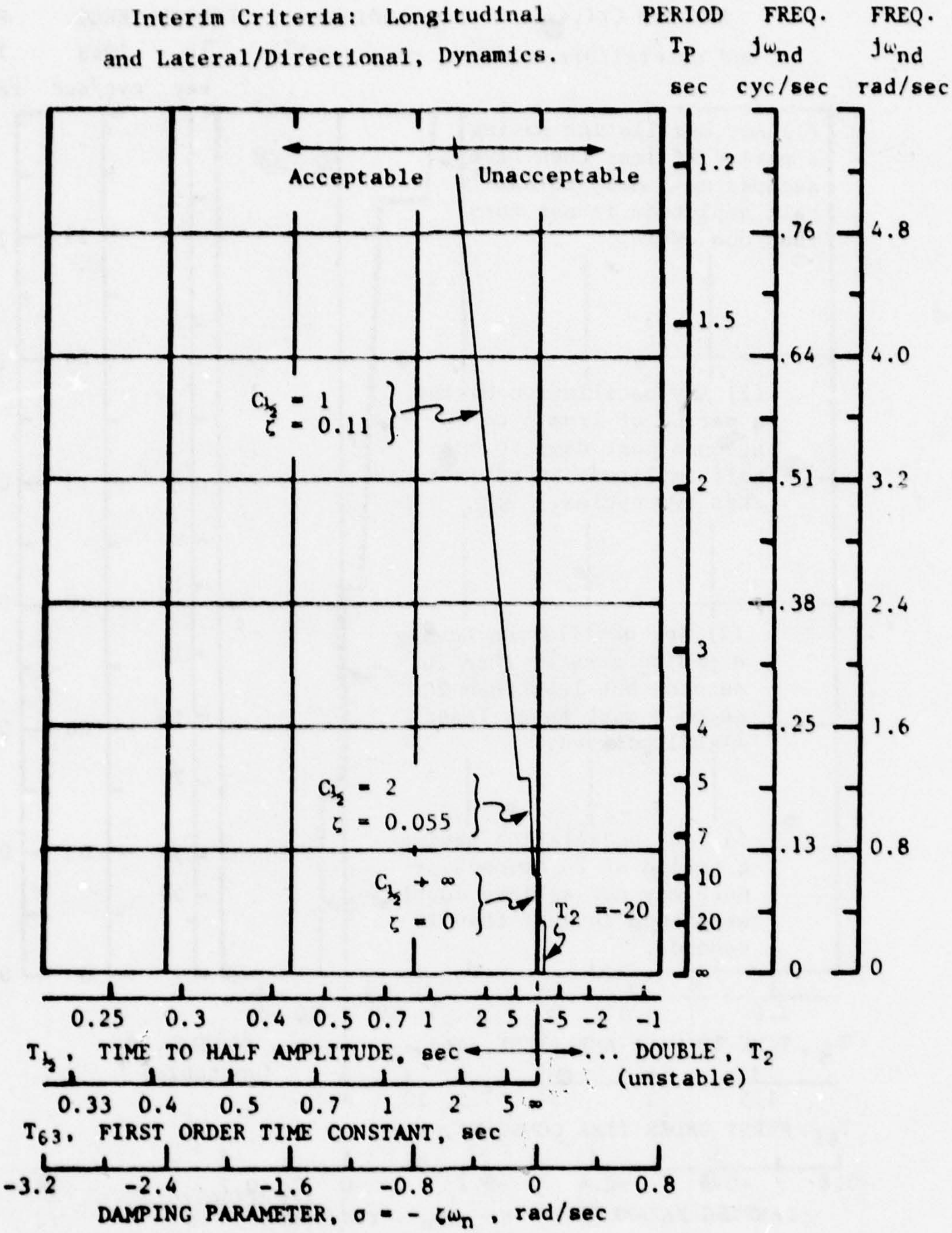


Figure 4-11. Plot of Current Interim Criteria Dynamic Stability Boundaries (Reference 4).

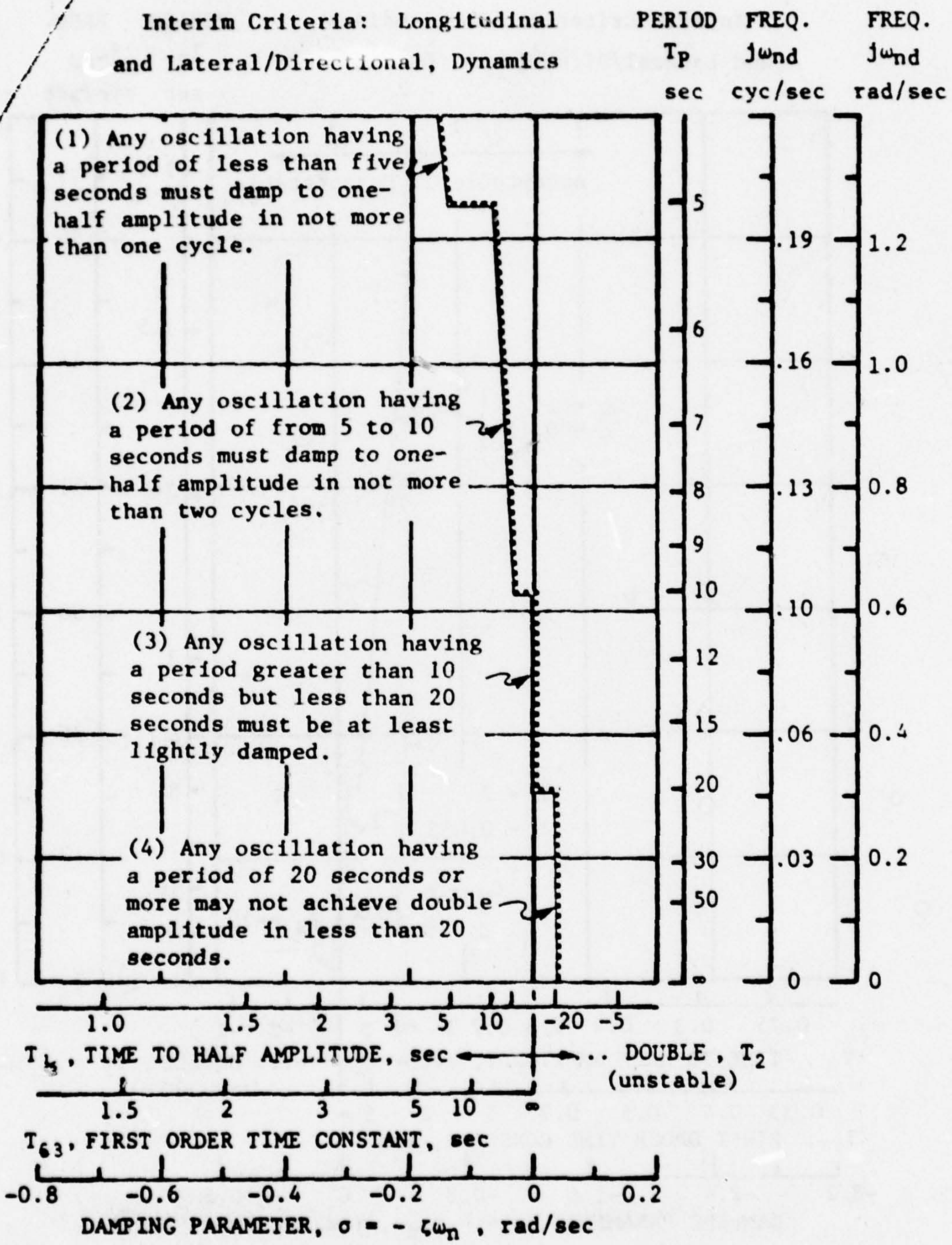


Figure 4-12. Plot and Description of Interim Criteria Oscillatory Boundaries.

(ζ), and the number of cycles required for the oscillation to damp to half amplitude ($C_{\frac{1}{2}}$).

When the words of the statements in paragraph (d) of the Interim Criteria are translated into plotted points on the complex plane, they appear as a boundary line made up of a connected series of four straight line segments on the figures. Each segment is representative of a numbered statement in the dynamic requirements. According to the Interim Criteria, helicopters with dynamic stability characteristics that are located to the left of this boundary meet the minimum requirements and those that are located to the right of the boundary do not. The equivalence between the parameters, cycles to half amplitude and damping ratio is shown on the figures. Lines of constant damping ratio and similarly lines of constant cycles to half amplitude are represented by rays or straight lines directed outward from the origin. Since only oscillations are addressed in paragraph (d), no boundary is specified on the real axis (horizontal axis) where only aperiodic motion can occur. If statement (4) of paragraph (d) is construed to impose a limit on the positive real axis, then the dynamic criteria permit unstable, pure divergences with a time to double amplitude as low as 20 seconds. Also, any oscillations with periods greater than 20 seconds may be unstable and can double amplitude in as little as 20 seconds. This last aspect of the current criteria will be discussed later in this section under "long term motions". For periods between 10 and 20 seconds, the boundary is the neutral oscillation line (the imaginary axis) and points must be located slightly to the left of it (damped oscillation region) to meet the criteria.

Before continuing the discussion on the mapped boundary for minimum acceptable oscillatory dynamics, it is useful at this point to review and compare the above information with the helicopter military specification since parts of the Interim Criteria are identical to that document.

The Military Specification Dynamic Stability Requirements

Intent of the MIL. SPEC. versus Interim Criteria

It is often stated that an intent of the Interim Criteria, FAR, and other regulatory documents of the FAA pertinent to IFR certification of helicopters is to give guidance in the determination and demonstration of "... minimum requirements that are needed to provide a level of safety ... commensurate with the development and expansion of the aviation system ... ... and to be responsive to the needs of the general public and the aviation community in fulfilling the agency's aviation safety responsibilities." The basic intent of MIL. SPEC. 8501A (Reference 5) is essentially different. The military specification entitled "General Requirements for Helicopter Flying and Ground Handling Qualities" covers the design requirements (as opposed to the demonstration requirements of the Interim Criteria) for satisfactory flying and ground handling qualities of U.S. military helicopters. The MIL. SPEC. 8501A sets forth those characteristics that are needed for visual flight conditions and instrument flight conditions (better stated for DOD missions as those that comprise non-precision and precision flight, e.g., like the precise control needed for aiming a weapon or flying a GCA). Also, it states under REQUIREMENTS; General, in paragraph 3.1.1: "... The required characteristics are those which are considered, on the basis of present knowledge, as tending to insure satisfactory handling qualities and are subject to modification as indicated by new information. Every effort shall be made by designers to provide additional desirable characteristics which have been omitted as specific requirements."

Although both the Interim Criteria and the MIL. SPEC. imply a "level of safety" theme (one directly and the other indirectly), the two documents differ considerably in stated purpose, objectives, and in application; namely, demonstration versus design criteria. Nevertheless, the MIL. SPEC. is considered an important document and a valuable reference for this study because it deals with helicopters exclusively and because parts of it are substantially the same as, or identical to, the Interim Criteria. It is also an important helicopter requirements document from the standpoint of its relative maturity, the vast sums of money invested, and the large amount of research effort accomplished and results obtained by government agencies, industry and other research facilities. For these reasons, considerable reliance is placed on this reference (when it is judged pertinent to this study) because of the existence of the documented, established helicopter criteria.

The IFR and VFR Oscillation Boundaries of 8501A

The specification details two dynamics boundaries (IFR and VFR) and uses almost identical phraseology compared to the Interim Criteria (Figure 4-13). In the MIL. SPEC., paragraph 3.6, Instrument Flight Characteristics, subparagraph 3.6.1.2 reads:

> "3.6.1.2 Longitudinal- and lateral-directional oscillations with controls fixed following a single disturbance in smooth air shall exhibit the following characteristics:
>
> (a) Any oscillation having a period of less than 5 seconds shall damp to one-half amplitude in not more than one cycle. There shall be no tendency for undamped small amplitude oscillations to persist.

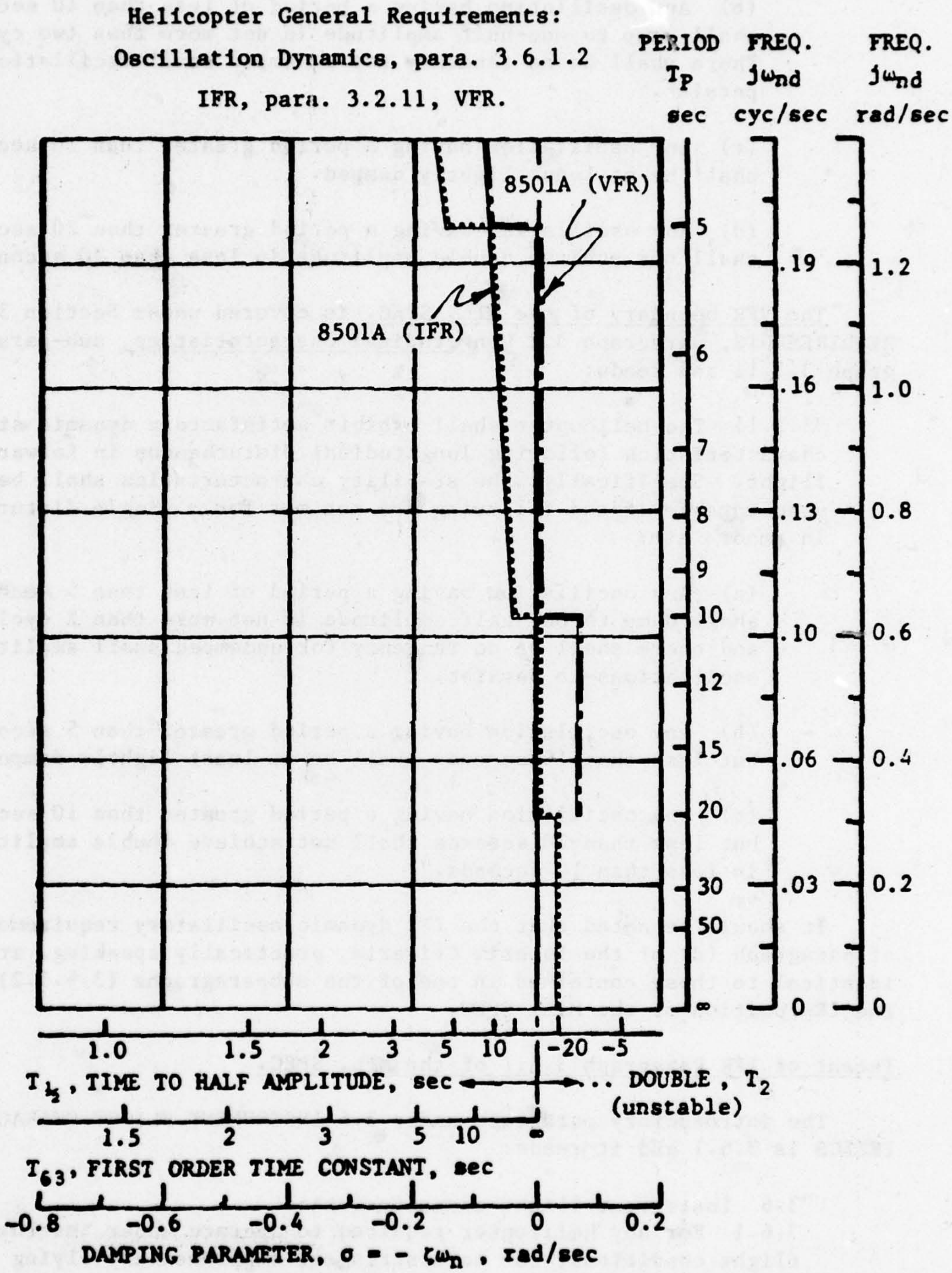


Figure 4-13. Plot of MIL-H-8501A Dynamic Stability Oscillation Boundaries

(Reference 5)

> (b) Any oscillation having a period of less than 10 seconds shall damp to one-half amplitude in not more than two cycles. There shall be no tendency for undamped small oscillations to persist.
>
> (c) Any oscillation having a period greater than 10 seconds shall be at least lightly damped.
>
> (d) Any oscillation having a period greater than 20 seconds shall not achieve double amplitude in less than 20 seconds."

<u>The VFR boundary of the MIL. SPEC.</u> is covered under Section 3. REQUIREMENTS, paragraph 3.2 <u>Longitudinal Characteristics,</u> sub-paragraph 3.2.11 and reads:

> "3.2.11 The helicopter shall exhibit satisfactory dynamic stability characteristics following longitudinal disturbances in forward flight. Specifically, the stability characteristics shall be unacceptable if the following are not met for a single disturbance in smooth air:
>
> (a) Any oscillation having a period of less than 5 seconds shall damp to one-half amplitude in not more than 2 cycles, and there shall be no tendency for undamped small amplitude oscillations to persist.
>
> (b) Any oscillation having a period greater than 5 seconds but less than 10 seconds shall be at least lightly damped.
>
> (c) Any oscillation having a period greater than 10 seconds but less than 20 seconds shall not achieve double amplitude in less than 10 seconds."

It should be noted that the IFR dynamic oscillatory requirements of paragraph (d) of the Interim Criteria, practically speaking, are identical to those contained in one of the subparagraphs (3.6.1.2) in the IFR portion of the MIL. SPEC.

<u>Intent of IFR Paragraph 3.6.1 of the MIL. SPEC.</u>

The introductory paragraph under 3.6 INSTRUMENT FLIGHT CHARACTERISTICS is 3.6.1 and it reads:

> "3.6 Instrument flight characteristics.
> 3.6.1 For any helicopter required to operate under instrument flight conditions, the more stringent supplementary flying qualities requirements of 3.6 shall apply, in addition to the

foregoing requirements of section 3. It shall be possible, without demanding undue pilot effort, to fly on instruments at all speeds, from hover to design cruise speed; for this purpose automatic stabilization and control or stability augmentation equipment, or both, may be employed, in addition to any required for compliance with visual flight criteria. The failure or disengagement of the equipment that provides the instrument flight characteristics shall not result in a degeneration of the stability and control characteristics of the helicopter below any of those specified in this specification for helicopters required to operate under visual flight conditions."

Three important points of the above paragraph 3.6.1 are:

- ... the more stringent <u>supplementary</u> flying qualities requirements of 3.6 shall apply, <u>in addition to the foregoing requirements of Section 3</u>.
- It shall be possible, <u>without undue pilot effort</u> to fly on instruments ... automatic stabilization and control or stability augmentation equipment ... may be employed.
- ... shall not result in a <u>degeneration of the stability and control characteristics of the helicopter below any of those specified in this specification for helicopters required to operate under visual flight conditions.</u>

In relation to the first point listed above, some of the MIL. SPEC. stability and control criteria that are pertinent to this subject area, and that are carefully covered in Section 3 as minimum <u>additional</u> requirements, are: minimum maneuverability characteristics ("concave-downward" requirement), satisfactory initial flight control-response characteristics and minimum longitudinal/lateral/directional control power and angular damping. (Paragraph 3.6.1.1 places additional, more stringent, requirements on the minimum control power and damping. The importance of these two parameters must be emphasized since they tend to characterize the type of control system, i.e., rate or acceleration type, that the basic aircraft will have. The values of these two parameters, will approximate or define the characteristic control time, i.e., the first-order time-constant, and the characteristic value of the final, steady-state angular rate in response to a control step input by the pilot.) Other closely related subjects addressed in Section 3 of the MIL. SPEC. include: vertical/collective pitch characteristics, power-on/power-off and autorotation characteristics, boosted or power-operated control characteristics, automatic stabilization control characteristics, stability augmentation system (SAS) characteristics and cross-coupling/control-intermixing effects and responses.

Omission of the other pertinent stability and control requirements of Section 3 of the MIL. SPEC. while meeting just the IFR oscillatory boundary requirements of subparagraph 3.6.1.2 could result in a considerably incomplete specification for a military helicopter and also could result in a grossly deficient and unsafe IFR aircraft from the stability and control/handling qualities point of view. For example, if a military aircraft intended for IFR flight did not meet the "concave-downward" requirement (the divergence and the maneuver stability criterion) for certain aft c.g. loadings, there is a good probability that the aircraft would tend toward being UNSAFE for IFR type precision flight in atmospheric turbulence. It would probably be unacceptable for military acquisition and IFR flight unless the design was modified or the flight envelope tailored accordingly.

With regard to the second point above, the phrases directly recognize the inter-play and connection between pilot workload and the possible need or use of artificial means to alleviate any problem. The subject of pilot workload (especially for single-pilot) is quite germane to the issues of IFR flight and certification and the need to resolve pilot workload level problems with artificial means (as opposed to just altering the dynamics) will be addressed elsewhere in the report.

The third point above emphasizes the fact that failure or disengagement of the artificial means that provide all the instrument flight characteristics shall not result in a "degeneration" or degradation of the stability and control characteristics below any of those specified for VFR flight. Restated, this means that, for <u>IFR</u> - <u>failure mode</u> flight (first-failure), all the specifications stated in Section 3 must be met and therefore includes the VFR longitudinal oscillation boundary of paragraph 3.2.11 as a valid IFR requirement. This is an extremely important point and is emphasized here because these two oscillation boundaries will be frequently referred to later, and (according to the above interpretation of the MIL. SPEC) are now labeled here as:

<u>IFR Longitudinal Dynamic Oscillatory Boundaries, 8501A</u>

- NORMAL-MODE (IFR Statements of paragraph 3.6.1.2)
- FAILURE-MODE (VFR Statements of paragraphs 3.6.1 and 3.2.11)

It might be added that during the information survey, the opinion was offered (and emphasized) by an originator of this specification (at NASA Langley) that these <u>two</u> oscillation boundaries constituted the lowest acceptable minimum oscillation dynamics that should be allowed and anything less than these two oscillation requirements are UNACCEPTABLE for IFR (precision) flight.

Aircrew Manning Requirements Under MIL. SPEC. 8501A

Early Manning Levels for IFR Flight

When the specification MIL-H-8501 evolved in the early 1950s and even later with the updated 8501A in the early 1960s, instrument flight in military helicopters was still in its very formative stages. Most of the IFR flight in military helicopters was being accomplished by a relatively small group of pilots "punching-through" overcasts or undercasts or involved with introduction to essentially automatic IFR approaches to hover for the Navy's ASW missions (Reference 1). Even the highly developed civil helicopter operation at Los Angeles did not start carrying scheduled passengers IFR until about 1965. The early Army IFR flights conducted at Fort Rucker in the mid 1950s were all conducted with two-pilot aircrews by flying in and out of stratus type clouds where turbulence was a minimum. The pilot did all the flight control work and the copilot did all the non-flying auxiliary tasks (Reference 12). In the Navy, the ASW mission was always accomplished with two pilots using the same division of duties, one pilot doing the flight control task and the other pilot accomplishing all other tasks. In those early days, as now, routine and regularly scheduled military IFR flights are normally accomplished with two-pilot aircrew manning levels. The civil operation conducted by LAA at Los Angeles operated under an FAA minimum aircrew requirement stated as: "... FAA requirements for a scheduled helicopter operation in a terminal area ... Crew Compliment: The minimum crew shall consist of two helicopter instrument qualified pilots" (Reference 12). Also, for LAA the instrument training standards for the pilots and copilots was very high and great emphasis was placed on unaugmented flight since the AFCS systems at that time did not have proven reliability and were non-redundant (Reference 2). The IFR two-pilot certification of the Sikorsky S-61 L/N was approved by the FAA and based on Interim Standards dated in 1962 (Reference 1).

Also, at that early time, in the later 1950s and early 1960s relatively extensive IFR helicopter flight research operations and procedures were being conducted by numerous government research agencies (especially NASA Langley), private industry and other research centers. At NASA Langley a great deal of the early important work was accomplished using a variable stability S-51 helicopter. This aircraft was highly instrumented for its time and many experiments were performed on precision tasks such as visual hovering and slow speed instrument approaches (maximum velocities up to about 45 knots) as well as general flying (References 42 and 56).

It was during that time, and largely due to the impetus provided by NASA Langley in conjunction with others, that the existing military specification (including the IFR section) was modified and updated as

8501A. Unfortunately, at that time, the subject of documenting the minimum aircrew level or configuration (and in a sense the acceptable aircrew workload levels) for the general MIL. SPEC. requirements was not directly addressed. There was a good reason why this occurred or was not necessary. At that time, there was never any doubt that IFR operations would be conducted with two-pilots if any (auxiliary) tasks other than just flight control of the helicopter were to be accomplished. It was presumed that if the Pilot-in-Command had to do anything more than a brief rudimentary position report or a trivial avionics/radio adjustment that another pilot (second pilot) would be on board to take over all the auxiliary (non-flight control) tasks. Another way of stating this is that the pilot that was manipulating the flight controls and maneuvering the aircraft in IMC flight conditions was an "UNLOADED" pilot. He was not required nor did he expect to perform, in any significant way, such auxiliary duties as:

- operation and adjustment of radio/avionics gear
- primary navigation and communication
- handle the details of interaction (and cooperation) with the ATC system
- perform fuel/cruise control management tasks
- operate and select systems
- extensive map reading or chart handling etc.

Without question, it was always expected that the second pilot was available to perform all the auxiliary tasks. Frequently, with these aircraft (at the time many helicopters were essentially unaugmented and had small or non-existent tail surfaces), he was heavily occupied with the flight control task of precision flight maneuvering (especially in turbulence) and wanted no additional workload. His workload level capability was at an acceptable limit and the amount of pilot compensation he had to provide in order to maneuver the aircraft safely and achieve a satisfactory level of performance was great enough that it required that he concentrate on flight control only. Under circumstances similar to these, it was mandatory for a second pilot to perform all the auxiliary tasks (Reference 12). If the IFR flight was long as well as difficult, the second pilot could exchange duties with the Pilot-in-Command in order to provide relief.

All the Instrument Flight Characteristics of MIL. SPEC. 8501A are based on an "UNLOADED" type pilot accomplishing the flight control task only. By implication, since it is admitted that auxiliary tasks exist for IFR flight in helicopters, then all the IFR requirements as encompassed by the entire MIL. SPEC. require, in effect, two-pilot minimum aircrew manning. For example, with this interpretation, the minimum requirements on oscillatory dynamics as stated in paragraph 3.6.1.2 of the MIL. SPEC. must be those minimum characteristics for oscillatory dynamics for two-pilot IFR operation.

During the information survey for this report (and during other interviews) with some of the originators and primary users of the MIL. SPEC., the two-pilot (or "UNLOADED" pilot) viewpoint was consistently voiced as the only proper and accepted interpretation of the minimum aircrew needed for IFR flight within the scope of that detailed by the IFR sections of MIL-H-8501A. This interpretation has been corroborated again recently with personnel at NASA-Langley (originally responsible for drafting 8501A) and is accepted here as fact for the purposes of this analysis and study.

Therefore, both of the IFR minimum oscillatory dynamics boundaries of the MIL. SPEC. detailed in earlier sections of this report are labeled with confidence as: "TWO-PILOT" boundaries (Figure 4-14). These are the substantiated, well-documented minimum dynamic oscillatory boundaries that have been used in the evaluation and acceptance of military helicopters for many years.

Suitability of Applying 8501A Information to Interim Criteria

With the guidance already provided by certain parts of the MIL. SPEC., it must be judged whether additional information can be provided by 8501A that will tend to improve and update the existing Interim Criteria for civil helicopters. The apparent different goals of the MIL. SPEC. 8501A versus the Interim Criteria are:

- Design Criteria of a helicopter for those acceptable requirements that tend to insure satisfactory handling qualities versus, (MIL. SPEC. 8501A).
- Demonstration Criteria of a helicopter for those minimum requirements that tend to provide "a level of safety", (Interim Criteria).

It is necessary to determine what, if any, additional sections of the more established, highly developed helicopter MIL. SPEC. can be used to good advantage in, or are applicable to, updating the Interim Criteria. (The same exercise is true for other criteria data, information, and requirements published elsewhere and believed to have a direct bearing and influence on the issues at hand.) In judging the value, relevance and applicability of any data pertinent to a study of this type, it would seem probable that there are some dynamics and

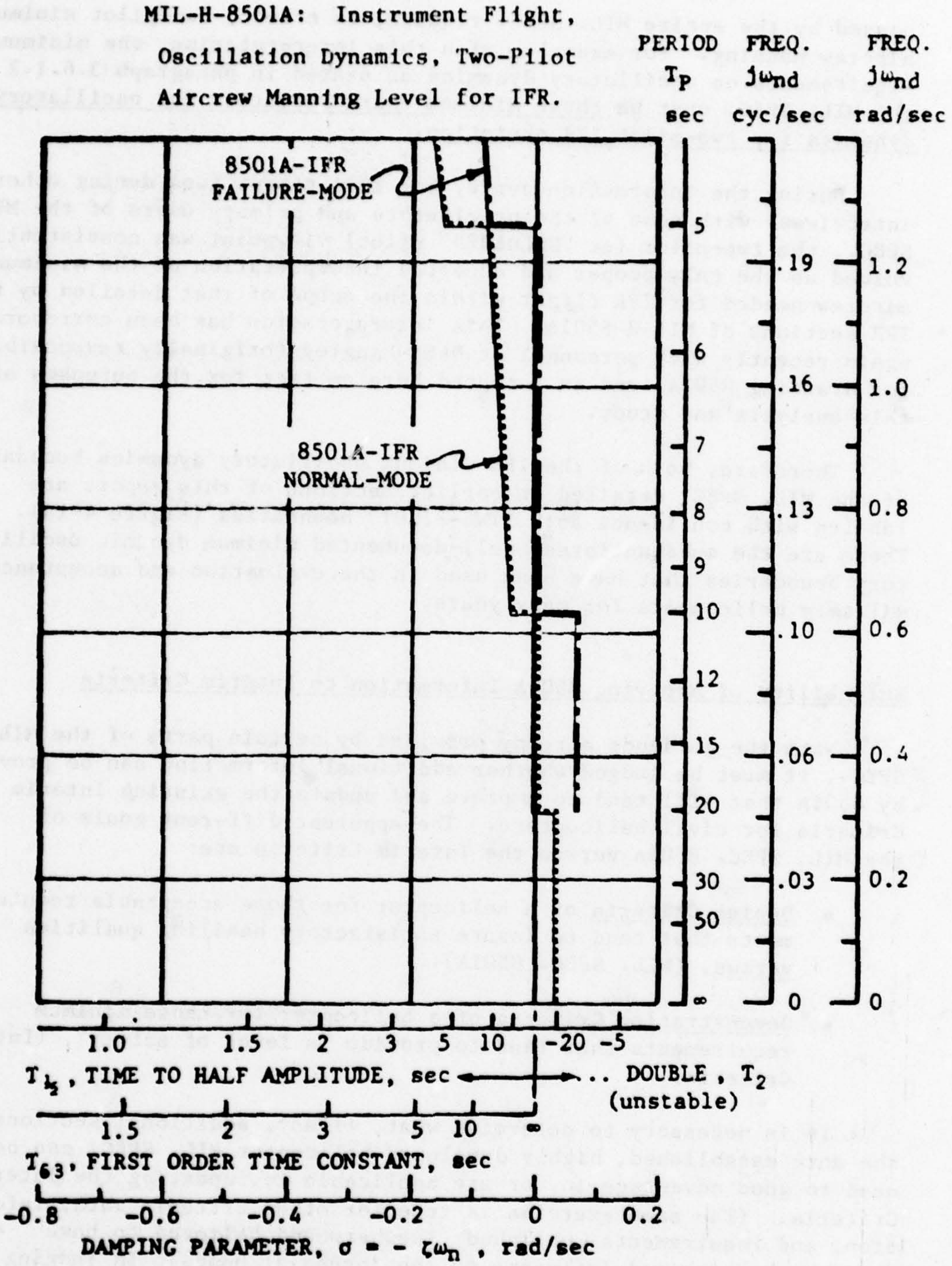


Figure 4-14. IFR Oscillatory Dynamics Boundaries of 8501A for Two-Pilot Normal and Failure-Mode Operation.

flying qualities that can readily be selected as "safety" oriented and others that are more representative of a measure of the "goodness or badness" of a configuration or design. The middle ground, where an overlapping and commingling of intent occurs, provides more of a challenge and requires analysis, pilot-rating, judgement, and consensus. With respect to MIL. SPEC. 8501A (and other published criteria and information) there are sections that can be reconciled or construed as tending toward safety-of-flight interpretations. Certain of these items, as well as material from other references, will be selected, defined, and used to modify, clarify, and add to the existing Interim Criteria.

Definition, Interpretation, and Labeling of Oscillation Boundaries

Based on the material in the previous dynamics sub-sections and the discussions and interpretations accomplished thus far, certain comments and statements may be made; some obvious -- (e.g. the Interim Standard IFR oscillation boundary is essentially identical to that of 8501A), some developed -- (e.g., for MIL. SPEC. 8501A, the two-pilot aircrew manning level interpretation for IFR flight and the two separate IFR dynamic oscillation boundaries).

The comments and statements are:

- The existing IFR oscillatory dynamics boundary of the current Interim Criteria (that is essentially identical to the IFR boundary of MIL., SPEC. 8501 paragraph 3.6.1.2) should be recognized, labeled, and defined as: "TWO-PILOT, NORMAL-MODE". It is to be interpreted as the oscillatory dynamics boundary defining the minimum longitudinal/lateral/directional requirements needed for normal-mode IFR flight for two-pilot aircrews.

- The existing longitudinal oscillatory dynamics boundary required to be met for IFR flight as stated in paragraphs 3.6.1 and 3.2.11 of MIL-H-8501A should be added to the Interim Criteria as those requirements needed for failed-state operations (first-failure, - continue to fly) and be recognized, labeled, and defined as: "TWO-PILOT, FAILURE-MODE". It is to be interpreted as the oscillatory dynamics boundary defining the minimum longitudinal/lateral/directional requirements needed for failure-mode IFR flight for two-pilot aircrews. The meaning here is extended past the longitudinal mode of motion minimums as specified in 8501A, and includes (for IFR conditions) lateral/directional modes of motion.

- In later sub-sections, the "TWO-PILOT, NORMAL-MODE" oscillatory dynamics boundary, defined first above, will be offered as a candidate boundary for dual labeling as: "TWO-PILOT, NORMAL-MODE" or "ONE-PILOT, FAILURE-MODE". It will be proposed as the oscillatory dynamics boundary defining the minimum longitudinal/ lateral/ directional requirements needed for failure-mode IFR flight for the single-pilot aircrew manning level.

- Considering the recent advances in the state-of-the-art equipment and aircraft design, it should be made clear that the above criteria defining the two minimum oscillatory dynamics boundaries should be recognized essentially as the absolute minima. Both of the boundaries should be considered primarily as "failure-limits" for civil IFR flight and not those prescribed to be met by designers and as representative of those satisfactory IFR handling qualities needed to achieve IFR flight with "a level of safety" using two-pilot and one-pilot aircrew manning levels. For example, it is also worth noting at this point, for the case of "TWO-PILOT, FAILURE MODE" IFR operation, that by meeting the minimum requirements precisely (as they are specified thus far with the new proposed boundary), the Pilot-in-Command could be required to manipulate the controls, maintain attitude and maneuver an aircraft under IMC conditions and turbulence that has an unstable long term oscillatory characteristic. It would be allowed to have, under this new specification (as it is now proposed), a long term oscillation that doubles amplitude in one-half of a cycle, (period equal to slightly less than 20 seconds and time to double of 10 seconds, per 8501A paragraph 3.2.11 statement c). This long period characteristic will be discussed in later sections of this report where the dynamics boundaries are divided into long-term and short-term characteristics.

- Recognize that the specification of only the minimum oscillatory requirements in the Interim Criteria, though necessary, does not sufficiently relate the minimum dynamic stability and control requirements and that added criteria are needed for completeness in order to provide those dynamics/flying qualities requirements necessary to achieve a "level of safety". For example, consideration should be given to the "concave-downward" requirement (to be discussed later) and whether it needs to be included in the IFR Interim Criteria in order to assure the aircrew of a minimum level of satisfactory maneuver characteristics and protection against divergent aperiodic modes. It is an especially important requirement for IFR flight in turbulence.

The new labeling and the boundaries for minimum oscillatory dynamics requirements are shown in Figure 4-15.

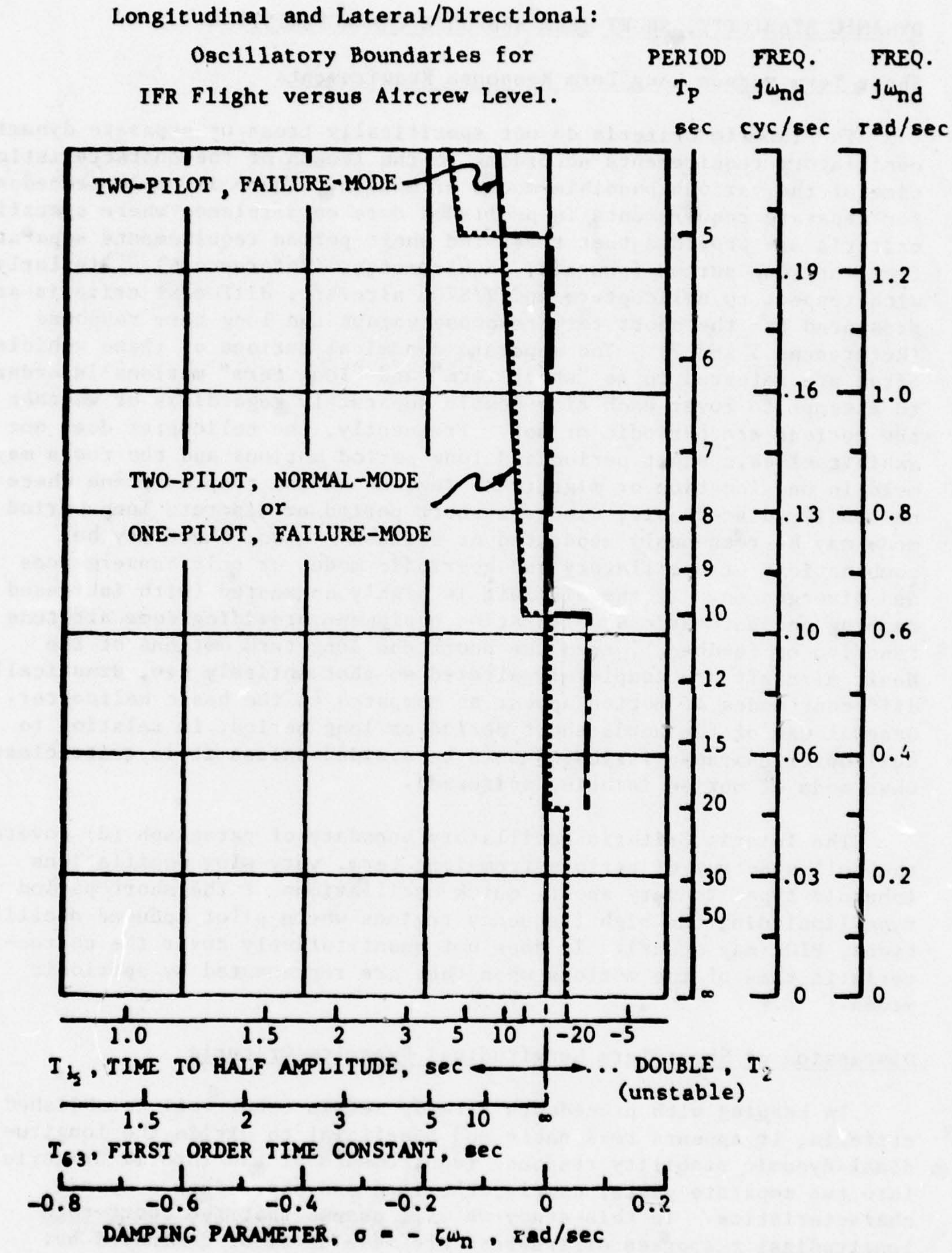


Figure 4-15. New Oscillatory Boundaries Defined for Interim Criteria.

DYNAMIC STABILITY, SHORT TERM RESPONSE CHARACTERISTICS

Short Term versus Long Term Response Requirements

The Interim Criteria do not specifically treat or separate dynamic oscillatory requirements according to the length of the characteristic time of the various possible modes of motion. There is ample precedent for separate requirements in published data on airplanes where specific criteria are provided that treat the short period requirements separately from the long period (phugoid) requirements, (Reference 6). Similarly, with respect to helicopters and V/STOL aircraft, different criteria are presented for the short term response versus the long term response (References 5 and 7). The separate dynamical motions of these vehicles often are referred to as "short term" and "long term" motions in order to attempt to cover each time domain separately regardless of whether the motions are periodic or not. Frequently, the helicopter does not exhibit classic short period and long period motions and the roots may meld in one location or migrate to regions on the complex plane where no readily discernable, discrete short period or discrete long period mode may be reasonably separated or defined. Also, there may be combinations of oscillatory and aperiodic modes or only convergences and divergences. If the aircraft is highly augmented (with increased damping and automatic stabilization equipment providing some attitude function or feedback), then the short and long term motions of the basic aircraft are completely altered so that entirely new, drastically different modes of motion appear as compared to the basic helicopter. General use of the words short period or long period, in relation to helicopter characteristics, should be avoided unless it is quite clear what mode of motion is being addressed.

The Interim Criteria oscillatory boundary of paragraph (d) covers the full spectrum of periods from long term, very slow oscillations (phugoid type) to very short, quick oscillations of the short period type (including the high frequency regions where pilot induced oscillations, PIO, may occur). It does not quantitatively cover the characteristic time of the motions when they are represented by aperiodic modes.

Discussion of Short Term Longitudinal Dynamics Criteria

In keeping with precedents already set in other well established criteria, it appears reasonable and beneficial to divide the longitudinal dynamic stability response requirements of the Interim Criteria into two separate parts; namely, the long and short term response characteristics. In this study we will assume that the <u>short-term</u> longitudinal responses of interest are made up of or dominated by:

- Short Term Gust Responses
- Short Term Control Responses

Also, the long term longitudinal characteristics of interest will be determined by:

- The ability to trim the aircraft accurately and quickly
- The response to the remnant of the gust motion
- The long period dynamics or an approximate time-constant characteristic of long term motions.

Maximum First-Order Time-Constants

Addressing the short term characteristics first, the modes of motion that represent the "fast" responses of the aircraft (usually angular motions) caused by a control input (or a gust disturbance) are of interest. Depending on the value of the angular damping, the flight control system will display either an "acceleration or rate" type controller for the vehicle. If the longitudinal pitch control sensitivity value is optimum, and pitch angular damping is large enough and in proper proportion to it, a control motion will exhibit the characteristics of a rate-type control system that pilots seem to prefer. With a rate-type controller, a step input will result in the establishment of a steady-state pitch rate that approximates a first-order response characteristic. If the control sensitivity and damping values of the basic vehicle do not provide a good rate response to a step input, a rate system may still be obtained by enhancing the angular damping and control sensitivity through the use of artifical stability and control augmentation systems. Usually the characterization of the responses developed by a step input with a rate control system is described in approximate terms using the "first-order time-constant" with the notation T_{63}. It is the time, in seconds, required for the pitch rate response to reach a certain percentage (63%) of its final steady-state value (or peak). Sometimes it is characterized as a response which will appear to achieve a quasi-steady state situation in the first few seconds, (i.e., the response may peak and then settle a little).

The horizontal axis of the complex plane is multiple labeled and first-order time-constants may be plotted directly on the graph. Helicopter pilots generally desire rate-type control systems with short time-constants (e.g. on the order of a half second or less). In order to obtain shorter time-constants together with an acceptable level of control effectiveness, relatively larger values of angular damping and control sensitivity are required. Minimum acceptable values of the ratio of control sensitivity to angular damping parameter provide steady state angular rates on the order of at least 25 degrees per second per inch of control input, (Reference 70).

In research work done at NASA Langley using the variable stability S-51 helicopter, investigations were made on acceptable and minimum criteria for control and response characteristics of helicopters (Reference 42). General VFR flying and precision tasks such as instrument approaches at relatively slow speeds were accomplished. The results of that research are presented in a series of graphs that display acceptable handling qualities boundaries of angular damping versus control power for the pitch axis. Two important items of information are included on these graphs in the form of minimum damping requirements needed for both instrument flight and visual flight. The two numbers are expressed in minimum values of the pitch damping parameter and may be converted to first-order type time-constants by taking their reciprocal value. Converting the two stated values for minimum damping to approximate first-order type time-constants, the values are; for <u>instrument flight</u>, the first-order time-constant is $T_{63} = 0.9$ seconds and for <u>visual flight</u>, $T_{63} = 1.6$ seconds. The points may be plotted directly on the negative real axis of the complex plane and are shown on Figure 4-16. The reciprocals of the minimum damping parameters values represent the maximum time-constants allowable. Time-constant values less than those listed above (for IFR and VFR) and decreasing are more acceptable and meet the requirement.

One of the purposes of selecting these values is that they tend to establish <u>maximums</u> for the first-order time-constant for rate systems. A flight control system of a basic helicopter that has a lesser pitch damping value (greater time-constant) would not meet the minimum damping requirements established by that Reference. For example, for IFR flight, a control system that exhibits a time-constant greater than 0.9 seconds would not meet the requirement and would barely appear to be consistent with or definable as a minimum satisfactory "rate" control system for routine IFR flight and precision approaches. These two values are proposed here as a first step to limit the roots and prevent these responses from collecting close to the origin where acceleration type (low damping) systems exist. As a rough approximation on minimum allowable frequencies, arcs of circles may be drawn (using the center as the origin and the radii as the first-order time-constants), to display new minimum boundaries near the origin. Another similar form of these types of boundaries is addressed again below.

Minimum Frequency Requirements

In order to insure good overall response characteristics, the region near the origin must be bounded and excluded as a possible area for the roots. Significant specifications, research data, requirements and criteria already exist, are documented, and refer to limits or boundaries in this region. The helicopter MIL. SPEC. tends to protect

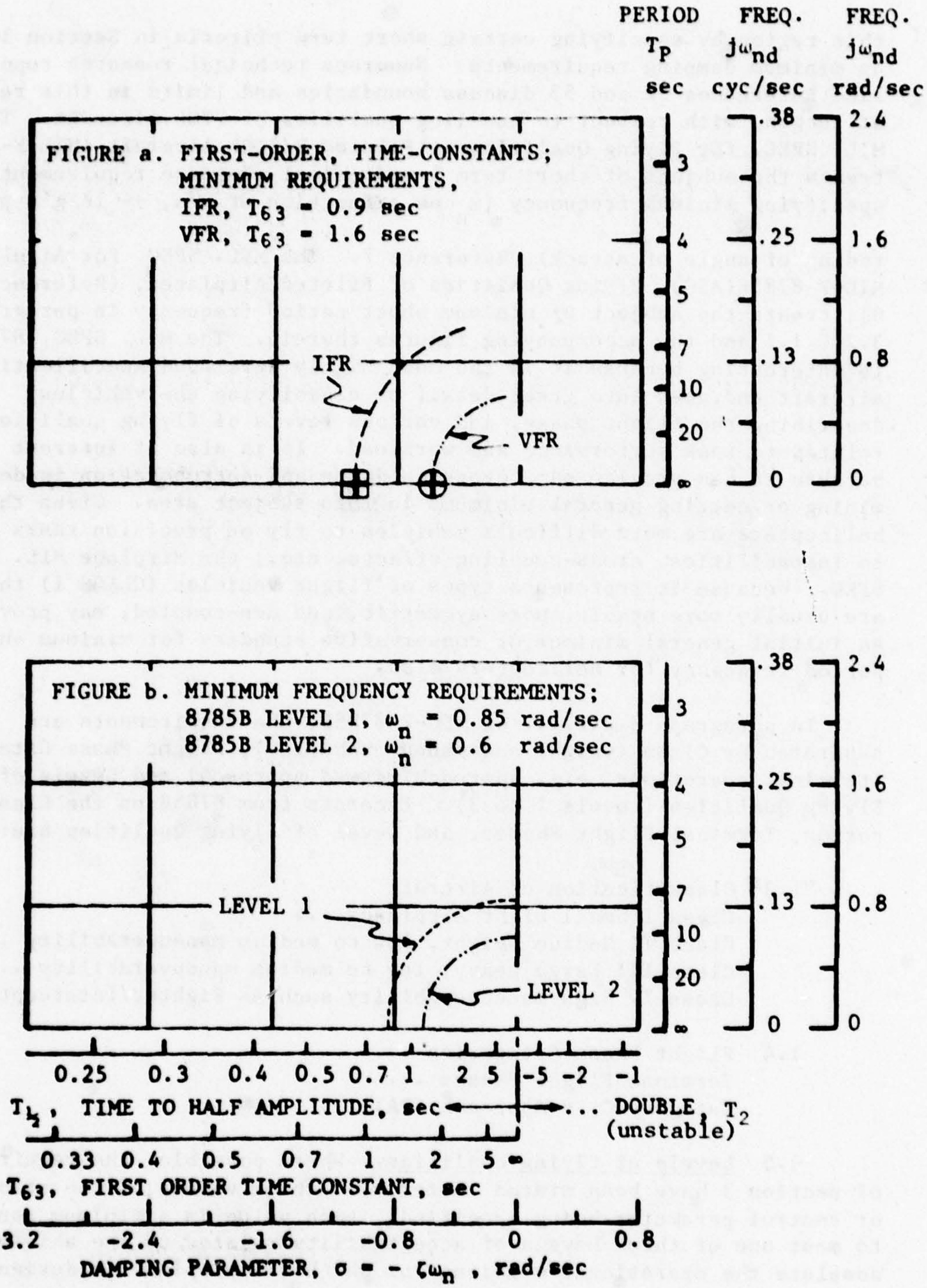


Figure 4-16. First-Order, Time-Constants and Minimum Frequency Requirements, (References 6 and 42).

this region by specifying certain short term criteria in Section 3 such as minimum damping requirements. Numerous technical research reports like References 52 and 53 discuss boundaries and limits in this region, at length, with respect to handling qualities of VTOL aircraft. The MIL. SPEC. for Flying Qualities of Piloted V/STOL Aircraft (MIL-F-83300) treats the subject of short term longitudinal response requirements by specifying minimum frequency (ω_n as a function of n/α, -- in g's per radian of angle of attack), Reference 7. The MIL. SPEC. for Airplanes, MIL-F-8785B(ASG), Flying Qualities of Piloted Airplanes, (Reference 6), treats the subject of minimum short period frequency in paragraph 3.2.2.1.1 and the accompanying figures therein. The MIL. SPEC. 8785B is interesting because it is the most highly developed specification on aircraft and goes into great detail on classifying the vehicles, describing the flight phase, and various levels of flying qualities related to task performance and workload. It is also of interest because it can provide some gross guidance and corroboration in determining or setting general minimums in this subject area. Given that helicopters are more difficult vehicles to fly on precision tasks due to instabilities, cross-coupling effects, etc.; the airplane MIL. SPEC., because it represents types of flight vehicles (CLASS I) that are usually more stable, more symmetric, and non-coupled, may provide an initial general minimum or conservative boundary for minimum short period frequency for helicopters also.

In paragraph 3.2.2.1.1 of MIL-F-8785B, the requirements are separated by Class (weight and maneuverability), Flight Phase Category (terminal operations, e.g. approach/missed approach) and Levels of Flying Qualities (Levels 1 to 3). Excerpts from 8785B on the Classification, Terminal Flight Phases, and Level of Flying Qualities are:

"1.3 Classification of Aircraft
Class I Small Light Airplanes ...
Class II Medium Weight, low to medium maneuverability ...
Class III Large heavy, low to medium maneuverability ...
Class IV High maneuverability such as Fighter/Interceptor ...

1.4 Flight Phase Categories ...
Terminal Flight Phases ...
Category C, c Approach (PA) ...

1.5 Levels of flying qualities. Where possible, the requirements of section 3 have been stated in terms of three values of the stability or control parameter being specified. Each value is a minimum condition to meet one of three Levels of acceptability related to the ability to complete the operational missions for which the airplane is designed.

The Levels are:

Level 1 Flying qualities clearly adequate for the mission Flight Phase

Level 2 Flying qualities adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists

Level 3 Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Category A Flight Phases can be terminated safely, and Category B and C Flight Phases can be completed."

If the specification were to be applied to one of the currently certified IFR helicopters for the CAT I-ILS approach/missed approach condition, it would appear the Class I, Category C and Level 1-Flying Qualities would be the applicable selection for the data related to minimum short period frequency and shown in the Figures of 8785B. In the applicable graph in 8785B, short period frequency is ploted versus n/α in g's/radian of angle of attack. Using a low value for n/α of about 2, a minimum short period frequency of 0.85 and 0.6 radians per second can be determined for Level 1 and Level 2 flying qualities respectively. In this discussion, it is assumed that Level 1 is "normal-state" flying qualities and that Level 2 represents degraded flying qualities commensurate with a "first-failure" situation. These minimums appear as portions of a circle with the center located at the origin and are shown on Figure 4-16 in this report.

Maneuver Stability Requirement

A requirement in MIL. SPEC. 8501A that provides for reasonable maneuvering characteristics in forward flight has been called "possibly the most compelling single handling quality" for helicopters (Reference 70). This requirement, as stated in Longitudinal Characteristics, subparagraph 3.2.11.1 (Appendix E), has been called by several titles such as Maneuver Margin or Maneuver Stability Requirement (References 35 and 70), the Divergence Criterion (Reference 55), Short-Period Requirement (Reference 43) and the Concave-Downward Requirement (Reference 70). It is a short term response characteristic that requires that the time history of normal acceleration (or angular velocity), in response to a specified longitudinal control input, "shall become concave downward within 2 seconds following the start of the maneuver and remain concave downward until the attainment of maximum acceleration." The phrase "and remain concave downward until the attainment of maximum acceleration" virtually eliminates the possibility of having divergences and still meeting the requirement. Hence, the Divergence Criterion essentially cannot be met if divergences are present. Also, this criteria provides for the establishment of a short term gust reponse which does not let the aircraft "dig in" subsequent to a gust upset.

The requirement was first adopted as a maneuver margin type criterion for helicopters because of the difficulty (as portrayed by NASA at that time) of determining stick position versus acceleration in turn maneuvers. Also, and more importantly, meeting the requirement was found to provide some "seat of the pants" cue or prediction capability by the pilot of eventual "peaking" of the coming acceleration (or angular velocity) response as a result of intentional pilot inputs or especially due to gust excitations. Further, from another handling qualities standpoint, it tends to assure the pilot of a given response characteristic to a given input and fixes a requirement on the characteristic short period roots for that region of the complex plane. Although it has been named the Divergence Criterion, it has been interpreted by others as having an impact on the oscillatory roots and/or the convergent real roots near the origin. This interpretation is well explained in Reference 70 for the two cases of the short term response where the stable oscillatory roots must be outside the boundary shown in that Reference in order to meet the criteria. Also, any real roots must satisfy certain positioning on the real axis so that "...the second root must be to the left of the first root's conjugate..." to satisfy the concave downward criterion (Figure 4-17). This interpretation is important in that it excludes combinations of low frequency, short period roots or real convergences that pilots relate to as generally unacceptable handling qualities. It is essentially a specification on maneuver margin. It requires the helicopter to have a "reasonable" acceleration trim gradient in order to meet the specification. Certain helicopter designs flying today can be loaded (with respect to c.g. location) so as not to meet the concave downward requirement. If they do not have sufficently large values of angular and vertical damping, they may need the addition of larger horizontal tail surfaces to meet this criterion.

It is felt here that this maneuver stability requirement (Concave Downward or Divergence Criterion) is an extremely vital aspect of handling qualities characteristics for IFR flight. If a helicopter cannot meet the concave downward requirement (because of design, configuration, c.g. location, etc.) there is a good probability that this aircraft would be rated as having poor IFR handling qualities, especially in moderate to heavy atmospheric turbulence. This particular criterion is so fundamental and vital for IFR flight that a pilot, flying an aircraft that is unable to meet the specification, would have to provide moderate to extensive compensation to control the aircraft on instruments. There is a good chance that the pilot would have difficulty in providing acceptable tracking performance at a satisfactory workload level for IFR type precision flight in turbulence

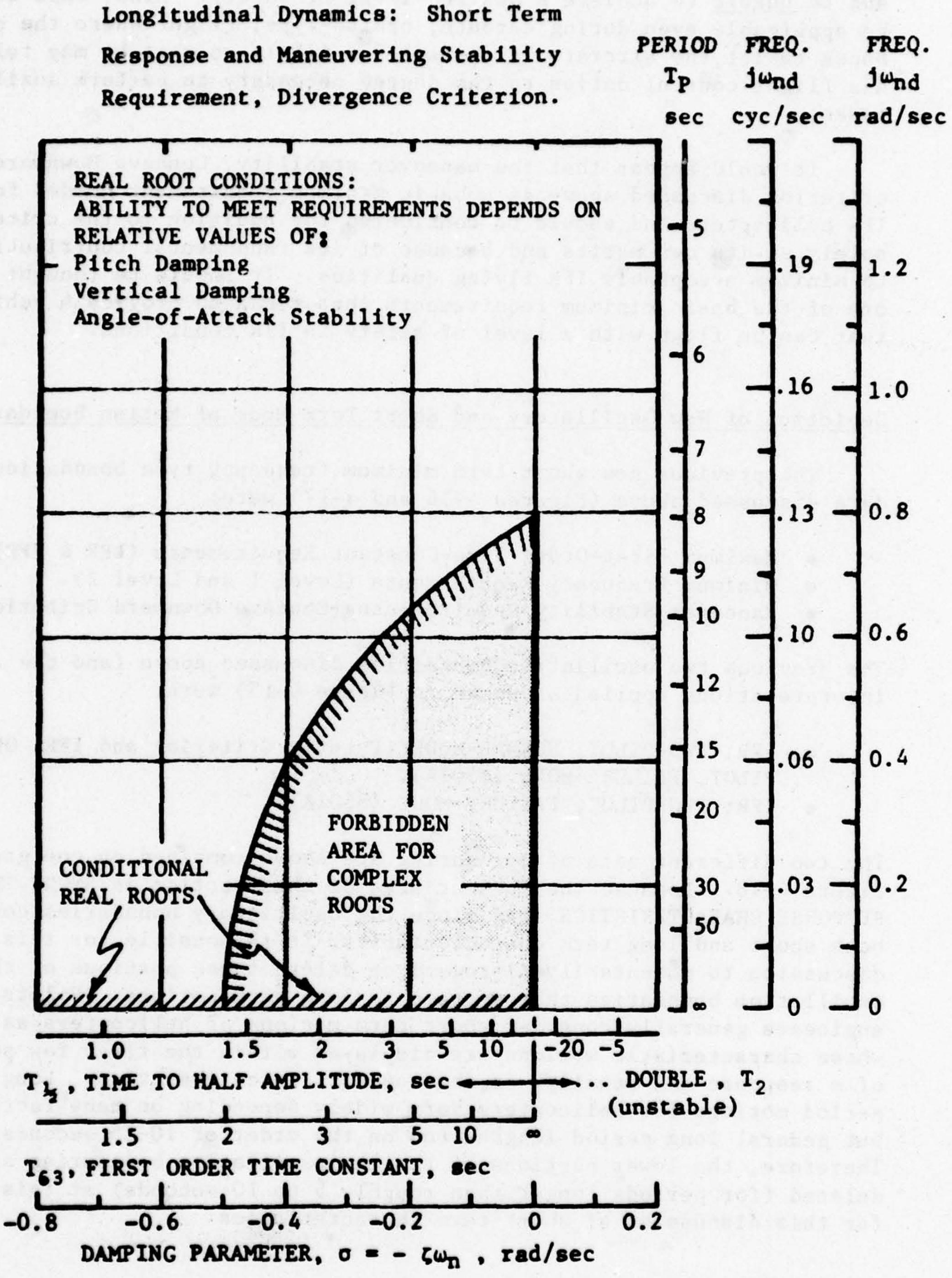


Figure 4-17. Concave Downward, Short Term Response Requirement of MIL-H-8501A, (Reference 5 and 70).

and be unable to achieve a desired level of safety. Also, this would be applicable even during enroute, cruise-type, flight where the pilot hopes to let the aircraft "fly-itself" a little so that he may relax his flight control duties to the degree necessary to perform auxiliary tasks.

It would appear that the maneuver stability, Concave Downward, criterion discussed above is a basic minimum requirement needed for all IFR helicopters and should be considered for addition to the criteria solely on its own merits and because of its fundamental contributions to minimum acceptable IFR flying qualities. It should be thought of as one of the basic minimum requirements that tends to provide a vehicle that can be flown with a level of safety in IFR conditions.

Depiction of New Oscillatory and Short Term Mode of Motion Boundaries

The previous new short term minimum frequency type boundaries and data discussed above (Figures 4-16 and 4-17) were:

- Maximum First-Order Time-Constant Requirements (IFR & VFR).
- Minimum Frequency Requirements (Level 1 and Level 2).
- Maneuver Stability Requirements (Concave Downward Criterion).

The previous two oscillation boundaries discussed above (and the interpretations applied as shown in Figure 4-15) were:

- IFR; TWO-PILOT, NORMAL-MODE (Interim Criteria) and IFR; ONE-PILOT, FAILURE-MODE (8501A).
- IFR; TWO-PILOT, FAILURE-MODE (8501A).

The two different sets of boundaries are shown combined on one graph in Figure 4-18. Because the subject area of this section is SHORT TERM RESPONSE CHARACTERISTICS, and since the oscillatory boundaries cover both short and long term characteristics, it is possible for this discussion to momentarily disregard or delete those portions of the oscillation boundaries that pertain to long term motions. Pilots and engineers generally consider short term motions of helicopters as those whose characteristic motions are displayed within the first few seconds of a response and usually, at the longest, twice that time. Long period motions for helicopters vary widely depending on many factors but general long period lengths run on the order of 10-25 seconds. Therefore, the lower portions of the two oscillation boundaries are deleted (for periods longer than roughly 5 to 10 seconds) at this time for this discussion of short term characteristics.

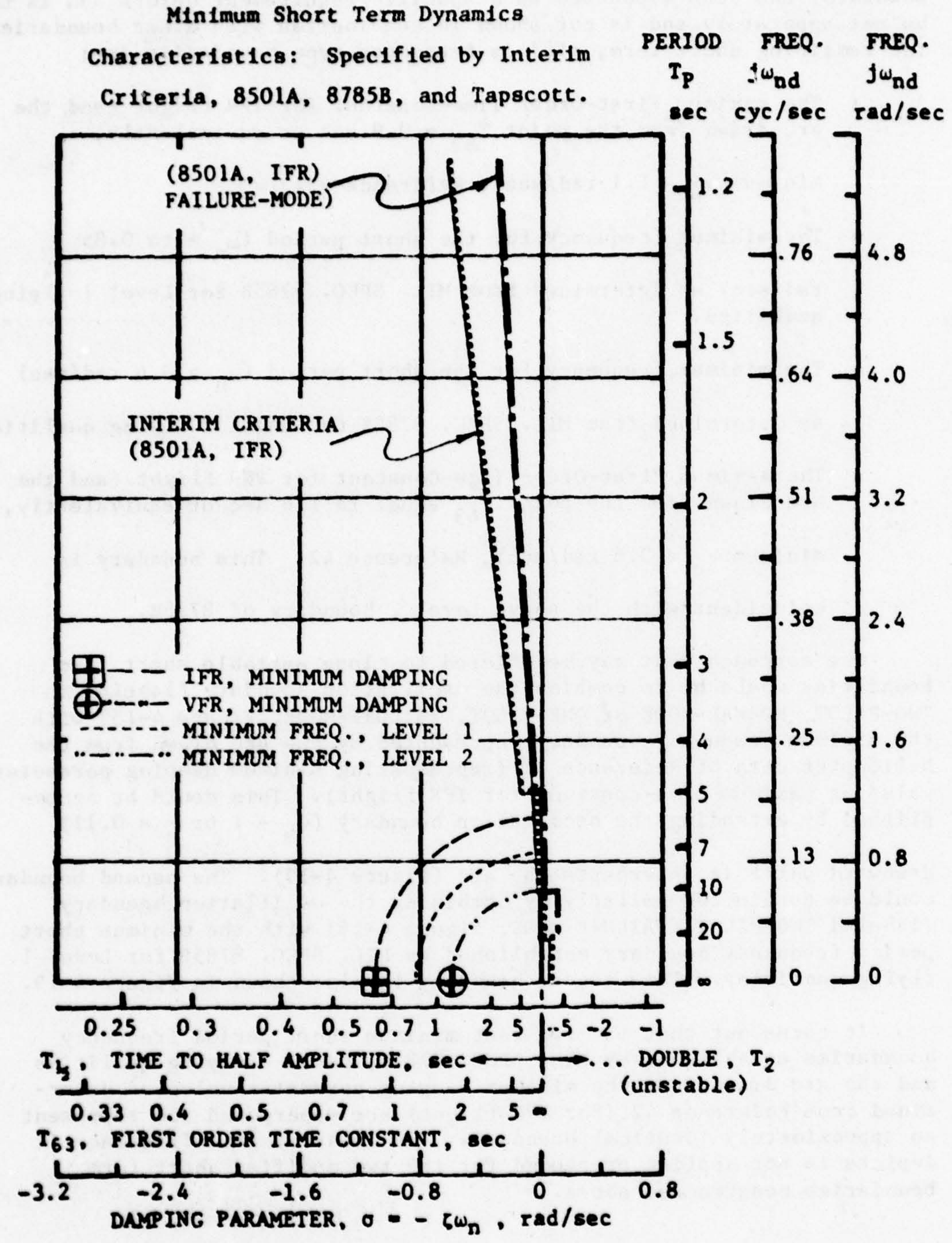


Figure 4-18. Short Term Minimum Frequency, Minimum Damping, and Oscillatory Boundaries.

Also, as mentioned before, the maneuver margin requirement (Concave Downward) has been discussed as a specific requirement before and is to be met separately and is not shown in combination with other boundaries. The remaining short term, minimum frequency type boundaries are:

- The maximum First-Order Time-Constant for IFR flight (and the arc drawn from the point $T_{63} = 0.9$ sec or equivalently, minimum $\omega_n = 1.1$ rad/sec), Reference 42.
- The minimum frequency for the short period (ω_n = to 0.85 rad/sec) as determined from MIL. SPEC. 8785B for Level I flying qualities.
- The minimum frequency for the short period ($\omega_n = 0.6$ rad/sec) as determined from MIL. SPEC. 8785B for Level 2 flying qualities.
- The maximum First-Order Time-Constant for VFR flight (and the arc drawn from the point T_{63} equal to 1.6 sec or equivalently, minimum $\omega_n = 0.6$ rad/sec), Reference 42. This boundary is coincident with the above Level 2 Boundary of 8785B.

One approach that may be offered to close suitable short term boundaries would be to combine the oscillation boundary (labeled as TWO-PILOT, NORMAL-MODE or ONE-PILOT, FAILURE-MODE, Figure 4-15) with the minimum frequency boundary represented by the arc drawn from the helicopter data of Reference 42 (representing minimum damping parameter value or maximum time-constant for IFR flight). This could be accomplished by extending the oscillation boundary ($C_{1/2} = 1$ or $\zeta = 0.11$) downward until it intercepts the arc (Figure 4-19). The second boundary could be constucted smilarly by combining the oscillation boundary (labeled TWO-PILOT, FAILURE MODE, Figure 4-15) with the minimum short period frequency boundary established by MIL. SPEC. 8785B for Level 1 flying qualities. This second boundary is also shown in Figure 4-19.

It turns out that the two last minimum short period frequency boundaries established by MIL. SPEC. 8785B, Level 2 flying qualities and the arc drawn from the minimum damping parameter value as determined from Reference 42 (for VFR flight) are superposed and represent an approximately identical boundary. The lower minimum frequency it depicts is not applied or needed for the two modified short term boundaries constructed above.

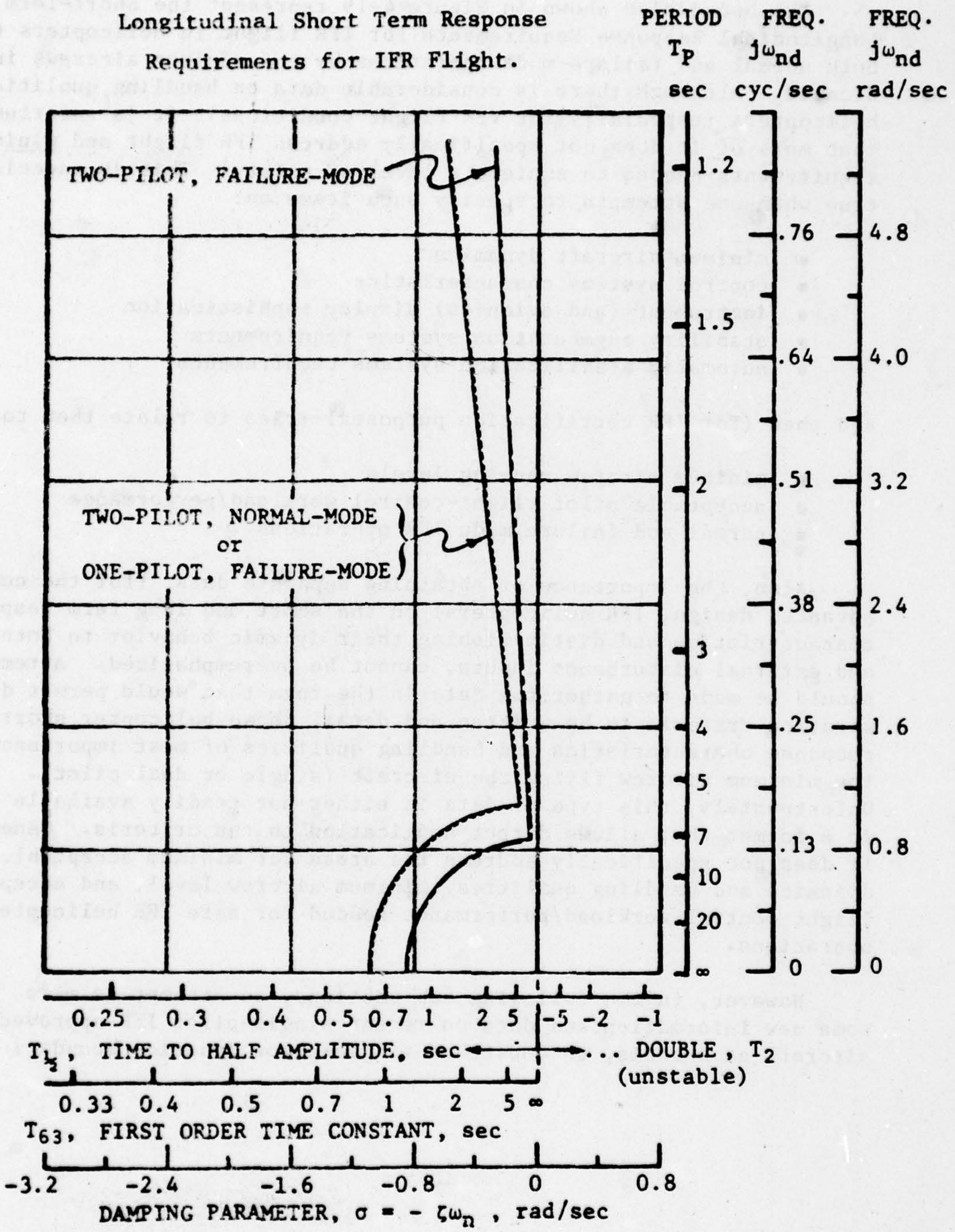


Figure 4-19. Longitudinal Short Term Response Requirements for IFR Flight.

The boundaries shown in Figure 4-19 represent the Short-Term Longitudinal Response Requirements for IFR flight in helicopters for both normal and failure-mode operations by the minimum aircrews indicated. Although there is considerable data on handling qualities of helicopters (especially for VFR flight conditions), it is unfortunate that more of it does not specifically address IFR flight and minimum requirements needed to achieve a level of safety. This is especially true when one attempts to specify such items as:

- minimum aircraft dynamics
- control systems characteristics
- instrument (and avionics) display sophistication
- stability augmentation systems requirements
- automatic stabilization systems requirements

and then (for IFR certification purposes) tries to relate them to:

- minimum aircrew manning levels
- acceptable pilot flight-control workload/performance
- normal and failure mode IFR operations.

Also, the importance of obtaining separate data, (for the current, advanced design, IFR helicopters) on the short and long term response characteristics and distinguishing their dynamic behavior to both pilot and external disturbance inputs, cannot be overemphasized. Attempts should be made to gather the data in the form that would permit demonstration criteria to be written and detail those helicopter short-term response characteristics and handling qualities of most importance to the minimum aircrew flying the aircraft (single or dual pilot). Unfortunately, this type of data is either not readily available or not in a format that allows direct application to the criteria. Generally, it does not specifically address the areas for minimum acceptable dynamics and handling qualities, minimum aircrew level, and acceptable flight control workload/performance needed for safe IFR helicopter operations.

However, in the following sub-sections, an attempt is made, using some new information and data on recent single-pilot IFR approved aircraft as a basis, to construct single-pilot dynamics boundaries.

DYNAMIC STABILITY, SINGLE-PILOT REQUIREMENTS

Recent Single-Pilot IFR Certifications

During the single-pilot IFR certification process, while the aircraft is being tested and the dynamic stability documented, the subject of pilot workload and performance is also addressed. This can be done during the documentation process of the helicopter or during separate IFR flying for that specific purpose as dictated by paragraph (j) of the Interim Criteria. In reviewing recent single-pilot IFR approvals of helicopters, several items are evident:

- Stability Augmentation Systems (SAS) or Stability and Control Augmentation Systems (SCAS) are installed and/or
- The aircraft are equipped with automatic stabilization equipment such as Autopilot Systems (AP) that contain, as the most basic function, ATTITUDE-HOLD features, (integral of attitude as a long term feedback, ATTITUDE-HOLD/AP).
- The SAS and SCAS systems use both attitude gyro signals (short term) and rate signals as feedback, (ATTITUDE-SAS or ATTITUDE-SCAS).
- ATTITUDE-SAS, ATTITUDE-SCAS, and ATTITUDE-HOLD/AP Systems usually rely on limited authority actuators that have between approximately 10 to 25% total swashplate authority depending on number and type of actuators used in each axis.
- As certified (and related in the Rotorcraft Flight Manuals) some of these vehicles were approved with a Flight Director System as a requirement for IFR flight and also, the ATTITUDE-HOLD/AP system must be on and operating for the duration of the IFR flight.

Several important points can be gleaned from the above information. The addition of the attitude gyro signal as a feedback quantity for the ATTITUDE-SAS and ATTITUDE-SCAS represents an extremely vital aspect to the certification. Given sufficient actuator authority, the attitude feedback system (ATTITUDE SAS or SCAS) provides a type of attitude stability to the dynamical system that is the foundation for the single-pilot IFR approval. Thus far, all recent single-pilot approvals have utilized some degree of stability or "stiffness" with respect to the horizontal plane (ATTITUDE-SAS or SCAS and/or ATTITUDE-HOLD/AP) to resolve stability and control and/or workload/performance requirements.

Since the "basic" helicopter (with its inherent stability) can only provide stability with respect to the velocity vector, stability (or stiffness) with respect to the horizontal flight path can only be provided by attitude gyro signals used in conjunction with augmentation systems and/or automatic stability equipment.

Whether this attitude stiffness (or ATTITUDE-FUNCTION) is provided as a result of ATTITUDE-SAS, ATTITUDE-SCAS, and/or ATTITUDE-HOLD/AP Systems, or any other type of ATTITUDE RETENTION UNIT OR FEATURE is not basically important. It just needs to be provided to some acceptable degree that is satisfactory for approval of the entire aircraft/pilot system offered for single-pilot IFR certification. The ATTITUDE-FUNCTION provided by ATTITUDE-SAS or SCAS is usually short-term since the control system concept (essentially rate-ordering or rate-command) requires that the attitude signal be "leaked-off" after a short time. This is necessary so that the pilot is not required to "buck" or cancel the attitude signal in the longer term by holding his cyclic control displaced. Use of the attitude-hold feature of the autopilot (ATTITUDE-HOLD/AP) provides the needed ATTITUDE-FUNCTION over the longer term. As stated in one Rotorcraft IFR Flight Manual:

> "...Attitude retention is the most basic system mode provided for IFR flight. In this mode, the cyclic controls are referenced to the pitch and roll attitude signal from the vertical gyro. The system will, without pilot intervention, hold whatever pitch and roll attitude the pilot places on the helicopter. This may be straight and level, a continuous turn or whatever attitude the pilot selects. ...this mode is mandatory for IFR flight."

As stated in that flight manual, the ATTITUDE-HOLD/AP will tend to hold the aircraft attitude without pilot intervention. Should he choose to maneuver the aircraft, the pilot needs only to disable the attitude-hold function (in this case, with the force trim release button) and use his normal flight controls to maneuver the aircraft. In this mode he will retain the short-term attitude function and will probably revert to essentially a rate-ordering or rate-command type control system as provided by the stability augmentation devices (ATTITUDE-SAS or SCAS). Use of the ATTITUDE-HOLD/AP system provides the pilot with more workload relief than the ATTITUDE-SAS or SCAS can provide because it delivers a long-term ATTITUDE-FUNCTION with a specified long-term aircraft attitude whereas ATTITUDE-SAS and SCAS provide only a short-term ATTITUDE-FUNCTION with no long-term specified aircraft attitude. For single-pilot approvals, flight control workload relief is an important aspect in the IFR certification process especially during the judgement of pilot attention to auxiliary tasks and ease of general IFR flight management.

Longitudinal Dynamic Stability versus the Attitude Function

With the installation of means that provide an ATTITUDE-FUNCTION such as ATTITUDE-SAS, ATTITUDE-SCAS, and ATTITUDE-HOLD/AP Systems, the minimum dynamic stability requirements as specified by paragraph (d) of the Interim Criteria are not readily applied or are of little consequence. A helicopter equipped with any of the above three types of systems should be able to easily pass the minimum oscillatory dynamic stability requirements using both attitude and rate feedback means, given enough gain and actuator authority. In fact, many aircraft with these ATTITUDE-FUNCTION devices installed usually exceed the minimum oscillatory dynamics requirements (period and damping) by generous amounts. But, the benefits gained by improving the modal characteristics of the dynamics above the presently stated minimum requirements are greatly overshadowed by the provision of attitude type stability to the aircraft/pilot system. If the ATTITUDE-FUNCTION is provided by an ATTITUDE-HOLD/AUTOPILOT and an ATTITUDE-SAS or SCAS system, then any workload problem is greatly mitigated and the longitudinal dynamics probably will far exceed the minimums so that these parts of the criteria are favorably resolved by this technique.

Short Term Dynamics of Augmented Helicopters

The short-term longitudinal response characteristics of a basic helicopter are greatly altered when attitude and rate feedbacks are utilized with artificial augmentation systems. The longitudinal, short-term response of the basic helicopter in forward flight is dominated by the angle-of-attack stability derivative. This derivative represents the "spring" between the helicopter and the velocity vector and the major contributors to it are the rotor and fuselage (unstable) and the horizontal tailplane (stable).

In forward flight, the short-term longitudinal motion of the basic helicopter (with no augmentation means, -- inherent stability of the basic vehicle) is approximated by a non-oscillatory, real-root convergence type motion. Even with a horizontal tailplane and the addition of effective rotor-hinge offset, the short term response in forward flight tends toward aperiodic motion and usually is dominated by a real root convergence, (References 69 and 43). Single rotor unaugmented helicopters with fully articulated blades and semi-rigid (see-saw) rotors that have relatively small flapping hinge offset (or equivalent hinge offset) normally have a lightly damped short term longitudinal response. The aperiodic, non-oscillatory short term longitudinal response for these machines is usually characterized or approximated by first-order, time-constants whose values may be a second or two. Rigid or hingeless rotor systems (or other rotor systems with larger equivalent flapping hinge offset) and tandem rotor helicopters generally have relatively more pitch damping. The approximate first-order, time-constants of these machines may be as low as a half second or one second.

If RATE-SAS or SCAS (RATE ONLY) or other similar means are added to the basic helicopter, the short-term longitudinal motion usually remains non-oscillatory and becomes more heavily damped. The value of the time-constant is usually reduced to values as low as a half-second and sometimes to values on the order of a few tenths of a second.

If ATTITUDE-SAS or SCAS (ATTITUDE PLUS RATE) is added to the basic helicopter, the primary or new mode of motion of interest for the short-term longitudinal response becomes an oscillation instead of an aperiodic motion. The main point to be noted here is that for the short-term longitudinal mode of motion to be oscillatory, some ATTITUDE-FUNCTION characteristic has to be incorporated in the dynamical system. (Depending on the gains used, lagged-rate feedback can provide a degree of short term attitude function that will appear as an oscillatory response also.)

This means that for the longitudinal oscillatory boundaries of the Interim Criteria to have an impact on the <u>short-term</u> response characteristics, the helicopter must have an ATTITUDE-FUNCTION type device installed and operating. If an ATTITUDE-SAS, ATTITUDE-SCAS or an ATTITUDE-HOLD/AP system is not installed (or inoperative), the short-term longitudinal response characteristics will be a non-oscillatory, aperiodic type motion and the Interim Criteria oscillatory boundaries cannot be readily applied for these types of short term motions (Figure 4-20).

In a sense, it seems surprising the way the IFR oscillatory dynamics boundaries of 8501A are now being applied as compared to what they were supposedly and originally intended for by the writers of that document. The oscillation boundaries were first drafted (almost as an adjunct) with primary concentration on the dynamics of essentially unaugmented tail-less helicopters in hover and slow forward flight.

Although not clearly documented anywhere, it appears, from a review of some of the most pertinent original studies (References 42 and 56) and from discussions with the originators and users (of the boundary), that the longitudinal boundary was primarily directed toward a long-term oscillation that occurs at hover and slow speed. It was a lightly damped or unstable oscillatory motion with periods ranging from about 8 to 20 seconds depending on aircraft speed and configuration. However, the full boundary does include additional limits as a function of different period lengths that can occur as speed changes to higher values. The IFR longitudinal oscillation boundary of 8501A (identical to the Interim Criteria) does not appear to have been intended as a minimum requirement boundary for short-term longitudinal oscillatory dynamics of highly (attitude) augmented helicopters.

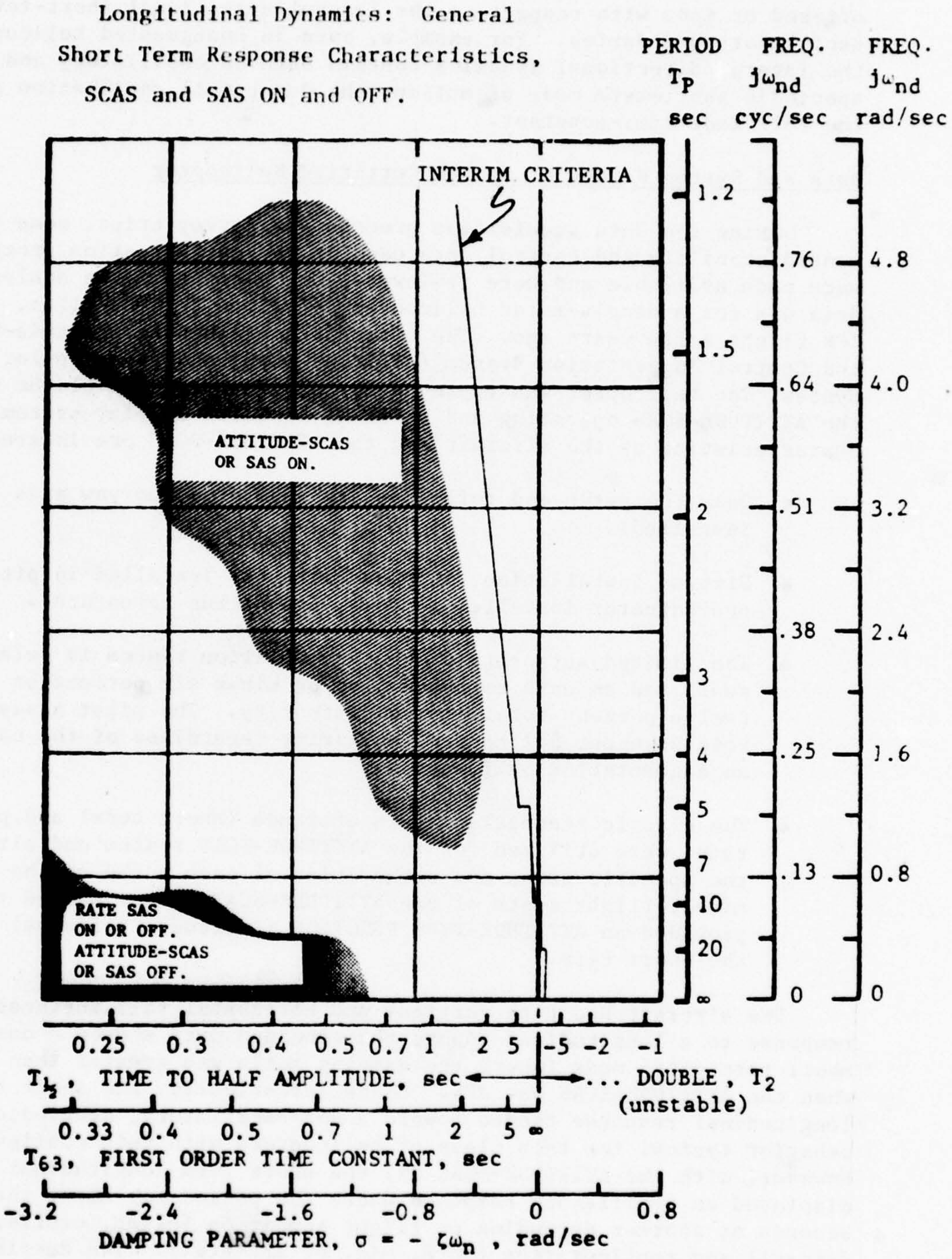


Figure 4-20. Effect of SCAS and SAS Systems on Short Term Response Characteristics.

It is worth noting here that the same arguments are not as readily offered or made with respect to the lateral/directional short-term oscillatory boundaries. For example, even in unaugmented helicopters, the lateral/directional dynamics contain both an oscillatory and aperiodic short-term mode of motion; the dutch roll oscillation and the roll mode time-constant.

Data and System Review of an IFR Certified Helicopter

During the data acquisition process and survey trips, some documented stability and control data used in the certification process were made available and were reviewed. One segment of the analyzed data was for a single-rotor helicopter certified for one-pilot, IFR flight a few years ago. The aircraft contained an Attitude-Stability and Control Augmentation System (ATTITUDE-SCAS) and an autopilot system. The helicopter was approved for single-pilot IFR flight with the ATTITUDE-SCAS operating and a FLIGHT DIRECTOR display system. The characteristics of the aircraft and the ATTITUDE-SCAS are interesting:

- Only the pitch and roll axes are augmented (no yaw axis actuator installed).

- Simplex installation, only one actuator installed in pitch and one actuator installed in roll, (no backup actuators).

- The limited authority of the augmentation system is relatively small and amounts to about plus or minus six percent or roughly twelve percent total control authority. The pilot always retains about 88% control authority regardless of the nature of an augmentation malfunction.

- The classic feedbacks, pitch attitude (short term) and pitch rate, were utilized for the ATTITUDE-SCAS system and although the specific gains and authorities of each could not be determined, flight tests of the ATTITUDE-SCAS system showed that it provided an ATTITUDE-TYPE FUNCTION (Attitude Stiffness) over the short term.

The aircraft had both vertical and horizontal tail surfaces. In response to a longitudinal input, the recorded data showed a damped short term pitch mode (where the damping ratio was greater than 0.7) when the ATTITUDE-SCAS was OFF. Characteristically, the short term longitudinal response tended toward a non-oscillatory, aperiodic type behavior typical for this class of helicopters with this configuration. However, with the ATTITUDE-SCAS ON, the short term longitudinal response displayed an oscillatory response where the period was about three seconds or shorter depending on flight condition (climb, cruise, descent) and configuration (fore, mid, or aft c.g.). The damping ratios appeared to range between about 0.2 and 0.35 depending on flight condition and configuration. Even with the relatively small actuator authority of this system, the addition of the ATTITUDE-SCAS (ON) provided a damped oscillatory short term response that easily met (and exceeded) the minimum requirements of the oscillatory dynamics as specified by the current Interim Criteria.

Analysis of the time history traces where the ATTITUDE-SCAS system was turned OFF, reveals a short term response characteristic that appears non-oscillatory and whose damping level is typically characterized by the value of the first-order time-constant. The point to be understood here is that as the damping ratio increases, the oscillation continues to appear less oscillatory until the complex roots join on the negative real axis and the motion becomes aperiodic. However, as soon as the roots divide, on the negative real axis, the root most remote from the origin ordinarily will quickly dominate the short term response. It is this root that will reveal the level of damping of the aperiodic response of the basic helicopter (as denoted by the time-constant). Note that with the ATTITUDE-SCAS OFF, the level of the damping of the short term, aperiodic response is characterized by the time-constant of the system (e.g., time-constants on the order of a few tenths of a second represent well damped first-order systems). For these two cases, (ATTITUDE augmentation OFF and ON), both the oscillatory and the non-oscillatory short term response characteristics appear to far exceed the minimum dynamic stability requirements of the criteria. Because only short term dynamics are being discussed here, it is apparent that with the ATTITUDE-SCAS OFF the (damped) short term response root will be well left of the criteria boundary and appears to easily exceed the requirements of the Interim Criteria boundary as shown in Figure 4-20.

This situation is caused by the fact that only the short term response characteristics are being addressed. It has been noted previously that a shortcoming of the Interim Criteria is that it attempts to treat all axes (pitch, roll, yaw) and all responses (short and long term) with one blanket specification and ignores, for example, the great importance of short term requirements for each axis. In Figure 4-20, it is obvious that the short term longitudinal response always will far exceed the minimum requirements with ATTITUDE-SAS OFF if the basic helicopter has any inherent pitch damping whatsoever. If RATE-SAS is used, and there is some degree of inherent pitch damping, the short term response will exceed the requirement with RATE-SAS OFF (or ON). Even though the oscillatory boundary of 8501A can be extended upward to cover very short term oscillatory dynamics, it was never intended as a short term dynamics boundary and is not readily applied when the short term response is not oscillatory.

A small portion of the data reviewed for this IFR certified single-piloted helicopter is shown sketched in Figure 4-21 with the new short term response boundaries constructed in Figure 4-19 of this Report. It is important to note here that the only way to get the longitudinal high frequency oscillatory responses on this vehicle is with ATTITUDE-SAS ON. Even RATE-SAS will not make the longitudinal short term response oscillatory since it generally increases the pitch damping of the aperiodic root (pitch mode) and keeps the character of the short term motion on or near the negative real axis. In order to make the short term response oscillatory some ATTITUDE TYPE FUNCTION has to be provided (ATTITUDE-SAS, ATTITUDE SCAS and/or ATTITUDE-HOLD/AUTOPILOT). The importance of the ATTITUDE FUNCTION to single-pilot IFR flight cannot be overemphasized. Even though a basic helicopter with good inherent pitch damping presents the pilot with a heavily damped short term response and similarly, with the addition of RATE-SAS, provides him with even better short term characteristics, these aforementioned systems cannot compete with the improvement in IFR flying qualities afforded by the ATTITUDE-FUNCTION.

With an ATTITUDE-SCAS, the pilot perceives a relatively high frequency oscillatory motion that displays a tendency over the short term to preserve ATTITUDE (with respect to a horizontal reference plane). If he utilizes the ATTITUDE-HOLD feature of an Autopilot he will still note approximately the same characteristics but now he can select specific aircraft attitudes and have them held over the long term. The fact that the oscillatory mode may be relatively lightly damped does not inhibit his desire for the ATTITUDE stiffness. If more damping is desired, increased actuator authority may be provided by increasing the "throw" of the one actuator on board (or adding more actuators, -- Duplex or Triplex systems). As stated previously, the addition of some type of ATTITUDE FUNCTION and the attendant increase in favorable handling qualities is the foundation for single-pilot IFR flight in helicopters. It provides the pilot not only with better dynamic stability and control characteristics but allows him to participate more easily in the accomplishment of auxiliary tasks and ameliorates many of his workload/performance problems.

Depiction of Single-Pilot, Normal-Mode Short Term Dynamics Boundary

A closer study of Figure 4-21 reveals several points:

- With ATTITUDE-SAS or SCAS ON, short term period lengths are reduced well below 5 seconds ($T_P < 3.5$ sec).
- With ATTITUDE-SAS or SCAS on, the damping ratio appears to be at least 0.2 and as large as about 0.30 or 0.35 even with the sole, relatively small authority actuator installed on the

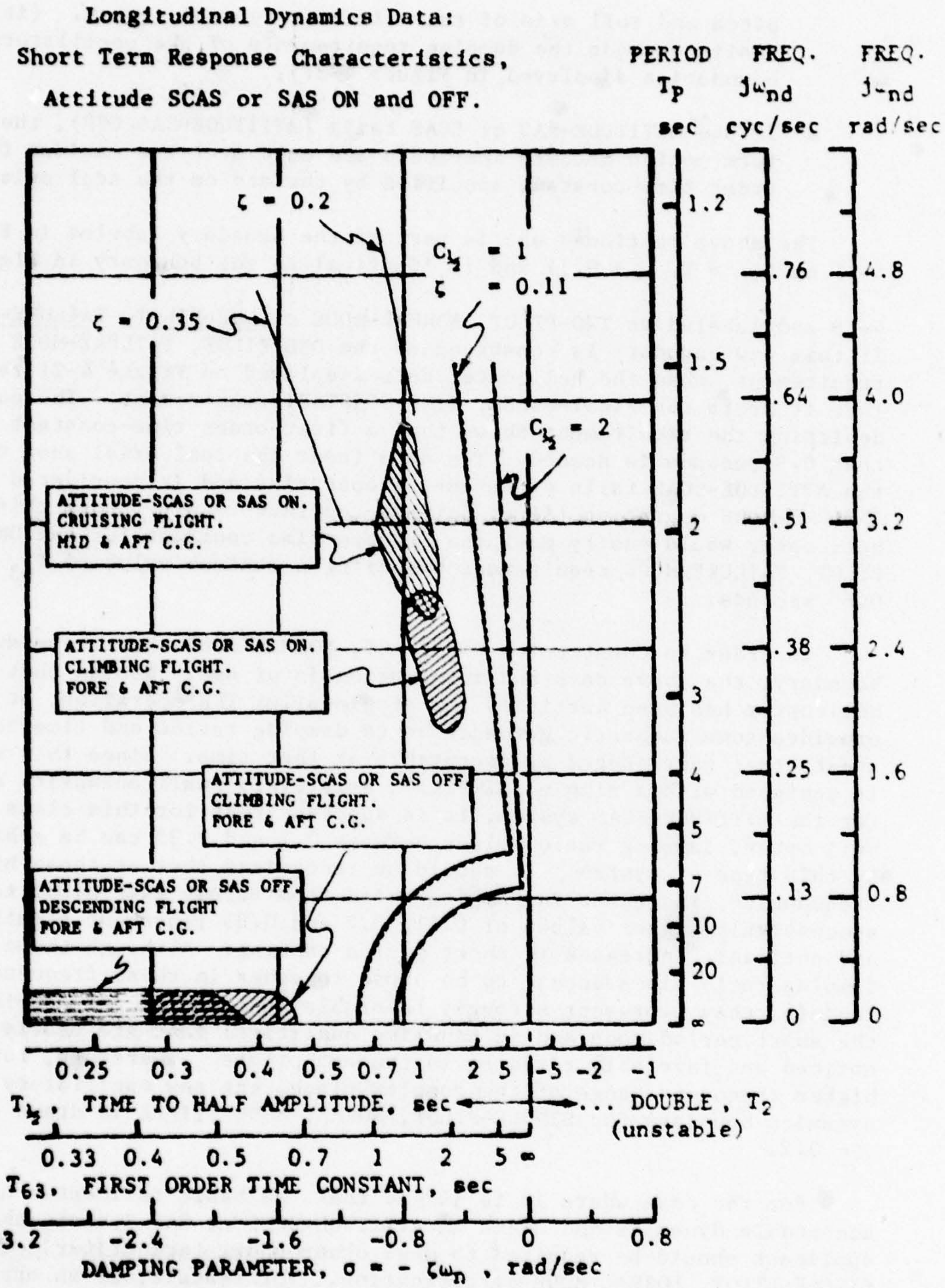


Figure 4-21. Longitudinal Short Term Dynamics Data for Recently Certified Single-Pilot IFR Helicopter.

pitch and roll axis of this aircraft control system. (it easily exceeds the damping requirements of the oscillatory boundaries displayed in Figure 4-21).

- If the ATTITUDE-SAS or SCAS fails (ATTITUDE-SAS OFF), the short term motion becomes aperiodic and must meet the maximum first-order time-constant specified by the arc on the real axis.

The above mentioned arc is part of the boundary labeled in Figure 4-21 as $C_{\frac{1}{2}} = 1$, $\zeta = 0.11$ and is identical to the boundary in Figure 4-19 and labeled as TWO-PILOT, NORMAL-MODE or <u>ONE-PILOT</u>, <u>FAILURE-MODE</u>. If this new boundary is construed as the ONE-PILOT, FAILURE-MODE requirement, then the helicopter data displayed on Figure 4-21 reveal that it meets the FIRST-ORDER, TIME-CONSTANT requirement. The curve depicting the requirement shows that a first-order time-constant less than 0.9 seconds is needed. The data (near the real axis) show that if the ATTITUDE-SCAS fails or becomes inoperative and is considered FAILURE-MODE operation (first failure-continue to fly), then this helicopter would easily meet the maximum time constant for the ONE-PILOT, FAILURE-MODE requirement by having a maximum value of $T_{63} =$ 0.65 seconds.

In order to construct a ONE-PILOT, NORMAL-MODE short term dynamics boundary, the above data and information is of use. Noting that this helicopter has been certified for single-pilot IFR operation, it provides some authentic guidance as to damping ratios and time constants that were judged as acceptable at that time. Since this vehicle is equipped with a single (SIMPLEX), relatively small authority actuator for the ATTITUDE-SCAS system, it is apparent that for this class of helicopter, damping ratio values between 0.2 and 0.35 can be achieved by this type of system. It should be recognized that at these higher frequencies, increases in damping ratio from values like 0.055 to successively higher values of 0.11, 0.2 and 0.35 represent significant and noticable increases in short period damping. Although those damping ratio lines appear to be close together in these frequency regions, they represent strongly favorable changes (in the damping of the short period mode and in handling qualities) that are easily noticed and favorably rated by instrument pilots. Therefore, for this higher frequency range of the complex plane, the new oscillatory dynamics boundary for SINGLE-PILOT, NORMAL-MODE flight is drawn at $\zeta = 0.2$.

For the case where it is judged that the basic helicopter has acceptable dynamics and needs no ATTITUDE-SCAS or SAS System, the applicant should be required to meet other short term criteria for SINGLE-PILOT, NORMAL MODE certification. For example, if an applicant feels that the helicopter's inherent dynamics are good enough that he does not choose to provide an ATTITUDE-TYPE SAS or SCAS SYSTEM, he will still have to satisfy the short term requirement. Also, the applicant may still be faced with the single-pilot workload problem and will probably solve that issue by providing an ATTITUDE-HOLD, AUTOPILOT. For this case, the pilot may, when he chooses, activate the ATTITUDE-HOLD feature so that the aircraft will maintain a specified attitude for the long term and allow him some leeway to accomplish his auxiliary tasks. However, should he choose to maneuver the aircraft himself, he will have to "break" the ATTITUDE-HOLD feedback and fly an aircraft that will have the characteristics of the basic helicopter. The aircraft's short term longitudinal control response (and gust response) probably will be aperiodic in nature and its characteristics will depend largely on how much pitch angular damping is inherently provided. Nevertheless, for these cases, his short term response behavior will be generally characterized by the first-order time-constant and should be representative of that class of control systems defined as rate-type. This helicopter should be required to meet some minimum acceptable, short term dynamics criteria.

It is often stated that an acceptable rate-type control system is characterized by a first-order time-constant that is one-half second or less (Reference 70). With this condition, an arc may be drawn, with the center as the origin and the radius equal to a first-order time-constant equal to 0.5 seconds, and joined with the damping ratio line ζ equal to 0.2. This new, completed boundary is now labeled ONE-PILOT, NORMAL-MODE (Figure 4-22).

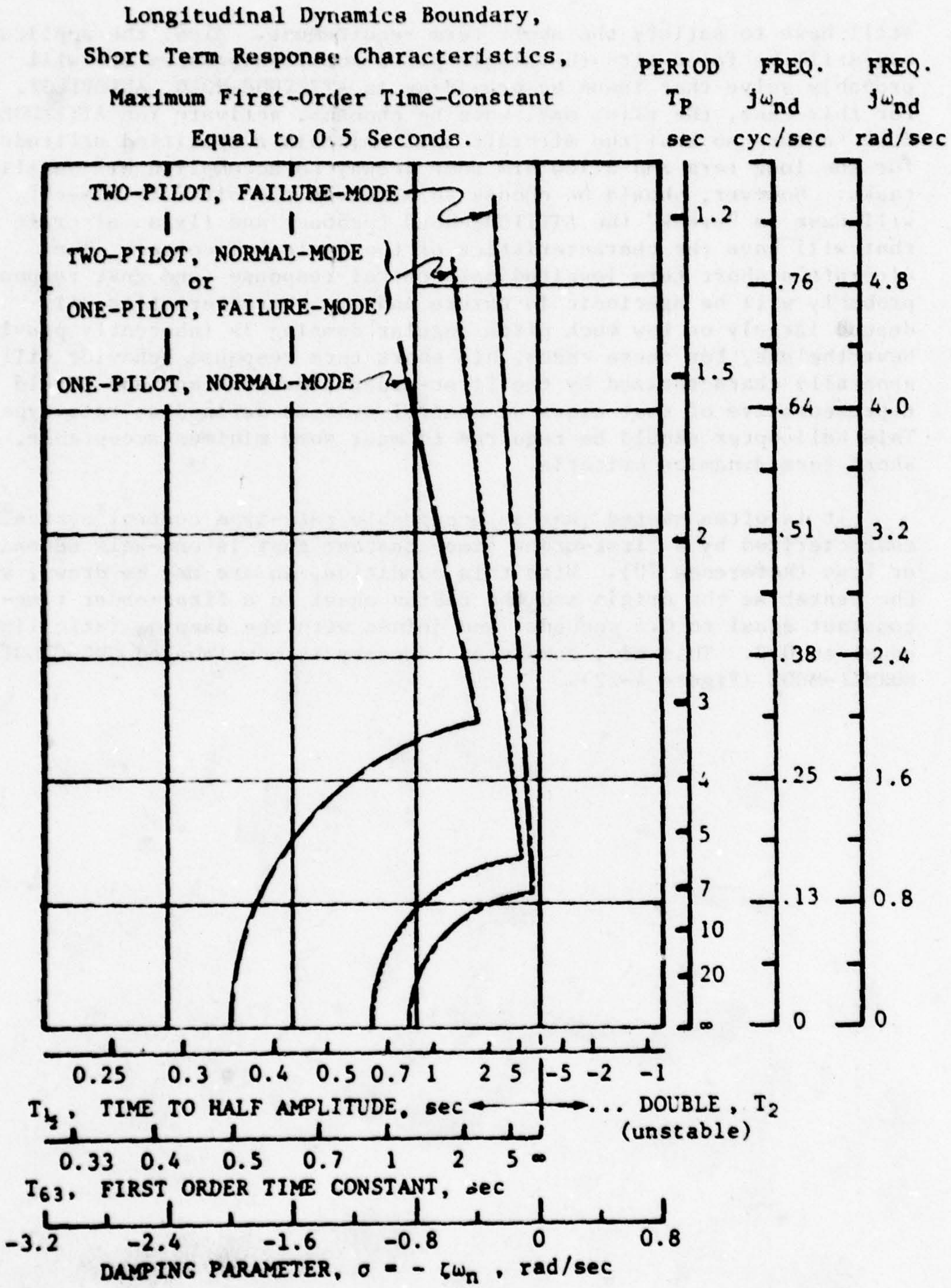


Figure 4-22. New Boundary for One-Pilot, Normal-Mode IFR Operation, (Case I: $T_{63} = 0.5$ sec).

THE DYNAMICS BOUNDARIES FOR SHORT TERM RESPONSE CHARACTERISTICS

Use and Interpretation of the Boundaries

According to Figure 4-22, an aircraft with a longitudinal ATTITUDE FUNCTION will have to meet the three upper positions of the boundaries as a function of manning level (ONE-PILOT or TWO-PILOT) and operating condition (NORMAL-MODE or FAILURE-MODE). It should be recognized that if a failure occurs, it must be of the type that allows the pilot to keep some level of attitude function to remain in the area where these upper (constant damping ratio) boundaries prevail. For example, if the aircraft had two or three actuators in a string in the longitudinal control system (DUPLEX OR TRIPLEX SYSTEM) and one failed but the pilot was able to isolate the problem and take the bad one "off-line", he still would have one or two longitudinal actuators left. This is not unreasonable and with fault isolation systems this could be done automatically and the pilot would retain an aircraft that still had an attitude function but at a reduced damping ratio and/or frequency. It is even possible that gain and authority adjustments could be made automatically to the remaining longitudinal actuators so that no system degradation would take place. However, this system may present the pilot with an intolerable "hard-over" problem should a second failure occur. If this possibility existed, it would probably be flight checked if it was deemed that a second failure was a likely possibility.

If the longitudinal ATTITUDE FUNCTION was provided by a single actuator (SIMPLEX SYSTEM) and it failed (ATTITUDE SAS or SCAS and/or ATTITUDE-HOLD/AUTOPILOT all inoperative) then the upper region boundaries are no longer of interest. The system will degrade to the inherent flying qualities and longitudinal dynamics of the "basic" helicopter. The short term longitudinal response will be approximated by the first-order time-constant. It will probably be a non-oscillatory, aperiodic type response and most importantly, the single pilot on board will have lost the ATTITUDE FUNCTION characteristic that may have enabled him to participate in the needed auxiliary tasks required for IFR flight. The pilot's workload/performance limits will change considerably but he is in a FAILURE-MODE (first failure - continue to fly) situation and is expected to complete the IFR flight without declaring an emergency. He will have to subordinate certain duties and actions and allow his workload to go up (and perhaps his performance to go down) but he can complete the flight safely. This is still a difficult situation for him and he will probably be thankful that he has an excellent rate type control system where the time-constant is less than one-half second or better still 0.2 or 0.3 seconds.

If the aircraft was initially certified for single-pilot IFR flight without an ATTITUDE-SCAS System (but with an ATTITUDE-HOLD, AUTOPILOT for workload relief), the "inherent damping" of the aircraft initially would have to be sufficient to provide the single-pilot with a rate type control system that had a time-constant shorter than a half-second. Also, if some reasonable failure could occur to this aircraft that would reduce the inherent damping (failure of a electronic or mechanical RATE-SAS system) and a FAILURE-MODE condition prevailed (first failure - continue to fly), the first-order time-constant would have to be shorter than 0.9 seconds according to these newly constructed boundaries. The condition would then be ONE-PILOT, FAILURE-MODE and the maximum allowable time-constant value would be 0.9 seconds. If the autopilot utilized its own actuators for the ATTITUDE-HOLD system, the pilot would still retain that valuable ATTITUDE FUNCTION and would probably attempt to continue to complete the flight without declaring an emergency. However, whenever he attempts to maneuver the aircraft he would be faced with what many would describe as barely a rate-type controller and bordering on acceleration-type. He would be required to increase his flight control workload level to assure good flight path guidance with this failed system but presumably could complete the flight safely but perhaps with some degradation in performance. This aircraft with this type of system would be carefully checked to see that it met the CONCAVE DOWNWARD requirements suggested as an IFR criterion in an earlier section of this Report.

Admittedly, the maximum time-constant of 0.5 seconds appears to be a very large increment in the requirement for the SINGLE-PILOT, NORMAL-MODE boundary (Figure 4-22). However, it should be noted that the first-order time-constant scale is non-linear when plotted in this way and tends to exaggerate the distances for incremental changes. For example, another SINGLE-PILOT, NORMAL-MODE boundary is shown for comparison (Figure 4-23) where the arc is drawn with a time-constant of 0.6 seconds (a worse system with less angular damping).

Use and interpretation of the boundaries shown in Figure 4-22 (and Figure 4-23) can be made for the TWO-PILOT cases in similar fashion to that described above for ONE-PILOT. The maximum first-order time-constants are somewhat less (0.9 and 1.2 seconds) and the damping ratios for the higher frequency regions are reduced (less stability).

Application of Minimum Damping Parameter to Boundaries

In the MIL. SPEC. for the Flying Qualities of Piloted V/STOL Aircraft, MIL-F-83300 (Reference 7), the short term longitudinal response requirements define minimum value boundaries for the damping parameter, $\zeta\omega_n$. These are specified for two levels of flying qualities (LEVEL 1 and LEVEL 2 in Reference 7) and appear as:

- LEVEL 1; $\zeta\omega_n = 0.5$ rad/sec
- LEVEL 2; $\zeta\omega_n = 0.25$ rad/sec.

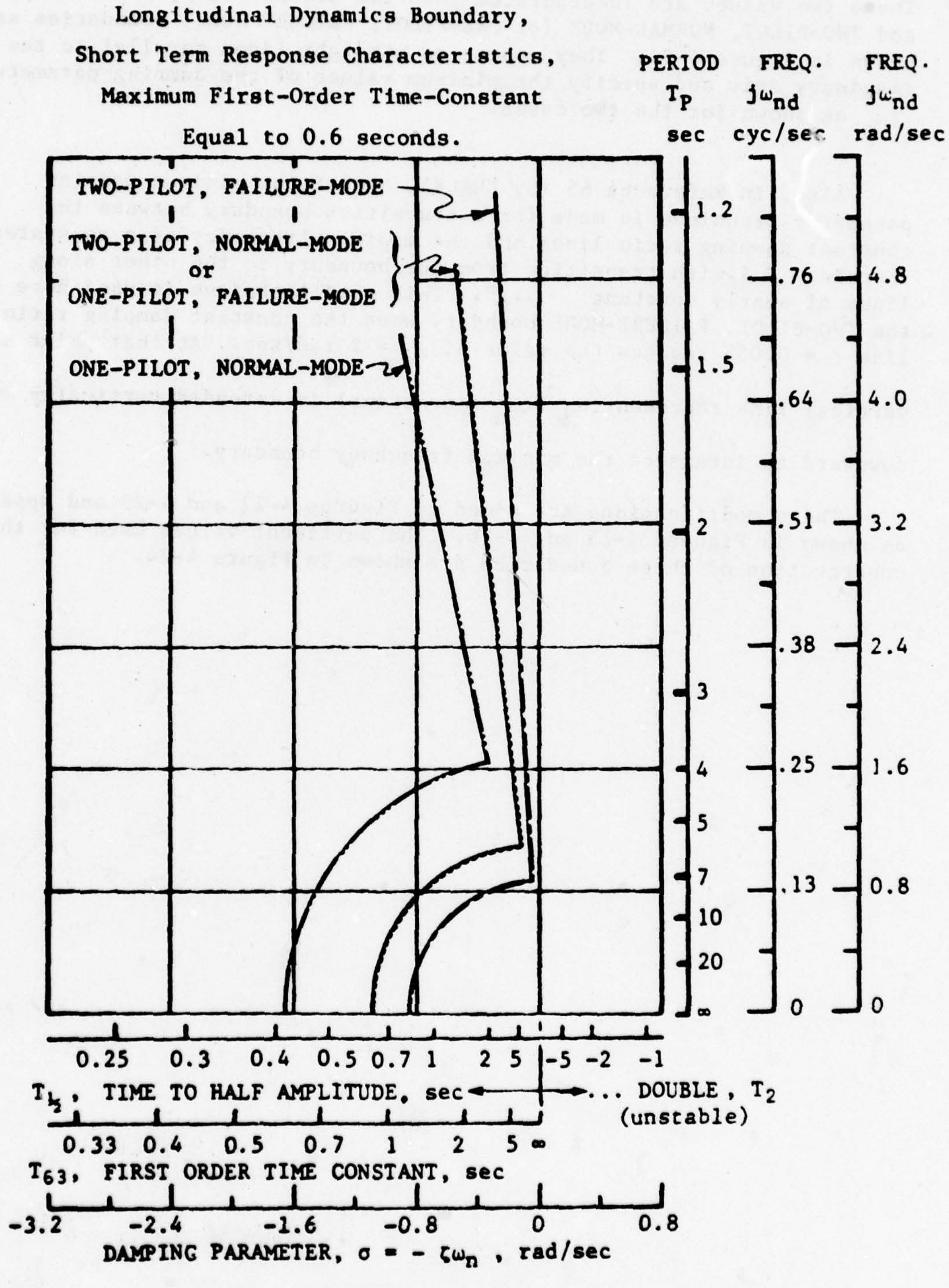

Longitudinal Dynamics Boundary, Short Term Response Characteristics, Maximum First-Order Time-Constant Equal to 0.6 seconds.

Figure 4-23. New Boundary for One-Pilot Normal-Mode IFR Operation, (Case II: $T_{63} = 0.6$ sec).

These two values are incorporated into the SINGLE-PILOT, NORMAL-MODE and TWO-PILOT, NORMAL-MODE (or ONE-PILOT, FAILURE MODE) boundaries as shown in Figure 4-24. They appear as straight lines parallel to the imaginary axis and specify the minimum values of the damping parameter $\zeta\omega_n$ as shown for the two cases.

Also, in Reference 65 (by CHALK), use of the minimum damping parameter technique is made for a transition boundary between the constant damping ratio lines and the minimum frequency arcs as stated therein: "...with transition from one boundary to the other along lines of nearly constant ...". This same technique is used here for the TWO-PILOT, FAILURE-MODE boundary when the constant damping ratio line $\zeta = 0.055$ reaches the value of $\omega_n = 2$ rad/sec. At that point a vertical line representing ($\zeta\omega_n =$ constant) is extended vertically downward to intersect the minimum frequency boundary.

These modifications are added to Figures 4-22 and 4-23 and appear as shown in Figures 4-25 and 4-26. The pertinent values used for the construction of these boundaries are shown in Figure 4-24.

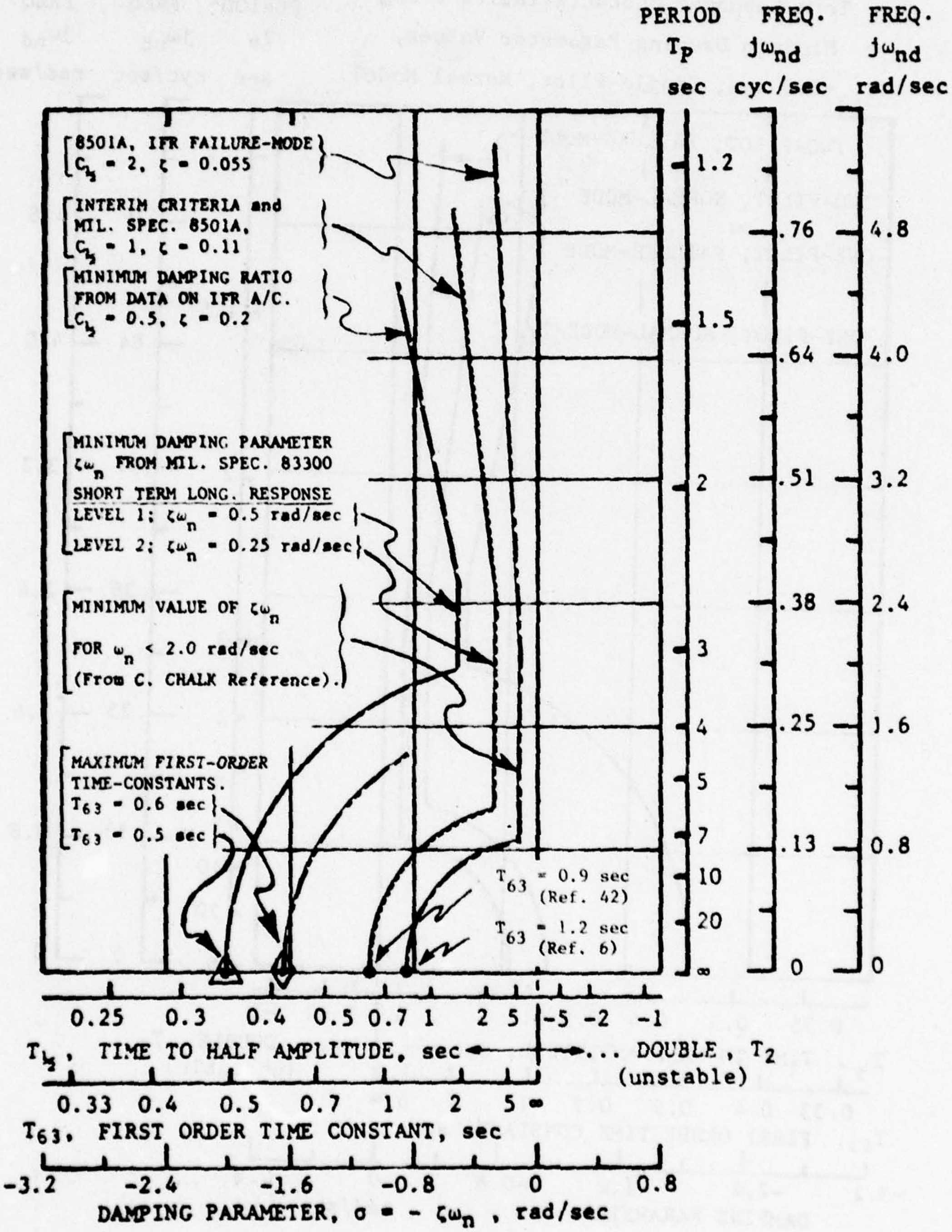
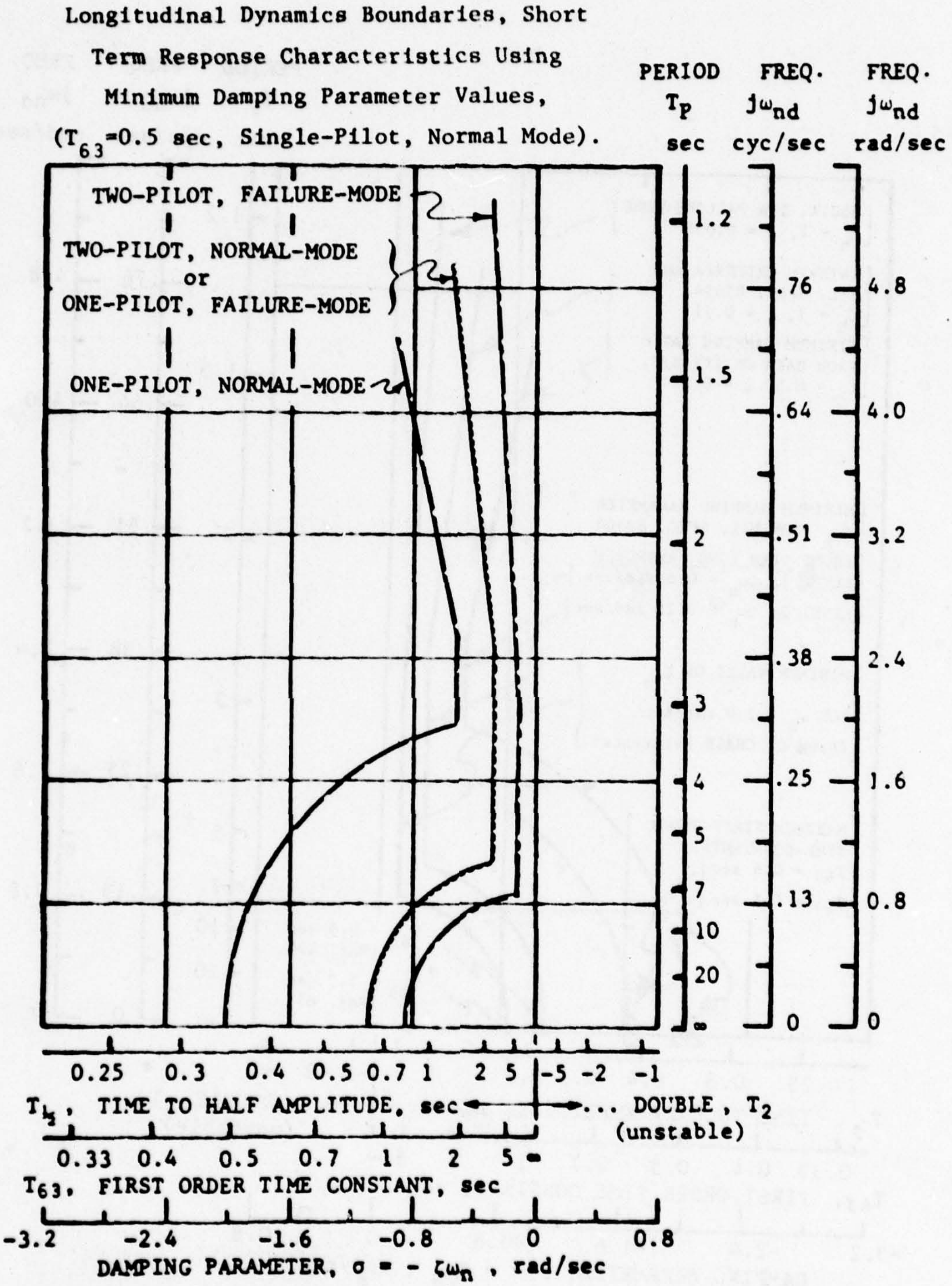


Figure 4-24. Definition of New Requirements Boundaries (References 4, 5, 6, 7, 42, and 65).



Longitudinal Dynamics Boundaries, Short Term Response Characteristics Using Minimum Damping Parameter Values, (T_{63}=0.5 sec, Single-Pilot, Normal Mode).

Figure 4-25. New Boundaries Using Minimum Damping Parameter Values, (Case I: T_{63} = 0.5 sec).

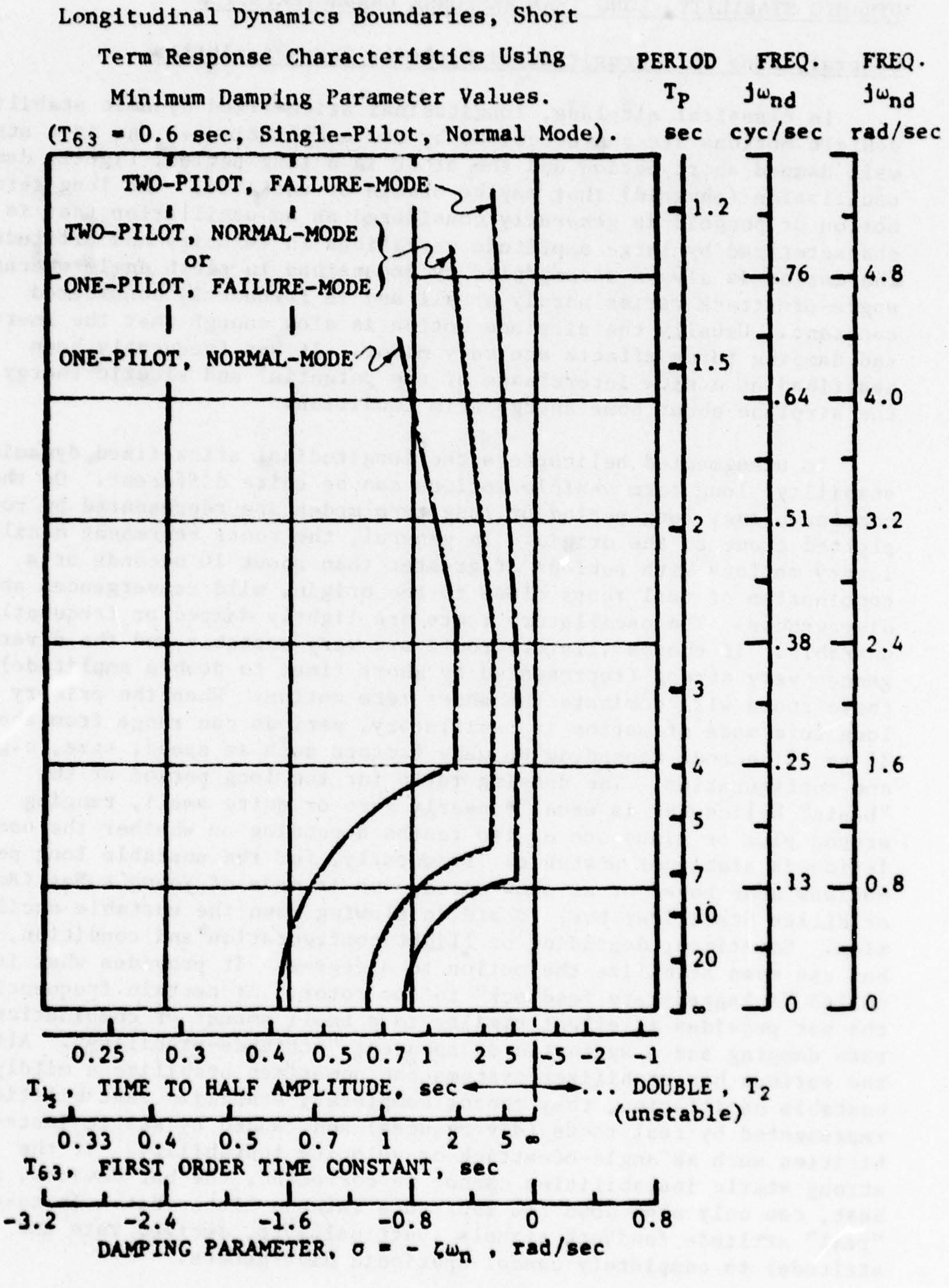


Figure 4-26. New Boundaries Using Minimum Damping Parameter Values. (Case II: T_{63} = 0.6 sec).

DYNAMIC STABILITY, LONG TERM RESPONSE CHARACTERISTICS

General, Long Term Longitudinal Dynamics Characteristics

In classical airplane, longitudinal stick-fixed dynamic stability, vehicle motions are characterized by two oscillations. One is a stable, well damped short period and the other is a long period, lightly damped oscillation (phugoid) that may be stable or unstable. The long term motion or phugoid is generally considered as an oscillation that is characterized by large amplitude variations in velocity and altitude. The motion is always accompanied by excursions in pitch angle whereas angle-of-attack varies hardly at all and is frequently considered constant. Usually the airplane motion is slow enough that the inertia and damping force effects are very minor. It has frequently been described as a slow interchange of the potential and kinetic energy of the airplane about some energy trim condition.

In unaugmented helicopters the longitudinal stick-fixed dynamic stability, long term vehicle motions can be quite different. On the complex plane, long period or long term modes are represented by roots plotted close to the origin. In general, the roots represent oscillatory motions with periods of greater than about 10 seconds or a combination of real roots close to the origin, mild convergences and/or divergences. The oscillatory roots are lightly damped or frequently unstable. If the oscillatory roots are very unstable and the divergences very strong (represented by short times to double amplitude), these roots will dominate the short term motion. When the primary long term mode of motion is oscillatory, periods can range from about 15 to 25 seconds depending on many factors such as speed, size, c.g., and configuration. The damping ratio for the long period of the "basic" helicopter is usually nearly zero or quite small, ranging around plus or minus one or two tenths depending on whether the oscillation is stable or unstable. Frequently, for the unstable long period motions near hover or at slow speed, use is made of Young's-bar (Bell or Hiller Stabilizer bar) to aid in slowing down the unstable oscillation. Sometimes, depending on flight configuration and condition, the bar can even stabilize the motion to a degree. It provides what is called "a lagged-rate feedback" to the rotor. At certain frequencies, the bar provides an effect similar to a small amount or combination of rate damping and a synthetic or apparent "attitude-stability". Although the various bar stabilizer systems can sometimes stabilize a mildly unstable oscillation, they cannot completely stabilize instabilities represented by real roots (divergences) and caused by static instabilities such as angle-of-attack or velocity instability. If the strong static instabilities cannot be corrected, the bar devices, at best, can only slow down the departure rates a little bit. It takes "real" attitude feedback signals (vertical gyro, derived rate and attitude) to completely cancel aperiodic divergences.

For artificially augmented helicopters, use is frequently made of "means" called Rate and Attitude Stability Augmentation Systems. On most recent single-pilot helicopter IFR certifications, Automatic Stabilization equipment is installed to provide workload relief for the pilot as well as total attitude stabilization of the aircraft through the use of autopilot systems. Both Attitude Stability Augmentation Systems and Attitude-Hold Autopilots utilize classic pitch rate and pitch angle feedback techniques and, given sufficient actuator authority along with the proper gains, can damp the short period motion quite heavily. Also, with sufficient authority, the phugoid may be adequately damped and suppressed with the attitude commands. Even unstable phugoids may be handled very well.

Generally, the use of rate and attitude feedbacks is a fundamental concept used to control the longitudinal dynamics of aircraft. However, if the feedback system of a helicopter is of the high gain type, then limited authority actuators (simplex, duplex, triplex systems in series) must be used in order to handle the control hardover problem. When these limited authority actuators saturate due to large inputs (e.g. during moderate to heavy turbulence), the aircraft response will revert to its "basic" stability and control. If the basic aircraft response is very unstable, then the modes of motion of the aircraft responses will tend toward these instabilities as the actuators tend to saturate. Under these circumstances (and depending on the relative values, limits, and characteristics of the influencing parameters and equipment), the pilot may begin to recognize the resulting irregular response behavior as a non-linear type of stability, control, and gust response characteristic.

Long Term Oscillation Boundaries, Interim Criteria and 8501A

The Interim Criteria address the long term motion area (close to the origin of the complex plane) under items 3 and 4 of paragraph (d), as:

"(3) Any oscillation having a period greater than 10 seconds but less than 20 seconds must be at least lightly damped.

(4) Any oscillation having a period of 20 seconds or more may not achieve double amplitude in less than 20 seconds."

The MIL. SPEC. 8501A addresses long term oscillations under two separate paragraphs. Using the reasoning put forth in an earlier section of this report labeled "Intent of IFR Paragraph 3.6.1 of the MIL. SPEC." both of these oscillation boundaries are construed as IFR boundaries, and for long term motions are labeled here and read as:

IFR Longitudinal Dynamic Oscillatory Boundaries, 8501A

- Normal-Mode (IFR long-period statements of paragraph 3.6.1.2).

"(c) Any oscillation having a period greater than 10 seconds but less than 20 seconds shall be at least lightly damped.

(d) Any oscillation having a period greater than 20 seconds shall not achieve double amplitude in less than 20 seconds."

- Failure-Mode (VFR long period statements of paragraph 3.2.11, including interpretation of paragraph 3.6.1 for IFR use).

"(c) Any oscillation having a period greater than 10 seconds but less than 20 seconds shall not achieve double amplitude in less than 10 seconds."

Regarding long term oscillation boundaries of 8501A, one item should be noted. Under 8501A, the IFR Failure-Mode oscillation boundary (also the oscillation boundary for Normal-Mode VFR flight) does not detail requirements for periods longer than 20 seconds for VFR flight, however, other paragraphs in Section 3 do impact on the long term behavior requirements.

Depiction of Long Term Dynamics Boundaries

The long term portion of the oscillation boundaries detailed by the Interim Criteria and the MIL. SPEC. 8501A are shown in Figure 4-27 and 4-28. The IFR Interim Criteria boundaries are identical to the IFR Normal Mode boundary of 8501A. The IFR Failure-Mode boundary of 8501A is also shown. The boundaries are labeled in accordance with the discussion offered earlier in this Report under "Definition, Interpretation and Labeling of Oscillation Boundaries".

When analyzing the boundaries that permit unstable longer term dynamics, a strict interpretation of the words of the Interim Criteria and their graphic presentations indicates that greater negative damping ratios (unstable) are allowed as period lengths increase past 10 seconds (for TWO-PILOT, FAILURE-MODE) and 20 seconds (for TWO-PILOT, NORMAL-MODE and ONE-PILOT, FAILURE-MODE). This occurs because the long term boundaries are drawn along lines of constant "Time to Double Amplitude". Since lines of constant "Cycles to Double Amplitude" (and lines of constant damping ratio) are represented by rays or straight lines radiating from the origin, then as period length increases the number of cycles to double amplitude decreases and damping ratio becomes more negative (Figure 4-28).

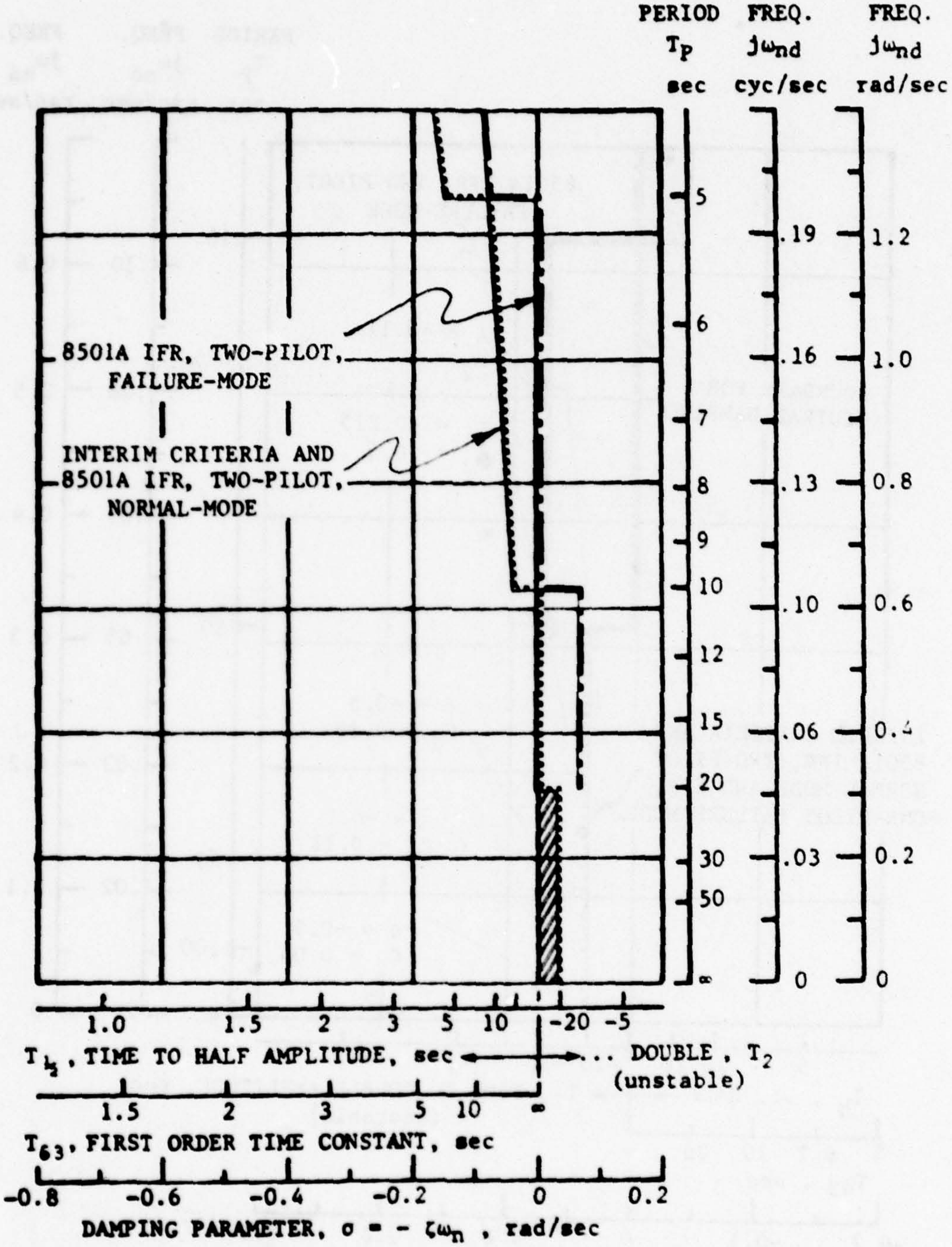


Figure 4-27. Plot of Interim Criteria and Requirements of 8501A for Long Term Response Region.

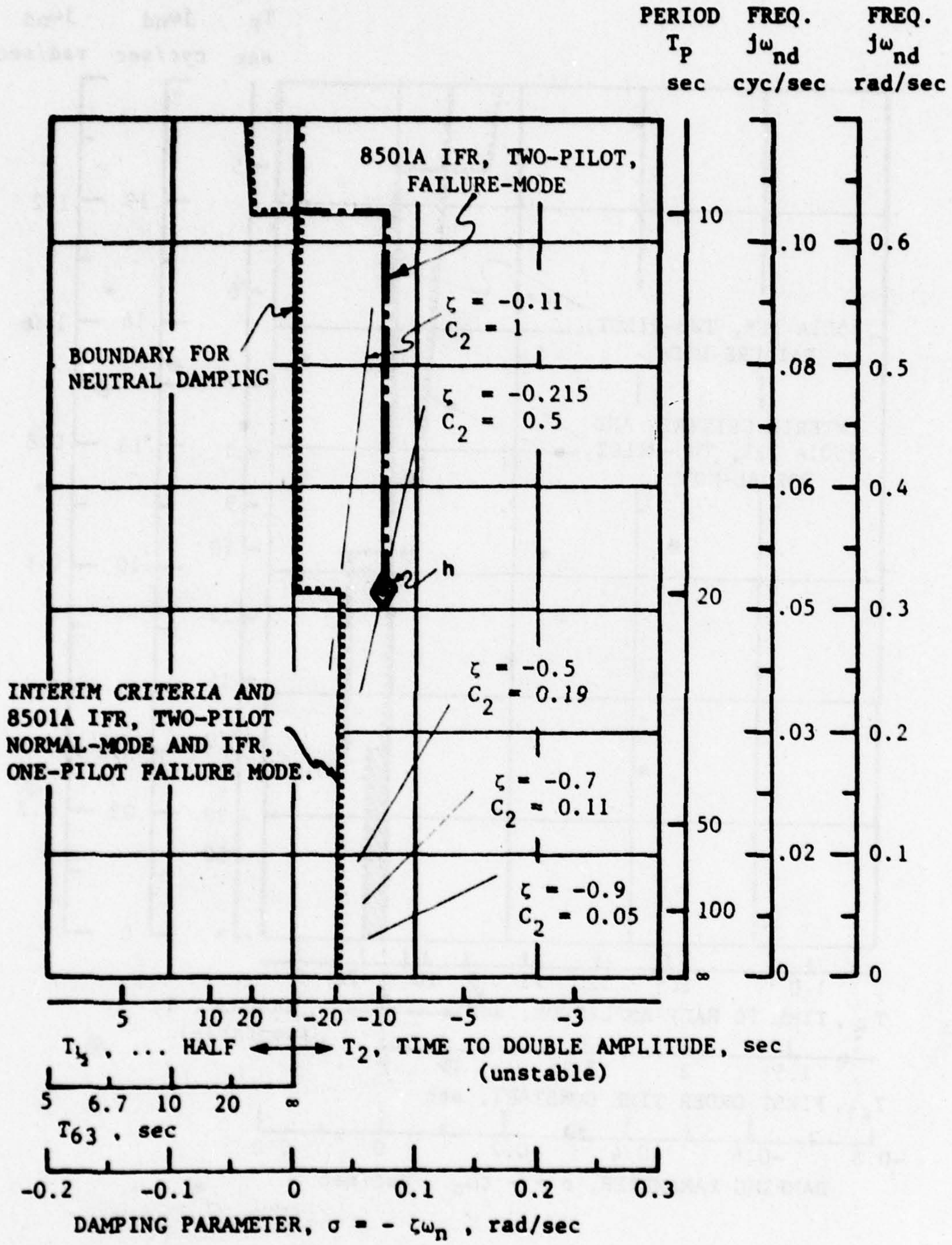


Figure 4-28. Comparison of Current Interim Criteria and MIL. SPEC. 8501A.

This is in contrast to the formulation of other shorter period boundaries of the Interim Criteria (paragraph d, items 1 and 2) and MIL. SPEC. 8501A (paragraph 3.2.11, items a and b) which define boundaries drawn along lines of constant number of Cycles to Half Amplitude (lines of constant damping ratio). Also, in Reference 3, the FAA "Interim Standards" for helicopter IFR certification are apparently excerpted from a document cited therein. The Dynamic Stability oscillation requirements are summarized there and the first three statements are essentially identical to that listed in this report but, the number (4) statement in Reference 3 reads:

> "Oscillations with a period of more than twenty seconds shall not double amplitude in less than one cycle."

If this interpretation is applied in place of the boundaries constructed along lines of Constant Time to Double Amplitude, the boundaries are drawn along lines of constant Cycles to Double Amplitude and would appear as shown in Figure 4-29. In that Figure, the boundary is constructed along a line where Cycles to Double Amplitude equal one (C_2=1) as stated for the FAA "Interim Standards" excerpted for Reference 3. One effect of drawing the boundaries for this region in this way is that it tends to limit those long period unstable oscillations where the damping ratios are becoming more and more negative (greater apparent instability).

The Flying Qualities Specification, MIL-F-83300, for V/STOL aircraft (Reference 7) also establishes oscillation boundaries, in this unstable region, along a line of constant cycles to double amplitude (constant damping ratio) instead of along a line of constant time to double amplitude.

Discussion of General Long Term Dynamics Boundaries

A review of the different closure paths or boundary possibilities near the origin is offered by the following discussion. The discussion centers primarily on the unstable area of the complex plane where unstable periods that are 20 seconds or longer are controlled by an Interim Criteria Boundary (Item 4 of Paragraph d). This unstable area (shown cross-hatched on Figure 4-27) is closed by a boundary that follows a path where, as period length increases, time to double amplitude is held constant (T_2 = 20 seconds). A general review of the actual character of the time histories of the modes of motion that exist or represent this area is helpful in understanding this discussion. The cross-hatched area is enclosed by lines that represent paths where Time to Double Amplitude are constant, Cycles to Double Amplitude are constant, Oscillations are Neutrally Damped, and Period is Constant. The path where Time to Double Amplitude is constant is described and detailed in the Interim Criteria. The path where Cycles to Double

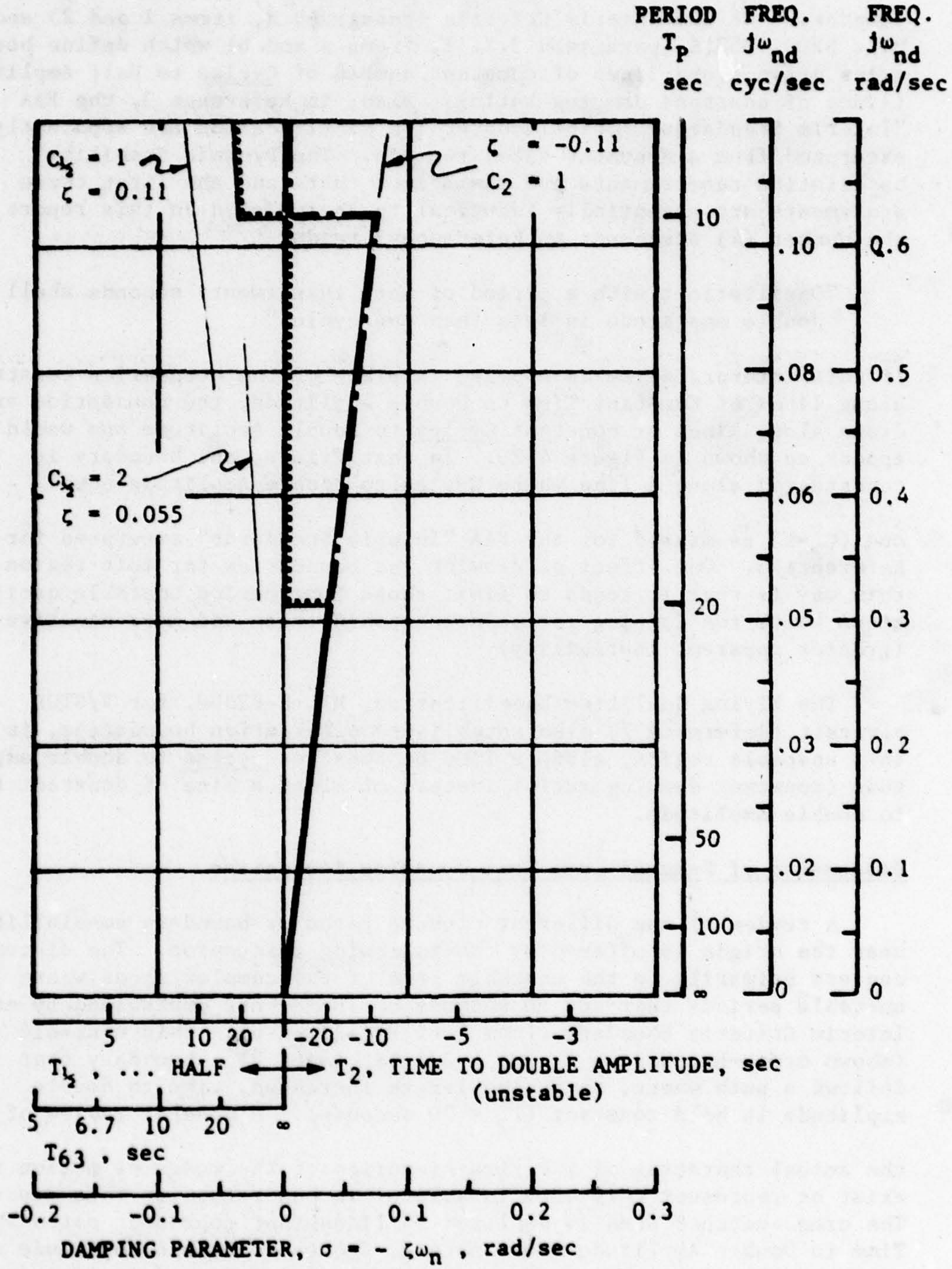


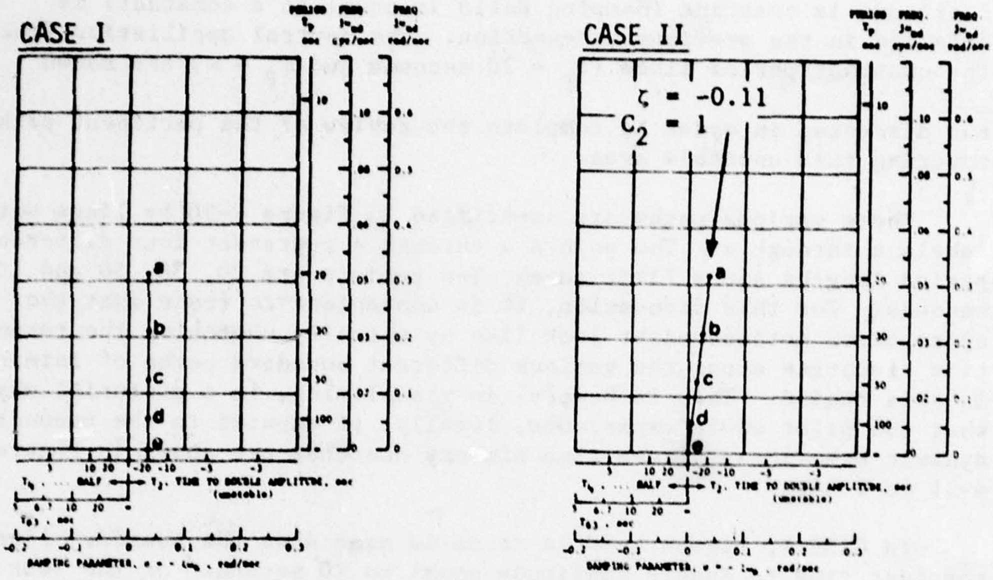
Figure 4-29. Closure of Long Term Boundaries Along Path of Constant Damping Ratio.

Amplitude is constant (Damping Ratio is equal to a constant) is detailed in the previous sub-section. The neutral oscillation line and the constant period lines ($T_P = 20$ seconds and $T_P \to \infty$) are shown and discussed in order to complete the review of the pertinent paths covering this unstable area.

These various paths are identified in Figure 4-30 by lines with labels a through e. The points a through e represent four different period lengths and a limit case. The periods are 20, 30, 50 and 100 seconds. For this discussion, it is convenient to trace what the approximate motions might look like by actually sketching the response time histories along the various different boundary paths of interest in this region. This is helpful in visualizing, in a pictorial way, what the pilot would experience, ideally, if exposed to the respective dynamic behaviors. These time history sketches are shown in Figures 4-31 to 4-34.

In CASE I, Figure 4-30, a trace is made down the boundary line for constant time to double amplitude equal to 20 seconds for the four example period lengths. These time histories are sketched in Figure 4-31. The envelope is constant with a time to double amplitude equal to 20 seconds. An initial upset of five degrees nose-up pitch attitude is considered and the resulting oscillations for the various periodicities is shown. If the oscillations are unstable, (and allowed to persist), the pilot always wants to know if there will be a "free return" or "incipient peaking" of the unstable response, how soon will it occur and what will be the maximum pitch attitude achieved at the first peak. This can be visualized by drawing just the first peaks of the previous responses (for the case where $\omega_n t$ equals π equals 180 degrees, the first peak). These "first peaks" for the above example cases are shown in the lower sketch of Figure 4-31. As expected, as period length increases, the oscillation amplitude shown by the first peak increases and becomes a divergence or aperiodic response (when period time approaches infinity -- the real axis) denoted by the envelope for $T_2 = 20$ seconds.

A second case is selected and defined as CASE II in Figure 4-30, where a trace is made down a boundary line for the long period region where "Cycles to Double Amplitude" are a constant and equal to one (constant damping ratio equal to -0.11). This case was discussed earlier in this Section under Depiction of Long Term Dynamics Boundaries. It is also referenced there as a stated FAA boundary for the "Interim Standards" as excerpted for the study cited in Reference 3. For periods greater than 20 seconds the boundary would appear as shown in Figure 4-29. The time histories along that boundary are sketched in Figure 4-32. The envelope of the oscillation now changes depending on the

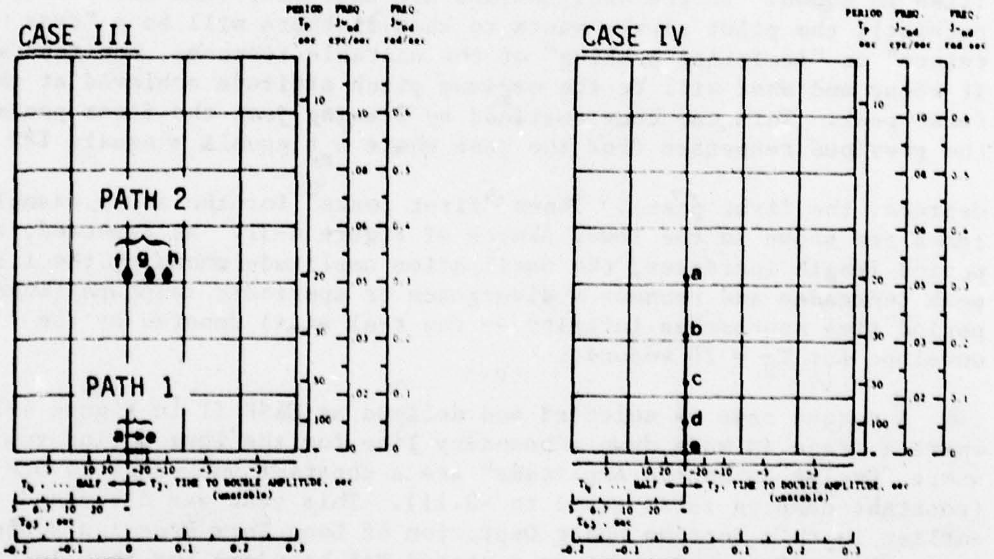


T_2 = Constant

T_P Varies

ζ & C_2 = Constant

T_P & T_2 Vary



PATH 1: Divergences

PATH 2: T_P = Constant

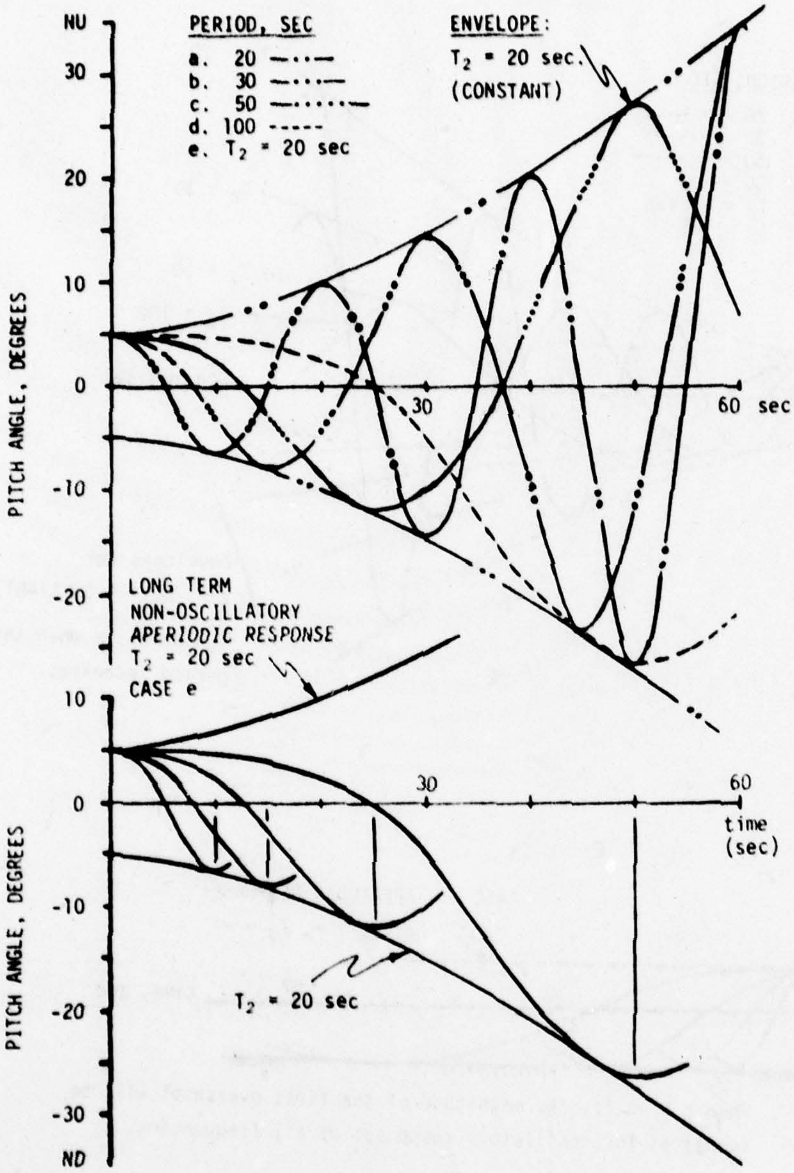
T_2 Varies

ζ = 0

Neutral Oscillation

T_P Varies

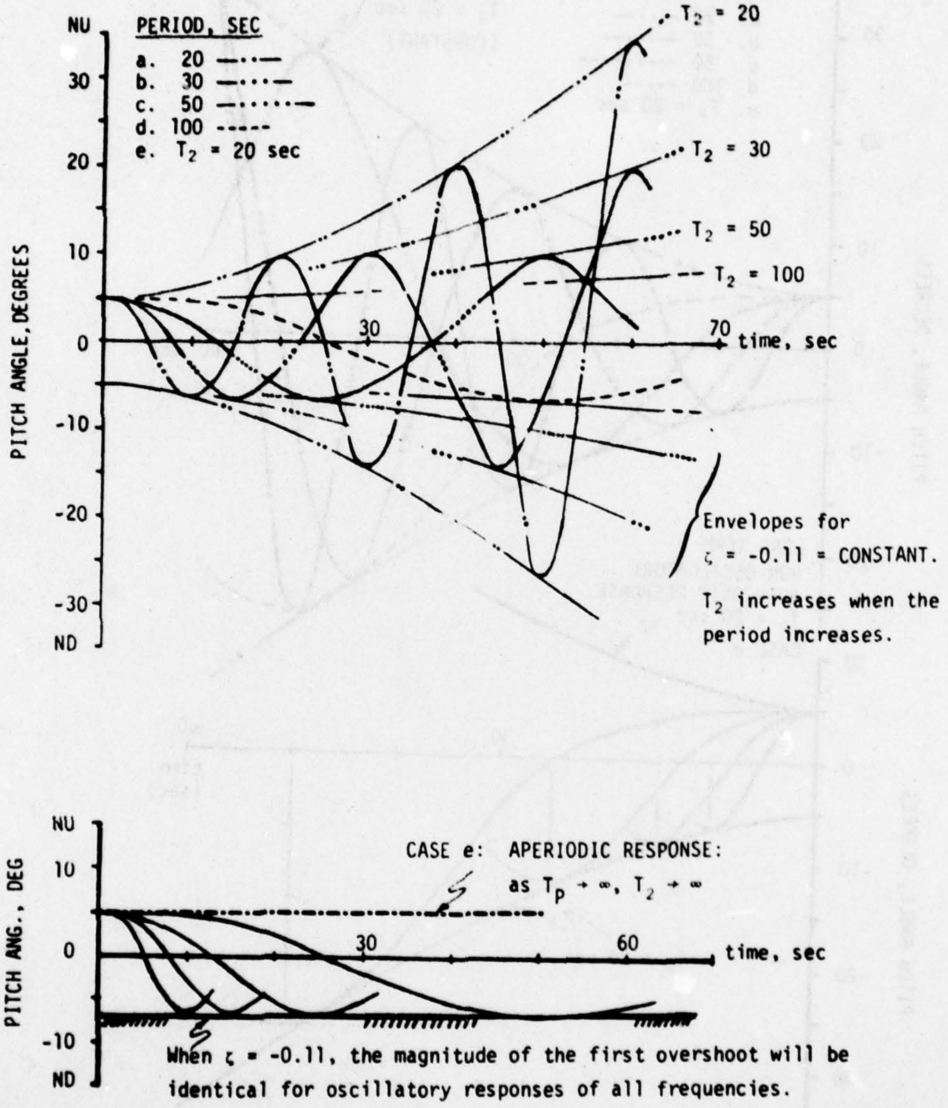
Figure 4-30. Long Term Motion Time-History Paths.



CASE I

Figure 4-31. Typical Time Histories with Time to Double Amplitude Constant.

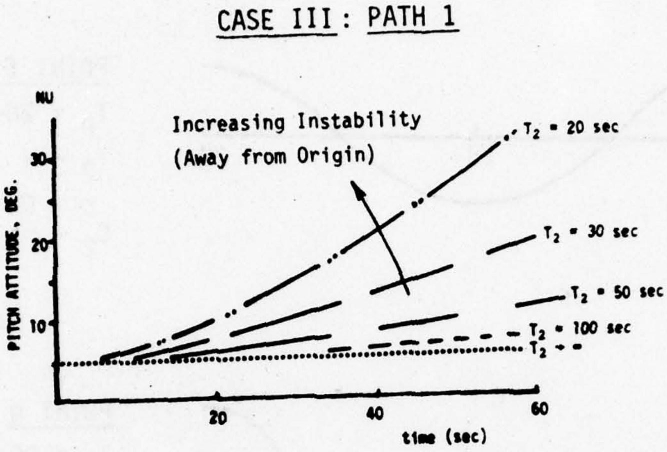
CASE II



Envelopes for $\zeta = -0.11$ = CONSTANT. T_2 increases when the period increases.

When $\zeta = -0.11$, the magnitude of the first overshoot will be identical for oscillatory responses of all frequencies.

Figure 4-32. Typical Time Histories with Damping Ratio Held Constant.


CASE III : PATH 1

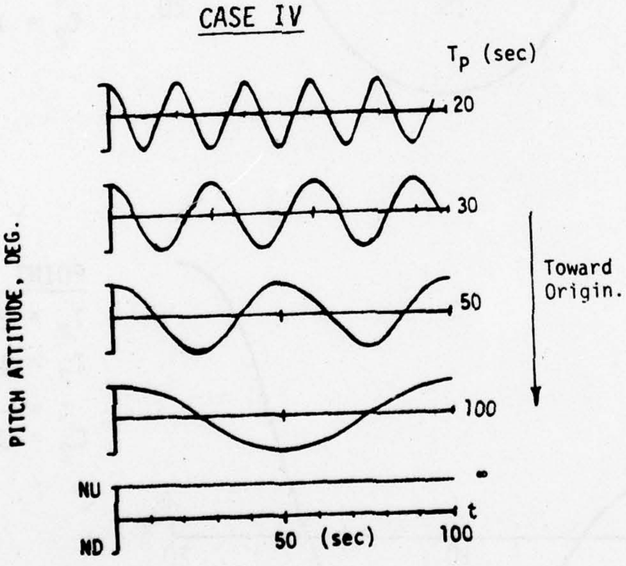

CASE IV

Figure 4-33. Typical Time Histories for Divergences and Neutral Oscillations.

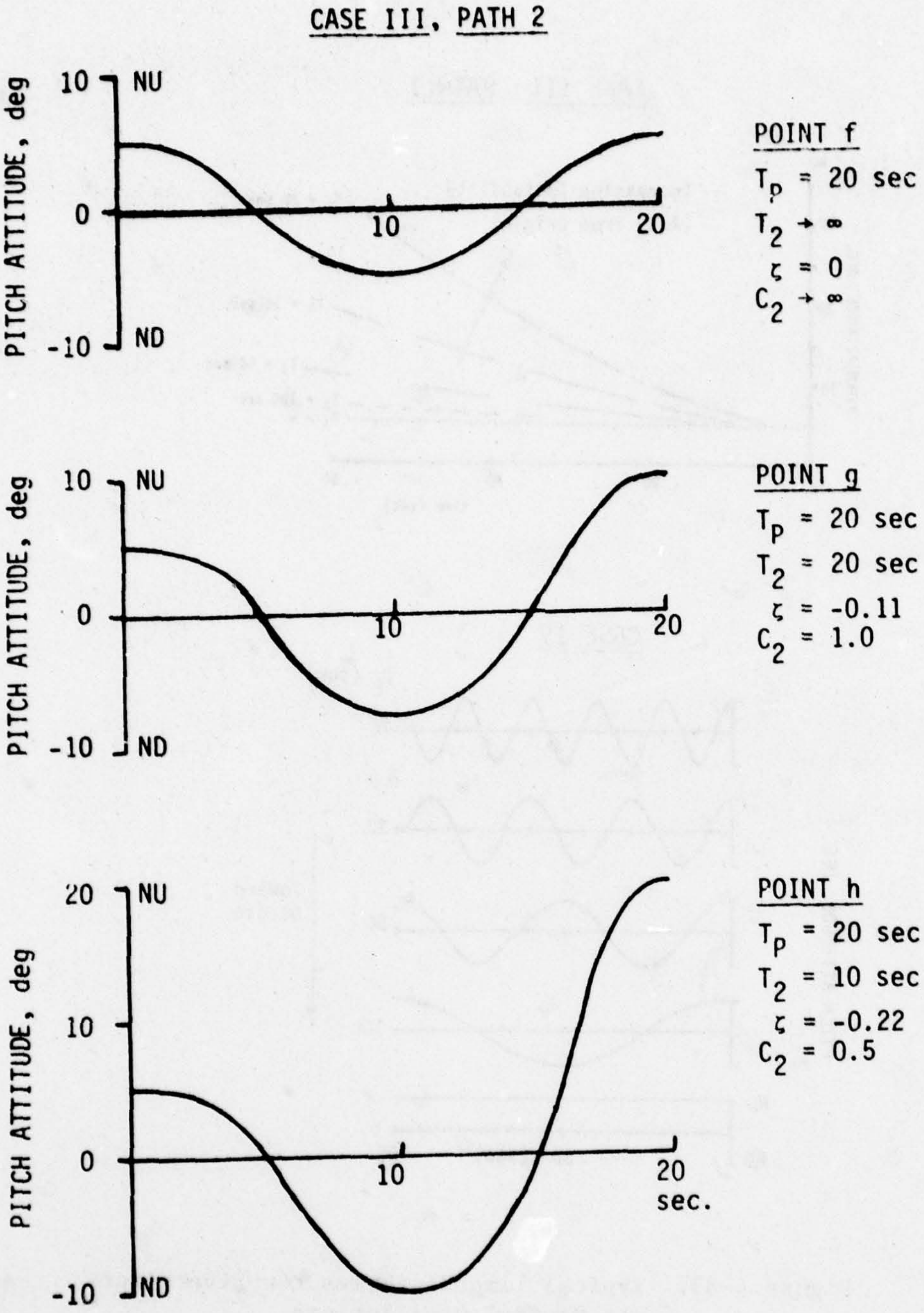


Figure 4-34. Sketch of Time History for 20 Second Period for Decreasing Time to Double Amplitude.

period length. As the period lengthens, the value of the damping parameter ($\zeta\omega_n$) is changing and the value of T_2 increases (less instability). The same analysis of the "free-return" or incipient peaking characteristics can be made as before and is shown in the lower sketch of Figure 4-32. It should be noted that the first peaks for the different period lengths are limited to a constant amplitude. This can be seen from the expression below where $\zeta = \text{constant}$ and $\omega_n t = \pi = 180$ for the first peak:

$$\Delta\theta = f(\omega_n t) = e^{\zeta\omega_n t} \cos \omega_n t$$

$$\Delta\theta = f(\pi) = e^{\zeta\pi} \cos \pi$$

$$\Delta\theta = -e^{\zeta\pi} = \text{Constant}$$

The interesting observation by the pilot is that he will always see the same amplitude at "peaking" regardless of period length. However, as period time lengthens (moving toward the origin), time to "first peak" or amplitude reversal increases.

A third case is selected and defined as CASE III, PATH 1 in Figure 4-30, where a trace is made from the origin out the positive real axis to lesser times to double amplitude (Increasing instability moving to the right on the real axis and outward from the origin to a value where $T_2 = 20$ seconds). Points along the real axis represent non-oscillatory responses. The oscillation boundary apparently does not apply and the limit value of 20 seconds is arbitrarily chosen here. The aperiodic modes are commonly called DIVERGENCES and represent that class of motions where no "free-return" or peaking of the response occurs. They are defined by exponential departures or growths and are shown in the upper sketch of Figure 4-33.

A fourth case is selected and defined as CASE IV in Figure 4-30 where a trace is made along the imaginary axes, the boundary line between stability and instability where only neutral oscillations occur, (no damping). The roots travel from a point representing a neutral osciliatory period of 20 seconds and move toward locations representing increasing period length until the roots coalesce at the origin, Period approaches infinity. A representation of these neutral oscillations is shown in the lower sketch of Figure 4-33.

A special case is selected and defined as Case III Path 2 in Figure 4-30. This path closes the top of the unstable area where a trace is made horizontally along the path for a 20 second period. The time to double amplitude is decreasing (greater instability). Points f and g mark the top of the IFR, TWO-PILOT, NORMAL-MODE and IFR ONE-PILOT, FAILURE-MODE unstable area. Point h (figure 4-28) marks the tip of the lower boundary for the IFR, TWO-PILOT, FAILURE-MODE boundary where the period is equal to 20 seconds and the time to double amplitude equals 10 seconds ($C_2 = 0.5$, $\zeta = -0.215$). Compliance with this IFR, TWO-PILOT, FAILURE-MODE boundary (8501A) permits an oscillation, with a period of almost 20 seconds, to be sufficiently unstable that it will double amplitude in one-half of a cycle.

Depiction of New Long Term Mode of Motion Boundaries

A study of the previous figures and the responses associated with the various boundaries suggests that the long period, lower frequency boundary of the Interim Criteria be considered as a boundary along a line of constant damping ratio, rather than a boundary based on Time to Double Amplitude. Utilizing boundaries equivalent to lines of Time to Double Amplitude permits oscillatory responses to become quite confusing or deceptive to the pilot in that it may be difficult for him to detect what the incipient character of the unstable response will be like. Similarly, the pilot cannot tell what the developed response will look like by viewing the character of the incipient departure. For example, consider an unstable oscillation like the one shown in the lower sketch of Figure 4-31 where the period length is representative of roots close to the origin. Using the curve shown in the Figure, where the period length is 100 seconds, an interesting observation can be made. This curve starts out with an initial upset of five degrees of nose up, pitch-angle. The response indicates that for the next 25 seconds the nose moves down (in a somewhat gradual manner) to a level pitch attitude and passing through. At this point, the pilot may have very little cue of the coming behavior of this long period, unstable motion. Should he choose to let it continue, he may be surprised by the response that occurs in the following few seconds after the nose passes downward through level flight. In the next five seconds it picks up about a five degree nose down attitude. Within about the next three seconds, it doubles amplitude (ten degrees nose down attitude) and is on its way to rapidly increasing to almost 30 degrees nose down attitude before peaking. Note that if the pilot cannot determine where the aircraft is settling, he cannot trim it (i.e., he is unable to reduce the residual to zero, especially in conjunction with light upsets). Closing the Interim Criteria boundary (for this region) along a line of constant damping ratio (though still permitting unstable oscillations) would restrict this type of unstable dynamic behavior. If this were done for the 8501A VFR boundary and the

Interim Criteria as well, the curves could appear as shown in Figures 4-29 and 4-35. The boundaries depicted in Figure 4-29 allow less instabilities in that they prevent all long term unstable oscillations from doubling amplitude in less than one cycle. The boundaries depicted in Figure 4-35 are a little more lenient and allow greater long term instabilities.

The TWO-PILOT, FAILURE-MODE boundary allows an unstable oscillation (with periods greater than 20 seconds) to double amplitude in less than one-half of a cycle. The boundary proposed for TWO-PILOT, NORMAL-MODE (and ONE-PILOT, FAILURE-MODE) would be less tolerant of long term oscillatory instabilities and require that an unstable oscillation must not double amplitude in less than one cycle (Figure 4-35 and Figure 4-29). On Figure 4-35 the boundaries are drawn along two different values of Cycles to Double Amplitude whereas on Figure 4-29 the boundaries are drawn along the same line or value of Cycles to Double Amplitude and a common boundary (for the two cases) exists for periods longer than 20 seconds.

Importance of Long Term Dynamics to Single-Pilot Certifications

It has been judged that the long period mode for airplanes does not have a strong impact on flying qualities if the phugoid dynamics are not too unruly, Reference 70. The period is usually long enough so that, if it is lightly damped or even slightly unstable, the pilot can easily control it by staying in the loop part of the time and providing control inputs. For tightly controlled precision flight (either IFR or VFR), this presents very little problem since the pilot will probably be making control inputs as frequently as one input every second or two. The full phugoid motion will never have a chance to develop and will probably not even be perceived by the pilot. However, for instrument flight in the cruise condition and especially for single-pilot manning levels, the pilot may find an unsatisfactory phugoid a fatiguing nuisance if he has to continually stay in the loop during long enroute flight times just to "catch" the phugoid motion periodically and prevent large aircraft upsets. His ability to relax and prepare for a difficult ILS approach is impaired and the ability to perform auxiliary tasks is compromised. That is, the pilot workload will tend to be too high for single-pilot IFR flight. He would much prefer an aircraft that is easy to trim and has a well behaved mode of motion so that the aircraft tends to stay on-course, on-altitude, and on-speed if there are no appreciable external disturbances.

In airplanes the classic phugoid motion is always depicted as a strictly longitudinal degree of freedom motion. The airplane is presumed to be highly symmetric. When it is disturbed, it is assumed that there are no significant power effects or cross coupling into other axes etc. and the motion that ensues is the ideal slow interchange of potential and kinetic energy (about a trim point) in the longitudinal degree of freedom only.

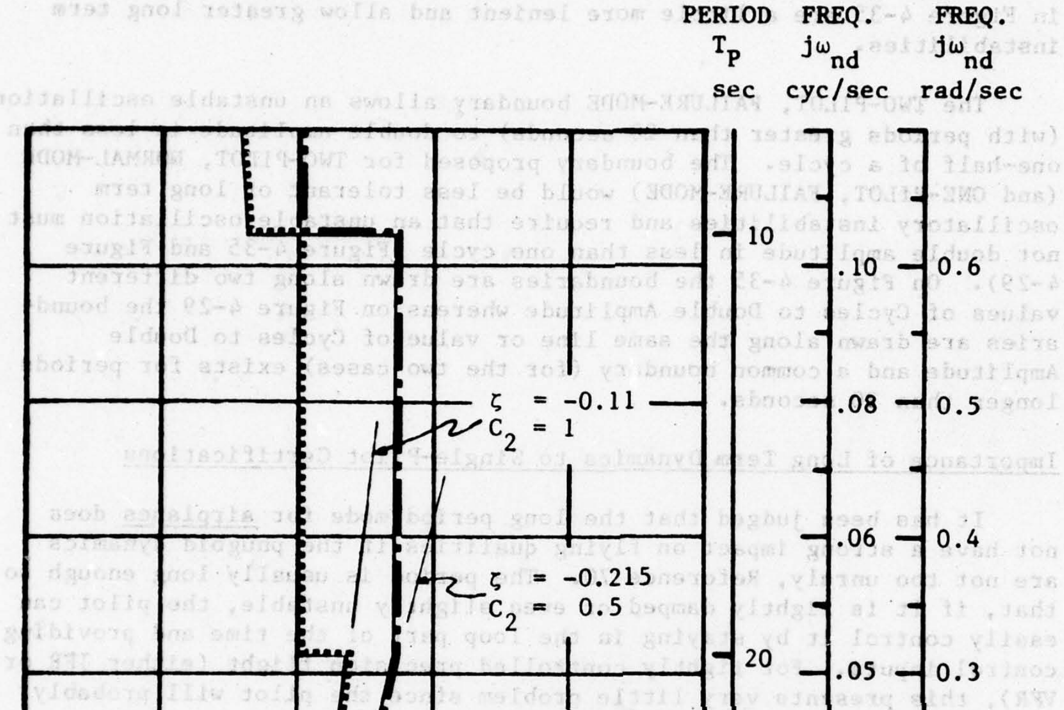


Figure 4-35. Alternate Closure of Long Term Boundaries Along Paths of Constant Damping Ratio.

For helicopters the situation is quite different. With a basic helicopter none of these conditions typically prevail without significant augmentation. The basic helicopter is highly non-symmetric, usually powerfully coupled, very trim sensitive about all axes to speed changes, and has a relatively higher equivalent drag (a "dirtier" machine) than an airplane. It may be much more difficult to trim accurately and may also have a very shallow pitch attitude gradient versus trim speed characteristic making it difficult to trim easily and quickly. If it is disturbed from trim and knocked off speed, it will probably yaw, roll, and descend over the long term. If allowed to continue, the roll angle may increase to large values just because it is off of the trim airspeed. The helicopter may make extreme attitude departures and continue to lose altitude with no attendant recovery due to the classical phugoid. The phugoid motion probably will not take place as an "ideal" longitudinal degree of freedom motion display but will show an unfamiliar "wallow" or roll off to high speed. This is not too surprising since in many cases, even tight control of pitch and roll attitude, as obtained from an ATTITUDE-HOLD, AUTOPILOT, will not guarantee that a particular helicopter will stay on heading, altitude and airspeed very well. Additional feedback loop closures using heading, altitude, and airspeed information are typically required for acceptable automatic tracking control (in order to achieve accurate, coupled flight path guidance).

It would appear that, for the single-pilot IFR certification of helicopters, the phugoid or long term motion of the helicopter takes on greater significance and importance compared to other aircraft and flight conditions. The subject of single piloted IFR helicopters is a relatively new area and it is difficult to find any directly applicable criteria stated anywhere on the acceptable long term dynamics required for a level of safety. Given that the single pilot must perform auxiliary tasks as well as fly the helicopter, the need for a fairly well-behaved phugoid or general long term motion about the pitch and roll axes should be apparent. This is especially true for those cases where the enroute portion of the IFR flight is one that requires heavy participation in auxiliary tasks. The single pilot will require that the helicopter "fly itself" for short intervals so he may take his hands from the controls in order to accomplish the auxiliary tasks necessary for the orderly, professional, and safe conduct of the flight. If the flight is being conducted at low altitudes, then the proximity of the earth and the unusual attitude, accidental upset, or unattended roll-off take on even greater significance.

From the above discussion, it would appear that for single-pilot IFR flight in helicopters, the long term motion should be good enough to provide the pilot with, at least, short intervals of relief from hands-on control in order to accomplish auxiliary tasks. This would seem to rule out any unstable modes for the longer term dynamical motions of the helicopter. If single or multiple axis ATTITUDE SAS, ATTITUDE SCAS and/or ATTITUDE-HOLD AUTOPILOTS provide this capability satisfactorily, then the long term motion will probably be sufficiently suppressed or stabilized and the requirement will be met.

Also, if the basic helicopter displays good inherent stability characteristics so as to provide the pilot with adequate long term dynamical characteristics that allow him to get out of the flight control loop for the intervals needed for auxiliary tasks, then the requirement will be met.

Since no present single-pilot dynamical boundaries exist in the current Interim Criteria and no requirements are specifically detailed for single-pilot IFR helicopter operations, it would appear that additional studies and research are needed to determine the minimum requirements in this area. Also, if the necessary long term dynamics and handling qualities are obtained without artificial augmentation and automatic stability systems, it must be carefully determined that they are not obtained at the expense of the short term dynamics.

Although there is insufficient information available in usable form now for constructing a ONE-PILOT, NORMAL-MODE long term dynamics boundary, a candidate requirement based on the comparison with previous long term boundaries and the discussion above is offered in Figure 4-36. The boundary is conjectural and draws on the previous remarks made above, i.e., that probably no instability should be allowed for the longer term motions, As the long term frequency increases, the ONE-PILOT, NORMAL MODE boundary is "stepped" similar to the other two boundaries, i.e., increased damping (along lines of constant damping ratio) is required as a function of the period of the long term motion.

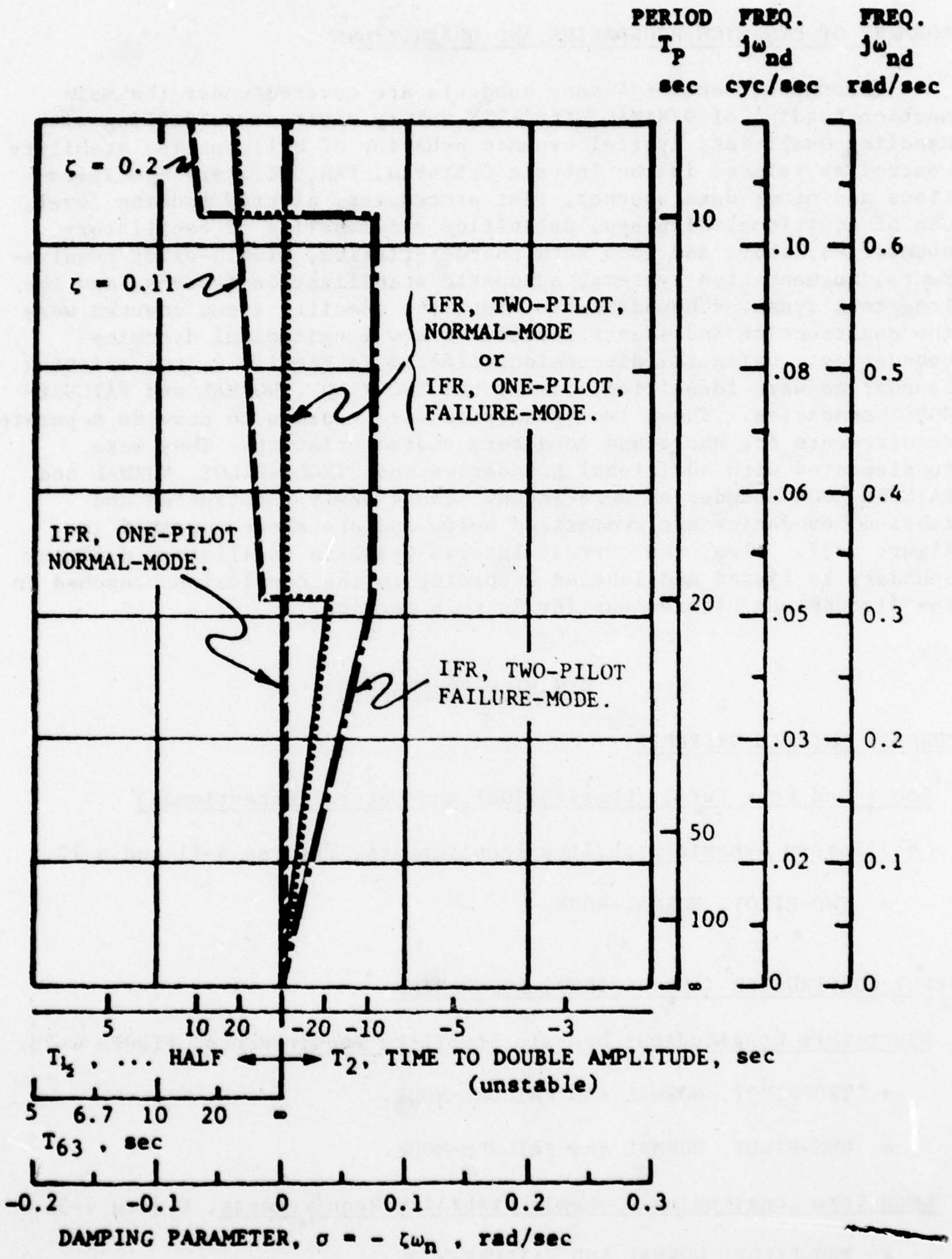


Figure 4-36. Depiction of a Single-Pilot, Normal-Mode Long Term Boundary.

SUMMARY OF DYNAMICS BOUNDARIES AND DEFINITIONS

Throughout Section 4 many subjects are covered under the main section heading of DYNAMIC STABILITY. They cover areas dealing with Handling Qualities, typical dynamic behavior of helicopters, stability control as related in the Interim Criteria, FAR, Military Specifications and other data sources, test procedures, aircrew manning level, use of additional displays, definition and labeling of oscillatory boundaries, short and long term characteristics, single-pilot requirements, augmentation systems, automatic stabilization systems, and the long term dynamics boundaries. Among the specific items covered were the construction and identification of new longitudinal dynamics boundaries. Using the discussions offered in Section 4, two existing boundaries were identified, namely the TWO-PILOT, NORMAL and FAILURE-MODE boundaries. These two boundaries were redrawn to provide separate requirements for short and long term characteristics. They were supplemented with additional boundaries and SINGLE-PILOT, NORMAL and FAILURE MODE boundaries were added. These newly constructed and labeled boundaries are summarized below and are shown together in Figure 4-37. Also, the current Interim Criteria oscillatory dynamics boundary is listed and labeled according to the conclusions reached in the discussions offered earlier in this section.

DYNAMICS BOUNDARIES

CURRENT INTERIM CRITERIA

Short and Long Term, (Longitudinal and Lateral/Directional)

Oscillatory Dynamic Stability Requirements, Figures 4-11 and 4-12.

- TWO-PILOT, NORMAL-MODE.

NEWLY CONSTRUCTED (AND DEFINED) BOUNDARIES

Short Term Longitudinal Dynamic Stability Requirements, Figure 4-25.

- TWO-PILOT, NORMAL AND FAILURE-MODE.
- ONE-PILOT, NORMAL and FAILURE-MODE.

Long Term Longitudinal Dynamic Stability Requirements, Figure 4-36.

- TWO-PILOT, NORMAL AND FAILURE-MODE.
- ONE-PILOT, NORMAL AND FAILURE-MODE.

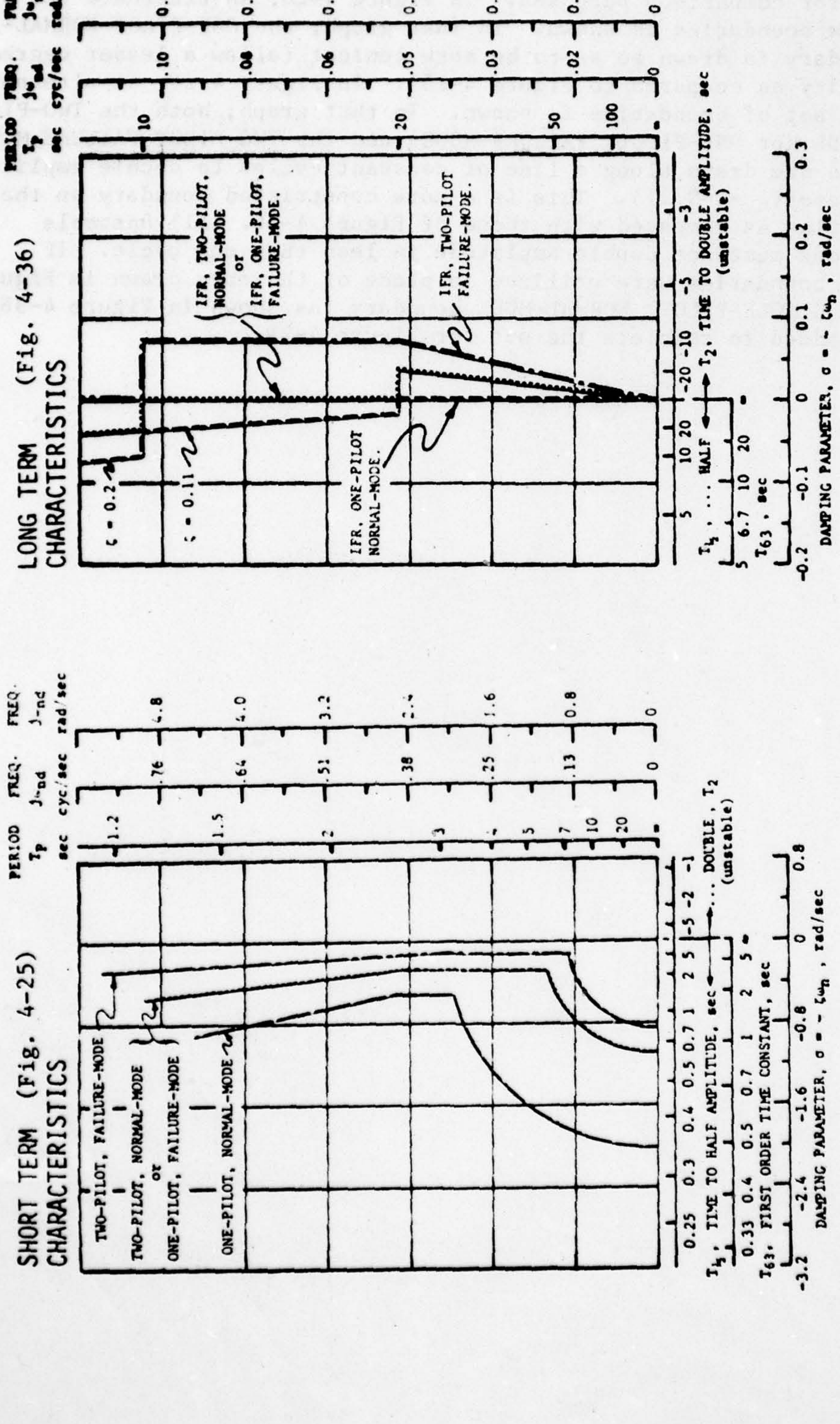


Figure 4-37. New Boundaries for Longitudinal Dynamics.

In the discussions on short and long term characteristics offered in earlier sub-sections, two additional sets of boundaries were constructed for comparison purposes. In Figure 4-26, an alternate set of short term boundaries is shown. In that graph, the ONE-PILOT NORMAL-MODE boundary is drawn so as to be more lenient (allow a lesser degree of stability as compared to Figure 4-25). In Figure 4-29, an alternate long term set of boundaries is shown. In that graph, both the TWO-PILOT, NORMAL-MODE (or ONE-PILOT, FAILURE-MODE) and the TWO-PILOT FAILURE-MODE boundaries are drawn along a line of constant cycles to double amplitude equal to one ($\zeta = -0.11$). This is a more constricted boundary on the instabilities as compared with those of Figure 4-36. All unstable oscillations must not double amplitude in less than one cycle. If these two boundaries were utilized in place of the ones drawn in Figure 4-36, the SINGLE-PILOT, NORMAL-MODE boundary (as shown in Figure 4-36) would be added to complete the set for Figure 4-29.

ADDITIONAL COMMENTS

Lateral/Directional Dynamics, General

Although the Lateral/Directional Dynamics are addressed in common with the Longitudinal Dynamics in the Interim Criteria and only partially covered in some parts of this section, a few additional comments are offered. The Interim Criteria also cover the Lateral/Directional case with the blanket criteria which covers both long and short term responses. However, several specific points were noted for lateral/directional dynamics while addressing the longitudinal dynamics. For example, Tapscott's and Reeder's work at NASA Langley with the variable stability helicopter also suggest minimum damping values in roll and yaw for IFR approaches (References 11 and 42). The minimum dampings for instrument flight for roll and yaw are specified as damping to inertia ratio values equal to about -2.5 per sec, (time-constants equal to 0.4 seconds or shorter). Also, according to some limited response data on an IFR certified helicopter, attitude type augmentation raises the frequency of the response of the helicopter to regions where periods are shorter than 5 seconds (depending on flight condition and c.g.) with the shortest periods seen on the order of less than two seconds. With SAS OFF the periods lengthen somewhat and the damping ratio is difficult to estimate accurately from the traces that were available.

Some yaw time history data was available for an IFR certified configuration with roll and pitch augmentation but with no yaw augmentation. It revealed a yaw period ranging from approximately 3 to 5 seconds (depending on flight condition and c.g. location) with roll and pitch augmentation OFF. The damping ratio ranged from 0.1 to about 0.25. With augmentation ON, at cruise speed,the period shortened to almost two and one half seconds and the damping ratio increased to about 0.3.

It appears that boundaries for the Interim Criteria for the lateral/directional case could be predicated in much the same fashion as that utilized for the longitudinal dynamics detailed previously. The motions should be divided into short and long term response characteristics and treated from the same standpoints of gust/control response, ability to trim, handling of the long term dynamics and the long term remnants of gust upsets.

Smoothing of Dynamics Boundaries

It would appear desirable to delete the "steps" from the dynamics boundaries as they now exist in the current Interim Criteria and some of the boundaries constructed in this report (Figures 4-12, 4-13, 4-29 and 4-36). These steps or corners occur at period lengths of 5, 10 and

20 seconds. Smooth curves have been used for boundaries of this type by avoiding the sentence statements for period and cycles to half-amplitude (Figure 4-12) and resorting to graphs without great discontinuities as utilized in References 61 and 67. Also, the use of displaying curves on graphs for dynamics boundaries in place of the word statements is quite common and is shown in the Airplane and V/STOL MIL. SPECS. (References 6 and 7).

Effects of Size on Flying Qualities Criteria

Numerous studies have been made and criteria established on the effects of size of the helicopters on minimum required angular damping, control sensitivity, and general flying qualities (References 5 and 60). Most of the data assembled and referred to in the previous discussions were for small to medium sized vehicles. The test results of Reference 60 for the pitch and roll axis revealed that the value representing the angular damping and control sensitivity characteristics could be reduced as the size of the vehicle increased. Reference 5 provides for this effect also (e.g., paragraphs 3.2.13 and 3.2.14). The conclusions reached in Reference 60, especially those pertaining to instrument flight, are interesting. Accordingly, allowances for size effects should be made in the criteria. The conclusions of Reference 60 are excerpted below:

- Values for minimum control sensitivity and angular-velocity damping combinations found to be acceptable for visual and instrument flight tasks for the large transport helicopter generally confirm the downward trend with vehicle size shown by the established flying-qualities criteria.
- Higher minimum combinations of control sensitivity and angular-velocity damping for both the pitch and roll axes were required to obtain satisfactory pilot ratings for instrument flight task than to obtain comparable ratings for visual flight tasks.
- Satisfactory pilot ratings for minimum control sensitivity values are closely related to the level of angular-velocity damping in a given test configuration.
- Before acceptable values of angular-velocity damping can be adequately defined for a given axis, consideration must be given to the level of damping reflected by other axes in order to assure that some measure of "damping harmony" exists.

SECTION 5

CONCLUSIONS

INTRODUCTION

The current procedures for IFR certification of helicopters have appeared to some, as an inconsistent, incomplete, and somewhat cumbersome process, but this study was unable to identify any unsafe practice or result for the IFR approvals studied in this report. The essential key for the IFR approval procedure or acceptance practice is the final determination by the FAA certification team (pilots/engineers), that the helicopter can be flown in the NAS with a level of safety, and with satisfactory performance and workload, for a critical scenario of IFR operational conditions and configurations. However, it is this "acceptance practice" and not "compliance with the engineering requirements" (of the Interim Criteria, FAR and other regulatory documents) that is responsible for the current level of flight safety and success of the system. Regardless of any changes or modifications to the engineering criteria, the importance of this acceptance practice as a fundamental requirement should be emphasized and the principle retained as an essential part of the certification process.

Briefly stated, helicopter IFR certification approval depends on:

- Flying qualities judgment that the helicopter can be flown under IFR conditions with a level of safety.
- Compliance with specific, measured minimum stability and control engineering criteria.
- Assessment by the testing pilot that the workload for the minimum aircrew is acceptable and that the pilot's flight control performance levels are satisfactory.

It appears that the principal determinant for a successful IFR approval of a helicopter is the flying qualities judgment that the aircraft can be flown with a level of safety on instruments by the minimum aircrew. This flying qualities judgment appears to dominate the measurement and documentation process that assures compliance with the engineering criteria. The determination of compliance with the dynamic stability and control (and trim) engineering criteria is important in itself and because it appears to dominate other engineering criteria such as the evaluation of compliance with static stability (force and position) criteria and documentation. Pilot workload/performance assessment is important (especially for single-pilot IFR certifications) because of the requirement of the minimum aircrew to satisfactorily participate in and successfully perform the auxiliary tasks (ATC/COMM/NAV, etc.) required for instrument flight.

General

The results of this study of the IFR certification process, Interim Criteria, and associated information indicate the following general conclusions:

A. The current Interim Criteria:

1. were found to be most applicable to IFR certification of essentially unaugmented helicopters using two-pilot aircrew manning levels but additional requirements and changes are needed to make the document more complete;

2. contain a section on dynamic stability oscillatory boundaries that are identical to that determined in MIL-H-8501A that are based on the equivalent of two-pilot aircrew levels. These oscillatory boundaries of 8501A were originally determined for the longer term motions associated with essentially unaugmented, tail-less helicopters for the hover/slow speed flight regime;

3. establish minimum dynamic stability requirements that are not readily applied to recently certified IFR helicopters. Many of these IFR aircraft are equipped with advanced stability and control augmentation systems and attitude-hold autopilots and exceed the minimum dynamic stability criteria to such a large degree that the established minimum requirements appear difficult to apply or utilize;

4. do not provide adequate information on precise engineering criteria to be documented (type and format), formalization of flight-test data acquisition techniques and standardization of data analysis reduction, and presentation methods. When existing documented engineering criteria data were analyzed for this study, frequently it was difficult to properly reduce some portions of the data in a manner that would permit easy applications and/or comparison to certification requirements. This can be variously attributed to the quality of the data, the variety of flight-test techniques utilized, and the type of information documented;

5. do not sufficiently relate or formalize how each different workload increment associated with -

- **different minimum aircrew level (one or two-pilots)**
- **different certification objectives (CAT-I or Non-Precision Approach)**
- **different augmentation, autopilot, control systems**
- **different display and avionics systems**
- **low and high-density ATC traffic situations**

impacts on or facilitates an effective approach to the total judgment of workload/performance in the IFR certification process of helicopters.

B. The dynamic stability and control statements of the current Interim Criteria:

1. address only oscillatory dynamics and apparently exclude or neglect the very common but extremely important aperiodic dynamics of helicopters. Quantitative consideration of non-oscillatory motions needs to be included in the requirements;

2. do not distinguish between requirements needed for short term dynamics versus long term dynamics and cover them both for all axes with a blanket specification. Separate criteria should be stipulated for short and long term dynamics;

3. do not cover or address certain other significant dynamic stability and control criteria important to the achievement of an acceptable rating of IFR handling qualities. For example, the criteria appear incomplete in that special or additional needed stability and control criteria items such as the "concave downward" requirement, specification of minimum allowable short period frequencies, minimum damping and control power, etc., need to be included.

C. All single-pilot IFR certified aircraft studied in this report utilize some type of augmentation and/or autopilot systems to resolve stability and control criteria and/or pilot workload/performance requirements. The judgment of acceptable pilot workload is especially acute for single-pilot IFR certifications and needs to be formalized since there is the strongest interplay between the handling qualities factors of the

pilot/vehicle system (stability and control, displays, tasks performance, augmentation systems, avionics, etc.) and the workload capability required by the pilot. Most single-pilot IFR certifications appear to require the ATTITUDE-HOLD mode as provided by an autopilot to provide flight control workload relief to the pilot so that he may participate in the performance of auxiliary tasks.

D. Although several viewpoints have been offered on the DISPLAY/CONTROL SYSTEM/WORKLOAD tradeoffs, most FAA personnel felt that there should be some minimum acceptable level of stability and control for a given required display system and aircraft, and that no trade off between display sophistication and stability/control/augmentation sophistication should be made.

E. Envelope Tailoring appears to have gained some acceptance as a satisfactory method of facilitating IFR certifications of new helicopter configurations.

F. The Interim Criteria need to specify separate stability and control requirements for one and two-pilot aircrew manning levels. There is also an important need to establish separate requirements for failure-mode operation.

APPENDIX A

INTERIM CRITERIA FOR HELICOPTER IFR CERTIFICATION

The Federal Aviation Administration developed and issued Standards for IFR certification of helicopters as early as 1970. These early criteria are mentioned in Reference 3 which cites a Federal Aviation Administration document; Letter SW-216, FAA-Southwest Region, "IFR Instrument Flight Requirements for Bell Model 212 Helicopter", Glen W. Welsh, and is dated July 1, 1970. Also, it should be noted that portions of the current helicopter IFR Interim Criteria (e. g. section on dynamic oscillations) emulate closely or were drawn from an already existing Military Specification on this subject; namely, MIL-H-8501A, General Requirements for Helicopter Flying and Ground Handling Qualities dated 7 September 1961. The contents of the Interim Criteria relate to helicopter trim, static, dynamic, and artificial stability, controllability, equipment for IFR operations, operating information - limitations, and evaluation of miscellaneous items on actual IFR flight such as in-flight IFR workload demands on the minimum required flight crew and handling of the helicopter in rough air turbulence. A collection of copies of the IFR Interim Criteria from various sources such as the FAA regions and aircraft industry reveals minor deviations in parts included or verbiage used. In addition to the complete Interim Criteria of the FAA excerpted below, examples of the changes noted in one of the two other versions are shown.

As excerpted, the subjects covered in this (Helicopter IFR Interim Criteria) are:

a) <u>Trim</u>. It must be possible to trim the longitudinal, lateral, and directional control forces to zero in steady flight at all approved IFR airspeeds, power, and configurations appropriate to the type. This must be accomplished by a recentering button or conventional trim controls. The trim device may not introduce any undesirable discontinuities in the force gradients, and its operation must be such as to provide gradual trimming without abrupt changes in the force or position. At these trim conditions, the control must exhibit positive self-centering characteristics. If it is necessary to turn the trim controls to operate, the direction of rotation must be such as to produce similar rotation of the rotorcraft about an axis parallel to the axis of the particular control.

Cockpit control free-play may not be excessive on the lateral and longitudinal axis. Motions of the control from the trim position, which result in no control surface response, may not cause objectionable handling characteristics, nor in any case exceed ±2 percent of total control travel.

(b) Static longitudinal control force stability. The helicopter must, at all forward speeds and at all trim and power conditions specified in this paragraph, possess positive static longitudinal control force stability with respect to speed. The slope of the control force versus airspeed curve must indicate that any significant change in airspeed is clearly perceptible to the pilot through a resulting change in stick force. Minimum perceptibility is interpreted to mean 1 pound per 6 knots speed change, excluding control friction. When the control force is slowly released with the rotorcraft at any airspeed within the applicable range specified in this paragraph, the airspeed must return to the specified trim speed ± 5 percent or 5 knots, whichever is greater.

The tests specified in subparagraphs (1), (2), (3), and (4) of this paragraph must be conducted at the critical weight and c.g., with the landing gear retracted (if retractable). Static longitudinal control force stability must be shown as follows:

(1) Climb. The stick force curve must have a stable slope over an airspeed range from 20 knots above to 20 knots below the trim speed with -

(i) Maximum continuous power; and

(ii) The rotorcraft trimmed at the best rate of climb speed or the minimum approved IFR airspeed, whichever is greater.

(2) Cruise. The stick force curve must have a stable slope over an airspeed range from 0.7 to 1.1 times V_H or V_{NE}, whichever is lower; and

(i) Level flight power at 0.9 times V_H or V_{NE}, whichever is lower; and

(ii) The rotorcraft trimmed for level flight at 0.9 V_H or V_{NE}, whichever is lower.

(3) Slow cruise. The stick force curve must have a stable slope over an airspeed range from .90 times minimum approved IFR airspeed to 1.30 times minimum approved IFR airspeed, with -

(i) Level flight power at 1.10 times minimum approved IFR airspeed; and

(ii) The rotorcraft trimmed for level flight at 1.10 times minimum approved IFR airspeed.

(4) Letdown at 500 feet per minute (ft./min.). The stick force curve must have a positive slope over an airspeed range from 20 knots above to 20 knots below the recommended approach speed with landing gear extended and retracted, if applicable, with -

(i) Power required to maintain 500 ft./min. letdown at recommended approach speed; and

(ii) The rotorcraft trimmed at the recommended approach speed.

(c) Lateral and directional static stability. For climbs of 1000 ft./min. or maximum continuous power climb, whichever is less, and for rates of descent of 1000 ft./min., at all approved IFR airspeed.

(1) In straight steady sideslip -

(i) At angles of sideslip up to 15 degrees, either side, the lateral and directional control movements and forces must increase in the stable direction and must be substantially proportional to the angle of sideslip as it is increased;

(ii) At angles of sideslip above 15 degrees, either side, up to the angle at which full directional control is employed or up to the maximum sideslip angle appropriate to the rotorcraft type, whichever is less, the directional control pedal forces may not reverse, and increased control deflection, if available, must produce increased angles of steady sideslip;

(iii) Sufficient bank must accompany steady sideslips to indicate clearly any departure from steady unyawed flight;

(iv) There may not be any undesirable discontinuities in lateral or directional force gradients; and

(v) There may not be any undesirable high breakout forces for the lateral and directional controls.

(2) The directional static stability, as shown by the tendency to recover from a skid with directional controls free, must be positive, with the landing gear retracted (if retractable).

(3) The lateral static stability as shown by the tendency to recover to level attitude from a sideslip with the lateral controls free, must be positive with landing gear-retracted (if retractable).

(d) Longitudinal-lateral-directional dynamic stability. Longitudinal-lateral-directional oscillations with controls fixed following a single disturbance in smooth air must exhibit the following characteristics:

(1) Any oscillation having a period of less than five seconds must damp to one-half amplitude in not more than one cycle. There may not be any tendency for small amplitude oscillations to persist.

(2) Any oscillation having a period of from 5 to 10 seconds must damp to one-half amplitude in not more than two cycles. There may not be any tendency for undamped small oscillations to persist.

(3) Any oscillation having a period greater than 10 seconds but less than 20 seconds must be at least lightly damped.

(4) Any oscillation having a period of 20 seconds or more may not achieve double amplitude in less than 20 seconds.

(e) Artificial stability. If the basic rotorcraft utilizes artificial means to meet the stability requirements in paragraphs (b), (c), and (d) of this Appendix, the reliability of artificial means must be substantiated.

(1) An artificial means may be used without a back-up or standby means provided the rotocraft -

(i) With the means inoperative, has all of the flight characteristics specified in Subpart B of this Part and, in addition, has positive lateral, longitudinal, and directional stick position stability and is free from tendencies towards excessively rapid or dangerous divergence.

(ii) Can be flown IFR without undue difficulty by the minimum crew with the means inoperative for a length of time equivalent to the useable fuel supply of the helicopter, but in any event not less than one hour. If useable fuel capacity of the helicopter is increased after certification, the requirement of this subparagraph must be met with the new fuel capacity, or else the length of time established with the previous fuel supply must be applied (either in the flight manual or on a placard) as an operating limitation.

(2) If the conditions of subparagraph (1) of this paragraph are not met, an equivalent backup or standby artificial means must be provided. Careful consideration must be given to the manner (e.g., automatic or manual switching) in which the backup or standby means is activated when the primary artificial means fails or malfunctions.

(f) <u>Controllability.</u> Throughout the approved IFR airspeed range there may not be dangerous divergence and uncontrollable tendencies following a sudden failure or malfunction of the artificial stabilization means or following the failure of a powerplant.

The control authority of an automatic stabilization device may not be of such magnitude that in case of failure of the device, insufficient control remains with the pilot for maneuvering in both normal and emergency conditions.

(g) <u>Equipment for IFR operations.</u> In addition to the basic equipment and installation requirements specified in Subpart F of this Part, the following apply:

(1) There must be provided and installed such additional items of equipment (e.g., flight instruments, navigational instruments, radio equipment and navigational aids) as are appropriate to the ground facilities to be used when operating under instrument flight rules.

(2) The following are required instruments:

(i) Non-tumbling gyroscopic bank and pitch-indicator with a five-inch diameter unless smaller instruments are found satisfactory during flight evaluation.

(ii) Gyroscopic direction indicator with a five-inch diameter unless smaller instruments are found to be satisfactory during flight evaluation.

(iii) Rate of climb (vertical speed) indicator (no lag type).

(3) Systems that operate the required flight and navigation instruments which are located at each pilot's station must meet the requirements set forth in § 29.1333.

(h) Instrument systems and other systems essential for IFR flight that could be adversely affected by icing must be provided with adequate ice protection, whether or not the rotorcraft is certificated for operation in icing conditions.

(i) Operating information and limitations. The pertinent information and limitations necessary for proper and safe operation of the rotorcraft under the instrument flight conditions for which approval is sought must be presented to the minimum required flight crew in the form of suitable placards or in the rotorcraft flight manual or both. A minimum approved IFR airspeed must be based on the technical merits of the rotorcraft characteristics.

(j) IFR flight. The rotorcraft must be flown in the air traffic control system under actual IFR day and night conditions for a period of at least five hours. The items evaluated during this period must include:

(1) Ability to operate the rotorcraft satisfactorily under IFR conditions in the air traffic control system without undue pilot fatigue or exceptional pilot skill or alertness.

(2) Cockpit leaks in precipitation as affecting pilot comfort and rotorcraft airworthiness.

(3) Pilot visibility in precipitation during low approaches.

(4) Glare and reflections from exterior lighting at night in clouds or fog or both.

(5) In-flight IFR workload demands on the minimum required flight crew.

(6) Handling of the rotorcraft in rough air turbulence.

Two other versions (Versions 2 and 3) of the criteria and standards for IFR certification of helicopters were obtained during the course of data acquisition.

Version 2 contained the heading shown below and listed essentially the same material detailed in Version 1 (shown in its entirety above).

Version 2 Heading:

Interim Criteria for Helicopter IFR Certification
FAR 27 and 29
Summary of Interim Criteria

However, Version 3 contained some changes and/or additions as compared to Versions 1 and 2. Version 3 also contains the Introductory paragraph shown below:

IFR
INSTRUMENT FLIGHT REQUIREMENTS
FOR
HELICOPTERS

The following criteria and standards are prescribed under the authority of Federal Aviation Regulations CAR 7.120/FAR 29.141-CAR 6.120/FAR 27.141 in the absence of specific requirements for type certification of a category A transport helicopter for instrument flight to insure equivalent level of safety. These criteria and standards constitute the certification basis for obtaining approval for instrument flight of helicopters.

The introductory paragraph cites the old CAR 6 and CAR 7 (updated to FAR 27 and 29) and mentions ". . . certification of a Category A transport helicopter . . .". Some of the changes or additions as compared to Version 1 (shown above) are detailed below:

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Static Longitudinal Control Force Stability

(1) Climb . . .

Note: If the applicant selects a higher climb speed than the basic helicopter performance data shows, the climb requirements of CAR 6.112(b) must be demonstrated at the higher airspeed selected.

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(4) Letdown at 500 Feet Per Minute (Ft/Min). The stick force curve should have a positive slope between 20 knots above and 20 knots below the recommended approach speed with landing gear extended and retracted, as applicable, with:

(a) Power required to maintain 500 ft/min letdown at recommended approach speed.

(b) Trim at the recommended approach speed.

Note: When the applicant proposes a three axes automatic stabilization equipment system to meet the minimum IFR requirement, noncompliance with the stick force trim and stability requirements noted above on the basic helicopter may be considered acceptable if equivalent safety is provided by that stability system and it is so demonstrated during the IFR certification program.

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Lateral and Directional Static Stability.

(1) In straight steady sideslip at all approved IFR airspeeds and for climbs or rates of descents of 1000 ft/min (if maximum continuous power climb is under 1000 ft/min, the aircraft should be stable at maximum rate of climb), the lateral and directional control movements and forces should increase in the stable direction and be substantially proportional to the angle of sideslip up to 15 degrees either side as the angle of sideslip is increased. At greater angles up to that at which the full directional control is employed, or a sideslip angle appropriate to the type is obtained, the directional control pedal forces should not reverse and increased deflection should produce increased angles of steady sideslip. Sufficient bank should accompany steady sideslipping to indicate clearly and departure from steady unyawed flight and there should be no undesireable discontinuities in either the lateral or directional force gradients nor should there be any undesirable high breakout forces.

(2) The static directional stability, as shown by the tendency to recover from a skid with directional controls free, should be positive at all approved IFR airspeeds and for climbs or rates of descents of 1000 ft/min. (If maximum continuous power climb is under 1000 ft/min, the aircraft should be stable at maximum rate of climb.)

(3) The static lateral stability, as shown by the tendency to recover to level attitude from a sideslip with the lateral controls free should be positive at all IFR airspeeds and for climbs or rates of descents of 1000 ft/min. (If maximum continuous power climb is under 1000 ft/min, the aircraft should be stable at maximum rate of climb.)

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Longitudinal-Lateral-Directional Dynamic Stability. Longitudinal-lateral-directional oscillations with controls fixed following a single disturbance in smooth air should exhibit the following characteristics:

(1) Any oscillation having a period of less than 5 seconds should damp to one-half amplitude in not more than one cycle. There should be no tendency for undamped small amplitude oscillations to persist.

(2) Any oscillation having a period of less than 10 seconds should damp to one-half amplitude in not more than two cycles. There should be no tendency for undamped small oscillations to persist.

(3) Any oscillation having a period greater than 10 seconds but less than 20 seconds should be at least lightly damped.

(4) Any oscillation having a period greater than 20 seconds should not achieve double amplitude in less than 20 seconds.

Note: Dynamic stability shall be tested by pilot inputs to the appropriate control system; the inputs shall be sudden pulse type inputs with immediate release. Inputs shall be of at least one inch deflection at the cyclic control stick grip and/or appropriate rudder pedal deflections.

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Artifical Stability

(1) In the event that the basic rotorcraft does not meet the stability requirements stated above, but utilizes artificial means to do so, the integrity of the artificial means should be of a high order. One manner of complying with the requirement (i.e. providing equivalent integrity) would be to use equivalent back up means (e.g., duplicate equipment); in this event careful consideration should be given to the manner (automatic or manual switching) in which the backup or standby means is brought into action when the primary artificial means fails or malfunctions. The reliability of the ASE shall be considered using Advisory Circular 29-1 as a means of compliance.

(2) If the helicopter is provided with a primary, artifical or boost means as noted above, a backup or standby system may be omitted provided the rotorcraft meets the following

(a) Has all of the flight characteristics specified in the other parts of CAR 6/FAR 27 and in addition, has positive lateral, longitudinal and directional stick position stability and is free from tendencies towards excessively rapid or dangerous divergence.

(b) Can be flown under IFR conditions without undue difficulty with the primary (and only) artifical means inoperative for a length of time equivalent to the usable fuel supply of the helicopter, but in any event not less than one hour. If the usable fuel capacity of the helicopter is increased after certification, the requirement of this paragraph should be met with the new fuel capacity, or else the length of time established with the previous fuel supply should be applied. (An operation limitation shall be shown either on a placard or in the flight manual.)

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Controllability (FAR 29.143). Throughout the approved IFR airspeed range there should be no dangerous divergence and uncontrollable tendencies following a sudden failure or malfunction of the artifical stabilization means or following the failure of a powerplant.

The control authority of the electronic stability devices should not be of such magnitude that in case of a failure of the device, insufficient control remains with the pilot for maneuvering in both normal and emergency conditions.

Note: Controllability tests shall include tests in the IFR mode, i.e. pilot in the loop with reference to flight instruments - hooded flight.

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Instrumentation - Communications.

	Requirement
(1) Bank and pitch instrument (VGI)	Five inch diameter*
(2) Directional gyro	Five inch diameter*
(3) Vertical speed instrument	IVSI

*Five inch instrument size is predicted on current standard instrument flight presentations with satisfactory response and acuity standards. Sizes deviating from these dimensions may be used if found satisfactory during evaluation.

The communications and navigation installations shall comply with the IFR equipment requirements appropriate to the facilities to be used, i.e. positive control area, positive control route segment, etc.

Instrumentation (FARs 29.1321, 29.1331 and 29.1333). The essential flight instruments shall be satisfactorily arranged and have a separate power source and each pilot display must be independent of the other system.

Icing Conditions. Although the helicopter shall be limited from flight into known icing conditions, systems which are essential to flight and are subject to any degree of icing in IFR weather conditions should have adequate protection against icing; these systems include:

(1) Pitot/static airspeed system - (FAR 29.1323)

(2) Vent systems

(3) Primary control systems (i.e., hydraulic actuators, servos, etc.)

Exterior Lights During Instrument Operations. The anticollision light and other exterior lights should cause no adverse conditions affecting the pilot during instrument flight.

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IFR Flight. As part of the certification flight testing, the helicopter should be flown in the air traffic control system, including high density areas, under actual IFR day and night conditions for a period of at least five hours.

Minimums for IFR operations will be those prescribed on approach plates for the facilities to be used.

Some of the items to be noted during operation in IFR conditions are:

(1) Overall system airworthiness of the pilot-helicopter combination in common ATC system.

(2) Cockpit leaks in precipitation as affecting pilot comfort and airworthiness.

(3) Pilot visibility in precipitation during low approaches.

(4) Glare and reflections from exterior lighting at night in clouds and/or fog.

(5) In-flight IFR workload demands on the minimum certificated crew, including operations in a high-density environment.

(6) Evaluating handling of the helicopter in rough air turbulence.

Operating Information and Limitations. The pertinent information and limitations necessary for proper and safe operation of the rotorcraft under the instrument flight conditions for which approval is sought should be presented to the minimum flight crew in the form of suitable placards and/or as a part of the rotorcraft flight manual. A minimum approved IFR airspeed should be based on the technical merits of the helicopter characteristics. The recommended operating procedures for the use of ice protection equipment must be furnished in the rotorcraft flight manual.

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APPENDIX B

HANDLING QUALITIES; DEFINITIONS AND PILOT RATING SCALE

General

For pilot/vehicle systems that are required to comply with a given set of Standards and Criteria with a satisfactory level of safety, workload, and performance; pilot rating is the most accurate and simplest method of assuring a suitable assessment of acceptability of the complete pilot/vehicle system for an intended task. Many studies using ratings in the evaluation of aircraft handling qualities have been accomplished by numerous agencies and the most noteworthy and familiar efforts have been accomplished by Messrs. George Cooper of NASA Langley and Robert P. Harper of the CALSPAN Corporation, Buffalo, NY.

Definitions and Rating Scales

In order to narrow and constrain some of the definitions and variables used in judgment on IFR helicopters, certain accepted and well recognized definitions, and rating scales are utilized here for convenience (excerpted verbatim from Reference 38). The terminology and ideas are useful in structuring certain of the other sections on Workload and Stability discussed in this report. Some of the most pertinent definitions needed in this study are shown below.

Handling Qualities - Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.

Mission - The composite of pilot-vehicle functions that must be performed to fulfill operational requirements. May be specified for a role, complete flight, flight phase, or flight subphase.

Flight Phase - A designated portion or segment of a complete flight. A mission phase. A flight phase may be represented by one or more separate tasks. Example: Takeoff, climb, cruise, descent, approach, and landing, (and emergency conditions).

Flight Subphase - That part of a flight phase having a single objective, and a single configuration or change in a configuration. Examples: Terminal area holding, glide slope capture, localizer capture, ILS tracking, wave-off.

<u>Task</u> - The actual work assigned a pilot to be performed in completion of or as representative of a designated flight segment.

<u>Control</u> - That part of a task which requires continuing actuation of the principal controls and use of the selectors as required. <u>Examples</u>: Movement between specified point, tracking, ILS or VOR tracking.

<u>Auxiliary</u> - That part of a task which involves the pilot in actions other than direct control of the aircraft. <u>Examples</u>: Navigation, communication monitoring, and selection of systems.

<u>Workload</u> - The integrated physical and mental effort required to perform a specified piloting task.

<u>Physical</u> - The effort expended by the pilot in moving or imposing forces on the controls during a specified piloting task.

<u>Mental</u> - Mental workload is at present not amenable to quantitative analysis by other than pilot evaluation, or indirect methods using physical workload (input) and the task performance measurements. An example would be the improvement associated with flight-director type displays which reduce the mental compensation normally required of the pilot.

<u>Performance</u> - The precision of control with respect to aircraft movement that a pilot is able to achieve in performing a task. (Pilot-vehicle performance is a measure of handling performance. Pilot performance is a measure of the manner of efficiency with which a pilot moves the principal controls in performing a task).

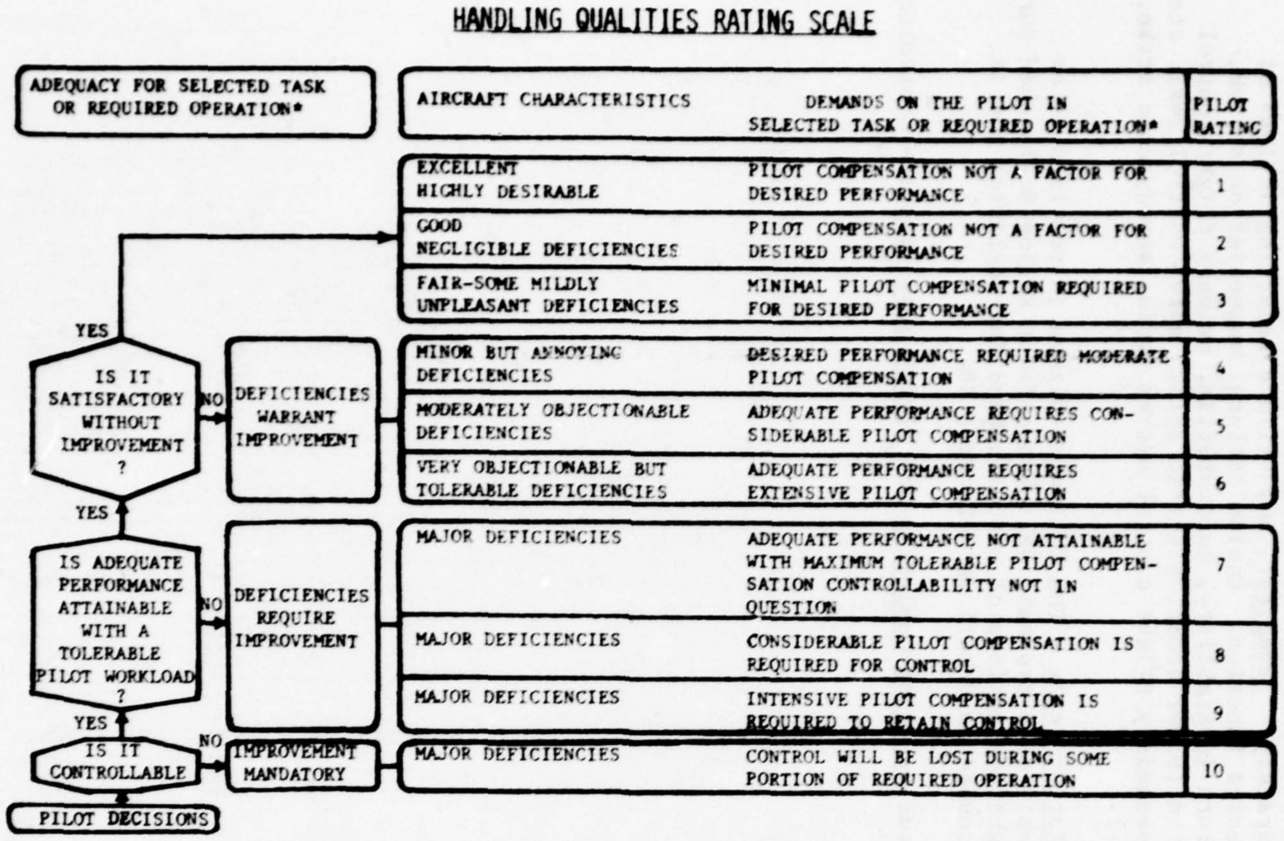
<u>Compensation</u> - The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics.

<u>Special Conditions</u> - The special circumstances pertinent to the evaluation (i.e., aircraft environment and pilot stress). <u>Examples</u>: Special conditions of weather and environment, turbulence, wind shear, ceiling, visibility - night, etc. Pilot awareness, surprise, or distraction with respect to impending failure or disturbances.

Failure State - A steady-state failure characterized by the various failed systems that affect the handling qualities (or possibly the need for flying qualities). The dynamic effect of a failure is called a change of state and should be noted separately. Examples: Any failure resulting in loss of selected function. Engine failure, augmentation system, failure in stability, autothrottle, primary flight control system (power boost, electric stick, servo control feel, etc.) or secondary flight control system (trim, aerodynamic brake, etc.).

Pilot Rating Scale - The following figure is provided as an example of a typical, well known Pilot Rating Scale used during flight evaluations of aircraft handling qualities and is discussed in detail in Reference 38.

The terms Handling Qualities and Flying Qualities are equivalent.



HANDLING QUALITIES RATING SCALE

AIRCRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*	PILOT RATING
EXCELLENT HIGHLY DESIRABLE	PILOT COMPENSATION NOT A FACTOR FOR DESIRED PERFORMANCE	1
GOOD NEGLIGIBLE DEFICIENCIES	PILOT COMPENSATION NOT A FACTOR FOR DESIRED PERFORMANCE	2
FAIR-SOME MILDLY UNPLEASANT DEFICIENCIES	MINIMAL PILOT COMPENSATION REQUIRED FOR DESIRED PERFORMANCE	3
MINOR BUT ANNOYING DEFICIENCIES	DESIRED PERFORMANCE REQUIRED MODERATE PILOT COMPENSATION	4
MODERATELY OBJECTIONABLE DEFICIENCIES	ADEQUATE PERFORMANCE REQUIRES CONSIDERABLE PILOT COMPENSATION	5
VERY OBJECTIONABLE BUT TOLERABLE DEFICIENCIES	ADEQUATE PERFORMANCE REQUIRES EXTENSIVE PILOT COMPENSATION	6
MAJOR DEFICIENCIES	ADEQUATE PERFORMANCE NOT ATTAINABLE WITH MAXIMUM TOLERABLE PILOT COMPENSATION CONTROLLABILITY NOT IN QUESTION	7
MAJOR DEFICIENCIES	CONSIDERABLE PILOT COMPENSATION IS REQUIRED FOR CONTROL	8
MAJOR DEFICIENCIES	INTENSIVE PILOT COMPENSATION IS REQUIRED TO RETAIN CONTROL	9
MAJOR DEFICIENCIES	CONTROL WILL BE LOST DURING SOME PORTION OF REQUIRED OPERATION	10

*DEFINITION OF REQUIRED OPERATION INVOLVES DESIGNATION OF FLIGHT PHASE AND/OR SUBPHASES WITH ACCOMPANYING CONDITIONS

Figure B-1. Typical Handling Qualities Rating Scale (Reference 38).

APPENDIX C

REFERENCE INFORMATION ON PROPOSED HELICOPTER REQUIREMENTS FOR OPERATING DURING AND AFTER ENGINE POWER LOSS

NOTE: The material in this appendix was excerpted from one section of a Report on a Background and User's Guide for the proposed version of MIL-H-8501. It has been circulated but not yet finalized (Reference 72).

The Section on Engine Power Loss (Section 3.6) has received generally favorable response and is offered here for general reference an information. Portions of Section 3.6 could be of use by research activities that may become involved in future rule making efforts. Section 3.6 Reference 72 reads:

3.6 ENGINE POWER LOSS

REQUIREMENT

3.6 Engine power loss. The requirements of 3.6.1 through 3.6.9.3 apply following an engine power loss of a single engine. In demonstrating compliance with these requirements, a realistic delay time (3.6.2) shall be incorporated between engine power loss and pilot action.

DISCUSSION

Paragraphs 3.6 through 3.6.9.3 address flying qualities requirements following an engine power loss of a single engine. The corresponding requirements of MIL-H-8501A, MIL-F-83300, and of proposed V/STOL specifications were, in some areas, very general in nature and also non-mission oriented. The requirements therefore have been expanded considerably and in some cases are completely new.

The approach taken in writing these requirements was to address separately those events which occur between the onset of engine power loss and the completion of the autorotative landing. The following was considered to be a logical progressive structure by which to address the requirements:

Phase I:	This phase begins with the onset of engine failure and terminates when the first intentional recovery action is initiated by the pilot.
Phase II:	This phase begins with the initial pilot recovery action and terminates when the helicopter is first under control in a steady descent.

Phase III:	Partial power or autorotative descents and maneuvers prior to the final deceleration to landing.
Phase IV:	The final deceleration to landing (flare, landing and rollout).

3.6.1 WARNING TIME

REQUIREMENT

3.6.1 Warning time. That interval of time from engine power loss until a clear and unambigous warning is furnished the pilot shall constitute the warning time. The warning may be a natural one such as acceleration, rate, displacement or sound, or it may be provided artificially. If an arificial warning device is required, it shall be reliable and essentially free from false alarms, and functional failure of the device shall be indicated to the pilot.

DISCUSSION

Certain parameters such as power setting, airspeed, density altitude, etc., may generally influence the time interval between power loss and pilot recognition of an inherent warning cue. For example, a pilot experiencing a power loss in hovering flight in a single-rotor helicopter would most probably receive an immediate warning due to the yaw attitude change. The same helicopter in a high-speed, low-power dive would probably provide little or no inherent warning until the pilot initiated a dive recovery. The designer must consider the entire operational spectrum and decide if adequate and timely inherent cues will be available. If not, then some type of engine-out-artificial warning system is required. If pilot recognition of engine failure depends on an artificial system then functional failure of the warning device must be indicated to the pilot.

3.6.2 DELAY TIME

REQUIREMENT

3.6.2 Delay time. The delay time shall be the warning time (3.6.1) plus a variable pilot reaction time. The period of time from initial loss of power to the time where a definite recovery input must be initiated to assure continued flight within the Permissible Flight Envelope shall not be less than the delay time. The following delay times are for single-engine helicopters and for multiengine helicopters for the first engine failure:

> For visual flight operations the delay time shall be the warning time plus 0.5 seconds, except,

For those Flight Phases where pilot attention must be diverted from the piloting task, or where the collective and/or cyclic control are unattended, the delay time shall be the warning time plus 1.0 seconds.

For instrument flight operations the delay time shall be the warning time plus 1.5 seconds.

For subsequent engine failure of multiengine helicopters the delay time shall be the warning time plus 0.5 seconds.

DISCUSSION

MIL-H-8501A requires a 2-second delay time prior to initiation of a collective control recovery input and no minimum delay time for the pitch, roll or yaw controls. Flight tests have shown that this requirement is unrealistic in that the collective control may not be the critical recovery control following an engine failure. Flight tests of the AH-1G, for example, indicate that the critical control may be collective, longitudinal or lateral depending on airspeed and power setting at the time of failure (Ref. 73 and 74). The approach taken in this specification is to specify a delay time which applies to all controls. In defining a realistic delay time, the time interval between warning and pilot reaction should be consistent with the piloting task at the moment of engine failure. The general breakdown of piloting tasks in 3.6.2 are: VFR closed-loop, VFR open-loop and instrument flight operations. The variable reaction times assigned to these tasks seem reasonable.

3.6.3 ENGINE POWER LOSS ON THE GROUND

3.6.4 ENGINE POWER LOSS IN FLIGHT

REQUIREMENTS

3.6.3 Engine power loss on the ground. It shall be possible, without excessive pilot compensation, to safely control the helicopter following a sudden engine power loss while conducting all ground operations, to include running takeoffs and landings. For rollouts on a level surface (paved or sod), the ability of the pilot to control heading and bring the helicopter to a complete stop shall not be limited by stability or controllability along or about any axis. This shall include rollouts with downwind and crosswind components up to the limits of the Service Flight Envelope and with initial forward ground speeds of:

Class I	35 knots
Class II, IV	45 knots
Class III	55 knots

3.6.4 Engine power loss in flight. It shall be possible without excessive pilot compensation, to safely control the helicopter following a sudden engine power loss at any combination of airspeed, altitude, normal acceleration, power setting and loading within the Service Flight Envelope. From considerations of operational requirements, the procuring activity shall designate which of the following requirements apply after the power loss.

3.6.4.1 Continue mission Multiengine helicopters required to continue the mission shall meet at least Level 2 requirements within the Operational Flight Envelope for all remaining Flight Phases.

3.6.4.2 Abort mission Multiengine helicopters required to terminate the mission shall be capable of safe withdrawal from Category A Flight Phases and shall meet at least Level 2 requirements within the Operational Flight Envelope for Category B and C Flight Phases.

3.6.4.3 Safe landing. Helicopters that must execute a partial power or autorotative descent to a safe landing shall meet the requirements of 3.6.5 through 3.6.9.3. All helicopters shall be capable of satisfying the requirements of 3 6.5 through 3.6.9 (excluding the landing) under instrument conditions.

3.6.4.4 Crew escape Where an ejection system (or equivalent) is provided the helicopter motion shall not diverge so rapidly that the ability of the crew to escape is impaired.

DISCUSSION

The primary purpose of paragraphs 3.6 3 and 3.6.4 is to assure that the helicopter is safely controllable immediately following an engine power loss. These paragraphs address power losses during both ground and flight operations. The last sentence of paragraph 3.6.4 recognizes that there are several possible situations that could exist following an in-flight failure. Briefly these situations are:

1. Continue mission
2. Abort mission
3. Execute a forced landing
4. Crew escape

It is not the purpose of this specification to decide which of these situations should be applied only to specify the flying qualities for each situation. The procuring activity will specify which of 3.6.4.1 to 3.6.4.4 shall apply.

APPENDIX D

COMPLEX PLANE, TYPICAL MODES OF MOTION, AND PLOTTING OF CHARACTERISTIC ROOTS

Introduction

When performing analyses on the dynamic motions of aircraft, it is convenient to plot or map the locations of the calculated characteristic roots, depicting the modes of motion of the vehicle, on the complex plane. Also, in the performance of experimental flight tests, certain quantities pertinent to the criteria may be measured or evaluated from the documented time history behavior of the aircraft. They are primarily:

- the lengths of the periods of oscillations in seconds
- the number of cycles (or fraction of a cycle) for an oscillation to either halve or double its amplitude
- the time (in seconds) for an oscillation to either halve or double its amplitude
- the damping ratio of the oscillation
- the approximate first-order, time-constant (in seconds) for non-oscillatory, aperiodic type motions.

This flight test information is also conveniently and properly displayed on the complex plane.

Expressions and Equations

Various expressions and equations are also useful in plotting, interpreting and analyzing the mode of motion, root locations on the complex plane in order to facilitate comparison of the acquired data with the minimum dynamic requirements of paragraph (d) of the Criteria. The oscillatory dynamics criteria are stated in terms of the Period of the Oscillation and the frequency dependent cyclic damping parameter called Cycles to Half (or Double) Amplitude. Equations and expressions defining these parameters and other useful terms are listed at the end of this APPENDIX.

During the course of the documentation of the aircraft, the time history behavior of the aircraft motions (due to a specified input) are recorded and analyzed. If the motion is oscillatory, the period is measured and the number (or fraction) of cycles to half (or double) amplitude are determined. Also, if the motion appears to approximate a first-order type non-oscillatory, aperiodic motion, the first-order time-constant is of interest and may be evaluated. Any textbook on the response of physical systems may be reviewed for methods used in approximating first-order, time-constants from time histories as well as determining damping ratios etc., for oscillatory systems (Reference 17).

Descriptions and use of the Complex Plane

In Figure D-1, the five pertinent regions or locations of the complex plane are shown. In Figure D-2, typical time histories of the dynamical motion are shown together with the most commonly applied nomenclature and characteristics for the five discrete modes of motion. In the previous two figures the lower case letters (a, b, c, d, e) of Figure D-2 depict and classify the modes of motion that exist in the regions similarly labeled in Figure D-1. In region (b) of Figure D-1, only stable oscillations with different damping ratios (or equivalently, number of cycles to half amplitude) can exist. In Figure D-3, typical stable oscillation time histories for region (b) for various damping ratios (cycles to half amplitude) are shown. Also, on the same figure, the lower right hand graph displays a plot of damping ratio versus percent overshoot (of the first peak of the oscillation) for a typical second order system. For example, it can be determined from this plot for a damping ratio of 0.055, (Interim Criteria, paragraph d, statement 2 where $C_{1/2} = 2$ is equivalent to a damping ratio of 0.055) that the first peak of the oscillation overshoots the final steady-state value by almost 90 percent. Also for damping ratios on the order of 0.6 or 0.7, the overshoot of the first peak is already less than about 10 percent. Although this heavily damped motion is still a true oscillation, a test-pilot experiencing the motion would probably consider the response essentially aperiodic since he generally cannot easily perceive the small overshoot or the remnant of the oscillation at these higher damping ratios and presumes that damping ratio is approaching a value of one (equal real roots, no-oscillation). However, the recorded time history will reveal that the motion is still oscillatory and the damping ratio and period can be determined if the appropriate parameter is measured and the quality and gain of the trace is handled properly (e.g. large, easy to read traces of pitch angular acceleration or pitch angular rate versus time).

The quantities and notation associated with plotting or mapping the characteristic mode of motion roots on the complex plane are shown in Figure D-4. A typical point, representing a root, is plotted for the example where the period of the oscillation is 8 seconds ($T_P = 8$ sec)

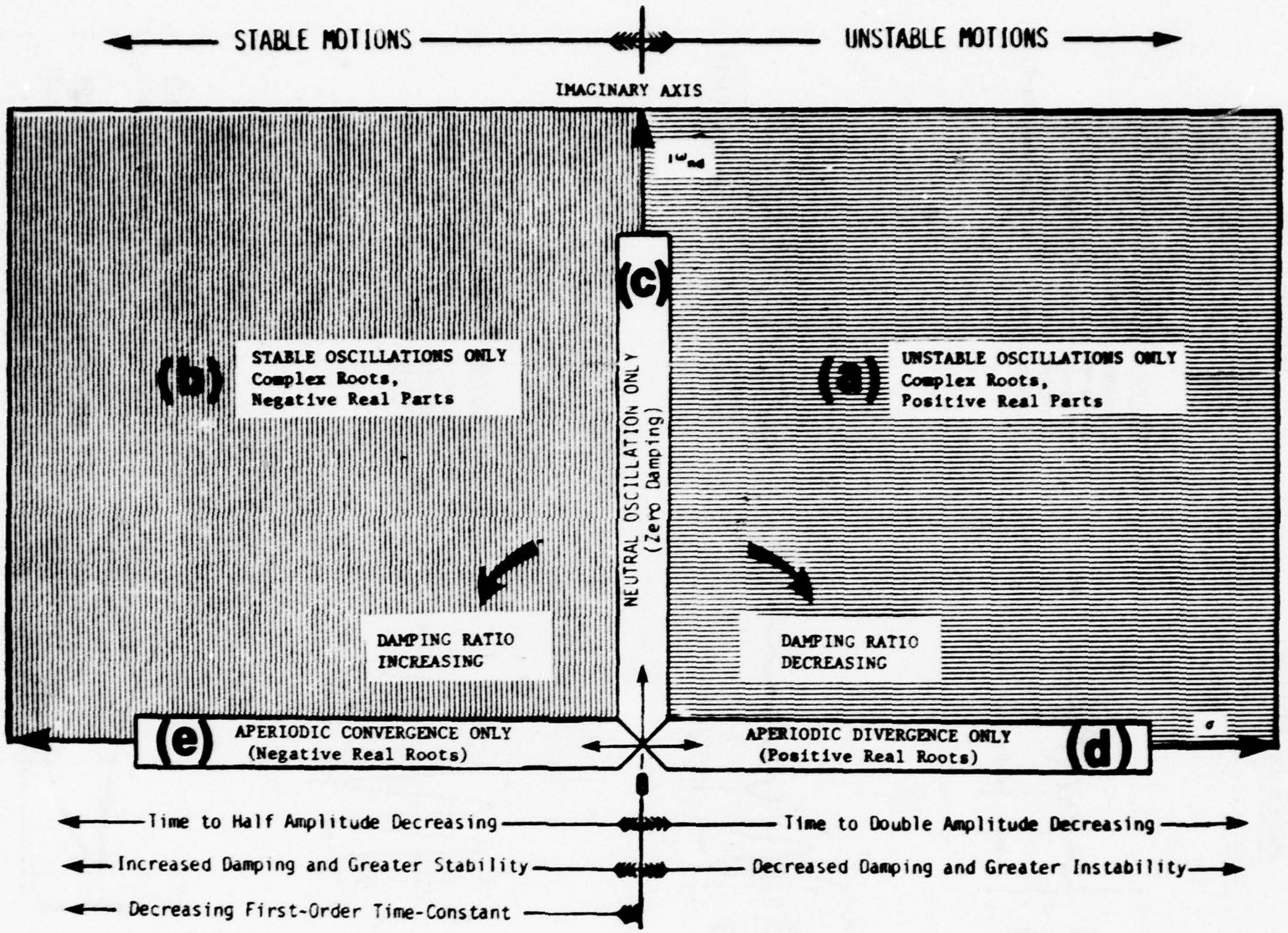
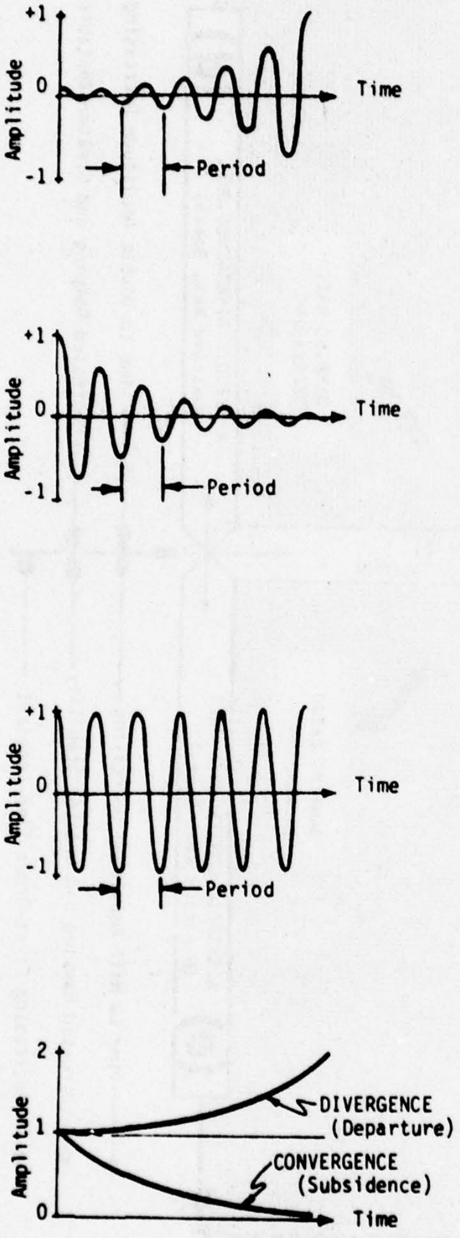


Figure D-1. The Complex Plane

MODES OF MOTION



NOMENCLATURE

(a) UNSTABLE OSCILLATION

(Undamped Oscillation)
(Divergent Oscillation)
(Increasing Oscillation)
(Damping Ratio: $0>\zeta>-1$)
(Complex Roots: Positive Real Part)

(b) STABLE OSCILLATION

(Damped Oscillation)
(Convergent Oscillation)
(Decreasing Oscillation)
(Damping Ratio: $0<\zeta<1$)
(Complex Roots: Negative Real Part)

(c) NEUTRALLY STABLE OSCILLATION

(Neutrally Damped Oscillation)
(Damping Ratio: $\zeta=0$)
(Complex Roots: Zero Real Part)

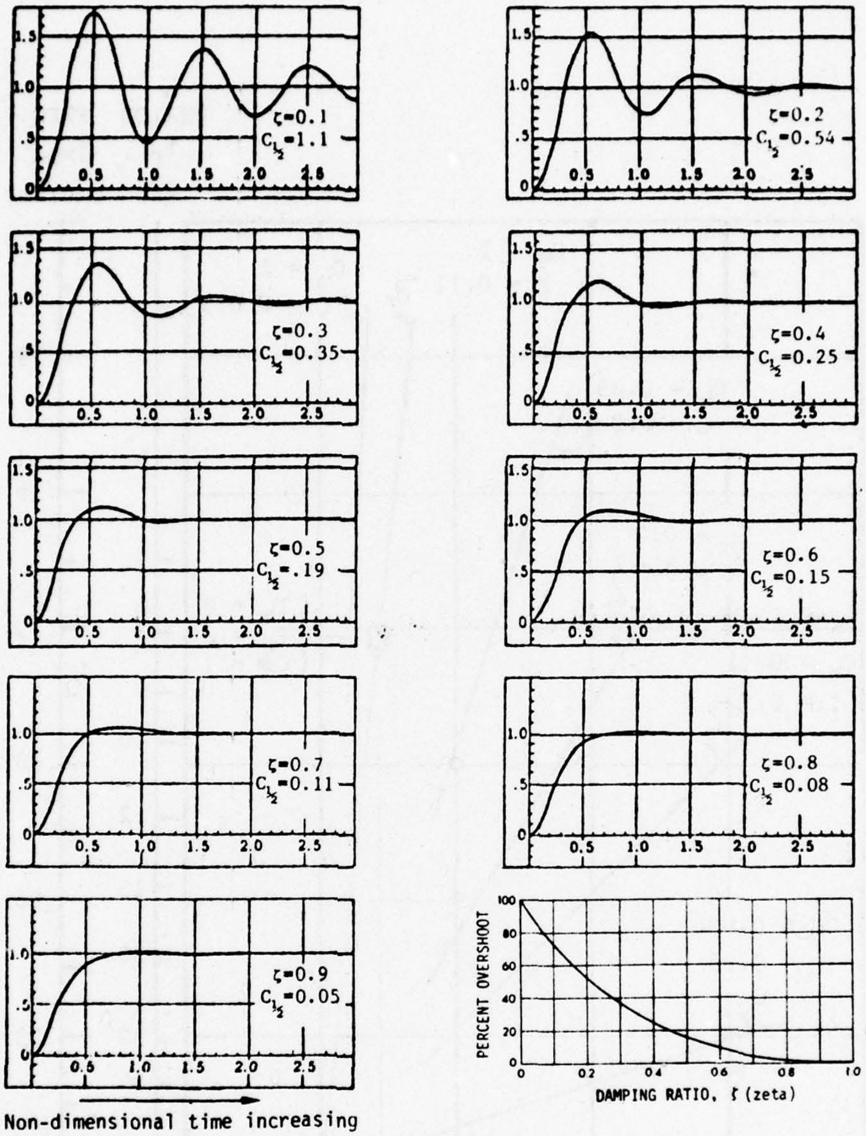
(d) NON-OSCILLATORY, APERIODIC MOTION

(Divergence: Positive real root)
($\zeta\leq-1$)

(e) NON-OSCILLATORY, APERIODIC MOTION

(Convergence: Negative real root)
($\zeta\geq+1$)

Figure D-2. Typical Characteristic Modes of Motion and Nomenclature.



$\frac{t}{T_n}$ & $T_n = \frac{2\pi}{\omega_n}$

SECOND ORDER SYSTEM:
Complex roots,
Negative real parts.
Step function input.

Figure D-3. Typical Stable Oscillation Time Histories for Various Damping Ratios (Reference 75).

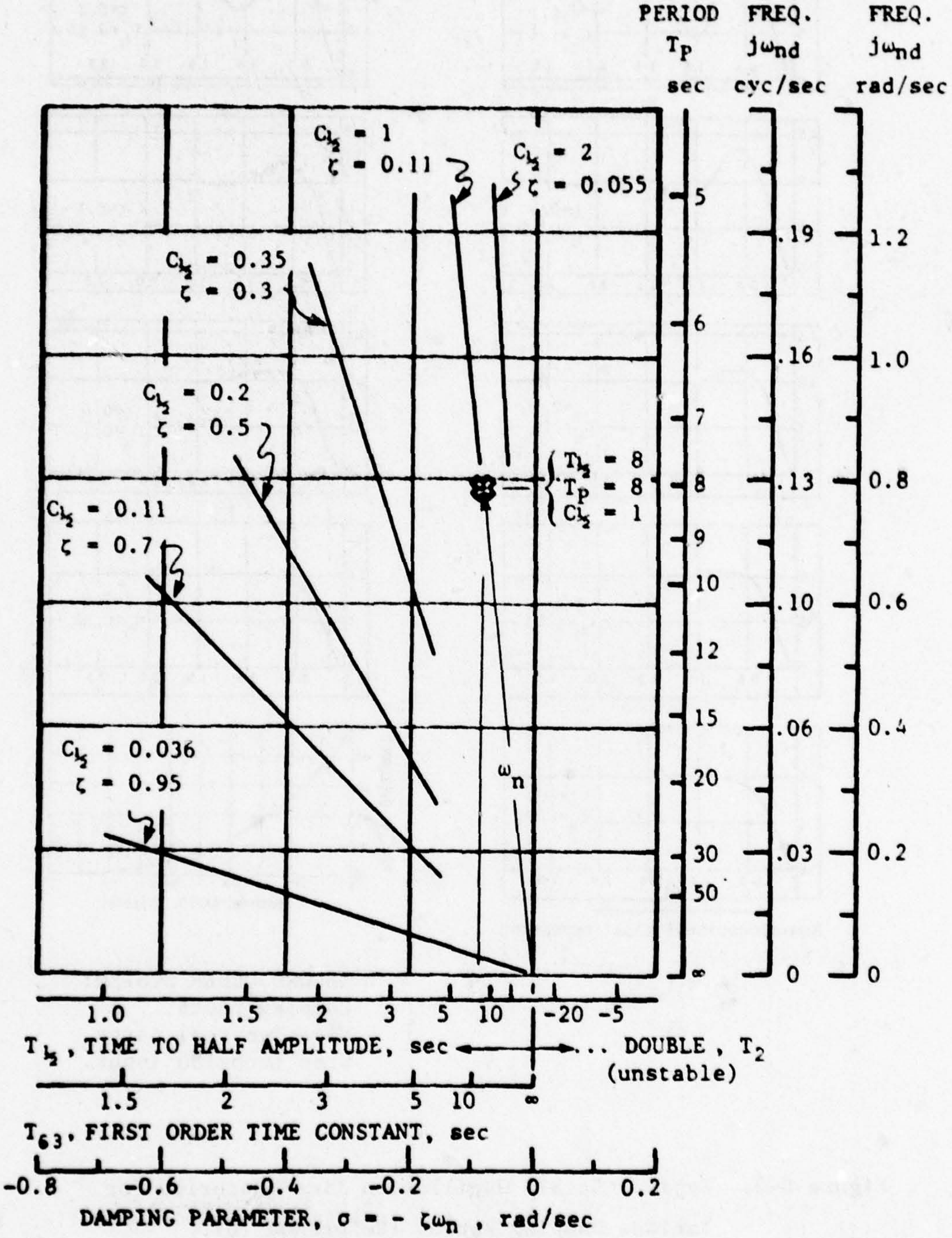


Figure D-4. Plot of Typical Root on Complex Plane.

and the time for the oscillation to subside to half amplitude is 8 seconds ($T_{1/2}=8$ sec). Also, for this case it is obvious that the number of cycles to half amplitude is one ($C_{1/2}=1$) and the damping ratio (ZETA) can be calculated to equal 0.11 ($\zeta = +0.11$) by equations D-6 and D-14. Note that when plotting roots, only the top-half complex plane is used (because of top/bottom complex plane symmetry) and therefore only one (the positive imaginary part) of two roots is shown for a complex pair.

An important point to be considered when analyzing aircraft response data for period and damping information is the type and parameter being used for the measurements. For example, if a longitudinal oscillatory time history of aircraft pitch response is being analyzed for <u>usable period</u> and <u>damping information</u>, the listings below detail the particulat parameters that may be measured and the probable resulting quality/accuracy of the desired data:

- For angular, short-term type response information:

Recorded Aircraft Parameter	Quality and Acuracy of Data
Pitch angular <u>acceleration</u> trace -	Excellent information.
Pitch angular <u>rate</u> trace -	Good information
Pitch angular <u>attitude</u> trace -	Probably poor information or essentially no usable accurate, easily discernable information for documentation. Qualitative information only.

- For Phugoid (velocity/displacement), long-term type, response information;

Recorded Aircraft Parameter	Quality and Accuracy of Data
Aircraft velocity, attitude, altitude, vertical-rate traces -	Excellent Information
Angle of Attack trace -	No usable information

The exclusive use of attitude traces in the determination of minimum requirements of the short term motion (period and damping of an aircraft oscillation) from flight-test data will only provide rough approximations of the aircraft's short term stability or departure tendencies and will not yield documentation type data. Although all the short term motion information is always contained in all the traces (e.g. angular acceleration, rate, and attitude) it is usually much harder to extract meaningful data on short term pitch oscillation period and damping from attitude traces than it is from the angular acceleration and rate traces. Unless sophisticated techniques and analyses are utilized on the attitude information, little, if any, accurate, usable information will be gleaned on the short term oscillatory motion of the aircraft with regard to the requirements of the criteria.

In well damped systems, rough approximations can sometimes be made on the short term period and damping of an oscillation by analyzing an attitude trace. Whether these approximations are good enough depends on the required accuracy, the intent of the analysis, and the quality of the short term period and damping data needed. For lesser damped systems or unstable systems the mode of motion may be such that the pilot may allow only one, two or possibly three "rate peaks" to occur before starting a recovery. For this case, the attitude trace will be of questionable use since probably no usable information on the short term period and damping will be noted.

During the inspection of some attitude trace information obtained during the study, it was noted that the traces were greatly reduced in apparent size and that the important short term frequency information had been largely filtered out or not intended for analysis. (The first information peak on the short term oscillation is usually always filtered out or missing in the attitude trace). The pitch angular acceleration trace and then the pitch angular rate trace (if recorded) would have been much more informative than the attitude trace in determining the needed short term information. It is obvious that, the attitude trace is one integration away from the rate data (or two integrations away from the angular acceleration data). On some of the data reviewed, only the attitude traces are shown for documentation while the rate and acceleration traces are not presented. Considering that many of the attitude augmented aircraft contain a primary motion mode of interest (namely, a short-term oscillation) that has a period length of less than five seconds and a damping ratio of less than about 0.6, attention should be given to the recording and analysis of the most revealing time history information in order to document this motion and determine the dynamic character of the system and compliance with the certification requirements. Also, if the aircraft does not contain some attitude feedback function, then character of the pitch mode (as approximated by the first-order, time-constant) is of interest.

In reviewing other data for certification of IFR helicopters, it was noted that for aircraft equipped with multiple axis augmentation (e.g. pitch and roll actuators installed), investigation and documentation was made for Stability Augmentation System failures or hardovers. In some of these data test flights, one axis of the SAS system was locked in a "hardover" position and the response of the aircraft was documented. Following the hardover input in one axis, the aircraft was permitted to respond in a multiple degree of freedom fashion. For example, for documentation of the longitudinal degree of freedom dynamic stability characteristics, a longitudinal cyclic pitch hardover was applied and the time histories of longitudinal motion were recorded. However, during this longitudinal free response measurement (and with the aircraft free to pitch, roll, and yaw) the SAS roll actuator was still on and operating and working hard. Its effect could readily be seen coupling into the pitch response. As the aircraft pitched and rolled off attitude, the coupling between axes became more pronounced and the SAS roll actuator trace showed larger excursions. The point made here is that the documentation analyst should be careful when investigating stability augmentation system OFF or "hardover" for a single axis. For example, he should avoid assigning an oscillatory characteristic to an unaugmented axis when in fact the apparent oscillatory unaugmented (pitch) response is the direct result of the remaining augmented axis (roll SAS actuator action) which is cross-coupling into the unaugmented axis (pitch).

Tabular Information

If the period and damping of the motion have been measured and determined, then various calculations and evaluations can be made with the equations and expressions provided at the end of this Appendix. Also, listings of some approximate values of frequency, damping parameter, time constants and damping ratios are provided in additional Tables at the end of this Appendix.

TABLE D-1

Useful Equations and Expressions

- Period of the Oscillation, T_p (sec);

$$T_p \text{ (sec)} = \frac{2\pi}{\text{Damped natural frequency, } \omega_{nd}} = \frac{2\pi}{\omega_{nd} \text{ (rad/sec)}} \qquad \text{(D-1)}$$

and similarly;

- Damped Natural Frequencies of the Oscillation, ω_{nd};

$$\omega_{nd} \text{ (rad/sec)} = \frac{2\pi}{T_p} \qquad \text{(D-2)}$$

or

$$\omega_{nd} \text{ (cyc/sec)} = \frac{1}{T_p} \qquad \text{(D-3)}$$

- Cycles to Half (or Double) Amplitude, $C_{\frac{1}{2}}$ (Non-dimensional, ND);

$C_{\frac{1}{2}}$ (ND) = [Damped natural frequency, ω_{nd} (rad/sec)] times [Time to half amplitude, $T_{\frac{1}{2}}$ (sec)] divided by [2π]. (D-4)

or

$C_{\frac{1}{2}}$ (ND) = [Damped natural frequency, ω_{nd} (cyc/sec)] times [Time to half amplitude, $T_{\frac{1}{2}}$ (sec)]. (D-5)

and

$$C_{\frac{1}{2}} \text{ (ND)} = \frac{\text{Time to Half Amplitude}}{\text{Period of Oscillation}} = \frac{T_{\frac{1}{2}} \text{ (sec)}}{T_p \text{ (sec)}} \qquad \text{(D-6)}$$

where

- Time of half amplitude, $T_{\frac{1}{2}}$ (sec):

$$T_{\frac{1}{2}} \text{ (sec)} = \frac{0.693}{\text{Damping parameter, } \sigma} = \frac{0.693}{-\zeta\, \omega_n \text{ (rad/sec)}} \qquad \text{(D-7)}$$

TABLE D-1 (Cont.)

Useful Equations and Expressions (Cont.)

- Additional useful expressions are:

$\sigma = -\zeta\,\omega_n$, damping parameter (D-8)

$\zeta = \cos\theta = \dfrac{\zeta\,\omega_n}{\omega_n}$, damping ratio (D-9)

ω_n = undamped natural frequency (rad/sec) (D-10)

$\omega_{nd} = \omega_n\sqrt{1-\zeta^2}$, damped natural frequency (rad/sec) (D-11)

And, just as importantly, although not alluded to in the Dynamics paragraph (d) of Interim Criteria, the expression for the First-Order, Time-Constant as applied to non-oscillatory aperiodic type motions:

- The First Order Time-Constant, T_{63} (sec);

$$T_{63}\text{ (sec)} = \frac{1}{\text{Damping parameter, }\sigma}$$

$$T_{63}\text{ (sec)} = \frac{1}{-\zeta\,\omega_n\text{ (rad/sec)}} \qquad \text{(D-12)}$$

Also, the relationships between Cycles to Half Amplitude and Damping Ratio may be derived as:

$$C_{\frac{1}{2}} = \frac{0.693}{2\pi}\sqrt{\frac{1-\zeta^2}{\zeta}} \qquad \text{(D-13)}$$

and similarly for the Damping Ratio, ζ (ND);

$$\zeta = \left[\frac{0.01217}{(C_{\frac{1}{2}})^2 + 0.01217}\right]^{\frac{1}{2}} \qquad \text{(D-14)}$$

TABLE D-2

Listing of Frequency and Period Values for Oscillations

Damped Natural Frequency $j\omega_{nd}$ rad/sec	Damped Natural Frequency $j\omega_{nd}$ cyc/sec	Period of Oscillation T_P sec
0.126	0.02	50.
0.2	0.03	31.4
0.209	0.033	30.
0.314	0.05	20.
0.4	0.06	15.7
0.419	0.066	15.
0.52	0.082	12.
0.6	0.095	10.5
0.63	0.1	10.
0.7	0.111	9.
0.79	0.126	8.
0.8	0.127	7.9
0.9	0.143	7.
1.0	0.159	6.3
1.05	0.169	6.
1.2	0.190	5.2
1.26	0.2	5.
1.4	0.223	4.5
1.57	0.25	4.
1.6	0.2546	3.9
1.8	0.286	3.5
2.0	0.318	3.1

TABLE D-2 (Cont.)

Listing of Frequency and Period Values for Oscillations

Damped Natural Frequency $j\omega_{nd}$ rad/sec	Damped Natural Frequency $j\omega_{nd}$ cyc/sec	Period of Oscillation T_P sec
2.09	0.333	3.
2.2	0.35	2.9
2.4	0.38	2.6
2.6	0.414	2.4
2.8	0.445	2.2
3.0	0.48	2.1
3.14	0.5	2.
3.2	0.509	1.96
3.4	0.541	1.85
3.6	0.573	1.75
3.8	0.605	1.65
4.0	0.637	1.57
4.19	0.667	1.5
4.2	0.668	1.49
4.4	0.700	1.43
4.6	0.732	1.37
4.8	0.764	1.31
5.0	0.796	1.26
5.2	0.828	1.21
5.23	0.833	1.2
5.4	0.859	1.16
5.6	0.891	1.12

TABLE D-3

Listing of Damping Parameter, and Time to Half Amplitude, and First-Order Time-Constant Values

Damping Parameter or Factor	Time to Half Amplitude for Oscillations	First Order Time Constant for Aperiodic Motion
$\sigma = -\zeta\omega$	$T_{\frac{1}{2}} = \frac{0.693}{\sigma}$ (or T_2)	$T_{63} = \frac{1}{\sigma}$
rad/sec	sec	sec
0.0346	20.	28.9
0.0693	10.	14.4
0.0866	8.	11.5
0.139	5.	7.2
0.2	3.46	5.
0.231	3.	4.33
0.347	2.	2.88
0.4	1.733	2.5
0.6	1.15	1.66
0.693	1.0	1.44
0.8	0.866	1.25
0.99	0.7	1.01
1.0	0.693	1.
1.2	0.578	0.83
1.386	0.5	0.72
1.4	0.495	0.71
1.6	0.433	0.63
1.732	0.4	0.58
1.8	0.385	0.56
2.0	0.347	0.5
2.2	0.315	0.45
2.31	0.3	0.43
2.4	0.289	0.42
2.6	0.266	0.38
2.77	0.25	0.36
2.8	0.247	0.36
3.0	0.231	0.33
3.2	0.217	0.31

TABLE D-4

Listing of Values of Cycles to Half Amplitude vs Damping Ratio and Angle

Cycles to Half Amplitude		Damping Ratio (Zeta)		Angle of Zeta
$C_{\frac{1}{2}} = \frac{T_{\frac{1}{2}}}{T_P}$		$\zeta = \cos\theta$		$\theta = \cos^{-1}\frac{\zeta\omega_n}{\omega_n}$
(ND)		(ND)		deg
...	--- ---	0.	--- ---	90.
12.6		0.009		89.5
6.3		0.017		89.0
4.2	--- ---	0.026	--- ---	88.5
3.2		0.035		88.0
2.5		0.044		87.5
2.2	--- ---	0.05	--- ---	87.13
2.	Interim Criteria	0.055		86.84
1.1		0.1		84.3
1.	Interim Criteria	0.11	--- ---	83.73
0.54		0.2		78.5
0.35		0.3		72.5
0.295	--- ---	0.35	--- ---	69.5
0.25		0.4		66.4
0.19		0.5		60.0
0.15	--- ---	0.6	--- ---	53.1
0.1125		0.7		45.6
0.1103		0.707		45.0
0.082	--- ---	0.8	--- ---	36.9
0.053		0.9		25.8
0.036		0.95		18.2
0.	--- ---	1.0	--- ---	0.

APPENDIX E

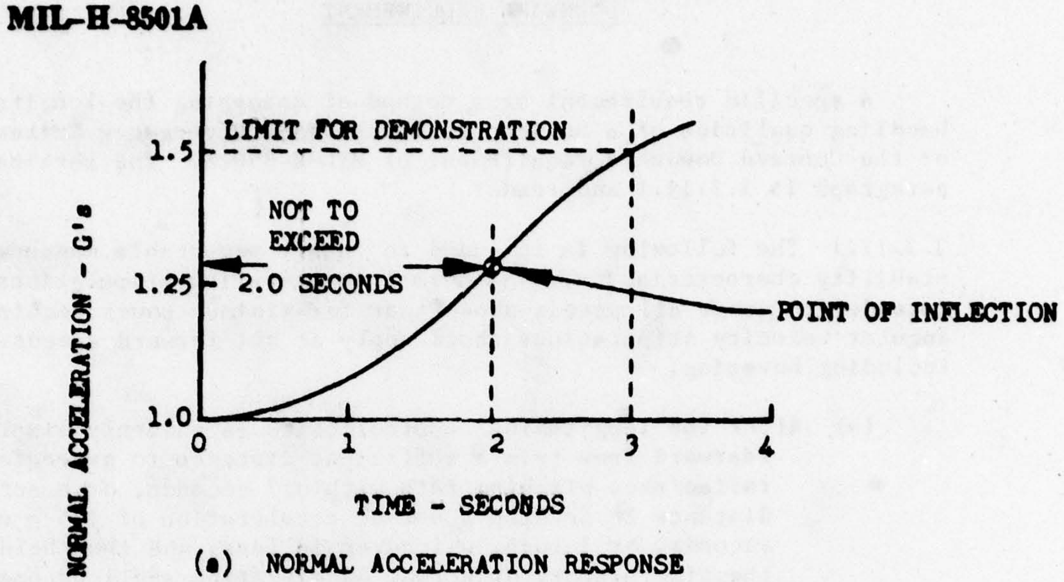
THE DIVERGENCE CRITERION OR CONCAVE DOWNWARD REQUIREMENT

A specific requirement or a method of assessing the longitudinal handling qualities of a helicopter is the NASA Divergence Criterion or the Concave Downward requirement of MIL-H-8501A. The pertinent paragraph is 3.2.11.1 and reads:

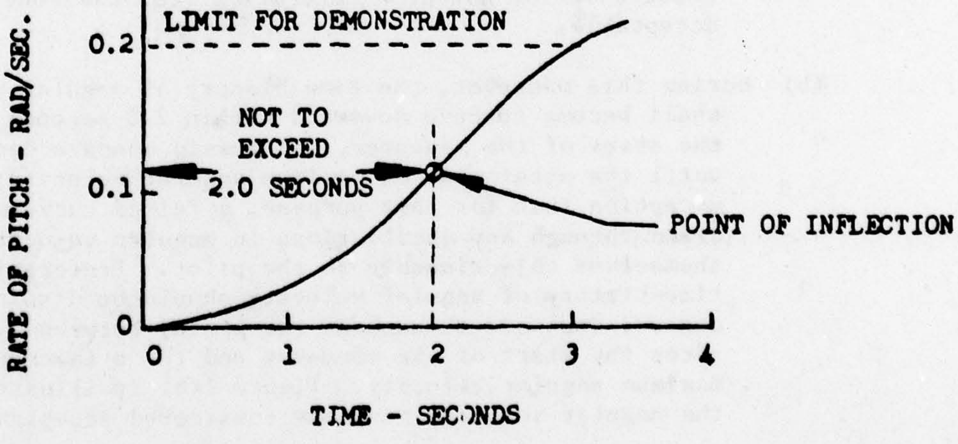
3.2.11.1 The following is intended to insure acceptable maneuver stability characteristics. The normal acceleration stipulations are intended to cover all speeds above that for minimum power required; the angular velocity stipulations shall apply at all forward speeds, including hovering.

(a) After the longitudinal control stick is suddenly displaced rearward from trim a sufficient distance to generate a 0.2 radian/sec. pitching rate within 2 seconds, or a sufficent distance to develop a normal acceleration of 1.5 g within 3 seconds, or 1 inch, whichever is less, and then held fixed, the time history of normal acceleration shall become concave downward within 2 seconds following the start of the maneuver, and remain concave downward until the attainment of maximum acceleration. Preferably, the time history of normal acceleration shall be concave downward throughout the period between the start of the maneuver and the attainment of maximum acceleration. Figure 1(a) is illustrative of the normal acceleration response considered acceptable.

(b) During this manuever, the time history of angular velocity shall become concave downward within 2.0 seconds following the start of the maneuver, and remain concave downward until the attainment of maximum angular velocity; with the exception that for this purpose, a faired curve may be drawn through any oscillations in angular velocity not in themselves objectionable to the pilot. Preferably, the time-history of angular velocity should be distinctly concave downward throughout the period between 0.2 second after the start of the maneuver and the attainment of maximum angular velocity. Figure 1(b) is illustrative of the angular velocity response considered acceptable.



(a) NORMAL ACCELERATION RESPONSE



(b) ANGULAR VELOCITY RESPONSE

Figure E-1. Typical Normal Acceleration and Pitch Rate Response (Reference 5).

GLOSSARY - GENERAL DEFINITIONS

AIR TRAFFIC CONTROL. Service operated by appropriate authority to promote the safe, orderly, and expeditious flow of air traffic.

AREA NAVIGATION (RNAV). Method of navigation that permits aircraft operations on any desired course within the coverage of station-referenced navigation signals or within the limits of self-contained system capability.

AUTOROTATION. Rotorcraft flight condition in which the lifting rotor is driven entirely by action of the air when the rotorcraft is in motion.

CATEGORY II OPERATION. With respect to the operation of aircraft, a straight-in ILS approach to the runway of an airport under a Category II ILS instrument approach procedure issued by the Administrator or other appropriate authority.

CEILING. Height above the earth's surface of the lowest layer of clouds or obscuring phenomena that is reported as "broken", "overcast", or "obscuration", and not classified as "thin" or "partial".

DECISION HEIGHT. With respect to the operation of aircraft, the height at which a decision must be made, during an ILS or PAR instrument approach, to either continue the approach or to execute a missed approach.

VISIBILITY, FLIGHT. Average forward horizontal distance, from the cockpit of an aircraft in flight, at which prominent unlighted objects may be seen and identified by day and prominent lighted objects may be seen and identified by night.

VISIBILITY, GROUND. Prevailing horizontal visibility near the earth's surface as reported by the United States National Weather Service or an accredited observer.

HELIPORT. An area of land, water, or structure used or intended to be used for the landing and takeoff of helicopters.

IFR CONDITIONS. Weather conditions below the minimum for flight under visual flight rules.

IFR OVER-THE-TOP. With respect to the operation of aircraft, means the operation of an aircraft over-the-top on an IFR flight plan when cleared by air traffic control to maintain "VFR conditions on top".

MINIMUM DESCENT ALTITUDE. The lowest altitude, expressed in feet above mean sea level, to which descent is authorized on final approach or during circle-to-land maneuvering in execution of a standard instrument approach procedure, where no electronic glide slope is provided.

NON-PRECISION APPROACH PROCEDURE. A standard instrument approach procedure in which no electronic glide slope is provided.

OVER-THE-TOP. Above the layer of clouds or other obscuring phenomena forming the ceiling.

PILOTAGE. Means navigation by visual reference to landmarks.

PRECISION APPROACH PROCEDURE. A standard instrument approach procedure in which an electronic glide slope is provided, such as ILS and PAR.

RNAV WAY POINT (W/P). Predetermined geographical position used for route or instrument approach definition or progress reporting purposes that is defined relative to a VORTAC station position.

ROUTE SEGMENT. Part of a route, i.c. each end of that part identified by -

(1) a continental or insular geographical location; or

(2) a point at which a definite radio fix can be established.

VFR OVER-THE-TOP. With respect to the operation of aircraft, means the operation of an aircraft over-the-top under VFR when it is not being operated on an IFR flight plan.

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