

**UNITED STATES ARMY
AEROMEDICAL RESEARCH UNIT
FORT RUCKER, ALA**

NOISE PROBLEMS

Associated with the Operation of

US ARMY AIRCRAFT

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**UNITED STATES ARMY MEDICAL RESEARCH
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ABSTRACT

This report describes and illustrates basic, as well as unique, characteristics of noise associated with the operation of Army aircraft. It summarizes the important facts relative to hazardous noise, its effects on man, the characteristics of noise generators, noise reduction concepts, and future noise problems. The purpose is to alert aviation medical officers, flight surgeons, and physicians in the Army to this problem, and provide guidance in those circumstances where a problem of potentially hazardous noise exists.

APPROVED:

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FOREWORD

This report summarizes the results of an experimental research program designed to investigate hazardous noise environments associated with the operation of Army aircraft. The acoustic measurements were conducted by the authors at Fort Rucker, Alabama.

A program of this nature cannot be accomplished without the cooperation of many individuals and organizations. Special credit is due the Flight Operations Division, U. S. Army Aviation Test Board, and the AC of S, G-3, USAAVNC, Fort Rucker, Alabama, for providing aircraft and crew members during field measurements.

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TABLE OF CONTENTS

ACKNOWLEDGMENT		i
ABSTRACT		i
FOREWORD		ii
INTRODUCTION		1
CHAPTER 1. BASIC INFORMATION ON ARMY AVIATION		3
Operational Mission of Army Aircraft	3	
Types of Aircraft and Primary Mission	5	
Brief Description of Operational Aircraft	7	
Current Trends in Army Aviation	10	
CHAPTER 2. METHODS AND MATERIALS		13
Instrumentation and Calibration	13	
Positions and Locations	14	
Relationship of Noise Measurements to Human Hearing	14	
CHAPTER 3. EFFECTS OF NOISE ON MAN		16
Basic Hearing of Man	16	
Auditory Effects of Noise	19	
Non-Auditory Effects of Noise	21	
Speech-Communication Interference	22	
Introduction	22	
Speech Interference	23	
Speech Communications in Aircraft	24	
Basic Hearing in Noise	25	
CHAPTER 4. PROTECTING MAN FROM HAZARDOUS NOISE EXPOSURE		29
Natural Factors Influencing Reduction of Noise	29	
Damage-Risk Criteria for Hearing	31	
Noise Reduction Concepts in Aircraft Design	35	
Personal Ear Protective Devices	36	
General Comments on Ear Protective Devices	39	
Recommendations	40	
Summary	40	

CHAPTER 5. CHARACTERISTICS OF NOISE GENERATORS	42
Basic Power Plants	44
Reciprocating Engines	45
Gas-Turbine Engines	55
Application of Gas-Turbine Engines to Fixed- and Rotary-Wing Aircraft	62
Propeller, Main Rotor, and Anti-Torque Systems	69
Propellers	70
Main Rotor Systems	89
Anti-Torque Systems	94
Transmission, Gear-Reduction, and Gear-Distribution Systems	101
Ground Support Equipment	115
Aerodynamic and Boundary Layer Disturbances	122
Ventilating and Air Conditioning Systems	125
 CHAPTER 6. FUTURE NOISE AND VIBRATION PROBLEMS IN ARMY AVIATION	 126
Army Aircraft Armament Systems	126
STOL and VTOL Aircraft	127
Vibrations Associated with Army Aircraft	129
 APPENDIX 1. PROCUREMENT INFORMATION ON STANDARD ARMY EAR PROTECTORS	 132
 APPENDIX 2. PROPOSED ARMY AIRCRAFT WEAPONS SYSTEMS	 133
 APPENDIX 3. PROPOSED STOL AND VTOL AIRCRAFT	 135
 BIBLIOGRAPHY	 137
 DISTRIBUTION LIST OF USAARU REPORTS	 140

ILLUSTRATIONS

1. Intensity Levels and Typical Human Speech-Hearing Responses	17
2. Hearing Damage-Risk and Speech-Communication (SC) Criteria	23
3. A Simple Sound Wave Generated by a Tuning Fork	29
4. Reduction of Sound Pressure Level with Distance	32

5. Directivity of Noise With and Without Propeller Pitch	72
6. Directivity of Noise Produced by Subsonic and Supersonic Propellers	73
7. Directivity Pattern of Rotational Type Noise	96
8. Directivity Pattern of Vortex Type Noise	97
9. Directivity Pattern of Vortex Type Noise at Low and High Mach Tip Velocities	97
10. Transmission and Gear-Distribution Systems of a Single-Engine Tandem-Rotor Helicopter (CH-21C)	104
11. Transmission and Gear-Distribution Systems of a Twin-Turbine-Engine Tandem-Rotor Helicopter (CH-47A)	107

FIGURES

1. Engine Exhaust Noise of CH-21C Helicopter Measured Underneath the Engine	50
2. Engine Exhaust Noise of CH-21C Helicopter Measured at 45 Degrees from the Exhaust	51
3. Engine Exhaust Noise of CH-21C Helicopter Measured at 90 Degrees from the Exhaust	52
4. Engine Exhaust Noise of CH-21C Helicopter Measured at 135 Degrees from the Exhaust	53
5. External Noise of CH-37B Helicopter Measured at 50' Distance, 2600 RPM, 16" MP	54
6. External Noise of CH-37B Helicopter Measured Near the Engine, 1500 RPM, 16" MP	55
7. External Noise of OV-1B Aircraft Measured at 50' Distance	58
8. External Noise of OV-1B Aircraft Measured at 50' Distance, 0 Degrees	59
9. 0470 Engine Test Noise Measured at a Distance of 5'2" Directly in Front of the Engine	80
10. 0470 Engine Test Noise Measured at a Distance of 6' Directly in the Propeller Plane	81
11. Internal Noise of U-8D Aircraft Measured at Head Level Between Pilot Stations	83
12. External Noise of OV-1B Aircraft During Ground Operations, Propeller Check, 83%, 1400 RPM	84
13. External Noise of OV-1B Aircraft During Ground Operations, Measured at 50' Distance, Flight Idle, 60% RPM	85

14. External Noise of U-1A Aircraft During Ground Operations	86
15. Internal Noise of CV-28 Aircraft During Flight, Measured at Head Level in the Left Seat, Directly in the Propeller Plane	87
16. Internal Noise of U-8D Aircraft During Flight at Normal Cruise, Measured Between the Pilots at Head Level, Propellers in Synchronization	88
17. External Noise of UH-19D Helicopter Measured at 50' Distance, Left Side	98
18. External Noise of CH-34C Helicopter Measured at 50' Distance	99
19. External Noise of CH-47A Helicopter During Ground Operations, Discharging Troops	100
20. External Noise of UH-1A Helicopter at a 5' Hover, Measured at 100' Distance, 6300 RPM, 0 to 180 Degrees Azimuth Readings	101
21. Internal Noise of CH-21C Helicopter During Cruise, 2500 RPM, 37" MP, 70 Knots IAS	105
22. Internal Noise of CH-21C Helicopter Measured at Head Level Position, Center Line Cockpit	106
23. Internal Noise of CH-47A Helicopter During a Hover, Measured at Head Level in the Left Troop Seat Positions	109
24. Internal Noise of CH-37B Helicopter Measured Beneath the Transmission Unit, Station 250	111
25. Internal Noise of CH-37B Helicopter During Cruise, 2600 RPM, 38" MP, 75 Knots IAS	112
26. Internal Noise of CH-47A Helicopter During a Hover, 83.5% RPM, Transmission and Engine Noise	113
27. Internal Noise of CH-47A Helicopter During Ground Operations, 7400 RPM, 150 PSI Torque	115
28. External Noise at Operator Position of MC-1 Air Compressor Unit	118
29. External Noise of MD-3 Ground Power Unit	119
30. External Noise at Operator Position of MD-3 and C-22A Ground Power Units	120
31. External Noise at Operator Position of MA-1 and MA-1A Ground Power Units	122
32. Internal Noise of CH-37B APU Measured at Station 402	123

INTRODUCTION

Intensive research has been and is being conducted by all three branches of the Armed Forces as well as by academic institutions and industry on the deleterious effects of high noise levels. It has long been recognized that continuing exposure to hazardous noise levels may result in temporary or permanent impairment of hearing. Army aviation personnel should, therefore, be familiar with the effects of hazardous noise and with measures which will prevent loss of hearing.

Medical personnel responsible for the health and welfare of aviation personnel exposed to hazardous noise must possess a thorough knowledge of the characteristics of potentially hazardous noise exposures associated with various aircraft operations. In most instances these exposures are complex and vary during different phases of ground and airborne operations. It is the responsibility of these medical officers not only to be familiar with this subject but to identify noise hazards and initiate conservation-of-hearing programs when indicated.

Background.

Between 1960 and 1963 the number of helicopters and light aircraft in the Army aviation inventory has increased from 4,500 to 6,000. Types of these aircraft are numerous, ranging from two-man configurations to larger designs which can transport as many as 32 fully equipped troops. In sharp contrast to this development, helicopter and light aircraft noise problems have been placed in the background as far as hazardous noise exposure is concerned, and although the majority of helicopters and light aircraft do not constitute extremely hazardous noise exposures, they do exceed damage-risk criteria for unprotected daily exposure. The effect of this noise on crew and passengers is rendered more potent because the cockpits of most Army aircraft are poorly sealed, acoustic materials used for sound insulation may be removed to increase payload (recent CH-21 experiences in Vietnam), and they are frequently flown with the windows and doors open, particularly during the summer months.

The Armed Forces-National Research Council Committee on Hearing and Bio-Acoustics (CHABA) was organized early in 1953 to provide consultation and advice to the Armed Forces in the general areas of 1) the effects and control of noise, 2) auditory discrimination, 3) speech communication, 4) the fundamental mechanism

of hearing, and 5) auditory standards. The term "bio-acoustics" includes the direct non-auditory effects of high-intensity sound and vibration on man's body, the relevant problems of noise generation, measurement and control, and the psychological and social reactions of man and of animals to noise. The committee as a whole meets at least annually. However, the major work of CHABA is carried out by "working groups" of consultants who deal with specific questions as they arise.

The military specification for acoustic noise levels in aircraft, MIL-A-8806 (ASG), was approved by the Department of Defense on 8 November 1954 and later revised on 25 October 1956. This specification is mandatory for use by the Departments of the Army, Navy, and Air Force. However, a recent study by the U. S. Army Transportation Research Command³⁴ clearly indicates that most aircraft being operated by the Army do not comply with this directive. It should be emphasized that industry has the capability of reducing the internal noise levels to meet military specifications. Miller and Beranek²⁶ report such an acoustic design achievement in the Vertol -44, commercial version of the CH-21 helicopter. In addition, the data contained in this study relevant to the UH-1A, B, D helicopters clearly demonstrate that good acoustic designing can be achieved in a military version of a modern turbine helicopter.

During the last decade, noise control became a matter of considerable social and economic importance. A need had developed therefore for an authoritative work covering the entire field. The Handbook of Noise Control¹³ was the first book to be published in the United States on the general subject of noise control. In addition, the Acoustical Society of America started publication of Noise Control in 1955²⁸. The U. S. Army Standardization Group, Panel on Auditory and Vestibular Problems, recently expressed its concern regarding the delay in implementing an effective hearing conservation program in the Army. It has been demonstrated that any expenses involved would be minimal compared to pensions paid by the Department of Veterans' Affairs for hearing loss incurred on active duty. Perhaps of more practical significance to Army aviation is the time and cost involved in training key personnel, such as aviators and mechanics, who might have to be relieved of aviation duties if hearing loss is incurred.

Chapter 1

BASIC INFORMATION ON ARMY AVIATION

To be effective, a combat force must have the ability to move, shoot, and communicate. We have seen fantastic developments in weaponry since World War II. The missile has replaced many pieces of artillery. It has even replaced, to some extent, the requirements for certain manned aircraft, both for intermediate range bombing and for intercontinental bombing purposes. Tube type artillery has also taken a backseat in anti-aircraft defenses. Within the immediate future we will see the missile in the hands of front line soldiers as both an offensive and defensive weapon. Communications have also improved at an almost equal rate. With foreseeable applications of vehicles and satellites, global communication techniques which were almost beyond imagination only a few years ago will become a reality. Thus, one of the primary roles offered by Army aircraft is increased communications in the field.

Previous concepts of movement and deployment have become obsolete to a great extent. The large troop and logistic complexes of the past are now prime nuclear targets. Units must disperse over a wide area, yet be quickly moved together for combat action, and again dispersed after the action. Our tactical forces must be ready to move within a matter of hours to combat areas anywhere on the earth. Upon arrival these same troops must be able to move over any type of terrain to take full advantage of the modern weapon systems which they possess. Today's constant threats to peace do not permit the modern commander to think in terms of specific geographic areas in which he might have to fight. He must be fully prepared to conduct combat operations in jungle, desert, mountain, or arctic environments with roads or without. No commander can depend upon having adequate road or rail networks to allow freedom of movement. The full freedom of movement necessary for modern warfare can be provided only by proper utilization of aircraft.

Operational Mission of Army Aircraft.

The primary mission of Army aviation is to augment the capability of the Army to conduct effective combat operations. This mission is accomplished in as many ways as aircraft can be used and in as many places as they can be flown.

Even though the use of aircraft in warfare is relatively new, extensive experience has been gained. Modern aircraft provide the commander with a faster, more flexible means of moving men and equipment into a combat area. Commanders must learn to take full advantage of this additional flexibility by utilizing presently available equipment at every opportunity.

There are few limitations in the use of aircraft. They can be used in the same manner as their ground equivalents. Their missions are parallel. If a requirement exists for a two and one-half ton truck, but no surface transportation is available, the equivalent aircraft should be used. The number and type of support missions which can be assigned to Army aircraft are almost limitless. The limits are generally the imagination of the users and the skill of the operators.

The Army aviator of today is highly skilled, and is required to operate under many adverse conditions. Therefore, a greater degree of refined capability and performance is necessary during all phases of aircraft operations. For this reason, as well as many others, the initial design and construction of Army aircraft should take into account factors which influence or contribute to fatigue and poor communications.

The operational needs which govern the assignment or adaptation of aircraft depend upon four primary objectives or functions. First, command liaison, courier and communication functions, including aerial wire laying, and aviation to assist in direction, coordination and control of forces in the field. Second, observation, visual and photographic reconnaissance, fire adjustment, and topographical survey. These functions include provision of aerial observation to amplify and supplement other Army methods of observation. The primary purposes are locating, verifying, and evaluating targets; adjusting fire and making terrain studies; or obtaining information on enemy forces, complementing that obtained by air reconnaissance agencies of other services. This includes limited aerial photography incident to these purposes. Third, airlift of Army personnel and material. This includes the transportation of Army supplies, equipment, personnel, and small units within the Army combat zone during the course of combat, and logistical operations. Also included is the movement of units to execute airlanded operations, the movement of reserves, and the shifting or relocation of units and individuals within the combat zone as the situation may dictate. The expeditious movement of critically needed supplies or equipment or both, supplementing ground transportation systems operating within the field, is another facet of the airlift function. This does not include joint airborne operations. Fourth, aeromedical evacuation. The function of aeromedical evacuation within the Army combat zone includes battlefield pickup of casualties (except those from the airhead or airborne objective area which is supported by Air

Force airlanded logistical support), air transport to initial points of treatment, and any subsequent moves to hospital facilities within the Army combat zone.

Ultimate utilization of aircraft for Army operations has yet to be obtained. The Army has profited from Korean experience in employment methods and equipment requirements. Large helicopters for troop and equipment movement have already been added to the Army family of aircraft. Modern weapons, with their great speed and range, require the most modern system of target acquisition and surveillance, but aircraft have been procured to perform the mission, and there are many more developments within the foreseeable future. The use and adoption of gas-turbine engines which provide greater horsepower at a reduced weight will be utilized in almost all future aircraft. Each new aircraft is designed for even more simplified maintenance and greater reliability. Although sophisticated by comparison to aircraft of only a few years ago, the aircraft being developed for the future are designed to live and operate with the soldier. For this reason, the vertical take-off and landing aircraft (VTOL) appears to have the greatest application to combat support. Such an aircraft is not dependent on improved airfields. The short take-off and landing aircraft (STOL) are also valuable combat vehicles. Even though STOL aircraft require a landing area larger than VTOL, a 500-foot clearance should prove suitable for the largest transports presently considered.

Types of Aircraft and Primary Mission.

Observation. Observation aircraft are used to report information concerning composition and disposition of enemy forces, troops, and supplies, and to adjust artillery fire. The majority of aircraft in this category require maximum visibility, a high rate of climb, endurance of three hours at cruising speeds, and a slow observation speed. They should be able to carry external loads and to permit vertical and oblique aerial photography. In addition, they are used for command control, liaison, lightweight re-supply, reconnaissance, and emergency evacuation.

Observation aircraft are:

OH-13H	Sioux
OH-23D	Raven
O-1A, E	Birdog
OV-1A, B, C	Mohawk

Attack. Attack aircraft are used to search out, attack, and destroy enemy targets using conventional or special weapons systems. These aircraft are used for limited interdiction, and very close air support missions. When suitably armed, they may also be used as a highly mobile anti-tank weapon. The most commonly used attack aircraft is the UH-1B (Iroquois).

Utility. Utility aircraft are used for numerous missions such as carrying cargo and/or passengers, aerial ambulance service, small tactical support and transport, and command and control purposes. Utility aircraft usually have an operating radius of approximately 300 nautical miles; a capability of carrying cargo for delivery by parachute or free-fall; and quick conversion to accommodate internally at least two medical service litters. Helicopters of the utility type are used for medical evacuation, instrument training, and general missions beyond the normal capabilities of those in the reconnaissance group. Command type aircraft in this category are designed as twin-engine aircraft capable of flying in all kinds of weather without losing the ability to land on short airstrips.

Aircraft in the utility category are:

UH-1D	Iroquois
UH-19C	Chickasaw
U-1A	Otter
U-6A	Beaver
U-8F	Seminole

Cargo. Cargo aircraft are used for logistical support as cargo and troop transports within a battle zone. Cargo types may also be used for such specialized missions as refueling, re-supply of ammunition to combat areas, and the evacuation of casualties or damaged equipment. In addition, those aircraft possessing a VTOL capability may be used as flying cranes to transport surface vehicles and other heavy equipment over natural or man-made obstacles. Designed to carry out the supply and evacuation missions, transport type aircraft are classified by their carrying capability: light transport with the capability of a one-and-one-half-ton payload; medium transport with the capability of three-ton payload; and heavy transport with the capability of a five-ton payload. In addition to payload, each aircraft must have an operating radius of at least 100 nautical miles when carrying a full cargo load and a full passenger capacity; the capability of quick conversion in order to carry as many standard medical service litters as possible; and also possess the ability to fly at night and in periods of limited visibility.

Aircraft in the cargo category are:

CH-21C	Shawnee
CH-34C	Choctaw
CH-37B	Mojave
CH-47A	Chinook
CV-2B	Caribou

Brief Description of Operational Aircraft.

OH-13H Observation Helicopter. The OH-13H, manufactured by Bell Helicopter Company, is a standard observation type helicopter designed for operations in confined areas of a combat zone. It can carry one passenger and two litter patients, or 400 pounds of cargo. It has a range of approximately 180 miles and a cruising speed of 60 miles per hour. The OH-13H is a multi-purpose aircraft designed for training, command and control, wire laying, aeromedical evacuation, radiological survey, armed reconnaissance and security, topographical survey, and light re-supply missions.

OH-23D Observation Helicopter. The OH-23D, manufactured by Hiller Aircraft Corporation, is a three-place helicopter with a single main rotor and anti-torque tail rotor system. Designed for confined areas of the combat zone, it can carry two passengers and two litter patients, or 400 pounds of cargo. The OH-23D is a multi-purpose helicopter designed for training, command and control, wire laying, aeromedical evacuation, radiological survey, armed reconnaissance and security, and light re-supply missions.

O-1A, E Observation Aircraft. The O-1A, E, manufactured by Cessna Aircraft Company, is a two-place, all metal, high wing aircraft designed to operate from short, unimproved or slightly improved airfields in the combat zone. It is capable of carrying an external load of 250 pounds of cargo under each wing, plus 200 pounds of cargo or one observer. It has a cruising speed of approximately 100 miles per hour and a range of about 400 miles. The O-1A, E is powered by a 213 horsepower continental six-cylinder, horizontally-opposed, air-cooled engine. It is a multi-purpose aircraft used primarily for reconnaissance, observation, battlefield illumination, wire laying, radiological survey, message drop and pickup, and radio relay.

OV-1A, B, C. The OV-1, manufactured by Grumman Aircraft Company, is a two-place, twin-engine, turboprop aircraft. The OV-1 is powered by two Lycoming T-53-L-3 turboprop engines, each producing 1,005 equivalent shaft horsepower and turning a three-blade Hamilton standard hydromatic propeller. This aircraft is a tricycle-gear, mid-winged, tri-tail type aircraft with engine nacelles mounted on top of the wings. The OV-1 aircraft is presently used in the Army for combat surveillance. This twin-turbine airplane gives the Army an entirely new capability for carrying a variety of cameras and electronic sensors. It is designed to operate from small, unimproved fields for purposes of visual, photographic and electromagnetic surveillance of target areas. Specifically, this aircraft is capable of being used for visual observation, day and night photography, electronic surveillance, and night and instrument operations. It provides the field commander with timely target

information, aerial fire direction, and post-strike damage assessment for Army medium long range weapons.

UH-1A, B, D Utility Helicopters. The UH-1A, B, or D, manufactured by Bell Helicopter Corporation, is a utility-type compact design aircraft which features the low silhouette and low vulnerability to meet combat requirements. It is a closed cabin helicopter of all metal construction. This helicopter is powered by a single gas-turbine Lycoming engine. The UH-1A can carry one crewman and four passengers; one crewman, two litters, and a medical attendant; or one crewman and a payload of 2,000 pounds. The UH-1B can carry one crewman and eight passengers; one crewman, three litters, and a medical attendant; or one crewman and a payload of 2,578 pounds. The UH-1B may be equipped with armament systems such as the XM-3 2.75" area rocket kit, 6ME3 machine gun kit, or the SS-11 anti-tank guided missile system when used in a fire suppressive role. The UH-1D can carry one crewman and twelve passengers; one crewman, six litters, and a medical attendant; or one crewman and a payload of 2,289 pounds. This helicopter is capable of operating from prepared or unprepared landing areas under instrument conditions. Cargo and equipment not feasible to load within the vehicle can be transported externally.

UH-19C Utility Helicopter. The UH-19D, manufactured by Sikorsky Aircraft, Division of United Aircraft Corporation, is a limited standard utility helicopter capable of carrying six troops or six litter patients, or it can carry a normal cargo load of up to 1,500 pounds. It has a crew of two (a pilot and co-pilot), and a cruising speed of approximately 80 miles per hour with a range of approximately 350 miles. The UH-19 is powered by a single 700 horsepower Pratt and Whitney engine, and has a surface ceiling of 15,400 feet. This helicopter is usually utilized in the movement of troops and supplies. Some other capabilities of this particular helicopter include re-supply, troop transport, reconnaissance and pathfinder operations.

U-1A Utility Aircraft. The U-1A, manufactured by DeHavilland Aircraft Company of Canada, Ltd., has an all metal, high wing configuration. It is an all-weather aircraft, powered by a 600 horsepower Pratt and Whitney engine, and is designed to operate from short unimproved or slightly improved airfields. This aircraft can carry a pilot and ten passengers, a pilot and 2,500 pounds of cargo, or a pilot, four litters, three ambulatory patients, and an attendant. Additional capabilities of this aircraft include the transportation of specialized teams, medical evacuation, battlefield illumination, and aerial re-supply.

U-6A Utility Aircraft. The U-6A, manufactured by DeHavilland Aircraft Company of Canada, Ltd., is an all metal, high wing monoplane powered by a single Pratt and Whitney engine driving a standard constant speed propeller. It is

designed to operate from short unimproved or slightly improved airfields in the combat zone. The U-6A can carry a pilot and five passengers, a pilot and 1,000 pounds of cargo, or a pilot, two litters and two passengers. There are provisions for two racks under each wing, each rack capable of carrying 250 pounds of equipment or cargo. This airplane can be used for courier service, messenger service, light cargo transport, light supply dropping and bombing, paratroop dropping, casualty evacuation, reconnaissance photographic duties, column control, wire laying, or camouflage checking. The U-6A has a non-retractable landing gear which may be replaced by a twin-float installation for operation from water or by ski installation for operations from snow or ice.

U-8F Command Aircraft. The U-8F, manufactured by Beech Aircraft Corporation, is a six-place, low wing monoplane powered by twin supercharge fuel injection engines. The U-8F is an improved, off-the-shelf aircraft, to meet the utility transport requirements of the Army. More versatile than the U-8D that it replaces, the U-8F can be quickly converted to carry litters or high priority type cargo. Distinguishing features of the aircraft are the square-tipped wing and tail surfaces, a large entrance door with integral stairs, three-blade propeller systems, compartmental separation between crew and passengers, and a retractable tricycle landing gear system. At the present time the aircraft is used primarily for transport of commanders and staff on command, liaison, and inspection missions. The U-8F maintains the basic flight characteristics of the older U-8D.

CH-21C Light Cargo Helicopter. The CH-21C, manufactured by Vertol Division of Boeing Airplane Company, is a single-engine, tandem-rotored helicopter capable of carrying two pilots and twelve troops, or two pilots and twelve litter patients. This aircraft has a normal cargo load of 3,000 pounds, a cruising speed of approximately 78 miles per hour, and a cruising range of approximately 400 miles. It is equipped with a single 1,425 horsepower reciprocating engine. Mission capabilities of this helicopter include aerial command post, salvage operations, air-to-ground fire support, and wire laying.

CH-34C Light Cargo Helicopter. The CH-34C, manufactured by Sikorsky Aircraft, Division of United Aircraft Corporation, is powered by a single reciprocating engine with a four-blade main lifting rotor and a four-blade anti-torque tail rotor system. It has space for eighteen troops or eight litters. This aircraft can carry a normal cargo load of 4,000 pounds. It has a cruising speed of approximately 85 knots. Mission capabilities of this aircraft include aerial command post, salvage operations, air-to-ground fire support, and wire laying.

CH-37B Medium Cargo Helicopter. The CH-37B, manufactured by Sikorsky Aircraft, Division of United Aircraft Corporation, is a twin-engine, all metal

helicopter designed as a troop and cargo transport and for evacuation of casualties. It is powered by twin reciprocating engines mounted in pods on each side of the fuselage, and is capable of carrying a load of 5,000 pounds. The CH-37B has clamshell doors and a loading ramp in the nose of the aircraft. It can lift approximately 23 troops or 24 litter patients.

CH-47A Medium Cargo Helicopter. The CH-47A, manufactured by Vertol Division of Boeing Aircraft Company, is a tandem rotor, twin-turbine powered medium transport helicopter. Power is furnished by two Lycoming T-55-L-5 free turbine-type engines. A rear ramp permits rapid straight end loading and unloading of troops, vehicles, and cargo. Bulky items which will not fit into the main cargo compartment may be transported on an eight-ton capacity external cargo hook beneath the aircraft.

CV-28 Medium Transport Aircraft. The CV-28, manufactured by the DeHavilland Aircraft Company of Canada, Ltd., is an all metal, high wing monoplane powered by two Pratt and Whitney reciprocating engines, driving a Hamilton Standard, full feathering, constant speed propeller. The CV-28 can lift more than three tons or 32 troops from an unimproved field less than 1,000 feet in length, and can carry this load to a radius of 175 nautical miles. It has a fully retractable tricycle-type landing gear and a power operated cargo door and ramp which permits direct cargo loading from the rear of the aircraft. The aircraft is designed for transport of troops or general cargo, for supply or paratroop dropping, and for medical evacuation.

Current Trends in Army Aviation.

Murray E. Kamrass²², in his study on trends for the Cornell Aeronautical Laboratory, Inc., Cornell University, commented that "Modern armies, for all their sophisticated impedimenta, such as effective weapons, target-locating devices and advanced communications systems, may be even less mobile than the Roman legions."

Secretary Cyrus R. Vance³⁷, in his remarks to Congressional committees, has stated, "If the history of warfare shows one constant, it is that victory on the battlefield goes to the side that can best maneuver and employ its firepower. This has been demonstrated by Caesar and his legions, by Genghis Khan, by Stonewall Jackson in his Valley Campaign, and more recently, by first the Germans and then the Allies in World War II. The progressive modernization of armies has been very largely a story of the effort of land forces to gain a conclusive advantage in their ability to move and employ their weapons against their enemies. This advantage lies in tactical mobility."

Citing similar military operations as recorded by history in all eras, General Herbert B. Powell²⁹ contends that mobility and firepower were the two most influential military factors bearing on either success or failure. Today the margin of firepower over mobility is undoubtedly the greatest ever attained. Strategic and tactical nuclear weapons, coupled with long-range delivery systems, pose a tremendous threat to any ground transported force. A modern army must have a high degree of elusiveness to avoid becoming an atomic target while at the same time possessing the flexibility necessary to exploit its own weapons, regardless of the type of war being fought. The only effective way of achieving this elusiveness and flexibility is through a concentrated effort toward an adequate airmobility capability.

In view of the increasing demand for tactical mobility, the Army has recently made a number of revolutionary proposals and accomplished significant changes in its organization structure.

The tailored division plan known as "Reorganization Objective Army Division," or "ROAD"¹⁰, is being adopted by the Army. Depending on the mission and operational environment, the division can be tailored by varying the number and type of assigned maneuver battalions within the three brigade organizations in each division. Secretary McNamara has stated that all Army divisions will complete the ROAD transition by the end of the 1965 fiscal year²¹.

On the basis of Hoelscher Committee recommendations for reorganization of the Army, the Army Mobility Command²² became a part of the Army's efforts to achieve the mobility needed to meet its global commitments. The new organization is to solve the difficult problem of mobility in the requirements of modern warfare - the ability to fight and move over swamps, jungles, deserts, mountains, water, and snow, and against opposition ranging from massive modern armies to small hit-and-run guerrilla bands. The Mobility Command will be responsible for research and development, production and procurement, supply management, and development of maintenance equipment for all types of mobility equipment and supplies. For the first time the problem of mobility will not be subordinated to the problem of firepower, and the Army's total mobility requirements will be handled by one organization.

The Rogers Committee on Army Aviation¹ established the requirements for training in support of the Army Aviation program during the period from 1960 to 1970.

The Army Tactical Mobility Requirements Board²⁰, headed by General Hamilton H. Howze, represents a further development and refinement of airmobility

concepts. Briefly, the Board has recommended that: 1) two types of completely airmobile combat units - air assault divisions and air cavalry combat brigades be created; 2) a number of special purpose air units, air transport brigades and corps aviation brigades be formed to give additional reconnaissance and lift capability; and 3) the number of Army aircraft be increased substantially to enhance the mobility of the ROAD division.

The 1964 budget submitted to Congress²¹ provides \$522 million for the procurement of 1,600 Army aircraft and an additional 15,000 training spaces to the Army's active duty strength. These additional aircraft and trained personnel will permit the Army to test the new concepts proposed by the Howze Board.

An analysis of these general guidelines, policy statements, and budget programming for future Army aviation activities indicates that any proposed research or hearing conservation programs for Army aviation personnel should consider the following factors:

1. A tremendous increase in the number of aviators and aircraft.
2. An increase in the utilization of Army aircraft (replacing other forms of transportation, and reduction in maintenance time which will increase the availability of aircraft).
3. A gradual transition from reciprocating to reaction type power plants (a shift to high frequency and variable prop components as significant contributors to noise levels).
4. An increase in the proportion of Army personnel exposed to the hazardous noise environments inherent in the operation of Army aircraft.
5. Increased operations at maximum power, airspeeds, and gross weights due to increased troop and cargo requirements, aircraft armament, and nap-of-the-earth flight techniques.
6. Initial and continuous exposure to instantaneous impact noise (aircraft armament).
7. A proposed reduction in the different types of Army aircraft (approximately 50%).
8. A reduction in the amount of cross-training of aviators.

Chapter 2

METHODS AND MATERIALS

The objective sound pressure level measurement program was designed to include the external noise exposures expected for ground crew personnel (during both maintenance and pre-flight check-out) and the internal exposure levels for crew and passengers. Every effort was taken to insure consistency and comparability of data by selecting the same open, sod area for ground measurements; operating in similar ambient conditions (including low winds); and utilizing the same instrumentation throughout the noise level survey. In addition, all of the aircraft were essentially production models in a normal operational configuration. There was no attempt to select aircraft on the basis of aircraft, engine or component part flight time since this study did not investigate the effects of aging upon the noise characteristics of a particular aircraft.

Instrumentation and Calibration.

The noise levels reported in this study were measured with a Rudmose, Model RA-100 (Serial No. 149). The RA-100 analyzer is a portable unit designed for analyzing noise in terms of sound pressure levels in octave bands. The A, B, C bands of the instrument correspond to the networks for sound level meters, and the eight octave bands are true pass bands extending from 37.5 through 9,600 cycles per second. The microphone used was the standard dynamic microphone furnished with the analyzer (Serial No. 50).

Prior to each use the analyzer was calibrated electrically, and also acoustically, if ambient noise conditions permitted (in situations where the ambient noise exceeded 80 db, no attempt was made to calibrate the instrument acoustically).

The instrument functioned properly during all phases of operation. A 25-foot microphone extension cable was used during the majority of the measurements. No loss or change in calibration occurred due to the use of the microphone extension cable.

Positions and Locations.

The majority of the measurements were made at normal head level positions, either sitting or standing. Head level height in the majority of aircraft ranged from 38 to 48 inches above the floor. In most instances the microphone was placed approximately eight to twelve inches from inside surfaces. The number and exact location of measurements were largely dependent upon the size, configuration, and mission requirement of each aircraft.

Noise measurements on the ground were completed with the microphone placed about 50 inches above the ground and unless otherwise specified, external noise measurements were made with the aircraft and observer on sod.

Positions near the aircraft are relative to angles from the front of the vehicle, or noise generator. Thus, positions directly in front are 0 degrees; positions directly to the side are 90 degrees; and, directly to the rear, 180 degrees (See Illustration 5, page 72).

Relationship of Noise Measurements to Human Hearing.

The intensity of airborne sounds related to human psychophysiological responses are usually measured in sound pressure levels (SPL), and expressed in decibels, reference 0.0002 microbar (dyne/cm²)*.

Noise may take the form of continuous narrow-band or wide-band types; or it may be intermittent sound, including single or repeated impacts or shocks. To evaluate the significance of a given noise exposure, the acoustic energy contained within eight octave bands are usually measured. The most common measurement of a noise spectrum is made in the frequency range between 37.5 and 9,600 cps. A single noise level reading representative of the total intensity within this frequency range is referred to as the over-all level (OAL)**. The following lists the eight octave bands, and their corresponding frequency ranges:

*The decibel represents a relative quantity and thus to have meaning, a reference must be specified. Almost all sound level measuring devices are calibrated to the sound pressure reference of 0.0002 microbar. This reference thus represents "0" db. It is the absolute threshold of hearing for a tone of 1,000 cycles per second.

**The over-all levels (OAL) reported in this paper are representative of those recorded from C-scale measurements. The C-scale represents a relatively "flat" frequency response from 37.5 through 9,600 cps and is the scale commonly used to express the intensity of over-all levels when the noise being measured is greater than 85 db. The over-all level is always equal to, or greater than, the sound pressure level within any of the octave bands.

<u>Octave Bands</u>	<u>Frequency Range</u>		
Band 1	37.5	-	75 cps
Band 2	75	-	150 cps
Band 3	150	-	300 cps
Band 4	300	-	600 cps
Band 5	600	-	1200 cps
Band 6	1200	-	2400 cps
Band 7	2400	-	4800 cps
Band 8	4800	-	9600 cps

Throughout the reading of this paper it should be remembered that the noise environments described and illustrated herein are representative of only one particular set of conditions and the noise may vary from one situation to another. To best evaluate a given noise environment one must complete a detailed noise evaluation of the particular noise exposure under question. Although it is not the intent of this report to present noise exposures that should be accepted unquestionably as representing a set noise exposure for a given type of aircraft, the noise measurements given do offer a means of making a fairly accurate estimate of the type and degree of noise exposures produced by similar noise generators.

There are many factors that have a direct influence on the noise generated by a given aircraft. Throughout this report emphasis is given to various elements, internal and external, that modify or limit the noise generated by various aircraft and aircraft systems during different phases of ground and airborne operations. The reader will find that there are many subsystems used in and around aircraft that contribute significantly to the total noise produced by a given aircraft.

Aeromedical personnel can obtain detailed information concerning the systems and components within aircraft by referring to appropriate Flight and Ground Maintenance Manuals. Changes and modifications of an aircraft's power plants, auxiliary power and related systems, structural modifications, communications and other electronic systems may cause radically different noise exposures. By referring to the information and data contained in these basic manuals, medical personnel can obtain a more comprehensive understanding of the different noise generators as well as mission profiles flown by a given aircraft. This knowledge, coupled with data and information on the noise exposures generated during different phases of operation, provides a meaningful and comprehensive understanding of the relative significance of the noises associated with the aircraft's operation.

Chapter 3

EFFECTS OF NOISE ON MAN

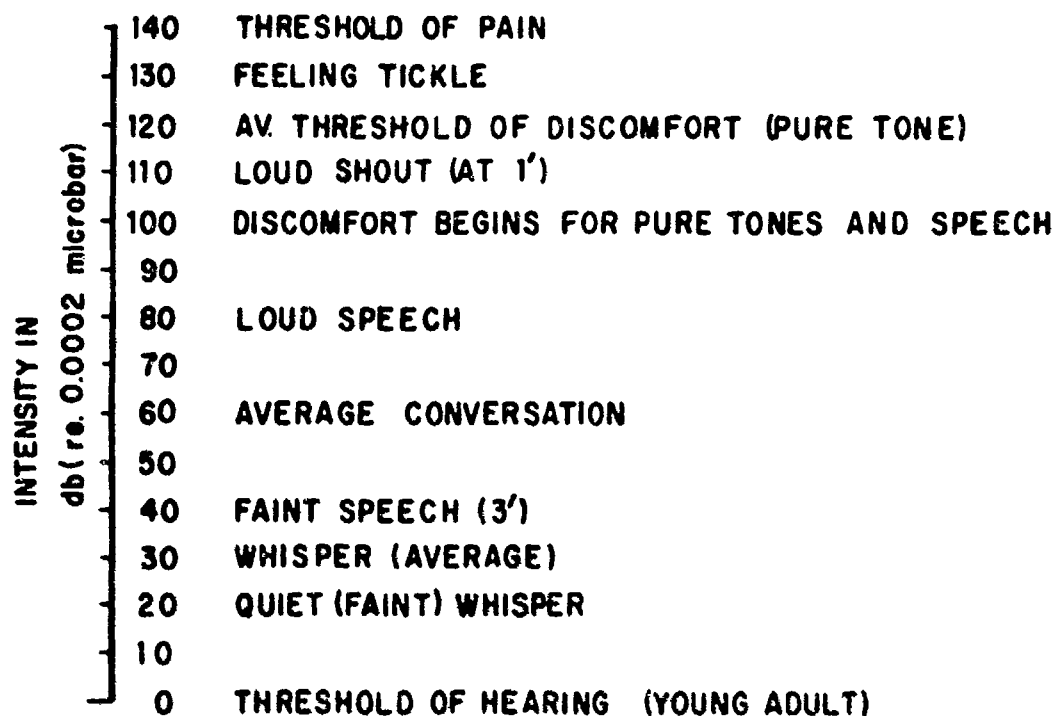
It is known that the ears of some individuals are more easily injured than others by noise. Further, noise usually causes more impairment in high pitched tones above the pitch ranges important for the understanding of speech. In the beginning, therefore, early damage may not be noticed by the individual concerned. Detection of these losses by the flight surgeon is doubly important, for they may be regarded as danger signs of further potential hearing losses. Continued exposure will cause progression of damage including involvement of the speech frequencies which, if allowed to reach an advanced stage, causes severe handicap.

This section will briefly review the more common effects of noise on man. A detailed review of extensive effects can be obtained from numerous texts^{3,5,13,32,33}.

Basic Hearing of Man.

Acoustic energies best perceived by man are propagated through the gaseous medium of air. It is through this medium that man possesses his most acute hearing responses. Basically, the human ear can be thought of as a pressure sensing device that is very sensitive to very slight pressure changes. In fact, a subject possessing normal hearing acuity can perceive, in very quiet surroundings, a tone of 1,000 cps at sound pressure level of as little as two ten-thousandths dyne per square centimeter (0.0002 dyne/cm^2 or microbar). The human ear can also respond to intense sound pressures in excess of 10,000 microbars before interaural distortions occur. Illustration 1 (Sound Pressures and SPL's of Typical Sounds) depicts pressures in dyne per square centimeter and the relative human ear responses. Corresponding sound pressure levels expressed in decibels are shown on the right side, along with various human ear responses.

As amazing as the ear is in its responses to sound pressure, it possesses equally amazing capabilities as a highly selective analyzer. Sounds can be selectively picked out when present in a background of other sounds. Central properties of hearing, such as auditory memory, pitch perception, and loudness relationships, are distinct capacities and abilities of man's hearing - thus, the ear is much more than a simple sound pressure receptor. It is a highly developed and intricate sensory



Illus. 1 Intensity Levels and Typical Human Speech-Hearing Responses

system through which tremendous amounts of information can be perceived. Types of auditory phenomenon perceived by the ear may be simple, like a pure tone, or complex, like speech.

The hearing frequency range for a person with normal hearing is between 20 through 20,000 cps. Hearing acuity at threshold level is not equally acute throughout these frequencies, however. Thus, the ear response at threshold level is nonlinear, but as intensity increases the ears' loudness response to the various frequencies, the response becomes considerably more linear. In fact, frequencies between about 100 through 10,000 cps produce sensations of almost equal loudness at sound pressure levels near 90 to 95 db.

The frequency range necessary for the effective perception and discrimination of speech signals is distributed between about 300 through 4,800 cps, and the most important audiometric hearing frequencies used to represent the basic speech hearing area is defined within threshold responses obtained at frequencies from 500 through 2,000 cps.

Despite the fact that man has a rather wide range of hearing response, the most important frequency range represented by octave bands is between 300 to

4,800 cycles per second. This is the range most necessary for the hearing of speech. Vowel and diphthong sounds contain vocalizations which represent, for the most part, the strongest sounds in speech. These sounds are distributed primarily in the lower portion of speech-hearing range. Consonants are composed of a mixture of voiced and unvoiced sounds; thus, many consonant sounds are not as strong as vowels and diphthongs. The majority of the consonant sounds are distributed in middle and higher frequency ranges. Since consonants are primary contributors to speech discrimination ability, a loss of hearing acuity in the frequencies above 1,000 cps can be expected to create some degree of speech discrimination problems.

Since the ear has rather well defined areas of hearing response, not all noises of the same intensity level will affect the ear equally the same. For instance, a noise of 120 db where the majority of the noise spectra are distributed in frequencies below 200 cps will not mask or interfere with the hearing for speech as much as a noise of the same intensity but where the noise spectrum is primarily present between 300 through 4,800 cps. Generally, noise of reaction type engines masks speech to a greater extent than noise produced by reciprocal engines.

The following describes some of the more important aspects of human hearing throughout the frequency range of man's hearing:

1. The most acute frequency range of hearing at threshold is between 1,000 to 6,000 cps.
2. Expressed by octave bands, the speech-hearing range is between 300 to 4,800 cps, and, when expressed audiometrically, the pure tone thresholds are between 1,000 and 2,000 cps.
3. The least acute range of hearing at threshold is found at frequencies below 1,000 cps.

Although the total range of hearing is usually between 20 to 20,000 cps, frequencies below 20 cps, if intense, can induce tactual vibrations of the body itself. Frequencies above 20,000 cps, if of sufficient intensity, may create heating of the body tissues although this phenomenon is not routinely encountered by man. From research conducted on low frequency response, von Békésy found that many subjects were able to give responses to frequencies as low as one cps³². Here again, however, we are not exactly certain as to whether the subjects were really hearing the stimuli or whether they were detecting it via some other sensory-neural pathway. In any event, future research will probably expand our knowledge concerning the response characteristics of human hearing for very low and very high frequency ranges.

Intensified interest is being shown not only to the total range of hearing acuity possessed by man, but also to its functional limitations. Introduction of aircraft powered by more powerful propulsion systems has created noise levels in lower and higher frequency ranges at intensities that exceed previous exposure levels. The general effects or influences of these intense frequencies on the hearing acuity and hearing functions are questionable.

A particular area of interest in man's response to noise is his threshold of pain. Due to the limited data on the subject, most definitions of pain threshold are not completely satisfactory. The best available evidence indicates that the threshold of pain for most individuals is usually close to 130 to 140 db above the absolute threshold of hearing. It should be remembered that propulsion and armament systems already exist that produce noise levels that considerably exceed the threshold of pain.

Auditory Effects of Noise.

a. Mechanism of hearing.

The pain threshold will be experienced at approximately 140 db (15-2,000 cps). The noise intensity capable of producing damage to hearing, exclusive of duration, has been placed at an over-all sound pressure level of between 150-160 decibels.

Accidental exposures, without ear protection, to levels above 150 db (reference 0.0002 dyne/cm^2) have been known to rupture the tympanic membrane, dislocate the ossicular chain, and cause a permanent loss of hearing.

b. Temporary hearing loss.

Short term changes (loss of hearing acuity) may be caused by excessive noise exposures. Complete recovery takes place but it may require hours or even days. Individual ears vary greatly in their susceptibility to temporary hearing loss. It is not known whether the same ears that show large temporary threshold shift will also be the ones that are the most susceptible to cumulative permanent hearing loss. Generally:

(1) The actual hearing level of the subject influences the degree and amount of temporary shift that occurs.

(2) The shift of hearing acuity after exposure is usually most evident in the higher frequencies, above 1,000 cps.

(3) Broad-band, steady-state noise at 85-95 db for a full eight-hour work day produces an average threshold shift of 10 db at the frequencies above 1,000 cps.

(4) Intermittent, non-steady-state noise exposures at 80-120 db for a full eight-hour work day produces an average drop of 5 db at frequencies above 1,000 cps.

c. Permanent hearing loss.

This type of loss, occurring from noise exposure, is the result of damage to the end organ of hearing, or organ of Corti. The damage is nerve (perceptive) type and cannot be repaired surgically or with medication. It is not amenable to any known treatment. Thus, once acquired, it remains. Temporary hearing losses and permanent hearing losses are not directly related in an isomorphic fashion. Many individuals who experience a marked temporary threshold shift after noise exposures may not experience permanent loss of hearing after repeated day-to-day exposures. In the same way, individuals who experience little temporary threshold shifts after noise exposures may acquire permanent hearing losses after a period of time. Generally:

(1) Noise induced hearing loss is usually bilateral. One ear may be a little better than the other, but both ears will exhibit a loss of hearing acuity.

(2) The frequency area of the permanent loss of hearing is not directly related to the frequency spectrum of the noise exposure that caused the loss.

(3) Even though a rather sharp drop occurs at only one frequency, this does not indicate that only this frequency will be affected with future exposures.

d. Presbycusis.

A loss of sensitivity for tones of high frequency is to be expected as part of the average aging process. The basis of the hearing loss is a degeneration of some of the hair cells toward the basal end of the cochlear. This type of hearing loss progresses from the higher frequency range into the lower frequency range. In many cases it is extremely difficult to distinguish between a presbycusis loss of hearing and a noise induced hearing loss. Reliable norms have been established for both male and female populations.

e. Tinnitus.

"Ringing in the ears" is experienced by many individuals who have been exposed to high intensity noise. It is subjectively apparent at approximately 3,000-6,000 cps, of pure tone in pitch, usually lasts for a short time at a loud level immediately following noise exposure, and then gradually diminishes. However, individuals with permanent losses due to noise exposure usually experience tinnitus for long periods of time. The tinnitus is most noticeable in quiet surroundings. During this study, numerous complaints of tinnitus were registered by instructors and students working in engine run-up areas. This condition would not occur if adequate ear protection were utilized!

Non-Auditory Effects of Noise.

Numerous studies have attempted to evaluate objectively the effect of noise upon human behavior. There is no doubt that noise can, under certain conditions, affect behavior. Whether such effects are beneficial or detrimental is the much disputed question! A brief summary of our present knowledge of these effects is presented below.

a. Psychological.

The work in this area has consisted primarily of developing criteria of annoyance based on variations of loudness, pitch, and modulation. In general, increases in annoyance have been demonstrated under the following conditions: 1) loudness; 2) high frequency pitch (both extremes of spectrum higher than the middle); 3) modulation in intensity or frequency; 4) sound which repeatedly changes its localization; 5) unnecessary or avoidable sounds; 6) sounds that interfere with speech communication; 7) noises consisting of complex sound fields; and 8) tones consisting of brief pulses.

b. Physiological.

No evidence exists that noise below 120 db significantly affects the blood pressure, pulse rate, visual acuity, or an electrocardiograph. However, intense sounds above 140 db may produce increased blood pressure, temperature, sweating, heart rate, glandular changes, and sharp muscle contractions.

c. Performance and efficiency.

This research area contains an extensive amount of contradictory information. Most reliable studies demonstrate little prolonged effect of noise and

the consensus of authorities is that noise below 120 db in intensity has no significant effect upon performance in most situations. Nevertheless, most personnel still prefer to work in a quiet rather than a noisy area. Aviators have reported subjective feelings of greater fatigue and irritability due to excessive noise^{6,23}.

Speech-Communication Interference.

Introduction. Interference with speech communications is one of the most significant areas of concern in most multi-place vehicles. One of the first necessary functions with which noise interferes is voice communication. The average speech power energy emitted by a speaker at a conversational level is approximately ten to twenty microwatts, when the power is averaged over a long time interval. The average sound pressure level for a normal speaking voice is approximately 60 to 70 db (reference 0.0002 microbar). Within the frequency ranges emitted by normal voices, the low frequencies are usually nondirectional, but at frequencies above 1,000 cps directional characteristics and effects are noticeable. The sound pressure level of a normal voice is usually greater in the axis directly in front of the lips, and decreases in magnitude at a position directly behind the head. The relative power of the various speech sounds is dependent, of course, on their voiced and unvoiced components. The power level of the strongest voice sound is approximately 47 microwatts, whereas the weakest consonant sound on the average usually contains a power of approximately 0.03 microwatts. When one takes a look at the relatively small acoustic energy potential of the voice, it is easily understood how even low-intensity noise produces considerable masking effect.

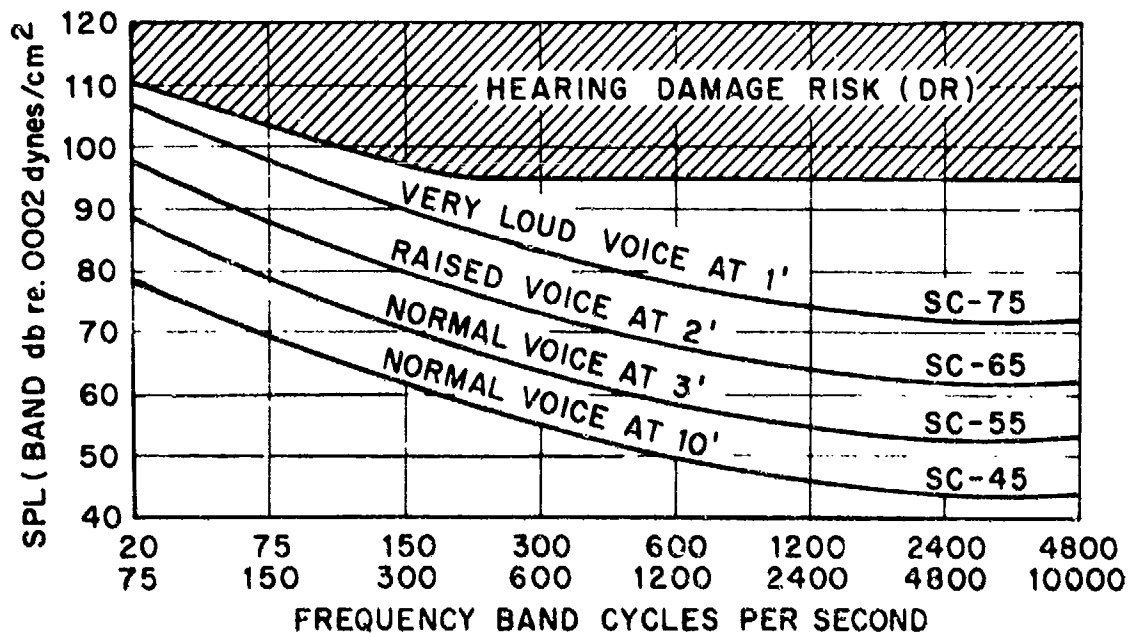
In many working spaces in Army aviation, effective performance of tasks often depends upon the ability of people to converse directly with each other. In these situations noise conditions should be adjusted to make communications suitable to the particular listening tasks that must be performed. The type of communication desired may be of various kinds, *i.e.*, hearing of conversation in a normal voice at a distance of about twenty feet, or being able to hear a danger signal at a distance of six feet. Acceptable noise environments of masking noise are dependent, therefore, upon the particular task involved and upon the degree to which speech communication is required in the performance of these tasks. The frequency spectrum and level of the masked noise, vocabulary used by the personnel, the level and quality of the voice, the distance from the speaker to the listener, and other factors must be considered or accounted for when determining with accuracy the speech interference levels.

In the large majority of noise environments that cause masking of speech, the listener does have the added ability to observe other functions such as movement of lips, gestures, and facial movements which increase total communication ability

by providing visual clues. Thus, the addition of visual clues to auditory clues should be accounted for when determining the true masking influence of a given noise in which personnel must carry on communication. Even though quantitative data is not available at present on the relative importance of such visual clues, it is reasonable to suppose that they do make a contribution.

Speech Interference. An appropriate measurement of the relative interfering effect of noise on speech communication is given in Speech Interference Level (SIL) which is the arithmetic average of the sound pressure levels measured in the three octave bands of 600-1,200, 1,200-2,400, and 2,400-4,800 cps. Engineering data and subjective tests have shown that these three octave bands cover the most important frequency range necessary for the understanding of speech.

Illustration 2 shows curves representing four different Speech Communication Criteria (SC) and Hearing Damage Risk. These curves are labeled SC-45, SC-55, SC-65, and SC-75, and the numbers refer to Speech Interference Levels (SIL).



Illus. 2 Hearing Damage-Risk and Speech-Communication (SC) Criteria

Associated with each of these curves is a corresponding communication condition which includes such factors as the level of voice necessary to maintain effective communication, the distance between listener and speaker, and the general nature of communication allowable. Field studies on speech interference level have provided information on the nature of possible communication in various types of noise environments. For a speech interference level of 45 db, relaxed conversation is possible; for speech interference of 55 db, continuous communication is possible, but usually requires raised voices. Intermittent communication can be carried out at noise levels with a speech interference level of 65 db, whereas only minimal type of communication is possible at speech interference levels of 75 db.

Speech interference levels become inaccurate measures of the masking effect of speech by noise if the noise contains intense low frequency components. Research conducted by Miller²⁵ has shown that low frequency masking noise, below 600 cps, if sufficiently intense, may mask speech completely. Speech interference levels computed from noise measurements taken within or near reciprocating or turboprop type aircraft may be totally inadequate when evaluating the masking effect of the noise they generate. It has also been shown that if narrow-band frequency components are present within 300 to 4,800 cps, the use of a speech interference level averaged from these bands may be meaningless. Research by Stevens, Miller, and Truscott³⁵ shows that a pure tone of 500 cps is the most effective sine wave masker of speech.

In the majority of situations where the masking noise has a smooth type spectrum and uniform time character, the speech interference levels do provide a reasonably good approximation of the effectiveness of the noise in masking speech.

Speech Communications in Aircraft. Man depends on his ability to conduct effective and versatile communication in order to accomplish his daily tasks, and there are many instances in which dependence on effective communication is vital. In Army aviation speech communication assumes a vital role; speech must communicate meaningful information that is understood accurately and immediately. There are many instances in which faulty speech communication contributes to incorrect action that results in decisions or responses that prove fatal. For instance, pilots flying modern aircraft must possess acute hearing ability, especially for speech signals. The majority of speech signals that a pilot depends upon while in flight are usually delivered through an electrical communication system. Recently the majority of voice communication systems have been greatly improved, and in fact, the majority of electrical communication systems have improved to the extent that more and more information is being transmitted to the pilot via auditory means. Previously, pilots had only to hear speech signals, which did not require a high degree of fidelity. Today, however, the ever increasing refinement of the aircraft

as a weapons system necessitates greater dependence on the sense of hearing, as, along with the primary speech signal, the pilot must monitor several other secondary auditory inputs.

Many factors, other than the noise level of the speech signal or the level of the background masking level, determine speech intelligibility. As already mentioned, one of the major determinants of the intelligibility of rather distorted speech signals is the familiarity of the listener with the vocabulary being used. During normal flight operations, the experience of the pilot and other flight crew personnel has a direct bearing on the general intelligibility of oral communications. During an informal research study on hearing in noise among pilots that was conducted at the School of Aerospace Medicine, Brooks AFB, Texas, it was readily apparent that when recordings of ground-to-air transmissions were used to determine hearing function in intense levels of ambient noise, pilots with several years' experience were able to make consistently better articulation scores than non-rated personnel.

Acceptable speech communication is relative to the degree of speech communication ability desired. For instance, the degree and type of voice communication required during a maintenance run-up of a turbine engine is restricted. In most instances the only voice communication attempted is during low power operation of the engine. Ground crew personnel, when working around these aircraft while the engines are operating, usually have one member of the ground crew who is in voice communication with a crew member in the cockpit. The ground crew member outside the aircraft is usually equipped with an APH-5 helmet. The muffs attenuate the masking noise that would otherwise interfere with auditory signals.

Basic Hearing in Noise. Auditory fatigue may create a slight temporary threshold shift; however, the majority of personnel can still carry on effective communication by increasing the intensity of auditory signals. Airborne communication systems allow the crew member to adjust the intensity of the incoming signals to meet his requirements. Only rarely is an individual found who experiences severe abnormal auditory fatigue. If ear protection is worn in intense continuous noise, not only is the hearing better protected against the noise, but also the ability of the individual to perceive meaningful communication signals is increased. The wearing of ear protectors decreases the masking effect of the noise and the desired auditory signal is somewhat easier to hear.

Firing range supervisors commonly complain that personnel wearing ear protectors would not hear warning signals and commands. The fact of the matter is that if all personnel on the range, whether they are firing or not, wear ear protectors, all will talk louder in order to be heard, and thus speech and warning signals can be understood. Public address systems installed at firing range positions have proven very successful.

In the majority of circumstances where noise environments exist that would mask speech, and where speech communication is a necessity, there is usually some provision made to allow communication, at least to a limited degree.

During the early stages of World War II the Psycho-Acoustic Laboratory at Harvard University initiated research designed to investigate the various effects of noise on the crew of an aircraft. During initial investigations it was readily evident that the effect of aircraft noise on psychomotor efficiency was not a major problem. Instead, it was found that the most serious effect of noise on the personnel of an aircraft was the decreased ability to gain full use of the communication and navigation facilities available.

There are various types of noises that may mask speech communication. The masking noise may have a continuous frequency spectrum, and may be continuous in time; it may have periodic components of one or more frequencies; or it may have irregular or impulsive characteristics. To accurately relate the masking effectiveness of a given noise environment one should have a knowledge of the general masking characteristics of the type of noise that is masking speech.

The greater majority of laboratory investigations have used white noise as a masker. In such experiments articulation scores for several types of materials have been plotted, and as already mentioned, articulation test results are significantly better for words in sentences than with isolated words selected from special vocabularies.

Harmon and King¹² conducted research on the vulnerability of human performance in communications. They stressed that the human link is one of the major problem areas related to military communications. Some of the major areas which influence the relative vulnerability of effective communication include:

1. Characteristics of the message, including the amount of information and intelligibility.
2. The physical environment, with emphasis on noise, atmospheric and thermal conditions, and stress, including isolation and confinement.
3. Characteristics of the human operator including sensory, perceptual, and intellectual capabilities; vigilance and susceptibility to fatigue; training and memory; social, motivational, and personality factors; and psychopathology.

Thus it is easily seen that there are many factors that may have a direct or indirect bearing on the final effectiveness of human communication abilities.

Noise may be one of the major considerations, but it is certainly not the only factor that has an influence on the ability to communicate.

The majority of noise environments where speech masking is a problem usually contain a noise spectrum that is not equally distributed throughout the hearing range, as is white noise. Miller²⁵ reports that high frequency bands of noise are more effective maskers of speech than are frequencies below 1,000 cps. At high noise levels, however, low frequency bands become more effective maskers.

Pure tones of low frequency mask speech more effectively than high frequency tones. Tones of between 300 and 500 cps are the most effective speech maskers. Square waves and pulses mask speech somewhat more effectively than sine waves since they contain frequency components that extend over a wider frequency range. However, for frequencies above 1,000 cps, sine waves, square waves, and pulses are not effective speech maskers.

Holland and Lee¹⁶, reporting on research they conducted on the influence of message distortion and message familiarity, found that introduction of a distracting task had a detrimental influence on the perception of materials presented by auditory avenues. They also found that previous familiarization with the material being presented significantly increased the intelligibility of distorted messages as presented, and finally, that familiarization was significantly more effective when provided through the same sense channel as that through which the distorted form of the message was subsequently presented.

Carterette and Cole⁸ conducted research on repetition and confirmation of messages received by auditory and visual senses. An attempt was made to determine how the auditory and visual modes of reception compare over successive repetitions of a message. A rating method was used to obtain operating characteristics for 60 heterogeneous words, and to make specific comparisons of the visual and auditory modes of reception. A single message was sent under difficult conditions of reception and was repeated until it had been assigned to the highest accuracy category or until it had been sent a maximum of six times. The comparisons showed that, over successive repetitions, accuracy of reception is a direct function of the confidence rating and is relatively independent of the intelligibility level. The accuracy of reception and the distributions of rating categories did not change markedly over trials.

Green¹¹, in a study of detection of complex auditory signals in noise, found that the human ear functions somewhat like a series of bandpass filters when receiving meaningful signals in an auditory field mixed with unwanted signals. The ear seemingly has the ability to widen or restrict the bandpass type filtering

characteristics of the hearing mechanism. Licklider¹⁹, in a report on aural presentation of meaningful information, stressed the fact that many areas of auditory ability are seemingly unexplored, and considerable research is needed in order to define, with accuracy, the degree to which hearing functions for a given task can be defined. For instance, he found that the detectability of a sinusoidal signal depends upon its duration and its frequency, as well as the distribution of signal energy over frequency.

When speech materials are presented by earphones, interaural phase has an influence on the detectability of the auditory signal. Hirsh¹⁵ investigated the effect of interaural phase on speech perception. Results of his research demonstrated that the phase relations of the speech and the noise at the two ears affect not only the masked threshold but also the articulation scores that are obtained for a given speech-to-noise ratio. For instance, when either speech or noise reaching the ear are 180 degrees out of phase, speech discrimination was significantly better than when the speech and noise signals were in phase (0 degrees). Thus, if two persons are speaking in an environment of noise, if the speech signal can be localized, the ability to understand the speech being uttered will probably improve. In very reverberant noise fields where speech localization is extremely difficult, if not impossible, speech discrimination would probably suffer.

The most effective application of interaural phase relationships is in situations where the ambient noise is high and the speech signals are being received through headsets. In fact, the majority of receivers of binaural headsets are connected so that the signal will be out of phase (180 degrees), thus taking advantage of the slight increases offered by interaural phasing.

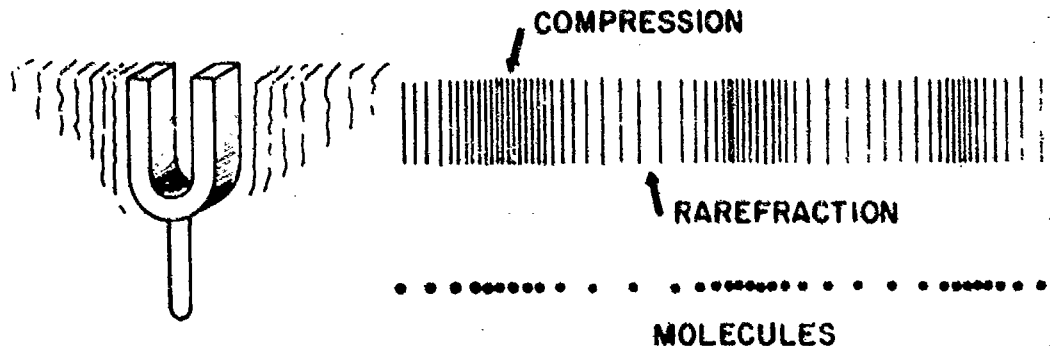
Chapter 4

PROTECTING MAN FROM HAZARDOUS NOISE EXPOSURE

Natural Factors Influencing Reduction of Noise.

At the majority of Army installations where aircraft operations are routine, a complexity of noise sources exist. Medical personnel must possess a fundamental understanding and knowledge of various factors that influence noise propagation. As part of aviation planning and expansion, the surgeon is often requested to assist post engineering personnel in assessing and evaluating noise along with other undesirable factors when a new construction is being contemplated. For instance, where is the best place to locate a new engine run-up area? To best evaluate this, as well as other noise problems, one should have an understanding of basic factors which can, and often do, influence noise propagation.

The most common pathway traveled by noise is through the medium of the surrounding air - the atmosphere. Illustration 3 depicts a simple sound wave generated by a tuning fork and propagated through the medium of air. Of course, in this illustration, the molecular displacements occurring in the air (gas) medium are one-dimensional, but they still represent the end result of such an acoustical disturbance - alterations in barometric pressure as a result of disturbances in the forms, condensations, and rarefactions of the molecules of air. The surrounding air is being constantly changed and altered by such factors as temperature, humidity, wind currents,



Illus. 3 A Simple Sound Wave Generated By a Tuning Fork

and density. Many of these factors, acting independently or combined, have a direct influence on the amount of noise that finally reaches a given point at a distance from its source.

Extensive researches and investigations have been conducted in attempts to answer the many questions concerning the characteristics of factors that influence the propagation of sound through an atmospheric medium, and much information and data have been obtained. It is not within the scope of this report, however, to present detailed information, but rather to present basic and brief concepts concerning the propagation of noise in open air.

The sound pressure level of a noise propagated in an ideal, homogenous atmosphere will decrease inversely to the square of the distance. Basically, a noise produced by a given noise generator, if propagated in an open space, would experience a considerable loss of acoustic energy due to spherical divergence from the source of the noise. In other words, as distance increases, the noise is going to have to "fill out" or "spread out" through a constantly increasing area, until finally the acoustic energy possessed by the noise has been spent or used up.

As it is not possible to predict all of the factors that might influence a given noise during its passage through the atmosphere, a review of some common factors, which are always present in varying combinations, may be of help in evaluating the effects of sound propagated in open air.

1. Altitude: Generally, the magnitude of the noise propagated at a given distance is progressively less with increasing altitude, since the density of the air decreases with altitude. The velocity at which sound travels is less with increased altitude, due to decreased temperature.

2. Temperature: Temperature is difficult to evaluate alone, but generally without the effect of wind, high (hot) ground level temperatures cause deflections which usually result in greater noise attenuation with distance from the source, and is primarily the result of heat inversion.

3. Wind: Wind currents, since they create disturbances in the atmosphere, likewise produce significant disturbances in the noise being propagated in the medium on which the wind is acting. Generally, the magnitude of a given noise is more intense at downwind positions from the source.

4. Humidity: Increased humidity increases molecular absorption and thus a greater attenuation of the noise exists and the amount of absorption of noise energy is due to viscosity of the air and the amount of water vapor in the atmosphere.

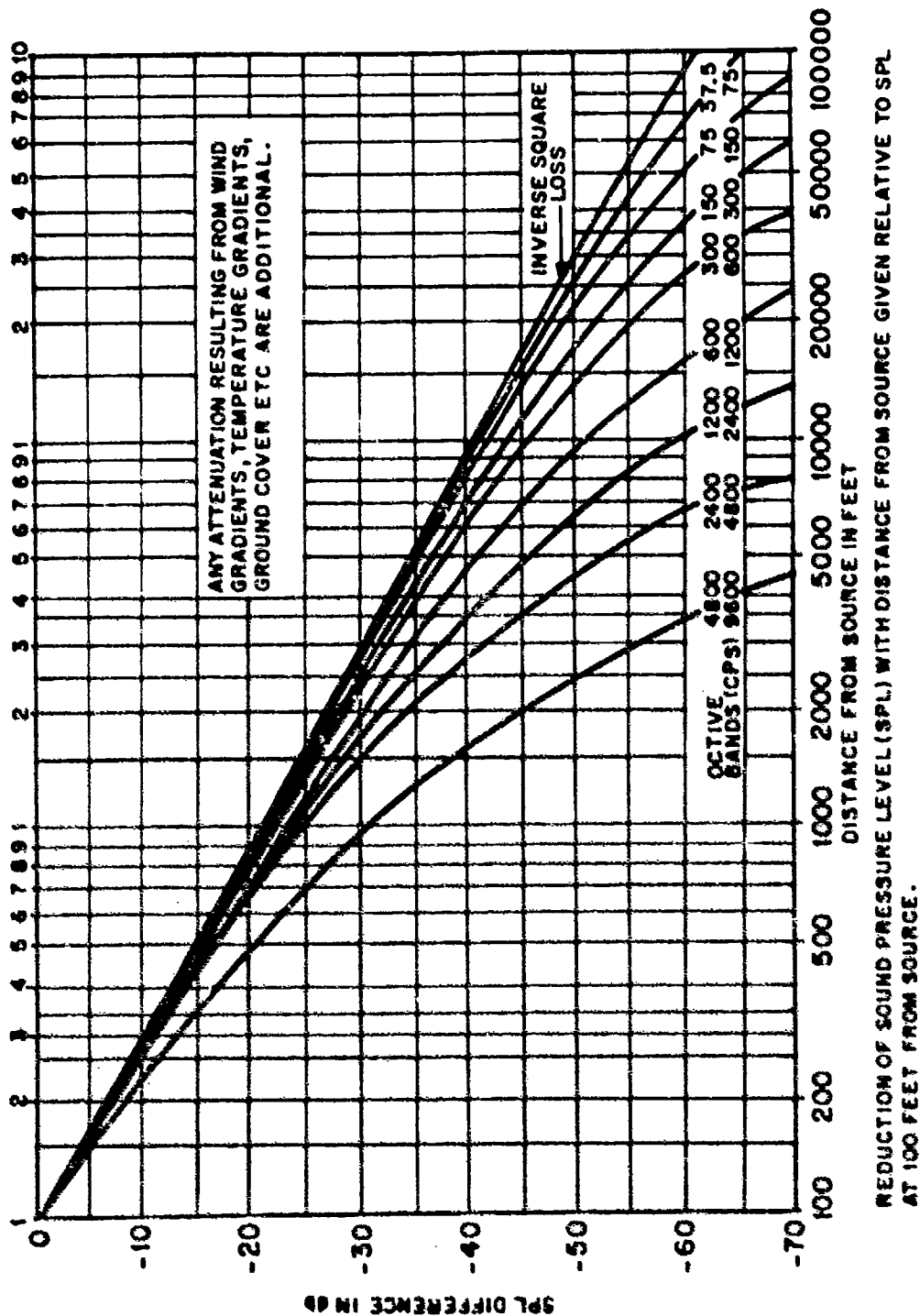
Generally, there are two processes by which acoustic energies are attenuated in an atmosphere: heat conduction and molecular absorption. Illustration 4 depicts the relative attenuation of sound expected in a normal atmosphere with relatively normal conditions of humidity and temperature, and without the effects of wind. As noted, following the plotting of the "inverse-square-law" shows a sound pressure wave decrease of approximately six db per doubling of the distance. Along with the inverse-square-law, are plottings of the amount of attenuation expected within eight octave bands from 37.5 to 9,600 cps. Note that the amount of attenuation expected at different frequency bands at a given distance from the source increases as frequency increases.

It is easy to understand why community noise problems are usually associated with noise generators that produce intense low frequency noise, such as large turboprop engines. Thus, if a large turboprop engine is operating at full power, the high frequencies are easily attenuated before they reach any great distance, but the low frequencies lose a much smaller amount of noise at the same distance.

Even though these curves represent a more or less theoretical condition, experience has shown that the amount of noise attenuations shown are usually exceeded in actual practice, especially at distances greater than 1,000 yards from the source.

Damage-Risk Criteria for Hearing.

Noise has been a constant companion of mechanization and industrialization. The acoustic energy associated with early power and propulsion systems was a by-product which offered no apparent advantage, but since the noise produced by these various machines could not be abolished, its presence was more or less accepted, and little, if any, concern was given to it. Man could "ignore" the greater majority of noises associated with high energy power and propulsion systems until they actually became painful. Man, judging from past experiences, and with regard to the degree of knowledge about such phenomena that existed at the time, believed that "pain" was a quite adequate criterion of whether or not a particular noise was harmful. But it soon became fairly evident that exposures to noises far below levels required to elicit physical pain could possibly create hearing losses, and unprotected exposures to some noises could, and evidently were, producing undesirable psychological and physiological results. From early twentieth century reports, and from the thousands of researches, investigations, studies, and observations that followed, increased interest and concern were being given to the possible undesirable effects of noise on hearing. Today universal acceptance is given to the premise that noise exposures under certain conditions can, and do, create both temporary and permanent threshold shifts of hearing.



Illus. 4 Reduction of Sound Pressure Level with Distance

Early in the 1950's it was becoming increasingly evident that some hazardous noise exposure criteria must be established. The major emphasis was to be placed on the establishment of a workable standard that would minimize, to the greatest extent possible, occurrences of permanent threshold shifts among those routinely exposed to noise. In July, 1950, the American Standards Association Sectional Committee Z24 on Acoustics, Vibration, and Mechanical Shock, discussed and devised plans for establishing a subcommittee composed of experts in the fields of hearing and noise to determine the allowable noise levels of day-to-day noise exposure. In May, 1951, the Z24 Committee authorized its chairman, Dr. L. L. Beranek, to appoint an exploratory group to make a special study of permissible, objectionable, and injurious effects of noise. Within a year a chairman of this special subcommittee was appointed and in May, 1952, Subcommittee Z24-X-2 on "Bio and Psycho-Acoustical Criteria for Noise Control" was established. Since the Subcommittee was to operate as a working group, its membership was limited to a small group of specialists. To broaden its application to many related noise exposure areas, frequent consultations and meetings were made with parent organizations and groups. The Subcommittee concentrated on an attempt to evaluate the various industrial noise criteria that had already been proposed by various organizations and groups. During these early meetings it became apparent that these criteria were based on fragmentary and frequently inadequate or incorrect evidence. Thus the Subcommittee decided to make its own collection and evaluation of data available from industry concerning allowable noise levels. To assist in evaluating and collecting this information and data the Subcommittee engaged Dr. Wayne Rudmose, who conducted a survey on the relationship of hearing loss to noise exposure.

Generally, the criteria developed during this period state that in the frequency range above 300 cps the sound levels in any one critical band shall not exceed approximately 85 db (reference 0.0002 microbar)¹⁸. Exposures to frequencies below 300 cps were not well defined, and only estimates were offered⁴.

The research during this period formed the basis for many military directives pertaining to hazardous noise exposures and conservation of hearing^{2,24,36}.

There are four basic factors that are generally specified in order to estimate the significance of a noise exposure: type of noise; intensity of noise; frequency spectrum of noise; and total duration of exposure per eight hours. The factors to consider when determining the estimated damage-risk of a given noise are:

1. Frequency spectrum: Narrow-band or impact type noises are given a ten db greater weighing value than is wide-band type noise. The noise levels recorded in the four frequency ranges from 300 through 4,800 cps are recorded and then the total is averaged and noted.

2. Intensity: The number, representing the average of the levels recorded above, is then evaluated. The "starting point" for intensity of exposure is, as stated, dependent on the type of noise. If narrow-band or impact type noise, the starting point for allowable exposure is 85 db; if wide-band, the starting point is 95 db.

3. Duration: One of the major consideration factors of the degree of damage-risk is the total duration of exposure per day.

The following table shows the general relationships of these factors when estimating the over-all damage-risk of a particular noise.

TYPE OF NOISE				Duration of Exposure in Minutes	
Narrow-band or Impact		Wide-band			
85 db	or	95 db	for	480	(8 hours)
95 db	or	105 db	for	48	
95 db	or	115 db	for	4.8	
105 db	or	125 db	for	.48	
115 db	or	135 db	for	.048	
125 db	or	145 db	for	.0048	

As noted from the above table, each ten db increase in the average sound pressure levels above a given point resulted in a movement of the decimal point by one place. For instance, if the noise exposure for a single turboprop engine run-up per day averaged 125 db within the frequency range from 300 through 4,800 cps, the maximum allowable time of exposure for an unprotected ear, per normal work day, would be about 48 hundredths of a minute. This represents an almost impossible situation. If the subject wore a set of ear protectors that offered an average attenuation (300 to 4,800 cps) of twenty db, he could remain in the same noise field for approximately 45 to 50 minutes per day.

As mentioned earlier, there are several important factors that medical personnel should consider when attempting to determine the relative degree of damage-risk resulting from a given type of noise exposure. For instance, damage-risk criteria are based on statistical evaluations of a large population group. Therefore, it does not take into account individual differences that may, and in all probability do, exist among aviation personnel. Some individuals have worked in moderately intense noise environments for many years and their hearing does not demonstrate losses of hearing acuity as a result of noise exposure; however, others who have worked in similar noise environments for the same period of time demonstrate greater

losses in hearing acuity than would be normally expected. Because of the great number of individual differences in noise reactions, and the emphasis placed on noise induced hearing impairment, it is easy to understand why the majority of proposed damage-risk criteria are quite conservative.

It should be remembered that the primary reason for the existence of a damage-risk criterion is to reduce, to the greatest extent possible, the occurrence of noise induced hearing losses among persons exposed to potentially hazardous noise. Thus, if the noise existing in a given area is considered potentially hazardous, it is better to require that more ear protection be worn than to discover, at a later date, that the noise was hazardous and that ear protection had been needed.

Noise Reduction Concepts in Aircraft Design.

Since excessive noise produces adverse effects on the occupants of aircraft, on equipment, and on structures, greater emphasis is being placed on noise control during the initial stages of design and construction. Noise control during initial design effectively reduces what otherwise might have been excessive and undesirable effects of noise and vibration. Aircraft designers are required to consider noise levels within occupied areas of the vehicle during all phases of ground and airborne operations²⁴. Emphasis is placed on the effects of the expected noise, not only on man, but on equipment, structures, and components. Aircraft designers and manufacturers must conduct a complete noise analysis which includes:

1. Conservative estimates of noise exposures occurring in occupied areas, areas containing equipment or components, structures near propulsion devices, and areas occupied by maintenance crews during ground run-up.
2. The type of noise spectrum specifying whether the noise has continuous, discrete, or mixed frequency components. These noise evaluations will be completed during all phases of ground and airborne operations.
3. Noise measurements of propulsion systems, ventilation systems, propellers, and other noise sources will be completed in order to increase the accuracy of the noise evaluation.

Noise control must be considered in the initial phases of aircraft design. Listed below are several considerations which may assist in reducing the undesirable noise:

1. Have propeller tip to fuselage clearance as large as possible.

2. Locate the exhausts of propulsion type engines as far aft and outboard as possible.

3. Mount transmissions, engines, and other vibration producing equipment on vibration isolation mounts, or at least on nonmetallic surfaces so that structurally borne noise is kept at a minimum.

4. Consider air velocities and locations of air conditioning outlets from an acoustical standpoint. Locate outlets as far from head level as possible.

5. Provide clean interior trim lines so that soundproofing may be installed at a later date, if deemed necessary.

6. Provide effective acoustical seals around doors, windows, ramps, etc., to prevent direct passage of noise between the exterior and interior of the aircraft. Effective seals also reduce noise produced by the passage of air over and through openings during flight.

7. Locate personnel compartments and noise sensitive equipment in low noise areas of the aircraft.

8. Locate maintenance check points and select check methods which insure minimum noise exposures.

Of course, the desired method of noise control is reducing the noise at the source. This is not always practical or possible, but consideration of certain critical factors during the original design: 1) type and location of the power plant; 2) type, diameter, and number of blades of the propeller; 3) type and location of air conditioning and ventilating equipment; 4) type, size; and location of transmissions; and 5) selection of electrical equipment that has low noise characteristics - will help the designer control or reduce noise and vibration. In some instances, soundproofing may be employed to reduce noise. However, since soundproofing materials increase the weight of the aircraft, their use is limited.

Personal Ear Protective Devices.

The importance of noise protection in many current Army aviation operations has resulted in continuing requests from various agencies for guidance on the most effective ear protectors. There are several recent comprehensive laboratory evaluations which summarize the effectiveness of noise-attenuating devices marketed by various manufacturers^{14,27,38}. In addition, K. K. Neely, et al, have a series of Canadian Research Medical Laboratory (DRML) reports collectively entitled

"Acoustic Properties of Headgear." Most of these are classified Canadian "Restricted" and, therefore, "Confidential" in the United States.

This section will present information on ear defenders and summarize important facts concerning the utilization of these ear protectors by Army aviation personnel. Procurement information is listed in Appendix 1.

Helmets: The Helmet, Flying, Protective APH-5, contains electrical headset H-75B/ATC with foam rubber earphone cushions. The amount of acoustic insulation provided by any aviator helmet is determined primarily by the type of ear cushion used therein. The black foam rubber cushions utilized in the present APH-5 helmet provide very poor attenuation in the low frequencies and less attenuation than the V51R ear plugs in the high frequencies.

One of the major factors affecting the attenuation of an earmuff, particularly at low frequencies, is the ability of the muff to seal itself to the head in the area surrounding the ear, thereby reducing the leakage of sound into the cup. Leakage can be caused by several factors: 1) due to the sling type suspension, an aviator may reduce its effectiveness by pulling the cushion away from the ear and preventing a good seal around the external ear; 2) when holes are punched in the cup to lead wires to an earphone or to provide a pressure release (cell holes in the muff must be provided with an airtight seal if the muff is to be an effective attenuator of sound); and 3) when eyeglasses are worn the metal or hard plastic earpieces must pass underneath the seal and a relatively large leak may be formed.

Earmuffs: The MSA Noisefoe Mark II model consisting of plastic ear cups with foam-filled pads and an adjustable headband is the standard Army earmuff. It provides eight to ten db of sound protection in the low frequencies (125-500 cps), an average of 25 db between 500 and 2,000 cps, and reaches a peak of 55 db at 4,000 cps^{14, 27}.

After reviewing the aural protector requirements, the Preventive Medicine Division, OTSG, has recommended that the David Clark Straightaway Model 372-8A and the Willson Sound Barrier 258 be adopted as Standard-A type for Army use.

The David Clark Model 372-8A is now Air Force Standard^{27, 38}. This model uses polyvinyl chloride closed-cell foam to make the ear seals and headpad. It attenuates noise over a wide range of frequencies and provides maximum comfort for prolonged periods of time.

The Willson 258 Protector³⁸ has replaceable fluid-filled vinyl ear seals that provide an airtight fit around the ears, polyurethane sponge inside each ear cup,

front and back fitted thermoplastic ear cups designed for maximum noise deflection, and a compact and lightweight headframe adjustable (by means of a slide hook) while being worn.

Ear plugs: The amount of attenuation and sound protection provided by the standard Army ear plug, V-51R (Mine Safety Appliance Company) has been verified in many publications^{14,27,38}. Approximately 25 db in the low frequencies (125-1,000 cps) and 35 db in the high frequencies (1,000-8,000 cps) can be obtained if the correct size is properly inserted into the ear canal. The V-51R is designed in five sizes to accommodate 95% of the male population. The ear plugs will last for one to two years in use. They may be cleaned with soap and water and provide inexpensive and effective ear protection.

At present, the two nonstandard ear plugs available to Army personnel are: 1) the Surgical Mechanical Research Ear plug, and 2) the Flents Anti-Noise Ear Stopple. The Preventive Medicine Division, OTSG, has recommended that both items be adopted as Standard-A type for Army use.

The SMR Ear Plug provides basically the same attenuation as the V-51R^{27,38}. Additional sound protection can be obtained if the plug is inserted deeply into the ear canal whereby 1) the acoustic seal creates a positive pressure in the captured air behind the plug, or 2) the device approaches or seals in the bony meatus, resulting in higher values of attenuation. The SMR is very comfortable for persons having straight ear canals. Discomfort may be experienced by those who have ear canals that are not straight, or when a positive pressure is created in the ear canal at the time of insertion of the plug. Retention in the ear canal is fair. The ear plug is washable in soap and water.

The Flents, a wax impregnated cotton ear plug, also provide attenuation almost identical to the V-51R²⁷. This material is shaped by the wearer to fit his own ear canals. User acceptability of this device is varied. The plugs become noticeably soiled when shaped by the wearer to fit his ear. Personnel who work frequently with fuels, lubricants, hydraulic fluids, etc., find the plugs too soiled after being handled. These ear plugs are usually discarded after one wearing. The use of Flents is especially applicable in situations in which personnel need only one-time use.

There are four requirements which must be met to insure user acceptance and maximum use of ear plugs: 1) The ear plugs must fit. They should be distributed only by persons who have been trained in the proper method of ear examination and plug fittings (preferably personnel assigned to the aviation dispensary). Each ear must be fitted separately since the size of the external canal often differs within the

same individual. A plug which is subjectively too large frequently proves to be too small; it feels large because it extends into the tender portion of the canal. The ear plugs should be large enough to seal tightly, but not so large as to cause true discomfort. Placing external objects into the ear is not a natural phenomenon, therefore a tightly fitting plug may feel uncomfortable until the individual has some feeling of what a good-fitting seal is like. 2) Each man must be taught how to insert and remove the ear plugs. Most men, and especially those with large fingers and short nails, will require considerable practice before they can insert ear plugs quickly and easily. Many do not get the full benefit of the plugs, or cannot use them at all, through lack of such indoctrination. 3) Personnel must be informed that they can hear voice and other auditory signals more clearly by utilizing ear plugs under noise conditions. This is true for both direct voice and radio communication. 4) Each man must be cautioned that his own voice will appear relatively loud to him when ear plugs are worn. Therefore he must raise his voice above the normal intensity so that it will be loud enough for others to understand.

General Comments on Ear Protective Devices

Insert type ear protectors are small enough to be carried easily and conveniently when not in use, and in this respect are superior to over-the-ear type protectors. This is especially true for persons whose need for ear protection is intermittent and/or is apt to be in areas distant from a supply of ear protectors.

A number of people cannot wear standard insert type ear protectors because of such conditions as infection in the external auditory canals, fungi in the external ear canal, and unusual sizes and shapes of ear canals. These individuals must rely on over-the-ear, noninsert, and helmet type devices for sound protection.

Over-the-ear type protectors provide warmth for the ears in cold weather. However, in warm and hot weather the devices become uncomfortably warm and cause excessive perspiration about the ears and neck. Over-the-ear type protectors are frequently incompatible with various items of personal equipment such as eyeglasses, parkas, and hats.

An ear plug-earmuff combination is more complicated to wear and remove than is either single device. Care must be taken so as not to break the acoustic seal of the ear plug when the muff or helmet is put on. Adjustment of the ear plug is more difficult when it is worn under an earmuff or helmet. Such adjustment will be necessary if the ear plug becomes unseated during use (i.e., pressure differential), or if momentary removal of the plug is desired.

Recommendations.

Mechanics, fuel truck drivers, and others whose hands come in contact with dirt, grease, and/or fuel during their normal duties should not use the malleable wax or vaseline-impregnated cotton types of ear plugs as the plugs will introduce irritating agents into the ear canal. When there is infection of the outer canal (external otitis), only dry cotton can be used safely as an insert ear plug. Standard helmets or headsets can be used under all circumstances for additional protection.

Regular or wax-impregnated cotton ear defenders can and should be worn by many persons in flight. Aviators should be cautioned that the barometric pressure in the space between the plug and the ear drum membrane does not always keep pace with the ambient pressure in rapid descents. If tight helmets are worn, only dry, porous cotton can be used safely as an ear protector.

All men working on or near the flight lines should wear ear protection at all times. They should be instructed that reciprocating and turbine engines, auxiliary power units, compressors, diesel powered vehicles, etc., generate sufficient noise to affect auditory acuity. These noises are neither as annoying nor as potentially hazardous as are jet aircraft noises, and they seldom cause psychological stress. They are therefore less likely to cause errors in maintenance duty performance, but intensities are high and exposure times are often long, thus necessitating ear protection though its need is not as obvious to the personnel concerned as it is in some other Army aviation activities.

Summary.

The amount of protection afforded by the perfect sealing of the external canal approximates 35 decibels. The addition of a helmet of good acoustic design can increase this protection only eight decibels due to the reception of sound waves on the facial bones, rib cage, and sternum, and their subsequent transmission to the ear.

The actual amount of sound protection or attenuation provided for a specific individual is determined by the fit of the device, its physical conditions, and the willingness and ability of the individual to use it properly.

The best ear protection presently available is provided by individual devices used in combination with one another. For instance, the standard V-51R ear plug and APH-5 helmet can provide very good ear protection from intense noise environments.

Units involved in training personnel in one of the various flying roles, in aircraft maintenance specialties, or in gunnery, should acquaint each student with the purpose and proper use of ear defenders. By doing so, these units can help to control the future incidence of acoustic trauma, thereby improving the efficiency level among Army aviation personnel regularly exposed to noise.

The wise use of ear protection must be augmented by periodic clinical and audiometric reexamination and wise personnel placement, and noise hazards should be considered in planning aircraft operations in order to minimize the frequency of acoustic trauma.

Chapter 5

CHARACTERISTICS OF NOISE GENERATORS

Approximately four years after powered flight was achieved and aerial flight was an actuality, the airplane was adopted for possible military use. From the time of the first application of an airplane for military purposes, the military forces contributed, in outstanding and ever expanding ways, to almost all facets of the growth and development of aviation. The development and uses of aircraft for military purposes during the First World War were rapid and revolutionary. Following the end of this war plans and programs were initiated in the United States that resulted in outstanding achievements in aircraft design, production, and versatility.

However, because of the much more sophisticated aircraft now available, noise and vibration which are inherent in aircraft operations, have increased until today's aircraft possess a multitude of complex noise and vibration mechanisms. Of necessity, increased emphasis is being given to controlling the undesirable elements of noise and vibration associated with the operation of modern aircraft. To understand the noise produced by aircraft, one must have basic knowledge of the noise characteristics of various noise generators in the aircraft.

Medical personnel in the United States Army and other military services are required to possess a thorough knowledge and understanding of the psychological and physiological effects of intense noise. Present understanding of the undesirable effects of noise on man is based almost entirely on the relationship of observed or measured human actions or responses to a given type of noise exposure. Thus meaningful evaluations of undesirable noise exposures are directly dependent on an accurate and meaningful definition of the acoustic energies generated by different noise producers.

In order to acquire and maintain a knowledge of the different noise environments to which individuals are exposed, it is essential that medical personnel understand the basic functions and workings of the different noise generators. In the same manner that a spectrum analysis of the noise increases the accuracy of determining the significance of a given noise, so does an understanding of the basic characteristics of the various noise generators increase the understanding and evaluation of the noise exposures produced during different phases of operation.

In the majority of instances medical personnel evaluate and determine factors of damage-risk for a given noise exposure directly from noise measurements taken at or near a person's place of duty. Making measurements of a given noise exposure is a relatively simple task, but determining the significance of a particular noise exposure position will be radically different during different phases of the operation. For instance, the noise exposures a mechanic receives while standing at the side of a turboprop engine during various power operations of the engine not only vary in intensity and frequency, but also in duration.

It should be remembered that noise measurements made at the place of duty are representative of only a short period of time, and represent only one particular sampling of the noise exposure. It is neither practical nor feasible, at least at the present time, to monitor individual noise exposures throughout each work day in order to determine the degree of exposure for each person who must work in hazardous noise.

Research, investigation, and observation have provided considerable information concerning fundamental characteristics of noise generators. However, for the most part, medical personnel must still evaluate undesirable and hazardous elements of a given noise exposure as best they can from the information available to them on a given noise exposure. This information, although often meager and inexact, is of greater value if one has a basic understanding of how noise exposures change in relation to different operations and functions of the individual noise generators.

This particular section presents information and illustrations that will assist concerned personnel in gaining a more comprehensive understanding of similarities and differences in the characteristic noises produced by noise generators during different operations. The basic concepts presented here should provide a more comprehensive understanding of changes and modifications of noise that can occur during different uses and operations of the noise producer. Insight should be gained into the unique complexities associated with various noise producing elements and the process by which the noise produced by various noise generators is altered or changed by variations in application and operation of the systems.

Although many internal and external factors may have a direct influence on the acoustical properties produced by a given noise generator, each of these mechanisms has certain unique and fairly well defined characteristics. Within limitations, the majority of noises generated by a given type of aircraft system or subsystem can be described and defined.

Noise characteristics of the basic power plants, propeller, rotor, and anti-torque systems; aircraft auxiliary systems; transmission, gear-reduction, and torque distribution systems; aerodynamic disturbances; and ground and airborne power systems are discussed in detail. Examples of each of the different noise generating components within each of the major areas is presented.

Basic Power Plants.

The basic power plant, since it is used to generate the power required to achieve and maintain aerial flight, is in many circumstances a major noise producing element. The power plants presently used in Army aviation are reciprocating engines, and turboprop and turboshaft or free-turbine engines. The reciprocating engine supplies shaft power to rotate a propeller or a rotor system. The turboprop engine supplies turbine-shaft power to rotate propellers or rotors, as well as providing slight additional thrust generated by the exhaust of the turbine engine.

In the past, the major portion of the developments and improvements in powered flight have been accomplished with the use of reciprocating type engines as the primary power package. Reciprocating engines for use as the major power package have improved dramatically since their first applications in the achievement of powered flight. During World War II even greater advancements were made in the capability of the reciprocating engines, but by the close of the War it was evident that the development of the reciprocating engine was swiftly approaching a point of diminishing returns. Noise problems associated with reciprocating engines have remained relatively the same for the past twenty years.

Following the close of World War II rapid advancements were made in the development of thermal-air propulsion engines, especially turbojet type engines. The reaction-type engines that have been developed thus far, i.e., turbojet, turbofan (including by-pass engines), turboprop, and free-turbine, have offered the greatest advantages as power plants for aircraft applications. Ramjet and pulsejet engines have not been as extensively developed and used, but may be utilized to a greater extent in future aircraft.

One particular type of power plant which has demonstrated very good performance and economy characteristics for the Army is the turboprop version of the gas-turbine family. Turboprop power plants provide outstanding characteristics for short take-off and landing performance, and combine the basically good features offered by both a propeller propulsion system and a gas-turbine engine. Turboprop power plant systems are composed of two basic operating designs. The first consists of a power plant in which the gas-turbine engine operates at a relatively constant speed, and the second consists of a power plant in which the engine, and the

propellers, vary in speed (rpm). Each offers distinct advantages, depending on its application.

Rotary-wing aircraft have experienced revolutionary modifications and changes during the past years. Until recently, the primary power plant has been the reciprocating engine. Developments in many areas, especially in the small gas-turbine field, have provided designers of rotary-wing aircraft with a large variety of power plants for rotary-wing applications. Gas-turbine power plants, when fitted to rotary-wing aircraft result in less noise than that commonly associated with such aircraft. Additionally, recent experiments have shown that rotor noise is a significant problem, whereas previously noise from the main rotor was not considered significant (primarily due to the intense noise associated with large reciprocating engine power plants). In all probability, future rotary-wing aircraft will make greater use of gas-turbine engines as basic power plants.

Within the scope of this report, the noise characteristics of each of the power plants of major concern will be discussed. The noise of ramjet, pulsejet, rocket engines, turbojet and turboprop engines are not discussed in detail.

Reciprocating Engines. Reciprocating engines are the basic power plant for many fixed- and rotary-wing aircraft presently used in the Army.

The various noise generators characteristic of reciprocating engines may be greatly influenced by the particular type of aircraft to which the engine is mated, the size and power range of the engine, and the type of exhaust system attached to the engine. If an engine is used to power a fixed-wing aircraft, the noise generated by the engine itself is usually less significant than the noise produced by a similar engine used to power a rotary-wing aircraft. This section will discuss in greater detail the influence of engine-to-aircraft mating on noise.

Noise generated by reciprocating engines may be quite complex. There are many and varied internal components which can have a direct influence on the noise. The most significant contributors may be isolated into exhaust noise, engine casing and resonance noise, noise from gear and shafts (including bearing supports), piston friction, and impacting noises.

During certain phases of operation reciprocating engines, especially large engines, may produce considerable vibration. This vibration may be propagated through the mountings of the engine to the wing or fuselage structures of the vehicle. These vibrations are most noticeable when the engine is operating at very low power (rpm); when the engine is placed under heavy power loadings (especially noticeable if the engine is at a low power setting when the heavy power loadings

are re-applied); and during operation of the engine when internal components and moving parts are imbalanced or defective. The extent and degree to which vibrations are noticed depend strongly on the type of engine, its relative location with respect to occupied spaces, the type and condition of its isolation mountings, and the type of vehicle to which the engine is delivering power.

In fixed-wing aircraft, structural vibrations resulting from engine operation may be directly related to propeller imbalances, which in turn generate rotational imbalances through the propeller shaft of the engine.

In rotary-wing aircraft, structural vibrations may result when high torque is placed on the engine by the rotors, and partly by the gear-reduction transmission systems. In some instances, depending on the location and type of transmission system between the engine shaft and the main rotor shaft, the intense low frequency vibrations produced by a rotor may result in direct feedback to the shaft of the engine, thus producing secondary engine vibrations.

In early reciprocating engines the propellers were mounted directly to the shaft of the engine, but with larger and heavier aircraft and more powerful engines, the size and efficiency of the propeller had to be increased. It was soon evident that the shaft speeds of large reciprocating engines could rotate propeller tips at velocities near the speed of sound, and this could set up undesirable forces within the propeller system which could result in structural failures of both propeller and engine. To eliminate this danger and maintain optimum engine speed, the engineers developed reduction gearing from the engine-to-propeller. To accomplish these gear reductions and still maintain engine and propeller shaft efficiency, the Army adopted the spur and pinion, external type, and the planetary, spur and bevel, types of gear reductions for use in reciprocating engines. Generally, small in-line engines utilize spur and pinion gear-reduction systems, and most radial type engines utilize planetary gear-reduction systems with either spur or bevel driving gear systems.

Although gear-reduction systems, as isolated components, may generate quite intense noise, they normally do not generate significant noise when utilized and operated as a functioning part of a complete engine. The only instance in which noise from these units might be considered significant would be in the event a sophisticated exhaust muffler system was used. Generally, the most significant noise generated by a gear-reduction system within a reciprocating engine would probably be found in the planetary gear system which utilizes spur gears. In this case, the noise would result from gear teeth impacting and would be most pronounced during high rpm and high gear force loadings. In any event, this noise would be significantly reduced by the structure of the engine housing and somewhat by the damping offered by the fluids present within the casings of the engine.

Inherent noises of gear-reduction systems are significant in larger reciprocating type engines due to a higher ratio of gear reduction, particularly if these engines are placed in the fuselage area of rotary-wing type aircraft.

During take-off large engines may utilize anti-detonant injection systems (ADI) in order to achieve an increased thrust during this maneuver. Since these systems are presently used only in fixed-wing aircraft powered by propellers, the major component of increased noise resulting from this operation is due to increased propeller torque and, in some instances, increased rpm. It is conjectured that the noise emanating from the engine and exhaust increases during this maneuver, but since it is significantly less intense than the noise being produced by the propeller, the engine noise is difficult to measure. Anti-detonant injection, or water-injection, controls detonation and preignition within the engine without any accompanying ill effects. In fact, the fluid-injection permits the development of more total power because of its cooling effects. Cooling is provided by the vaporization of the fluid during combustion because the water absorbs heat that would otherwise be absorbed through the cylinder walls. Thus the engine can develop more power even though the manifold pressure and rpm settings remain unchanged. As this operation places heavy stress on the engines, fluid-injection operation is limited in frequency and time duration per operation. This limits the length of exposure to the intense noise generated during this operation.

One of the major noises associated with the operation of a reciprocating engine is produced by the exhaust. Medical personnel should have a basic understanding of the factors or influences that various exhaust systems may have on the exhaust gases before they are expelled into the surrounding atmosphere. Exhaust systems may be very simple devices, usually associated with very small engines, or they may include intricate inter-components. Generally, an exhaust system includes all manifolds or stacks utilized for collecting and conducting the exhaust gases from the cylinders of the engine to points of discharge. Prior to discharging the exhaust gases, the exhaust system may conduct the gases to a turbo supercharger, a system utilizing exhaust heat or cooling exhaust gases, to a flame damper system, or a system that will reduce the noise created by the exhaust.

At the present time, noise generated by the turbo supercharger is of little significance since the majority of aircraft in the Army that are fitted with such units are dual or multi-engine aircraft, and thus the system is isolated from the main fuselage.

Manifold exhaust systems collect the exhaust gases from three or more cylinders before discharging the gases. Open exhaust manifold systems discharge the exhaust gases directly to the atmosphere, either through integral outlets or

through outlets which may include heat exchangers, flame dampers, or noise silencers. The turbomanifold type exhaust systems discharge the exhaust directly to turbo superchargers where the kinetic energy of the exhaust is partially extracted to rotate the turbine section of the supercharger unit.

Exhaust shrouding is any complete or partially complete enclosing device to control heat transfer from the exhaust system to the aircraft. Such devices include heat deflectors, baffles, and cowl wells. Influence of shrouding on exhaust noise is not evident during normal engine and exhaust functions. If the engine exhaust is ported through the wing, or through ports located above, below, or behind the wing, the noise produced by the exhaust gases may be increased if the phenomenon occurs whereby the gases accelerate as they port down the tubing, thus causing shock waves as they finally exit. If this phenomenon does occur, it is usually associated with a certain power range of engine operation (a high power setting), and the noise generated is most intense at positions to the side of the exhaust ports.

A primary heat exchanger is a heat transfer device installed within an exhaust system where the exhaust passes through one part and regular air passes through the other part of the heat transfer surface. It is used for heating of non-contaminated air, usually for aircraft heater units. Such units, when installed on an exhaust system, may have a significant influence on the amount of exhaust noise invading occupied areas within the aircraft, especially in single-engine aircraft where the exhaust port(s) is located near the main fuselage. For instance, noise within a U-6A is slightly less when the heat exchanger device is installed on the exhaust.

In some instances, a heat exchanger unit, if not properly designed or installed, may resonate when a certain power setting range is attempted. If this does occur, it is most noticeable aboard single-engine aircraft.

Mountings of the exhaust system may also influence the noise generated by the exhaust. If structurally mounted, the exhaust tubing is directly supported by the aircraft's structure and mated to the engine by flexible coupling and thus a direct avenue of noise and vibration from the exhaust, as well as the engine, is established. If the exhaust tubing is engine mounted, it is connected directly to the engine. Exhaust systems mounted in this manner are not mounted or supported directly by the structure of the aircraft and thus do not directly communicate noise and vibration to the structure of the vehicle. Although the noise cannot be transmitted structurally by direct contact, the exhaust noise can be propagated to surrounding structures and areas by acoustical excitation, especially if the exhaust port is near areas or compartments containing modes of natural frequency resonance.

Engine exhaust noise is generated by the expulsion of the hot combination gases through a manifold exhaust tube or directly from the cylinders of the engine. This noise is characteristic of the interval of the individual periodic expulsions of the gases and is most pronounced in the lower frequencies. Exhaust noise is related to the number of engine cylinders, the rate of discharge (depending on engine rpm), and the type of exhaust ducting and muffler system used. If the exhaust ducting system is such that excessive dynamic pressures are built up prior to the dumping of the exhaust gases, the exhaust gases, when released, may create shock waves which generate a significant increase in the magnitude of the exhaust noise.

The lowest frequency of the discharging exhaust gas noise spectrum is related to the number of exhaust discharges per cylinder per second (in engines where two or more cylinders fire simultaneously the discharges are counted as one), thus exhaust noise usually corresponds to the frequency of the engine cylinder firings. Generally, the frequency spectrum of the exhaust noise will demonstrate progressive shifts into slightly higher frequency ranges as the engine rpm increases. These changes are difficult to observe when the engine is powering a propeller or rotor system because the noise emanating from the propeller or rotor is usually more intense than the noise emanating from the exhausts.

In order to illustrate some of the characteristics of exhaust type noise, measurements were completed on the engine and exhaust noise generated by the reciprocating engine of a CH-21C (Shawnee). The CH-21C is powered by a Wright R1820 radial, single-row, reciprocating engine. The engine is mounted within the fuselage aft of the cargo compartment. Power from the engine is transmitted from the mid transmission and from it, longitudinally, to the fore and aft transmissions where reduction-transmission units reduce the rotational speeds being delivered to the tandem rotors. The engine itself does not contain reduction-gear systems. The speed of the drive shaft between the engine and the main transmission, including the area between the transmissions, is the same as the engine shaft speed. The engine is also fitted with a single-stage, two-speed, supercharger unit for high altitude operations.

Noise measurements of the exhaust noise of the CH-21C were completed while the engine was operating and the rotors were disengaged. Thus the noise measurements obtained are representative of noise emanating from the engine. The measurements were completed on the ground and the distances and angles were measured from the exhaust port on the right side of the fuselage.

A good example of the shift in the frequency spectrum of the exhaust noise resulting from increased engine rpm is shown in Figure 1. These noise measurements were made at a position directly beneath the engine exhaust port. As the

engine speed increased from 1,500 to 2,500 rpm, not only did the over-all noise level increase about five db, but there was a significant shift of the peak intensity from the 75 to 150 cps octave band to the 150 to 300 cps octave band. There was also a noticeable increase in the acoustic energies produced in the higher frequency range.

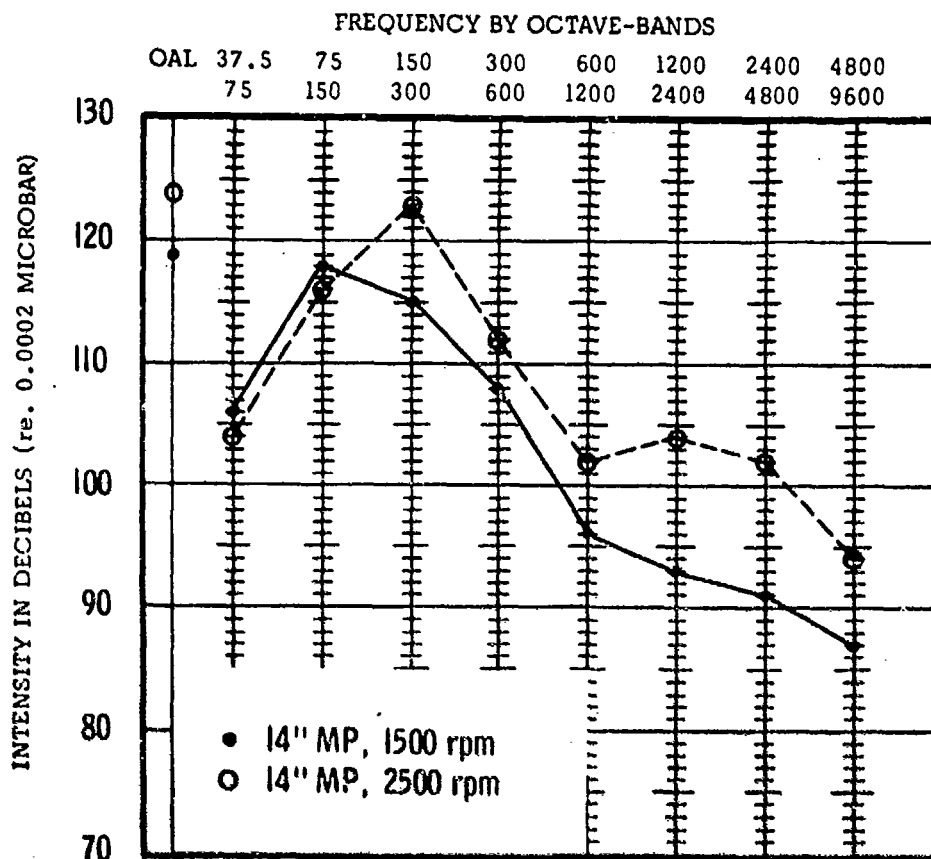


Fig. 1 Engine Exhaust Noise of CH-21C Helicopter
Measured Underneath the Engine

Exhaust noise is predominately low frequency, but higher frequency components are generated. These are most pronounced at positions near the exhaust ports and most intense when the engine is operating at high power.

Since the exhaust noise associated with a reciprocating engine is related to the pulsations of the exhaust gases, the noise is restricted to dominating only the low frequency range. As a result, exhaust noise is not highly directional. Noise

measurements of exhaust noise are depicted in the noise plottings of Figures 2, 3, and 4. These noise measurements were completed at distances of 50 and 100 feet from the exhaust port on the right side of a CH-21C helicopter. The measurements were taken with the engines operating at 1,500 and 2,500 rpm, and, since the rotors were not engaged, only fourteen inches of manifold pressure were required. The results of these measurements indicate the relatively nondirectional noise propagation characteristics of the low frequency acoustic energy, particularly the relative similarity of the exhaust noise below 300 cps at positions of 100 feet from the exhaust port.

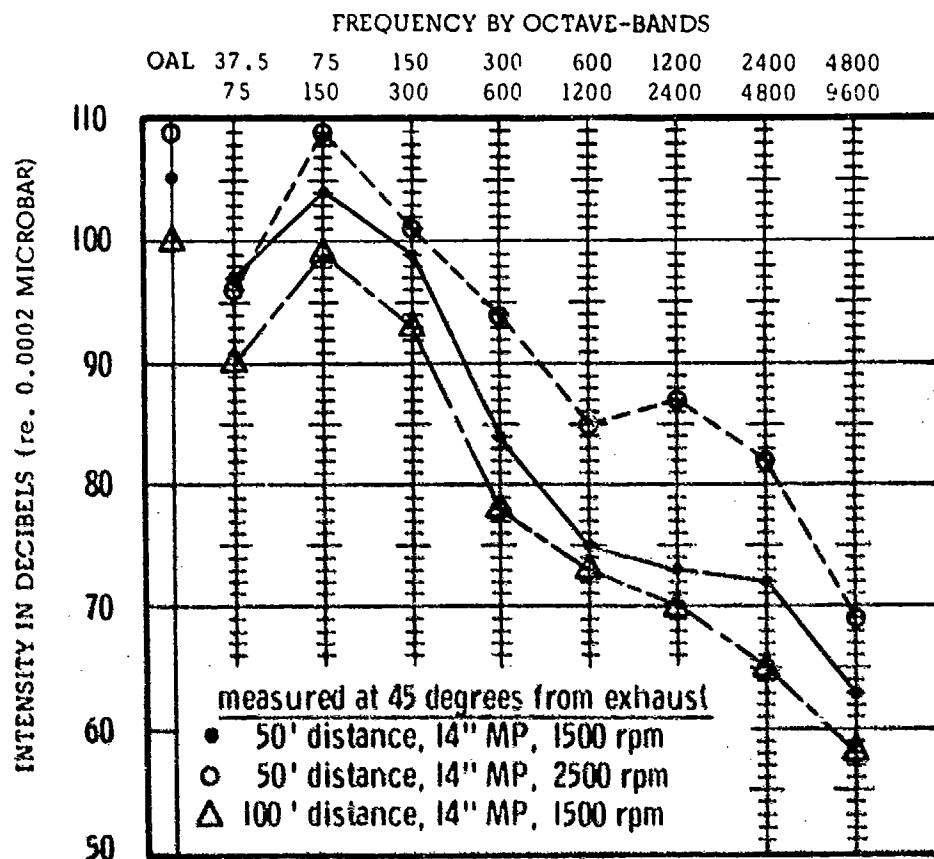


Fig. 2 Engine Exhaust Noise of CH-21C Helicopter
Measured at 45 Degrees from the Exhaust

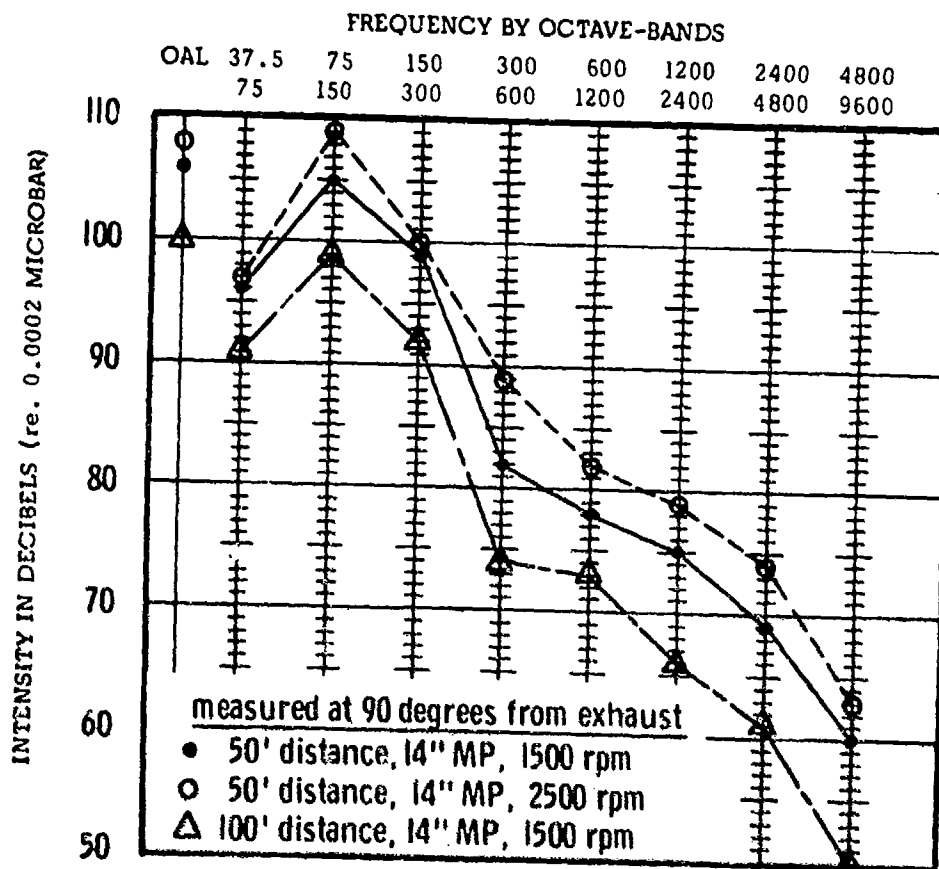


Fig. 3 Engine Exhaust Noise of CH-21C Helicopter
Measured at 90 Degrees from the Exhaust

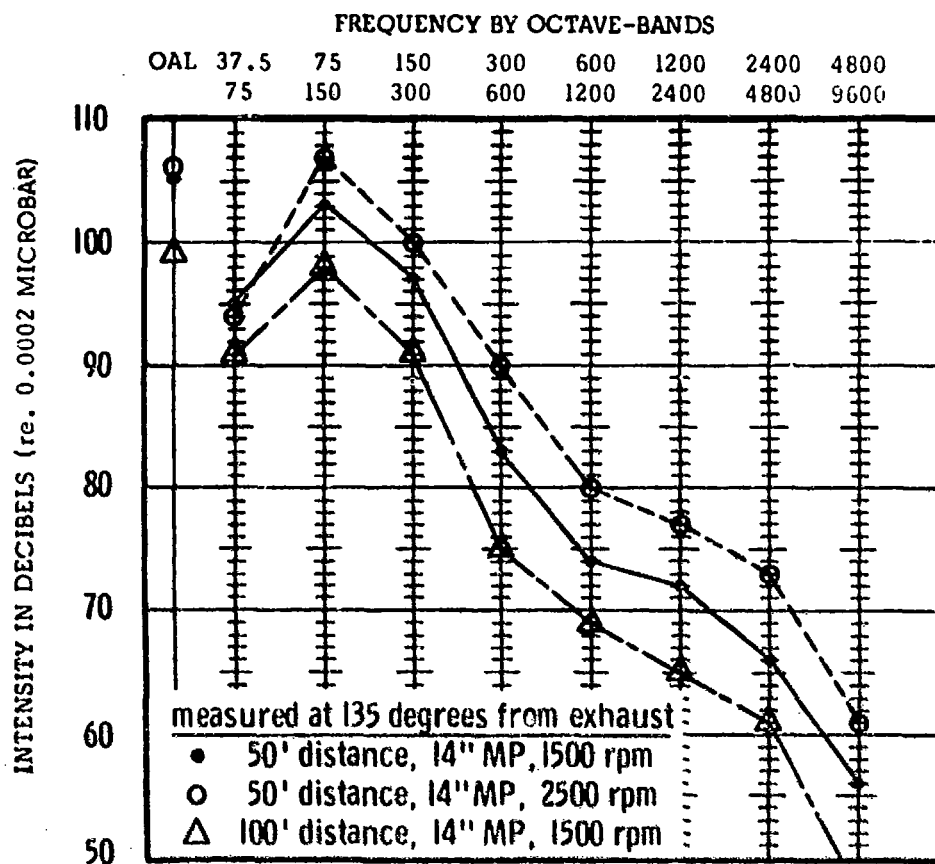


Fig. 4 Engine Exhaust Noise of CH-21C Helicopter
Measured at 135 Degrees from the Exhaust

A good example of the directional characteristics of exhaust noise can be seen in Figure 5. The measurements were made at a distance of 50 feet from the center line of the right engine, and at positions of 0, 90, and 135 degrees from the front of the engine. The aircraft was a CH-37B. The rotors were rotating slowly, and did not produce significant noise levels to mask the noise being generated by the exhausts. The exhaust system on the CH-37B is a two-port type located in the rear of the engine which dumps the exhaust gases directly aft of the engine. Note that as one moves toward the rear of the engine the intensity of the noise increases. Since the most intense noise is distributed in the lower frequency ranges, the overall noise increased five db when the observer moved from directly in front of the engine to a position of equal distance, but directly to the side of the engine, and increased another eight db when the observer moved aft of the engine to a position of about 135 degrees.

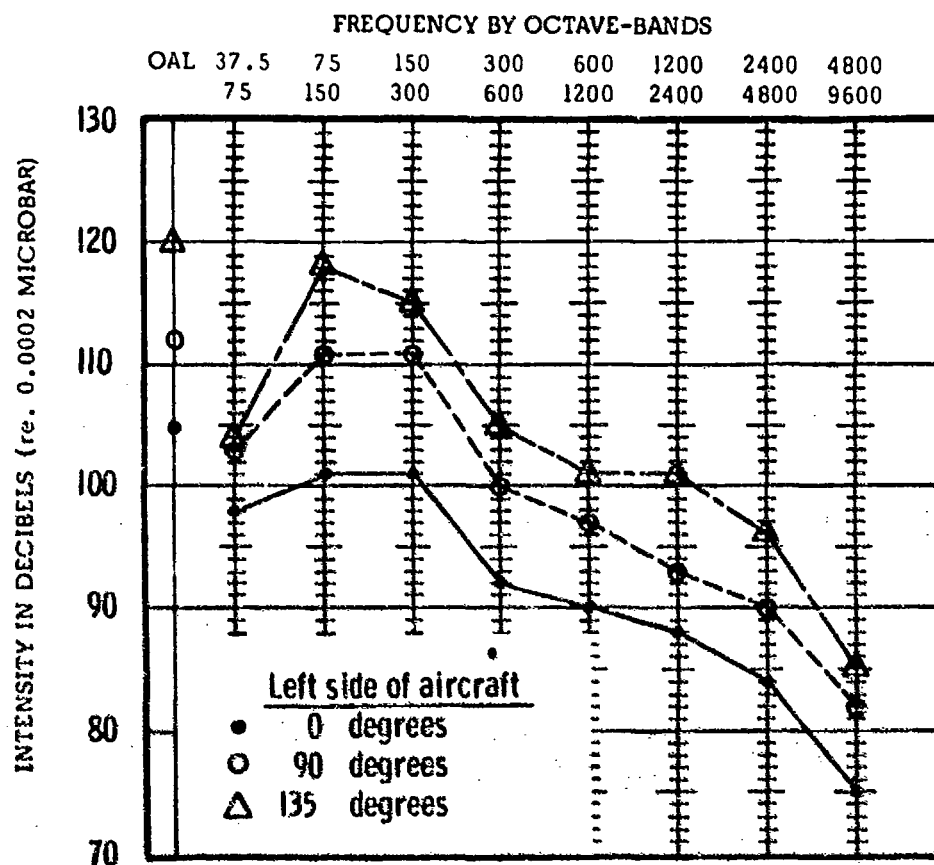


Fig. 5 External Noise of CH-37B Helicopter Measured at 50' Distance, 2600 RPM, 16" MP

An example of near field exhaust noise is shown in the plottings of Figure 6. The exhaust noise was once again measured on a CH-37B, but the rotors were disengaged and only the engine was operating. Note that as the observer moves to a position closer to the rear of the engine and nearer the exhaust area, there is a slight increase in the higher frequency noise. This type of noise exposure would be expected for ground maintenance or crew personnel who stand fire guard during engine starting.

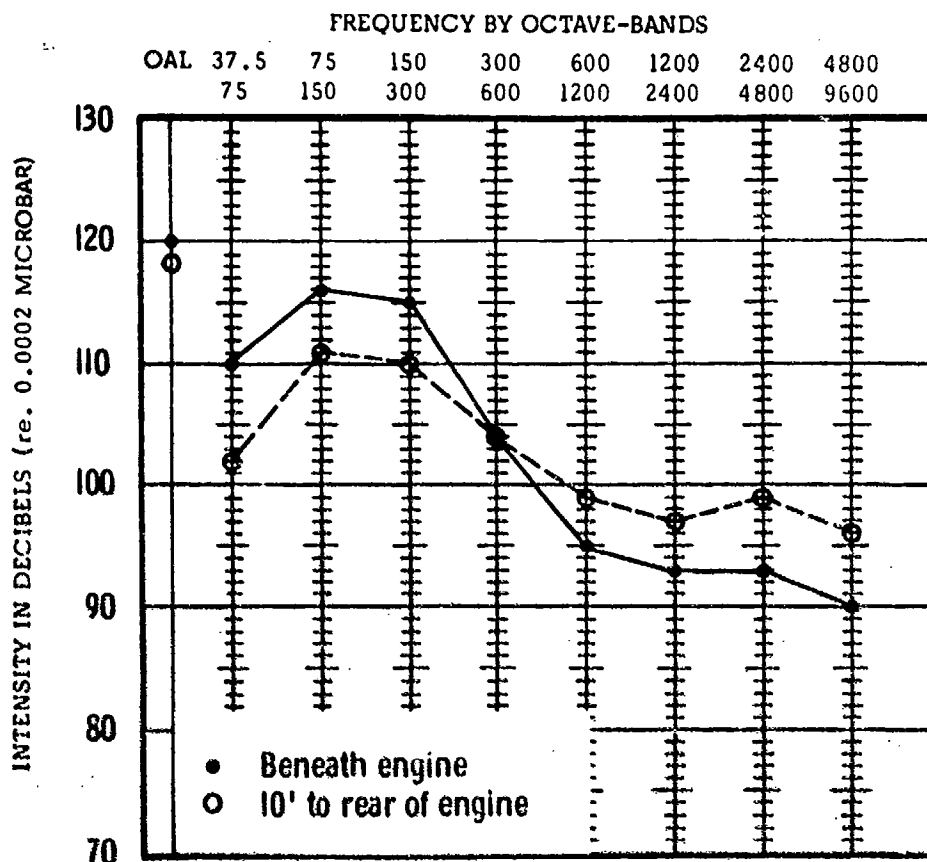


Fig. 6 External Noise of CH-37B Helicopter Measured Near the Engine, 1500 RPM, 16" MP

Gas-Turbine Engines. Turboprop and turboshaft power plants have not been as extensively developed and applied as have turbojet power plants, but during the past few years extensive developments and designs have resulted in outstanding improvements of basic turboprop and turboshaft power plants for fixed- and especially rotary-wing applications. The size, type, and power ranges available from these

power plants are quite varied, and although design and construction characteristics differ from one type to another, all have certain basic characteristics: 1) each type has an integrated gas-turbine type engine that supplies the basic power; 2) each unit utilizes a gear-reduction gear and transmission system to reduce the very high engine shaft speeds to a slower propeller or rotor shaft speed; 3) each system depends on a rotating propeller or rotor system to obtain the thrust necessary to obtain powered flight; and 4) even though a gas-turbine type engine is utilized as the basic power plant, very little thrust is obtained from the jet exhaust from the engine. In the basic types of turboprop and turboshaft engines thus far utilized by the Army for fixed- or rotary-wing aircraft, these four basic characteristics will remain the same.

A basic functioning component of turboprop power plants is the propeller or rotor system, but these systems are discussed in a later section. The major components considered here consist of the basic engine and the gear-reduction transmission systems, since these two components actually make up the inherent primary functioning parts of a given turboprop or turboshaft type power plant.

The engine of a turboprop or turboshaft power plant functions basically the same as does a turbojet engine. The air enters the compressor stages of the engine where it is compressed and directed through the diffuser sections into the combustion stages of the engine. In the combustion section fuel is injected and mixed with the air, and burned. The hot, expanding gases are directed through guide vanes where they impinge on the gases, thereby providing the power to drive the compressor sections, the engine accessories, and the gear-reduction system which in turn supplies controlled torque to the propeller or rotor system. After the gases have passed through the turbine stages they continue to flow through the exhaust casing and are finally expelled into the atmosphere.

A characteristic of the turboprop engine is that changes or alterations in power are not related to engine speed, but by turbine inlet temperature. During flight the propeller maintains a constant engine speed; usually referred to as 100 per cent rated speed of the engine, and it corresponds to the best design speed at which the most power and best over-all efficiency can be obtained. Power changes are effected by changes in fuel flow. An increase in fuel flow results in increased power at the turbine stage. The turbine absorbs or reacts to the increased energy and transmits it to the propeller in the form of torque. The propeller, in order to absorb the increased torque, increases blade angle, thus maintaining a constant engine rpm.

Since these engines operate at very high main shaft speeds, gear-reduction systems must be utilized to reduce the high speed engine shaft rpm to a lower propeller shaft rpm, but since the thrust provided by the propellers is dependent on blade

pitch and not propeller rpm, the propellers actually rotate at a relatively constant speed during all phases of flight. Because of the intense noise associated with turboprop propeller systems, even while on the ground, decreased propeller speeds were obtained by providing a ground and flight idle throttle control, thus reducing the high rpm of the propeller and in turn causing a reduction in the noise generated by the propeller.

Turboprop power plants generate noise from various sources. Some of the primary noise producing sources are 1) propellers (discussed in a following section; 2) compressors and turbines, including intake ducting; and 3) direct structural vibrations from engine and propeller systems.

The actual engines of the constant speed turboprop power plants do not constitute the major noise problem. It is the noise emanating from the propellers that poses a greater noise problem than the noise generated by the internal components of the engine, the gear-reduction system, and the jet exhaust. At present most of these noise generating components are located at positions away from occupied areas, since the majority of turboprop aircraft are powered by either two or four engines which are usually located within the wing.

The higher frequency noise associated with turboprop power plants is greater than with conventional propeller systems. This high frequency noise of turboprop engines is generated by the compressor of the gas turbine and radiates out through the air intake, thus the design and location of the intake may directly influence the directional radiation of this noise. Since this noise is usually high frequency, it is easily deflected. In some cases the use of a conical spinner may produce a lateral distribution of this noise due to acoustic reflection. Figure 7 depicts the noise measured at a distance of 50 feet from an OV-1B aircraft with only the turbine engine operating at 42 per cent rpm (10,568 rpm). During these measurements the propeller was not operating, thus the noise is characteristic of that generated by the compressor stages of the engine. The OV-1B is fitted with two Lycoming T-53 engines and the compressor sections feed air through circular openings around the gear-reduction and propeller shaft housing. A narrow-band peak is in the higher frequency range of 2,400 to 4,800 cps. The most intense noise elements are propagated directly forward of the engine and as one moves to the sides the narrow-band noise lessens in intensity.

Figure 8 illustrates the influence of increased engine rpm and propeller operation on the noise generated at a position directly in front of the aircraft at a distance of 50 feet. When the engine was operating at 42 per cent and the propellers were not engaged, the narrow-band noise components were noted in the 2,400 to 4,800 cps octave band. However, when the propellers are engaged and the

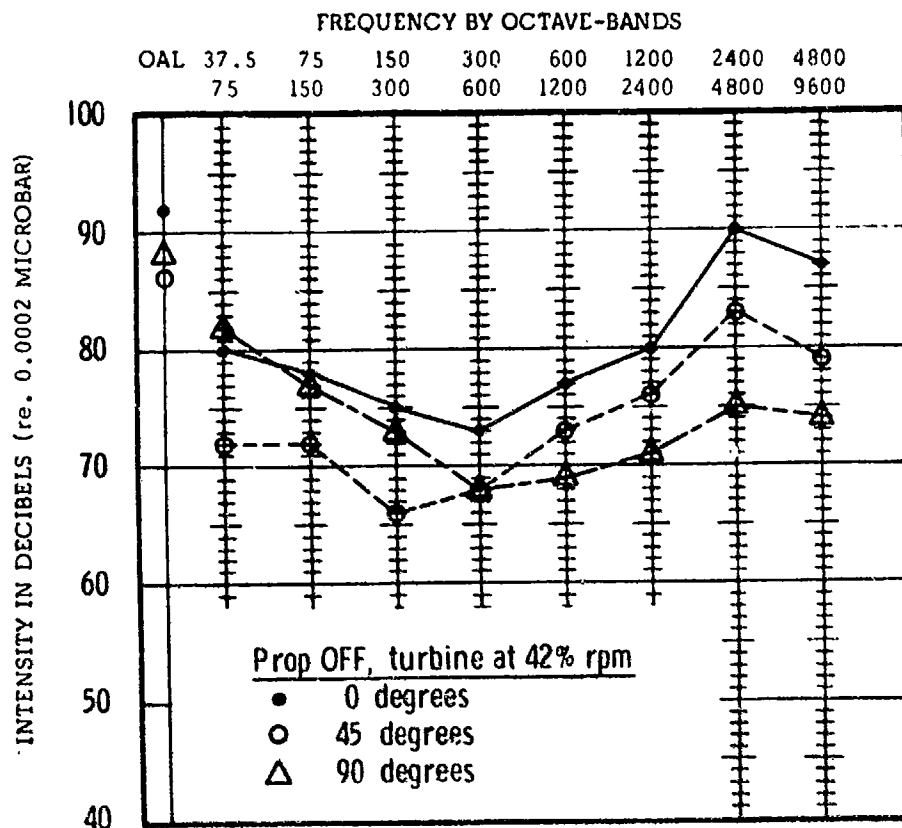


Fig. 7 External Noise of OV-1B Aircraft Measured at 50' Distance

engine rpm is increased to 60 per cent, the noise generated by the propeller is quite evident. When the propeller is operating, the low and mid frequency noise increases, and due to the increased rpm of the engine, the narrow-band component shifted from the 2,400 to 4,800 cps band to the 4,800 to 9,600 cps band. The dominance of propeller noise and the relative shifting of the engine compressor noise into higher frequency ranges, account for the fact that noise generated by the engines becomes less evident when engine and propeller systems are operating at high power. Since the propeller noise is distributed primarily in the lower and mid frequencies, it is quite possible that the discrete high frequency noise generated by the compressor stages of the engine may be very noticeable. For instance, during the propeller check of the OV-1B the discrete noise emanating from the compressors is subjectively quite noticeable, and for this reason, noise level readings alone may not indicate their presence.

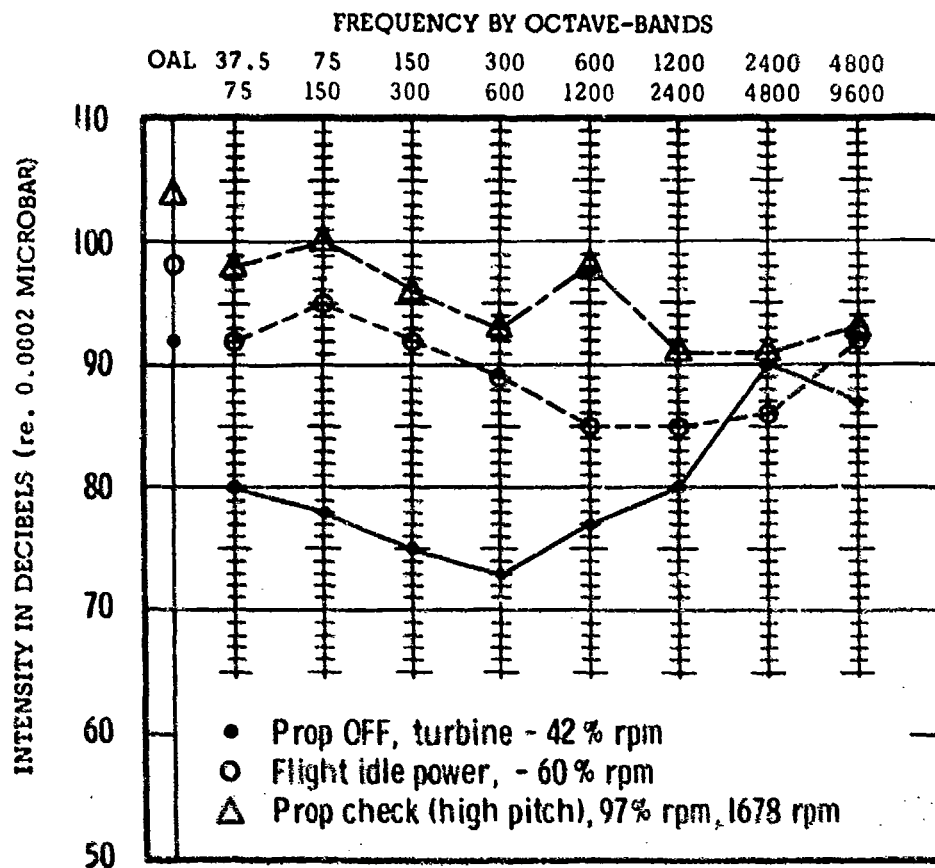


Fig. 8 External Noise of OV-1B Aircraft
Measured at 50' Distance, 0 Degrees

A few turboprop power plants generate singular narrow-band noise components. There are other engines that may generate a complexity of high frequency components that cover a rather wide frequency range. Usually, the degree of complexity of the noise generated by an engine is related to the type and number of compressor sections, particularly the frontal compressor sections. For instance, the compressor section of the Lycoming T-53 engine (OV-1B) consists of five axial stages and a single centrifugal stage.

Turbine shaft exhaust noise is of little significance due to the smallness of the gas-turbine engine and the fact that the majority of the thrust is converted into torque power. For instance, the T-53 engine of the OV-1B can generate approximately 124 pounds of thrust. The noise resulting from the exhaust of a turboprop is less noticeable than would be the noise generated by the equal thrust generated by a pure jet engine because the exhaust noise of the turboprop is much less

intense than the noise generated by the propellers. Conditions under which maximum jet thrust is produced are also conditions during which maximum propeller noise exists.

Some turboprop engines utilize power augmentation for added power during take-off. Augmented power usually consists of a water-alcohol injection system. The water-alcohol injection mixture increases the mass flow through the turbine section of the turboprop engine. Injection of the fluid into the engine provides an increase in torque pressure. This increased power reduces the take-off distance and improves the initial climb-out characteristics of the aircraft. Augmented power is available for about one to two minutes of operation. During augmented power, the increased torque results in an increase in the noise produced by the propellers.

Several factors must be considered in order to achieve a significant reduction in the noise generated by fixed-wing turboprop aircraft. Thus far, significant noise reductions have necessitated changes or modifications of internal components of the power package. Newer turboprop aircraft have increased gear reduction for ground operations. Reducing the rpm of the propellers on the ground during ground run-up and taxi significantly decreases the intensity of the noise created by the propeller. The basic exhaust thrust produced by turboprop gas turbines is relatively the same during all phases of the aircraft's operation since the engine usually operates at the same power.

In general, the major noise problem created during the operation of turboprop power plants is associated with the compressor stages of the engine. Compressor noise is most evident during ground operations and is most pronounced at locations in front of the engine. Compressor noise is most evident in the higher frequency ranges and tends to become less evident as propeller rpm increases. Due to the distinct spectrum differences between the noise generated by the propellers and that generated by the compressor, the compressor noise may be quite noticeable even though it is less intense than propeller noise.

Turboshaft Power Plants. The majority of small turboshaft engines are presently being utilized for rotary-wing applications. These power plants are basically the same as turboprop engines, except for slight component modifications.

Some of the major sources of noise from turboshaft engines are 1) compressor stages of the engine; 2) exhaust gases emanating from the engine exhaust duct nozzle; 3) structural vibration of engine, engine mountings, and areas surrounding engine (this includes acoustically induced structural vibration); and 4) the engine drive system, including bearing, gear, shaft distribution, and accessory drive systems.

Of the various noise generators associated with the operation of turboshaft engines the noise generated by the compressor and turbine stages of the engine, direct-drive (nonreduced) shaft distribution systems, and the engine exhaust (of powerful engines) are of major concern. Since the majority of turboshaft engines are mated to rotary-wing aircraft, the noise generated by the rotor and anti-torque rotor gear-reduction units represents a significant noise problem, but these systems are discussed in a subsequent section.

Compressor noise, like that of a turboprop engine, is the result of disturbances caused by the passage of air through the compressor stages of the engine. The frequency characteristics of the compressor noise is determined by the rotational speed of the compressor blades, the number and relative position of the stator blades, and the number of blades in the compressor unit. The noise of multistage compressor units is usually determined by the first-stage compressor units, but in some instances the latter stages may contribute to the total noise. Multistage compressor units usually differ in diameter. Normally the larger diameter wheels are located nearer the intake and may have a different number of blades per wheel or unit. Differences in the number of blades, varying compressor disc diameters, and varying rotational speeds create different fundamentals and harmonics. As the engine operates at a varying rpm the spectra of the noise also vary or shift frequency. Generally, as the rpm increases, the most intense acoustic components generated by the compressor move into the higher frequency range.

The noise produced by the compressor stages of turboshaft engines: 1) is most intense in the higher frequency range; 2) usually contains narrow-band noise components; 3) is highly directional in its pattern of propagation; 4) becomes less audible as the rpm of the engine increases; 5) attenuates rapidly with increasing distance; and 6) is easily attenuated by fuselage structures and by acoustic treatment of intake.

Noise associated with the exhaust of most turboshaft engines is not an outstanding problem because the majority of exhaust energy generated by the engine is converted into torque shaft energy by the turbine stages of the engine before being expelled through the exhaust port. Thus the exit velocity of the exhaust gases is relatively low. These factors, combined with turbulent mixing of the exhaust, create an exhaust noise that is significantly reduced from that associated with exhausts of pure jet engines.

Most turboshaft engines that are used for rotary-wing aircraft are mounted near occupied areas and are usually mounted horizontally. Therefore, they require a rather complex shaft transmission system. Almost all turboshaft engines contain a shaft gear-reduction system which is integrated within the engine (the externally

mounted gear-reduction system will be discussed later). Since most turboshaft engines are mated directly to the fuselage structure of the vehicle, noise and vibration generated by the engine are transmitted directly through the structures of the vehicle. Compressor noise, even though present, is not noticeable at internal stations, but the noises produced by rotating shafts and gears within the engine may produce quite significant noise levels.

Application of Gas-Turbine Engines to Fixed- and Rotary-Wing Aircraft. Early in 1951, as the result of winning an industry-wide competition, Lycoming was awarded a government contract to develop the first American gas-turbine engine to be designed specifically for helicopter operation. The Lycoming Gas Turbine Department was established at Stratford, Conn., shortly thereafter. Since its inception, the Gas Turbine Department has pioneered numerous advances in gas-turbine design under the direction of Dr. von Franz, who engineered Germany's first mass-produced jet engine during the final phases of World War II.

It is impossible to develop an engine without disadvantages, but the gas-turbine type engine, when compared to that of reciprocating engines, has certain distinct advantages. There is little reason to mention size, as it is readily apparent that a gas-turbine engine is approximately one-half the size of a comparably powered reciprocating engine. The reduction in maintenance time, however, is of primary importance. Required maintenance on gas-turbine power plants is relatively simple compared to that of reciprocating engines because of the comparatively few moving parts. There are no spark plugs, magnetos, pistons, rings, valves, air filters, and other components which require considerable time to maintain. Another advantage is that gas-turbine power plants can use a greater range of fuels than can reciprocating engines.

General Description of T-53 Gas-Turbine Engine. The T-53 gas-turbine engine is a free power turbine type power plant of minimum size and weight, maximum reliability and life. It has three engine mounts to permit simplified installation and removal. The T-53-L-1 type helicopter version engine has a military maximum shaft horsepower of approximately 860, but in the UH-1A helicopter it has been derated to approximately 770 shaft horsepower. The T-53-L-3 turboprop version has a rating of 960 shaft horsepower, and the T-53-L-5, a combination engine, also has a rating of 960 shaft horsepower. Later versions will not be discussed in this report.

The gas-turbine engine operates on the same basic principles as the reciprocating engine. There is an intake system in which the air passes to the inlet housing, compressor in the compressor section, ignition and burning in the combustion section, power to the turbine wheels, and then exhausts out of the tail pipe. All air that enters the engine must come through the inlet housing unit. This unit

also contains a reduction mechanism and power output shaft. The compressor section is located just aft of the inlet housing and contains an axial compressor in five stages and a centrifugal compressor. Between the five stages of the axial compressor there are five sets of stators (nonrotating) plus an exit guide vein located after the #5 stator. The diffuser section mounts to the centrifugal compressor housing and extends out to the combustion section. The diffuser section transports the compressed air to the outside or to the largest diameter of the engine. It also has veins welded to the forward side of the airflow path to give a smooth and even flow. The combustion section is mounted to the diffuser section on the front and the exhaust diffuser section at the rear. This is the section where the fuel is mixed with air and burns to provide the hot gases which impinge upon the turbine wheels, causing the wheels to rotate, thus producing torque power. The exhaust diffuser section extends from the marmon clamp to the aft end of the engine. The exhaust diffuser disposes of the hot gases after they have passed through the turbine wheels.

Free Power Turbine. The T-53 gas-turbine engine is referred to as a free power turbine as there is no mechanical linkage between the first stage, the second stage power turbine, or the turbine wheel. The only connection is the action of the hot gases passing over the blades of the turbine wheels. The main advantage of this is in starting.

Reduction-Gear Section. Reduction gearing is located forward at the engine's "cold end" to provide greater reliability and life for gears in high speed bearings. The reduction-gear housing inside the intersection of the inlet housing is of fairly simple construction and is quite similar to that found in piston engines. The sun gear at the center is driven directly by the power shaft at speeds of over 20,000 rpm, and then to three idler gears. These gears are mounted forward of the accessory drive carrier and are supported directly by roller bearings on both sides of the planetary sun gear. This carrier also forms the torque meter unit which measures power output by translating shaft torque to pounds of pressure on a calibrated indicator in the cockpit. The bell gear, which mates with the three idler gears, also includes the power output shaft at the forward end and completes the reduction-gear system. Reduction in speed from the power turbine's 19,000 rpm down to approximately 6,400 rpm is accomplished by the gears just described. In other words, an approximate 3.22 to 1 reduction ratio is obtained by the gear-reduction system.

Accessory Drive System. An accessory drive gearbox is mounted in the bottom of the air inlet housing. It contains an accessory drive gear train and a combination pressure and scavenge oil pump assembly which is driven by 1) a bevel gear mounted on the compressor rotor and 2) an accessory drive gear mounted in the accessory drive carrier located in the air inlet housing. The power take-off or auxiliary drive provides up to 300 horsepower at 6,000 rpm. The accessory drive

carrier and the pinion gear mating with it (which is attached to the short shaft) are revolving at 13,600 rpm when the engine is operating at full power. A pinion gear drives a bevel gear or start-generator gear at 7,100 rpm with the take-off facing aft. This bevel gear in turn drives the oil air separator gear assembly, which is located to the right of the starter gear, at 5,700 rpm with the take-off forward. This starter gear also drives the oil pump pad which is on the left side of the bevel gear. At 4,000 rpm, with take-off forward, the gas producer tachameter shaft gear drive (to the right of the generator pad) is driven by an oil-air separator gear assembly at 3,700 rpm, with the take-off aft. The oil pump drive gear assembly drives the fuel control drive gear to the left of the generator pad at 3,700 rpm with the take-off aft. A shaft gear in the fuel control drive gear assembly drives the cooling fan gearbox (located on the left of the generator pad) at 3,700 rpm with the take-off forward.

Compressor and Centrifugal Housing Assembly. The compressor housing is a matched, magnesium alloy assembly consisting of two halves which are not interchangeable. The compressor housing is bolted to the air inlet and centrifugal compressor housing. The centrifugal compressor housing is a hollow two-piece magnesium alloy casting with holes drilled along the diffuser connecting flange to allow warm air from the compressor to enter the housing chamber which is the source of supply for the deicing unit. The centrifugal compressor housing is bolted to the diffuser section.

The compressor rotor assembly is an axial centrifugal type. It consists of five axial rotor assemblies and a centrifugal compressor which are retained on the compressor rotor sleeve. The threaded end of the compressor rotor sleeve screws into the compressor rotor rear shaft. The compressor rotor rear shaft is supported by #3 bearings and splines into the first stage turbine wheel adapter at which point it is secured by a retaining unit.

The axial flow compressor consists of five discs holding stainless steel, low hardness level, nonchip blades for the initial stages fitted together with five spaces. The first disc forms a bearing support for the #1 ball bearing which is followed by an aluminum compressor disc. A row of airfoil section veins (stators) are bolted to the compressor housing and lie between each of the rotating stages of the compressor. The function of these stators is to change slightly the direction of air between each compression disc and to build up pressure between each stage. Stator blades are cut from ten-inch strips of rolled steel and are of constant airfoil shape.

Following the fifth stage of axial flow is another steel spacer and then a titanium centrifugal compressor, which is a two-piece, machine mass assembly hollowed in the center section to cut down weight. The combination axial-centrifugal compressor produces a 6:1 compression ratio.

T-53 Helicopter Turboshaft Operation. Air enters the gas-turbine engine through the inlet housing and flows past the inlet guide veins, which remove as much of the turbulence as possible from the incoming air before passing the air directly to the axial centrifugal rotor assembly. After flowing past each successive rotor and stator stage, and the centrifugal stage, the air is compressed into its final ratio of 6:1. On the centrifugal rotor the air passes through the diffuser where the high velocity energy is changed to pressure energy and into the cool air shroud which surrounds the combustion chamber. During ignition, two spark igniters located on the combustion chambers at the 120- and 240-degree positions ignite the starting fuel supply from five starting fuel nozzles. Two of these starting nozzles work with the igniters in assisting combustion while the other three nozzles assist in flame propagation. It is the flame from these starting nozzles which heats the main vaporizing tubes. When the main fuel supplies become ignited the starting nozzles and spark igniters are shut off.

As the main airflow enters the combustion chamber it divides into two distinct pathways. One is allowed to go to the rear of the combustion chamber for primary combustion where it enters the head of the combustion chamber liner, passing between liner and housing, and from the T-canals to the combustion area. This primary air is mixed with the fuel in the eleven T-shaped main vaporizing tubes and then annular combustion takes place. During this process the secondary air, which is two-thirds of the compressed air, is introduced through small scoops, holes, and louvers just aft of the mating flange at the junction of the combustion chamber and engine diffuser. This secondary air has several jobs to perform. It is required to complete the combustion taking place in the primary section, to pass some cooling air to the exhaust gases, and finally to help insulate the stainless steel components of the combustion section from the direct blast of gases burning at approximately 3,000° F. It also controls the flame area and prevents it from moving forward or aft.

After the mixing of the primary and secondary air in the combustion chamber the air flows further forward, turns 180 degrees, and enters the first stage turbine nozzle at approximately 1,600° F. This component directs air at the most effective angle for impingement on the first stage turbine wheel of the gas producer whose sole job is to drive the compressor and accessory gearing mounted on the bottom of the inlet housing. After passing through the first stage turbine, the gas flows past the second stage turbine nozzle and enters the single stage free powered turbine where most of the remaining energy is converted into useful shaft power. Reduction in speed from the power turbine's 19,000 rpm down to a little over 6,000 rpm is accomplished by the planetary gear system which offers a gear reduction of approximately 3.22:1. As the gas leaves the power turbine, it is exhausted into the surrounding atmosphere. These exhaust gases play an important role in the safe operation of an engine during flight. The tail pipe temperature should be monitored because

excessive temperatures will burn the turbine wheels and other components located at the hot end of the engine.

Accessory Air Bleed Systems. An air bleed type system is usually necessary on most gas-turbine engines to improve compressor acceleration characteristics. The system automatically unloads the compressor of small quantities of compressed air during a period in the engine acceleration cycle when faster compressor acceleration is more desirable than the slight power loss to the engine in the bleed air. Usually a ring of bleed air holes are provided in the axial compressor housing at the exit guide vein location just forward of the centrifugal compressor. At this same location a metal strap fits around the compressor housing like a brake band to cover these bleed band holes. When the bleed band is relaxed, compressor air bleeds from the bleed hole. The bleed band is tightened or relaxed over these bleed holes by a pneumatic control unit which is usually mounted on the right side of the compressor housing. The movement of the bleed band works automatically depending upon the differential pressure on the inlet side and the discharge side of the compressor stages. For instance, in the T-53 type engine bleed air is usually shut off when the compressor reaches 78% rpm or lower. The opening and closing of the bleed holes is gradual to prevent any abrupt changes in engine operation.

T-53 Mohawk Turboprop Operation. The Mohawk is equipped with two model T-53-L-3 turboprop engines driving model 53C51 hydramatic propellers. Each engine consists of a reduction-gear section, an axial-centrifugal compressor, a diffuser, a combustion chamber, a gas producer turbine, a three-powered turbine, and an exhaust diffuser. The compressor consists of five axial stages and one centrifugal impeller which produce a 6:1 compression ratio. The gas producer turbine (first stage) drives the compressor and the free turbine (second stage) drives the power shaft. Power is extracted from the power shaft through the reduction-gearing section which drives the splined propeller shaft. This shaft arrangement provides power extraction at the air inlet end and permits the mounting of the accessory drives and power take-off on the inlet housing of the engine.

Operation. In general, the turbine section of the turboprop engine is similar to that of a turbojet engine. The main difference is the design and arrangement of the turbine. In the turbojet the turbine is designed to extract only enough power from the high velocity gases to drive the compressor leaving the exhaust gases with sufficient velocity to produce the thrust required of the engine. The turbine of the turboprop engine extracts enough power from the gases to drive both the compressor and the propeller. Only a small amount of power is left as jet thrust. Usually the turboprop engine has two or more turbine wheels. Each turbine wheel takes additional power from the jet stream, with the result that the velocity of the jet stream is decreased substantially. The T-53-L-3 Lycoming engine has only two

turbines, one to drive the compressor section and the other to drive the propeller system; thus, the turboprop engine has two independently driven rotating turbines. One drives the compressor shaft and the other drives the propeller assembly. This has some advantages since both the propeller and compressor may be operated at rotational speeds that produce the best proportional efficiencies. This allows the propeller to operate at high speed during take-off and climb, thus reducing the tendency of the propeller to stall. Propeller speed can then be lowered at altitude with a subsequent reduction in tip compressibility losses. The independent turbine can be compared with a two-speed reduction gear for reciprocating type engine combinations. The compressor units for turboprop engines may be either axial flow or centrifugal flow types. To reduce the over-all lengths of the T-53 engine the compressor is made up primarily of an axial and partially a centrifugal type compressor system. With a centrifugal system four additional axial compressor stages would be necessary which would extend the engine about twelve inches in length.

Engine Trimming. Due to manufacturing tolerances all T-53-L-3 engines do not produce their rated power at the same per cent of compressor speed. Similarly, acceleration characteristics vary from one engine to another with some engines requiring proportionally higher fuel flows than others for the same power increase. In view of these factors, and since the fuel control must satisfy the power producing and accelerating characteristics of the individual engine in which it is installed, it becomes necessary to tailor the fuel metering characteristics of the control to the individual requirements of the engine. This procedure is known as trimming the engine. Only four adjustments are permitted or should be attempted when the power control is engine installed. They consist of take-off speed setting adjustment; ground idle and reverse power setting speed adjustment; main pressure regulator valve adjustment; and main selector lever external reverse stop.

Gas producer rpm is adjusted by two throttle cam adjustment screws. These screws, externally located, raise or lower the throttle cam in order to adjust fuel flow as required by engine condition. The screw nearest the drive end of the control adjusts take-off gas producer rpm. The other screw adjusts ground idle speed settings and reverse power. The adjustment of take-off trim will have little effect on idle and reverse power, but a small idle trim adjustment may have a larger effect on reverse power.

Starting. Most turboprop engines are started by pneumatic power. The engine is equipped with a pneumatic starter which is driven by bleed air supplied by either an auxiliary pneumatic power unit (ground equipment or installed pneumatic unit) or by bleed air from an engine which is already operating, as in the case of multiengine powered aircraft. The starter unit is geared through a clutch to reduction gears of the engine. When the unit is supplied by air it brings the

engine up to starting speed. By the time the engine reaches a given speed, usually about 60% rpm, the air to the pneumatic starter is shut off and the engine continues to accelerate until it reaches a speed that exceeds the speed of the starter. The clutch then disengages allowing the engine to turn free of the starter and the starter turbine to stop. Once the starting cycle is begun, each operation in the cycle is automatic.

Summary. Since turboprop engines have reached the stage of development where they are now used extensively as aircraft power plants, experience has shown that in many instances these engines have far exceeded expectations in performance and economy of operation. The following are among the principle advantages gained by turboprop engine application:

1. Simplicity of design and construction. The turboprop contains fewer moving parts than does the reciprocating engine; hence, the number of parts which may fail because of wear is reduced. Furthermore, it is easier to isolate and correct troubles within the engine itself.
2. A very low weight to power ratio. This characteristic is also termed specific weight and is found by dividing the weight of the engine by the equivalent horsepower (ehp). For instance, the T-53 engine weighs 520 pounds and has a weight to power ratio of approximately .5, whereas conventional reciprocating engines usually have specific weights of from 1.00 to 1.75.
3. Low fuel consumption. Turboprop engines have been developed to attain a specific fuel consumption of less than 0.40. This means that the engine consumes approximately 0.40 pounds of fuel per equivalent horsepower per hour.
4. Low drag installation. Since turboprop engines are much smaller in diameter than equivalent reciprocating engines, the nacelle containing the turboprop engine can be designed to produce much less drag when the aircraft is in flight.
5. Operational flexibility. The turboprop engine performs well at sea level, under take-off conditions, and it also gives a good performance at altitudes over 30,000 feet. It is limited in higher speed operation because the propeller efficiency drops off rapidly when the aircraft speed is more than 500 to 600 miles per hour. At these speeds turbojet engines are more efficient.
6. Power output of turboprop engines. The power delivered by a turboprop engine increases very rapidly with increasing airspeed because the density and total energy of the air to the compressor becomes greater. This is because of a ram effect produced by the airplane as it rushes through the air. Thus, at sea

level and at 500 miles per hour, the power delivered by a turboprop engine may be approximately 45% greater than during static take-off power. No direct comparisons can be made between gas-turbine turboprop engines and reciprocating type engines. However, since the reciprocating engine propeller combination receives its thrust from the propeller, a comparison can be made by converting the horsepower developed by the reciprocating engine to thrust. If one compares the thrust curve from a reciprocating engine to that of a jet engine, it is obvious that the gas-turbine engine will out-perform the jet engine at flight speeds below approximately 375 miles per hour. Since the conventional engine produces higher thrust in this range, it will have better take-off and initial climb characteristics.

Propeller, Main Rotor, and Anti-Torque Systems.

For many years propellers have been the originators of the most intense noises associated with powered flight, and with the introduction of more powerful reciprocating engines and stronger blade materials, propeller noise increased in magnitude. The higher noise levels were related to increased propeller blade tip velocity and increased torque loadings. The mating of propeller systems with reaction type engines resulted not only in an increase in the intensity of the noise generated by the propellers, but also in a change in the frequency distribution of the noise.

In early stages of development a propeller was a fixed pitch type and constructed of wood. Later, propellers were constructed of metal and the pitch of the blades was adjusted automatically by counterweights that were sensitive to centrifugal force. Some blades were adjustable, but had to be adjusted to a set angle while on the ground and could not be varied during engine operation. Later improvements and developments allowed adjustments in the pitch of the blades which could be controlled automatically or manually during flight.

The development of propeller systems on which the pitch of the blades could be adjusted resulted in outstanding improvements because the desired thrust for various phases of flight could be varied separately from engine rpm alone. Also, variable pitch blades allowed the development of more powerful and efficient power plants. Higher altitudes could be achieved by allowing greater blade pitch adjustments. The development of variable speed propeller systems also allowed the development of a constant speed propeller system.

Propeller systems have been highly developed and when used as the basic component of propulsion offer several advantages: a high thrust for take-off as well as a high degree of efficiency for normal cruise conditions, distinct advantages for shortening landing distances by providing a negative (reversal) thrust, and within

certain limitations, produce noise that is somewhat less intense than noise produced by turbojet engines.

Propeller and rotor systems are powered by reciprocating engines, turbo-prop engines, turboshaft engines, or by free turbine engines. Noise generated by propeller and rotor systems is usually complex and varies considerably depending on the particular type of mating of propeller or rotor systems to power plants. Normally, the higher the rpm of propellers or rotors and the greater the torque applied to the systems, the more significant will be the noise they generate. Highly developed propellers and rotors capable of handling high torque forces are commonly mated to powerful reaction or reciprocating type engines.

Many factors have a direct influence on the noise generated by a propeller, i.e., rpm, tip speeds, blade pitch, number of blades, etc., and it is rather difficult to illustrate one particular factor without including other contributing noise factors. For this reason, the first part of the section will be devoted to describing the basic noise characteristics and noise modifying elements, and in a later section detailed examples of these various noise elements will be presented. In the following section rotor and anti-torque rotor noise will be discussed similarly.

Propellers. Propellers may be divided into three general classifications according to the speed at which the blade sections travel during maximum engine performance*:

1. Subsonic-propellers - the tips of the blades travel at subsonic speeds (less than Mach 1.0) throughout the range of rpm provided by the power plant.
2. Transonic-propellers - the tips of the blades travel at speeds which are supersonic as well as subsonic, depending on the operation of the engines.
3. Supersonic-propellers - the tips of the blades travel at supersonic speeds throughout the range of engine operation.

Propellers may be classified further by blade pitch control into one of the following:

1. Fixed pitch - stationary blade angle which does not change during flight.

*During conditions of standard atmosphere (sea level) of 59° F. and 29.921 inches of mercury, propeller tips traveling at speeds in excess of 1116.8 feet per second (661.7 knots) are considered as being supersonic.

2. Constant speed, with variable pitch - blades that rotate at relatively constant blade tip speeds and the blades vary in pitch.

3. Controllable pitch - blades that vary in pitch throughout the range of propeller operation.

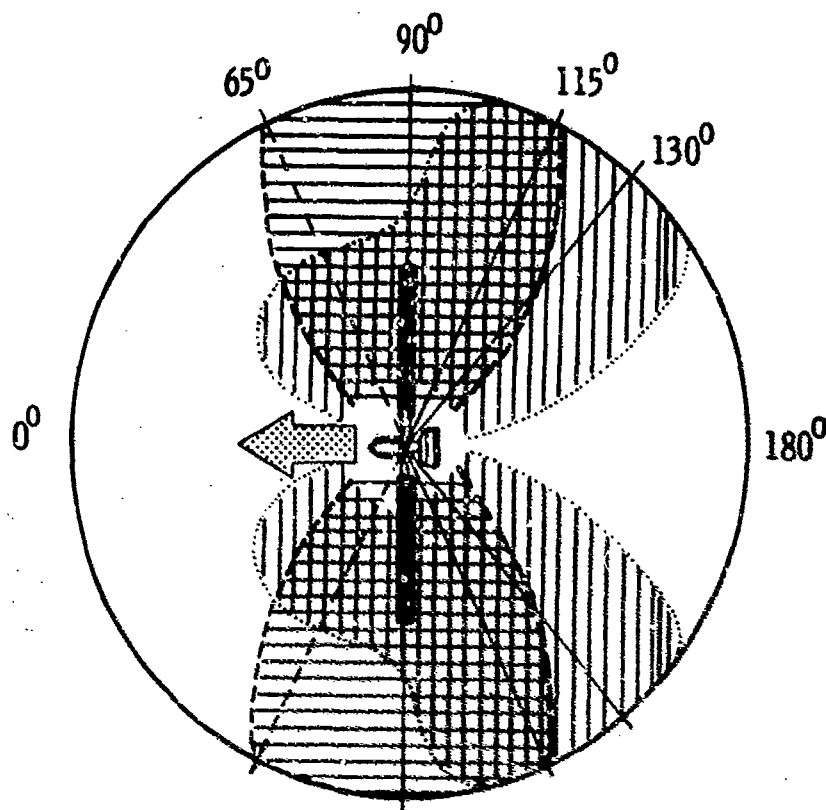
4. Two-position pitch - blades that vary from high to low pitch, depending on propeller rpm.

5. Ground adjustable (set positions) - the desired pitch is selected and set manually prior to flight.

Propeller noise emanates from two primary sources: first, pressure disturbances in the surrounding air media which rotate with the propeller blades, referred to as rotational noise; and second, vortices created in the propeller wake that are produced by the propeller blades during their rotation. The pressure fields produced by a propeller become more intense as the rotational speed increases and are most pronounced at the tip of the rotating blades. Rotational type noise is directly influenced by the torque applied to the blade and the blade thrust generated by the rotating blades. These factors are further influenced by the pitch (angle) of the propeller blade, by the camber of the blade, and by the thickness and chord distribution of the blade.

As a subsonic propeller rotates around a central axis the blades create disturbances in the surrounding air and part of these pressure disturbances are converted into acoustic energy. Without pitch the noise generated by a rotating propeller tends to be propagated directly within the propeller plane, but when pitch is applied to the blades the maximum noise now shifts to a position which is about 30 to 50 degrees behind the plane of the propeller. This phenomenon is depicted in Illustration 5 (prop-radiation-graphic). The horizontal lines represent the general noise pattern of a propeller rotating without applied pitch to the blades, and the vertical lines represent the shift in the directivity of the noise that results when pitch is applied to the blades.

Propeller rotational noise has a discrete frequency spectrum which is harmonically related to the blade passage frequency. At subsonic tip speeds, the acoustic energy is present in the form of high frequency harmonics. As sonic and supersonic tip speeds are obtained, an observer notices an increase in the over-all noise level as well as a significant increase of noise present in the higher frequencies.



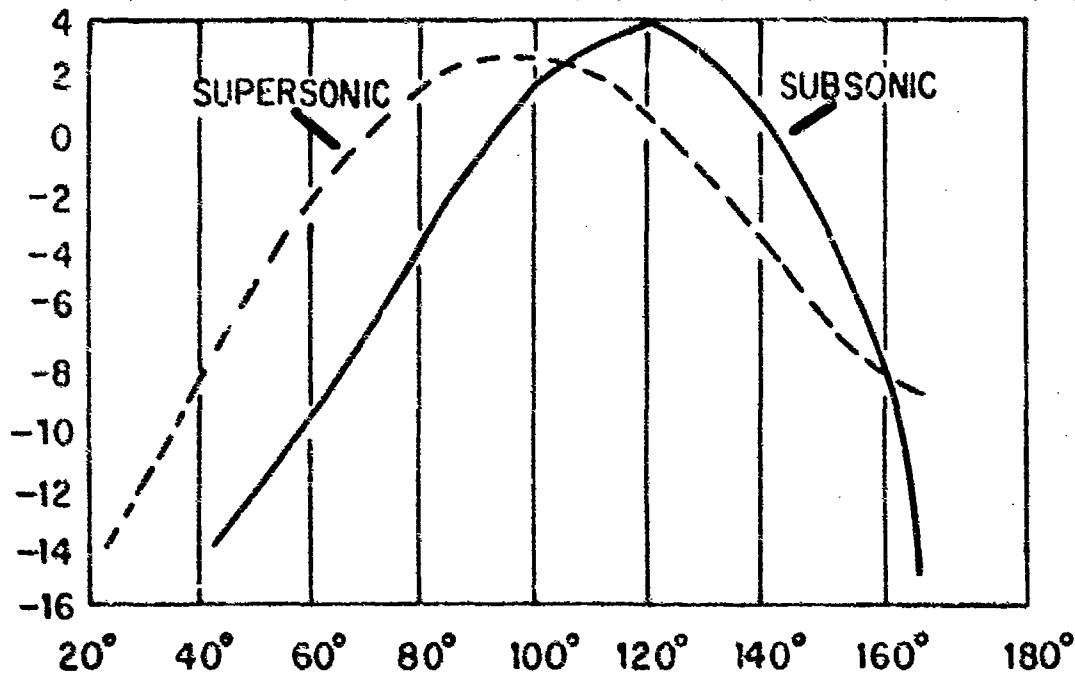
Illus. 5 Directivity of Noise With and Without Propeller Pitch

As propeller tips rotate at supersonic speeds, the acoustic energy present in higher harmonics becomes more intense than the acoustic energy generated by the fundamental, and higher frequency noise components are most noticeable in the acoustic field generated by a supersonic propeller. Even though the higher harmonics contain more intense noise than the fundamental, the peak frequency range is still contained within frequencies below 1,200 cps.

As already mentioned, vortices generated by a propeller produce a noise in higher frequency ranges than do rotational disturbances. The frequency spectrum of the noise generated by vortex disturbances is more or less continuous in nature and tends to shift into progressively higher frequency ranges with increases in propeller tip speeds. In general, vortex noise is usually most evident at positions located in front of the blade. The acoustic energy of vortex noise is related to the relative pressure resistance of the aerodynamic flow (or passage) encountered by the propeller. Under certain conditions when the propeller is spinning at low tip

speeds, the noise resulting from vortex formations may exceed the rotational noise. At high propeller tip speeds the vortex noise is evident only at higher frequencies. This, when a propeller is rotating at high tip speeds, the dominant noise is created by intense pressure disturbances resulting from the rotating blades. This dominant noise is representative of rotational noise and is most prominent in the lower frequency ranges. Vortex noise, although present, is less intense than rotational noise but may be evident in the higher frequencies.

Propeller tip velocity has a direct influence on the noise pattern generated by the propeller. Illustration 6 depicts the directivity characteristics of the noise produced by a subsonic and supersonic propeller. At subsonic tip speeds the noise generated by the propeller is most intense at positions just aft of the propeller plane, usually between 100 to 140 degrees from the front of the propeller. The directional pattern changes when propeller tip speeds approach and exceed the speed of sound. At supersonic tip speeds the directivity pattern of the maximum noise shifts to a position directly in line with the propeller plane and as the blade tips rotate at, or near, the speed of sound (Mach 1.0) the noise generated by the propeller becomes more intense, resulting from increases in the magnitude of both the rotational and vortex noise components. The increased intensity of the vortex and rotational noise is directly related to the increased propeller tip speeds. Also, when the propeller tips rotate at, or exceed, the speed of sound there is a noticeable increase in the noise generated within the higher frequencies. Very high propeller blade tip speeds are usually associated with propeller systems powered by turboprop



Illus. 6 Directivity of Noise Produced by Subsonic and Supersonic Propellers

power plants. Increasing propeller tip speeds beyond the supersonic range do not cause a further shift in the directivity pattern of maximum noise generated by the propeller blades, but merely restrict the general spread or angle of the maximum acoustic energy distribution.

Over-all noise levels generated by supersonic propellers are of greater concern than equally intense noises generated by a subsonic propeller. In general, supersonic propellers not only cause an increase in the noise emanating from the propeller, but also produce an increase in the intensity of the higher frequencies above the fundamental. This increase in the intensity of the noise spectrum above the fundamental (which is usually below 150 cps) results in a noise field that is of greater concern than that below it. Also, the noise created by supersonic propellers that produce higher frequencies are more efficient maskers of speech communication.

Torque, or the amount of twisting power applied to a propeller shaft, has a direct and significant influence on the noise generated by a propeller. A propeller rotating at a constant rpm will produce more noise when torque is increased. In fact, the amount of torque applied to a given propeller or rotor system is a more significant influence on the noise produced by the propeller than the rpm of the propeller itself. Most of our present day power plants, especially those used to power large fixed- and rotary-wing aircraft, maintain a relatively constant propeller shaft speed. When increased thrust is required from the propeller, the propeller rpm is maintained at the same speed and the desired increases in thrust are obtained by the delivery of increased torque. The most common expression of torque is in pounds per square inch (psi). During a static run-up, as torque increases, the intensity of the propeller noise is most dominant at locations behind the propeller plane.

When torque is maintained at a constant value, the thrust provided by a propeller decreases as airspeed increases. Initially, the total noise generated decreases with increasing forward velocity of the vehicle, but at a higher velocity the effect of motion on the generated noise actually produces an increase in the total noise generated within the propeller plane area.

Generally, the highest torque applications are associated with augmented thrust. Augmented thrust from both reciprocating and gas-turbine (turboprop) engines is obtained by the use of fluid-injection (sometimes referred to as water-injection). During augmented power the engine can develop more torque power which results in increased thrust. The increased torque, when applied to the propeller shaft, results in an increase in the propeller noise (primarily due to the increased pitch of the blade systems).

Blade thickness, which varies considerably from one type of propeller system to another, apparently has only a slight influence on the intensity of the noise produced by a propeller; however, there are numerous other factors related to a propeller system that may have a direct or indirect influence on the frequency spectra of the noise. For instance, although the width of the propeller blades does not cause a significant change in the frequency of the fundamental, the intensity distribution of the higher frequency harmonics may be altered. This phenomenon is related to certain operational characteristics. Usually, the greater the width of a propeller blade, the slower will be the speed of rotation required to produce a desired thrust. As a result, noise variations produced by a propeller system with wide blades is directly influenced by the total thrust derived from the blades, the amount of torque applied to the blades, and the directional properties of the acoustic disturbances generated by the blades.

Considerable research has been conducted on increasing and decreasing the number of blades within a propeller system. All factors being equal, the addition of more blades to a propeller system will result in a decrease in the over-all noise. By increasing the number of blades in a particular propeller system, the general effect is to cancel out all higher frequency harmonics except those directly related to multiples of the number of blades. The number of blades in a propeller system, when evaluated against the frequency of times each blade in the system passes a fixed point, determines the fundamental frequency of the noise generated by a propeller.

At a constant propeller rpm, the greater the number of propeller blades, the higher will be the blade passage frequency, and the fewer the number of blades, the lower will be the frequency of blade passage. For instance, a three-bladed propeller rotating at 1,000 rpm will have a blade passage of 50 times per second and this a fundamental frequency of 50 cycles per second. The fundamental frequency, as well as the harmonics generated by the propeller, are directly influenced by the frequency of the occurrence of each of the disturbing mechanisms - the individual propeller blades. When rotating at low tip speed the fundamental is the most pronounced of the frequency components generated by the propeller, but as propeller tips approach the speed of sound the harmonics increase in magnitude until they reach a point where they are more intense than the fundamental. The most intense frequency component produced by a supersonic propeller is usually found to be a direct multiple of the blade passage frequency.

In general, increasing the number of blades (usually not exceeding four) allows an increase in the distribution of horsepower per blade. In several instances, especially from turboprop propeller systems, increasing the number of blades from

three to four allowed the following modifications and changes to be made without penalizing total performance: 1) the total diameter of the propeller was reduced, which also resulted in a greater fuselage to propeller tip clearance, and 2) the propeller tip speed could be reduced, resulting in less intense propeller noise.

A frequency shift of the fundamental as well as the higher frequency harmonics is produced by increasing the number of blades in the propeller system. For this reason, a four-blade propeller will generate a somewhat more intense higher frequency spectrum than will a three- or two-blade propeller.

The application of contrarotating propellers has been investigated, and although greater potential blade propulsion energy is represented, the aerodynamic disturbances created by a one-blade system apparently interact on the second blade system. Investigations determined that utilizing contrarotating propeller systems resulted in a significant increase, rather than a decrease, in the noise. In a similar manner the disruption or distortion of airflow impinging on the blades of a rotating propeller may result in a significant increase in the noise and vibration produced by the propeller. This phenomenon is usually associated with propellers located aft of the fuselage or wing areas, commonly referred to as "pusher-type" propeller systems. The increase in noise and vibration results from disruptions in the atmospheric medium through which the propeller blades must pass. As the more or less evenly distributed atmosphere is separated by leading structures of the aircraft, areas of high and low pressure are created, thus producing a distortion of otherwise equally distributed atmosphere. If a propeller is mounted aft of the main fuselage or wing, the blades receive unevenly applied pressure loadings from the disrupted and uneven airflow created by the passage of the aircraft through the atmosphere. This disrupted airflow impinging on the blades may create a situation in which the alternating stresses encountered by the blades result in a misalignment of the plane of rotation. If this occurs the propeller creates movements in yaw around the axis of the propeller shaft. This type of phenomenon is not commonly encountered by current Army aircraft, but designs now under study for future VTOL and STOL aircraft powered by pusher-type propellers may result in such applications. Of course the significance of such propeller matings may be dictated by several variables, but, in general, this particular type of propeller system can be expected to generate more noise and vibration than a similar power plant and propeller system that is mounted forward of the fuselage and wing areas.

The type, size, and number of blades in the propeller, the type of power plant, the relative degree of aerodynamic disturbances created before the atmosphere impinge upon the blades of the propeller, and operational factors may have a direct influence on the degree of noise and vibration created by such aircraft-to-power plant matings.

Unique Turboprop Propellers. Propeller systems mated to turboprop power plants must meet rigid requirements. The propellers must possess good structural integrity, be almost perfectly balanced, and the blades must be accurately and reliably controlled throughout all phases of pitch change.

Turboprop propellers have unique operational features that directly influence the noise they produce:

1. Since the propellers rotate at very high blade tip speeds, intense noise is generated relative to the magnitude of rotational disturbances they create.
2. Because of high blade tip speed, the angle of maximum noise radiation is usually located almost directly in the propeller plane.
3. Due to the increased frequency of blade tip passage, turboprop propellers generate harmonics that are usually more intense than the fundamental.
4. Since most turboprop propellers rotate at a relatively constant speed, changes in blade pitch and torque may result in significant alterations in the intensity, frequency distribution, and acoustic radiation patterns of the propeller noise.
5. To achieve the best possible braking action during landing roll, reversed pitch is accomplished at high torque values. Rather intense noise is generated during this maneuver due to high propeller tip speeds and torque values.

Since turboprop propellers rotate at higher rpm than propellers powered by reciprocating engines, there are less structurally induced low frequency vibrations due to imbalances and misalignments that cause yaw in the central axis of the propeller shaft. Needless to say, if yaw in propeller rotation does occur, excessive vibrations may result due to the very high propeller shaft rpm.

Turboprop propeller systems possess very good thrust reverse characteristics. As the propellers of aircraft are reversed in pitch there is usually a noticeable increase in noise produced by the propellers. The noise produced during reversed pitch is of short duration and is most dominant in the frequency ranges below about 600 cps. The magnitude of the noise resulting from propeller reversal is dependent on the angle of pitch attained during reversal, the amount of torque applied, the rpm of the propeller, and the basic aerodynamic features of the blades of the propeller. Most propeller reversals do not invert blade pitch more than a minus eight to ten degrees. Since the thrust of the propellers is reversed, the directional characteristics of the noise are swiftly altered. During the initial phase

of landing the noise from the propellers is most pronounced at positions in line with, and just aft of the propeller plane, but when the angles of the propeller blades are reversed, areas in line and just forward of the propeller plane contain the most pronounced noise.

Noise generated during thrust reversal may be more intense in some aircraft than in others. For instance, turboprop STOL aircraft powered by free turbine engines that utilize reverse propeller pitch to reduce landing roll may generate more intense noise than aircraft powered by constant speed power plants. Free turbine engines provide their best propeller reversal when the engine is operating at high rpm and consequently high torque is applied to the propellers resulting in increased noise. Even though this type of application of reversed propeller thrust may generate more intense noise than constant speed engines, the duration of time required for propeller reversal is somewhat less due to rapid loss of torque once it is applied to the propellers. The majority of propeller driven aircraft that utilize propeller blade reversal systems have constant speed propellers and power plants, and the noise they produce during reversed pitch is of little significance at far-field positions due to the very short duration of time the noise exists. This is true even though the noise consists of intense low frequency components.

A rather unique feature of turboprop power plants is a device referred to as a negative torque control. Negative torque control (NTC) systems are installed on most turboprop engines in order to automatically provide increased pitch (decreased rpm) whenever a negative torque condition (propeller driving engine) occurs. When negative torque is sensed by the negative torque system the pitch of the propeller is increased. Once the engine power is restored the propeller system returns to normal pitch operation. The negative torque control is automatic during normal flight conditions.

Because of the intense sonic vibrations associated with turboprop power plants, multiengine aircraft utilize a special propeller synchronization system which significantly reduces the annoying factors of randomizing type propeller noises (phase-in phase-out type noise) as well as offering significant reductions of sonic vibrations which could otherwise promote or contribute to structural fatigue.

Highly developed and integrated synchrophasing systems are installed on almost all military dual and multiengine turboprop aircraft. The synchrophase system, along with other related propeller and engine control units and components, make up the highly integrated turboprop propeller and power plant system.

When the throttle is advanced to the "flight" range, the engine rpm is controlled through the synchronizer or by mechanical reference governing. When

operating in the lower rpm "ground" throttle range, the propeller blade angle is controlled through a coordinator-potentiometer mounted on the engine and actuated by the fuel control unit. Propeller control is proportional to the throttle setting through the ground control range to a full reverse blade angle control of minus 9.2 degrees.

The synchrophasing operates through a basic synchrophaser system to maintain propeller blade position in relation to the blades of the other propellers, i.e., the blade tips of adjoining propellers do not pass the same relative point at the same time. This system reduces harmonic vibrations, noise levels, and other associated vibrations which could contribute to structural fatigue.

An acceleration stabilized propeller governor, located on the rear of the propeller power unit, is provided to correct the blade angle of its respective propeller in order to maintain the desired engine speed during any normal flight attitude. Whenever the throttle is in the flight range the propeller governor controls the rpm of its respective engine either electrically (through the propeller synchronizer) or mechanically (through an individual mechanical reference governor).

An electrically powered propeller synchronizer provides a controlled electrical reference signal which drives a propeller governor reference motor on each engine at the same speed, thus achieving synchronized speed operation of all engines. The propeller synchronizer is energized during engine operation whenever the throttles are in the "flight" range and the propeller synchronizer system is engaged (selected by the pilot). With the synchronizer engaged, synchronous propeller shaft operation at any engine speed between the range of 94.5 to 100 per cent rpm will result. During synchronizer operation the speed of all engines will be synchronized to the speed of the engine with the most forward throttle position. In the event malfunction causes the rpm of the engine to become either less than 92.5 per cent rpm or greater than 103 per cent rpm, control of that engine will automatically be changed from the propeller synchronizer to its mechanical reference governor and will be maintained at 97.9 per cent rpm. If the throttle of an engine whose speed is being controlled by its mechanical reference governor is advanced forward of the other three throttles, the speed of the synchronizer-controlled engines will increase. Under these conditions, the torque of the mechanical reference governor controlled engine will increase as its throttle is advanced, but its rpm will remain at 97.9 per cent.

Figure 9 illustrates the general influence increased propeller rpm may have on the noise emanating from propeller disturbances. The noise measurements were taken at a position directly in front of the propeller. The noise was produced by a horizontally opposed six-cylinder Continental 0470 engine with a fixed pitch,

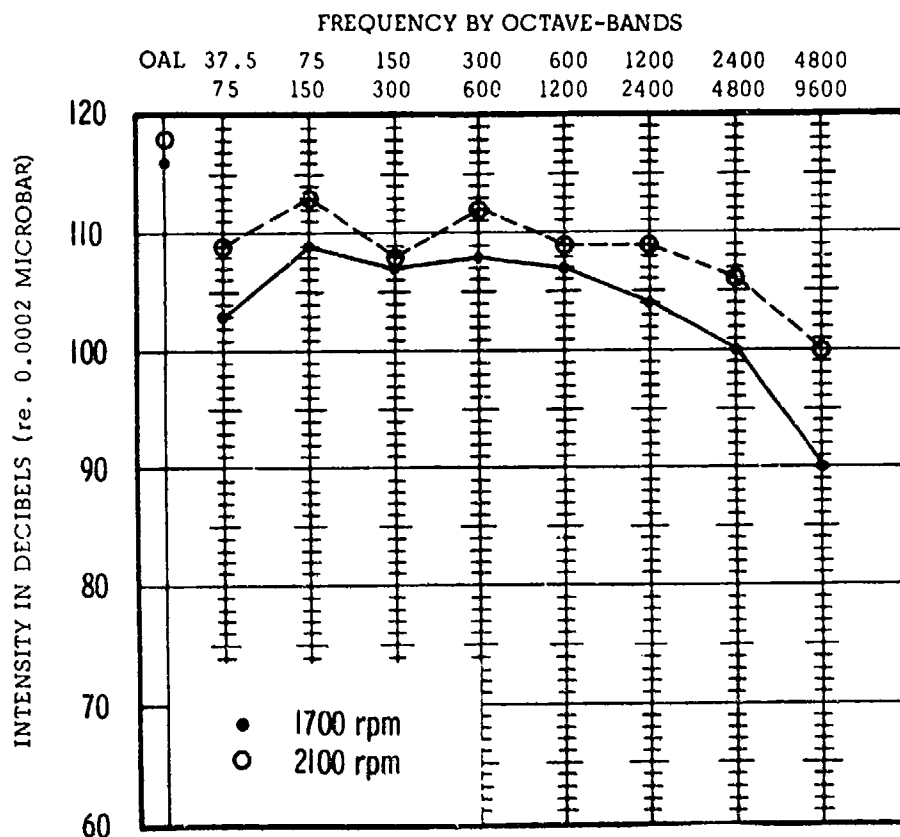


Fig. 9 0470 Engine Test Noise Measured at a Distance of 5'2" Directly in Front of the Engine

two-blade propeller of 7.5 feet diameter. The measurements were accomplished while the engine was installed on an open test bed. Since the propeller has fixed blade pitch, increased rpm does not create a change in propeller pitch. Also, the presence of higher frequency energy is evident when the propeller blade tips increase in velocity. With the engine operating at 1,700 rpm the propeller rotates at a blade tip velocity of approximately 668 feet per second (0.60 Mach), and at 2,100 rpm propeller tip velocity increases to approximately 824.6 feet per second (0.74 Mach). Since the propeller blade remains at the same pitch the increased propeller tip speeds clearly account for the generation of vortex as well as rotational noise. Once again, the total spectra shows a more wide-spread alteration of the noise than the differences in the over-all noise level reveal.

Figure 10 shows noise emanating from the same engine during similar operations, but these plottings represent the noise propagated directly in the

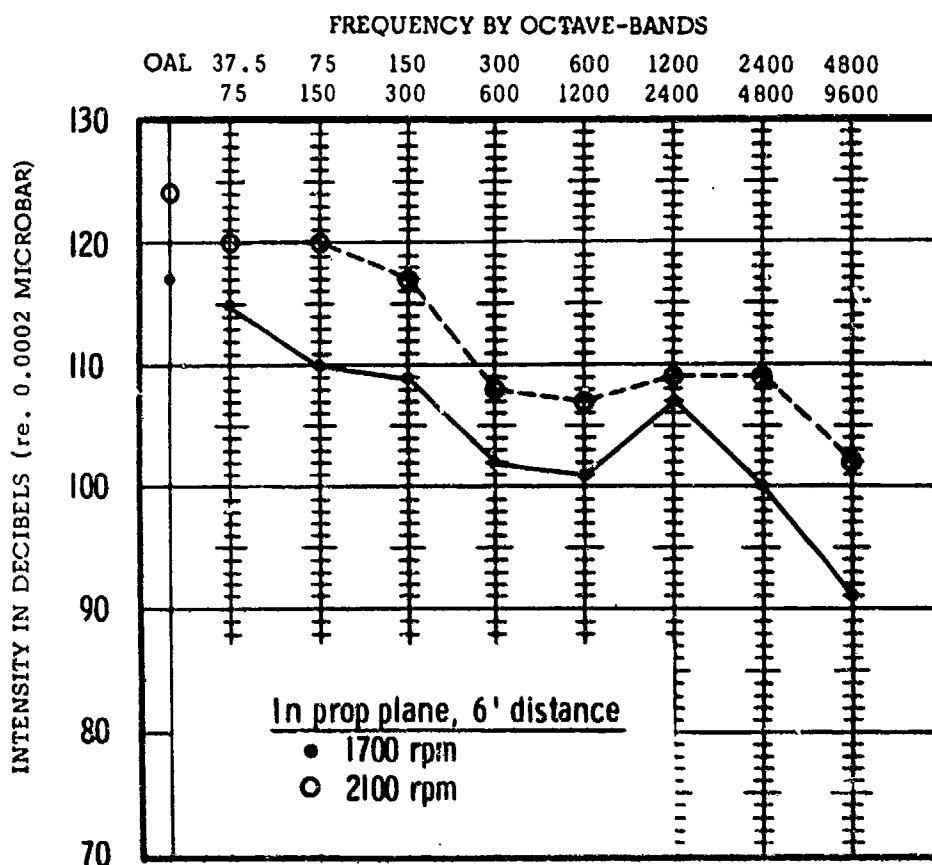


Fig. 10 0470 Engine Test Noise Measured at a Distance of 6' Directly in the Propeller Plane

propeller plane. The fundamental of blade passage becomes somewhat more important since the noise generated directly in the propeller plane is directly related to the number of blade tip passes that occur per second. At 1,700 rpm the blade passage is 56.5 times per second, and at 2,100 rpm the frequency of passage increases to 70.7 times per second. The noise increases noted at the side of the propeller plane are representative of the rotational noise, most evident at frequencies below about 300 cps, and higher frequency harmonics that are related to the fundamental frequency that is quite annoying to the majority of people. Of course, two-blade propeller systems are generally louder than a three- or four-blade system operating at equal power. Generally, two-blade type noise is more annoying because the time duration between individual blade disturbances is increased to a value where the human ear perceives the noise, not as a continuous steady type noise, but rather somewhat like a slapping and pulsating noise.

General observations of noise created by small reciprocating engine propellers indicate that the noise generated by small, high speed, fixed pitch propellers contains a wider and more evenly distributed frequency range than that commonly associated with medium size engine-propeller systems. When referring to a propeller system, the use of the term "constant speed" is probably often misunderstood. For the most part, a distinction should be made, especially between reciprocating and turboprop powered constant speed propellers. First of all, the constant speed type propeller used on reciprocating engine aircraft usually operates during take-off at much higher speeds than during normal flight, and one should be careful not to erroneously assume that the term "constant speed" propeller means that the propeller will only operate at a constant rpm. A good example of noise generated by a constant speed propeller system during take-off and climb is the U-8D aircraft.

Figure 11 illustrates an increase of the propeller noise generated within a U-8D aircraft during two phases of high engine and rpm power settings. The U-8D is powered by two Lycoming O-480 engines that are fitted with three-blade constant speed, hydraulic controlled, and full feathering type propellers. Once the desired altitude has been achieved and the throttles retarded to normal cruise power, the automatic propeller power control system is engaged. The noise illustrated here is produced almost entirely by rotational noise. During take-off the propeller tips rotate at approximately 880.0 feet per second (0.788 Mach). As the engine rpm increased, the propeller tip velocity likewise increased resulting in increased noise. The noise produced by the propellers during take-off resulted in an over-all increase in the intensity of the noise, as well as a broadening of the noise spectrum. One factor contributing to the broadening of the higher frequency range during increased propeller rpm is the shift of the blade passage frequency into higher ranges. For instance, the fundamental blade passage during take-off is 109.1. After power has been reduced the width of the spectrum of the noise narrows and the over-all noise level decreases. During climb the reduced engine power and propeller shaft rpm shifted the propeller tip blade speeds to 776.5 feet per second (0.695 Mach) and also shifted the frequency of fundamental blade passage to 96.3 times per second.

Intense propeller noise is commonly associated with take-off operations due to the requirements for increased engine and aircraft performance. The propeller becomes a significant noise generator primarily because of increased propeller tip speeds. As the rpm is increased, thus offering greater power, the propellers rotate at faster speeds and by taking smaller, but faster, amounts of the air, increased take-off performance is achieved. Normally, after rpm is reduced, the blades of the propeller system increase in pitch (angle) and take larger displacements of the air. At constant rpm, the higher the altitude, the greater will be the pitch required of the blades.

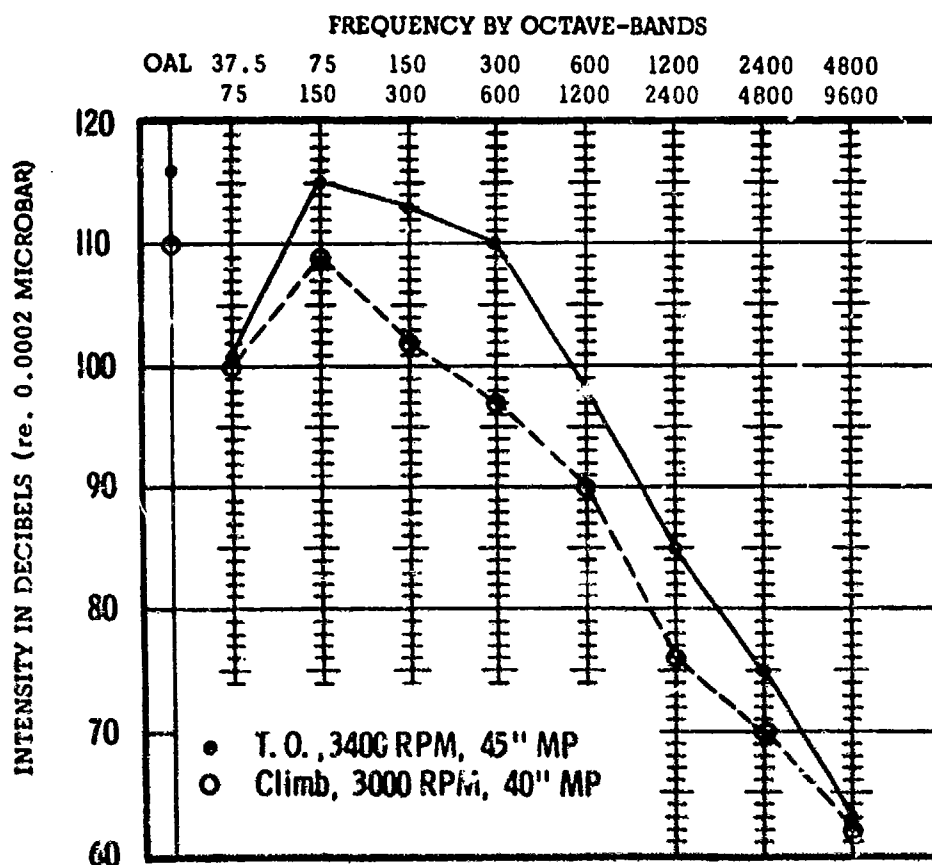


Fig. 11 Internal Noise of U-8D Aircraft Measured at Head Level Between Pilot Stations

Figure 12 shows the characteristic noise distribution of an OV-1B measured at 45, 90, and 135 degrees at a distance of 50 feet. The noise is representative of only one engine and measurements were completed with the propeller rotating at a blade tip speed of 0.733.1 feet per second (0.656 Mach) and a blade passage frequency of 70 times per second. The blades were also operating at a high pitch. The noise plottings indicate only slight change in over-all levels, but rather significant differences in spectra were found. In front of the propeller plane (45 degrees) the noise spectrum was relatively flat. In the plane of the propeller the lower frequency range increases and the noise is not as evenly distributed through the frequency spectra. Aft of the propeller plane (135 degrees) the noise emanating from the propellers is the most intense of the three positions due to the combination of blade tip speed and thrust (torque) which combine to create a relatively intense, low frequency, type noise.

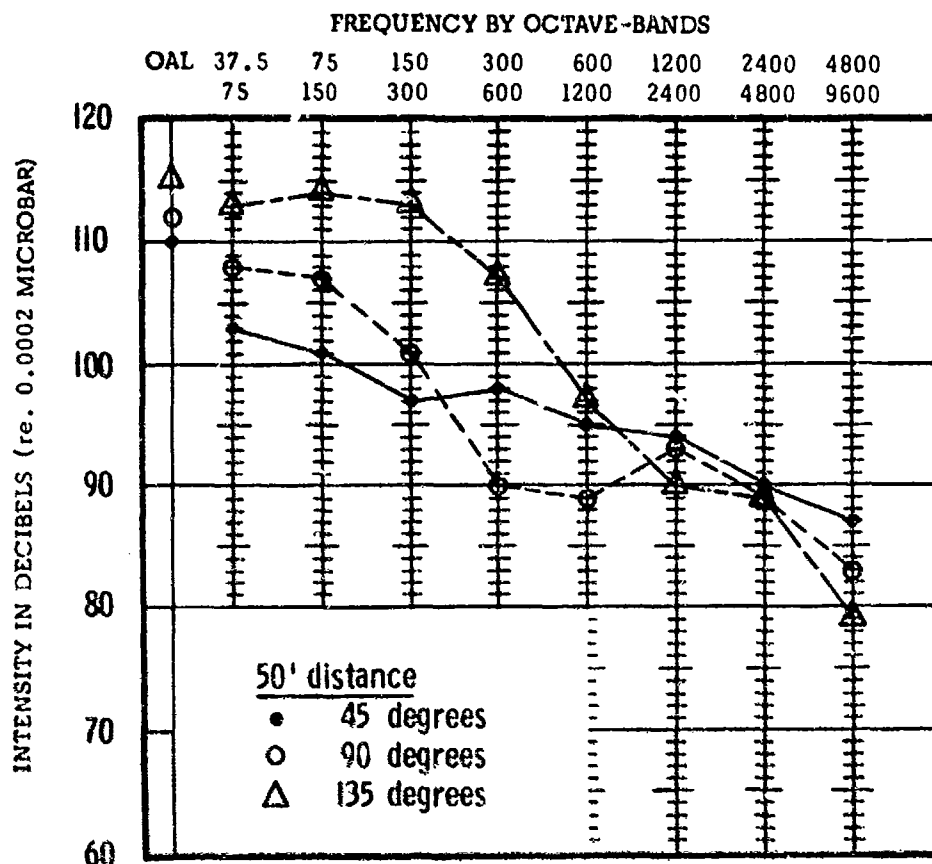


Fig. 12 External Noise of OV-1B Aircraft During Ground Operations, Propeller Check, 83%, 1400 RPM

Figure 13 shows differences in the noise produced by the same aircraft at the same positions and distance, but during these measurements the propeller rpm was decreased by 199.0 feet per second (equal to a decrease of 0.178 Mach) and the blade pitch was also decreased. Since the power plant is a free turbine type engine, as propeller rpm is decreased the engine rpm is also decreased. Decreased propeller tip speed and blade thrust significantly decreased the rotational noise produced by the propeller and, as a result, at a position of 45 degrees, the presence of engine noise is quite evident in the 150 to 300 cps frequency range. At a location within the propeller plane (90 degrees) the most dominant noise is related to the frequency of blade passage, which is 51.0 times per second, and at 135 degrees the most dominant noise emanates from the aerodynamic displacements created by the propeller blades, and is most pronounced in the 75 to 150 cps band.

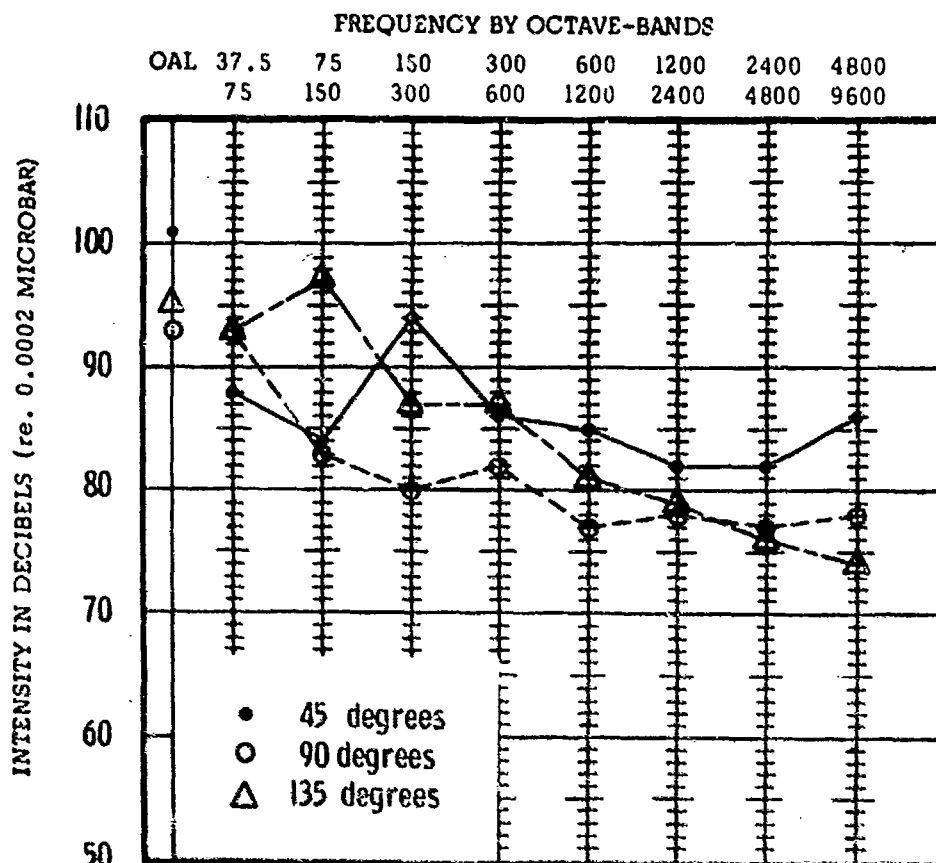


Fig. 13 External Noise of OV-1B Aircraft During Ground Operations, Measured at 50' Distance, Flight Idle, 60% RPM

Figure 14 also shows the effect of propeller pitch on the noise generated by the propeller. In this instance the propeller noise of a U-1A aircraft was measured at a distance of twelve feet directly under the wing and at a position just aft of the propeller (45 degrees). The aircraft was located on sod during the measurements and wind blast was negligible. The noise plottings in the illustration show a general increase in the noise throughout the frequency spectrum, with about a six db increase in intensity due to a change of blade pitch. Increasing the pitch of the blade required considerably more torque, and since the blade is a constant speed type, the increases in rpm are negligible. Note that the manifold pressure increased from 17.5 to 27 inches during this operation, indicating a considerable increase in applied torque to the propeller system due to increased resistance generated by the increased pitch of the propeller blades.

Figure 15 gives examples of the noise generated in the propeller plane of a CV-2B during take-off. Note the difference in the noise produced by the propellers

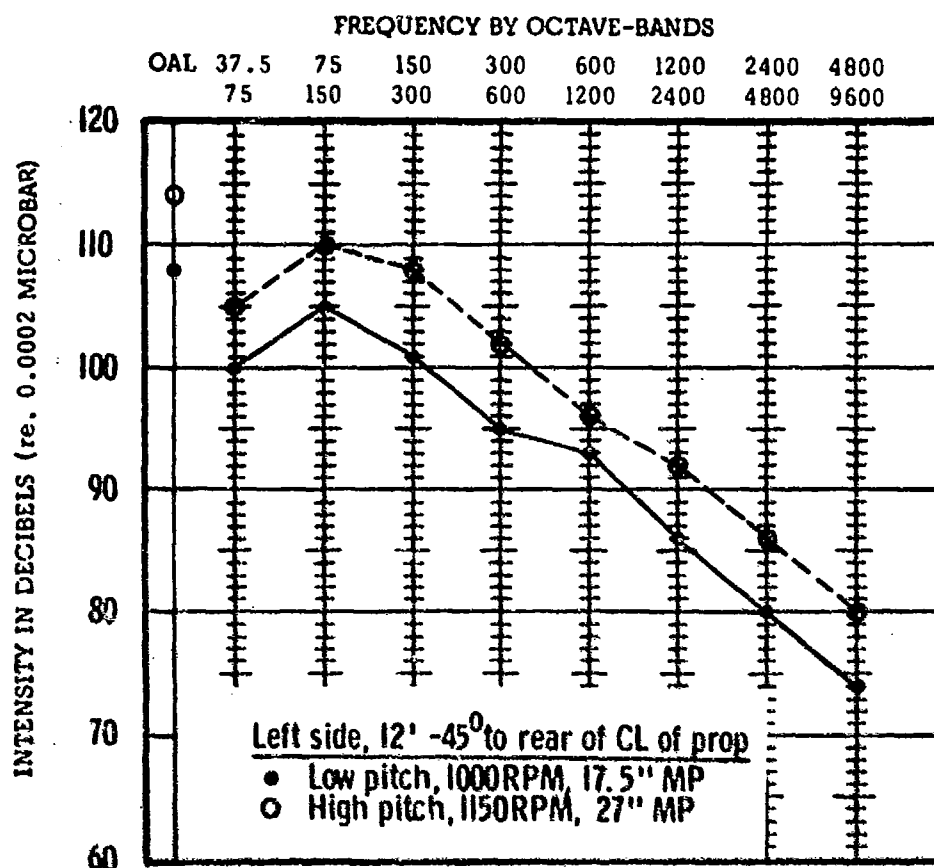


Fig. 14 External Noise of U-1A Aircraft During Ground Operations

during take-off with the engines operating at 2,700 rpm and 50 inches of manifold pressure, and the noise produced when the engines are reduced in power to 2,000 rpm and 32 inches of manifold pressure. The most significant noise is propagated in the lower frequency ranges and tends to fall off continuously with increasing frequency.

Most aircraft powered by reciprocating engine-propeller systems produce vibrations that are the direct result of imbalances of the propeller. If a propeller is out of alignment, or imbalanced, considerable vibration may result within the engine and, in turn, the structures of the aircraft. Propellers that are misaligned or misbalanced may generate structurally induced vibrations due to disturbances in yaw as they rotate around a central axis. For instance, if a propeller is imbalanced as it rotates around a central axis, it will generate imbalanced torque actions which cause the propeller shaft to move in positions of yaw. This phenomenon, added to other imbalances within the engine itself, may generate significant vibrations.

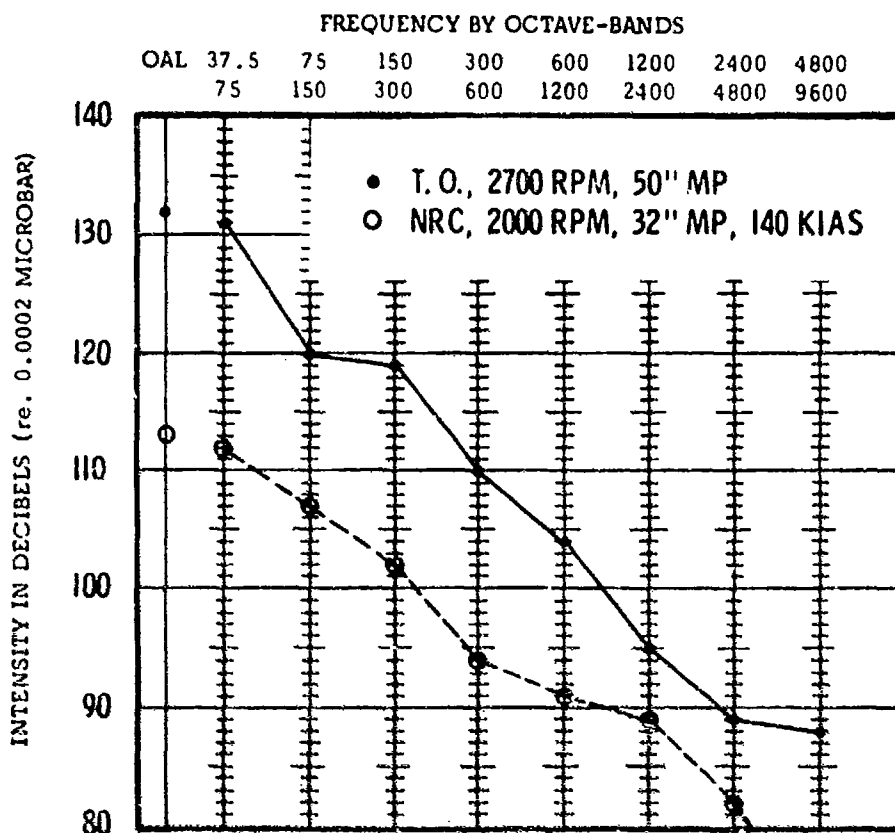


Fig. 15 Internal Noise of CV-2B Aircraft During Flight, Measured at Head Level in the Left Seat, Directly in the Propeller Plane

Propellers may also generate vibrations of the aircraft structure by the dynamic pressures exerted by the rotating propeller blades. The pressures generated by the propeller impinge on the side of the fuselage and wings, thus setting up a form of induced vibration. This type of vibration is usually found to be most intense in the propeller plane area of the vehicle.

Figure 16 illustrates the magnitude of change within various frequencies which can result due to propeller rpm differences. The differences shown here were measured between the pilots of a U-8D twin-engine aircraft during normal cruise. The rpm synchronization was adjusted manually until an "ideal" synchronization was obtained. The intensity versus frequency ranges are representative of 30-second intervals. The total radiated acoustic energy of a propeller increases with propeller tip speeds. The radiated energy of subsonic propellers may be less than one-one

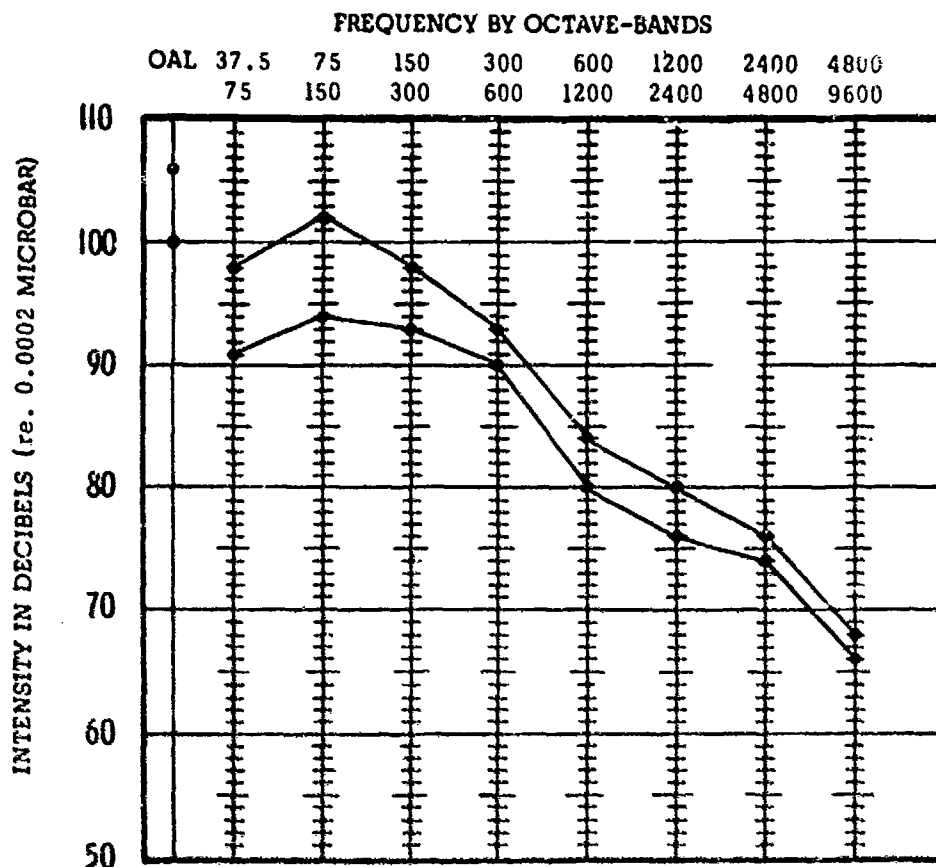


Fig. 16 Internal Noise of U-8D Aircraft During Flight at Normal Cruise, Measured Between the Pilots at Head Level, Propellers in Synchronization

thousandth of one per cent of the propeller power, whereas for a supersonic propeller the acoustic energy may be several per cent of the total power of the propeller.

The frequency characteristics of propeller noise are directly related to the blade passage frequency. For all propellers, subsonic and supersonic, the lowest frequency component is determined by the fundamental blade passage frequency, and all other frequency peaks are multiples of the fundamental. Propellers rotating at subsonic blade tip speeds generate the most intense noise element at the fundamental, and supersonic propellers generate their most intense noise component in the harmonics. The noise spectra generated by subsonic propellers may also possess broad peaks in the frequency range above 1,000 cps. This increase is due to shedding of boundary layer disturbances and vortices from the blades, and is commonly referred to as vortex noise. Supersonic propellers generate intense noise elements in the higher frequencies. The major noise component is associated with rotational factors such as blade displacement and aerodynamic loadings.

The location of the observer relative to the direction of propeller rotation may have a definite bearing on the noise received at a given position. During rotation (ground level) the sound field may be considerably affected by induced variations in the airflow or by the presence of a surface (a wing, for example). In general, the approaching side of a blade produces more intense sound pressure displacements than the retreating side.

Main Rotor Systems. Rotor noise is much more involved and difficult to explain than simple propeller noise. The components which generate and modify rotor noise are complex and slight operational changes result in rather significant changes in the noise.

Noise, resulting from rotor(s), is produced by aerodynamic disturbances or direct structural (mechanical) vibrations, or both. In most instances, the noise emanating from aerodynamic disturbances is the most significant.

Two components comprise the bulk of the noise associated with propellers and rotors - rotational and vortex noise. Rotational noise, as the name implies, is directly related to disturbances generated by the rotor blades as they rotate. This noise is directly related to the blade passage frequency and is associated with the total thrust and torque developed by the rotor blades. The frequency of the noise generated by the rotors is multiple and is determined by the frequency of the blade passage. If blade passage frequency is low, the lower frequency noise produced by the rotor is inaudible.

Rotational noise is associated with several aerodynamic forces. Forces of drag and lift are created when a blade passes through an elastic medium. These forces cause disturbances of the air medium with both positive and negative alterations, which are transmitted as pressure waves at frequencies determined by the air loading blade passage and force variation. At a fixed position near the rotors, the fundamental frequency of these pressure waves corresponds to the blade passage frequency.

It is generally accepted that rotational noise is primarily a function of the total thrust produced by the blade of a rotor or propeller system. Thus, if the number of blades is increased, the total intensity of the noise is reduced.

At slow rotor tip speeds the main rotor rotational noise is the dominant noise. As tip speeds increase, the noise present in the higher frequency range becomes evident. The higher frequency noise is the product of vortex noise produced by the main rotors and anti-torque rotor rotational noise. In some instances, high speed gear transfer systems may generate high frequency noise.

The frequency components of rotational noise are easily identified as multiples of the blade passage frequency. Since rotational noise is directly related to blade passage frequency, this noise contains discrete frequency components. To accurately define these components one must acquire a narrow-band noise analysis. Blade passage frequency is high, and since the discrete frequency components are multiples of blade passage, several discrete components may be present in a single octave band measurement. For this reason, the sound pressure level (SPL) readings obtained by octave band analysis do not indicate or define the number or magnitude of the individual discrete frequency components present in a given octave.

The blades of a rotating rotor system produce vortices which take the form of audible noise, called vortex noise. As a blade rotates at slow tip speeds, the directivity of the noise is in the form of concentric spheres as a function of local stresses on the medium. At high tip speeds a distortion of vortex noise pattern occurs. High blade speed causes the directivity pattern of the noise to elongate from a concentric sphere shape. The distribution of the maximum noise has moved to a position just forward, above, and below the advancing blade.

Vortex noise moves with the rotating blade, and as a result, vortex noise measured by the observer has undergone modulations due to the blade passage frequency. Vortex noise from rotors contains frequencies that are directly related to the blade tip speed. The directivity pattern of vortex noise rotates with the rotating blade and is consequently modulated by the frequency of blade passage.

In many instances, even though the rotational noise produced by the rotors is more intense than that generated by other noise components, it is subjectively less noticeable because the fundamental and lower harmonics are not within the audible range of man's hearing. Thus, in the majority of cases, the anti-torque rotational noise and the vortex noise of the main rotor is subjectively more noticeable.

Vortex noise results from stresses acting on the surrounding air through which the blade passes. Vortex noise is distributed in the higher frequency ranges and is influenced by the aerodynamic flow of air over the blade and also by the frontal area of the blade. Vortex noise produced by main rotor systems is the most significant single noise factor associated with the various rotor noise components.

The influence of thrust on two-blade rotor systems produces more noise than for three-blade rotor systems when operating at lower blade loadings. Generally, as blade loading increases, the significance of vortex noise increases and the significance of rotational noise decreases. Essentially, a two- or three-blade rotor system, at equal hovering efficiency, produces approximately the same amount of

vortex noise, but the rotational noise level of the three-blade rotor system is appreciably lower than for a two-blade rotor system. These two conditions are basically true when equal thrust is being produced by the rotor-blade system.

Since the noise from rotor systems is generated by the blades, the pattern of the noise rotates with the blades. The maximum noise radiation is found at positions opposite the direction of thrust and at angles of about 30 degrees from the center line axis of the blade.

Various aerodynamic parameters, including number of blades, blade tip speed, thrust, and blade loading determine the contribution of rotational and vortex noises to the over-all noise generated by main and anti-torque rotors. Of these various parameters, blade tip speed is the most significant. In most instances, a reduction in blade tip speed results in a more significant reduction in the over-all noise than any other single component.

Increased rotational and vortex noise results from main rotor thrust increases. Usually, two-blade rotors have higher blade loadings than three-, four-, or five-blade rotors. Rotational noise may remain about the same when going from a two- to a three-blade rotor, but vortex noise will usually be more dominant from rotors with fewer number of blades. Since vortex noise is directly dependent on blade tip speeds, the greater the number of blades in a rotor system, the lower will be the requirements for high blade tip speeds. In other words, a three-blade rotor system requires slower blade tip speeds than a two-blade rotor system in order to produce an equal amount of total rotor thrust.

Both noise components, rotational and vortex, increase with blade tip speed. However, rotational noise tends to make a greater change with increases in blade tip speed than does the vortex noise. The significance of the noise sources vary depending on the size of the vehicle. Small helicopters with high speed rotors produce rotor noise that usually dominates the acoustic energies generated by the anti-torque rotors.

A study of the noise characteristics of helicopter rotors at tip speeds between 100 to 900 feet per second were conducted by Hubbard and Magliere¹⁷ at the Langley Helicopter Tower. Their investigations suggest that noise of full scale helicopter rotors results mainly from conditions of unsteady flow. Results further indicate that both tip speed and disc loadings have an important influence on noise radiated from the rotors.

During rotor stall, sound pressure levels increased at all frequencies, but particularly at the higher end of the spectrum. The evidence of Hubbard and

Magliere suggests that a highly peaked wave form exists due to possible Doppler effects associated with high tip speed operation. At low or moderate tip speeds the rotor is usually of secondary importance as a noise source, but can become a major source when other noise components have been reduced. At high tip speeds the rotor may be the dominant noise source of a helicopter. During these investigations noises from other sources were minimized and thus the noise emanating from the rotor could be evaluated more accurately. During tests it was noted that noise from the rotor varied markedly as a function of the tip speeds and disc loadings. Disc loadings were measured in pounds per square foot from a range of tip speeds from 300 to 900 feet per second. In general, for a given value of disc loading, the lower over-all sound pressure levels were associated with lower tip speeds. Exceptions occurred when the rotor was stalled, in which case the over-all sound pressure level increased to a marked degree. At any given tip speed a relatively large amount of noise is generated at low values of disc loadings. This operational condition corresponds to ground run-up prior to increasing blade pitch for take-off. For the latter consideration each blade is operating in or near the wake of the preceding blade and thus may be in a highly turbulent flow region.

Low and high blade angles or pitch show significant differences in the frequency and intensity of the noise produced by the rotors, particularly at higher frequencies. As disc loading increases close to stall conditions, sound pressure levels at all frequencies increase, particularly in the higher frequency ranges. Investigations of wave forms at different rotor tip speed show that the peaks occurred at frequencies of blade passage. One significant feature noted is that the peak is accompanied by high frequency fluctuation just forward of the blade, and low frequency fluctuation just aft of the blade. Wave form analysis further suggests that Doppler effects may play a significant role in the generation of these peaks. These peaks may dominate at higher tip speed and particularly at low values of disc loading. The noise appears to be increased by turbulent air (similar to the situation when a blade rotates in or near the wake of a preceding blade).

Other factors that may contribute to the intensity of noise levels are the degree, type, and condition of acoustic treatment; aging of the vehicle's primary and secondary systems; condition of rotors (a defective or imbalanced rotor system may produce rather severe vibrations); and conditions of seals at windows, cargo, and escape hatches. In addition, during ground and hover operations, such factors as terrain features will influence the noise generated by the vehicle.

One of the various noises associated with helicopters is the acoustic phenomenon referred to as blade or rotor slapping. Blade slapping does not always occur, but when it does it is a significant and dominating noise generator. The relative significance of blade slapping is most pronounced in larger vehicles and is also noted

to be more significant in tandem-rotor helicopters than in single-rotor vehicles. Blade slapping noise is distinctly audible and is most pronounced in the lower frequency range, usually below 600 to 800 cps. The peak noise level resulting from blade slapping is between 100 through 500 cps. The noise produced by blade slapping is very intense and, since it covers a broad frequency range, easily masks the less intense noises generated by other components.

During low flight speeds a probable cause of blade slapping is the rapid angle of attack changes which a blade experiences as it encounters its own or the previous blade's wake⁹. A possible increase in pressure compressibility may increase the severity of the effect as the angle of attack changes. Abrupt changes in blade angle cause increased lift and consequently the trailing wake system is also changed abruptly. These abrupt changes in wake lead to an impulse type noise which produces wide frequency distributions. Less severe angles of blade attack can alter the characteristics of the boundary layer on the blade and the vortex noise may be reinforced at blade passage frequency. As a blade passes through trailing vortices the results of sudden force variations on the blade elements near the rotor tip can produce rotor slapping noise.

Rotor slapping does not usually occur during a climb maneuver. During climb the traveling vortices of the rotor blades are directed away from the blades. Whereas, during a partial power descent, when rotor slapping is quite common, the rotors are moving through their own wake. During high speed flight the effect of rotor wake is less pronounced and thus the slapping noise is probably not the product of rotor wake. Increased rotor speed, necessary for high speed flight, probably causes shock waves to form on the advancing blade, while local shock waves may explain the rotor slapping that occurs during high speed flight⁹.

Blade slapping is more common in tandem-rotor helicopters during almost all phases of powered flight because of the trailing vortices that are present from both rotor systems. Twin two-bladed rotors in tandem configuration seem to have a greater tendency to produce blade slapping throughout various flight profiles. Research on the Bell HSL helicopter⁹ has shown that the sudden rise in the sound pressure level associated with blade slapping occurs periodically at the blade passage frequency for a single rotor. Blade slapping, associated with the CH-47A, seems to occur during most flight conditions⁹. It is generally believed that blade slapping occurs as the aft rotor leaves the region of forward to aft rotor overlap. Significantly different noises may be generated by tandem or two-rotor systems during cruise conditions due to the interaction between the two rotors (the disturbed air from the front rotors is transmitted to the rear rotor system). In hovering, there is apparently little interaction between the two rotor systems. Rotor slapping noise of tandem rotor vehicles may be reduced by decreasing the total area of blade

overlap and by increasing vertical separation between the passage plane of the rotors.

Generally, the total noise generated by rotors can be reduced by, first, reducing blade tip speeds. As mentioned, this factor alone will help reduce both rotational and vortex noise. Second, providing greater thrust distribution through the rotor system. This can be achieved by simply increasing the number of rotor blades required to provide a given thrust. For instance, increasing the number of blades in a rotor system from two to three would result in increased total thrust, and would generate less noise.

In a study of frequency modes that exist in rotor blades, Brooks and Leonard⁷ report that the natural frequencies of the rotor blades can be appreciably altered by varying the location of the blade hinges. With two properly located flapping hinges, blade designs are possible which eliminate or greatly reduce conditions of resonance between the blade and the natural frequencies of the harmonics that are air loaded.

In order to reduce the tip speeds of main rotor systems the blade area must be increased. In many instances this may be accomplished by increasing the number of blades in the rotor system.

Anti-Torque Systems. The rotational noise generated by anti-torque rotors is usually the most pronounced of the various noises generated by such systems. A critical look at the frequency spectrum of anti-torque rotor noise shows the presence of discrete sound pressure levels at multiples of the blade passage frequency.

Subjectively, the noise produced by most anti-torque rotor systems is louder than either rotational or vortex noise components generated by the main rotor. However, tail rotor noise, especially from high speed anti-torque rotors, may be significantly reduced.

The vortex noise produced by anti-torque rotors tends to increase with an increase in the number of blades and with higher rotor tip speeds. When tip speeds exceed about 500 to 700 feet per second, vortex noise is less evident and rotational noise becomes dominant.

Several factors must be considered in order to reduce the total acoustic energies generated by the various noise components of helicopters with main and anti-torque rotor systems.

Noise generated by the main rotors is predominantly low frequency, and noise generated by the anti-torque system is usually distributed within the higher frequency ranges. Thus any method designed to reduce the total noise of a helicopter with main and anti-torque rotor systems must consider both of these noise generators.

Generally, the noise associated with main rotor operations, dominantly distributed within the low frequency range, is subjectively less annoying or irritating than the higher frequency noise generated by high speed anti-torque rotor systems. The difference in subjective response to these two different types of noise is due to the psychophysiological response of the human auditory system. Noise from anti-torque rotors is especially irritating and annoying if it contains narrow-band frequency components.

Intense noise associated with high speed anti-torque rotors can be reduced by simply increasing the number of blades in the anti-torque system. Increasing the number of blades allows a reduction in both rpm and diameter of the anti-torque rotor because, as the number of blades is increased, there is a greater distribution of horsepower per blade. Aircraft manufacturers seem to be generally aware of this factor, and future helicopters which utilize anti-torque rotor systems will probably have three to four blades.

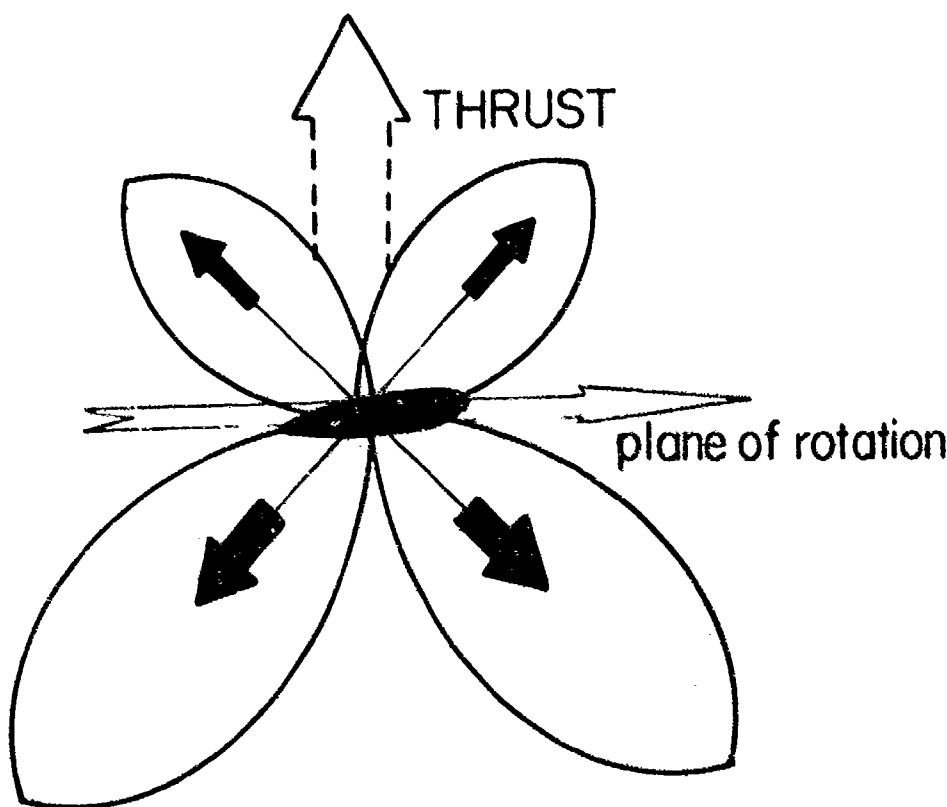
The over-all noise of a helicopter varies for different modes of operation. During hover, the pressure disturbances resulting from the passage of the rotor blades are fairly constant, especially at locations near the center axis of the rotor. Slight variations in pressure disturbances may occur due to directional or control alterations during the hover maneuver, but disturbances are usually of little significance. During forward flight the rotors create a variation of pressure disturbances due to asymmetrical loadings of air acting on the blades. In order to obtain and maintain forward flight the blades in the rotor system vary in pitch and angle of attack as they rotate 360 degrees around a central axis. The variations of the mechanical movement of the blades create a variation in pressure displacement as the blades rotate.

Hover maneuvers require a greater amount of rotor torque than forward flight. When a helicopter is hovering the power required to maintain a constant lift is greater than during forward flight. During forward flight the rotors require less power or torque because the helicopter has obtained a certain amount of momentum.

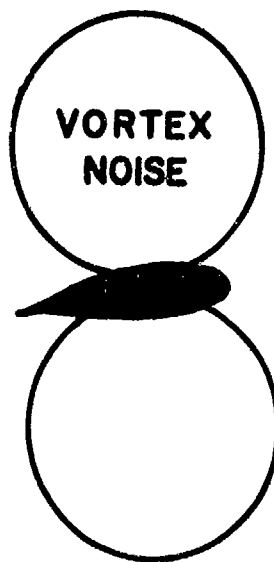
Increased torque requirements during a hover result in a greater demand on the power plant and this increased demand results in more intense noise emanating from the power plant. Generally, as torque from a power plant increases,

there is a greater amount of strain and stress applied to the components of the engine which delivers the shaft horsepower. As these components are receiving greater stress the noise generating mechanisms of each component increase.

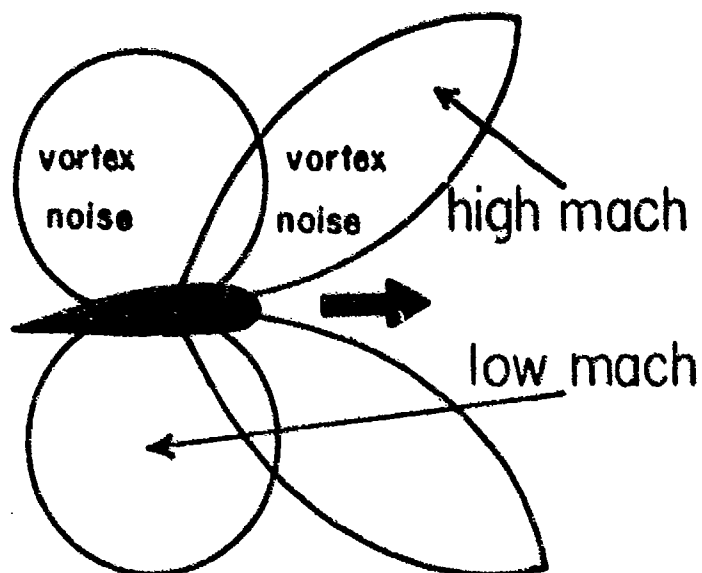
Illustration 7 (rotor thrust) depicts the basic directivity pattern of rotational type noise as the blade rotates around an axis. This type of noise pattern tends to rotate with the rotating rotor blades. Illustration 8 (vortex) demonstrates the general pattern of directivity assumed by vortex type noise. The directivity as shown is illustrative of vortex noise distribution at low tip speeds. It is to be noted that vortex noise emanates as concentric spheres as a direct result of local stresses, but at high tip speeds, as shown in Illustration 9 (high tip vortex) the concentric patterns become distorted. As tip speeds increase the general directivity pattern of the vortex noise tends to elongate the spheres and shift the upper end toward the direction of blade rotation. Since the vortex noise rotates with the rotor blades, the vortex noise measured at this position has already been modulated by the blade passage frequency.



Illus. 7 Directivity Pattern of Rotational Type Noise



Illus. 8 Directivity Pattern of Vortex Type Noise



Illus. 9 Directivity Pattern of Vortex Type Noise
at Low and High Mach Tip Velocities

Figure 17 shows results of noise measurements made at a distance of 50 feet at various positions around a UH-19D helicopter during ground run-up. The UH-19D has a single three-blade rotor with a diameter of 53.0 feet and a single two-blade anti-torque tail rotor with a diameter of eight feet, nine inches. The most intense noise was generated by the main rotors. During these noise measurements the rotors were rotating at a tip speed of 589.4 feet per second (0.528 Mach). The secondary noise between 1,200 and 4,800 cps contained a combination of noise elements generated by the exhaust of the engine (nine-cylinder, radial Pratt and Whitney R1340) and the anti-torque tail rotor system.

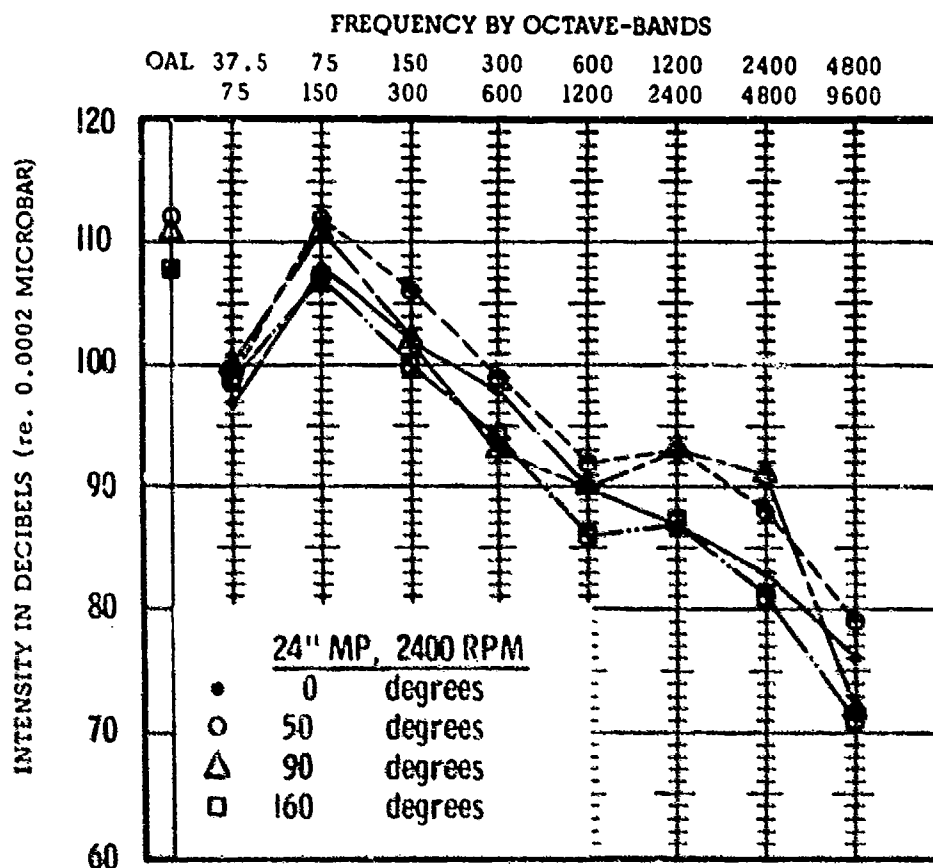


Fig. 17 External Noise of UH-19D Helicopter
Measured at 50' Distance, Left Side

Figure 18 illustrates the noise generated by a CH-34C helicopter at various positions at a distance of 50 feet. The general configuration of the CH-34C is similar to that of the UH-19D, except the CH-34C has a main rotor that is three feet greater in diameter and has four blades instead of three, the tail rotor has four

blades instead of two, and a nine-inch greater diameter. During these noise measurements the rotor had a blade tip speed of 513.1 feet per second (0.459 Mach). Noise emanating from the main rotors is predominate in the lower frequency range, and the noise emanating from the anti-torque rotor system was not pronounced due to the noise reduction characteristics afforded by the increased number of blades.

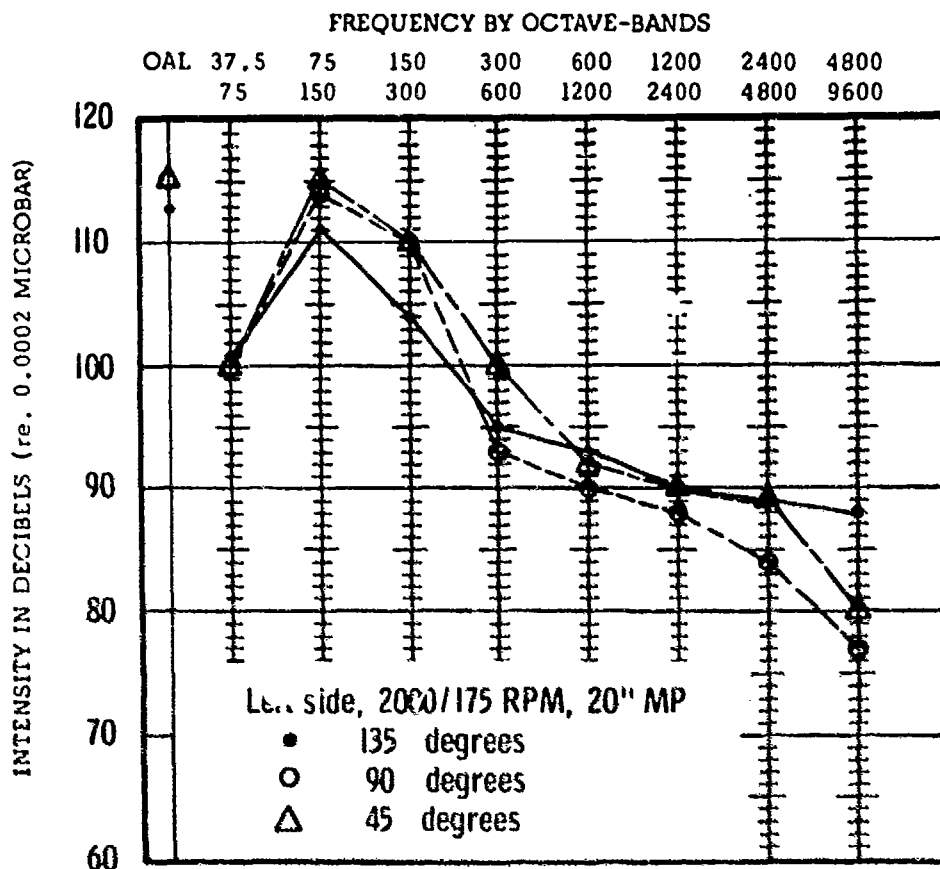


Fig. 18 External Noise of CH-34C Helicopter Measured at 50' Distance

Figure 6, page 55, shows results of noise measurements made at various locations at a distance of 50 feet from a CH-378 helicopter during ground run-up. During these measurements the main rotor had a blade tip speed of 799.1 feet per second (0.715 Mach) and the tail rotor had a blade tip speed of 681.7 feet per second (0.610 Mach). Sound pressure levels at the side and rear of the vehicle were most intense. In front of the aircraft the most dominant single noise element was from the main rotor, and at the side of the aircraft a combination of rotor and exhaust noise was evident. At the 135 degree location three noise generators were quite pronounced. The lower frequency noise was generated by the main rotor and

the exhaust, and the somewhat higher frequency noise emanated from the anti-torque rotor system.

Figure 19 illustrates noise generated by the tandem-rotor, dual turbine CH-47A helicopter during various phases of ground run-up. During these noise measurements the rotors were operating at blade tip speeds of 640.7 feet per second (0.574 Mach). The noise spectrum was considerably flatter than that associated with single rotor helicopters and the noise was most intense at positions to the side of the vehicle. The blade passage profile of the tandem rotors overlap and during rotation each rotor is influenced by the aerodynamic disturbances created by the other rotor blades. During certain phases of operation the interaction of aerodynamic disturbances created by the rotors produces a rotor slapping noise which is quite noticeable.

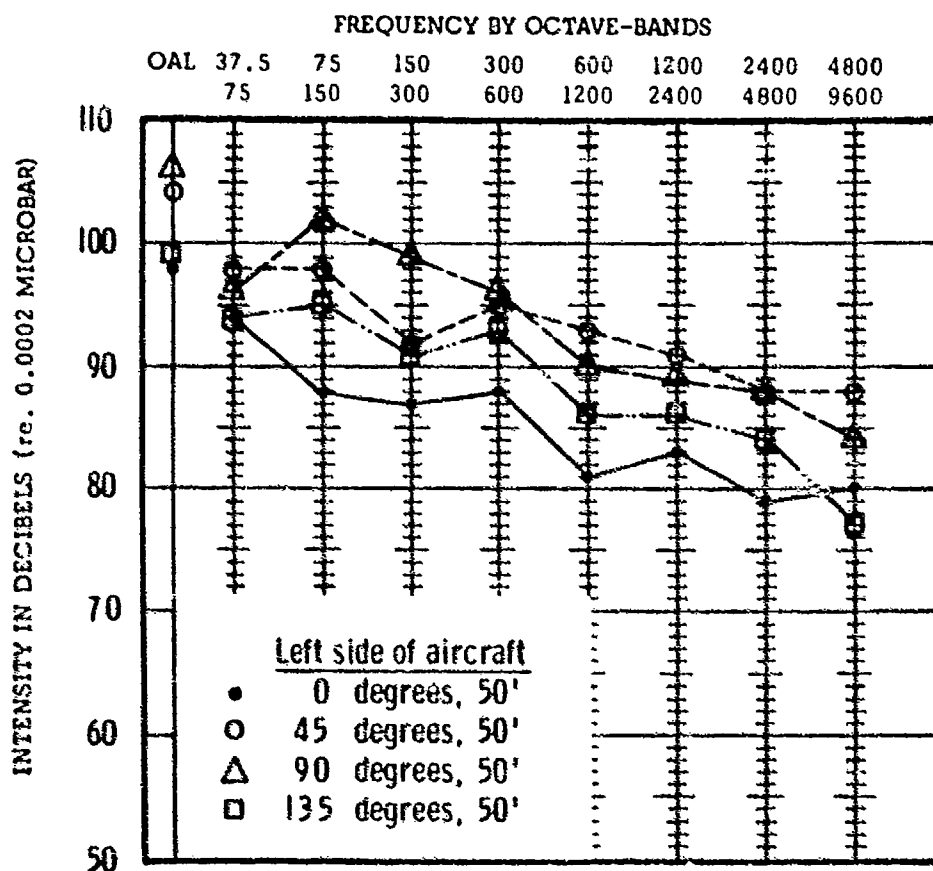


Fig. 19 External Noise of CH-47A Helicopter
During Ground Operations, Discharging Troops

Figure 20 shows two noise envelopes for a UH-1A helicopter during a hover at a distance of 100 feet. The upper noise envelope represents the low to high noise levels recorded in the frequency range from 37.5 through 600 cps and the lower envelope represents the low to high noise levels recorded in the 600 through 9,600 cps range. The most dominant noise is contained within the lower frequency range and becomes most pronounced at locations aft of 90 degrees. The higher frequency noise, although less intense, tends to follow the same general pattern. During these measurements the main rotor blades were traveling at a tip velocity of 710.9 feet per second (0.637 Mach).

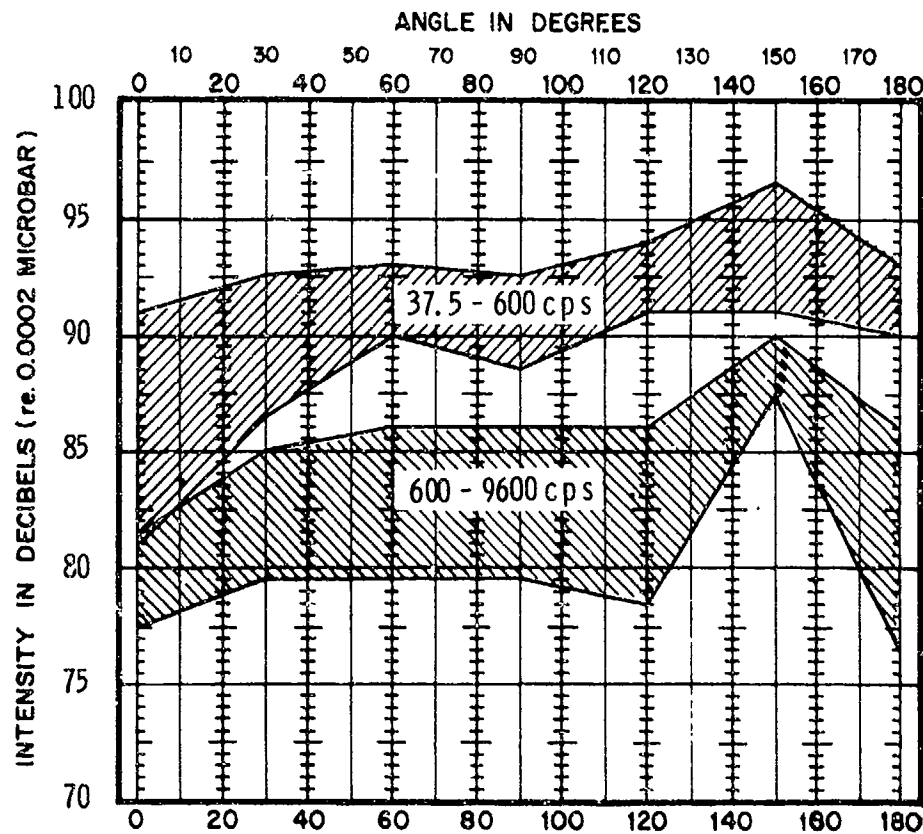


Fig. 20 External Noise of UH-1A Helicopter at a 5' Hover, Measured at 100' Distance, 6300 RPM, 0 to 180 Degrees Azimuth Readings

Transmission, Gear-Reduction, and Gear-Distribution Systems.

Many present day aircraft, especially rotary-wing types, employ large transmission and gear-reduction systems. These systems are used to reduce the high

rpm of the power plant shaft to lower rpm that is delivered to propellers, rotors, and anti-torque systems. In general, the total system includes torque distribution shafts from the power plant, transmission and gear-reduction sections, and final distribution shafts. Of the various systems utilized, those pertaining to rotary-wing application are the most significant noise generators. Therefore, only rotary-wing systems are discussed and illustrated.

The noise generated within occupied areas by these gear and shaft systems is most significant in rotary-wing aircraft where transmission units are located within or near the main fuselage. The noise spectrum generated by transmission system powered by reciprocating engines usually contains lower frequency components than those transmission systems powered by gas-turbine engines. The higher frequency components produced by gas-turbine powered transmissions result from the higher gear-meshing speeds of gas-turbine power plants. For instance, a gas-turbine engine may produce an engine shaft speed of 17,000 rpm, whereas a reciprocating engine may produce an engine shaft speed of 3,000 rpm. If both of these shaft inputs must be reduced to a rotor shaft speed of 212 rpm then it is evident that gear-transmission and shift systems mated to the gas-turbine engine will rotate at a higher rpm than the gear-transmission and shaft systems mated to a reciprocating engine that produces a lower rpm. Thus, the higher the rotational speeds of the gear systems within the transmission, the higher will be the frequency components generated by the meshing and impacting of the gears.

There are a number of types of gears used in conjunction with gear-reduction, transmission and distribution systems. These gears vary in shape, size, weight, complexity, and in the manner of application, but there are two main types - gears that contact in parallel shafts (in-line), and gears which make contact at nonparallel angles, usually less than 90 degrees. Parallel, in-line, gears are commonly used in reciprocating engines and also for mating the power plant to other auxiliary rotational systems. Nonparallel gear matings are commonly used in helicopter applications where the shaft of the main rotor is at a different angle than the center line shaft of the power plant. A few of the major types of gears that contribute to the noise generated by rotary-wing aircraft are:

Bevel type gears which have conical pitch surfaces and are used to make shaft contacts at angles less than 90 degrees. The two shafts must be in the same plane. Bevel gears are used as shaft distribution units in many helicopters with anti-torque rotors where the torque distribution shaft must distribute power to the tail rotors.

Worm gears which transfer rotational motion from one shaft to another. Worm gears transfer shaft motion at right angles. This type of gear system offers

several advantages. The wheel gear shaft can be rotated in either direction by changing the rotational direction of the worm drive and, because the gear systems are mated at right angles to each other, they can be located in a relatively small space. Worm gears are commonly used in the extension and retraction of landing gears and wing flaps.

Planetary and sun gears are gear systems specially located and arranged to create a rotational reduction between the center shaft and the exterior shaft. A centrally located shaft, the "sun gear," is connected to the rotation of the outer shaft by usually three "planetary" gears. Planetary gear systems are used in gear-reduction units for both propeller and rotor systems, and usually consist of pinion or spur reduction gearing or both.

Impacting and meshing of gears during rotation may stimulate natural frequency resonances, but friction created during gear contact is the major source of noise associated with gear movements. The major frequency spectrum resulting from gear tooth contact is dependent on the frequency of contact, the harmonics and natural frequency characteristics of the gears, the gearbox housing, and the gear shafts.

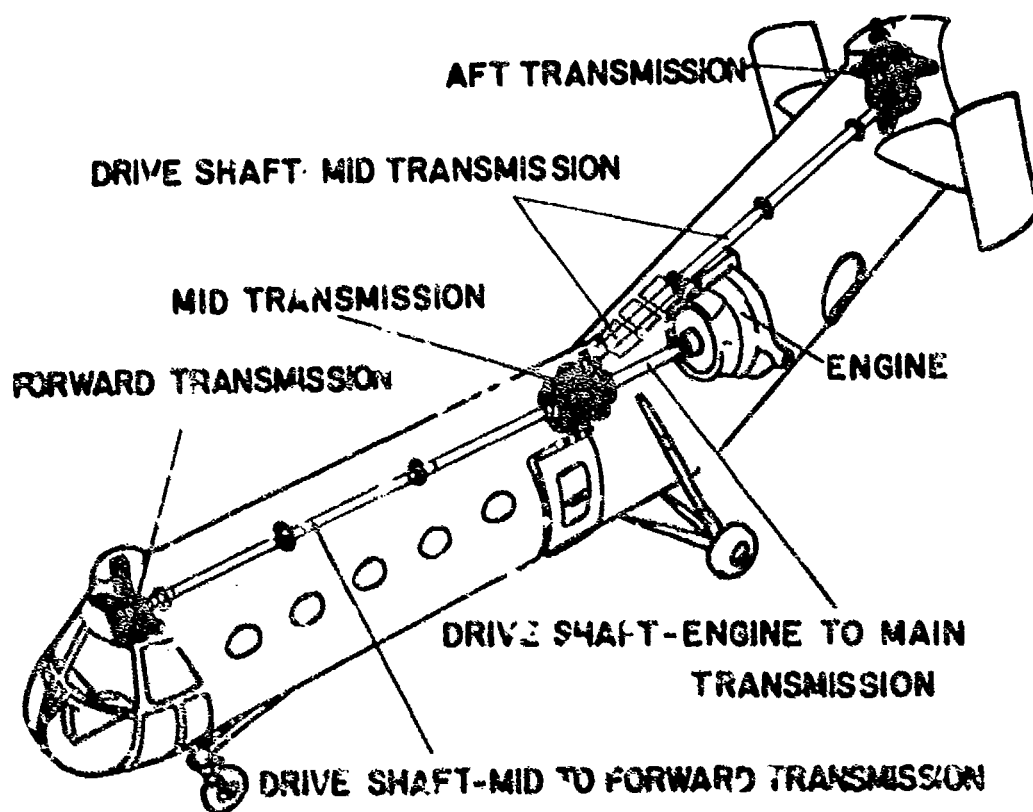
Gear assemblies usually require a gearbox. The gearbox serves to support entrance and exit shafts, confine and retain lubricants, and provide a shield against noise and vibration. Gear housings are important sources of noise propagation. The housings or gear cases are resonant chambers, and when in contact with structures and components of the vehicle provide a direct pathway for propagation of noise and vibration generated within the transmission housing.

The majority of helicopters utilize a power distribution system to deliver torque to main rotor(s), anti-torque rotor(s), and auxiliary components and systems. Within these systems the transmissions, gear-reduction units, couplings, bearings and bearing supports, and drive shaft systems may generate noise. In most instances these power drive systems contribute significantly to the internal noise environment, but produce little, if any, significant noise at far-field positions.

The total noise produced by power drive systems is complex and composed of a variety of noise produced by subsystems, parts, and components. The gear noise alone is quite complex and is determined or influenced by stresses placed on the gears, friction and impacting during rotation, oil and air packeting, variations of casing and housing of radial noise components, and frequency and torque of gear impacting. Usually the greater the torque the more intense will be the elements of the noise resulting from gear friction and impacting.

In addition to gears as a significant source of noise in most helicopters, there are other noise generators that must also be considered. Torque distribution shafts, bearings, bearing supports, couplings, and secondary shaft distribution units contribute to the total internal noise, especially within tandem-rotor helicopters which employ lengthy distribution shafts from the power plant to a rotor. Tandem-rotor helicopters are designed in such a manner that the power distribution shaft passes through the upper part of the fuselage above the passenger compartment. Power shafts and their related components usually generate higher frequency noise that is directly related to shaft rpm, torque, and bearing and support friction.

Illustration 10 depicts the relative complexity of shaft distribution and transmission systems of a single-engine tandem-rotor powered helicopter, the CH-21. The CH-21 is powered by a single air-cooled radial engine which is mounted within the fuselage aft of the cargo-passenger compartment. Power is transmitted



Illus. 10 Transmission and Gear-Distribution Systems of a Single-Engine Tandem-Rotor Helicopter (CH-21C)

from the engine to the mid-transmission and from it, longitudinally, to the fore and aft transmissions. The mid-transmission serves only to distribute shaft power from the engine, and gear reduction is achieved only at the forward and aft transmissions. For this reason the single drive shaft between the engine and the mid-transmission, and the shafts from the mid-transmission to the forward and aft transmissions, rotate at the same rpm as the engine, thus the mid-transmission gear system has a constant rpm equal to that of the engine. The influence of shaft and gear speeds is shown in Figure 21. The noise plottings shown were recorded at positions within a CH-21C during normal cruise. The engine was operating at 2,500 rpm with 37 inches of manifold pressure, and the helicopter was cruising at an indicated airspeed of 70 knots. Although the over-all noise level remained relatively the same, the noise spectra at the three locations indicated the influence of gear and shaft rpm on the internal noise components. Noise emanating from the rotors is most pronounced at 75 to 150 cps. During these measurements the rotors were operating at 257.7 rpm and at blade tip velocities of 576.0 feet per second

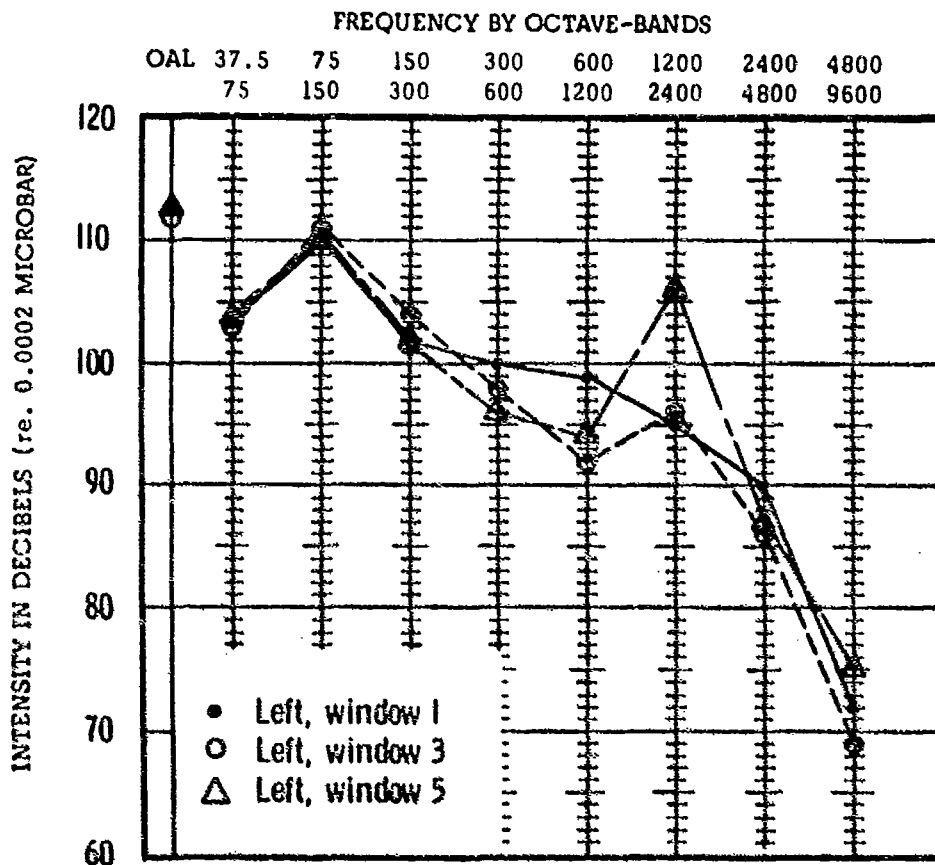


Fig. 21 Internal Noise of CH-21C Helicopter During Cruise, 2500 RPM, 37" MP, 70 Knots IAS

(0.516 Mach). The noise measured at the front of the cargo-passenger area (window one) shows the presence of both rotor and transmission (gear reduction) noise. At positions adjacent to the mid-transmission unit the noise generated by the higher speed transmission unit becomes evident. At window five, which is directly below and in front of the mid-transmission, the presence of the noise generated by the higher speed shafts and gears is further increased. The narrow-band noise that peaks at 1,200 to 2,400 cps is primarily associated with gear meshing and impacting of the bevel gear systems housed within the mid-transmission unit.

It has been fairly well demonstrated that increased torque applied through a gear system will result in an increase in noise. Figure 22 gives a good illustration of how an increase in torque, while maintaining a constant rpm, will increase the noise produced by increased meshing and impacting forces of gears within the transmission system of a CH-21C helicopter. The most noticeable change occurred in the

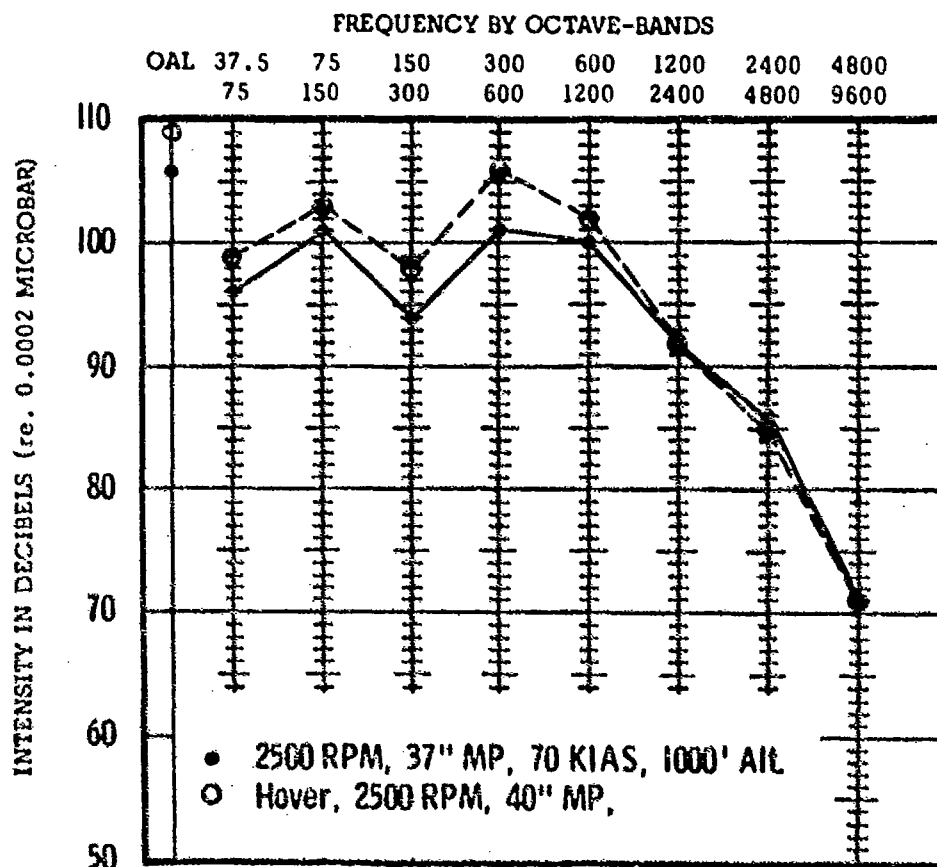
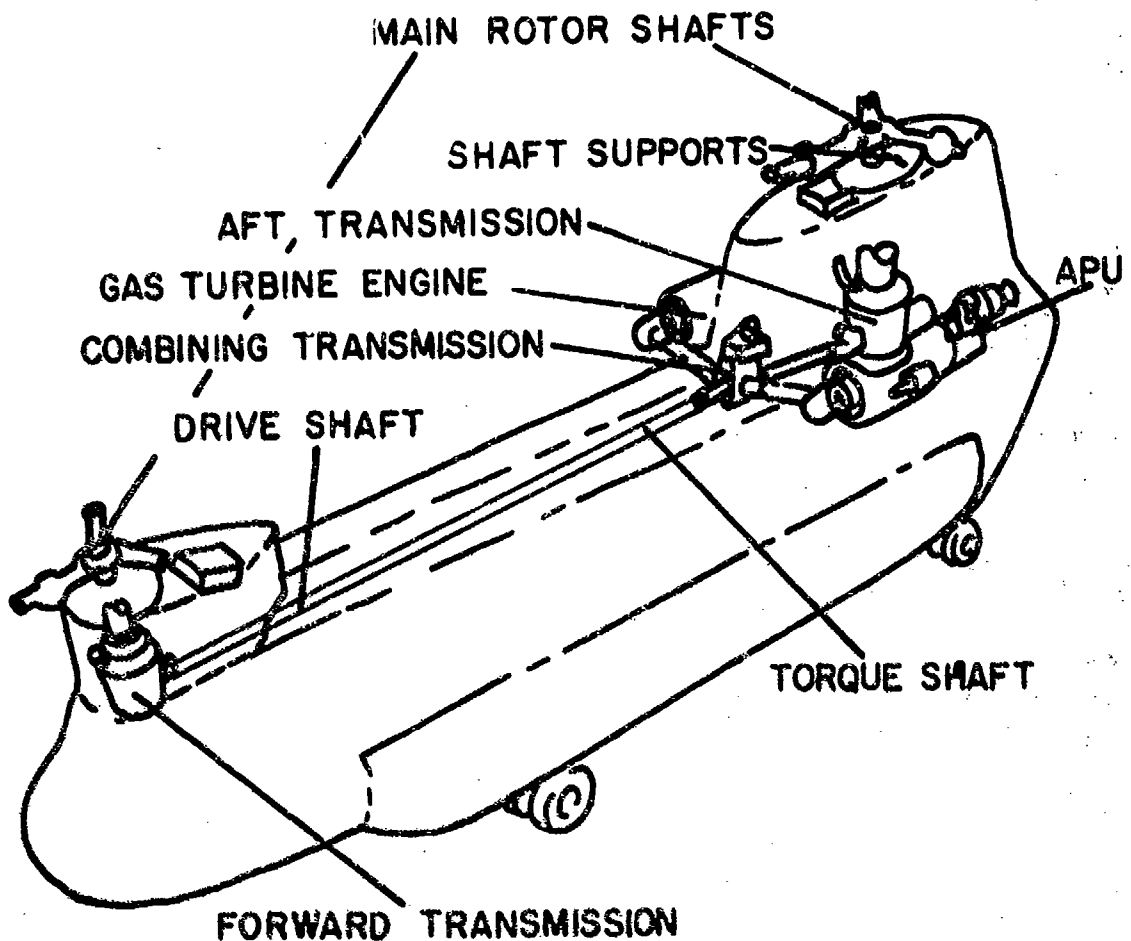


Fig. 22 Internal Noise of CH-21C Helicopter Measured at Head Level Position, Center Line Cockpit

frequency range below 600 cps. It is interesting to note that increased torque without changes in rpm only caused an increase in the level of the noise but did not cause a shift in the frequency distribution pattern of the noise.

An illustration of the transmission and shaft distribution system of a CH-47A is shown in Illustration 11. The CH-47A is a tandem twin-turbine rotary-wing aircraft designed for heavy duty operations. The helicopter is powered by two Lycoming T-55-L-5 turboshaft engines mounted on the upper aft section of the fuselage. The engines simultaneously drive two tandem three-bladed rotary blades



Illus. 11 Transmission and Gear-Distribution Systems of a Twin-Turbine-Engine Tandem-Rotor Helicopter (CH-47A)

through a combining transmission, drive shafting, and reduction-gear system. The forward transmission is mounted above the aft section of the cockpit. The aft transmission, combining transmission and drive shafting, is located in the aft section above the main cargo and entrance door. Drive shafting from the combining transmission to the forward transmission is housed within a tunnel on the top of the fuselage. The combining transmission combines the power delivered by the engines and transmits it at reduced shaft speed to the forward and aft transmissions where additional gear reduction is achieved. The various transmissions provide a total gear reduction of 66-to-1. Noise emanating from the various transmission systems is quite complex and varies from one gear-reduction unit to another. For instance, noise emanating from the forward transmission will contain relatively simple noise components, whereas the total noise generated near the aft transmission area will contain a mixture of transmission type noises. Noise exposures in the aft sections of the helicopter will be a mixture of noise components emanating from the compressor and turbine sections of the engines, the combining transmission, and the main aft transmission. Figure 23 demonstrates the general complexity of the noises produced within the cargo area of the CH-47A during a hover maneuver. At the forward position, between the first windows, noise from the forward rotor is evident in the lower frequency range, and noise emanating from the forward transmission is evident at the 1,200 to 2,400 cps frequency range. At windows three and four the transmission noise decreases, but noise due to overlapping of the rotors becomes more pronounced, especially in the area at the fourth window from the front. Then at the aft location, between the fifth windows, noise generated by the rotating sections and components of the engines (combining transmission and aft transmission) creates a significant increase in the noise levels above 600 cps.

Rotor noise may be more intense than transmission noise because the noise generated by the transmission, especially the combining and gear-reduction transmissions, is distributed within a higher frequency range and usually contains narrow-band noise components. In general, if transmission systems are located above occupied area, the noise environment it generates within the helicopter will be considerably more intense than if the same unit were mounted aft or forward of occupied areas.

Controlling the noise produced by power drive systems is not an easy task to accomplish. The noise produced by internal components of a transmission system are of greatest significance if the frequency of the noise approaches natural modes of resonance in the casing wall. High frequency noise can be controlled more easily than low frequency noise. Proper acoustic treatment may help reduce the intrusion of the higher frequencies into occupied areas of the vehicle. In many instances acoustic treatment will not reduce the over-all level of the noise, but will significantly reduce the "loudness" of the noise. The noise generated by power drive

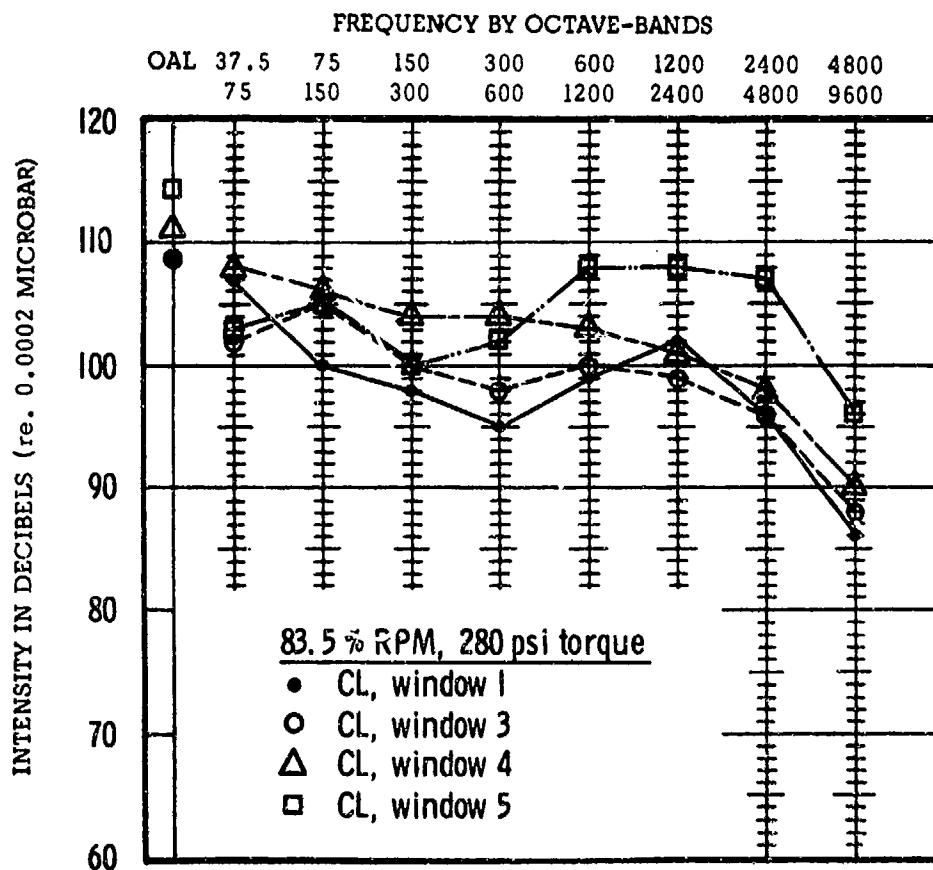


Fig. 23 Internal Noise of CH-47A Helicopter During a Hover,
Measured at Head Level in the Left Troop Seat Positions

systems can be radically altered and reduced as better engineering techniques and materials are made available.

Summary of Noise Problems Associated with the Transmission and Related Systems. Transmission and related systems do not produce significant noise levels within the majority of fixed-wing type aircraft, but these systems and their components do generate rather significant noise levels within occupied areas of many rotary-wing type aircraft. The type of noise generated by transmissions and gear-distribution systems is complex and may vary considerably from one aircraft to another. Such factors as aging, the general condition of the individual gears and shafts within the systems, the type and amount of fluids within the casings, the type and condition of the vibration isolators, and many other factors have a direct bearing on the resulting noise. When determining the degree of noise hazard associated

with a given rotary-wing type vehicle, aeromedical personnel should maintain an awareness of the noise exposure related to these subsystems.

Even though acoustic differences may exist from one unit to another, one can offer a concept of the noise generating characteristics that will remain basically the same from one unit to another. The main transmission gear-reduction unit is a complex system of gears and shafts that converts the high rpm from the engine shaft to lower rpm for the rotor shaft. The most common gear system in the majority of units is the planetary type. The individual gear components are, in most instances, the primary determiners of the noise emanating from the total system. The amount of gear reduction and torque provided by a given transmission system will influence the amount and type of noise generated by a system. The following listing offers some concept for the amount of gear reduction requirements placed on some of the transmission gear-reduction systems in rotary-wing type aircraft (specified in ratio):

<u>VEHICLE</u>	<u>MAIN ROTOR</u>	<u>TAIL ROTOR</u>
OH-13 (all)	9:1	2:1
OH-23B	9.17:1	1.89:1
CH-21C	9.69:1	N/A
CH-37B	14:1	3:1
CH-47A	66:1	N/A
UH-1 (all)	20.38:1	2.17:1

The amount of gear reduction required from a gear-reduction system is substantially greater in aircraft powered by gas-turbine engines than those powered by reciprocating engines. The radical gear-reduction ratio differences between the two types of power plants are dictated by the main shaft rpm supplied from the engine. For instance, the Lycoming T-53-L-9 turbine engine in the UH-1B aircraft has a shaft input to the gear-reduction transmission unit of approximately 6,397 rpm, and requires a gear reduction of 20.38 to 1 for the main rotors and a reduction of 2.17 to 1 for the anti-torque tail rotor. The Pratt and Whitney R2000 reciprocating engine in the CH-37B has a maximum shaft input of 2,600 or 2,700 rpm, and requires a gear reduction of 14 to 1 for the main rotors and 3 to 1 for the anti-torque tail rotor systems. The requirement for higher gear-reduction capability of transmission systems mated to aircraft powered by turbine type engines will probably remain the same. If anything, when newer and equally efficient rotor systems are developed, even slower rpm will be required to power the rotor systems, thus requiring greater gear-reducing capabilities in the gear-reduction systems.

Gears within the transmission are the major determiners of the noise emanating from the system. Impacting and friction of the individual "teeth," gear

friction, and shaft imbalances; all contribute to the total noise. Since the magnitude and the frequency spectrum of the noise are determined by these systems, the ratio of input to output rpm determines the frequency pattern of the noise. Observers near the main transmission in a reciprocating engine powered helicopter will notice that the noise generated by the transmission is more intense in the lower frequency bands. Figure 24 shows noise measurements made beneath the transmission unit of a CH-37B. The transmission unit in this aircraft has a two-stage planetary gear system. The noise generated by this unit is quite audible when standing beneath the unit, especially when the observer is not wearing ear protective devices. When wearing ear protection that attenuates the extraneous noises existing within the vehicle, one can detect audibly the "chattering" type noise resulting from gear teeth impacting. The noises generated within areas near the transmission are intense enough to mask effective speech communication. One can conduct meager

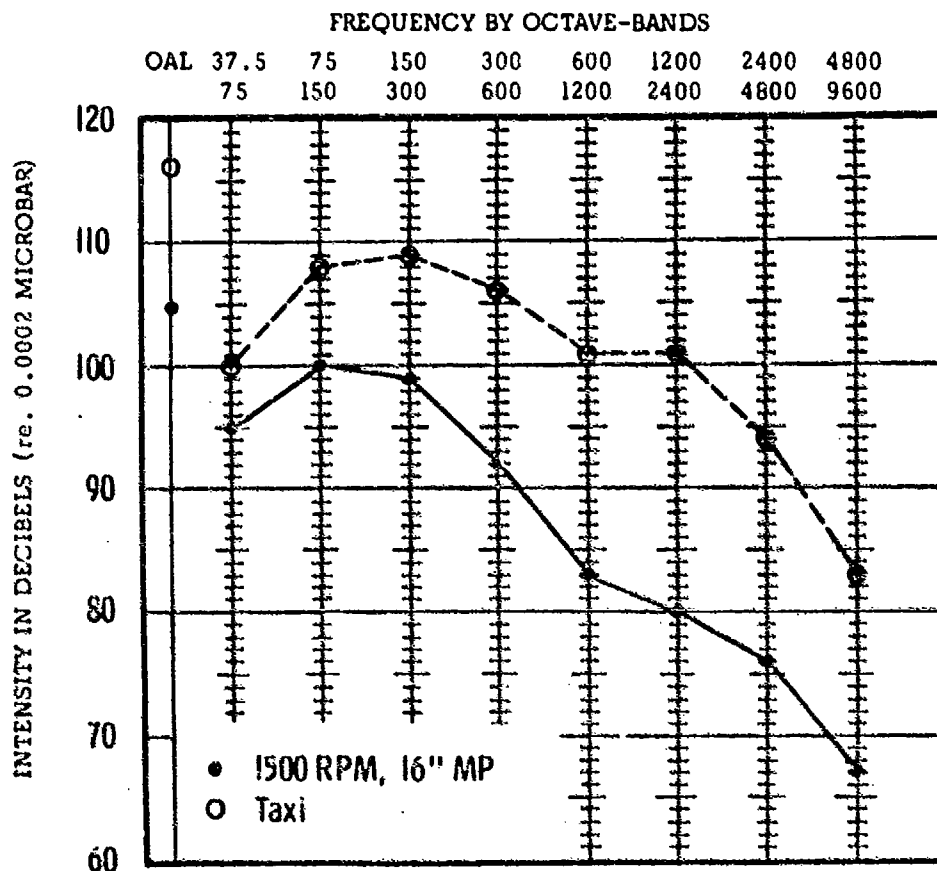


Fig. 24 Internal Noise of CH-37B Helicopter Measured Beneath the Transmission Unit, Station 250

speech communication by shouting in the ear of the person being spoken to, but, if proper ear protection is worn, speech communication ability can be improved significantly.

During flight the internal noise near the transmission unit is less noticeable due to the intrusion of other intense noise producing mechanisms. Figure 25 shows noise measurements made at six and twelve inch distances from the base of the transmission unit in the CH-37B. The over-all noise shows no difference, however, when the microphone is placed nearer the transmission, thereby increasing the pickup of noise emanating from this area, but there are noticeable differences in the frequency range between 37.5 and 300 cps, and again between 1,200 and 9,600 cps.

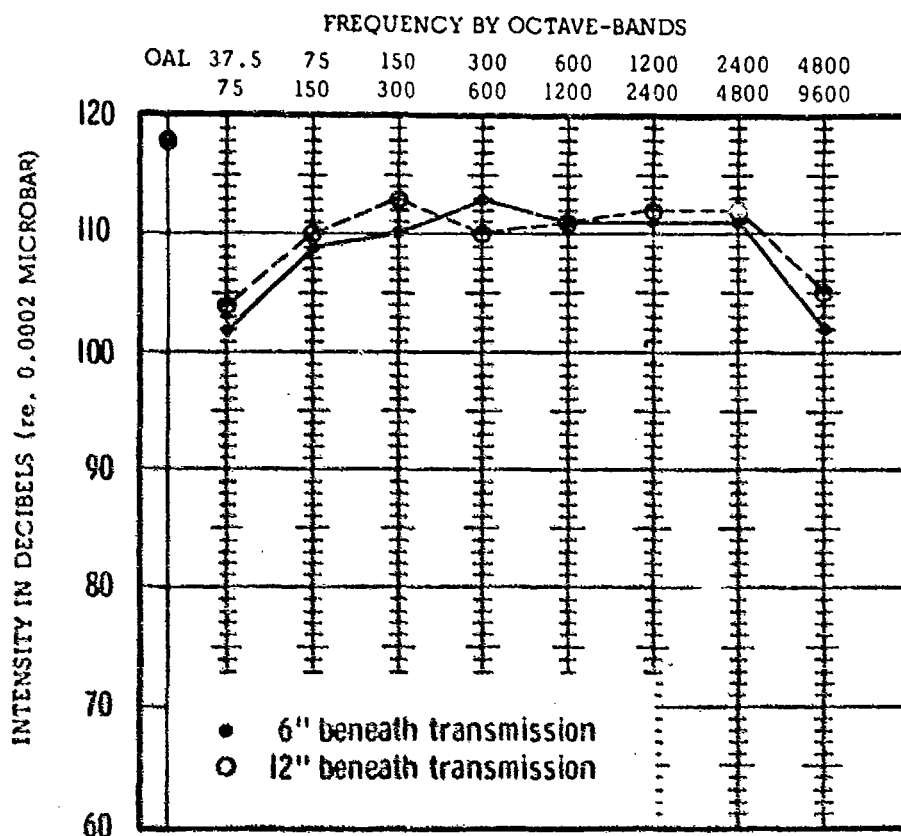


Fig. 25 Internal Noise of CH-37B Helicopter During Cruise, 2600 RPM, 38" MP, 75 Knots IAS

The transmission system in the CH-47A (Chinook) consists of a forward transmission, an aft transmission, a combining transmission, two engine transmissions, and drive shafting. Power from the engine transmissions is transmitted through separate drive shafts to the combining transmissions. The combining transmission combines the power of the engines and transmits it at reduced shaft speed through drive shafts to the forward and aft transmissions. The very high speeds of the engine are reduced to lower speeds for the rotor blades by an over-all ratio of 66 to 1.

Figure 26 shows noise measurements made at a distance of eighteen inches beneath the center line of the forward transmission unit and twelve inches beneath the center line of the aft transmission. During these measurements the aircraft was operating at 83.5% rpm, maintaining 280 psi torque, and a 20-to 30-foot hover (measured from the tail of the vehicle) above a sod covered area. As noted, the noise levels are radically different between these two locations. The noise levels

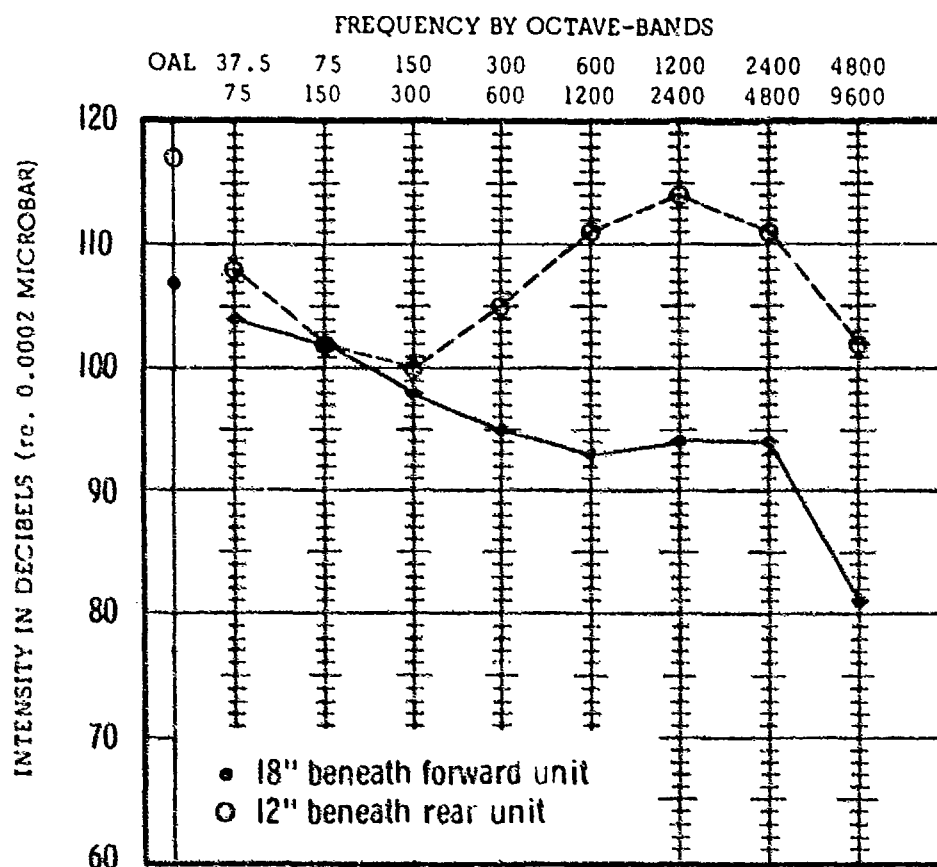


Fig. 26 Internal Noise of CH-47A Helicopter During a Hover, 83.5% RPM, Transmission and Engine Noise

are more intense at the aft position because of the added noise producing mechanisms of the combining transmission and the engines. The increased noise in the higher frequency areas, especially above 300 cps, is a mixture of noise emanating from the gear-reduction components of the combining transmission that is located in front of the aft transmission unit, the rotational and frictional noise emanating from the aft rotary-wing drive shaft, and from the turbine and compressor stages of the two engines. The noise produced at locations near the aft section of this aircraft can be reduced, especially within the higher frequency ranges, by properly designed, constructed, and fitted acoustic treatment material. The standard CH-47A helicopter is equipped with acoustic blankets for both forward and aft transmission areas.

Figure 27 depicts changes in noise emitted at a position eighteen inches directly below the center line of the forward transmission unit. The two noise plottings show the influence of acoustic blanket installation on the frequency spectrum. As noted, the over-all noise level shows negligible change, but there are considerable differences in the frequency spectrum. The noise in the lower frequency ranges (below 600 cps) increased with the installation of the blankets, whereas the noise in the higher frequency bands decreased. Many investigators have reported an increase in the lower frequency ranges when heavy acoustic padding was used to attenuate noise. Even though this phenomenon occurred, decreasing the high frequency noise emanating from the transmission unit caused a significant reduction in the objectionable characteristics of the noise. The results of our investigation indicate that the blankets should be installed whenever operationally feasible to reduce the occurrence of exposure of personnel to intense narrow-band noise components.

Generally, the higher the shaft speeds of the basic power plant, the more dominant will be the acoustic energy produced by the internal components of the transmission system. Transmission systems of large reciprocating engines generate gear and component noise which is distributed primarily in the lower frequency ranges. Transmission systems of small, low rpm, gas-turbine engines, like the T-53 turbine engine, will generate noise which is distributed within a higher frequency range than that of reciprocating engine powered aircraft. Transmission systems of larger, higher rpm, gas-turbine engines, such as the T-55 engine, generate more higher frequency noise than either reciprocating or small gas-turbine powered transmission systems. For instance, the reciprocating engine in the CH-34C is a Wright R1820 engine that can produce 2,800 rpm; the small gas turbine in the UH-1B is a Lycoming T-53 engine and produces 6,607 rpm; and the Lycoming T-55 gas-turbine engine fitted in the CH-47A generates an even higher rpm of 14,500.

It can be assumed that the greater majority of gear-reduction systems fitted in most future rotary-wing aircraft powered by gas-turbine engines will generate noticeable acoustic energy in a higher frequency range than presently associated with reciprocating type power plants.

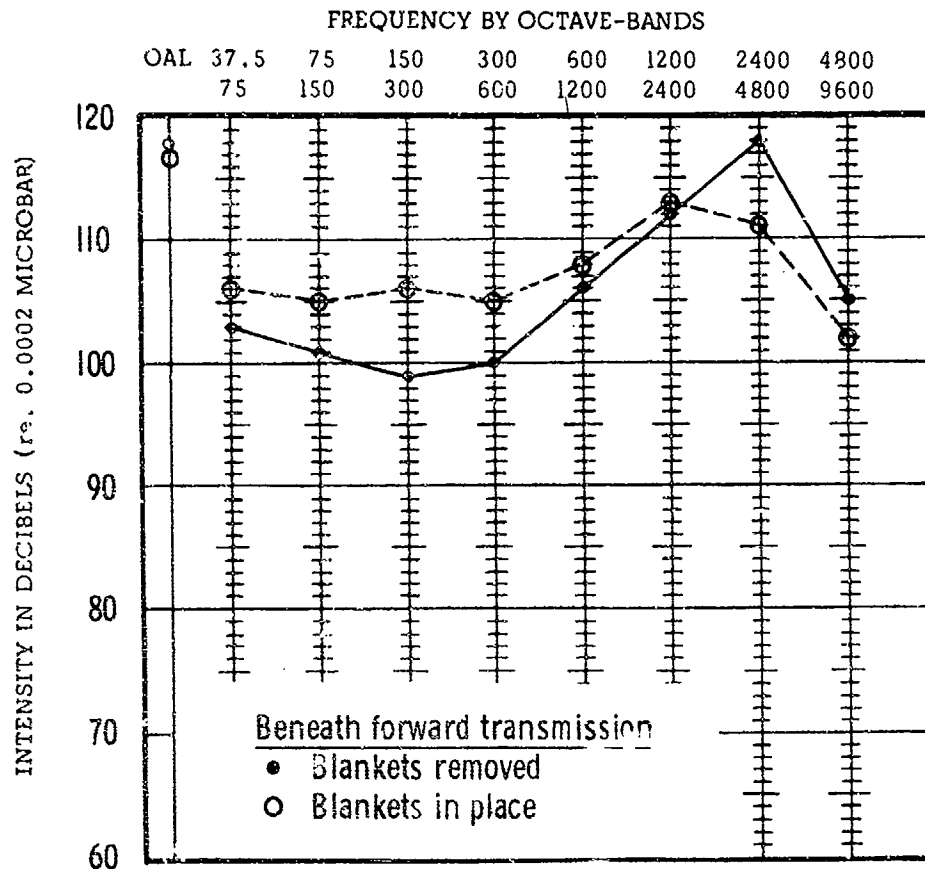


Fig. 27 Internal Noise of CH-47A Helicopter During Ground Operations, 7400 RPM, 150 PSI Torque

Careful considerations must be given to transmission systems of the future, especially if they produce intense noise in the higher frequency ranges. Subjectively, the transmission noise of the CH-37B is more acceptable than the transmission noise of the CH-47A. An examination of the levels recorded in the two aircraft (reference Figure 24, page 111, and Figure 27, above) shows that the over-all noise levels are almost the same, but due to the frequency distribution differences, the CH-37B is less "intense."

Ground Support Equipment.

Ground support equipment and functions are required on all fixed- and rotary-wing aircraft to assure that the aircraft is maintained in a safe, reliable, and proper manner. The increasing complexity of modern aircraft requires a perfect balance between the rapid and effective maintainability of the aircraft and

the ease to which the aircraft can be returned to, and retained in, a state of operational readiness. A variety of ground support equipment is used to accomplish this successfully.

Not all of the various ground support units or systems generate noise, but there are many units which depend entirely on installed power packages in order to achieve their given function(s). The two most commonly used power packages that fill this need are small reciprocating engines and small gas-turbine engines. Some of the most commonly used ground power units which use reciprocating or gas-turbine engines are:

1. Ground vehicles used to transport, transfer, load, unload, and tow. The majority of these vehicles, at the present time, are powered by reciprocating engines or receive electrical power from storage batteries. These units do not necessarily constitute a noise hazard.

2. Electrical power may be delivered to an aircraft to energize batteries and/or provide the necessary electrical energy to activate the starter units, or motors, of the power plants. These units usually supply alternating current, direct current, or a combination of alternating and direct current. The majority of such units are powered by reciprocating engines. The units may be operated for rather long periods of time and as a result - even though the noise levels generated by such units are not extremely high - may pose a significant damage-risk problem primarily due to the extended duration of exposures. The mass of electrically powered equipment installed in modern aircraft not only places increasingly greater requirements on electrical ground support equipment, but also the units may be required to operate for long periods of time - even during routine ground maintenance and calibration.

Power plants that depend on electrical power for starting may use an electrical ground power unit until the engine is started. Multiengine aircraft only require auxiliary electrical power until one engine has been started, at which time the ground power unit is shut down, and the remainder of the aircraft engines are started from the power supplied by the operating power plant.

3. Pneumatic ground power units are usually required when starting reaction type engines. These units are usually powered by small gas-turbine units. The noise generated by these units is characteristic of small, impeller-type, gas-turbine units, containing discrete, high frequency components. During normal operations the pneumatic power unit is started just prior to the starting of the power plant(s). After the aircraft's engine is started, the unit is usually shut down. The Chinook and the Mohawk are using engine-mounted turbine starters. These starters

are roughly divided into two types. One unit is, in actuality, a small gas-turbine burning jet fuel in its own combustion chamber. The other uses solid fuel in cartridge form which is fired into a breech. However, instead of the gases slowly moving a large piston whose linear motion is transformed by helical splines to rotary motion, the hot gases resulting from the combustion of the cartridge propellant are nozzled against a turbine wheel and the rotating turbine shaft, through a system of reduction gears, and drive the engine. Engines started by cartridge-start units reduce significantly the amount of noise exposure of maintenance and ground crew personnel during the starting of the power plants of reaction type engine aircraft. No longer will personnel be required to operate the pneumatic ground power units. The noise associated with the starting of the engines will actually be less, and by cutting out one of the significant noise generators during ground maintenance operations, the total noise exposure of our ground maintenance personnel will be reduced.

4. Ground air conditioning equipment, including cooling, heating, and/or ventilating units, may produce significant noise exposures. In most instances these units are powered by reciprocating engines. As these units are usually operating while maintenance, repair, and other tasks are being accomplished within the vehicle, and as they are operated for long periods of time, by themselves, or in combination with other ground support equipment, the noise generated near them may be quite intense.

There are many other types of ground support equipment that produce rather intense noise exposures, but the most significant, if considered on the basis of a routine, day-to-day noise exposure are those just mentioned. Medical personnel, while evaluating the hazardous noise areas and jobs at a particular installation, should maintain an awareness of the large variety of ground support equipment used by aviation personnel.

Auxiliary Power Units. Modern aircraft systems require a variety of auxiliary systems that are used to provide electrical power, hydraulic and air power, heating and air conditioning, compressed air, etc. The majority of the auxiliary systems are portable, but some units may be installed within the aircraft. Generally, an auxiliary power unit provides a method of driving aircraft accessories without utilizing power from the main engines. Auxiliary power units may provide shaft power to drive pneumatic accessory power transmission systems and pneumatic starters, or may be used to supply both shaft power and compressed air. These units may also provide electrical alternating current, direct current, or a combination of alternating and direct current power. Most of these units produce acoustic energies of enough magnitude to warrant hazardous noise consideration. Units using reciprocal engines create most of their noise in the lower frequency ranges below 600 cps, whereas those powered by gas turbines produce most of their acoustic energy in the higher frequency ranges.

Each of these various types of ground support equipment possesses different noise characteristics, and not all produce potentially hazardous noise. Those which use an internal power unit usually create some degree of noise while operating. In some cases the noise generated by individual units is of primary concern, especially from those powered by reciprocating gas-turbine engines.

Many of these units are operated for long periods of time during ground check-out and maintenance operations. In many instances, maintenance personnel receive a more hazardous noise exposure from the ground support equipment than from the noise produced by the engines of the aircraft. Usually, the more intricate and complex the weapon system or aircraft, the greater will be the demands for use of auxiliary ground support units to operate the various systems.

Reciprocating Power Units. Figure 28 shows the noise generated at the operator position of an MC-1 air compressor power unit. These noise measurements

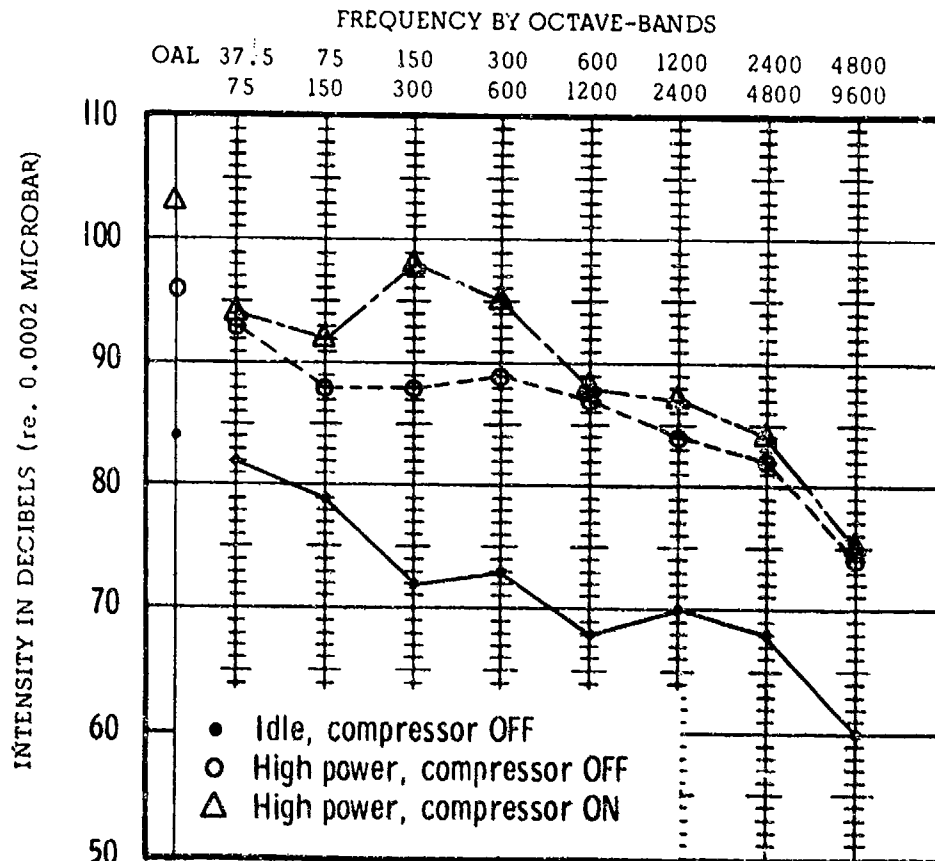


Fig. 28 External Noise at Operator Position of MC-1 Air Compressor Unit

demonstrate the influence that a mode of operation may have on the noise. With the engine at idle power and the compressor stage disengaged, the over-all noise level is 84 db and exhaust noise is the dominant noise generator. The noise from the exhaust is distributed primarily in the low frequencies (37.5 through 150 cps). As power is increased, the magnitude of the exhaust noise also increases, causing an increase of twelve db in the over-all noise. The higher rpm also creates more intense harmonics within the spectrum of the exhaust noise, but the first octave band still contains the most intense noise. When the air compressor stage is engaged, the over-all noise increases to 103 db, and the spectrum demonstrates an increase in the 150 through 600 cps frequency range due to compressor component noise. With the compressor engaged, exhaust noise is still most pronounced in the very low frequency ranges.

Most auxiliary electrical power units are powered by reciprocating engines, and the exhaust port is usually located at the opposite end from the operator's panel. Figure 29 shows noise plottings at three positions near an MD-3 electrical power unit.

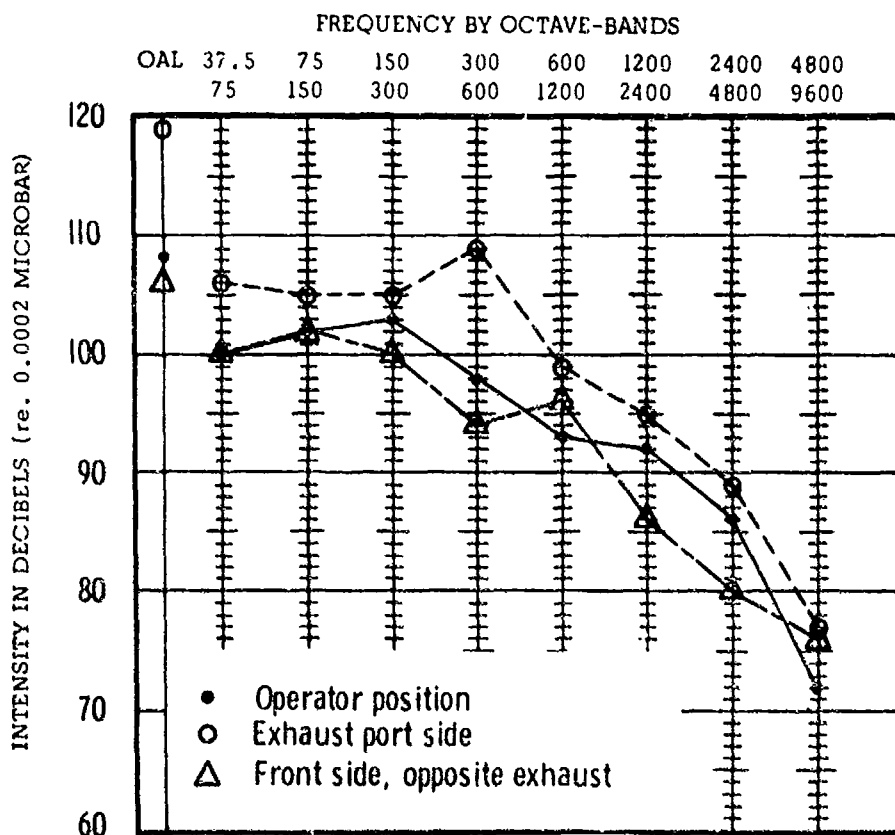


Fig. 29 External Noise of MD-3 Ground Power Unit

The noise generated at the operator's position is considerably less than the noise generated at the exhaust port side. The spectra of these three noise exposures is characteristic of that produced by reciprocating engine powered ground power units. Figure 30 shows comparisons of noise generated at the operator's location of two types of electrical ground power units. The MD-3, a somewhat larger unit than the C-22A, not only generates a somewhat more intense over-all noise level, but also a slightly different noise spectrum. Although noise generated by both units is characteristic of reciprocating engine exhaust noise, the noise spectrum of the MD-3 unit peaks in a slightly higher frequency range than does the noise generated by the C-22A.

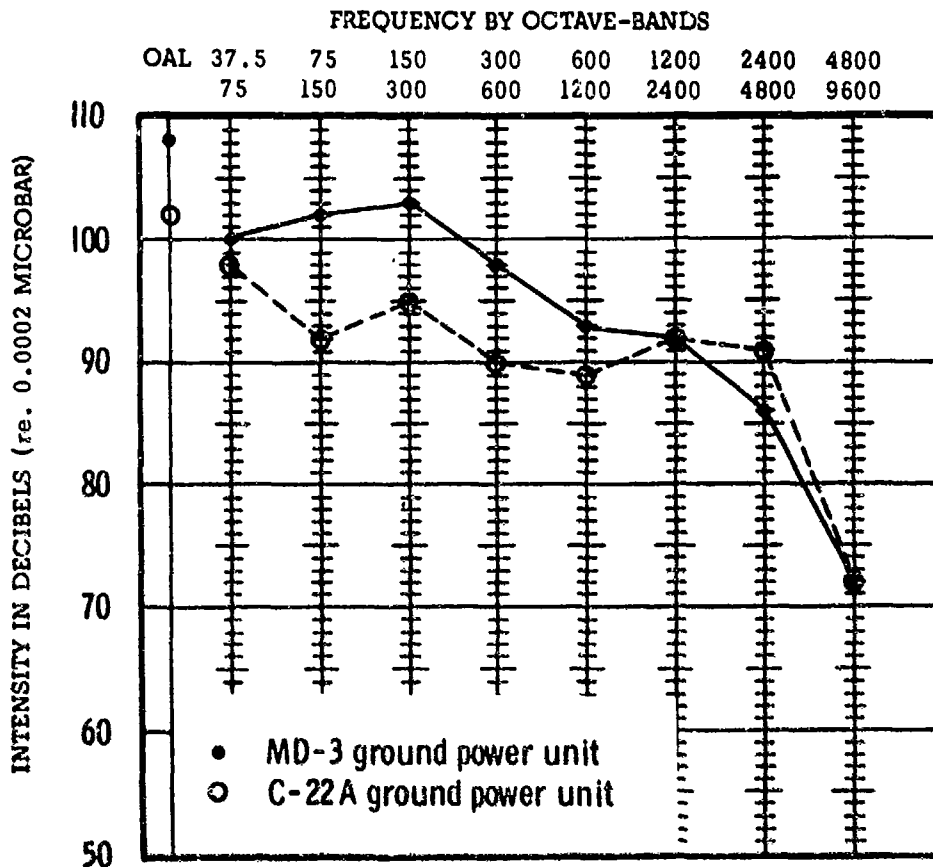


Fig. 30 External Noise at Operator Position of MD-3 and C-22A Ground Power Units

Ground power units powered by reciprocating engines generate a noise spectrum that is most pronounced in the lower frequency range and the exhaust is the major determinant of the frequency characteristics of the noise. The most intense

noise is usually found at locations near the exhaust port. Also, as engine loading increases, the noise level tends to increase due to increased torque required from the engine. Even though the exhaust (where the noise is usually found to be most intense) is located at a position opposite the control panel, it should be remembered that, when the unit is parked next to an aircraft or engine, the operator's panel is usually placed so that a full view of the aircraft or engine is afforded the GPU operator. For this reason, noise generated by the exhaust is propagated at locations between the GPU and the aircraft - thus personnel working on the aircraft may receive a significant amount of exhaust noise.

For the most part, ground power units are fitted with quite effective mufflers, but since the major noise component is generated within the lower frequencies, the amount of noise attenuation is limited.

Gas-Turbine Power Units. The requirements and utilization of ground and airborne auxiliary gas-turbine units have increased steadily. Gas-turbine auxiliary ground power units, such as the MA-1 and MA-1A units, are used to provide pneumatic power for starting many gas-turbine type power plants. The MA-1A is the newer version of the MA-1. The MA-1A is utilized primarily for the purpose of providing pneumatic power for starting gas-turbine type power plants, whereas the older MA-1 unit is utilized to provide forced air ventilation and circulation within the interiors of aircraft. The noise levels generated by the MA-1A unit demonstrate the significant degree of noise reduction which can be achieved by proper design, engineering, and noise control considerations. The MA-1 and especially the MA-1A units are routinely used by ground crew personnel for engine starting.

Utilization of gas-turbine units and gas-turbine compressors will probably increase and broaden in scope of application, especially for aircraft powered by reaction type power plants.

Figure 31 shows a comparison of noise measurements made at the operator positions of the MA-1 and MA-1A pneumatic power units. The MA-1A is trailer mounted and is a gas-turbine, air driven generator of 191 horsepower. The unit delivers 2.2 pounds of air pressure per second at an air pressure of 52.5 psi. This type of unit is required whenever a gas-turbine engine of an aircraft is started. As more and more turbine powered aircraft are developed and added to the inventory for military operations, the need and utilization of such ground power units will increase. Needless to say, the noise exposures generated by these units are extremely intense, and a factor to consider is that personnel are required to work around such units for rather extended periods of time. The degree of significance imposed by such work schedules is dependent on the duration of exposure incurred by ground maintenance personnel.

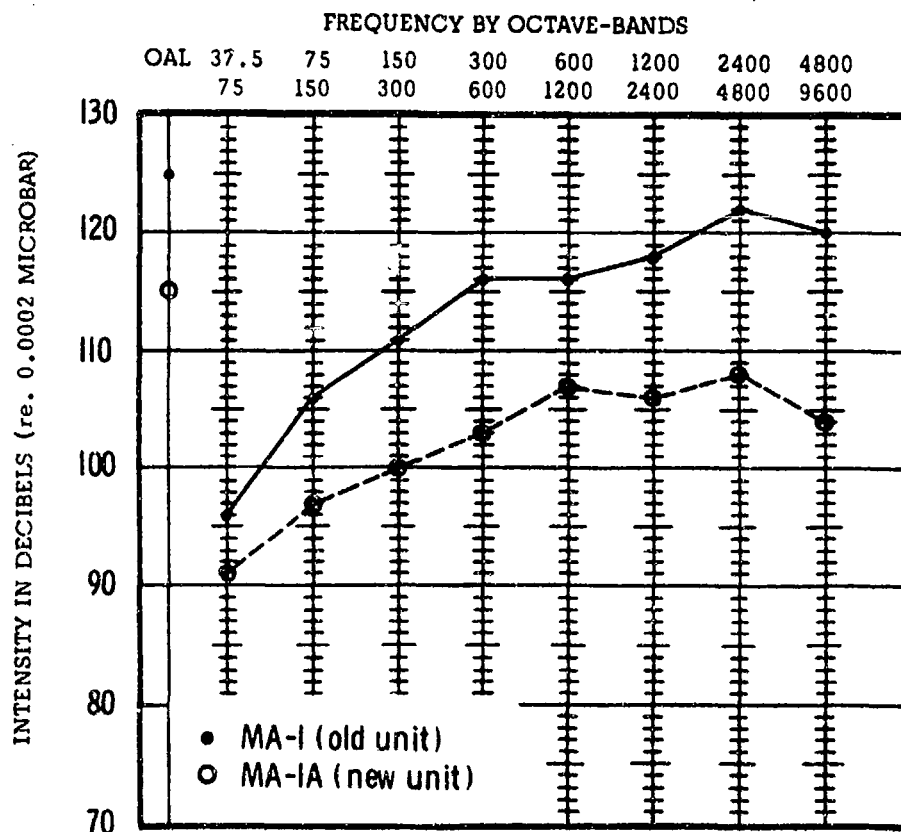


Fig. 31 External Noise at Operator Position
of MA-1 and MA-1A Ground Power Units

Figure 32 shows the general noise exposure generated by the electrical auxiliary power unit fitted in the CH-37B. As noted, the most intense noise is distributed within the lower frequency ranges, and is due to the reciprocating engine used to power the electrical generating mechanisms of the unit. This auxiliary unit is turned off after the engines of the aircraft have started as there is no requirement for operating the unit during normal flight since electrical power is provided by the generators of the main engines.

Aerodynamic and Boundary Layer Disturbances.

Aerodynamic noise generated by disturbances in the boundary layer surrounding a moving body is common to almost all aircraft, and when associated with high speed aircraft may result in quite significant noise problems. The degree of significance is directly related to the speed of the vehicle and the relative location or position of the occupant within the aircraft.

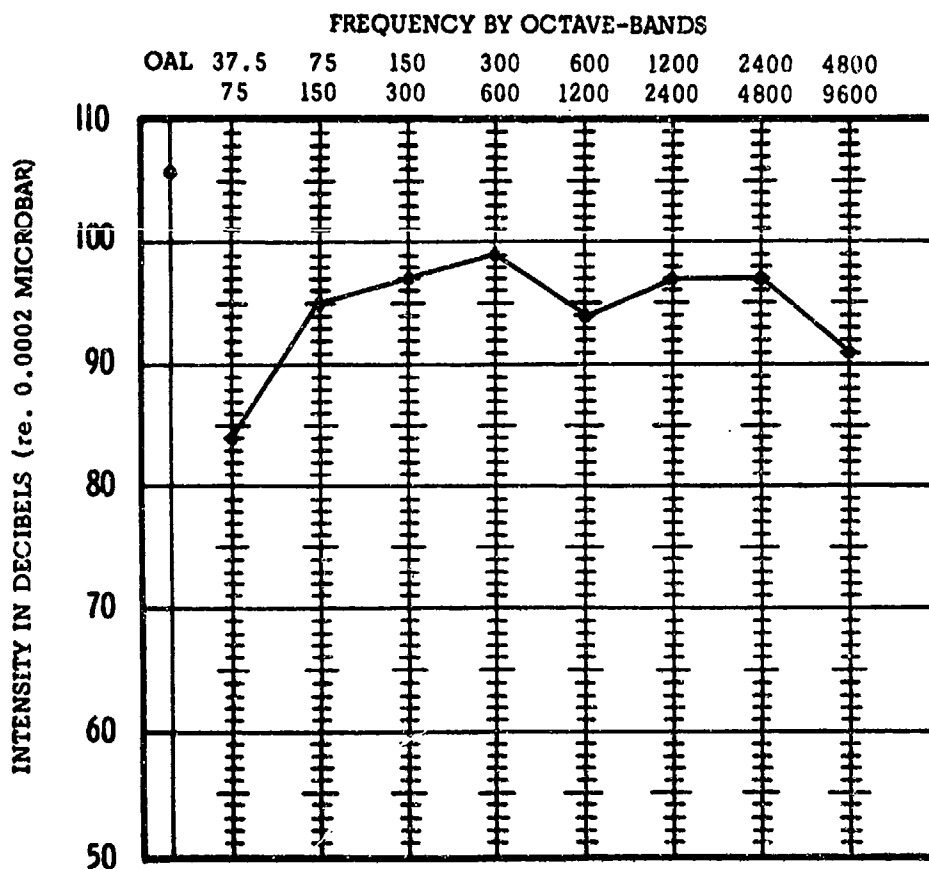


Fig. 32 Internal Noise of CH-37B APU Measured at Station 402

Noise due to aerodynamic disturbances has assumed a role of major significance due to the increased airspeeds now obtainable by the majority of military aircraft. As airspeed increases, especially at lower altitudes, noise due to aerodynamic disturbances assumes greater importance. At higher altitudes, aerodynamic noise is less significant than during operation at lower altitude at the same speed.

Boundary layer noise is a phenomenon associated with high speed passage of a moving body through an atmosphere. Boundary layer disturbances are generated by a thin layer of air next to the skin of the fuselage. The greater the speed, the more significant the boundary layer influences on noise and vibration generated internally. Boundary layer disturbances not only generate noise problems, but may also produce sonic fatigue. These intense disturbances may interfere with speech reception and/or discrimination, interpretation of information instrument readings, operation of guidance controls, and auxiliary power systems.

Boundary layer disturbances are associated with high speed aircraft and are gaining significance due to increased performance characteristics of newer aircraft. Noise due to aerodynamic disturbances is of primary concern because it increases the intensity of the middle and higher frequencies which results in a greater degree of speech masking. At present boundary layer noise is not a serious problem, but as Army aircraft attain faster speeds the importance of this type of noise can be expected to increase.

Air and Dive Brake Systems. Aviators of high performance aircraft can increase maneuverability and reduce landing speeds by extending a speed (or air) brake panel into the airstream. Speed brakes are usually hinged and, when extended outward and forward into the airstream, increase drag. Since these systems are usually controlled hydraulically, the degree of extension can be controlled throughout its entire range. The majority of systems are extended into the airstream at positions variable from full open through full closed operations. By extending the air brake into the slipstream, the turbulence and air passage friction increases the noise and vibration which, in turn, are transmitted through the surrounding support and extension system. The nearer the air brake to occupied areas, the more noticeable will be the noise and vibration generated by the system during deployment.

Airspeed and altitude have a dominant influence on the degree of noise generated during the deployment of an air brake. Generally, the higher the airspeed, and the lower the altitude, the more intense will be the air brake noise. Air brakes of some aircraft may produce more noise as airspeed is decreased because at very high speeds the brake would not open fully, but as the speed decreases the brake slowly extends further into the slipstream, thus producing more noise with decreasing airspeed.

Landing Gear Noise. The extension of an aircraft's landing gears into the slipstream may produce an increase in internal noise similar to that produced by the extension of an air brake system. Generally, the extension of a landing gear system produces only a slight increase in internal noise because most landing gear systems are housed within wing wells. However, if an aircraft has part, or all, of the landing gear housed within the main fuselage, noticeable noise may result when the landing gear is extended. Main landing gears mounted in pods and attached to the sides of the main fuselage do not usually generate much noise once the wheels are extended. The actual noise level increases only slightly during operation of the wheel well doors, but since the doors operate with rapid movements, there may be a "thudding" or "slamming" as the doors open and close (especially during closing). When extended into the airstream, the basic noise resulting from air friction will be low frequency in character. Higher frequency elements of the noise are attenuated by the structural damping.

Ventilating and Air Conditioning Systems.

Fans, blowers, re-cycling airflow units, as well as the air distribution ducts and vent systems, create various types and degrees of noise. These various noise sources are as follows:

Fans which move masses of air are usually of two basic types - axial or centrifugal. Axial fans are commonly referred to as propeller-type fans. Centrifugal-type fans move the air outward from the central axis of rotation, and are the more commonly used type aboard aircraft, especially in providing air circulation and cooling for electronic equipment.

Airflow noise is created by air friction and resonance as air flows through and out of circulation, ventilation, and other airflow retainers. Ventilation airflow noise is usually created by the use of fans and/or ram air within the aircraft. Noise is generated either by the motor and blades of the circulating fan or by aerodynamic friction produced as the air mass is propelled through exits of the air ducts.

Chapter 6

FUTURE NOISE AND VIBRATION PROBLEMS IN ARMY AVIATION

Army Aircraft Armament Systems.

The development program for armed helicopters began in 1956 when the Commanding General of the U. S. Continental Army Command became concerned over the likelihood of having to fight brush-fire wars. These wars would require forces which could be deployed quickly to a troubled area and be tailored to fit a particular task. As a result of a directive to major headquarters to consider the creation of mobile task forces to perform the function, the U. S. Army Aviation School activated a unit called the Sky Cavalry Platoon in March, 1957. This was a reconnaissance-type force completely mounted in armed helicopters. Based upon the experiments and experiences of this unit, later redesignated the 8305th Aerial Combat Reconnaissance Company, and subsequent troop tests, the concept of Army helicopters with automatic weapons, rockets, and guided missiles has been accepted and, therefore, standard weapon systems are being adopted.

Arming Army aircraft greatly enhances the capability of these aircraft to accomplish their assigned missions as these armed aircraft are immediately available and responsive to ground commanders. They perform the most recent functions of Army aviation - aerial fire support. Aircraft within the field Army, which are to be used primarily in a fire support role, will have an integrated or built-in weapon system which will be a more or less permanent installation. These would not be detachable except for the end item, the weapon itself. The use of common mounting methods allows for maximum flexibility in the selection of weapons systems to be utilized on a particular mission. Eventually an integrated weapons system will be developed that will include all of the fire control equipment as an integral part of the aircraft system.

The number of armament systems scheduled for test and evaluation by Army aviation units is quite extensive (see Appendix 2). At present the missile and rocket systems do not constitute serious noise problems. However, preliminary measurements of the XM-1, XM-2, and M-6E3 machine gun systems indicate that a potentially hazardous situation exists with automatic weapons. The peak sound pressure levels vary considerably. This variation is primarily due to 1) type of system, 2) type of gun mountings, 3) location of the muzzle in relation to occupants of the aircraft,

and 4) whether the cockpit and cargo windows and/or doors are open or closed. Firing maneuvers, i.e., ground fire (bore sighting), hovering, and various cruise airspeeds are not significant variables.

An investigation of the hazardous noise associated with the helicopter armament program will be conducted at Fort Rucker during the next few months.

STOL and VTOL Aircraft.

Short take-off and landing (STOL) refers to aircraft capable of taking off from and landing on short unimproved landing areas. VTOL or vertical take-off and landing includes all nonrotor aircraft capable of taking off and landing within 50 feet of a 50-foot obstacle.

Putman³⁰, in a report on environmental and engineering characteristics of unconventional, high performance, VTOL aircraft, emphasized that during the developmental stages special attention should be given to the unique types of noise and vibration that might be generated by these vehicles.

Many different configurations and operating principles of vertical and short take-off and landing aircraft have been proposed (see Appendix 3). A few aircraft have been sufficiently developed and operated to allow fairly extensive noise and vibration studies. These investigations have been conducted on a small scale, but there is some evidence that the majority of high performance STOL and VTOL aircraft present distinct noise problems, primarily those associated with the power plant and/or type of propulsion system used. The problem is further complicated by such variables as blade loading, jet exhaust velocity, and propeller tip Mach number. Each of these factors will have a direct influence on the amount and type of noise produced.

Generally, it can be expected that as more powerful and efficient power plants become operational, the feasibility of high performance STOL and VTOL aircraft will increase. For example, gas-turbine engines have expanded into a variety of modified versions. Some of the newer power plants are turbofan, bypass, and direct-thrust lift types. The outstanding improvements recently made in the development of small gas-turbine engines have offered a wide range of turboshaft engines for rotary-wing applications. The majority of these units offer medium shaft powers, good economy, and in many instances, reduced noise. At present, exhaust noise emanating from reciprocating engines in conventional helicopters remains one of the most dominant noise sources. However, it is believed that in properly designed turbine powered helicopters, engine noise can be reduced to the point where it can be assumed that the main source of noise is due to the shedding of vortices from the

main rotor. Investigations of noise generated by various blade loadings and rotor tip speeds have shown that the noise level decreases with decreasing tip speed and blade loadings. Measurements have indicated that helicopter rotor noise fluctuates in amplitude at a rate corresponding to the blade passage frequency.

Present data indicate that VTOL aircraft powered by pure turbojet engines produce excessive noise levels for city operation. The most significant noise produced is due to the mixing of the jet exhaust with ambient air. The majority of STOL and VTOL aircraft utilizing jet type engines will require a wide range of thrust, but these aircraft will probably not need augmented thrusts, such as afterburning. The velocity of the jet stream has a direct influence on the amount of noise produced and accounts for a wide range of noise levels.

The present trend is toward the utilization of turbofan and bypass engines as basic power plants for VTOL aircraft. The turbofan engine offers some potential for noise reduction due to its inherently low jet exhaust velocity. However, substantial levels in the higher frequency bands may be present due to the combined effects of fan noise and incomplete mixing of primary and secondary air. As research and development continue in the application of turbofan engines, it is expected that the noise characteristics of these engines will improve and the final production of highly developed turbofan engines will demonstrate significantly less noise than present day turbojet engines. The bypass engine, on the other hand, has similar noise problems to the jet type engine since the primary airflow passes through the combustion section producing tremendous exhaust velocity.

Turboprop aircraft produce very intense noise levels. However, this propeller noise may be reduced by either reducing the propeller tip Mach number or by increasing the number of blades, or both. The majority of high performance turboprop powered vehicles incorporate three- or four-blade propeller systems. Increasing the number of blades beyond four will probably not result in significant noise reductions and would increase the complexity of the propeller system. The most practical application for noise reduction in propeller systems is usually achieved by reducing the propeller tip Mach number.

A large amount of work is being expended on the reduction of noise in and around conventional aircraft, and this effort may produce breakthroughs that will be applicable to STOL and VTOL aircraft. However, it must be remembered that the VTOL aircraft need three to four times the installed thrust of conventional aircraft and therefore the noise problem is more acute from the onset.

Vibrations Associated with Army Aircraft.

During the past few years considerable research has been conducted on the causes, effects, and control of vibration. A major part of this research has been applied specifically to modes and phases of vibration expected, or presently existing, in fixed- and rotary-wing aircraft. The results indicate that man and/or machine can be exposed to definite restricting modes of vibration energies before certain undesirable effects occur.

Although the majority of research in this field has been directed toward undesirable effects or influences, there may be certain factors and types of vibrational modes that are somewhat desirable. For instance, Randle³¹ studied the influence of vibration on helicopter pilots and found that they utilize the vibration which they perceive as a sensory evaluation tool. Seemingly, the modes of vibrations perceived assisted the pilot in evaluating normal flight features during control of the aircraft, and also assisted in the detection and diagnosis of possible system malfunctions. Randle further emphasized the possible utilization of simulated vibrational modes as a practical training device in the initial phases of helicopter pilot training.

Vibrations of primary concern are related to mechanical, acoustical, or aeroelastic disturbances. Listed below are some of the more significant operational areas or circumstances where undesirable vibration may be present.

1. Maintenance test areas:
 - a. Reciprocating engines;
 - b. Gas-turbine engines, jet type;
 - c. Propeller, rotor, and engine run-up; including reciprocating, turboshaft, and turboprop power plants.
2. Ground power equipment:
 - a. Pneumatic hand tools;
 - b. Large diesel engine powered generators.
3. Aircraft during ground run-up operations:
 - a. Reciprocating engines in rotary- and fixed-wing aircraft;
 - b. Acoustically induced vibration of jet exhaust of reaction type engines during high power operation;
 - c. Propellers and rotors.

4. Aircraft while airborne:

a. Structurally propagated vibrations due to excitations created by 1) power plant disturbances; 2) engine exhaust vibrations; and 3) engine shaft feedback from propellers and rotors.

b. Acoustic and aeroelastic vibrations induced by 1) engine exhaust of reciprocating or gas-turbine engines; 2) pressure disturbances generated by rotor or propeller blades; 3) structural response due to increased airspeed and dynamic loadings; and 4) other responses, such as vibrations induced due to aerodynamically stimulated wing and surface flutter (related to high speed).

Various methods are available to help reduce undesirable vibrations. One of the most common avenues of propagation is by structural vibration. The power plant may produce considerable vibration and the degree to which these energies are transmitted through the aircraft are often dependent on the type and condition of devices used to control the vibrations. Methods of vibration reduction are detailed below.

1. Vibration isolation and anti-vibration systems. Power plant mountings are usually designed to minimize the transmission of vibrations into the structure of the aircraft and prevent resonant vibrations of the aircraft structure by vibratory forcing functions generated by the operation of the power plant.

2. Power plant-propeller system vibrations. Vibrations generated by power plants and propellers, when propagated directly through the structure of the vehicle, may produce excessively high levels of vibration. These vibrations, if present, result from inherently imbalanced forces and couples of the engine, unavoidable imbalances in the propeller, and occurrences of small errors in blade pitch and the rotational profile of the propeller. These undesirable forces are usually controlled by the use of isolation mounting systems. These systems are essentially flexible supports which allow vibrating forces acting on the power plant to be neutralized by small, nonresonant oscillations of the power plant mass itself, thus isolating the vibratory disturbances from entering the aircraft directly. This type of engine-to-frame mounting is used primarily when the vibrations generated by the engine, components, and/or propellers are within a frequency range that approximates resonant frequencies of the structures and components of the aircraft to which they are mated.

3. Absorption mounting systems absorb the energy of power plant vibrations and dissipate it as heat within the absorbing material of the mounting. They are commonly used on aircraft whose power plant components are attached to the aircraft structure and generate vibrations at frequencies much higher than the

natural modes of vibration of the aircraft structure. Absorption type mounting systems are commonly used to reduce the transmission of vibration to the aircraft structure on vehicles containing a) turbojet and turbofan engines that depend on exhaust thrust for propulsion of the aircraft; b) independently mounted auxiliary stage superchargers; c) independently mounted gear-reduction units not driving propellers; and/or d) ramjet and rocket power plants.

4. Isolation mounting systems are usually provided when the following are used: a) reciprocating engine and propeller combinations, including both radial and in-line engines; b) reciprocating engine in a submerged installation which drives propellers through an extension propeller shaft; c) independently mounted propeller assemblies; d) independently mounted gearbox-propeller combinations; 3) aeropulse or intermittent type jet engines; or f) turboprop engines.

Summary. Discomfort of aircrew personnel may result from excessive vibration and can, in many instances, interfere with the successful accomplishment of an assigned mission. Flutter and other aeroelastic disturbances, associated with more sophisticated Army aircraft, may generate disturbances sufficiently violent to cause almost instantaneous failure of the structure affected. Free and forced vibrations may cause excessive structural stresses within the aircraft which lead to fatigue failures. Excessive vibrations of installed components may result in malfunction or failure of such components. Needless to say, vibration energies of these magnitudes usually produce physiological and psychological disturbances. Aviation medical research has demonstrated that the human system cannot tolerate as high a level of vibration as permitted by the allowable stresses in the aircraft structure.

It is obvious that certain vibration limitations must be emphasized, especially where man is concerned. Emphasis is being placed on eliminating excessive, or undesirable, vibration associated with aircraft operations. Inherent within this program is reducing 1) human physical fatigue and discomfort, 2) hearing disturbances among aircrew personnel, 3) undesirable effects of vibration on equipment and aircraft structures, and 4) improving audible communication. If these areas are considered during the early phases of aircraft design and development, the undesirable aspects of vibration on future Army aircraft can be minimized.

APPENDIX 1

PROCUREMENT INFORMATION ON STANDARD ARMY EAR PROTECTORS

The following standard Army items are included in TA 21 (Peace):

(a) Helmet, Flying, Protective APH-5

<u>Federal Stock Number</u>	<u>Size</u>	<u>Approximate Cost</u>
8415-577-4142	Medium	\$93.90
8415-577-4143	Large	

(b) Aural Protector, Ear, Sound

<u>Federal Stock Number</u>	<u>Approximate Cost</u>
4240-361-3612	\$12.00

(c) The Standard Army V-51R Ear Plugs and carrying case are included in the Medical Stock List as follows:

<u>Stock Number</u>	<u>Description</u>	<u>Unit</u>
6515-299-8287	Case, Ear Plugs	each
6515-664-7858	Plug, Ear, Noise Protection, Extra Small	pkg. 24s
6515-299-8290	Plug, Ear, Noise Protection, Small	pkg. 24s
6515-299-8289	Plug, Ear, Noise Protection, Medium	pkg. 24s
6515-299-8288	Plug, Ear, Noise Protection, Large	pkg. 24s
6515-664-7859	Plug, Ear, Noise Protection, Extra Large	pkg. 24s

If plugs are not available, they may be ordered through Medical Supply.

APPENDIX 2

PROPOSED ARMY AIRCRAFT WEAPONS SYSTEMS

<u>DESIGNATION</u>		<u>DESCRIPTION</u>
Old	New	
XM-1	XM-1	Armament Subsystem, Helicopter, .30 Caliber, Machine Gun, Twin Gun.
XM-1	XM-1E1	Armament Subsystem, Helicopter, .30 Caliber, Machine Gun, Twin Gun.
XM-2	XM-2	Armament Subsystem, Helicopter, 7.62 mm, .30 Caliber, Machine Gun, Twin Gun.
	XM-3	Armament Subsystem, UH-1B, 2.75 inch Area Rocket Weapons System (ARWS), 24 Rockets on each side.
	XM-4	Armament Subsystem, CH-34, 2.75 inch Interim Area Rocket Weapon System (IARWS), 24 Rockets on each side.
XM-138/75	XM-5	Armament Subsystem, Helicopter, 40 mm Grenade Launcher.
XM-153/154	XM-6	Armament Subsystem, CH-21, 7.62 mm Machine Gun, Quad Gun.
XM-153/155	XM-6E1	Armament Subsystem, CH-34, 7.62 mm Machine Gun, Quad Gun.
XM-6E3	M-6	Armament Subsystem, UH-1B, 7.62 mm Machine Gun, Quad Gun.
	XM-7	Armament Subsystem, M-60C, Machine Guns mounted on LOH.

Old	<u>DESIGNATION</u>		<u>DESCRIPTION</u>
		New	
		XM-8	Armament Subsystem, 40 mm, Grenade Launcher mounted on LOH.
		XM-9	
		XM-10	Armament Subsystem, Follow-on 7.62 mm XM-2 Subsystem, mounted on OH-13 and OH-23 Helicopters.
		XM-11	ATGM SS-11 mounted on UH-1B.
		XM-12	Armament Pod, Aircraft, 20 mm Automatic Gun. (This is a podded configuration of gun, 20 mm automatic: M-61. 1250 rounds of ammo will be self-contained in the pod).
		XM-13	Armament Pod, Aircraft, 40 mm Grenade Launcher. (This is a podded version of the XM-75).
		XM-14	Armament Pod, Aircraft, Caliber .50 Machine Gun. (This is an "off-the-shelf" procured gun pod utilizing the M-2 gun for fixed-wing use).
		XM-15	Armament Subsystem, Helicopter, 7.62 mm Machine Gun, Twin High Rate Gun. (This unit is a system to replace the M-6).
		XM-129	Launcher, Grenade. (This is a redesigned version of the XM-75 to reposition the drive drum).
		XM-133	Machine Gun, 7.62 mm, Gas Drive. (This is the high cyclic rate gun with gas drive).
		XM-134	Machine Gun, 7.62 mm, Electric Drive. (This is the high cyclic rate gun with electric drive).

APPENDIX 3

PROPOSED STOL AND VTOL AIRCRAFT

1. Rotor Aircraft other than Conventional Helicopters:

Piasecki 16 H Pathfinder (reciprocating, rotor + shrouded prop).

2. Gyrodyne: (jet assisted rotors)

a. McDonnell XV-1 (gas turbine).

b. Fairey Rotodyne (gas turbine).

3. Propeller Aircraft:

a. Deflected Slip Stream.

(1) Ryan VZ-3RY Vertiplane (gas turbine).

(2) Fairchild (reciprocating).

b. Tilt Wing.

(1) Kaman K-16B.

(2) Hiller X-18 (gas turbine).

(3) Vertol VZ-2 (gas turbine).

(4) Ryan XV-8A (reciprocating) (Army).

c. Tilt Propeller.

(1) Curtiss-Wright X-19 (AF/Army/Navy).

(2) Bell XV-3 Convertiplane (reciprocating) (Army).

4. Shrouded Propeller Aircraft:

- a. Doak VZ-4DA.
- b. Piasecki 16 H Pathfinder (reciprocating, rotor + shrouded prop).

5. Fan Lift Aircraft:

- a. Piasecki Airgeep - Seageep I (reciprocating).
- b. Piasecki Airgeep II (reciprocating).
- c. Vanguard Air and Marine Corps Vanguard 30.
- d. Vanguard 2D Omniplane.
- e. General Electric - Ryan XV-5A (Army).

6. Jet Aircraft:

- a. Lockheed XV-4A Hummingbird (Army).
- b. Ryan Vertijet X-13 Pogo.
- c. Bell X-14A.
- d. Hawker Siddeley XV-6A (AF/Army/Navy).

7. Tri-Service (turboprop) (AF/Army/Navy):

- a. Chance Vought, Ryan, and Hiller XC-142A (VHR 447).
- b. Bell X-22A.

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