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Dynamic Characteristics of Flight Simulator Motion Systems

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PREFACE

The Flight Mechanics Panel (FMP) of the Advisory Group for Aerospace Research and Development has maintained a continuing involvement in assessing the fidelity of aircraft simulation. Based on work performed by an earlier FMP Working Group on Approach and Landing Simulation and in recognition of the growing need for a common method of assessing motion quality the FMP, in October 1976, established Working Group ≠07 - FMP Working Group on Flight Simulation Motion Quality. The Working Group was charged with defining and determining metrics of the hardware-delivered performance of the various degrees of freedom of the motion system, etc. Because "quality" could be inferred to include a study of the drive algorithms of motion systems as well as the hardware-delivered performance, the Group suggested in May 1977 a change in its title to FMP Working Group on the Dynamic Characteristics of Flight Simulator Motion Systems. The scope of the Working Group included attending to not only the "classical" characteristics of motion generation systems, such as maximum travel and bandwidth of operation, but also to characteristics expressing smoothness of motion and the levels of interaction between various degrees of freedom. The panel did not address the acceptability of specific characteristics.

The Terms of Reference for Working Group ≠07 were promulgated in October 1976, and the membership was approved by the National Delegates Board in March 1977. At its first meeting on 18 and 19 May 1977 at NASA Ames Research Center, the Working Group reviewed the Terms of Reference, defined in more detail its projected scope, and tentatively identified the characteristics it was to study. At its second meeting at the Royal Aircraft Establishment's facilities in Bedford UK on 7 and 8 November 1977, the Working Group further refined and standardized the dynamic characteristics it planned to measure, heard presentations by several of its members on preliminary study efforts, and discussed plans of the membership to test and verify the characteristics. The third meeting of the group took place on 21 and 22 April 1978 at Brussels, Belgium. At this meeting, the results of the study efforts of the members were discussed and put into formal context as definitive characteristics. Problems of measurement were discussed and alternatives tabled for review. At its final meeting on 17 and 18 October 1978 at the National Aerospace Laboratory NLR in Amsterdam, Netherlands, the draft of the Group's final report was reviewed and approved.

WORKING GROUP 07 - MEMBERSHIP

Mr. D.LEAN - Chairman Mar 77 - Oct 78
Superintendent, Flight Dynamics Division (FSL),
Flight Systems Dept
Royal Aircraft Establishment
Bedford MK41 6AE, Beds., U.K.

Prof.Dr.Ir. O.H.Gerlach - Chairman Oct 78 - Jun 79
Department of Aerospace Engineering
Delft University of Technology
Kluyverweg 1
2629 HS DELFT, Netherlands

Mr. J. C. DUSTERBERRY
Research Assistant to the Director
NASA Ames Research Center
Mail Stop 200-10
Moffet Field CA 94035, USA

Mr. F. ERDMANN, Dipl.-Math.
Flight Simulator Department
DFVLR
D-33 Braunschweig Flughafen, Germany

Dr. D. FALCO
AERITALIA
Corso Marche 41
Torino, Italy

Ir. W.P. KOEVERMANS
National Aerospace Laboratory NLR
P.O. Box 90502
1006 BM AMSTERDAM, Netherlands

Mr. K.J. STAPLES
Flight Research Division
Royal Aircraft Establishment
Bedford MK41 OAL, Beds., U.K.

Mr. J. VALLEE
Ingenieur du Centre de Simulation
Centre d'Essais en Vol
13800 - Istres, France

Colonel P.T. KEMMERLING - Executive Secretary
Director, Directorate of Equipment Engineering
Aeronautical Systems Division
Department of the Air Force
Wright-Patterson Air Force Base, Ohio 45433, USA

Throughout the course of its activities, the Working Group received valuable advice and assistance from several research simulator motion system experts. Special acknowledgement for their contributions is made to:

Ir. M.Baarspul, and
Mr. J.G. den Hollander,
Delft University of Technology, the Netherlands;

Ir. C.J.Jansen
National Aerospace Laboratory NLR, Amsterdam, the Netherlands;

Mr. P.Verey, and
Mr. D.Marshall,
Flight Research Division, RAE Bedford, United Kingdom;

Dr. E.Martin,
Directorate of Equipment Engineering, ASD, WPAFB, Ohio, USA.

Special appreciation is also extended to Sqdn Ldr D.Stangroom, Executive FMP, AGARD NATO, Paris, France, for his outstanding assistance during the entire course of the Working Group's activities.

CONTENTS

LIST OF SYMBOLS

a	acceleration
A	specific force
A_p	peak value of acceleration noise
DFT	Discrete Fourier Transform (App. A)
H	describing function
IDFT	Inverse DFT
k_i	integer number of periods within measurement length of 10.24 s
N	number of samples per measurement length (= 1024)
PSD	power spectral density
r	ratio
r_{hn}	high-frequency nonlinearity ratio
r_{ln}	low-frequency nonlinearity ratio
r_n	acceleration noise ratio
r_p	peak ratio
r_r	roughness ratio
RMS	root mean square
T	transformation matrix
t	time
Δt	sample time interval
Δt	time required to reach 63 % of input acceleration (dynamic threshold)
α	DFT constant
σ	standard deviation
ω	circular frequency (rad/s)

subscripts:

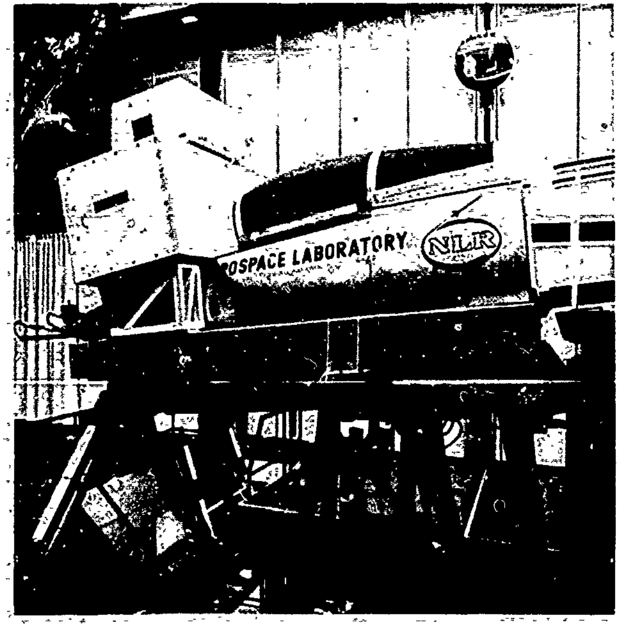
f	fundamental
i	input signal
hn	high-frequency nonlinearity
ln	low-frequency nonlinearity
n	noise
r	roughness

DYNAMIC CHARACTERISTICS OF FLIGHT SIMULATOR MOTION SYSTEMS

1. INTRODUCTION

In the last five years, there has been a sharp rise in the number of simulation facilities employing multiple degree-of-freedom motion systems; however, until recently no substantive attempts have been made to measure the performance of these systems. Those measurements that have been made and published have not been made in a uniform way, so that it is difficult to compare different systems. While data on the gross excursions, velocities and accelerations of these systems have been generally available in the literature, dynamic response, noise and other imperfections were usually neither carefully measured nor was information on them widely distributed. In the training environment particularly, there has been little incentive to make such measurements. Training simulators have only one objective - to train aircrews - and actual simulator performance is clearly not as essential as an appearance of correspondence with reality sufficient to produce positive transfer of training. Changes in motion system behavior have traditionally been measurable only through subjective means such as pilot opinion. The hazard in this approach within a research context is that changes made to improve pilot performance in the aircraft may prove only to be changes which improve pilot performance in the simulator. With the appearance on the market of very large, high performance motion systems, such as that being constructed by LMT, France, it is becoming increasingly important that some quantitative method of measuring and reporting the dynamic characteristics of flight simulator motion systems be developed, as a first step towards the assessment of motion quality of all simulation devices.

A review of the recent literature indicates that only two United States facilities have conducted quantitative studies bearing on the assessment of motion system dynamic characteristics. These facilities are the Franklin Research Center (FRC) and the NASA Langley Research Center. The FRC has completed a contract with the US Air Force to test an improved hydraulic servo valve that reduces or eliminates the familiar "turn-around bump" which occurs in many motion systems when the platform slows down, stops, and changes direction. Perhaps even more significant is the finding that this improved valve does not exhibit the tendency to instability encountered with commercially available valves. NASA Langley has conducted extensive research on its six-post motion system, with the principal emphasis on the development of improved software, or drive algorithm techniques, for a synergistic six degree-of-freedom motion system. NASA's contribution to motion dynamic characteristics has been to add compensation terms to the drives of one of these systems to achieve a five-fold increase in bandwidth while retaining an acceptably low "turnaround bump". To improve motion smoothness, work started in 1968 in the Netherlands at the Department of Mechanical Engineering of Delft University of Technology to develop a motion system with low friction. This was realized by introducing hydraulic jacks with hydrostatic bearings, eliminating stick-slip phenomena, which were up to then present in existing systems (see Reference 1). Nowadays these jacks are being applied in commercially available systems.



In January 1977, the Department of Aerospace Engineering at Delft University of Technology, the Netherlands, published a pioneering study (Reference 2) which brought into direct focus the need for the development of a universal understanding of the dynamic characteristics of flight simulator motion systems. The Delft Study identified the characteristics of a motion system which determine the fidelity of motion cues as:

a. The performance limits in each degree of freedom.

b. The motion system describing function.

c. The spectral power distribution and RMS value of the acceleration noise in each of the various degrees of freedom of the motion system.

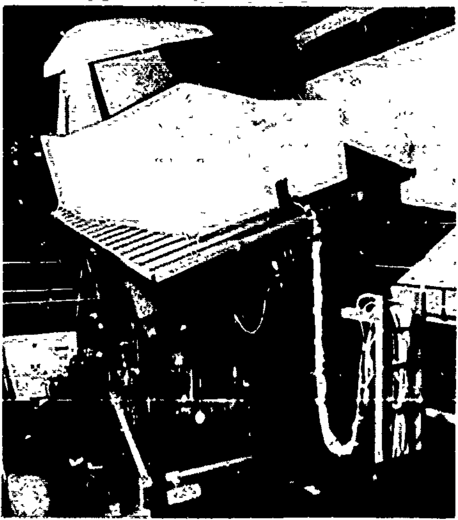
The initial efforts of Delft included not only identification of these characteristics, but also the development of generalizable procedures for measuring these parameters. This work contributed significantly to the definitions and procedures established by Working Group 07 - the Flight Mechanics Panel (FMP) Working Group on Dynamic Characteristics of Flight Simulator Motion Systems.

Several useful results can be expected from the publication of an uniform and systematic method of measuring the dynamic qualities of flight simulator motion systems. The first, of course, has already been mentioned. It will become possible to compare directly the characteristics of two different motion systems in terms of smoothness, etc, and not just in terms of maximum excursion, velocity, and acceleration of the several available degrees of freedom. A second possible use is to aid system designers and operators in system diagnostics. The Working Group recognizes that there are a number of different diagnostic techniques available to the engineer who designs or tunes a system of this type, and suggests that the techniques described here are an addition to that repertoire. Specification is a third possible use of these techniques. In specifying training simulators, the United States Air Force pioneered a widely distributed motion system specification when it published MIL-STD-1558 in February 1974 (Reference 3).

It was outside the Terms of Reference of Working Group 07 to investigate the requirements of flight simulator motion systems. These requirements are dependent on the aircraft to be simulated, its mission, and whether training or aircraft research and development is the projected use of the simulator. In training, the cost and availability of other training aids are also important factors influencing the requirement.

It is important to recognize that the Working Group was not required to make a judgment on acceptable characteristics. This is largely a physiological consideration. Furthermore, acceptability is unlikely to be uniquely defined. While a maximum acceptable level of acceleration noise might be defined, other characteristics may be strongly task dependent, or even depend on the presence of a visual system and on its field of view. In this connection, the Flight Mechanics Panel in conjunction with the Aerospace Medical Panel has set up another Working Group (AGARD AMP-FMP WG10) concerned with the Fidelity of Flight Simulation for Pilot Training. This Working Group will include specialists in human perception and training as well as engineering specialists. Should Working Group 10 choose to address the required quality, as well as the fidelity, of motion, then it should be noted that it will be only in the context of training; the motion needs of research and development simulators may be very different.

This AGARD-Report specifies a uniform method of measuring and reporting those characteristics which might be used in writing performance specifications.



The dynamic characteristics of flight simulator motion systems are not the only factors involved in satisfactory simulator motion performance. In those cases where motion is a simulator requirement, the motion system is used to generate at the pilot's station a specific force vector similar to the specific force that would be sensed by the pilot of the simulated aircraft or other vehicle. Constraints on the displacement of any motion system limits the duplication of this specific force to brief instants of time. The wise choice of the computer algorithm or motion logic to achieve a satisfactorily similar specific force is, in addition to the motion system dynamics, an important consideration. Involved in this choice is the speed of the simulator computer, for long frame times for the computation of the aircraft/motion drive equations will add a transport lag to the overall system. The software and computation time are therefore critical choices which must be made in conjunction with the motion system dynamics in order to provide the system user with the simulator motion characteristics necessary for a given task. Working Group 07 did not address motion drive logic or computer algorithms in its deliberations, although it does recognize their importance in determining the overall quality of a motion simulator.

The recommended definitive characteristics which follow in paragraph 2 quantify the dynamic characteristics of flight simulator motion systems in a standardized, repeatable fashion. Additional goals have been that these measurement techniques apply to systems with both electrical motor and hydraulic drives, and those with independent and synergistically interrelated motions in different degrees of freedom. It has been the intent of the Working Group that this measurement technique produces results which are mathematically precise while easily relatable to physical phenomena.

In order to experimentally validate the measurement techniques considered before making final recommendations, the members of Working Group 07 undertook to apply each candidate measurement approach to motion simulators of varying types and size. Each candidate technique was attempted on systems with electric motor drives as well as on systems with hydraulic drives with conventional or hydrostatic jacks, and on systems with independent and with synergistically interrelated motions in the various degrees of freedom. Displacement capabilities of these various systems ranged from fractions of a meter to over 35 meters. Both position and velocity servosystems were investigated. As a result of these preliminary studies, some candidate techniques were dropped, others were modified, and a recommended set of measurements finally evolved.

The remainder of this AGARD-Report is broken down into three paragraphs and three appendices which relate to the experience, recommendations, and conclusions of WG 07.

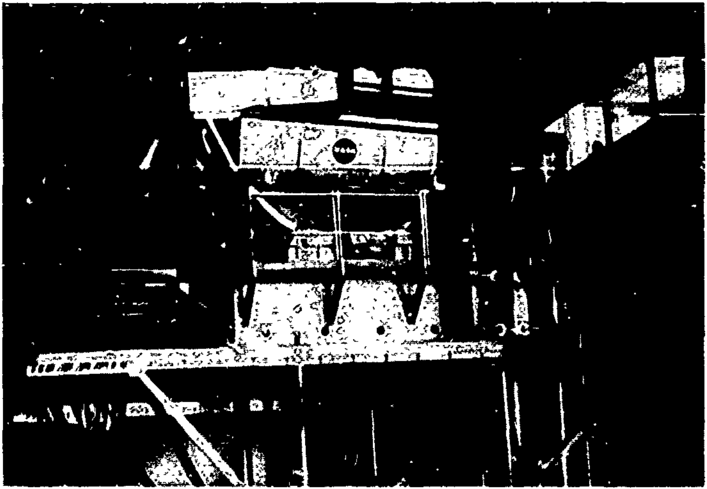
Paragraph 2 includes a definition of, discussion of, and measurement and display methodology for each of the recommended definitive characteristics. Since there is a great deal of interaction among the procedures described, it is recommended that the reader familiarize himself with the entire content of paragraph 2 prior to embarking upon the measurements required for any particular characteristic. It is also important that the reader acquaint himself with the content of Appendix A; this appendix provides the necessary detail and background to assure consistency among the data taken and interpretation of those data from system to system and from operator to operator.

Paragraph 3 contains a discussion of alternative measurements which were considered, and the reasons for not including these in the final recommended set. Several comments are also made regarding other features which, while they may influence motion system performance, were not among the alternatives considered for measurement and the rationale for these omissions.

Paragraph 4 summarizes the conclusions and recommendations resulting from the deliberations of Working Group 07.

Appendix B provides a detailed discourse on the reasons for selecting acceleration as the metric for several of the characteristics. Comments in this appendix delineating the difference between <u>specific force</u> and <u>acceleration</u> will be especially helpful to the reader who has not been heavily involved in the field of motion simulation.

Appendix C contains the results of measurements made by several members of Working Group 07 employing the techniques recommended in paragraph 2. These measurements, made on a selection of representative systems, should serve to illustrate the measurement techniques and the methods of data analysis and display discussed in paragraph 2 and Appendix A.



2. RECOMMENDED DEFINITIVE CHARACTERISTICS

2.1 General introduction

In this report Working Group 07 has defined the engineering parameters that contribute to simulator motion system dynamic characteristics. These characteristics are:

a. Excursion limits for single degree of freedom operation.

b. Describing function.

c. Linearity and acceleration noise.

d. Hysteresis.

e. Dynamic threshold.

Of particular concern are those characteristics which result in unwanted cues, whether correlated or uncorrelated with the command signals. Smoothness, jerk, backlash, and reversal bump are common terms used in discussions regarding motion quality. These are considered to be subsumed by c) linearity and acceleration noise.

Acceleration has been chosen as the metric for a number of these characteristics even though it is not the metric that is conventionally used for some of them, such as threshold and linearity. There are several reasons for this choice:

1. The synergistic nature of several of the platform motion system designs makes accurate measures of displacement in the various degrees of freedom difficult, if not impossible.
2. Specific force and angular acceleration are the characteristics sensed by the pilot of a simulator. (The relationship between specific force and linear acceleration is discussed in Appendix B).
3. Even if acceleration is not the direct input signal to the motion system, the input signal is computed from the desired acceleration.

The recommended characteristics a, b, c and d are measured by applying a sinusoidal input signal to the system. In order to obtain mutually comparable data, the methodology must be standardized. Appendix A provides detailed information concerning the generation, measurement and analysis of output signals with sinusoidal input signals.

The frequency and amplitude variation of this input signal are summarized below:

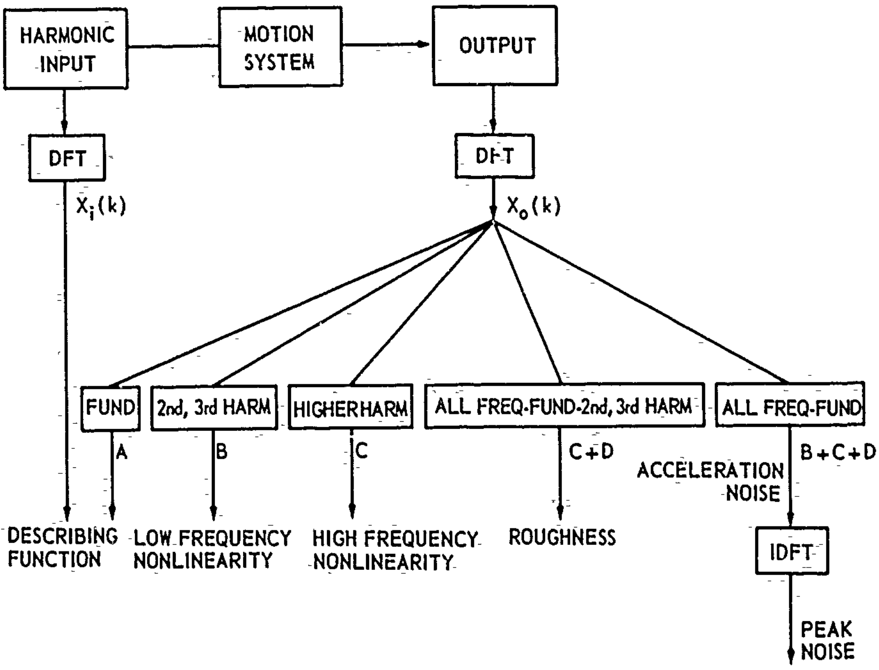
Characteristic Investigated	Input Signal Frequency (Note: $N.\Delta t = (1024)(.01) = 10.24$ s is assumed. See Appendix A for details).	Input Signal Amplitude
a) Excursion	$\frac{k_i}{10.24}$ Hz; $k_i = 2, 5, 10, 20, 50$	Amplitude <u>varied</u>
b) Describing function	$\frac{k_i}{10.24}$ Hz; $k_i = 1, 2, 5, 8, 10, 15, 20, 50, 80, 100$	Amplitude fixed at 10% system limits
c) Linearity and acceleration noise	$\frac{k_i}{10.24}$ Hz; $k_i = 5$	Further analysis of data recorded under a)
d) Hysteresis	≤ 0.01 Hz	100 % and 1 % system limits

In general, identification of system dynamics is simplified using deterministic input signals, especially if the primary interest is in the error of the system. If the input signal is restricted to a single sinusoid, the error can be determined easily. Moreover, the time invariant linearity errors are easily separated from stochastic errors. Another advantage of the sinusoidal input over other elementary deterministic signals such as impulses, steps, or ramps, is that it better resembles the continuous signal normally input during simulation.

The measured output acceleration signals consist of a periodic signal contaminated by a stochastic component. After Discrete Fourier Transformation, this signal is partitioned into the following components:

- Fundamental or first harmonic (A)
- Second and third harmonics (B)
- Fourth and higher harmonics (C)
- Stochastic residue (D)

The relationships involved are summarized in the following diagram.



Using the prescribed methodology, a limited set of measurement runs is sufficient to identify: the describing function (A), the low frequency (B) and the high frequency (C) nonlinearity, the acceleration noise (B, C and D) and the roughness (C and D).

The excursion limits for single degree of freedom operation are divided into the system limits and the operational limits. The system limits are the absolute maxima of motion. The operational limits (i.e., the useable excursion limits), determined by means of an objective criterion, are measured by varying the excitation amplitude at certain specified frequencies until the acceleration noise ratio exceeds a standardized level. Increasing and decreasing the amplitude will provide the upper and lower limits respectively.

The describing function is determined from measurement at an input amplitude of 10 % of the system limits at a set of recommended frequencies. The data taken to determine the operational limits at approximately 0.5 Hz are also used to calculate nonlinearity and roughness. This frequency is chosen as the basic reference frequency in order to be consistent with a measurement prescribed in Reference 3, which is the only presently known standard for motion system requirements.

A very low frequency (≤ 0.01 Hz) input signal is used to measure the hysteresis of each actuator separately. The measured response time to an acceleration step input is used to define the dynamic threshold.

A detailed description and discussion of the different measurement procedures is given in the paragraphs which follow in this section.

In concluding this introduction to the description of the recommended characteristics, some notes are offered regarding the choice of the location at which the characteristics are determined.

Clearly, the characteristics measured at the pilot's position are of primary importance. However this is not always a practical choice since this position generally does not coincide with the centroid location, i.e., the reference point for the control of the motion platform in different degrees of freedom. Thus, motion generated within a single degree of freedom for the simulator may result in motion at the pilot's position with several components; e.g., a roll input to the motion system may generate mutually dependent roll and sway components at the pilot's position. In such cases, the determination of parasitic accelerations (in the non-stimulated degrees of freedom) is hampered. For this reason the centroid location is suggested as the location where the characteristics are to be measured or transformed to by computation. For motion systems not having a unique centroid location, a practical choice must be made. In any case, it is important to mention the location of the reference points and axes for the data presented. The points at which the measurements were taken together with the usual pilot's position should be indicated.

2.2 Excursion Limits

2.2.1 Definitions

Two types of excursion limits are distinghuished: system limits and operational limits. The system limits are defined as the extremes for displacement, velocity, and acceleration which can be reached during controlled single degree of freedom operation. The operational limits are defined as the amplitude of the acceleration output signal, in response to a single degree of freedom sinusoidal input signal, at which the acceleration noise ratio (see para 2.4) reaches prescribed values. In general, upper and lower operational limits will be determined. To the extent that is achievable, it is recommended that the operational limits measurements be carried out for noise ratios, r_n, of 0.2, 0.4 and 0.8. This will cover a reasonably wide range of motion system characteristics.

2.2.2 Discussion

The excursion limits of a simulator motion system are inherent in its basic engineering design. This design is of course influenced by the cleverness of the designer, the relative importance to the user of the magnitudes of the various defining characteristics, and economic considerations. These inherent limits can be compromised by simultaneous combinations of displacement, velocity, and acceleration demands, and, in the case of some systems, by simultaneous motion in other degrees of freedom, either because of the geometry of the system or because of limitations of the system power supply.

The so called system limits are to be computed from elementary design parameters or can be measured by isolating the limits to a simple form by applying appropriate command signals. Strict prescriptions resulting in standardized system limits can hardly be given. Since it is not possible to standardize the means by which system limits are derived, published values for system limits should be interpreted with care.

This is one reason why the so called operational limits are introduced. Although it is of interest to know the system limits, it is thought to be more important to have insight into the really usable motion range. In this context this means a motion range reasonably free from acceleration noise. This aspect is reflected in the criterion defining the operational limits.

These limits form the boundary of the motion range with an acceleration noise ratio lower than the indicated value. It provides an objective measure of usable performance envelopes. The operational limits are measured with simultaneous demands for combinations of displacement, velocity, and acceleration.

2.2.3 Measurement

As already pointed out in the discussion, the determination of the system limits wil differ from system to system. Consequently, no particular method of measurement is recommended. However, in order to increase the usefulness of published figures, the procedure used to arrive at these figures must be indicated. Further, it is of vital importance to indicate whether or not there are limiting factors other than those reflected in the defined system limits. One such limitation would be any short-term capabilities, such as is the case when a relatively low hydraulic flow capacity is backed up by accumulators.

The operational limits are measured by applying sinusoidal input signals of different amplitudes at several frequencies. The signal generation and basic data analysis must be performed according to the procedures outlined in Appendix A. The frequency of the sinusoidal input signal is set at a discrete value and the amplitude is increased from zero up to the system limit for that frequency. This is repeated through the entire band of usable frequencies. If it is at all feasible, the measurements should be performed at least at the following frequencies:

$$(k_i/10.24)\ \mathrm{Hz},\quad k_i = 2,\ 5,\ 10,\ 20 \text{ and } 50$$

It is possible that if data are taken only at the frequencies recommended above, the contours for the operational limits, as discussed in paragraph 2.2.4, will not close, see Figure C6 for example. The range of measurements at the low frequency end of the spectrum can be extended by taking $k_i = 1$. If this is not sufficient, the number of samples and/or the sample time interval may be increased in order to increase the product $N.\Delta t$, which in turn increases the frequency resolution. System resonances or the possibility of damage may rule out obtaining sufficient data to close the contours at high frequencies.

Upper and lower limits for acceleration noise ratios (refer to paragraph 2.4 for the definition of the noise ratio, r_n) of $r_n = 0.2$, 0.4 and 0.8 can be found by interpolation in the manner illustrated in Figure 1. In this figure, for a given frequency, the determined noise ratios are plotted versus the amplitude of the output velocity. This amplitude is computed from the standard deviation of the fundamental of the acceleration output signal (again see paragraph 2.4) by using the following equation:

$$a_{\dot{x}} = \left(\frac{\sqrt{2}\sigma_{\ddot{x}}}{\omega_i}\right) = \frac{10.24\sigma_{\ddot{x}}}{\pi\sqrt{2}.k_i}\ \frac{m}{s} \text{ or } \frac{rad}{s}$$

(Units for $\sigma_{\ddot{x}}$ in m/s^2 for translation and in rad/s^2 for rotations are assumed).

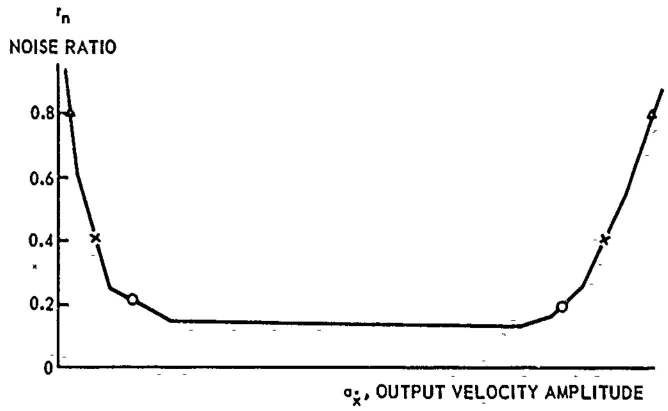


Fig. 1 Noise ratio graph

For real measurements see Appendix C, Figures C1 and C2.

2.2.4 Display

The system limits can be displayed in tabular form, typically as shown below for a three-degree-of-freedom system.

	TRAVEL	VELOCITY	ACCELERATION
HEAVE	± .3 m	± 1. m/s	+ 15. − 28. m/s^2
ROLL	± .28 rad ± 16°	± 1.28 rad/s ± 73 °/s	± 19. rad/s^2 ± 1090 °/s^2
PITCH	± .27 rad ± 15.5°	± .9 rad/s ± 50 °/s	+ 5.5 − 8. rad/s^2 +315 −460 °/s^2

TABLE 1: Tabulated system limits.

The operational limits as well as the system limits for sinusoidal input signals can be displayed in a diagram of velocity versus frequency. To obtain a convenient plot, the logarithms of the velocity amplitudes for the relevant limits are plotted versus the logarithms of the frequency. The lines for the system limits drawn in the sample figure, Figure 2, are computed by assuming that the maximum amplitude of the sinusoidal output signal is given by the system limit. In the case of asymmetric limits, the lowest value is taken. Lines indicating an acceleration noise boundary can be interpolated between the measurement points of the operational limits.

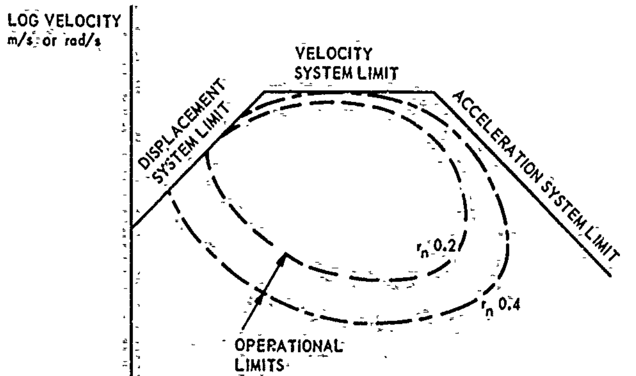


Fig. 2 Excursion limits for sinusoidal input signals

For real measurements see Appendix C, Figures C3 through C6.

2.3 Describing function

2.3.1 Definition

The motion system describing function at a given frequency is defined as the complex ratio of the Discrete Fourier Transform (DFT) coefficients for the fundamental frequency of the measured output and input accelerations.
That is,

$$H(k_i) = \frac{X_o(k_i)}{X_i(k_i)}$$

for a sinusoidal input signal with an amplitude of 10 % of the system limit at the frequency $\frac{k_i}{10.24}$ Hz.

2.3.2 Discussion

The describing function defined here is the so called "sinusoidal input describing function" commonly used in the area of nonlinear systems (Ref.5). This definition is consistent with the procedure used to determine the describing function after the computation of the Discrete Fourier Transform (see Appendix A). The basic analysis used to determine the describing function is identical to that performed in determining the acceleration noise and related parameters, and is decribed in paragraph 2.4.

The values of the describing function are not identical to corresponding values of the system transfer function. Actually, all motion systems have more or less nonlinear dynamics. Consequently, they do not have unique transfer functions. Strictly speaking, the describing function is only valid at the measurement frequency and amplitude. However, for only slightly nonlinear systems, the describing function values generally do approximately match the transfer function of a linear system. In such cases, this transfer function can be considered a linearized description of the system dynamics.

The describing function values provide information concerning the dynamics of the system loop controlling the motion simulator. However, since the concept of lead compensation is generally adopted in the area of simulation, the describing function values should be measured for the lead compensated system as well, in order to show the actual motion system dynamics.

2.3.3 Measurement

The measurements have to be carried out with sinusoidal input signals, according to the procedures outlined in Appendix A, using an amplitude of 10 % of the system limits. As far as is feasible, the following range of input frequencies is recommended:

$$(k_i/10.24)\ \text{Hz};\ k_i = 1,\ \underline{2},\ \underline{5},\ 8,\ \underline{10},\ 15,\ \underline{20},\ \underline{50},\ 80,\ 100$$

The operational limits have also been measured at the frequencies underlined.
The measurements are to be performed for each degree of freedom, for both the uncompensated and the lead compensated system.

2.3.4 Display

The test results are displayed in the form of Bode plots showing the modulus $|H(f)|$ and phase angle $\measuredangle H(f)$, where $f = \frac{k_i}{10.24}$ Hz.

For each degree of freedom of motion, one plot shows the describing function values for both the uncompensated and the lead compensated motion system, see Figure 3.

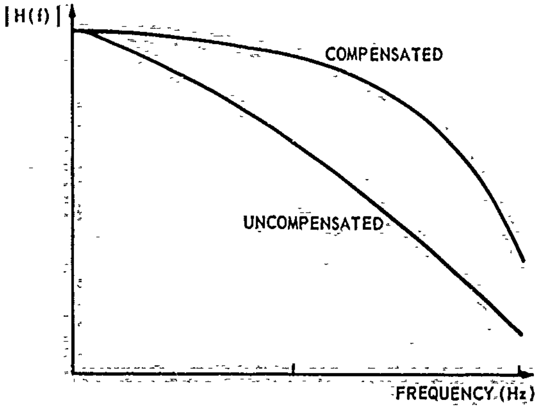


Fig. 3a Describing function modulus vs frequency

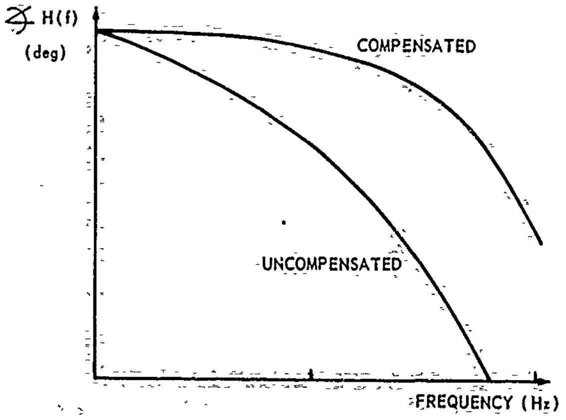


Fig. 3b Describing function phase angle vs frequency

For real measurements see Appendix C, Figures C7 through C10.

2.4 Linearity and acceleration noise

2.4.1 Definition

Acceleration noise is herein defined as the perturbation of the output acceleration from its nominal value. For sinusoidal input signals, as considered here, the nominal value of the output acceleration is defined by the sinusoid having the same frequency as the input sinusoid. The amplitude and phase shift are obtained by minimizing the mean square of the difference between this sinusoid and the actual output acceleration (as is performed in a DFT routine).

Two kinds of acceleration noise are distinguished here:

a) The acceleration noise in the stimulated degrees of freedom: e.g., heave acceleration noise caused by heave motion

b) The acceleration noise in the nonstimulated degrees of freedom, called parasitic acceleration (e.g., pitch due to heave motion), which expresses the levels of interaction between the various degrees of freedom.

Acceleration noise includes all deviations from the response of an ideal time-invariant linear system and therefore encompasses effects due to external disturbances.

In order to obtain further insight into the nature of the acceleration noise, the following two main acceleration noise components are defined:

a) A component reflecting the harmonic distortion.
This component has its spectral power concentrated at frequencies harmonically related to the input frequency.

b) A stochastic component, which is the residue of the acceleration noise minus the harmonic distortion component.

The harmonic distortion component represents the distortion due to time invariant nonlinearities. This component is further subdivided into:

- low-frequency nonlinearity, which is the sum of the second and third harmonics
- high-frequency nonlinearity, which is the sum of the fourth and higher harmonics.

The combination of the high-frequency harmonic distortion with the relatively high frequency stochastic disturbance is considered to be a measure of the roughness of the response, and provides an indication of the smoothness of the motions produced. Besides presenting acceleration noise components in terms of standard deviations, dimensionless ratios are introduced which are normalized to the standard deviation of the fundamental of the acceleration output signal.

2.4.2 Discussion

In paragraph 2.3, the concept of describing functions has been discussed as a suitable technique to describe the dynamic capabilities of a motion system. Since only the fundamental harmonic component of the response is taken into account, this describing function technique pertains solely to a nominal response.

In this paragraph, linearity and acceleration noise are considered as phenomena reflecting other aspects of the dynamics of a motion system. Acceleration noise as well as (non)linearity may be discussed in terms of acceleration errors. The nominal response or reference signal is defined to be the fundamental harmonic.

The data analysis adopted, based upon the determination of the power per frequency interval of the output signals (see Appendix A), provides the capability of a detailed analysis of the acceleration noise component. The principles of the analysis are discussed below.

The response of an ideal time invariant system, which is not necessarily linear, to a sinusoidal input signal generally results in a pure periodic component. This periodic component can be partitioned into a fundamental (first) harmonic and higher harmonics. The second and third harmonics can be looked upon as first order estimates of asymmetric and symmetric distortion respectively. The combination of these estimates provides a description of linearity errors resulting in relatively low-frequency components with respect to the nominal response. As the human motion receptors are less capable of detecting these low frequency errors, the second and third harmonics are not taken into account in calculating the roughness. The fourth and higher harmonics similarly provide a description of the relatively high frequency linearity errors.

The acceleration noise ratio gives an average value of the acceleration noise. Whether this noise will be perceivable depends on the actual time history. The absolute maximum of this time history is presented as the peak value and expressed as the peak ratio r_p, which is the maximum value divided by the amplitude of the fundamental.

In practice, motion system output accelerations will consist mainly of a periodic component, but will be more or less contaminated by a stochastic component. Nondeterministic external disturbances as well as error sources within the system (e.g., dry friction) are responsible for this contamination. The power of this stochastic component will generally be spread over the whole frequency range considered, while the periodic components appear at frequencies harmonically related with the fundamental frequency. Clearly, if transient effects are present the periodicity of the deterministic response component is distorted. In such cases, the pure deterministic response component will exhibit power not concentrated at harmonics. For this reason, the response must be completely stationary before starting the sampling procedure.

The roughness component has been defined as the sum of the higher harmonics and the stochastic component. This implies that within that content, no distinction is made between pure deterministic roughness and roughness resulting from stochastic disturbances. One illustration for the rationale behind this definition is the well known motion reversal bump. This unwanted disturbance can be either a deterministic bump, accurately reproducible, or a more or less random bumpy response at several levels of motion. It is clear that both these phenomena equally contribute to a degradation in the smoothness of a system.

2.4.3 Measurement and data analysis

All the characteristics mentioned above are computed from the time histories already recorded during the measurement of the operational limits (at the 5/10.24 Hz frequency, with amplitudes from zero up to the excursion limits). For each set of measurements for the various degrees of freedom, the accelerations within all six degrees of freedom are measured in order to determine the acceleration noise and the corresponding parasitic accelerations.

Driven axes

An estimate of the spectral power distribution is obtained from the DFT of the sampled sequence of the appropriate acceleration output signal.
Measurement and basic data analysis shall be in accordance with Appendix A. The average power in each frequency interval is equal to the mean square value or variance of the signal in the corresponding frequency interval.

From the separate power components, the variance of the various components is computed in accordance with the relationships given below.

- fundamental output $\sigma_f^2 = \sigma^2(k_i),\ k_i = 5 \quad (\text{i.e., } \frac{5}{10.24} \text{ Hz frequency})$
- acceleration noise $\sigma_n^2 = \sum_{i=1}^{m} \overset{2}{\sigma}(i) - \sigma_f^2$
- low frequency nonlinearity $\sigma_{1n}^2 = \sigma^2(2k_i) + \sigma^2(3k_i)$
- high frequency nonlinearity $\sigma_{hn}^2 = \sum_{l=4}^{\frac{m}{k_i}} \sigma^2(lk_i)$
- roughness $\sigma_r^2 = \sum_{i=1}^{m} \sigma^2(i) - \sigma_f^2 - \sigma_{1n}^2$

where m = 350, which limits the highest frequency considered to 35 Hz.

The time history of the acceleration noise is reconstructed by using the inverse Fourier transform (IDFT) on the DFT of the acceleration signal, after X(k) for $k=k_i$ and $k > m$ has been eliminated. The peak value of the noise is then given by: $A_p = \max \{ |x_n(n)| \}$.

The results of the measurements will be further expressed by means of the following dimensionless ratios:

a Modulus of the describing function $|H(\omega, A)| = \sigma_f/\sigma_i$
b Acceleration noise ratio $r_n = \sigma_n/\sigma_f$
c Peak ratio $r_p = A_p/(\sigma_f . \sqrt{2})$
d Low-frequency nonlinearity ratio $r_{1n} = \sigma_{1n}/\sigma_f$
e High-frequency nonlinearity ratio $r_{hn} = \sigma_{hn}/\sigma_f$
f Roughness ratio $r_r = \sigma_r/\sigma_f$

Undriven axes

The standard deviation and peak value of the parasitic acceleration can be determined from the recorded time histories directly.

2.4.4 Display

Driven axes

- The standard deviation and the peak value of the acceleration noise are plotted versus the amplitude of the nominal output velocity, see Figure 4.
- The time history of the observed acceleration signal will be displayed as shown in Figure 5.
- The values obtained for $|H(\omega, A)|$, r_n, r_p, r_{1n}, r_{hn} and r_r, will be displayed versus the acceleration amplitude $(\sqrt{2}.\ \sigma_f)$ as illustrated in Figure 5.

Undriven axes

- The standard deviation and peak value of the parasitic accelerations are presented versus the amplitude of the nominal output velocity (as in Figure 4).

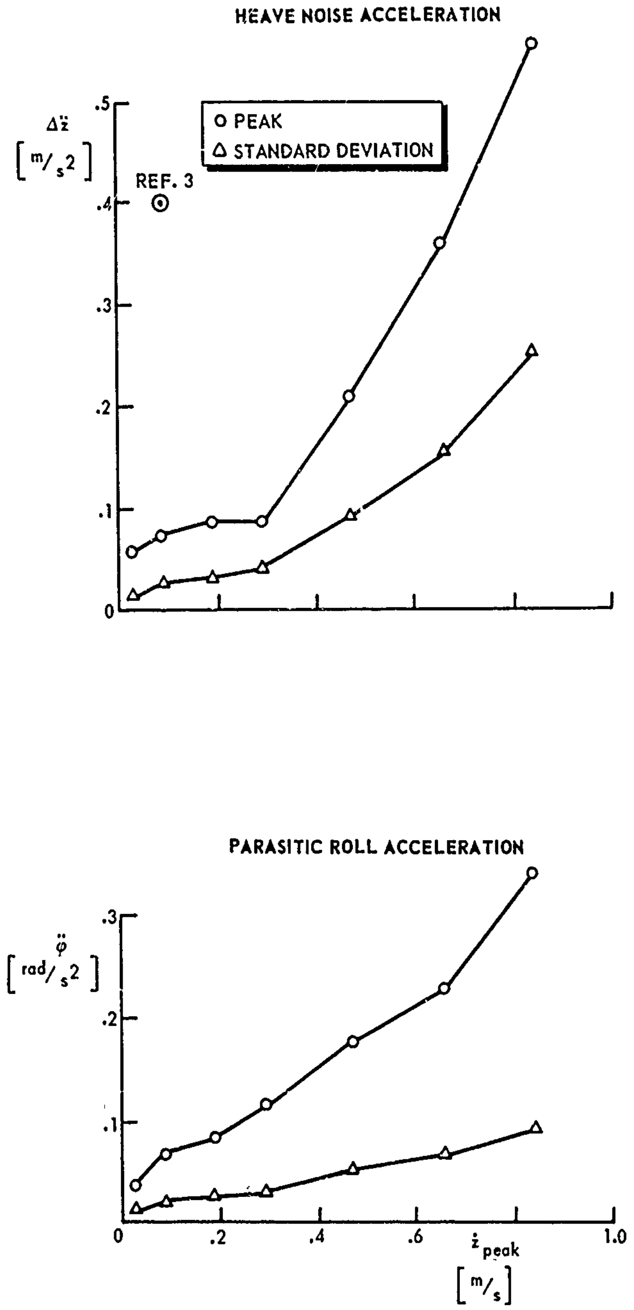


Fig. 4 Acceleration noise during heave sinusoid excitation

For real measurements see Appendix C, Figures C11 through C15.

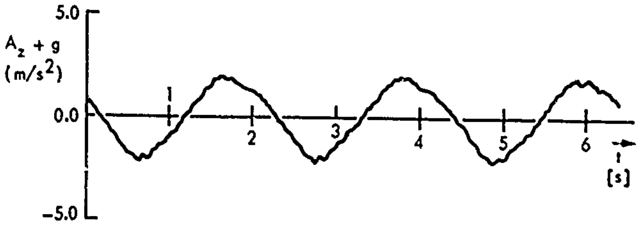


Fig. 5a Time history of specific force A_z

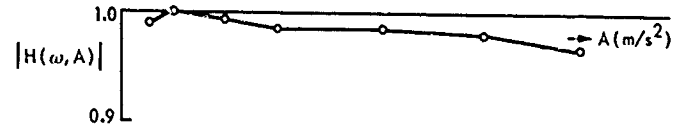


Fig. 5b Modulus of describing function M

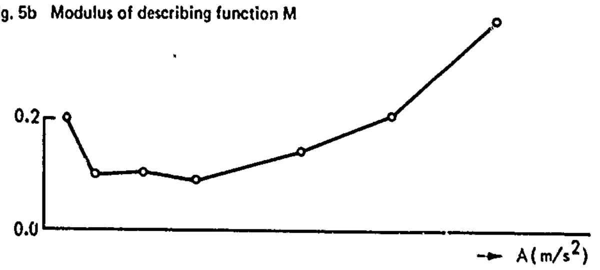


Fig. 5c Noise ratio r_n

Fig. 5d Peak ratio r_p

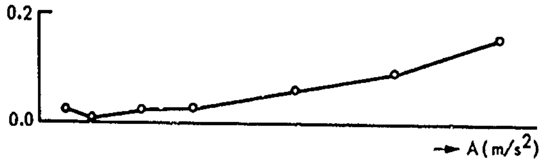


Fig. 5e Low-frequency non-linearity ratio r_{ln}

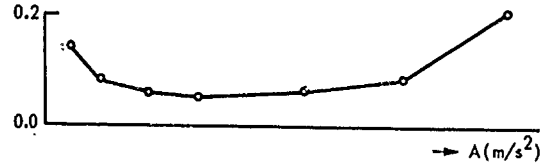


Fig. 5f High-frequency non-linearity ratio r_{hn}

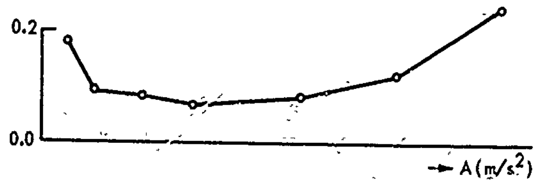


Fig. 5g Roughness ratio r_r

For real measurements see Appendix C, Figures C16 through C19.

2.5 Hysteresis

2.5.1 Definition

Hysteresis is defined as the difference in output displacement error resulting from the same magnitude of command displacement acting in opposite directions of motion. The result is expressed as an absolute displacement and as a percentage of total available displacement. This definition includes the backlash of systems where backlash is not forced to one side due to gravity forces.

2.5.2 Discussion

Hysteresis is primarily of importance when tilt is used to generate low frequency specific forces longitudinally and laterally.

In most cases the hysteresis will be of a very small magnitude, so that a very accurate position measurement is necessary. As it is not considered feasible to acquire such a precise position signal in each degree of freedom at the centroid, the hysteresis of each actuator will be measured separately and converted to hysteresis per degree of freedom.

Instead of plotting actual output against input position command, a better display of hysteresis is obtained by plotting the output displacement error versus input position command.

2.5.3 Measurement

The measurement is made using a very low frequency (≤ 0.01 Hz) sinusoidal command signal in order to avoid the effect of dynamics. For systems with a large travel it may be possible that even with 0.01 Hz the effect of dynamic will be present necessitating the use of a lower frequency. The amplitude is to be as great as possible before any limiting device comes into operation. If there is reason to suspect that the hysteresis might be different for very small amplitudes, an additional measurement with a small amplitude (e.g., 1 % of stroke) can be made.

2.5.4 Display

The test results are recorded on an XY plot with unequal calibration factors, in such a way that a clear plot is obtained, see Figure 6.

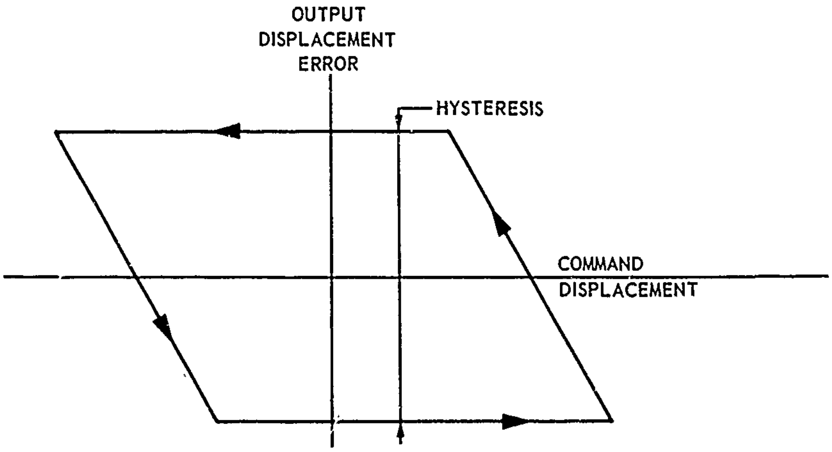


Fig. 6 Hysteresis plot

For real measurements see Appendix C, Figures C20 and C21.

2.6 Dynamic threshold

2.6.1 Definition

The dynamic threshold is based on Δt, the time required for the output acceleration to reach 63 % of the input acceleration command.

2.6.2 Discussion

When the command input signal to a motion system remains below a certain threshold, the motion platform will not move at all. Because the acceleration input will be integrated once (for velocity controlled systems) or twice (for position controlled systems) the motion platform will start to move after some time, even for very small acceleration inputs. Therefore Δt, the time required for the output acceleration of a system to reach 63 % of the acceleration command, has been chosen as an indication of the dynamic threshold of the system, regardless of whether the system has a position or velocity threshold. The larger the time Δt, the greater the dynamic threshold of the system.

Δt is composed of a part due to the dynamics (lag) of the motion system and a part due to threshold, hence the suggested name of dynamic threshold. By way of example, for a system with a position threshold, the threshold part of the time Δt will be a function of the acceleration input according to: position threshold = $0.5\ a_i \cdot \Delta t^2$.

This method of measurement will also detect any time delays that might occur between the computed motion drive signal and the motion system response. An advantage of this measurement is the ability to compare systems with different drive-laws, such as position or velocity control.

2.6.3 Measurement

An acceleration step input, from which the appropriate drive signal is derived, is used as the input signal to the motion system in its neutral position. Δt is measured at several input acceleration levels in both directions. To remove the influence of backlash before the measurement is made, the neutral position must be reached by means of a premeasurement square wave input as indicated in Figure 7.

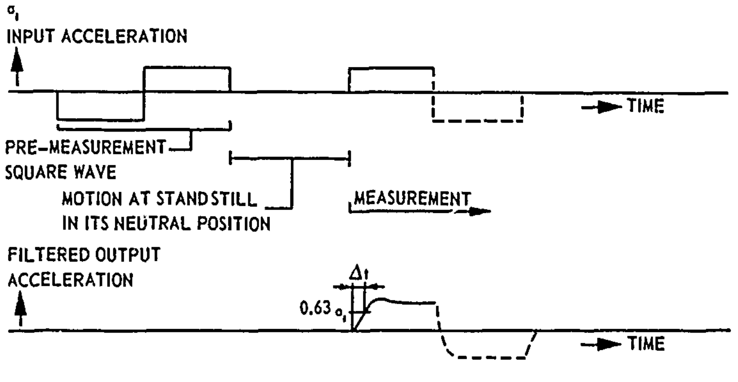


Fig. 7 Measurement of dynamic threshold

The output acceleration will be sampled with a sample time T_s of one millisecond, or, if that is not feasible with T_s as small as possible. A pre-sample first-order lowpass filter with a time constant of 10 milliseconds will be used to reduce high-frequency signal noise. The sampled acceleration will still show the influence of cross-talk from the AC power supply, and at the lower acceleration levels this will lead to an optimistically small value of Δt. Therefore this signal is additionally filtered by a digital moving average filter. Averaging is performed over n_{av} = 20 samples for 50 Hz and over 17 samples for 60 Hz power supplies. Corrections are applied for the delays due to the filter operations (0.01 s and 0.095 s for n_{av} = 20; or 0.01 s and 0.08 s for n_{av} = 17). At very low acceleration levels, Δt decreases due to the relatively larger amount of noise at different frequencies on the output acceleration; this region of input acceleration may be considered not measurable.

2.6.4 Display

Δt is plotted as a function of a_{input} as illustrated in Figure 8.

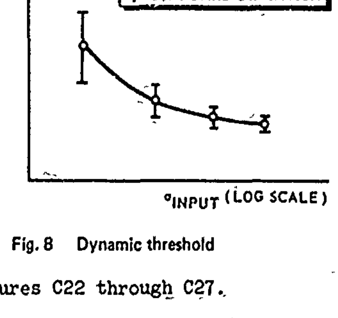


Fig. 8 Dynamic threshold

For real measurements see Appendix C, Figures C22 through C27.

3 GENERAL DISCUSSION

During the course of its deliberations, the Working Group has considered a number of alternative ways of defining the characteristics of motion systems. The definitive characteristics recommended are contained within paragraph 2. In this section, some of the alternatives considered are discussed along with the reasons why these alternatives were not adopted. In addition, some discussion is devoted to features which have been judged inappropriate to this task since they do not form the basis for measurement of the actual characteristics, even though these features undoubtedly influence the performance of a motion system.

3.1 Linearity

Retaining its concept of the acceleration vector as the important metric, the Working Group originally defined linearity error (Reference 4) as the absolute value of the difference between a constant acceleration input and the measured, steady-state acceleration output.

A number of difficulties arise with this definition. A time delay is clearly involved between the generation of the input and the measurement of the output if a steady-state condition is to be achieved. This time delay should be as long as possible to ensure that all transients in the response have decayed. On the other hand, an excessive time delay results in system limits being violated. For systems with either a fast response or extended system limits, this presents little difficulty. However, some systems may be trapped between these two limitations. Applying the input from an offset position of the motion system in order to extend the available time delay (unless a velocity limit is the restriction) can result in a measurement different from that obtained from the neutral position, particularly for balanced systems. The direction of the initial input, particularly for unbalanced systems or those with unequal area jacks, can also affect the measured error. Finally, the noise of the measured signal can make the accurate determination of the degree of nonlinearity difficult.

3.2 Acceleration noise

The original definition utilized the Discrete Fourier Transform (DFT) technique described in Appendix A, but merely presented the results as peak and rms values of the perturbations from the nominal acceleration output. This is a simple procedure but much useful information is suppressed. In particular, a given level of noise may be obtained either from a distorted sine wave output, or by a high frequency variation about a relatively pure mean response. The technique of analysis adopted now allows these two conditions to be distinguished. In the process, it permits the extraction of a measurement of linearity error which obviates the difficulties indicated above (Para 3.1). Furthermore, it allows the low frequency nonlinearity, which will probably be of little concern to the pilot, to be distinguished from the high frequency nonlinearity, which may or may not be of concern (depending on the frequency of the input). It can also distinguish the roughness, which is always of concern. Yet this technique still produces a measure of overall noise. The presence of isolated or discrete disturbances (e.g., "reversal bump") cannot be uniquely identified from the DFT analysis, but these are readily illustrated by subtracting the fundamental frequency from the DFT and generating the inverse DFT.

Utilization of this technique requires no additional measurements; all that is involved is further analysis of signals already recorded under the operational limit measurements described in paragraph 2.2.

3.3 Hysteresis

This is the one characteristic in which displacement is used as the important parameter. Initially the conventional hysteresis loop was defined by plotting output displacement against commanded displacement. However all the systems measured exhibited very small hysteresis, and only at very small values of the input was it possible to generate a significant loop. Consequently, it is now recommended that displacement error be plotted against input displacement. Ideally the displacement between earth and the chosen reference point, normally the centroid of the platform, should be measured. This is not generally practicable. In most cases, the measurements would be derived from the position transducers located on the motion system, and usually fitted to the actuators. Compliances which may exist beyond their end points, backlash in particular, is not then detectable. The Working Group has decided that the rather eleborate instrumentation required for proper measurement is not justified for a characteristic which appears of little significance in a well designed and serviceable system. Important potential sources of hysteresis, such as backlash in the position transducer, friction, or spool valve nonlinearities, should be exposed by the technique proposed.

3.4 Backlash

Backlash is associated with some form of dead zone or mechanical slop in a system. It is apparent that backlash can influence a system's behaviour, regardless of whether the system is unbalanced or balanced. In a balanced system its presence will be much more apparent since a drive force of the order of the friction force in the backlash zone is likely to consume the freeplay, whereas for an unbalanced system gravitational forces normally, but not always, have to be overcome.

The impulsive nature of the discontinuities due to backlash led the Working Group to believe that it could be detected by acceleration measurements. The technique (Reference 4) devised was a natural extension of that for dynamic threshold (paragraph 2.6) where the initial time to reach 63 % of the commanded acceleration was defined as Δt_1, and the time for the output to reach 63 % of a commanded reversal in acceleration was defined as Δt_2. The backlash was defined as $\Delta t_2 - \Delta t_1$, where these times are measured for the same change in acceleration (i.e., both magnitude and direction).

Application of this technique (References 4, 5 and 6) led to many results indicating negative backlash, which is clearly impossible. Further consideration indicates that this result is scarcely surprising. The technique depends on an assumption of system linearity. The reversal command is generated when the system is in a state different from that for the initial command. Consequently, for a nominally balanced system, the balance rams will be applying a different force at the initiation and at the reversal commands.

To further test the validity of the technique, NLR (Reference 7) mounted two accelerometers on their motion system, one fixed and the other with adjustable backlash. For backlash greater than 1 mm, they found that the technique produced plausible results. However, at more realistic values of backlash - for example 0.2 mm - the expected time delay was obscured by the effects of friction and/or structural dynamics; again Δt_2 was less than Δt_1.

The Working Group concludes that the original definition was unsatisfactory and has been unable to conceive of an alternative. It should be noted, however, that any adverse effects of backlash are contained within the measurements of acceleration noise, and may also contribute to the results of hysteresis, although not now necessarily separately identifiable.

3.5 Constant Speed Measurements

The Working Group deliberated on the desirability of separate acceleration noise measurements at constant velocity (Reference 2). Since these measurements would provide no information in addition to that now obtained with the noise measurement technique adopted, these separate constant velocity measurements have been omitted. Such tests may, however, still be useful for diagnostic purposes (Reference 2).

3.6 Other factors

The Working Group is well aware that motion systems have many features which are germane to their performance and which have not so far been considered. Of special note in this regard is the servo control system. The design of such systems is considered to be adequately covered by well established techniques and is likely to be perculiar to each system in use. The latter fact creates certain difficulties of interpretation. It is desirable that the characteristics of the motion system be measured in as near a basic configuration as possible. However, many control systems have inextricably built into them compensation networks to correct for such things as phase lag or amplitude attenuation. It is neither considered reasonable nor practical to ask that such control systems be dismantled. It does however require that any compensation should be clearly defined in those systems where it is not possible to also measure the basic system, in order to avoid misleading comparisons among various motion systems.

It is well known that hydraulic oil temperature affects the performance of many motion systems. It is assumed that measurements will be made at the normal operating temperature of the oil.

Hydraulically powered systems often can operate continuously only at some fraction of their maximum capability. Maximum performance is obtainable for a limited period by back-up accumulators. In general the definitions call for measurements of a single axis at a time; under these conditions, limitations due to available continuous power are unlikely to be significant for systems with independent axes. Synergistic systems, on the other hand, may well be limited even when only one axis is driven. It is particularly important that due regard be paid to this feature, particularly during measurements of excursion limits (paragraph 2.2).

Synergistic systems have very different excursion limits under multiple axis drive in comparison with single axis drive. The Working Group has not considered it practical or useful to address the question of the driving of several axes in this context since the matrix of possible combinations is excessive. The results obtained depend on the priorities assigned to various axes; those priorities are not necessarily unique even for any one system and may also be task dependent.

A number of other features of motion systems also affects their performance. These include bleed orifice settings, seal or piston leakage, valve center characteristics, distortions and resonances in drives and support structure, among others. These are largely design features which the Working Group has not considered within its terms of reference.

4 CONCLUSIONS AND RECOMMENDATIONS

The Working Group has agreed that the production of specific force and angular acceleration is the raison d'etre of motion systems in piloted flight simulators. The physical limitations on the size of motion systems mean both that certain other characteristics need to be measured and that acceleration can be used as a more appropriate metric for both translational and rotational motions. A total of nine different terms often used in the description of motion system quality or limitations have been identified. Several of these are interrelated and the definitions have been reduced accordingly to measurements under five separate headings.

Of the five headings, three (excursion limits, describing function, and linearity and acceleration noise) are obtained from sinusoidal inputs of varying frequency and amplitude followed by analysis using the Discrete Fourier Transform technique. The other two headings require step inputs of acceleration of varying amplitudes (for dynamic threshold measurements), and the measurement of displacement using a very low frequency sinusoidal input (for hysteresis). Consequently, a compact series of tests has been defined which does require, however, adequate data logging facilities and fairly sophisticated analysis.

The describing function of motion systems is often measured in the course of designing compensation networks to correct for amplitude and phase deficiencies, but it is exceptional for a complete series of tests to be made determining all the important characteristics which are defined in this report. The Working Group strongly recommends that such measurements be made as an aid to determine the validity of any results obtained from simulation. In research and development, it is axiomatic that the characteristics of the equipment used in any experiments should be properly identified, quantified and published.

The characteristics of the motion systems of several of the members of the Working Group have been measured and a selection of the results is presented in Appendix C. These results indicate that for a number of representative systems, application of the techniques recommended is practical and produces meaningful descriptions of the systems.

Backlash is the one feature which the Working Group considers worthy of separate identification and quantification and for which no suitable technique of measurement has been devised. If its presence is significant, it will be subsumed by acceleration noise and possibly by hysteresis. However, its value as a diagnostic is such as to suggest that further effort should be expended to resolve this deficiency.

The work of AGARD FMP WG 07 here reported forms one small element in the considerations of AGARD AMP-FMP WG10 on the fidelity of flight simulation for pilot training. The question of fidelity depends not only on the quality of the equipment, with unacceptable equipment producing unwanted or false inputs to the pilot, but also the techniques of usage. The manner of usage is dictated by the need to reproduce those features of the real world which make a significant contribution to the way the pilot behaves, or to his ability to learn correctly. It would be appropriate for WG10 to recommend further work aimed at defined specification requirements. Insofar as the quality of equipment is concerned, it would be appropriate for a separate Working Group to do for, say, visual systems, what WG 07 has done for motion systems. To this end, AGARD has proposed to set up such a Working Group on visual systems. This is strongly supported. Computational, auditory and control loading systems fall in the same category, and it is recommended that consideration be given as to whether these systems are amenable to the same sort of treatment.

The Working Group has not set standards of acceptability for any of the measured characteristics. It is recommended that further work be done to set such standards. It is recognized that both the task and the dynamics of the vehicle will be important factors, as will other components of the simulator equipment. However, a limited set of vehicle dynamics and a few tasks under IFR conditions would form a starting point for trials based on subjective assessments on several different systems, and would eliminate the major effect of the visual system in confounding motion simulator investigations.

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APPENDIX A

GENERATION OF SINUSOIDAL INPUT SIGNALS AND ANALYSIS OF THE OUTPUT SIGNALS

INTRODUCTION

The generation of the motion system input signals and the sampling and analysis of the output signals must be standardized in order that different systems may be compared with each other. For convenience, as is explained in the main text, sinusoidal input signals are used in most of the prescribed tests. The procedures prescribed are to be followed in detail in order to assure mutually comparable results.

Signal generation data sampling

Figure A1 shows the general signal flow for signal generation and data logging. The prescribed sampling interval is $\Delta t = 0.01$ s, which results in a Nyquist frequency of 50 Hz (314 rad/s). Since the frequency content of interest extends up to 35 Hz (220 rad/s), the contamination of the measured signals by cross-talk from AC power supplies must be eliminated in practice. The measured signals must be analog prefiltered in case they contain power above 65 Hz (408 rad/s) in order to avoid aliasing effects below the upper frequency limit of 35 Hz. The design of the presampling filter will be a compromise between overall accuracy and complexity. The only stringent requirement placed on the filter is the reduction of any signal power above 65 Hz to an insignificant level prior to sampling. The distortion due to presampling filtering in the frequency range of interest, i.e., lower than 35 Hz (220 rad/s), can be corrected during discrete signal processing. The order of the low pass presampling filter influences the necessary correction. As the order increases, the amount of necessary correction decreases, and a corresponding increase in the overall accuracy results. The run length will be 1024 (2^{10}) samples at 100 samples per second, resulting in a frequency resolution of (1/10.24) Hz (0.0977 Hz or 0.6136 rad/s).

The input signals are generated in the time domain using the following expression:

$$X(n.\ \Delta t) = a \sin\left[\left(\frac{2\pi\ k_i}{N.\ \Delta t}\right)(n\ .\ \Delta t)\right]\ ,\ n = 0,1,2,\ldots,N-1$$

where:

a = amplitude of the input signal

$\frac{2\ \pi\ k_i}{N.\ \Delta t}$ = frequency of the input signal (rad/sec)

k_i = integer number of periods of the input signal within the measurement length of N samples (N = 1024)

By computing the time series of the input signals using the expression given above, an integer number of periods within the sampling period is guaranteed. Before starting the sampling procedure, the response of the system must be stationary; there must be no influence from transients due to improper initial conditions. The moments at which the outputs of the digital to analog converters are updated and of the instants in time of the signal sampling must be carefully synchronized (preferably controlled by the same clock). The sample time Δt must be accurately held constant.

Analysis of the output signals

The set of characteristics computed from the output signals are related to the standard set of mutually independent output signals. Let the standard set of output signals be represented by:

$$\underline{x}_0\ (t) = \begin{bmatrix} \ddot{x}_s(t) \\ \ddot{y}_s(t) \\ \ddot{z}_s(t) \\ \ddot{\phi}_s(t) \\ \ddot{\theta}_s(t) \\ \ddot{\psi}_s(t) \end{bmatrix}$$

The standard output signals $\underline{x}_0\ (t)$ can be computed from a suitable set of transducer signals $\underline{x}_m(t)$ according to:

$$\underline{x}_0\ (t) = \left[T_m\right]\ \underline{x}_m\ (t) \qquad \text{(A1)}$$

The matrix $\left[T_m\right]$ depends on the location and type of the measurement transducers.

The measured transducer signals in digitized form are distorted by the characteristics $H_{pf}(j\omega)$ of the analog presampling filter. Signals not compensated for the presampling filter dynamics are indicated below by an apostrophe ($\underline{x}'_m(t)$). In Figure A2, a block diagram of the basic signal processing is shown. The first part of the processing embraces the calculation of the Discrete Fourier Transform (DFT) of the standard output signals, symbolically written as:

$$\underline{X}_0\ (k) = \text{DFT}\ \{\ \underline{x}_0\ (n)\ \}\ ,\ k = 0,1,2\ldots\ N-1 \qquad \text{(A2)}$$

In the block diagram of Figure A3, this part of the processing is presented in detail. If the transformation matrix T_m describes a linear transformation, the computation of $\underline{X}_0(k)$ can easily be reduced, as will be shown later on (Equation A6). In general, however, the calculation proceeds as follows:

First, the sampled time sequence $\underline{x}'_m(n)$ are corrected for the presampling filter characteristics (H_{pf}). For reasons of computational efficiency, the operation can best be performed in the frequency domain. The DFT of $\underline{x}'_m(n)$ may be computed via a Fast Fourier Transform (FFT) routine, yielding

$$\underline{X}'_m(k) = \text{DFT}\{\underline{x}'_m(n)\} \tag{A3}$$

Using

$$\underline{X}_m(k) = \underline{X}'_m(k)/H_{pf}(j\frac{2\pi k}{N.\Delta t})$$

the presampling filter dynamics are completely eliminated. Applying the Inverse Discret Fourier Transform (IDFT) yields the corrected measured signal sequences in the time domain:

$$\underline{x}_m(n) = \text{IDFT}\{\underline{X}_m(k)\} \tag{A4}$$

From these time sequences for $\underline{x}_m(n)$, the standard output signals $\underline{x}_0(n)$ can be obtained using Equation (A1). Finally the output signals $\underline{x}_0(n)$ are transformed to the frequency domain by computing the DFT of these sequences.

The complete procedure described above may be combined into:

$$\underline{X}_0(k) = \text{DFT}\{\left[T_m\right].\ \text{IDFT}\{\frac{\text{DFT}\ \underline{x}'_m(n)}{H_{pf}(j\frac{2\pi k}{N.\Delta t})}\}\} \tag{A5}$$

It can easily be seen that if T_m describes a linear transformation, Equation (A5) can be simplified to:

$$\underline{X}_0(k) = \frac{\text{DFT}\{\left[T_m\right].\ \underline{x}'_m(n)\}}{H_{pf}(j\frac{2\pi k}{N.\Delta t})} \tag{A6}$$

The power per frequency interval $\sigma^2(k)$ for the different signals can be computed from their DFT coefficients:

$$\underline{\sigma}^2(k) = C\ |\underline{x}(k)|^2 \tag{A7}$$

where C is a constant which depends on the definition of the applied DFT, as will subsequently be shown.

Since extensive use of DFT concepts is made deriving the results presented in this report, and since the definitions embodied in these DFT concepts are presented in the literature in different ways, clarity in formulation is demanded in order to avoid confusion. We herein define the DFT of a sequence of N samples as:

$$X(k) = \text{DFT}\{x(n)\} = \alpha \sum_{n=0}^{N-1} x(n)\, e^{-j\frac{2\pi kn}{N}}, \quad k = 0,1,2,\ldots N-1 \tag{A8}$$

The corresponding IDFT is:

$$x(n) = \text{IDFT}\{X(k)\} = \frac{\alpha}{N} \sum_{k=0}^{N-1} X(k)\, e^{j(\frac{2\pi kn}{N})}, \quad n = 0,1,2,\ldots N-1 \tag{A9}$$

where α is an arbitrary constant For instance in Reference A1, a definition has been used specifying α equal to 1/N, while in Reference A2, α is taken equal to 1. As both X(k) and x(n) are periodic with period N, according to (A8) and (A9), shifted versions of the definition outside the ranges 0,1,...,N-1 can be found in the literature as well.

It can be shown that an estimate of the power per frequency interval is given by the following expression when the factor α is retained (Reference A1):

$$\sigma^2(k) = \frac{1}{\alpha^2 N^2}\left[|X(k)|^2 + |X(N-k)|^2\right], \quad k = 1,2,\ldots,(\frac{N}{2}-1) \tag{A10}$$

Since $|X(k)| = |X(N-k)|$ and $|X(k)| = |X^*(k)|$,

this relation can be simplified to:

$$\sigma^2(k) = \frac{2}{\alpha^2 N^2}\ |X(k)|^2 \tag{A11}$$

$$\sigma^2(0) = \frac{1}{\alpha^2 N^2}\ |X(0)|^2$$

Taking distinct combinations of the frequency intervals, the power of the separate components can be computed as is done in paragraph 2.4.3 in the main text.

The reader familiar with spectral analysis of sampled time sequences will note that the so-called unsmoothed spectral estimate has been used to estimate the power per frequency interval in (A10) and (A11). If stochastic signals are present, Equation A11 provides an inconsistent estimate of the power per frequency interval (References A2 and A3). However, the averaging of sequential estimates or the application of an appropriate window can provide a consistent estimate. The types of signals considered in this report are basically deterministic periodic signals contaminated by a relatively small stochastic component. In this case, the variance of the estimate of the power in a frequency interval containing the contributions of the deterministic part of the signal is relatively small. In the final presentation of the results (paragraph 2.4.4), only figures obtained by summing over mutually orthogonal stochastic power contributions are considered. This results in small variances for the estimated sums. The only acceptable smoothing procedure for the analysis involved is averaging over sequential estimates. This is sometimes referred to as the Barlett procedure (Reference A2). This procedure consists of repeating the measurements and the basic analysis. Application of any other known smoothing procedure is unacceptable due to the bias introduced, which results from leakage. The leakage involved will violate the fundamentals of the analysis presented. If the prescribed run length and sample interval are used without smoothing, the analysis will normally result in sufficiently consistent estimates. Only in those cases where the signal contains a relatively large stochastic component will the consistency be poor and smoothing become necessary. In such a case, the question can be raised whether it will be worthwhile producing accurate figures for inaccurate systems.

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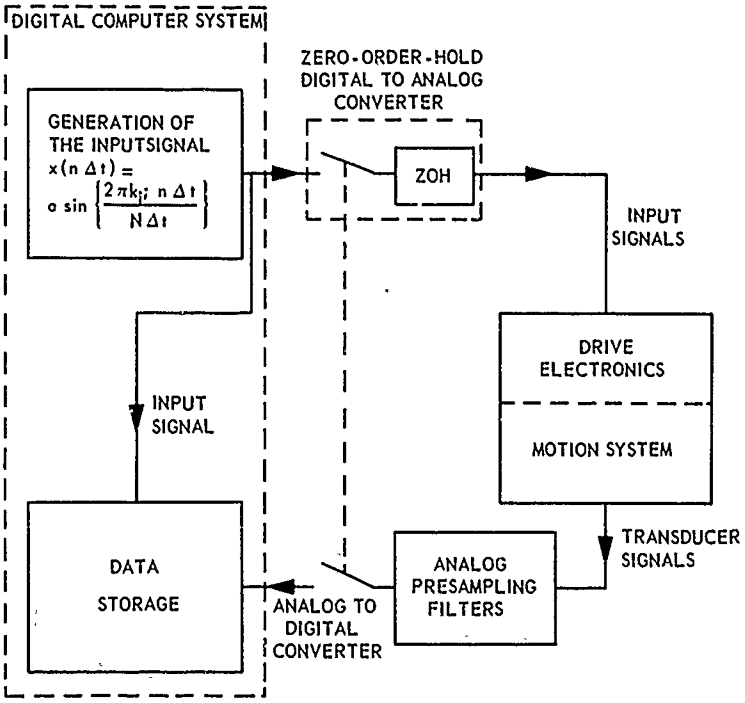
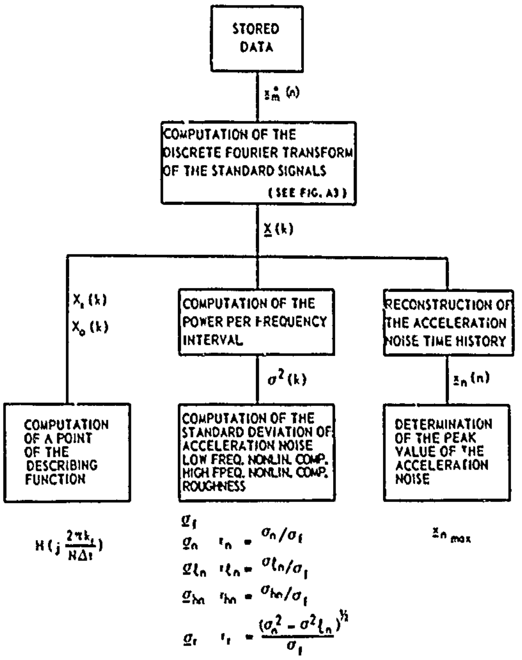
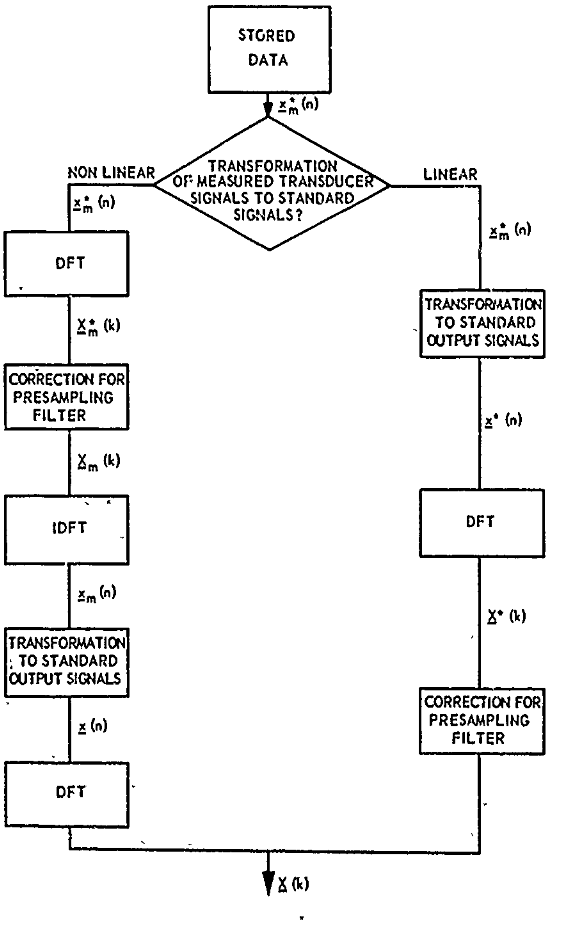
A3 Jenkins, G.M., Watts, D.G. Spectral Analysis and Its Applications, Holden-Day, San Francisco 1968.



A1 Signal generation and datalogging



A2 Data analysis



A3 Computation of discrete fourier transform of the standard signals

APPENDIX B

NOTE ON ACCELERATIONS AND SPECIFIC FORCES

In this report, frequent use is made of two closely related, yet distinctly different notions pertaining to translation motions, viz:

- (linear or translational) acceleration, $\vec{a}$,
- specific force, $\vec{A}$.

In the present context, translational accelerations, $\vec{a}$, can perhaps be best defined as the second time derivative of displacement, or, as the case may be, as the first time derivative of velocity.
Specific force, $\vec{A}$, is defined as the external - i.e., nongravity - force acting on a body, per unit of mass of that body.
Both acceleration and specific force have an identical dimension. They are related by the fact that the (linear) acceleration of a body is the vector sum of the specific force acting on that body with the acceleration due to gravity, $\vec{g}$:

$$\vec{a} = \vec{A} + \vec{g}$$

The prevailing confusion between $\vec{a}$ and $\vec{A}$ is certainly not diminished by the fact that any "accelerometer" is sensitive to the specific force-not to the acceleration, which the name of the instrument misleadingly suggests. This applies equally to the various sensors in the human body which act as accelerometers, such as those in the vestibular system. They are all sensitive to specific force rather than (linear) acceleration.

One of the purposes of equiping a manned flight simulator with a motion system is to generate at the pilot's station the same angular accelerations and specific forces - rather than linear accelerations - as would occur in actual flight. Since the motion capabilities are constrained, the objective is to at least generate nearly the same angular accelerations and specific forces. It therefore makes sense to discuss the dynamic characteristics of motion systems, as far as the translational motions are concerned, in terms of specific forces rather than accelerations.

On the other hand, the most fundamental and persisting limitation of any motion system is its limited displacement capability with additional constraints resulting from velocity and acceleration limitations. Displacement as well as velocity result from acceleration; consequently, the limits can only be discussed in terms of acceleration.

Fluctuations in the specific force vector can either be due to fluctuations in the linear acceleration or fluctuations in the orientation relative to the gravitational force vector. For this reason disturbances can be better discussed in terms of acceleration rather than specific force errors. These fluctuations are therefore described in the report in the usual way as acceleration noise.

From the foregoing, it is clear that from the point of view of the pilot sensing the simulated motion, one would be interested in characteristics in terms of specific forces rather than (linear) acceleration. However, as argued above, this would not uniquely describe the system characteristics. For this reason, linear acceleration is used as the metric for translational motions.

APPENDIX C

INTRODUCTION

The results presented in this Appendix are a first trial of several Working Group members to measure and present the recommended characteristics as prescribed in paragraph 2. It is expected that in the near future more dynamic characteristics of flight simulator motion systems will become available.

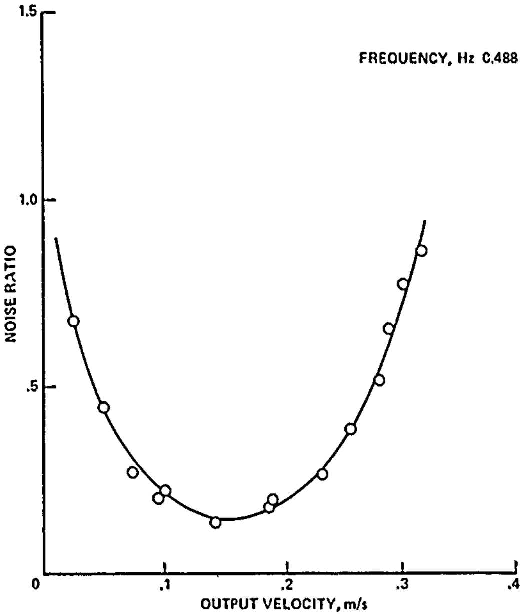


Fig. C1 Noise ratio against output velocity for heave of a position controlled three-degrees-of-freedom hydraulic motion system (see Fig. C3)

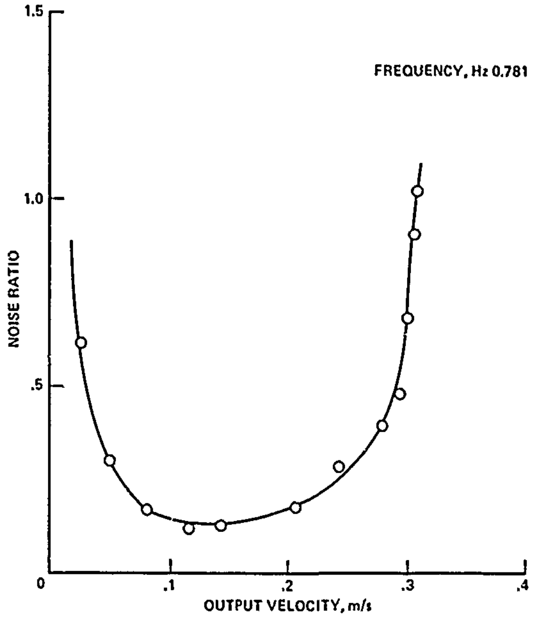


Fig. C2 Noise ratio against output velocity for heave of a position controlled three-degrees-of-freedom hydraulic motion system (see Fig. C3)

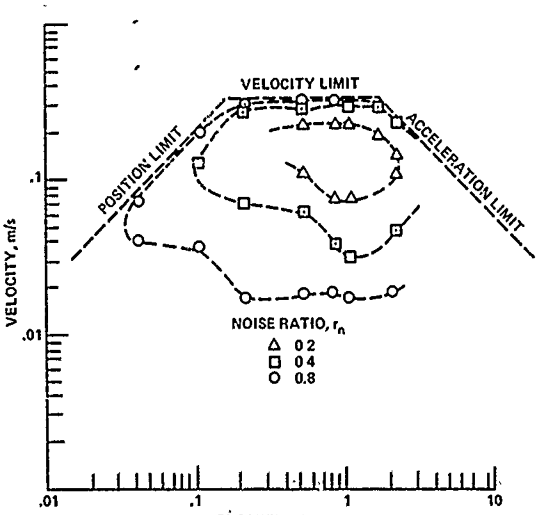


Fig. C3 System and operational limits for heave of a position controlled three-degrees-of-freedom hydraulic motion system

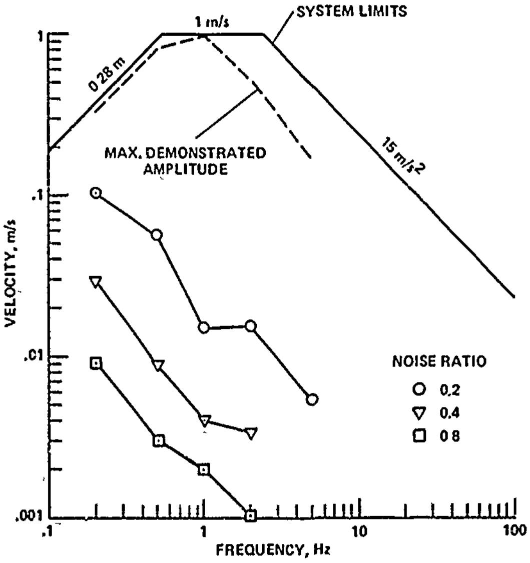


Fig. C4 System and operational limits for heave of a position controlled three-degrees-of-freedom hydraulic motion system with hydrostatic bearings

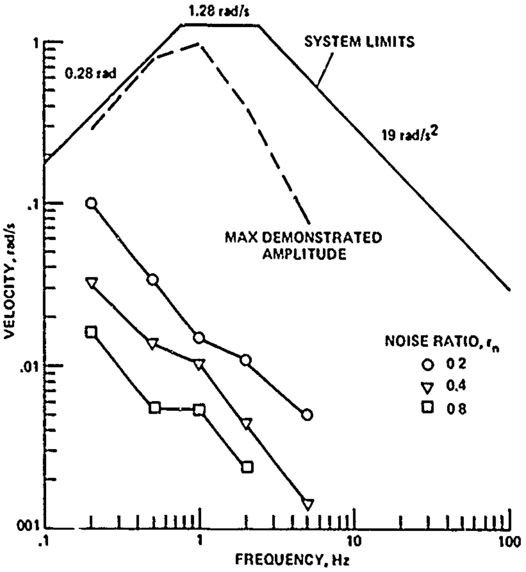


Fig. C5 System and operational limits for roll of a position controlled three-degrees-of-freedom hydraulic motion system with hydrostatic bearings

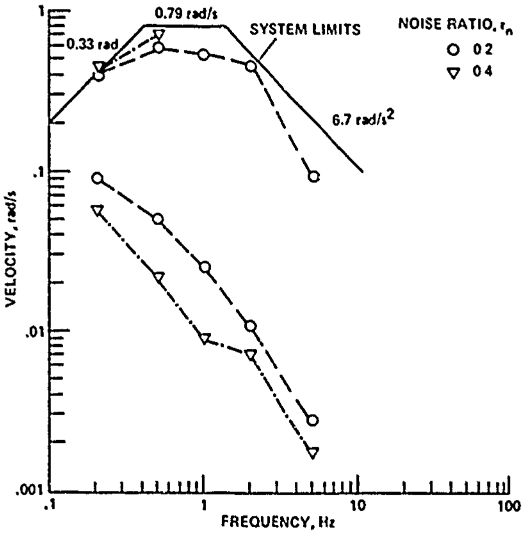


Fig. C6 System and operational limits for roll of a position controlled four degrees-of-freedom hydraulic motion system with hydrostatic bearings

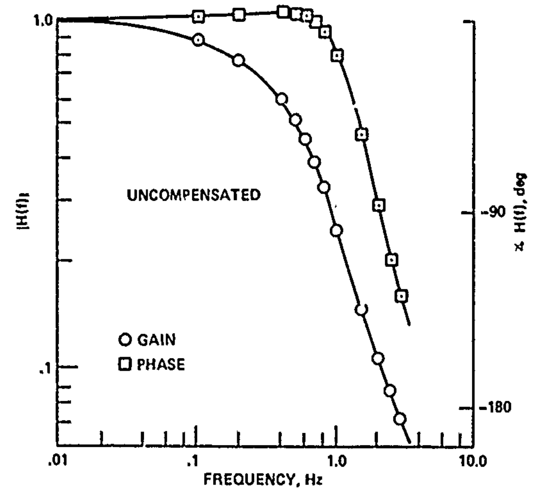


Fig. C7 Describing function for heave of a position controlled three-degrees-of-freedom hydraulic motion system

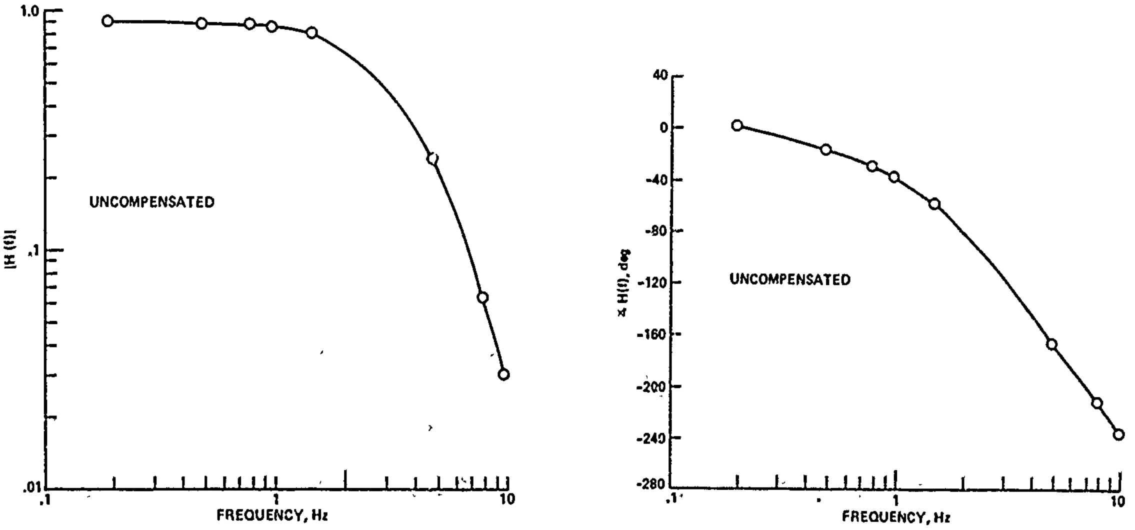


Fig. C8 Describing function for heave of a position controlled three-degrees-of-freedom hydraulic motion system with hydrostatic bearings

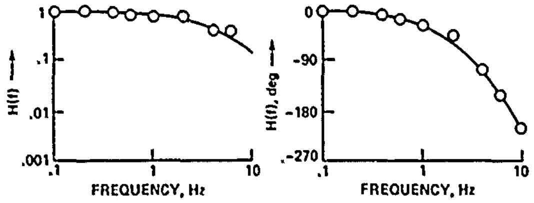


Fig. C9 Describing function for heave of a velocity controlled four-degrees-of-freedom hydraulic motion system

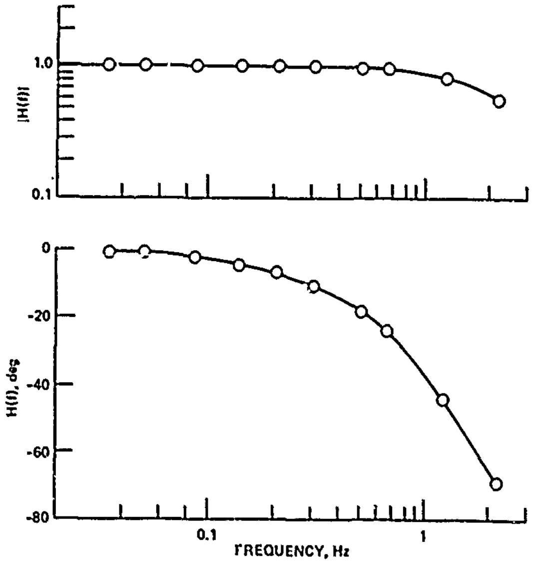


Fig. C10 Describing function for longitudinal motion of a velocity controlled six-degrees-of-freedom electric motion system

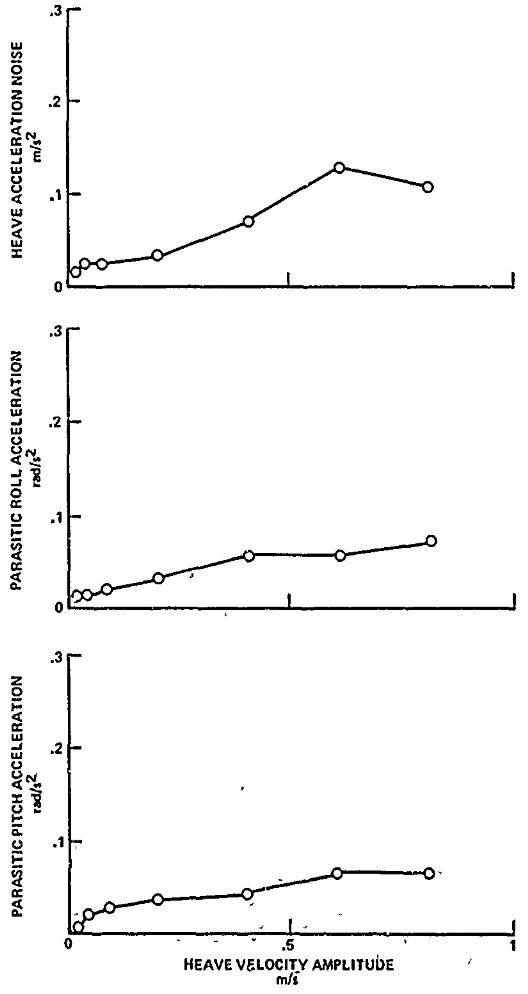


Fig. C11 Acceleration noise for 0.5 Hz sinusoidal heave excitation of a position controlled three-degrees-of-freedom hydraulic motion system

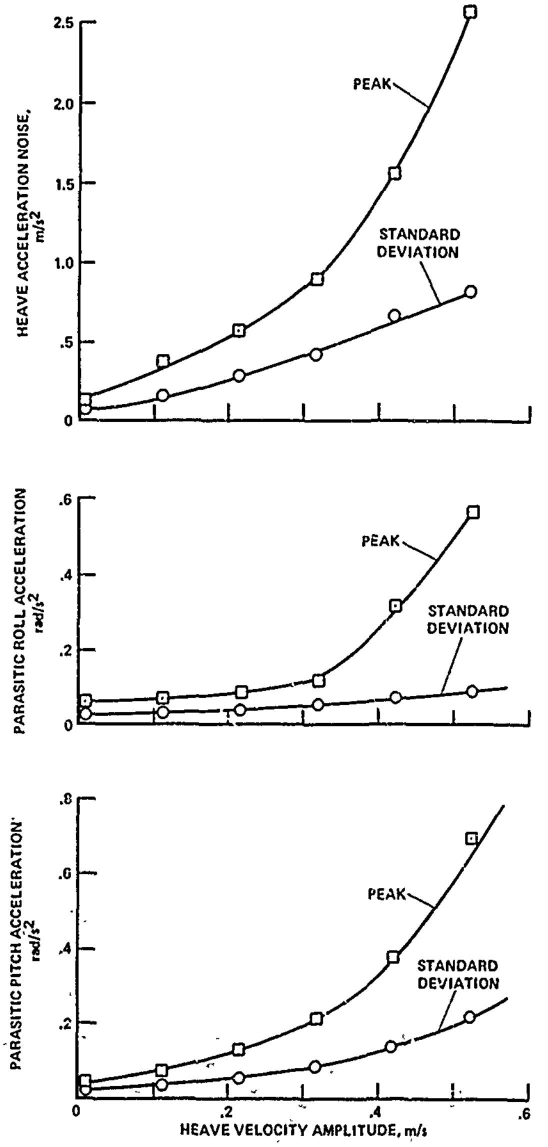


Fig. C12 Acceleration noise for 0.5 Hz sinusoidal heave excitation of a position controlled three-degrees-of-freedom hydraulic motion system with hydrostatic bearings

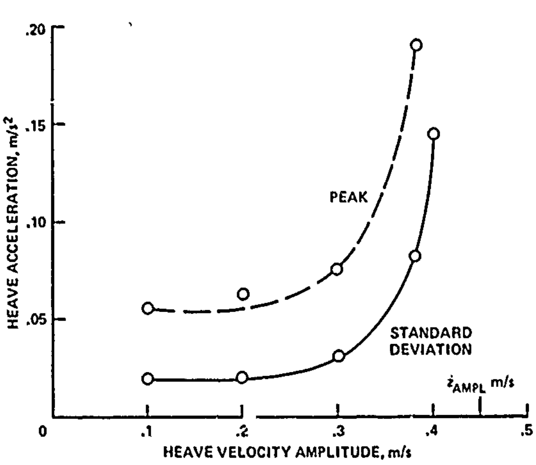


Fig. C13 Acceleration noise for 0.5 Hz sinusoidal heave excitation of a velocity controlled four-degrees-of-freedom hydraulic motion system

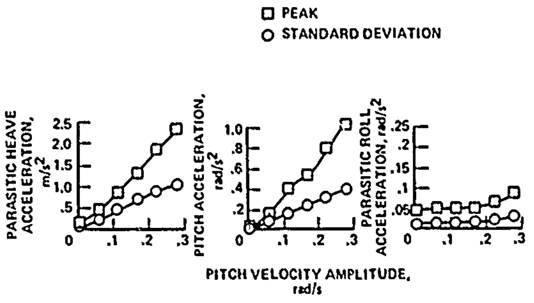


Fig. C14 Acceleration noise for 0.5 Hz sinusoidal pitch excitation of a position controlled three-degrees-of-freedom hydraulic motion system

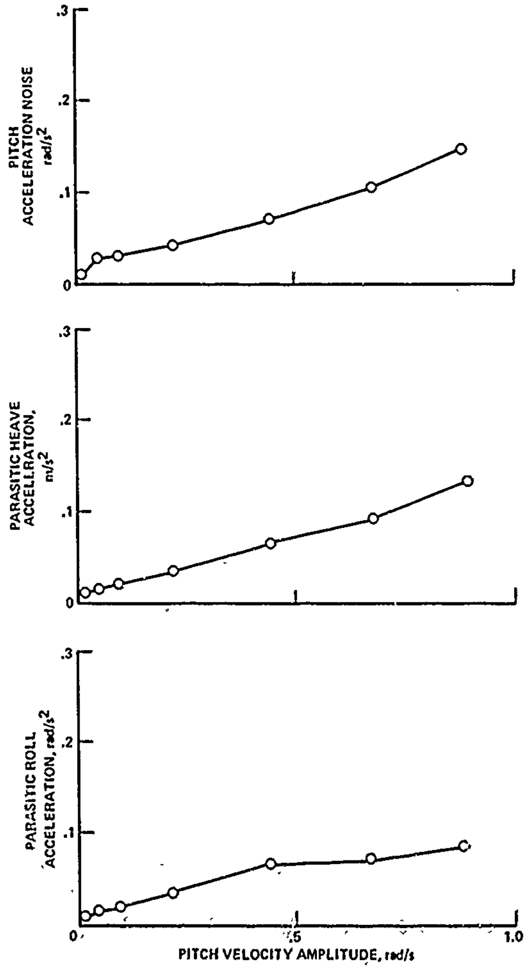


Fig. C15 Acceleration noise for 0.5 Hz sinusoidal pitch excitation of a position controlled three-degrees-of-freedom hydraulic motion system with hydrostatic bearings.

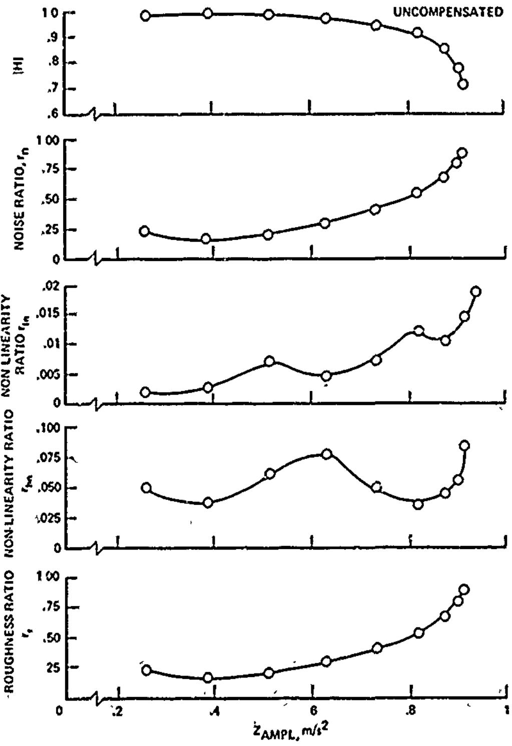


Fig. C16 Linearity and acceleration noise for 0.5 Hz heave excitation of a position controlled three-degrees-of-freedom motion system

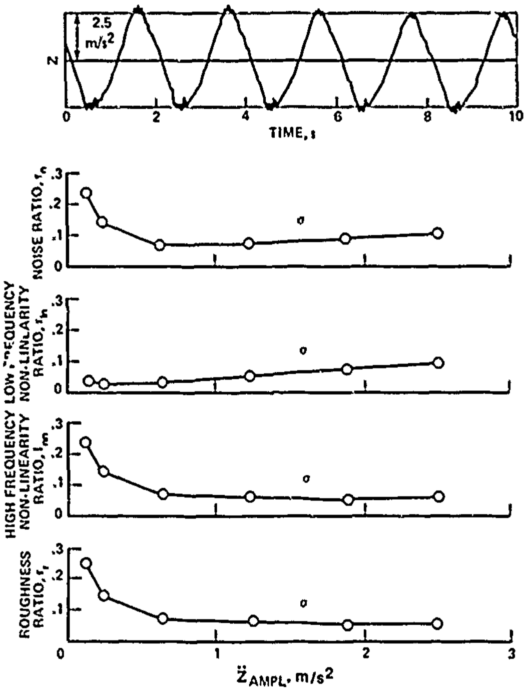


Fig. C17 Linearity and acceleration noise for 0.5 Hz heave excitation of a position controlled three-degrees-of-freedom hydraulic motion system with hydrostatic bearings

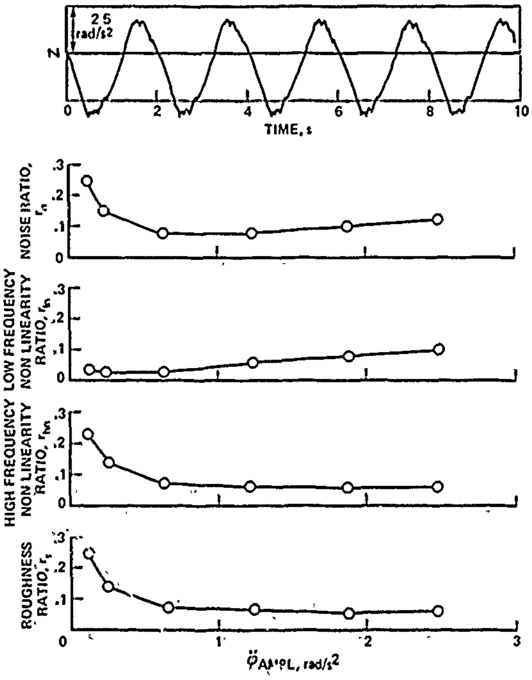


Fig. C18 Linearity and acceleration noise for 0.5 Hz roll excitation of a position controlled three-degrees-of-freedom hydraulic motion system with hydrostatic bearings

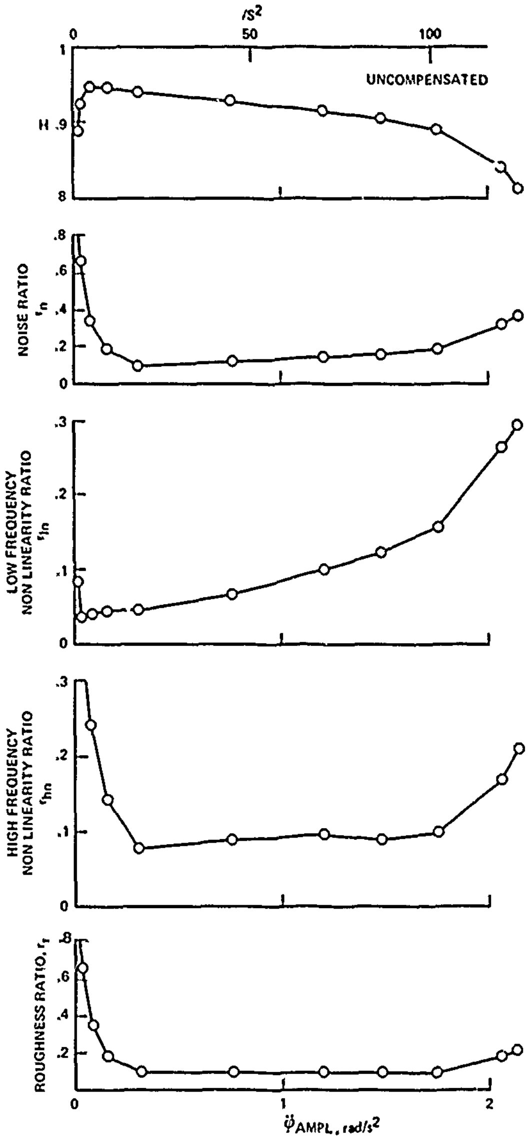


Fig. C19 Linearity and acceleration noise for 0.5 Hz roll excitation of a position controlled four-degrees-of-freedom hydraulic motion systems with hydrostatic bearings

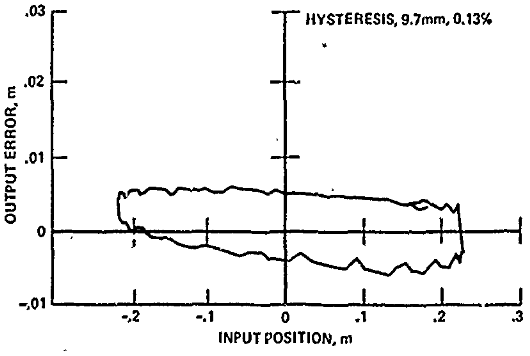


Fig. C20 Heave axis hysteresis of a position controlled three-degrees-of-freedom hydraulic motion system

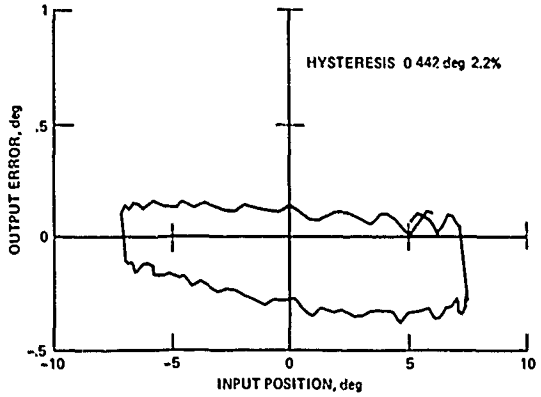


Fig. C21 Roll axis hysteresis of a position controlled three-degrees-of-freedom hydraulic motion system

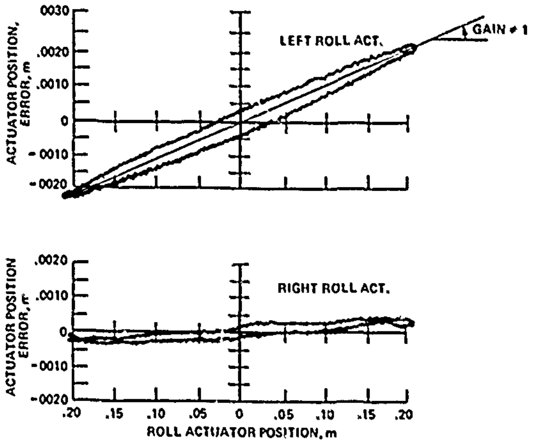


Fig. C22 Roll axis hysteresis of a position controlled four-degrees of-freedom hydraulic motion system with hydrostatic bearings

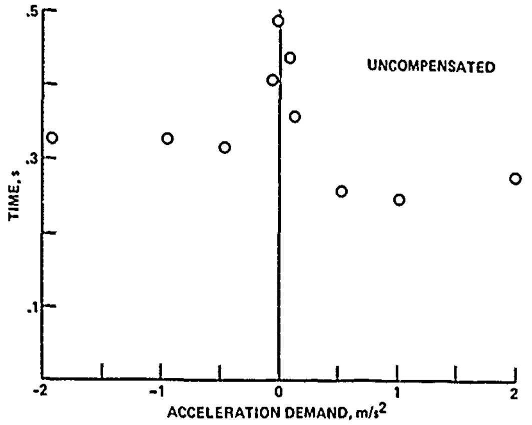


Fig. C23 Threshold for heave on a step acceleration inputsignal of a position controlled three-degrees-of-freedom hydraulic motion system

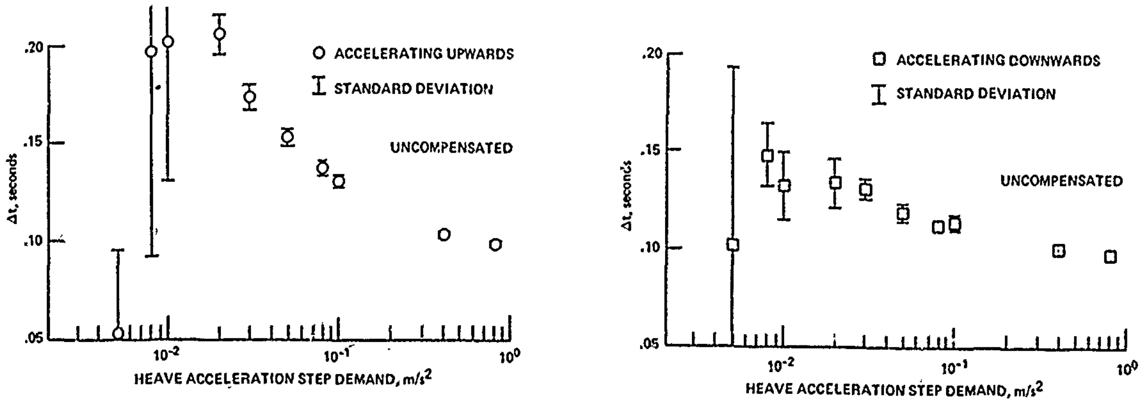


Fig. C24 Threshold for heave on a step acceleration inputsignal of a position controlled three-degrees-of-freedom hydraulic motion system with hydrostatic bearings

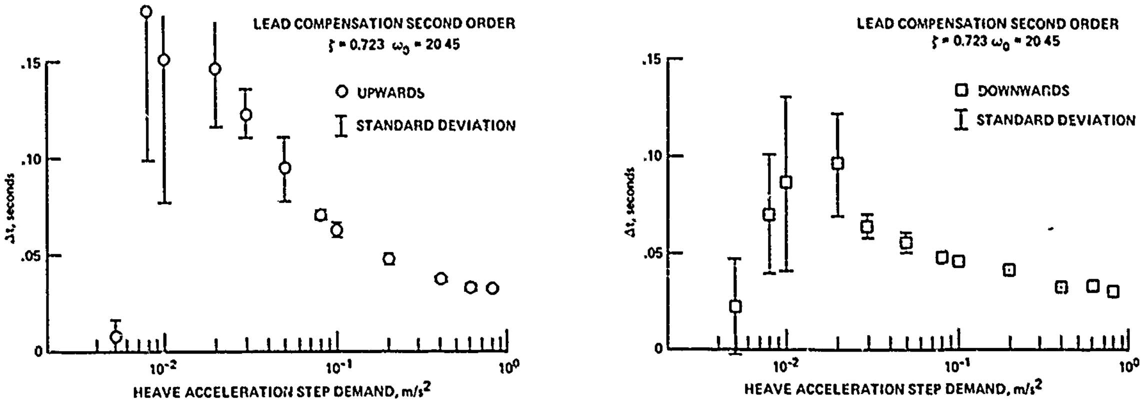


Fig. C25 Threshold for heave on a step acceleration inputsignal of a three-degrees-of-freedom hydraulic motion system with hydrostatic bearings

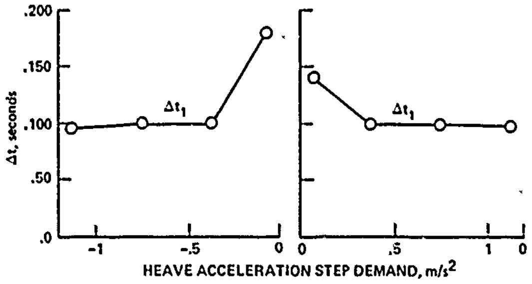


Fig. C26 Threshold for heave on a step acceleration inputsignal of a velocity controlled four-degrees-of-freedom hydraulic motion system

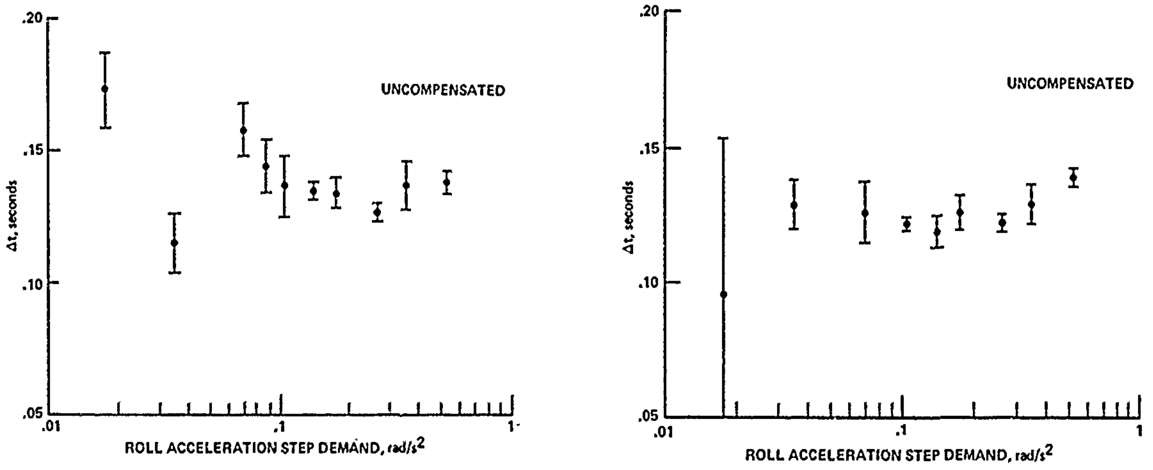


Fig. C27 Threshold for roll on a step acceleration inputsignal of a position controlled four-degrees-of-freedom hydraulic motion system with hydrostatic bearings

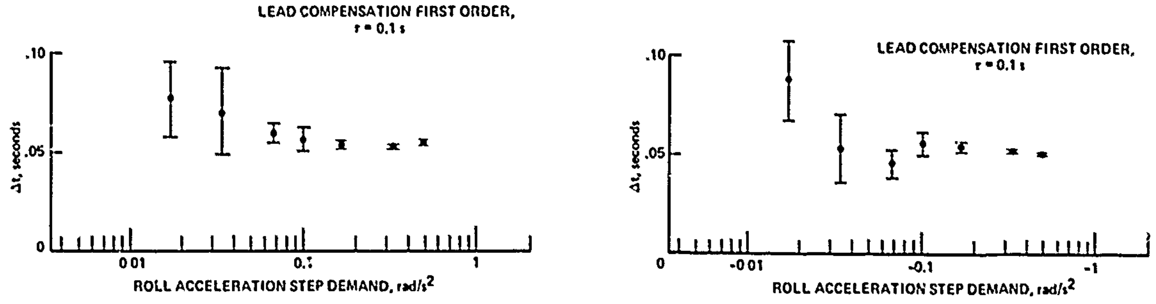


Fig. C28 Threshold for roll on a step acceleration inputsignal of a position controlled four-degrees-of-freedom hydraulic motion system with hydrostatic bearings

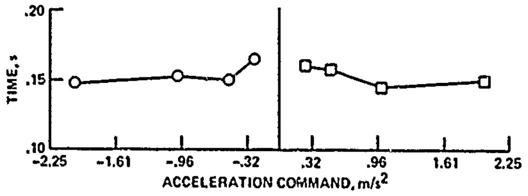


Fig. C29 Threshold for lateral motion on a step acceleration inputsignal of a velocity controlled six-degrees-of-freedom electric motion system

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14. Abstract

In the last five years, there has been a sharp rise in the number of simulation facilities employing multiple degree-of-freedom motion systems; however, until recently no substantive attempts have been made to measure the performance of these systems. Those measurements that have been made and published have not been made in a uniform way, so that it is difficult to compare different systems. While data on the gross excursions, velocities and accelerations of these systems have been generally available in the literature, dynamic response, noise and other imperfections were usually neither carefully measured nor was information on them widely distributed.

This ~~Advisory~~ Report specifies a uniform method of measuring and reporting motion performance characteristics, developed by a Working Group of the Flight Mechanics Panel of AGARD. Such a uniform method, in addition to aiding system comparison, can assist in system diagnosis and might be used in writing-performance specifications. The definitive characteristics selected for system description are excursion limits, describing function, linearity and acceleration noise, hysteresis, and dynamic threshold, definitions and methods of measurement and display are given, illustrated by measurements on particular motion systems.

This Advisory Report was prepared under the sponsorship of the Flight Mechanics Panel of AGARD.

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DYNAMIC CHARACTERISTICS OF FLIGHT SIMULATOR MOTION SYSTEMS
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AGARD-AR-144

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DYNAMIC CHARACTERISTICS OF FLIGHT SIMULATOR MOTION SYSTEMS
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