Some Effects of Stability on Low-Altitude Ride Quality

DONALD L. GRANDE* AND NOAH D. SHOWALTER JR.†
The Boeing Company, Renton, Wash.

High-speed low-altitude missions subject the crew and the subsystems to an extremely severe vibration environment. The integration of the flight crew into the weapon system requires consideration of the cockpit displays, the navigation and target acquisition subsystems, the automatic control systems, and the dynamic characteristics of the airframe and flight controls. The aeroelastic response of a long-range strategic type of airplane is analyzed to illustrate some of the considerations that must be included in designing for low-altitude flight. The effect of changes in stability characteristics on dynamic response is calculated, and the effects of the changes on the subjective discomfort of the crew are evaluated. The results indicate that significant improvements in ride quality can be achieved through modifications to the stability characteristics of the airplane and illustrate the considerations required to improve weapon system effectiveness.

Nomenclature

$C_{L\alpha}$ = lift curve slope
D = relative discomfort ratio
f = frequency in cps
$\hat{F}(\ )$ = cumulative probability of equaling or exceeding the variable
g = acceleration of gravity
K_D = incremental damping parameter, defined in text
k_D = damping signal amplification ratio
K_s = incremental stiffness parameter, defined in text
k_s = stiffness signal amplification ratio
L = turbulence scale factor
M = Mach number
T = frequency-response function
q = dynamic pressure
S = area
σ = rms value
Φ = power spectral density
Ω = generalized frequency argument

Superscript

j = a particular discomfort transfer function

Subscripts

a/p = airplane
D = subjective discomfort
i = input to system or speed-altitude combinations
I_N = normalized input spectrum
o = output of system
u = gust velocity
t = horizontal tail

Introduction

THE operation of military aircraft at low altitudes and high speeds is an effective technique for penetrating enemy radar defenses. Such missions, however, frequently expose the aircraft to a very intense turbulence environment and impose exacting performance requirements on the crew. Low-altitude flight test programs have shown that the capability of the crew often limits the performance of the airplane. Because crew capability is directly related to the displays in the crew compartment, the subsystems available for navigation and target acquisition, the automatic systems for control of the aircraft, and the dynamic response of the controls and airframe, each of these items must be properly integrated with the flight crew to assure the ultimate performance of the weapon system.

Background on Low-Altitude Flight

Control of an aircraft during high-speed low-altitude operations is difficult because of the inadequacy of the human senses and the slow reaction time of the pilot. Low altitudes allow little latitude for error, and high speeds require almost instantaneous reaction to correct deviations from the desired flight path and to evade obstructions. Radar systems are necessary to assist the crew in proper flight-path control. Development of automatic terrain following equipment will enable the crew to perform this function more accurately, but this type of operation results in complete reliance on electronic-type equipment with resultant psychological and reliability implications.

Operational experience and recent flight test incidents have emphasized the increase in severity of the turbulence environment associated with low-altitude operations when compared with that experienced at the high altitudes for which most current aircraft have been designed. The nature of the turbulence near the ground is strongly influenced by the mechanical interaction with the surface obstacles causing very strong eddies and vortex action. This environment has a significant influence on the structural design of the aircraft as well as on the ability of the crew to perform their duties. In addition, this rough ride compounds such psychological stress factors as awareness of the result of errors, concern over escape in emergencies, and lack of confidence in the operation of the various systems. These factors must be considered during the conceptual stage of advanced strategic aircraft in order to attain the design objectives in the finished product. The following analysis of the effects of stability on ride quality illustrates the type of consideration that is required to arrive at the optimum airplane design for low-altitude operation.

Analysis of Ride Quality

Advanced weapon system objectives for low-altitude high-speed penetration can be achieved by providing a suitably low gust response in the crew compartment of the airplane. Because the ability of the crew to perform their functions is a relatively fixed condition, the airframe and control systems must be designed to provide the required crew environment. The dynamic response of an airplane results from the interaction of four design properties: 1) airplane geometry and

Presented as Preprint 64-771 at the AIAA Military Aircraft Systems and Technology Meeting, Washington, D. C., September 21–23, 1964; revision received February 19, 1965. The authors wish to acknowledge the assistance of C. J. Heffron in conducting the analysis described herein.

* Senior Group Engineer, Airplane Division. Associate Fellow Member AIAA.

† Project Engineer, Airplane Division.

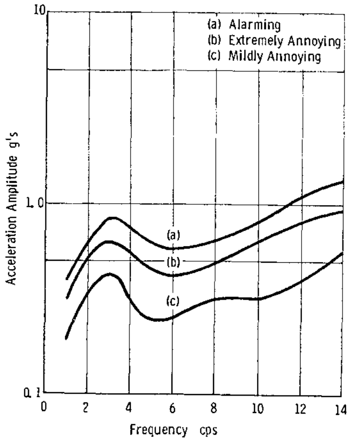

Fig. 1 Subjective discomfort levels for sinusoidal vibrations.

mass properties, 2) aeroelastic characteristics, 3) control dynamics, and 4) stability characteristics.

The airplane geometry and mass properties are fundamental factors, with the influence of wing sweep angle and wing loading being well understood. These properties are usually dictated by speed and range requirements, and appreciable changes are undesirable since they would compromise the performance of the weapon system.

The aeroelastic characteristics of the airframe can contribute significantly to the discomfort of the crew. These characteristics are most important in large, low-load factor airplanes and become less important in small, high-load factor airplanes because of the increase in the frequencies of the elastic modes of the airframe. The frequency and shape of each airframe vibration mode is determined by the mass and stiffness distributions within the structure. Whereas the mode shapes can be altered by changing the locations of masses within the airframe, the frequencies of the modes are relatively insensitive to reasonable changes in stiffness.

The control system can greatly influence the gust sensitivity of an airplane; however, the design of the control system and autopilot are usually completed after the basic airframe design has been set. Thus, although control effects cannot be included in early estimates of gust response, their influence should be monitored continuously during development to preclude any unnecessary degradation in ride quality.

Automatic flight control systems and stability augmentation systems are capable of providing a relatively broad range of stability characteristics and handling qualities. The state of the art in autopilot and stability augmentation hardware is such that these systems are capable of influencing both the rigid airplane and the elastic modal response of the airframe. Since it is normal engineering practice to investigate the effects of the stiffness and damping characteristics of the automatic flight control system on handling quality,

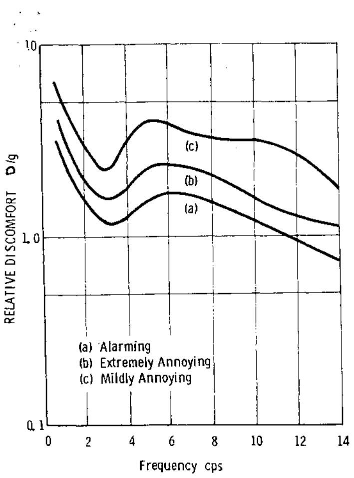

Fig. 2 Relative discomfort frequency, response functions.

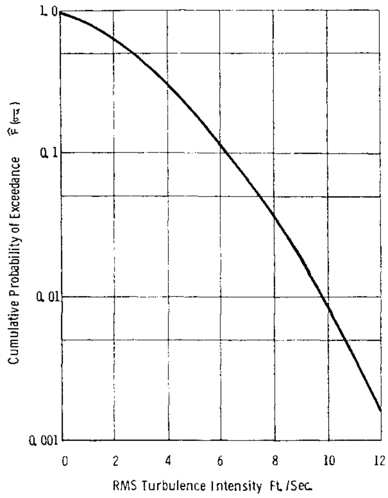

Fig. 3 Cumulative probability of exceeding turbulence intensity for 800-ft altitude for VFR daytime flights.

this is also a logical area of investigation with respect to the effects on ride quality.

The purpose of this study is to evaluate changes in ride quality that can be achieved through variations in the airplane stability for the purpose of illustrating the type of considerations that should be given to each of the four problem areas discussed previously. Two types of stability variation are considered: 1) additional pitch stiffness, and 2) additional pitch damping. These two variations are types of change that can be achieved through stability augmentation systems.

Limitations on the crew during low-altitude penetrations are caused by accelerations due to exposure to continuous turbulence. Therefore, the problem should be studied from a power spectral approach rather than from a discrete gust approach. The analysis of airplane dynamic response to atmospheric turbulence utilizes the same power spectral analyses used in gust response problems. An additional transfer function relating crew compartment accelerations to subjective discomfort is included in the equations to evaluate the effects of acceleration amplitude and frequency on the crew.

Basic Ride Quality Relations

The basic relations used in the ride quality analysis are developed in Ref. 1; only the more pertinent equations are

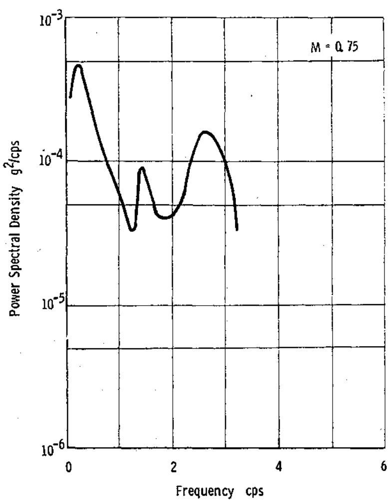

Fig. 4 Crew compartment acceleration spectrum for basic airplane.

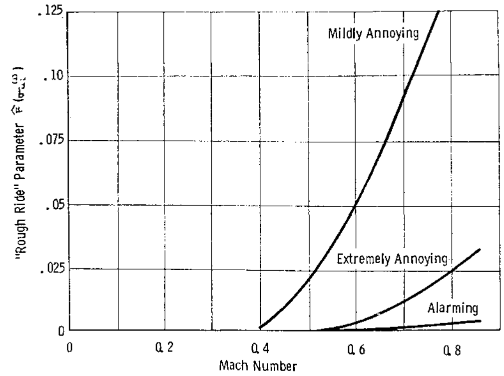

Fig. 5 Cumulative probability of exceeding discomfort thresholds for basic airplane.

described below. The basic equation for airplane response to random gust excitation is

$$\Phi_0(\Omega) = \sigma_u^2|T(\Omega)|^2\Phi_{IN}(\Omega) \tag{1}$$

The effects of continuous vibration on the crew are evaluated by the use of vibration test data such as those shown in Fig. 1. This figure presents thresholds of constant subjective discomfort as a function of the peak amplitude for sinusoidal vibration. These curves are taken from Ref. 2 and represent the results of a group of closely controlled tests conducted on flight crews using simulated aircraft fixtures. These test results illustrate the influence of vibration frequency and amplitude on the subjective discomfort of flight crews.

Based on the data shown in Fig. 1, the discomfort transfer functions described in Ref. 1 can be developed describing the relative discomfort as a function of frequency for a unit acceleration amplitude. These transfer functions are presented in Fig. 2. Inserting the discomfort frequency-response function in Eq. (1) results in

$$\Phi_{0D}(\Omega) = \sigma_u^2|T_{a/p}(\Omega)|^2|T_D(\Omega)|^2\Phi_{IN}(\Omega) \tag{2}$$

Equation (2) is the fundamental equation for the analysis of ride quality involving the response of the airframe to atmospheric turbulence, and the effect of the crew compartment response on the discomfort sensed by the crew.

The mean-square discomfort ratio is obtained by integrating Eq. (2) between the limits of zero and infinity:

$$\sigma_D^2 = \sigma_u^2 \int_0^\infty |T_{a/p}(\Omega)|^2|T_D(\Omega)|^2\Phi_{IN}(\Omega)d\Omega \tag{3}$$

As discussed in Ref. 1, it is necessary to establish a criterion for the intensity of discomfort due to random excitation that corresponds to the discomfort intensity present at the thresholds in Fig. 1. The most reasonable criterion appears to be the equality of σ_D. The relative discomfort ratio D associated with each threshold in Fig. 1 is unity, and the corresponding rms value σ_D is $1/(2)^{1/2}$, since the subjective discomfort levels were established during sinusoidal vibration at each frequency. Therefore, it is assumed that the pilot reaches these thresholds of discomfort under random vibration when the value of σ_D reaches $1/(2)^{1/2}$.

Table 1 Modal frequencies

Mode no.	Freq., cps
1	1.43
2	2.31
3	3.20
4	4.86
5	7.52
6	10.99
7	13.82
8	27.99

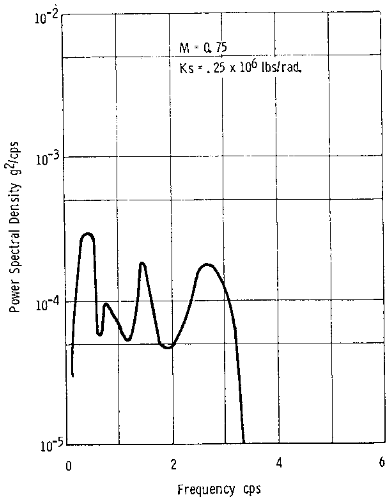

Fig. 6 Crew compartment acceleration spectrum with added pitch stiffness, K_s = 0.25 × 10⁶ lb/rad.

Thus the rms turbulence intensity required to reach each discomfort threshold is

$$\sigma_{u_i}{}^{(j)} = 1/(2)^{1/2}\sigma_{D_i}{}^{(j)} \tag{4}$$

where $\sigma_{D_i}{}^{(j)}$ is obtained from Eq. (3) using unit turbulence intensity. The subscript i denotes the particular combination of speed and altitude and the superscript j the appropriate discomfort threshold. The cumulative probability of the crew reaching or exceeding the jth discomfort threshold is then equal to the cumulative probability of reaching or exceeding a turbulence intensity of $\sigma_{u_i}{}^{(j)}$. This quantity, denoted by $\hat{F}(\sigma_{u_i}{}^{(j)})$, is referred to herein as the "rough ride" factor. The cumulative probability of operating at or above a given speed without encountering the discomfort threshold is called the "ride quality" factor and is given by

$$\hat{F}(M_i{}^{(j)}) = 1 - \hat{F}[\sigma_{u_i}{}^{(j)}] \tag{5}$$

The cumulative probability of exceeding various values of turbulence intensity, denoted by $\hat{F}(\sigma_u)$, is presented in Fig. 3. These data are taken from Ref. 3, based on some early B-47 flight tests conducted at an altitude of 800 ft under visual flight rules (VFR) conditions.

Analysis of Advanced Strategic Airplane

Based on the foregoing discussion, an advanced type of variable sweep aircraft is analyzed to evaluate the changes

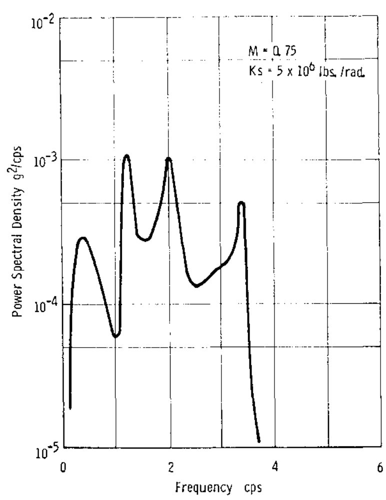

Fig. 7 Crew compartment acceleration spectrum with added pitch stiffness, K_s = 5 × 10⁶ lb/rad.

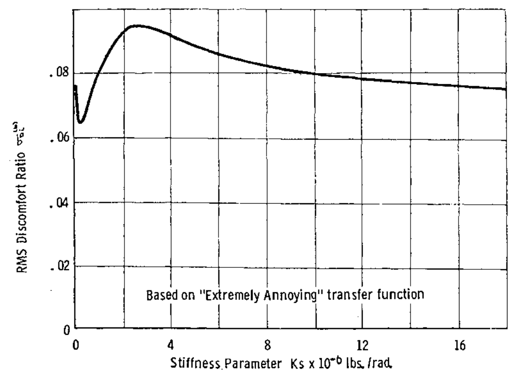

Fig. 8 Variation of discomfort ratio with stiffness for $M = 0.75$.

that can be obtained in ride quality through variations in stability characteristics. This study evaluates the dynamic response of the basic airframe and the changes that result from variations in the stability parameters.

The analysis is based on a gross weight corresponding to the fuel and weapon loading that would exist following a low-altitude penetration to the target area, but prior to the delivery of the weapon. This results in a wing loading of about 94 lb/ft².

The frequencies of the eight elastic degrees-of-freedom used in the analysis are listed in Table 1. The first mode is predominantly forward body bending, and the other seven are very highly coupled wing and fuselage modes compared to those normally encountered on subsonic-type aircraft.

The frequency response function of the airframe is calculated based on 1) rigid airplane pitching and translation, 2) eight flexible airframe degrees-of-freedom, 3) corrected spanwise lift distribution, 4) unsteady lift growth, 5) downwash effects on the tail, and 6) gradual penetration of the gust front. The normalized power spectrum of gust velocities is taken from Ref. 4 and is described by the equation

$$\Phi_{IN} = L/\pi[(1 + 3\Omega^2L^2)/(1 + \Omega^2L^2)^2] \tag{6}$$

where the frequency argument is in rad/ft. The value for the turbulence scale factor L is taken as 500 ft.

For the purpose of this study, the "extremely annoying" level of subjective discomfort is selected as the maximum acceptable level that the pilot can tolerate for periods of 10 to 12 min. This level is selected in preference to the "alarming" level, since it appears to be more applicable for slightly longer periods of exposure to turbulence. Should the pilot exceed this level, it is assumed that his discomfort becomes unbearable, and his control of the aircraft becomes marginal to the degree that he must reduce speed or climb to a higher altitude to reduce the roughness of the ride.

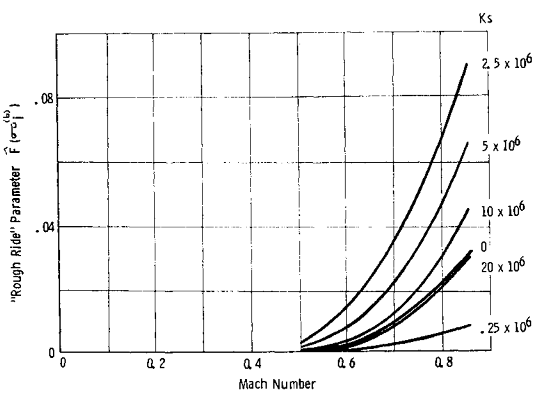

Fig. 9 Cumulative probability of exceeding "extremely annoying" discomfort threshold with added pitch stiffness.

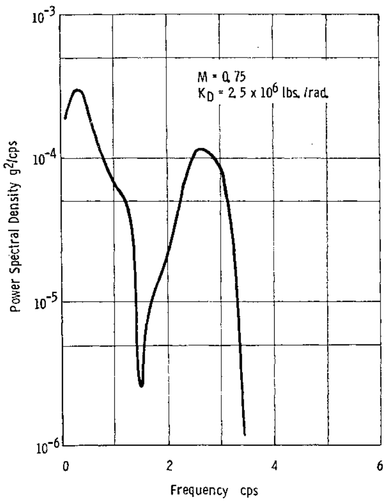

Fig. 10 Crew compartment acceleration spectrum with added pitch damping, $K_D = 2.5 \times 10^6$ lb/rad.

The appropriate transfer function from Fig. 2 can thus be inserted into the equations, and appropriate values of $\sigma_{D_i}{}^{(j)}$ and $\hat{F}(\sigma_{u_i}{}^{(j)})$ can be calculated.

Results

A typical crew compartment vertical acceleration power spectrum is presented in Fig. 4 for $M = 0.75$ to illustrate the relative contributions of the various airplane modes. The high peak at 0.25 cps corresponds to the response of the short period pitch mode of the airframe, and the two higher frequency peaks are elastic modes. The response of the modes above 3 cps is omitted to simplify the comparative evaluation. Figure 5 shows the "rough ride" factor $\hat{F}(\sigma_{u_i}{}^{(j)})$ for the three subjective discomfort thresholds as a function of Mach number for the basic airplane. To interpret this figure, consider the airplane to be flying at sea level with the weight described earlier at a Mach number of 0.75; under these conditions the flight crew will equal or exceed the "extremely annoying" threshold of discomfort 1.7% of the time. It should be noted that these figures apply rigorously only to a statistically large number of aircraft flying for many hours.

Effects of Pitch Stiffness

The study is now continued to illustrate some changes in ride quality that can be achieved through variations in air-

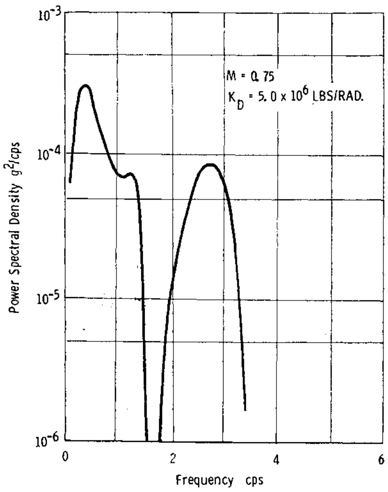

Fig. 11 Crew compartment acceleration spectrum with added pitch damping, $K_D = 5 \times 10^6$ lb/rad.

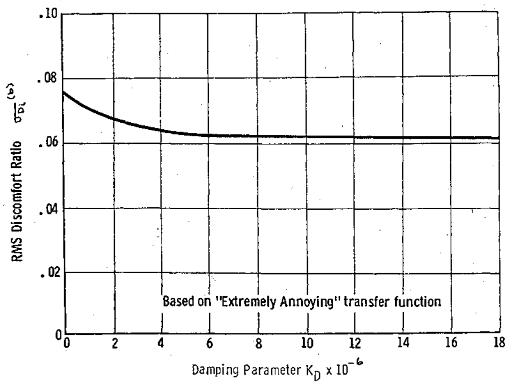

Fig. 12 Variation of discomfort ratio with damping for $M = 0.75$.

plane stability. The influence of stability augmentation on ride quality is presented with two variations in phasing. The first of these involves changing the pitch stiffness of the airplane. A force is included at the tail that is proportional to and in opposition to displacements at the tail. It is assumed for the purpose of this study that the stability augmentation system has adequate capacity and frequency-response to be effective in all degrees-of-freedom.

An incremental stiffness factor is defined as

$$K_s = qS_tC_{L\alpha t}k_s \tag{7}$$

K_s has the units of lb/rad and hence can be considered as an aerodynamic force per unit angle of attack.

Figure 6 presents the cockpit acceleration spectrum for $K_s = 0.25 \times 10^6$ lb/rad. Comparing this cockpit response to that for the basic airplane in Fig. 4 shows a decrease in the amplitude of the short period pitch mode, whereas the response in the two elastic modes is somewhat higher. The new response peak at a frequency of 0.75 cps results from the added degree-of-freedom of the feedback control system. Figure 7 presents the cockpit acceleration spectrum for $K_s = 5 \times 10^6$ lb/rad. Comparing this spectrum to those in Figs. 4 and 6 shows the amplitude of the short period pitch response to be essentially unchanged from that in the preceding figure, whereas the two elastic modes have increased greatly in amplitude and in frequency. The most interesting result, however, is the large response in the added degree-of-freedom of the feed back control system at a frequency of 1.25 cps. This degree-of-freedom is now one of the major responses of the airplane.

Because the acceleration spectra are changing quite drastically with variations in K_s, Fig. 8 shows the variation of the rms discomfort ratio as a function of K_s. The improvement in $\sigma_{Di}^{(b)}$ for small values of K_s results from the decrease in amplitude of the short period pitch mode. As K_s is increased above a value of about 0.25×10^6 lb/rad, the increase in response of the other degrees-of-freedom tends to overshadow this improvement.

Figure 9 presents the "rough-ride parameter" $\hat{F}(\sigma_{u_i}^{(b)})$ as a function of Mach number for several values of incremental pitch stiffness. This figure illustrates that the cumulative probability of exceeding the discomfort threshold at Mach 0.8 can vary from 0.7% for $K_s = 0.25 \times 10^6$ to 6.8% for $K_s = 25 \times 10^6$, thus degrading the ride quality by a factor over nine.

Effects of Pitch Damping

Another analysis considers the effects of altering the airplane damping by including a force at the tail that is proportional to and 180° out of phase with the vertical velocity at the tail. It is assumed for the purpose of this study that adequate capacity and frequency-response is available in the stability augmentation system to be effective in all degrees-of-freedom. An incremental damping factor is defined as

$$K_D = qS_tC_{L\alpha t}k_D \tag{8}$$

The units of K_D are the same as for K_s.

Figures 10 and 11 present the cockpit acceleration spectra at Mach 0.75 for values of $K_D = 2.5$ and 5.0×10^6 lb/rad, respectively. Comparing these figures to the spectrum for the basic airplane in Fig. 4 shows the decrease in amplitude of the short period pitch mode and the strong suppression of the elastic modes. The small response peak appearing in Fig. 11 at a frequency of 1.25 cps results from the added degree-of-freedom of the feedback control system.

The rms discomfort ratio is shown in Fig. 12 as a function of the incremental damping factor. This curve shows a steady improvement in the cockpit response characteristics as K_D is increased up to about 5×10^6 lb/rad. Beyond this value very little improvement results from further increases in K_D.

Figure 13 presents the "rough-ride parameter" $\hat{F}(\sigma_{u_i}^{(b)})$ as a function of Mach number for several values of incremental damping. This figure illustrates that an increase in damping of $K_D = 5 \times 10^6$ lb/rad at Mach 0.8 will reduce the frequency of exceeding the threshold from 2.4% down to about 0.6% of the time, thus improving the ride quality by a factor of 4.

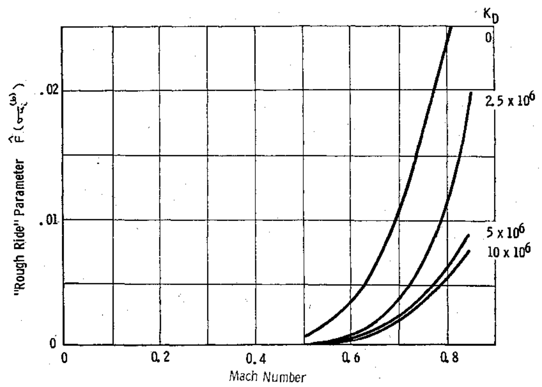

Fig. 13 Cumulative probability of exceeding "extremely annoying" discomfort threshold, with added pitch damping.

Conclusions

This study illustrates the effect of pitch stiffness and pitch damping on the ride quality of a large low-load factor airplane. Whereas additional damping tends to improve the ride quality, the effect of varying stiffness must be closely watched in order that the added excitation of the elastic modes does not overshadow a reduction in the amplitude of the short period pitch mode. It is emphasized that this study covers only one aspect of the ride quality problem. The achievement of satisfactory ride quality and performance in an operational weapon system will require similar studies of the other aspects that affect ride quality and performance.

References

[1] Grande, D. L., "Some effects of random turbulence on weapon-system performance," Aerospace Eng. **21**, 35–43 (1962).

[2] Parks, D. L. and Snyder, F. W., "Human reaction to low frequency vibration," The Boeing Co., Wichita Div., Doc. D3-3512-1 (July 24, 1961).

[3] Jackson, C. E., Thorsen, K. R., Wherry, J. E., and Dempster, J. B., "The influence of dynamic loads on aircraft fatigue," Wright Air Development Center TR 59-507, pp. 449–478 (August 1959).

[4] Press, H., Meadows, N. T., and Hadlock, I., "A reevaluation of data on atmospheric turbulence and airplane gust loads for application in spectral calculations," NACA Rept. 1272 (1956).