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RIDE QUALITY OF TERMINAL-AREA FLIGHT MANEUVERS

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SUMMARY

Complex terminal-area flight maneuvers being considered for airline operations may not be acceptable to passengers. To provide technology in this area, a series of flight experiments was conducted by NASA using the U. S. Air Force Total In-Flight Simulator (TIFS) aircraft to obtain subjective responses of a significant number of passenger test subjects to closely controlled and repeatable flight maneuvers. Regression analysis of the data produced a mathematical model which closely predicts mean passenger ride-comfort rating as a function of the rms six-degree-of-freedom aircraft motions during the maneuver. This ride-comfort model has been exercised to examine various synthesized flight maneuvers.

INTRODUCTION

Complex terminal-area flight maneuvers, used in conjunction with area-navigation and 4-D takeoff/approach techniques, are being considered to reduce fuel usage, noise pollution, and air-traffic congestion. Flight research to determine the feasibility of incorporating such unusual flight maneuvers into routine operations is part of NASA's Terminal-Configured-Vehicle Program (ref. 1). Such maneuvers, however, may not be acceptable to passengers since certain combinations of linear and angular motions are known to be upsetting to the human vestibular system. Several years ago, exploratory flight experiments concerning maneuver effects on ride quality conclusively indicated that criteria are needed which include more than just vertical and lateral motions (ref. 2). As ride comfort is a significant factor in determining acceptance and use of air transportation, a need exists for technology which will allow prediction of the degree of passenger comfort for terminal-area flight maneuvers.

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Technology applicable to anticipated needs does not presently exist. Ride-comfort research has been conducted both in the field, aboard commercial and research vehicles, and in the laboratory using motion simulators. Laboratory simulators, however, lack motion capability sufficient to simulate flight maneuvers, whereas field tests aboard commercial vehicles do not allow precise control and repetition of a given maneuver. To provide the technology from which ride-quality predictive relations and criteria can be established for terminal-area maneuvers, a series of flight experiments was conducted by NASA using the U. S. Air Force Total In-Flight Simulator (TIFS) aircraft (fig. 1). The TIFS, piloted by a magnetic tape, was used to expose passenger test subjects to closely controlled and repeatable flight maneuvers. This paper describes these experiments, the regression analysis applied to the data to produce a

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ride-comfort model, and the results obtained when the model was exercised for various synthesized flight maneuvers.

TEST VEHICLE

The U. S. Air Force Total In-Flight Simulator (TIFS) is a C-131H transport (similar to a Convair 580 commercial transport) modified into a variable-stability research aircraft. Figure 2(a) illustrates the distinctive features of the aircraft. A simulation cockpit, mounted on the nose of the C-131H, is designed to place evaluation pilots in an environment configured to closely duplicate that of the cockpit of the aircraft being simulated. Special provision is made for independent control of the forces and moments about all three motion axes. Included are aerodynamic surfaces mounted vertically above and below each wing to provide side-force variation with very littl rolling or yawing moment, aileron-type flaps immediately outboard of the engine to provide direct lift control, and servo-operated throttles to provide longitudinal force variation. High-performance electrohydraulic actuators drive the existing ailerons, elevator, and rudder to produce rolling, pitching, and yawing moments, respectively. In the standard Convair cockpit, safety pilots monitor the simulation in progress and have the capability of disengaging the variable-stability system and resuming control of the aircraft at any time. The variable-stability system includes an analog computer and associated electronics located in the aft cabin. Inputs to the computer come from the evaluation pilot's controls and airplane motion sensors. A digital recording system capable of recording 58 individual variables, such as airplane motions and pilot control inputs, logs test results for engineering evaluation.

Figure 2(b) illustrates the TIFS modifications made for ride-quality testing. The standard TIFS simulation cockpit was replaced with a noise fairing. The aircraft cabin section between the cockpit and computer (fig. 3) was outfitted with wood paneling, curtains, and a carpet to create an airline-type atmosphere. Five standard Convair double seats were provided for the 10 test subjects. Each passenger seat was provided with a reading light, an adjustable outlet of conditioned air, a seat pocket with airsickness bag, and an emergency evacuation instruction card. A restroom, equipped with a marine-type toilet, was provided adjacent to the test-subject area. The TIFS hydraulic console area was soundproofed and trimmed with wood paneling to muffle the sound of continuous-duty hydraulic boost pumps. All but one pair of test-subject seats were adjacent to a window. An additional double seat for the flight-test director was provided immediately behind the test subjects, together with voice communications to the pilots and test engineer and a public address system for instructing the passenger subjects during flight. A closed-circuit television camera was mounted in the safety cockpit to record copilot head motions, and another camera was mounted behind a panel to record activity of a few of the test subjects. For the ride-quality experiments, the pilot-control inputs were replaced by magnetic tape command signals. These command signals were then combined with appropriate filtering and shaping to generate commands to the TIFS flight control surfaces necessary to produce the desired aircraft motions. A two-axis side stick controller gave the ccpilot the capability of maneuvering the aircraft with the variable-stability system engaged. Further details concerning the TIFS modifications for ride-quality research and test techniques employed are reported in reference 3.

FLIGHT TESTS

Flight Maneuvers

Maneuvers investigated individually consisted of one of three basic components (steady descent, steady turn, or longitudinal deceleration) of typical terminal-area flight maneuvers. A few combinations of two or three of these components were used to study subjective responses to more complex maneuvers (e.g., a turning decelerating descent, etc.). The range of each maneuver motion variable (e.g., approach angle, roll angle, etc.) somewhat exceeded the motion variable range normally encountered during terminal-area maneuvers of commercial passenger aircraft. Table I summarizes both the ranges of key motion variables and the number of unique variable combinations tested for each type of maneuver. Maneuvers, generally of 30-second duration, were sequenced at approximately 90-second intervals on 2 test tapes of 24 segments each.

The excellent repeatability of flight maneuvers provided by magnetic tape control of the aircraft is illustrated in figure 4. The figure presents time histories of four appropriate motion parameters measured during a particular maneuver flown on two different flights. The maneuver shown is a turning decelerating descent, which was probably the most complex and extreme maneuver tested and therefore was one of the most difficult to repeat. Differences in parameter values are relatively minor between flights and are essentially constant over the time duration of the maneuver for the three parameters (roll angle, pitch angle, and indicated airspeed) which were specifically controlled by the motion-command tape. Differences could be expected to be nearly constant because each of the three parameters was recorded on the drive tape in terms of parameter deviation from a reference flight condition. The slight shifts in parameter values between the two flights are associated with minor changes in reference flight conditions by the copilot to avoid weather, to stay within a certain test area, or to increase/decrease test altitude.

Passenger Subjects

Thirty-two passenger subjects of both sexes were chosen from among NASA employees, university students, and the general public to include a range of age and previous flight experience and to represent air travelers in general. Table II compares characteristics of the passenger subjects with those of air travelers in general. Approximately 1 hour prior to a given test flight, 10 of the test subjects were assembled and briefed on the purposes of the TIFS Ride-Quality Program in general and of the upcoming flight in particular. The subjects were informed of the types and degrees of motion to be tested and of the ability of any subject at any time to terminate the input motion by a simple hand signal (such termination, in fact, occurred more than once). After all questions were answered, each subject signed a statement of voluntary participation and boarded the aircraft.

Test Procedure

Once all passenger subjects were aboard and seated with seat belts secured the TIFS aircraft took off and during about 15 minutes climbed to the appropriate test area, altitude, and heading. The aircraft was then trimmed in straigh and level flight and the variable-stability system engaged. The motion-command tape recorder was started and the motion command signals were brought to full strength. For the next 30 to 40 minutes the aircraft was piloted by the tape recorder, with the exception of occasional pitch and roll trim changes by the copilot to keep the aircraft within safe test airspace. As the various test maneuvers were experienced in the aircraft, the beginning and end of each evaluation interval (typically 30 sec) were announced over the aircraft's public address system by the test director. At the end of each evaluation interval, each passenger subject recorded on a rating sheet his estimate of his own total comfort on a 7-point rating scale employing undefined descriptors ranging from "Very Comfortable" to "Very Uncomfortable" (see table III). In addition, each subject was asked to report in a "Comments" column any aspect of the passenger environment which he considered dominant in his assessment of personal comfort. Upon completion of the entire set of motion test segments, the motion command signals were attenuated, the tape recorder was stopped, the variable-stability system disengaged, and the aircraft returned to the Langley Research Center and landed. During the return trip, the passenger subjects completed summary questionnaires stating their assessments of the overall comfort (using the 7-point scale) of the test ride and of specific aspects of ride comfort (e.g., motion, noise, seat comfort, etc.). Upon landing, the passengers deplaned and, after a short debriefing, were dismissed.

RESULTS

The 2 test tapes of 24 segments each provided a total of 48 individual flight maneuvers to be repeated 4 times. With 10 subjects onboard each flight, the resulting 192 flight maneuvers provided a grand total of 1920 individual ride-comfort ratings. Space does not permit tabulation of individual ride-comfort ratings versus flight-condition variables. For each flight, the total number in each comfort rating is presented in table IV, however, to indicate that the entire ride-comfort rating scale was used and to provide a general idea of consistency between flights. It should be pointed out that between flights using the same maneuver tape there were sometimes differences in test altitude and air turbulence. The mean ride rating for all maneuvers was 3.63 and the corresponding standard deviation was 1.50.

During one 2-hour flight, subjects were exposed to two identical programed sequences to investigate possible changes in test subject's comfort ratings of identical segments spaced 1 hour apart. The results reported in reference 4 indicated no significant effect of time.

To illustrate detailed typical results, the time histories of all 13 recorded motion variables and the 40 individual ride-comfort ratings are presented in figure 5 for the 4 flights of a turning decelerating descent maneuver.

DATA ANALYSIS

Because of the great number of variables involved and the desire to develop a ride-quality model from the data, the regression analysis approach was used to analyze the data. Several analyses were employed to explore the suitability of various parameters and parameter combinations (e.g., peak value accelerations, rms velocities, etc.) to provide a meaningful model.

The simplest measure of each motion variable is the maximum deviation of that variable from zero during the maneuver interval. Initial correlation and regression analyses therefore used as input data maximum variable values which were read directly from time-history plots. However, this approach presented two major difficulties. It was frequently difficult to decide which value of a given variable in a given maneuver interval should be recorded. In addition, amplitude-duration effects were totally lost. Therefore, a further analysis used as independent variables the root-mean-square (rms) values of each motion variable. Table V presents the simple correlations existing among the various rms motion variables and the resulting individual ride-comfort ratings. On the basis of these correlations and to facilitate the comparison of results with those of vibratory-motion ride-comfort experiments, a linear regression analysis was used to obtain the following ride-comfort model based on rms linear accelerations and angular rates:

$$\text{Ride-comfort rating} = 1.65 + 8.32n_x + 15.1n_y + 21.5n_z + 0.183p - 1.20q - 0.238r$$

where: n_x = rms longitudinal acceleration; p = rms roll rate

n_y = rms transverse acceleration; q = rms pitch rate

n_z = rms normal acceleration; r = rms yaw rate

The multiple correlation coefficient for the model is 0.57 and the regression F statistic is 156. The relationship between the ride-comfort rating predicted by this equation for each test maneuver and the mean value of the corresponding 10 experimental passenger ratings for that maneuver is shown in figure 6. For the 192 maneuvers the rms difference between predicted ride-comfort rating and mean experimental rating is 0.55; the corresponding correlation coefficient is 0.85.

APPLICATION OF RIDE-COMFORT MODEL

Method of Application

The ride-comfort model has been used to predict the ride comfort of computer-synthesized simple turns, descents, and decelerations with pitchover. The rms value of each of the six motion variables over the maneuver duration wa calculated and then substituted into the regression equation to obtain a ride-comfort rating. A synthesized turn (fig. 7) is based on three assumptions: a sinusoidal roll-rate time history during turn entry and exit; the lift versus angle-of-attack characteristics of the aircraft (in this case the TIFS); and a level, fully coordinated turn. Roll angle is assumed to be the analytical integral of roll rate. The roll angle, in turn, specifies the normal acceleration, which together with the airspeed determines the pitch angle and hence the longitudinal acceleration. Euler transformations resolve the net aircraft rotation rate into both the assumed roll rate and the corresponding pitch and yaw rates. Parameters which can be varied are airspeed, maximum roll angle, maximum roll rate, and turn duration. The effects of aircraft motion response to atmospheric turbulence are approximated by superimposing on each of the six motion-variable time histories a random oscillatory signal having a zero mean and an appropriate standard deviation. These standard deviations (table VI) were selected by examining rms motion amplitude data obtained aboard commercial airline flights (ref. 5). Similar maneuver synthesis techniques were applied to steady descents and longitudinal decelerations. On an rms amplitude basis, agreement between corresponding variables is quite good. The ride-comfort rating predicted by the comfort model for the synthesized maneuver is 3.1; the mean experimental rating given the actual maneuver is 2.9.

Steady Turns

The variation of predicted ride-comfort rating with roll angle in a steady turn is shown in figure 8(a) for various turbulence levels. For zero and light turbulence, ride comfort is little affected by roll angles less than 20° but degrades rapidly and becomes "Uncomfortable" at about 50°. Turbulence intensity significantly degrades ride comfort for small roll angles but has a much smaller effect as roll angle increases. As the turbulence intensity increases, the roll angle above which ride comfort significantly degrades increases. For zero bank angle and for the various turbulence intensities, ride-comfort rating predicted by a two-degree-of-freedom regression model developed at the University of Virginia (ref. 6) are shown along the ride-comfort axis. Also shown in figure 8(a) are steady-turn data obtained by the University of Virginia during ride-quality flight experiments using the NASA Jetstar aircraft (ref. 7). Agreement is quite good.

The variation of predicted ride-comfort rating with roll angle for various airspeeds is shown in figure 8(b). The slight degradation of comfort at low roll angles with decreasing airspeed is due to increased longitudinal acceleration accompanying increase in pitch angle. For roll angles greater than 30°, decreasing airspeed improves the predicted comfort by increasing the aircraft yaw rate (because the yaw-rate regression coefficient is negative). For typical terminal-area airspeeds, the influence of airspeed on ride comfort in turns appears to be minor.

The variation of predicted ride-comfort rating with roll angle in steady turns for various maximum roll rates is shown in figure 8(c). Maximum roll rates typical of transport aircraft operations appear to have little influence on passenger comfort.

The effects of turn duration (time at maximum roll angle) on the variation of predicted ride-comfort rating as a function of roll angle are shown in figure 8(d). At roll angles less than 27°, increasing duration has a slightly beneficial effect. This effect occurs because of decreased rms roll rate and increased rms pitch and yaw rates (which have negative regression coefficients). For roll angles greater than 27°, the rapid increase in linear acceleration (particularly normal acceleration) with increasing roll angle reverses the situation, so that increased duration results in a degradation of comfort. However, in either case, the effects of turn duration appear to be minor except at high roll angles.

Steady Descents

The variation of predicted ride-comfort rating with steady descent pitch angle for various turbulence intensity levels is shown in figure 9. Because aircraft attitude is constant, ride comfort predicted by the regression model depends only on rms normal and longitudinal accelerations, which are symmetric about a zero pitch angle. This symmetry is due to the nature of the regression model employed and may not properly predict the ride comfort of large nose-up pitch angles. The degradation of ride comfort with increasing pitch angle is practically linear. The effects of turbulence intensity are relatively constant over the range of pitch angles shown. The ride-comfort ratings predicted by the University of Virginia regression model for a zero pitch angle are also shown on the figure.

Longitudinal Decelerations

The variation of predicted ride-comfort rating with average longitudinal deceleration is shown in figure 10(a) for various turbulence intensities. The airspeed is assumed to start at 200 knots and decrease over a 20-second interval (with a sinusoidal time history) at zero pitch angle. This deceleration is followed immediately by a 10-second pitchover to a final pitch angle of -5°. The effect on ride comfort of increasing average deceleration appears to be minor. The effects of turbulence are almost constant over the range of decelerations shown. Ride-comfort ratings predicted by the University of Virginia regression model at zero deceleration are also shown on the figure.

The effects of average deceleration on predicted ride comfort for various negative final pitch angles are presented in figure 10(b). The mean slope of this variation decreases as the magnitude of the final pitch angle increases and may actually become negative at pitch angles more negative than -10°. This is because the pitchover greatly increases the rms normal acceleration for higher airspeeds. Thus, increasing the average deceleration to decrease the airspeed at pitchover reduces the normal acceleration contribution to discomfort. Reduction of airspeed prior to initiating any substantial pitchover will therefore improve ride comfort. The results also suggest that the maximum negative pitch angle be limited to a value of 10°.

CONCLUDING REMARKS

A series of flight experiments has been conducted using a variable-stability research aircraft and a significant number of passenger subjects to investigate the ride quality of terminal-area flight maneuvers. The data obtained have been analyzed through multiple linear regression to produce a ride-comfort model. The model predicts the ride comfort of a flight maneuver as a function of the rms six-degree-of-freedom motions of the aircraft during the maneuver. Application of the model to computer-synthesized maneuver time histories indicates that:

(1) Roll angle during steady turns should be limited to a maximum of 30°

(2) The effects on ride comfort of roll rate, airspeed, and duration during steady turns are minor.

(3) Nose-down pitch angle during steady descents should be limited to a maximum of 10°.

(4) Ride comfort during longitudinal deceleration and pitchover is primarily dependent upon the change in pitch attitude and is only mildly affected by the average longitudinal deceleration.

(5) Reduction of airspeed prior to initiating any substantial pitchover will improve ride comfort.

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TABLE I. - TIFS FLIGHT TEST MANEUVERS

Maneuver type	Variables	Range	Combinations of unique variables
Descent	Pitch attitude	-13.5° to 6.5°	11
	Descent rate	-1.37 to 23.77m/sec	
	Initial altitude	1036 to 3231 m	
Turn	Roll attitude	±50°	23
	Roll rate	±20 deg/sec	
	Airspeed	135 to 205 knot	
	Altitude	427 to 3322 m	
Longitudinal deceleration	Longitudinal deceleration	0.06 to 0.18 g unit	10
	Descent acceleration	0 to 0.79 g unit	
	Final pitch attitude	-6.6 to 0.9°	
	Pitch rate	-5.2 to 0 deg/sec	
	Initial altitude	731 to 3292 m	
Combination	Longitudinal deceleration	0.06 to 0.18 g unit	
	Descent acceleration	0 to 0.6 g unit	
	Final pitch attitude	-5.2° to 3.3°	4
	Pitch rate	-4.9 to 0 deg/sec	
	Roll altitude	±42°	
	Roll rate	± 15 deg/sec	
	Initial airspeed	190 to 210 knot	
	Initial altitude	1006 to 3170 m	
Total number of maneuvers			48

TABLE II. - TIFS MANEUVER EXPERIMENT

PASSENGER SUBJECT CHARACTERISTICS

Characteristics	Air travelers in general, percent	Test subjects, percent
Age:		
20 yr and under	18	16
21 to 40 yr.	45	53
41 to 60 yr.	32	31
61 yr and over	5	0
Sex:		
Male	75	66
Female	25	34
Frequency of flying (number of times in last 2 yr):		
0	17	6
1 to 3		19
4 to 9	63	31
10 to 25		44
25 and over	20	

TABLE III. - RIDE-COMFORT RATING SCALE

Very comfortable	1
Comfortable	2
Somewhat comfortable . . .	3
Neutral	4
Somewhat uncomfortable . .	5
Uncomfortable	6
Very uncomfortable	7

Table IV. - RIDE-COMFORT RATING DISTRIBUTION

Maneuver tape	Flight test	Rating of -						
		1	2	3	4	5	6	7
II	1	16	43	44	38	58	31	10
I	2	28	53	46	29	50	26	8
II	3	32	48	37	28	68	26	1
II	4	23	61	43	43	51	17	2
I	5	5	47	52	52	68	16	0
I	6	5	41	43	55	81	11	4
II	7	13	70	62	38	46	7	4
I	8	9	43	63	46	55	20	4
Total		131	406	390	329	477	154	33

TABLE V. - CORRELATION MATRIX OF ALL EXPERIMENTAL FACTORS

	Indicated airspeed	Climb rate	Altitude	Flight path angle	Pitch angle	Roll angle	Yaw rate	Pitch rate	Roll rate	Normal acceleration	Transverse acceleration	Longitudinal acceleration
Comfort rating	.147	.232	.086	.210	.212	.199	.184	.378	.207	.493	.219	.305
Longitudinal acceleration	-.060	.415	-.163	.356	.820	.055	.104	.249	.004	.290	.156	1
Transverse acceleration	-.207	-.154	-.085	-.130	.085	.578	.616	.553	.616	.440	1	
Normal acceleration	.059	-.050	-.087	-.068	.157	.689	.642	.925	.585	1		
Roll rate	-.179	-.508	-.011	-.499	-.036	.909	.921	.764	1			
Pitch rate	-.163	-.288	-.111	-.277	.125	.865	.861	1				
Yaw rate	-.288	-.510	-.053	-.485	.033	.964	1					
Roll angle	-.174	-.505	-.034	-.502	-.010	1						
Pitch angle	-.154	.485	-.114	.426	1							
Flight path angle	.068	.980	-.110	1								
Altitude	.211	-.055	1									
Climb rate	.209	1										
Indicated airspeed	1											

TABLE VI. - MOTION-VARIABLE STANDARD DEVIATIONS ASSUMED FOR AIRCRAFT TURBULENCE RESPONSE

Variable	Turbulence Intensity			
	Zero	Light	Moderate	Heavy
Longitudinal acceleration, g unit	0	0.002	0.020	0.040
Transverse acceleration, g unit	0	.003	.030	.060
Normal acceleration, g unit	0	.010	.100	.200
Roll rate, deg/sec	0	.2	2.0	4.0
Pitch rate, deg/sec	0	.1	.6	1.1
Yaw rate, deg/sec	0	.1	.8	1.6

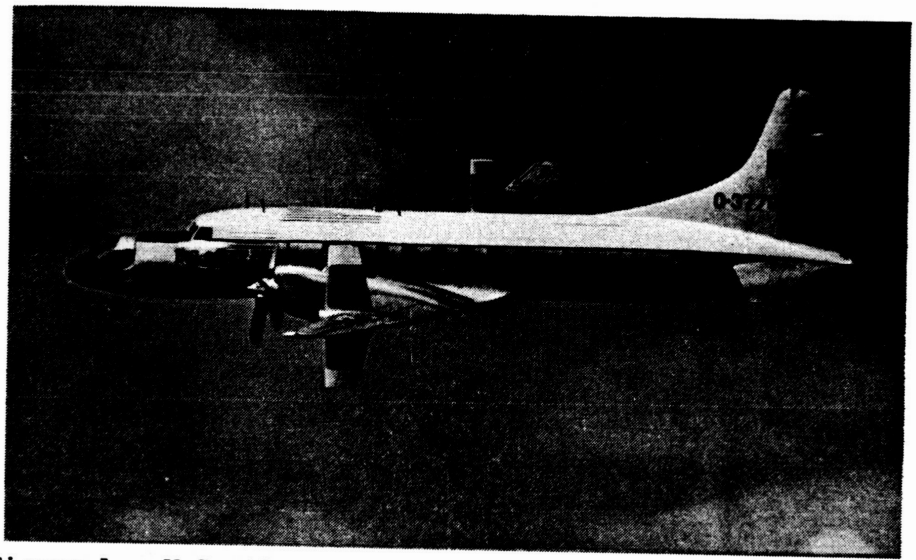


Figure 1.- U.S. Air Force Total In Flight Simulator (TIFS).

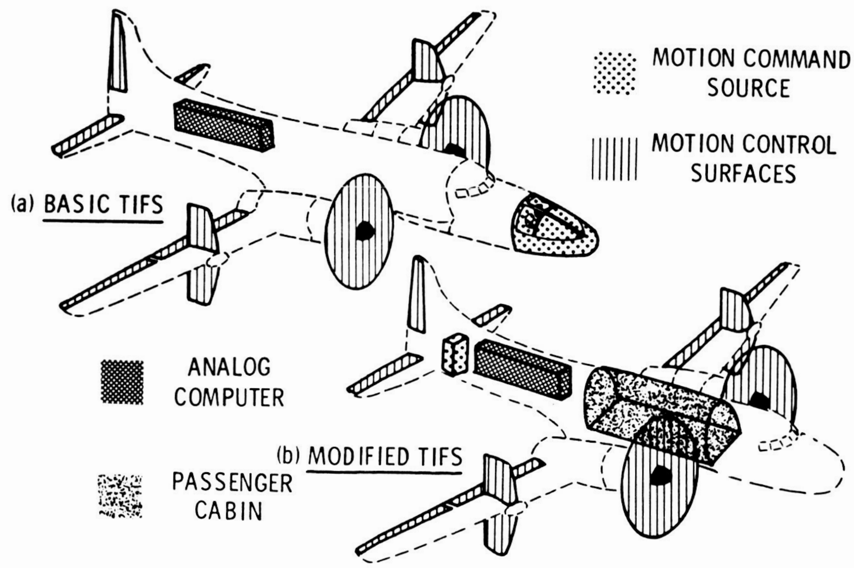


Figure 2.- TIFS modifications for ride-quality research.

Figure 3.- TIFS passenger cabin for ride-quality experiments.

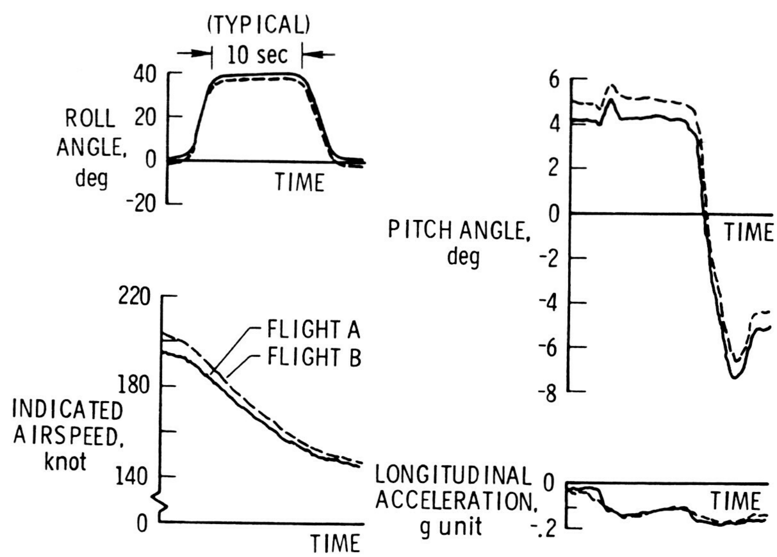
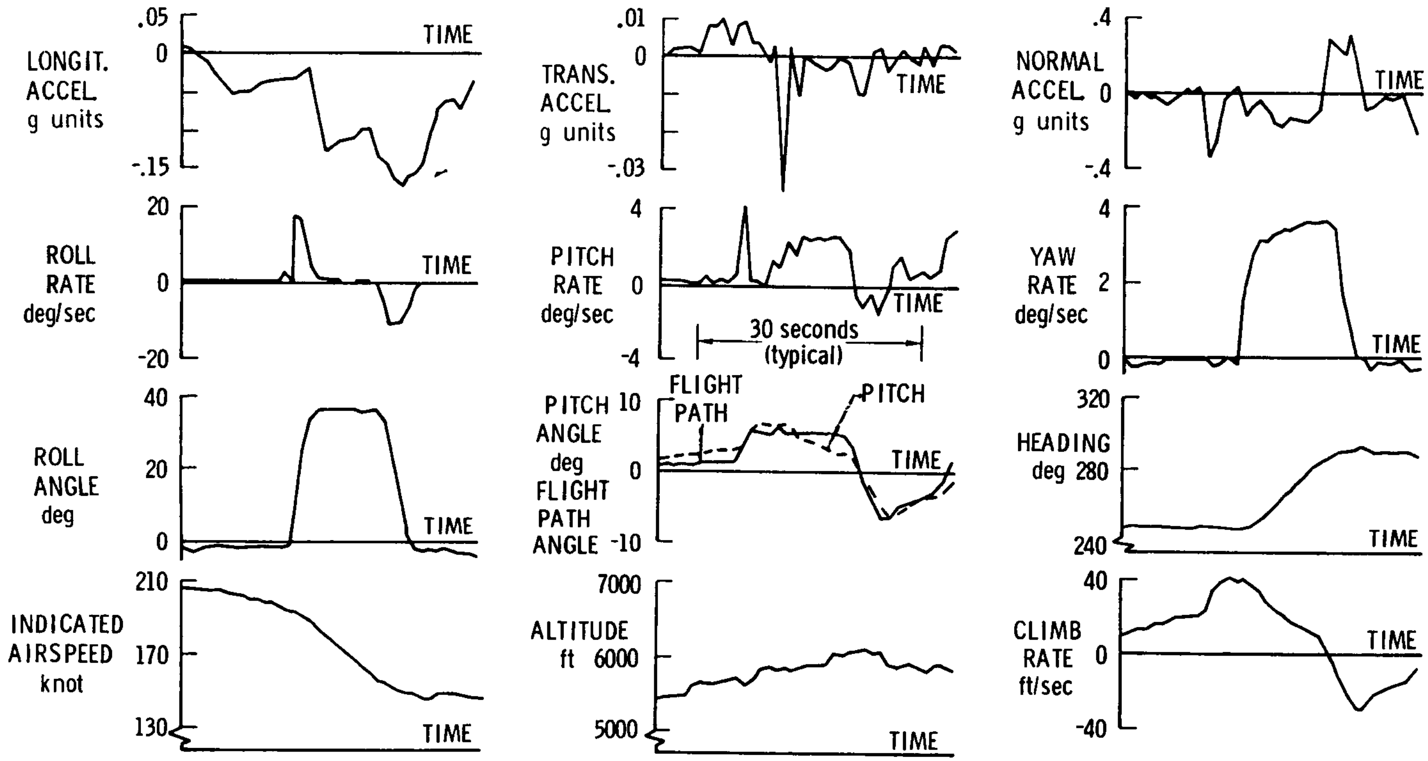


Figure 4.- Example of maneuver repeatability between flights for tape-controlled TIFS in turning decelerating descent.



(a) Time histories of recorded motion variables for turning decelerating descent.

FLIGHT	SEAT 1	2	3	4	5	6	7	8	9	10	MEAN RATING
	RATING										
2	2	7	6	2	4	5	4	2	6	7	4.5
5	5	5	6	5	5	5	4	5	2	3	4.5
6	5	4	6	4	3	3	5	5	5	5	4.5
8	4	3	5	3	5	5	5	4	4	5	4.3

(b) Individual ride-quality ratings obtained during maneuver repetition of four separate flights.

Figure 5.- Example objective and subjective data obtained during TIFS maneuver experiments.

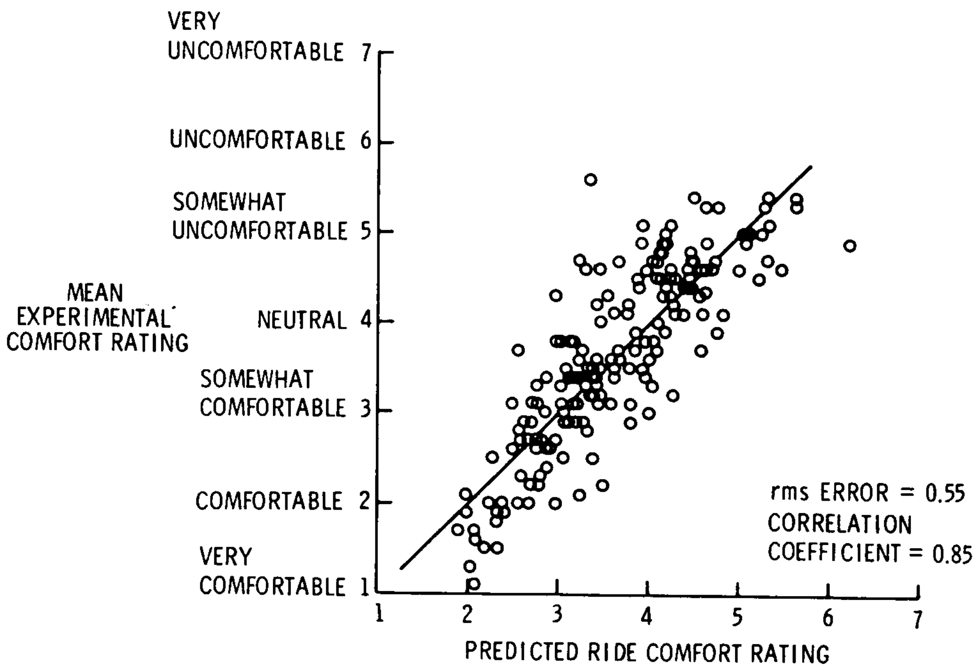


Figure 6.- Experimental rating as a function of model prediction of ride quality.

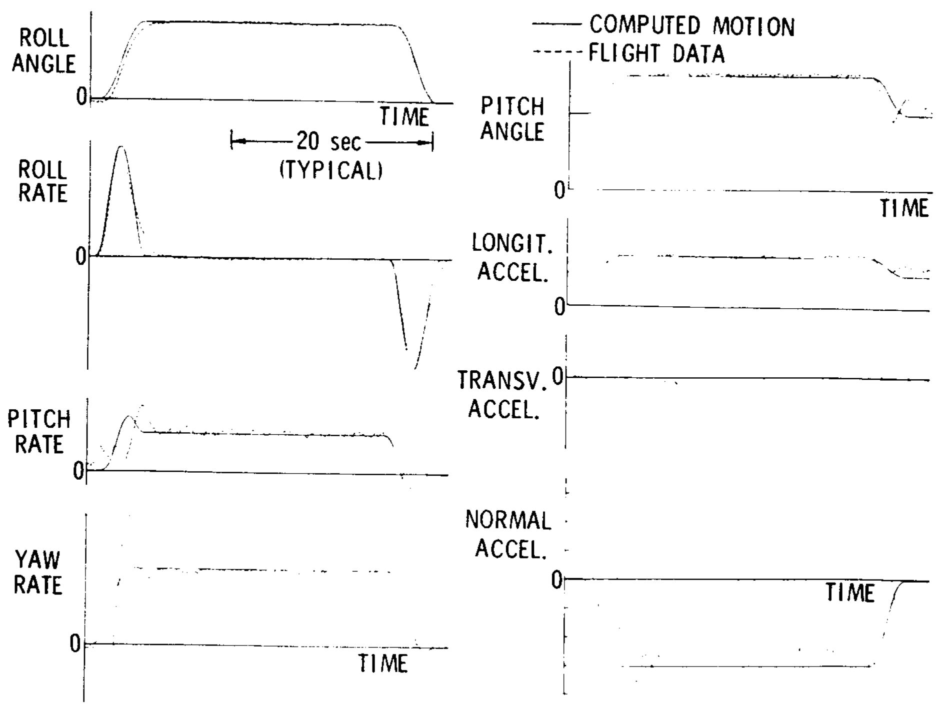
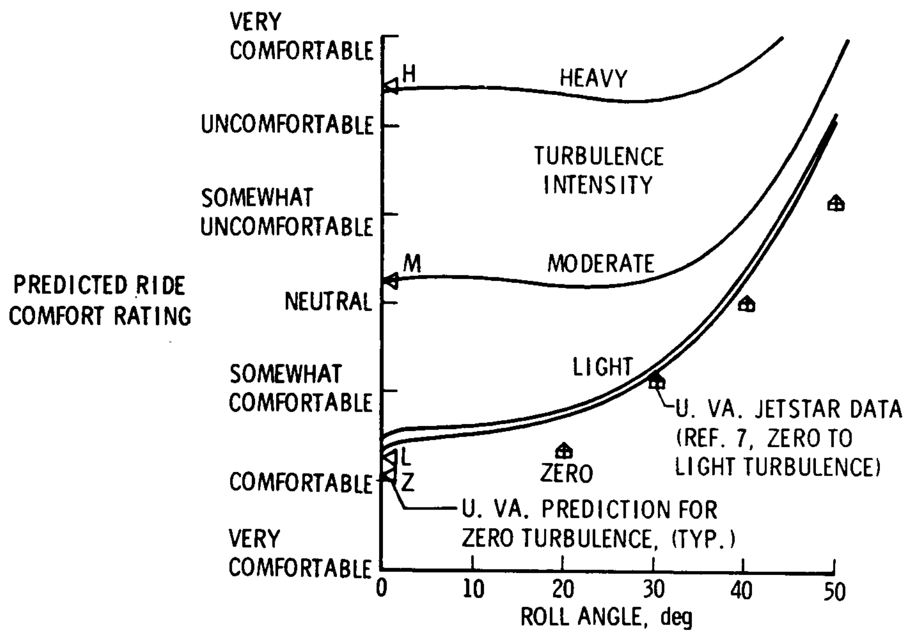
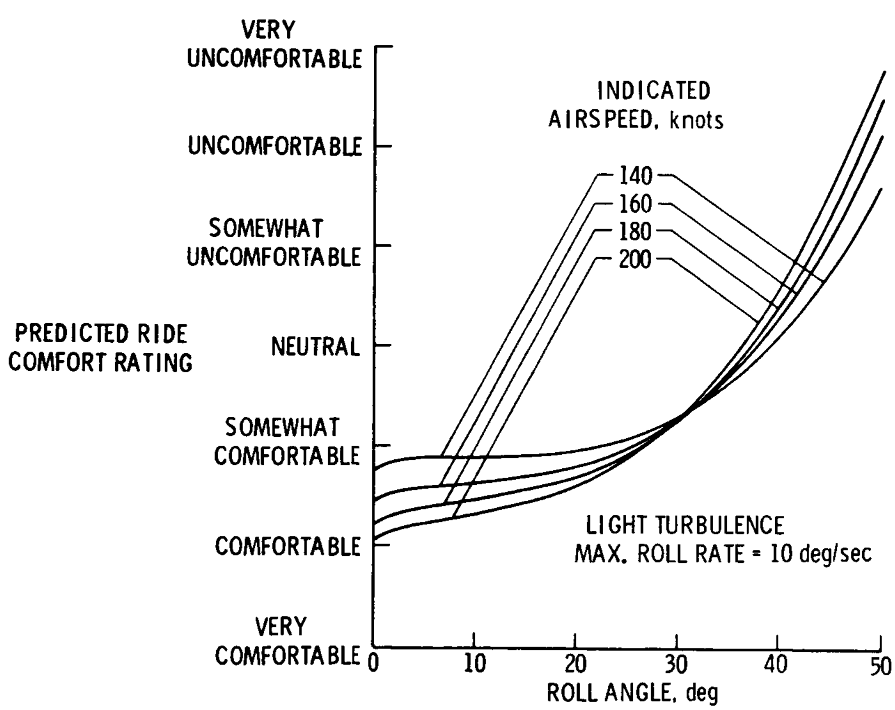


Figure 7.- Time history of example computer-synthesized maneuver (steady turn).

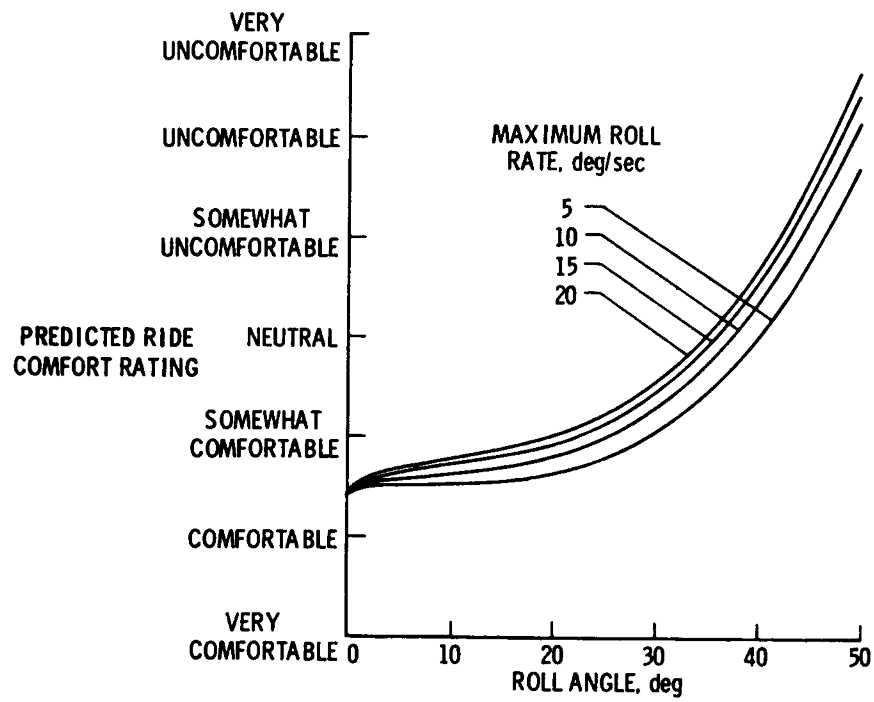


(a) For various turbulence intensities.

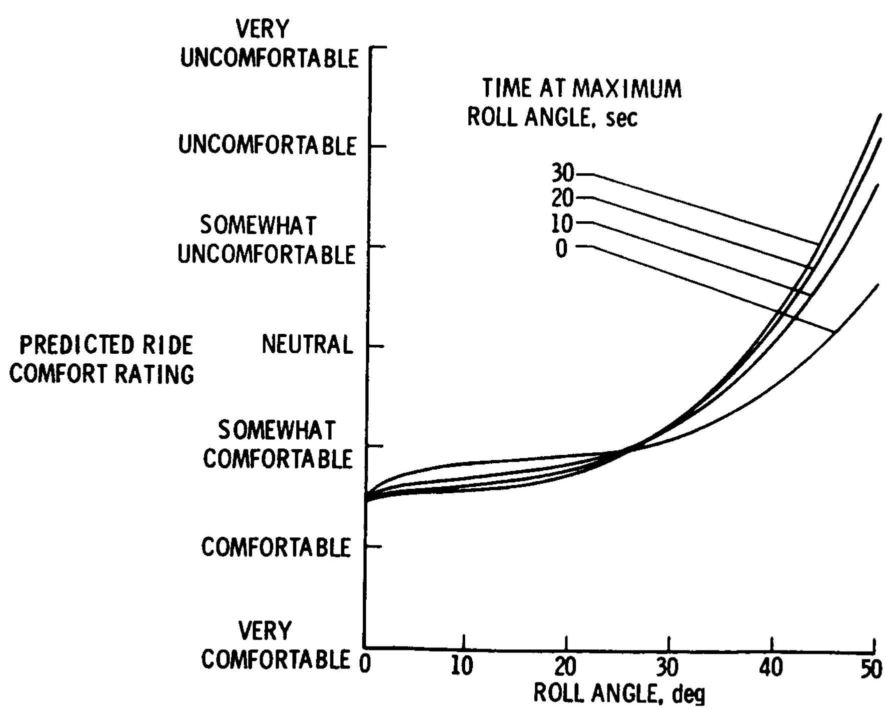


(b) For various airspeeds.

Figure 8.- Predicted comfort of steady turns.



(c) For various maximum accelerations.



(d) For varying durations.

Figure 8.- Concluded.

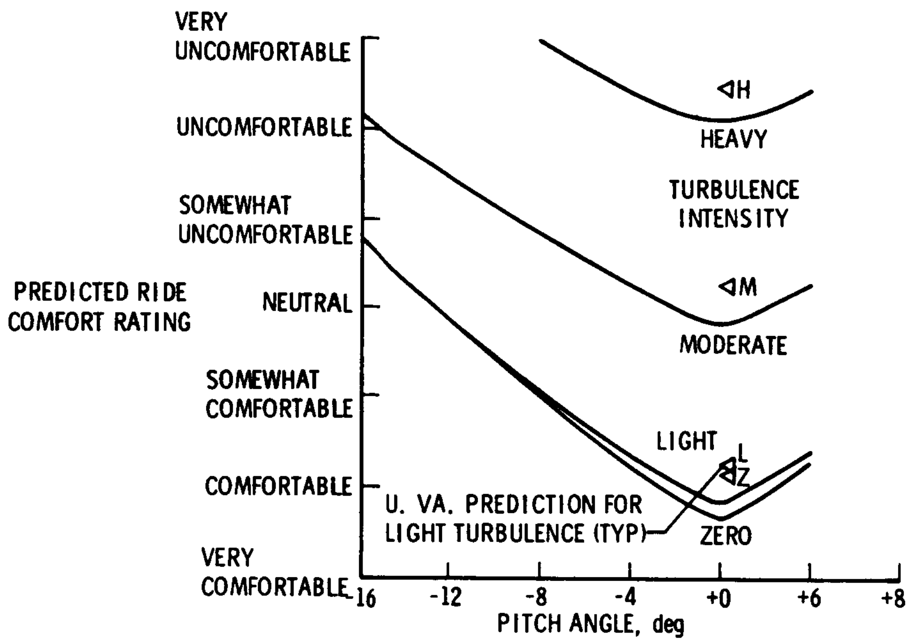
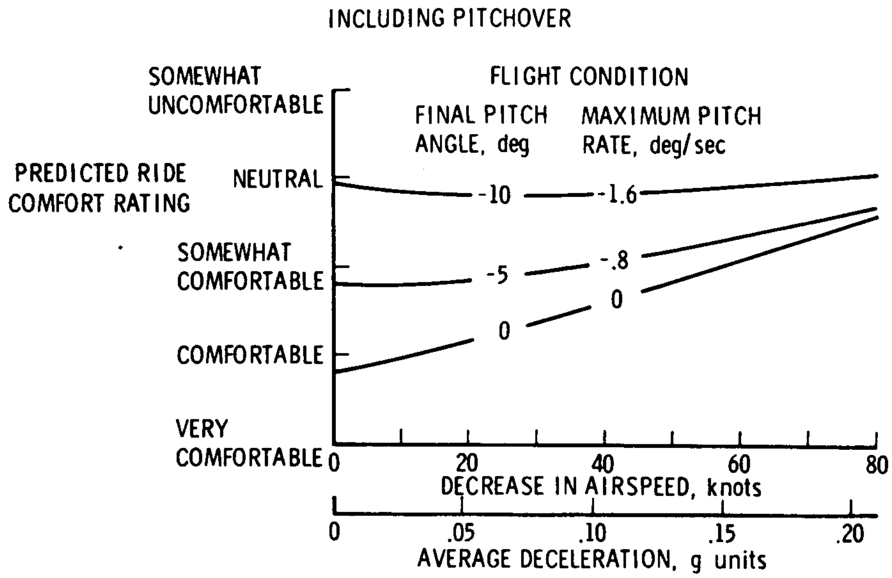
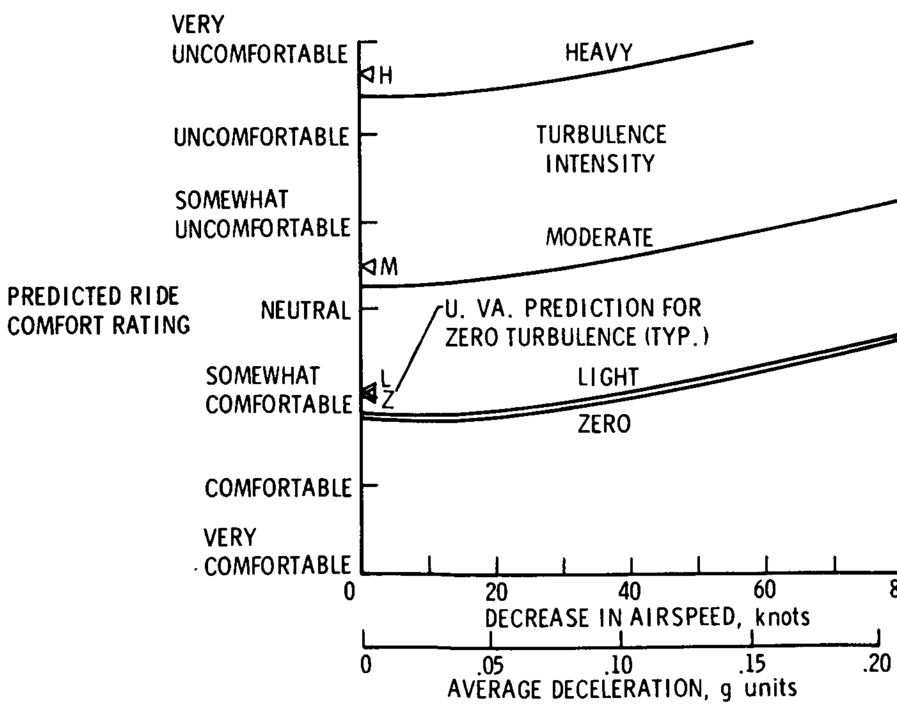


Figure 9.- Predicted comfort of steady descents for various turbulence intensities.



(a) For various turbulence intensities.



(b) For various final pitch angles.

Figure 10.- Predicted comfort of longitudinal decelerations.