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PASSENGER RIDE COMFORT TECHNOLOGY FOR

TRANSPORT AIRCRAFT SITUATIONS

By

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16. Abstract

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SUMMARY

A brief overview is given of NASA research in ride comfort and of the resultant technology. Three useful relations derived from the technology are presented together with five applications of these relations to illustrate their effectiveness in addressing various ride comfort situations of passenger transports.

INTRODUCTION

Passenger ride comfort can have a significant influence in determining acceptance and use of various modes of air transportation. The definition of ride comfort as used in the present paper is expressed as the impact on the passenger of all aspects of the vehicle physical environment that affect his acceptance of the ride. The time has arrived when some reasonable level of comfort is expected by the traveling public. Advent in the late 1950's of jet transports, cruising at high altitude where the air is generally smooth, made possible levels of ride comfort in long-haul transportation far superior to anything previously attainable. Many situations still arise, however, where ride comfort can be adversely affected if special attention is not given in the design and/or operations of the aircraft. (See ref. 1.) To address these situations, ride comfort technology is required, but until a few years ago, key portions of this technology involving human factors was only poorly understood. At that time NASA initiated research effort directed toward identifying the various critical factors and toward providing quantitative relations to account for these factors in problem situations.

Aircraft situations which can lead to ride comfort problems fall into three general categories: input environments to the vehicle; aircraft operations; and aircraft configurations. Four example problem situations are listed as follows:

Environments
- Wind shears and gusts
- Turbulence
- Trailing-vortex wakes
- Runway roughness and waviness

Operations
Cruise at low altitude
Terminally configured vehicle maneuvers
Excessive rate of change of cabin pressure
Cabin temperature too warm

Configurations
Unswept wings and/or low wing loadings
Outsize fuselage/empennage surfaces
Propulsion systems producing noise/vibration
Marginal size seats and legroom

Input environments which influence the ride-motion environment consist of both naturally occurring phenomena such as gusts or turbulence and man-generated phenomena such as trailing-vortex wakes or runway roughness. Incidentally, runway roughness will become an increasingly important factor with the advent of aircraft such as supersonic transports having relatively flexible fuselages and high take-off speeds. Aircraft operations influence ride environments in the form of motions caused by maneuvers, of pressure changes caused by rapid descents, or of too high temperature. Finally, aircraft configurations influence the ride environment by size and shape of external surfaces which generate aerodynamic perturbing forces; by onboard equipment, such as power plant noise and vibrations; and by passive equipment which directly interface the passengers such as marginal size seats with limited elbowroom and legroom.

The present paper has two primary objectives: (1) presentation of a brief overview of NASA ride comfort research effort and (2) description of useful relations derived from the technology together with several applications of these relations to illustrate their usefulness in addressing air transport ride problems situations.

SYMBOLS

a	acceleration
C	comfort rating on a 7-point scale
dB(A)	A-weighted noise level, dB
E	event (given ride situation)
g	acceleration of gravity, 9.8 m/sec^2
$\dot{h}$	rate of change in altitude, m/min
ℓ	seat legroom, cm
p	roll rate, deg/sec
S	satisfaction

T	temperature, ^{o}C
V	indicated airspeed, knots
w	seat width between armrests, cm
γ	flight-path angle, deg
δ	Kroneker δ
θ	pitch angle, deg
σ_a	standard deviation of acceleration, g units
ϕ	roll angle, deg

Subscripts:

cm	compound maneuver
dc	descent or climb maneuver
E	event
env	environmental (factors other than maneuvers, seating space)
$\dot{h}$	rate of change in altitude
ι	longitudinal direction
man	maneuver
max	maximum
mot	motion
no	noise
po	pitchover
rms	root-mean-square value
seat	seating space
T	temperature
t	transverse direction
trip	total trip
turn	turning maneuver

v vertical direction

z normal direction to cabin floor

RESEARCH PROGRAM

Analysis Method

A schematic of the analysis method (ref. 2) to assess ride comfort is illustrated in figure 1. A vehicle forcing function (e.g., turbulence and maneuvers) is converted into a ride-motion environment for the passenger using the appropriate transfer function for the vehicle system being analyzed. This environment together with other inputs (e.g., noise and temperature) provides a total ride environment from which a comfort evaluation is obtained using a transfer function which represents the passenger. Since response to a given ride environment can vary widely between subjects, a statistical approach is employed wherein the evaluation is expressed as a mean subjective comfort response. The calculated comfort evaluation is then related by a subjective value transfer function to a satisfaction evaluation of the flight in the context of the overall trip. Since trip satisfaction can also be influenced by factors other than ride comfort (e.g., cost, time, schedule, and safety), the subjective value transfer functions for ride comfort are not independent of other factors. Thus, the satisfaction model presented herein represents satisfaction in the context of a particular type operation (e.g., U.S. commuter operation).

Selection of Research

At the beginning of NASA research in transport aircraft ride quality in the early 1970's, the level of technology varied substantially for the several components of the analysis method shown in figure 1. Turbulence environment forcing functions to the aircraft had been measured and reasonably well quantified in statistical terms (refs. 3 and 4) as a function of factors such as altitude, terrain, and time of year. Vehicle transfer functions had been derived (e.g., ref. 5) and for the larger transport airplanes were generally well quantified because of other needs (e.g., aircraft dynamic stability and structural dynamics). Factors significant in affecting subjective reaction were not well defined both in regard to identification and to quantification of their character and magnitude (ref. 6). The subjective transfer function was poorly defined with prior research efforts generally limited to laboratory studies of vertical and transverse sinusoidal motions (e.g., ref. 7). Much of the work had been directed toward tolerance and task performance level and had dealt with relatively high motion magnitudes in the discomfort regime (these were, in fact, the type of data that subsequently provided the basis for ISO standard ISO-2631 (ref. 8), which offers provisional guidance for ride comfort vibration levels). Consequently, ride comfort evaluation technology was generally qualitative in character. Subjective value function technology was limited to only a few areas (costs and trip time), whereas ride comfort effects were a relatively unknown quantity.

Overall evaluation of the state of the art of ride comfort technology then existing (e.g., ref. 9) indicated that implementation of the analysis method outlined in the previous section would require inputs and quantitative relations which could only be obtained from additional data generated by carefully structured experiments.

Experimental Effort

The approach taken in generating experimental data appropriate for ride comfort modeling is illustrated in figure 2. In this approach, subjective evaluations of ride comfort were obtained and compared with the measured ride environment. These evaluations were obtained for both fare-paying passengers and experienced test subjects traveling onboard scheduled air carriers (ref. 10) and for test subjects in controlled experiments on research aircraft (refs. 11 and 12) or ground-based simulators (e.g., refs. 13 and 14). On air carriers, test subjects gave subjective ratings periodically during the flight plus an overall rating for the total flight, while simultaneously, fare-paying passengers gave an overall rating at the conclusion of the flight. Data from air carriers were particularly useful in qualitatively identifying both the environmental factors important in real-world situations (see list at top of fig. 2) and the nature and magnitude of these environmental factors.

Controlled experiments using research aircraft were carried out to systematically investigate situations of interest (e.g., maneuvers) which would not normally be experienced in any significant amount during air carrier operations. Controlled experiments using simulators were carried out to gain a detailed understanding of the influence of factors or factor components on discomfort. Examples (refs. 13 to 20) include effects of single-degree-of-freedom vibrations with either sinusoidal or random frequency content and of various degrees of freedom alone or in combination; effects of single frequency or random noise, with and without vibrations; and effects of seat transmissibility on response to input vibrations through the floor.

Information generated by the various experimental studies has been used to model (relate) passenger comfort as a function of various ride environment inputs. These models range in complexity from simple relations for single-degree-of-freedom motion inputs (e.g., ref. 17) obtained from simulator data to complex relations for multiple-degree-of-freedom random inputs obtained by regression analysis of flight data (ref. 21). While present models are useful as illustrated later, there is yet no fully comprehensive and reliable model to meet all situations. As technology builds, considerable improvement in comfort models can be expected.

Those interested in obtaining a more detailed understanding of NASA research and resultant technology are referred to the proceedings of NASA-sponsored ride quality symposia held in 1972 and 1975 (refs. 22 and 23). These proceedings also contain much valuable information concerning research outside NASA both in the United States and in the United Kingdom plus a description and critique of ISO-2631 (ref. 8).

Ride comfort research presently underway or envisioned by NASA centers in two areas. The first area concerns vehicle-unique phenomena of unusual environments (such as single-tone noise in civil helicopters) which will periodically arise with advent of either new transport vehicles or new vehicle operations. The second area includes various individual effects items (see list above the Ground-Based Simulators photograph of fig. 2) where detailed information is required to gain a better understanding of ride comfort phenomena and to refine comfort-rating models.

USEFUL RIDE COMFORT RELATIONS

Three ride comfort relations which are useful in addressing transport aircraft problem situations have been developed as follows from NASA research technology:

(1) Comfort Model Relation — to provide the subjective transfer function for relating ride environment to ride comfort (see fig. 1)

(2) Ride Satisfaction Relation — to provide the subjective value function for relating ride comfort to trip satisfaction (see fig. 1)

(3) Response Integration Relation — to provide a method for appropriately weighting and summing the series of local comfort ratings (experiences) of a trip to obtain an overall evaluation of comfort and satisfaction

Although the complexity and content of the relations are subject to individual judgment and to the data base available, the present state of the art is considered sufficiently advanced to define each relation in reasonably meaningful terms.

Comfort Model Relation

From the several comfort rating models developed during the course of the research effort, a composite model has been developed which is comprised of the more important ride environmental factors in a relatively simple form. This model, shown schematically in figure 3, was derived from flight data primarily of small to medium size (15 to 60 passenger) turboprop airplanes in short-haul type operations and, thus, may not be fully applicable to other transport situations. The model provides a numerical rating of subjective comfort response C, where C has the following descriptors:

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

The model lists in parallel the three groupings of maneuver factors, environmental factors (motion, noise, temperature, and pressure), and seating-space factors, inasmuch as data analysis to date indicated little additive or cross-coupling effects between these three groups. Relations for the maneuver-factors group are based on regression analysis of controlled-experiment results (1920 test-subject data points) carried out by NASA in-house effort using the USAF Total In-Flight Simulator (TIFS) research aircraft. (See ref. 24.) Relations for the environmental factors group and for the seating-space factors group are based on results of scheduled air carrier surveys (2976 test-subject data points) carried out by the University of Virginia.

According to the model, the mean subjective comfort rating for a unique ride event (situation) is the maximum value provided by any of the three factor groups for that event:

$$C_E = \max\left(C_{env}, C_{man}, C_{seat}\right)$$

The model relates the mean subject comfort to the factors of each factor group as follows:

Environmental Factors Group:

$$C_{env} = 2 + C_{mot} + C_{no} + C_{\dot{h}} + C_T$$

where

$$C_{mot} = 18.9\sigma_{a,v} + 12.1\sigma_{a,t} \qquad \left(\sigma_{a,v} \geq 1.6\sigma_{a,t}\right)$$

$$= 1.62\sigma_{a,v} + 38.9\sigma_{a,t} \qquad \left(\sigma_{a,v} < 1.6\sigma_{a,t}\right)$$

$$C_{no} = 0.19(\mathrm{dB(A)} - 85)$$

$$C_{\dot{h}} = 0.005(\dot{h} - 90)\delta_{\dot{h}} \qquad \begin{pmatrix} \delta_{\dot{h}} = 1 \quad \text{for} \quad \dot{h} > 90 \text{ m/min} \\ \delta_{\dot{h}} = 0 \quad \text{for} \quad \dot{h} \leq 90 \text{ m/min} \end{pmatrix}$$

$$C_T = 0.054(T - 20.5)\delta_T \qquad \begin{pmatrix} \delta_T = 1 \quad \text{for} \quad 2 + C_{mot} + C_{no} + C_{\dot{h}} > 3.4 \\ \delta_T = 0 \quad \text{for} \quad 2 + C_{mot} + C_{no} + C_{\dot{h}} \leq 3.4 \end{pmatrix}$$

Maneuver Factors Group:

$$C_{man} = C_{turn} \text{ or } C_{po} \text{ or } C_{dc} \text{ or } C_{cm} \quad \text{(depending on type maneuver)}$$

where

$$C_{turn} = 0.293 + 0.0665 \left|\phi_{max}\right| + 0.07 \left|p_{max}\right| + C_{no} + C_{\dot{h}} + C_T$$

$$C_{po} = 1.75 + 22.1a_{z,rms} + C_{no} + C_{\dot{h}} + C_T$$

$$C_{dc} = 0.151 + 0.098 \left|\theta_{max}\right| - 0.118\gamma_{max} + 0.0195V_{max} + C_{no} + C_{\dot{h}} + C_T$$

$$C_{cm} = 1.48 + 12.3\sigma_{a,l} + 32.8\sigma_{a,t} + 11.62\sigma_{a,v} + 0.022\dot{h}_{rms} + C_{no} + C_{\dot{h}} + C_T$$

Seating Space Group:

$$C_{seat} = 1 + \left[0.0077(63 - w)^2 + 0.16(30 - \ell)^2\right]^{1/2}$$

$$\text{for} \quad 30 < w \leq 63 \quad \text{and} \quad 18 < \ell \leq 30$$

The equations presented are intended to provide first-order evaluations of ride comfort. More detailed evaluations must await further advancements in the technology to resolve presently open issues, including the importance of spectral content for noise and motion, the ability of more complex models to account for increased variance, and the validation of models through acquisition of test data appropriate for establishing model accuracy for all types of transports (e.g., fixed-wing commuter, helicopters, and wide-body jets).

Ride Satisfaction Relation

Comfort judgments need to be related to a more value-oriented variable to provide assessment of the influence of ride comfort on traveler acceptance and use of a system. The value-oriented variable chosen was the percentage of passengers satisfied with the ride, that is, the fraction of passengers who, when querried at the conclusion of a flight, said they would be willing to take another flight at least without hesitation. Based on passenger questionnaire data (861 passenger samples) from air carrier surveys, the satisfaction relation shown graphically in figure 4 was established (ref. 25). This relation can be applied to subjective comfort response data to obtain the probability of satisfying a given percentage of the passengers. Implicit in the output, however, are all the system input variables to the subjective value function as illustrated in figure 1. Research to date has made no attempt to separately quantify the effects of each input variable; however, such quantification is ultimately needed to trade-off comfort with other system components.

Response Integration Relation

During an aircraft flight, a series of unique ride environment events is experienced by the passengers. While the mean comfort rating for each of these events can be established by application of the comfort rating model described. the problem remains concerning the manner in which these "local" comfort ratings (experiences) can be integrated to obtain an overall response for the entire flight. This problem was addressed by employing comfort rating data obtained from the special group of test subjects who rode scheduled airlines. To a high degree of accuracy, the overall comfort ratings of these subjects were found to be related to the mean overall response of the passengers onboard the same aircraft (ref. 26). An approximate relationship was established for weighting the series of local comfort ratings (obtained periodically) of the test subjects into a rating which closely matched their overall trip comfort rating. For a series of local ride events of equal time duration

$$E_1, E_2, E_3, \ldots, E_n$$

the corresponding weighting factors to be applied to the event comfort rating can be expressed as

$$1^{3/4}, 2^{3/4}, 3^{3/4}, \ldots, n^{3/4}$$

This relationship, a 3/4-power weighting function, is assumed appropriate for weighting any series of local mean comfort rating experiences into an expected total trip mean reaction of passengers. This weighting implies that a memory decay occurs (events at the beginning of a flight being less important than events at the end) such that a passenger's overall reaction to the flight is a stronger function of the latter portions of the flight than the beginning. The total trip comfort rating in equation form is

$$C_{trip} = \frac{\sum_{E=1}^{n} E^{3/4} C_E}{\sum_{E=1}^{n} E^{3/4}}$$

TECHNOLOGY APPLICATIONS

The three ride comfort relations described in the previous section when integrated into the analysis method previously outlined provide the predictive method shown in figure 5. This figure gives inputs to the aircraft and to the comfort-rating model identified to date as important. The rating value provided by the comfort-rating model for a given ride situation is shown as input either to the ride satisfaction relation for determining ride event satisfaction or to the event weighting/summing relation for determining total trip comfort and total trip satisfaction. The method shown in figure 5 or selected portions thereof can be used to address a variety of transport aircraft problem situations. Example applications will be presented to illustrate various uses to meet different types of needs.

Evaluation of Uprigged Spoiler

One of the simple applications of the technology is in evaluating the ride comfort for a given measured environment within the aircraft. One such application was carried out in evaluating the effects of uprigged spoilers on ride comfort during landing approach. Use of such uprigged spoilers during landings is a promising approach for reducing the magnitude of trailing vortices from large transports and, thereby, reducing hazard of vortex-caused upset to following aircraft (ref. 27).

Since the deployment of spoilers is known to worsen the ride environment in aircraft, an exploratory ride comfort investigation was carried out at the NASA Dryden Flight Research Center by the University of Virginia to evaluate ride effects. Portable equipment for measuring and recording the motion environment was placed onboard the Boeing 747 airplane for one flight of simulated landings at high altitude (≈3000 m) during which uprigged spoilers of various deflections were deployed (fig. 6). The dynamic motion ride environment was measured and typical results are shown in the lower portion of the figure. These results were used as inputs to the C_{mot} equation of the comfort-rating model to provide mean comfort ratings for various amounts of spoiler deflection and for sideslip at a single spoiler deflection. A scale of percent passengers satisfied, obtained from the ride satisfaction relation of figure 4, is also shown in figure 6. The results indicate that use of uprigged spoilers would degrade the number of passengers satisfied with the ride by 10 to 15 percent depending on spoiler deflection. For real landings at much lower altitude, where a higher level of air turbulence can be expected, use of uprigged spoilers could possibly have a somewhat greater adverse effect on ride comfort.

Identification of Key Factor in Complex Maneuver

A combination of ride environment factors, experienced either simultaneously or in close succession, can result in an uncomfortable ride without direct indication of which factor or factors contributed most to discomfort. Such a situation occurred in a research aircraft investigation (ref. 24) by NASA of a curved decelerating descent typical of that which could be employed, using advanced navigation aids, for localizer/glide-slope capture in a relatively short distance. A mean comfort rating of 4.8 (somewhat uncomfortable) was given by test subjects who rode in the aircraft. Use of the comfort-rating model was employed to identify which factor or factors in the maneuver provided the greatest adverse influence on ride rating.

As shown in figure 7, the approach followed was to divide the complex maneuver into simple segments which could be individually analyzed. Generally each segment had only one dominant ride environment factor. For each segment, the maneuver ride input was quantified and the comfort rating for that input was determined by use of the maneuver motion component of the comfort-rating model. Finally the comfort rating was converted to expected ride satisfaction through use of the satisfaction relation. As can be seen from the results of figure 7, the key segment identified was that which involved a 3.2-degree-per-second pitchover of the aircraft in which the predicted ride rating was 5.1 and predicted passenger (PAX) satisfaction was 61 percent. The negative normal acceleration experienced in this pitchover was quite unpleasant to passengers. Deceleration before pitchover, such as was carried out during the turn, rather than after pitchover was a wise choice since it reduced as much as possible the magnitude of the negative normal acceleration.

Derivation of Equicomfort Levels of Environments

The comfort-rating model and ride satisfaction relation can be used not only to evaluate passenger response to a given input environment (as illustrated in the previous example) but also to derive an upper boundary of the magnitude of a ride environment which could be expected to provide a given level of passenger satisfaction. Since a ride environment consists of a combination of various environmental components, information on component combinations is desirable. The present example (fig. 8) considers three environmental components: vertical random motion, transverse random motion, and noise. For many ride event situations, these three components are often the most important factors affecting comfort in transport aircraft.

The approach used was to determine the mean comfort-rating value (from fig. 4) which corresponded to the desired value of percent passengers to be satisfied. The comfort-rating model was then evaluated to provide information for constructing the graphs shown in figure 8. The graphs present levels of environment combinations consistent with obtaining either of two levels of number of passengers satisfied: 70 percent or 90 percent. In applying any such information to an aircraft situation, the user should remember that the levels of both the motion and noise environment generally are significantly higher in the rear portion of transport aircraft than in the forward cabin.

The approach described could be used to generate such relations for any component combination of the comfort-rating model. Such ride comfort relations should prove useful in carrying out cost-benefit trade-offs between alternate approaches for improving the ride comfort of a given aircraft design.

Importance of Wing Loading

Ride comfort technology can be used to provide the designer direct trade-off information on ride comfort effects of varying any particular aircraft parameter which affects the vehicle transfer function. To illustrate, the effects on ride comfort of varying the wing loading of a commuter-type aircraft have been addressed. (See fig. 9.) The ride situation selected was that of a 5670-kilogram (12 500-pound) unswept wing aircraft cruising in straight and level flight and experiencing the atmospheric turbulence inputs found at a 900-m altitude over mountainous terrain. Noise, temperature, and seating space were considered to be satisfactory. The vertical and lateral responses of the aircraft to the probabilistic distribution of atmospheric turbulence were first calculated for a range of wing loading conditions to provide the expected ride environment. The comfort-rating model and ride satisfaction relations were then used to convert the calculated ride environment into a ride satisfaction evaluation expressed in terms of the cumulative probability of achieving a given percent of passengers satisfied with the ride situation.

The cumulative probability curves for four wing loadings are shown in figure 9. At both ends (final few percent) of the probability curves, the satisfaction values and trends should not be considered to be particularly accurate because of limitations in the comfort data analysis and modeling (e.g., linear regression analysis and linear modeling). Over most of the range, however, and including the knee of each of the curves, the probability characteristics should be significant and reasonably valid. In the range of 80 to 90 percent passengers satisfied, very significant improvements are evidenced as wing loading is progressively increased from 972 N/m^2 (about 20.3 lb/ft^2) to 2510 N/m^2 (54.2 lb/ft^2). The trends also indicate that further increase in wing loading would not be overly beneficial.

Prediction of Total Trip Ride Characteristics

Full exercise of the method presented in figure 5 is required to predict total trip ride comfort and passenger satisfaction. Further details are outlined in figure 10 wherein the trip is divided into equal time segments of segment time duration appropriate for addressing each ride environment event. For each event situation, inputs to the aircraft need to be established. Some inputs, such as turbulence, are random in nature and are a function of altitude, geographic features, and time of day. Other events, such as maneuvers, are more controlled in nature but still can have random variations. Inputs therefore need to be described in terms of probabilistic distribution of intensity. With these inputs, the vehicle transfer characteristics, and the ride relations described earlier, a Monte Carlo type approach can be used to calculate the probable ride comfort rating and passenger satisfaction for each segment of the trip. These results can then be weighted through use of the memory decay relation, summed and normalized to provide values for the total trip.

The approach described above was used to calculate the ride characteristics for a commuter airline demonstration project. This project, the Canadian Airtransit STOL Demonstration Program, was considered to be particularly attractive for such study because of

(1) Addition of comfortable seats with generous seating space to an aircraft otherwise considered to have a nonluxury ride

(2) Use of STOL terminal area operations

(3) Opportunity for comparison with U.S. commuter ride experience

(4) Tailoring of trip to enhance business traveler acceptance (high frequency schedule, downtown-to-downtown time saving, and total trip service approach)

(5) Trip situation (aircraft configuration, flight operations, type travelers) was considered to be sufficiently different from the model development data-base situations to check model validity

As shown at the top of figure 11, ride environment measurements and passenger ratings of the trip were obtained on 61 flights of the DHC-6-300 aircraft used by Airtransit. The average duration of each flight was 52 minutes. The analytical prediction of ride used 26 2-min event segments (2 climb, 2 turn, 20 straight and level at 1050-m altitude, and 2 descent) and included effects of temperature, noise, and seating, as well as of motions and maneuvers. Take-off and landing ride on the runway was not included. Further description of the Airtransit operations and of the associated ride comfort study is given in reference 28.

Comfort rating results are presented in the lower portion of figure 11 in terms of cumulative probability of achieving given values of comfort based both on prediction and on actual passenger surveys. The predicted probability of achieving a given comfort rating agreed with survey data for the higher rating values and was conservative (predicted a lesser probability) for the lower rating values, with the predicted curve displaced toward the uncomfortable direction a maximum of 0.7 rating point. This degree of agreement is considered to be very good.

Total trip satisfaction results are presented in figure 12 in terms of cumulative probability distribution, based both on predication and actual passenger survey responses. Agreement was fair over the knee of the curve. Also included in figure 12 are calculated results for the Airtransit situation but with two differences typical of a U.S. commuter operation using DHC-6 aircraft: use of conventional 19-passenger seating rather than 11-passenger seating, and use of estimated turbulence conditions associated with cruise at 600-m altitude rather than at 1050 m. The predictions are in very good agreement with passenger survey data from a U.S. commuter operating over a trip length approximating that of Airtransit. The difference in both predicted and survey results for the two operations indicates that the combination of different seating and turbulence factors does have a very significant influence on passenger satisfaction. Comparison of the end-point passenger survey results for the two carriers indicates a surprisingly large difference in probability of satisfying (willing to take another trip having the same ride) all passengers on a trip. The probability was over 60 percent for the Airtransit situation but less than 10 percent for the U.S. commuter. Very likely, the high fraction (93 percent) of the business-trip commuters on the Airtransit flights liked the special operational features incorporated to enhance business traveler acceptance (see item (4) mentioned previously) and they were not as adversely influenced by a less than comfortable ride as predictions would indicate. Better predictive treatment of trip satisfaction must await the development of a good disaggregate demand model in which ride comfort is included as only one of the number of factors (e.g., trip cost, trip time, and schedule frequency) believed to have significant influence.

CONCLUDING REMARKS

A brief overview has been given of NASA research in ride comfort and of the resultant technology together with reference to key technical publications. The research has resulted in the collection of a very substantial amount of ride environment and ride comfort data. Three relations, derived from these data, which are considered particularly useful for addressing transport aircraft ride comfort situations, have been described with sufficient quantitative definition for practical application. Five applications of these relations have been presented to illustrate their effectiveness and limitations in addressing various ride problems or situations in aircraft design and system operations.

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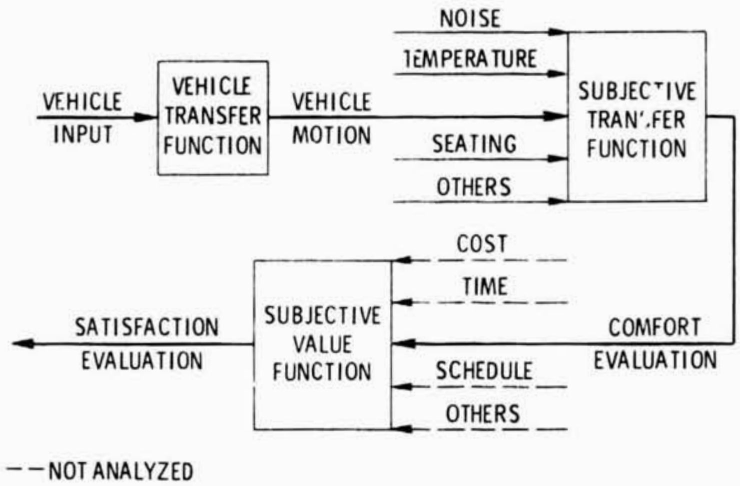

Figure 1.- .nalysis method employed to assess ride comfort.

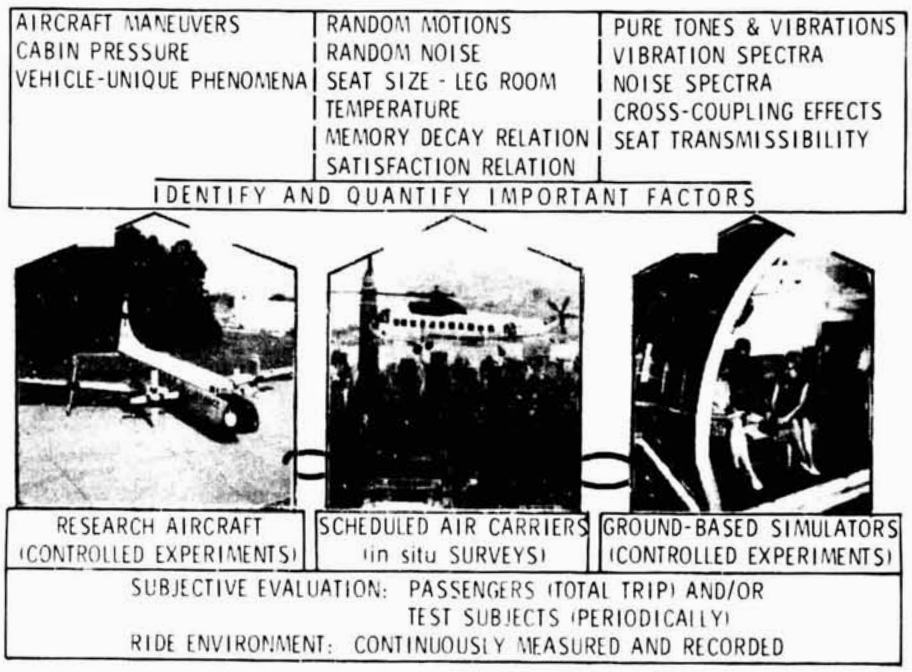

Figure 2.- NASA ride comfort research program.

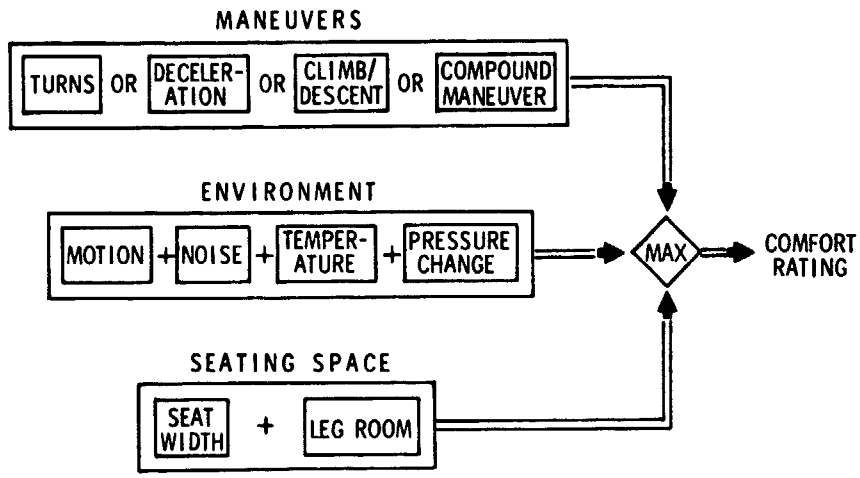

Figure 3.- Block diagram of comfort rating model for use as the subjective transfer function.

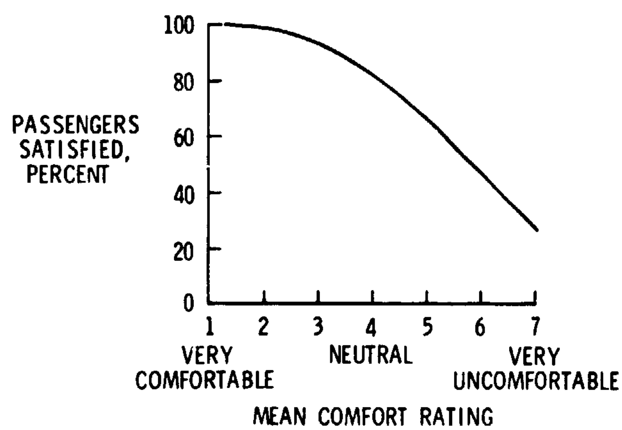

Figure 4.- Ride satisfaction relation.

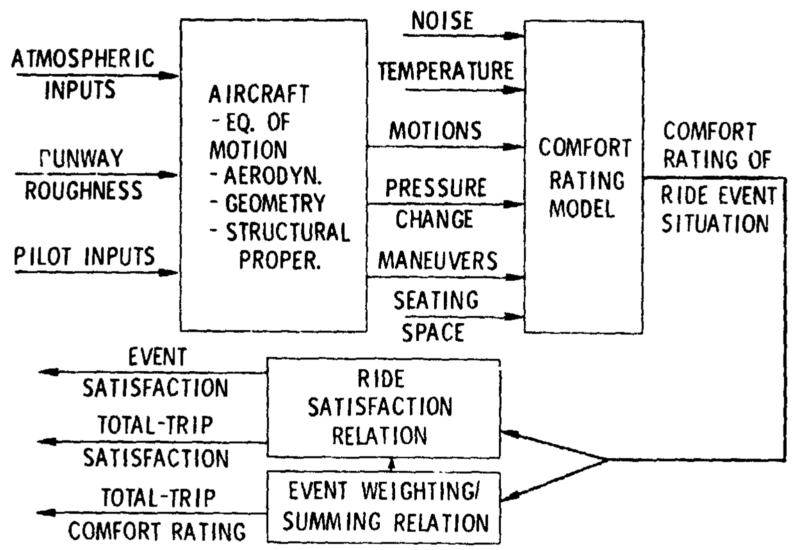

Figure 5.- Predictive method for ride comfort and passenger satisfaction as developed to date.

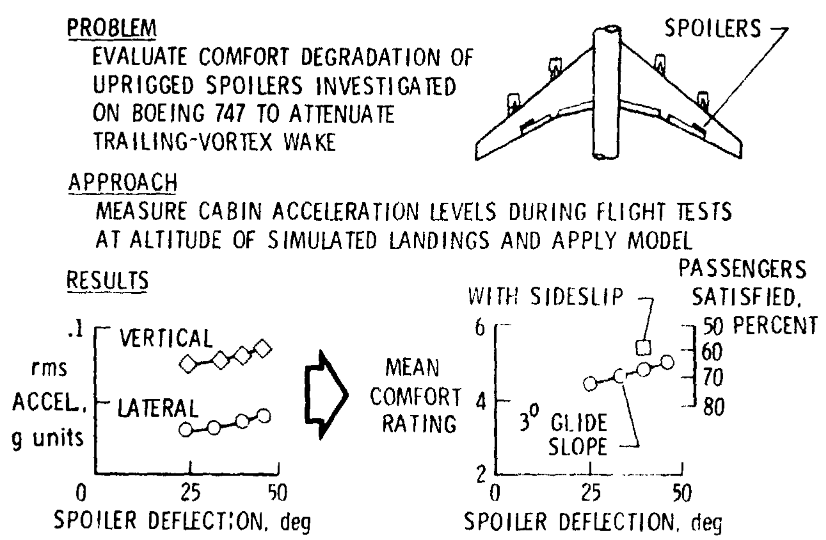

Figure 6.- Ride evaluation of aircraft using uprigged spoilers during simulated landings.

PROBLEM

IDENTIFY KEY FACTOR(S) INFLUENCING THE "SOMEWHAT UNCOMFORTABLE" RATING GIVEN BY TEST SUBJECTS

APPROACH						
•DIVIDE COMPLEX MANEUVER INTO SIMPLE SEGMENTS	STRAIGHT AND LEVEL	TURN ENTRY	DECEL. IN 20^0 TURN	TURN EXIT	PITCH-OVER	STEADY DESCENT
•QUANTIFY MANEUVER RIDE INPUT	NONE	8^0/sec ROLL	0.08 g LONG.	-10^0/sec ROLL	-3.2^0/sec PITCH	-5^0 PITCH/ 550 m/min
•APPLY COMFORT RATING MODEL	2.0	2.4	2.0	2.6	5.1	3.2/4.3
•APPLY SATISFACTION RELATION (% PAX)	98	96	98	94	61 ↑ KEY FACTOR	89/76

Figure 7.- Ride evaluation of a complex maneuver.

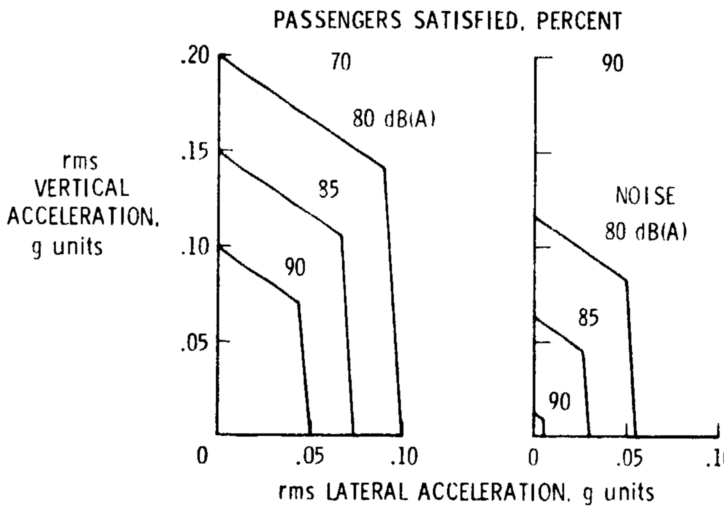

Figure 8.- Equicomfort combinations of motion and noise.

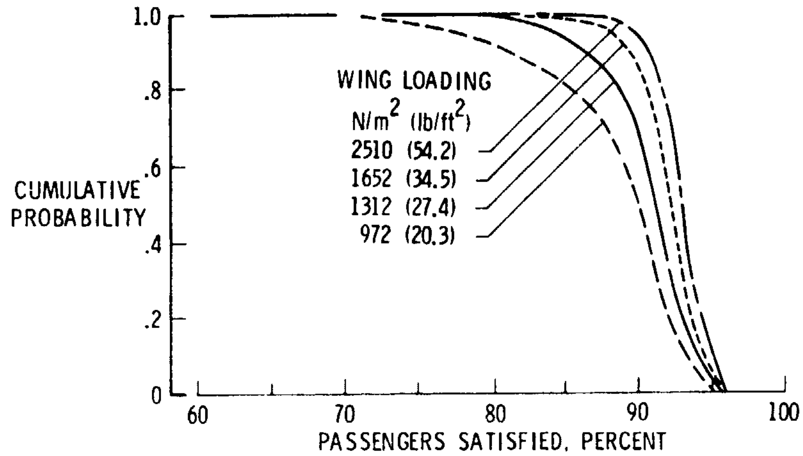

Figure 9.- Effect of variation of wing loading on ride satisfaction of commuter-type transport aircraft.

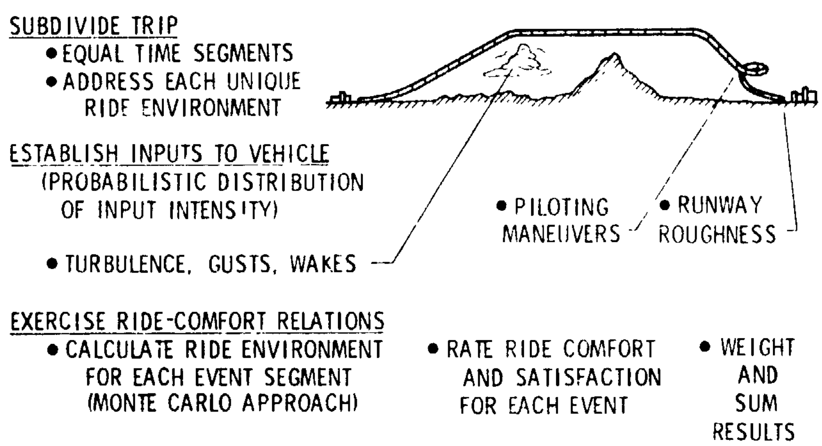

Figure 10.- Approach for total trip prediction of ride comfort and satisfaction.

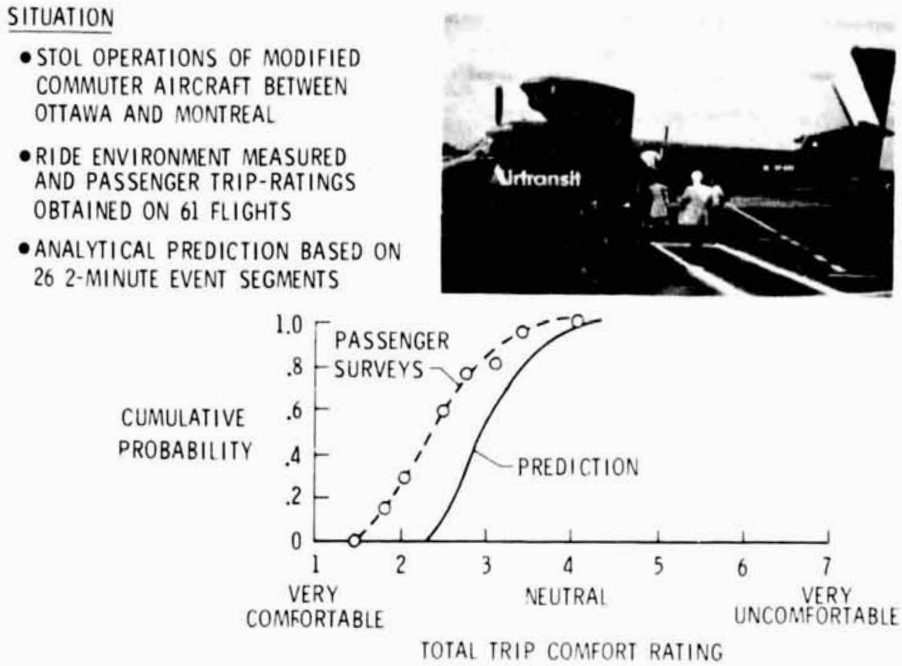

Figure 11.- Total trip ride comfort for STOL demonstrator transport.

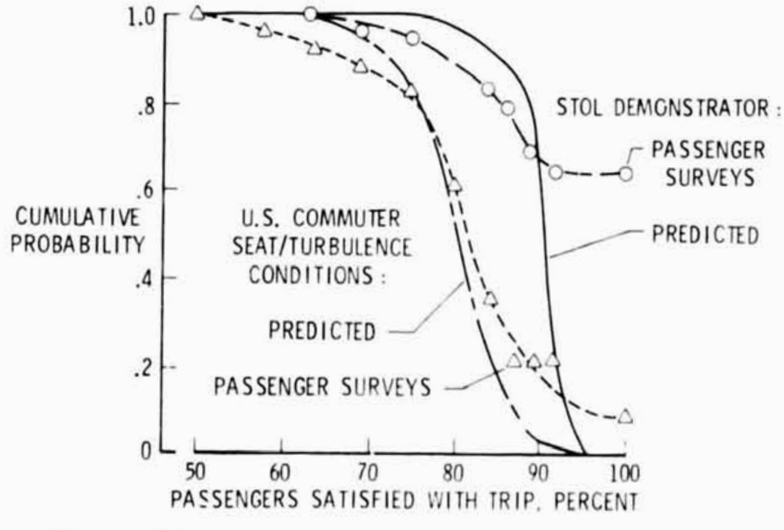

Figure 12.- Total trip satisfaction for STOL demonstrator transport.