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Determining STOL Ride Quality Criteria—Passenger Acceptance

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The ability to mathematically model human reaction to variables involved in transportation systems offers a very desirable tool both for the prediction of passenger acceptance of proposed systems and for establishing acceptance criteria for the system designer. As a first step in the development of a general model for STOL systems, a mathematical formulation is presented which accepts as inputs nine variables felt to be important in flight under STOL-type conditions and presents an index of human response as the output. The variables used are three linear motions, three angular motions, pressure, temperature, and noise level. The model is based on a deterministic approach, and was calibrated using data obtained by recording quantitative subjective responses of special test subjects while simultaneously measuring all variables. Several aircraft types were used under both experimental flight conditions and commercial airline operations. Ride quality criteria developed by using the model to study response to various combinations of the variables over extended ranges of frequency, amplitude, and rates of change will be presented. The results can be used to establish specifications for stability augmentation systems to improve the ride quality of existing STOL aircraft.

Introduction

UNTIL recently the matter of understanding the relationships between the several parameters involved in a transportation system and the passenger's acceptance of that system has received little attention. Although the literature contains many reports of work related to demand modeling or the prediction of modal splits, most approaches are concerned only with the tradeoff of time and cost. Other important factors are lumped together and arbitrarily included in some sort of empirical coefficient.

In an air transportation system of the type being proposed for short-haul STOL operations, the quality of the ride as it affects the comfort of the passenger has been recognized as an important parameter. This is illustrated in Figs. 1 and 2, which present data obtained from two recent surveys of the attitudes, habits, and preferences of travelers.[1,2] One involved the interviewing of frequent travelers from the academic community with the interviews being conducted in their offices; the other analyzed questionnaire data obtained in flight from a group of test subjects whose occupations ranged the gamut from secretary and student to airline pilot and engineer or scientist.

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It is clear from Fig. 1 that comfort rates as one of the most important considerations for both groups. The relative importance of the various factors included in an overall judgment on comfort is shown in Fig. 2. Here it is seen that the motion of the aircraft is perceived as quite important in determining over-all comfort. However, such factors as temperature, noise, and seat comfort cannot be ignored in any study of the effect of ride quality on passenger acceptance.

The ability to study these relationships quantitatively and develop a mathematical model of human reaction to variables involved in transportation systems is a very desirable step. Because of the importance of the comfort variables and the relative ease with which numerical relationships between stimuli and response can be obtained, ride quality was selected as the first acceptance variable for detailed study in a program to develop such models. This paper reports on the initial results from that program. Extension is planned to include all essential inputs due to vehicle properties, system characteristics, passenger characteristics, and passenger preconditioning. This should provide a powerful tool for the prediction of passenger acceptance of proposed systems and for establishing acceptance criteria for both the system and hardware designers. For example, the present results are being used to establish standards of comparison to determine the level of stability augmentation (if needed) to improve the ride quality in a Twin Otter.

Experimental Program

The experimental program consisted of a series of flights by a selected subject group on a regularly sched-

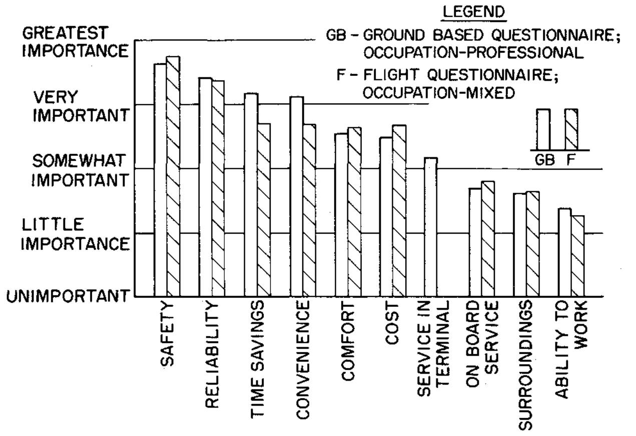

Fig. 1 Factors in air travel satisfaction.

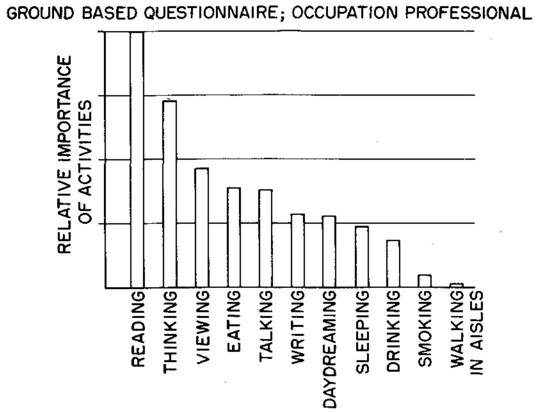

Fig. 3 In-flight activities.

uled commercial airline with associated equipment to measure both the environmental variables and the subjective response of a group of subjects. A total of 100 flight segments were flown aboard three different aircraft, YS-11, F-227, B-737, for a variety of turbulence conditions and over a variety of terrain (both flat and mountainous). There were either one or two subjects per flight segment and a minimum of six flight segments were obtained for each of nine subjects. The response of the subjects was scheduled by time and involved a subjective evaluation of comfort every two or four minutes during flight in response to the motion environment.

Consideration was also given to obtaining a quantitative measurement of task performance from the experimental subjects. However, this was omitted on the basis of Fig. 3, also obtained from the previously referenced attitude studies. Interference with the ability to read has never seemed significant from qualitative observations, even on the roughest flight; eating is not an activity anticipated to be involved in short-haul STOL; and, finally, the relatively low importance placed on the ability to write (recall that the subject group for these attitude surveys consisted of professional types) in flight made the effort required to obtain task performance data of marginal benefit.

Data Acquisition

In addition to the six motion variables consisting of three linear accelerations and three angular accelerations, the temperature and noise levels were monitored. Motion variables were recorded on NASA-provided equipment shown in Fig. 4, which was placed on the cabin floor directly in front of the subject's seat location. The motion data was recorded on a standard FM tape recorder and later reduced for analysis using a time series analysis program.[3] The temperature and noise levels were manually recorded. A typical trace of the recorded data is shown in Fig. 5. The comfort response is based on a five-point scale from 1, very comfortable, to 5, very uncomfortable.

Model Development

Two models have been developed based on these data and a third proposed. At present they are a function of only the motion variables since the other comfort parameters were either substantially constant or not measurable for the aircraft used. The first model is an extension of the work done by Van Deusen.[4] The comfort, C, of the passenger is related to the rms accelerations and their cross correlations by

$$C = C_0 + \sum_{j=1}^{6} \alpha_j \bar{a}_j^{\,\nu_j} + \sum_{j=1}^{6} \sum_{i=j+1}^{6} \beta_{ij} \bar{b}_{ij}^{\,\mu_{ij}} \tag{1}$$

where

$$\bar{a}_j = [\frac{1}{T} \int_0^T a_j^2(t)dt]^{1/2} \tag{2}$$

are rms accelerations in the vertical, transverse, longitudi-

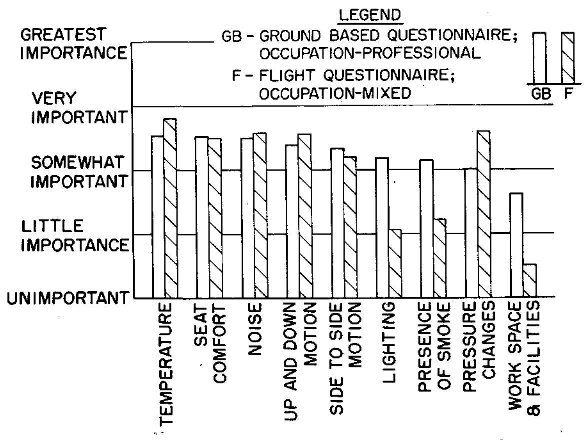

Fig. 2 Factors in determining aircraft comfort.

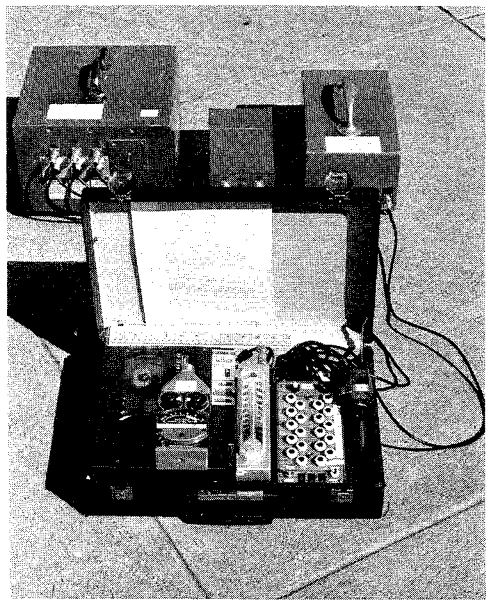
Fig. 4 Experimental equipment.

Table 1 Range of motion variables

Acceleration	Range	Median
Vertical	$0 \rightarrow 0.10$g	0.06g
Transverse	$0 \rightarrow 0.14$g	0.013g
Longitudinal	$0 \rightarrow 0.14$g	0.012g
Pitch	$0 \rightarrow 1.6$ rad/sec^2	0.07 rad/sec^2
Roll	$0 \rightarrow 1.6$ rad/sec^2	0.20 rad/sec^2
Yaw	$0 \rightarrow 1.0$ rad/sec^2	0.04 rad/sec^2

nal, pitch, roll, and yaw directions and

$$\bar{b}_{ij} = \left[\frac{1}{T}\int_0^T a_i(t)a_j(t)dt\right]^{1/2};\ i \neq j \tag{3}$$

are the cross correlations of each variable with all others. The α_j's and β_{ij}'s are weighting factors and the ν_j's and μ_{ij}'s are scaling exponents. A physical interpretation of the model is to consider the α's and β's as sensitivities of the human subject to the different directions of acceleration and the scaling exponents as representative of the nonlinearity of the human sensor. For the data obtained to date this equation has the form‡

$$C = 1.8 + 11.5\bar{a}_{\text{vert}} + 5.0\bar{a}_{\text{trans}} + 1.0\bar{a}_{\text{long}} + 0.25\bar{a}_{\text{pitch}} + 0.4\bar{a}_{\text{roll}} + 1.9\bar{a}_{\text{yaw}} \tag{4}$$

where the linear accelerations have the units of g's and the angular accelerations, rad/sec^2. This model was obtained using a composite of a least squares fit of the data and isocorrelation curves of the variables. A measure of the goodness of fit is indicated by the number of points whose predicted comfort rating differs from the actual by more than one, which for this model is approximately 10%.

In order to interpret this model it is necessary to note the following; First, since all the field data were taken during normal flight conditions, there was no control over the accelerations. Thus the process of going to the limit of a single degree of freedom is not appropriate except perhaps for the most dominant term. Second, the range of values for each of the accelerations varied considerably and are shown in Table 1.

With these in mind, it can be seen that the vertical acceleration is the predominant factor, with transverse and yaw accelerations also relatively important. It can be expected that the inclusion of cross correlations will allow for a more precise evaluation of the role each variable plays. It is recommended that a value of 3.5 for C be the acceptable limit for most commercial flight applications.

The second model, patterned after Rustenberg,[5] has the form

$$C = C_0 + \sum_{i=1}^{6}\sum_{j=1}^{4}\gamma_{ij}\int_{\delta_{j-1}}^{\delta_j} f^{\tau_j}\,\phi_i(f)df \tag{5}$$

where γ_{ij} are weighting factors; f, the frequency; $\phi_i(f)$, the power spectrum in each of the six acceleration variables; $\delta_{j-1} \rightarrow \delta_j$, the frequency range; and τ_j, the dependence on frequency in the frequency range.

The δ's and τ's are assumed as in Rustenberg's development to be given by a "human response function." Here we assume the following form patterned after the response

‡This model is based on a preliminary data evaluation and in the more general case can be expected to be nonlinear and contain cross correlation terms. The amount of data evaluated to date restricted the number of determined coefficients. Thus the model presented is one which contains only a linear form of the comfort equation.

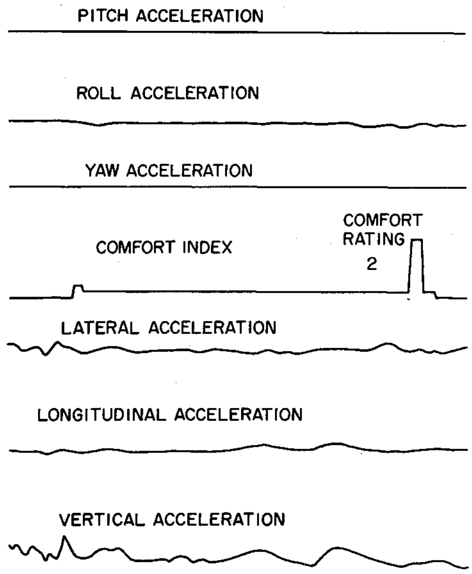

Fig. 5 Typical data output trace.

curves given in Ref. 6.

$$\begin{array}{ll} 0 \leq f \leq 2.0 \text{ cps} & \tau = 0 \\ 2 < f \leq 5.0 \text{ cps} & \tau = 0.6 \\ 5 < f \leq 20 \text{ cps} & \tau = 0 \\ 20 < f & \tau = -1 \end{array} \tag{6}$$

In the present model the human response function is considered constant for each direction; this will be relaxed for future models and the relationship established from the data.

The best fit of the data for this model is given by§

$$\begin{aligned} C = 1.8 &+ 10.6 \int f^{\tau}\phi_V(f)df + 2.0 \int f^{\tau}\phi_T(f)df \\ &+ 0.1 \int f^{\tau}\phi_L(f)df + 0.7 \int f^{\tau}\phi_P(f)df \\ &+ 0.3 \int f^{\tau}\phi_R(f)df + 0.15 \int f^{\tau}\phi_Y(f)df \end{aligned} \tag{7}$$

where V, T, L, P, R, Y represent the vertical, transverse, longitudinal, pitch, roll, and yaw directions, respectively. Here it is again seen that the vertical acceleration is the dominant one. The number of points exceeding the actual comfort response by more than one is 11%.

The third model postulated takes into account both of the above approaches. It relates the comfort to the rms values of acceleration in discrete octave bands.

$$C = C_0 + \sum_{i=1}^{6}\sum_{\Delta f=1}^{N} K_{i,\Delta f}\,\bar{a}_{i,\Delta f}^{\ \epsilon_{i,\Delta f}} + \sum_{i=1}^{6}\sum_{j=i+1}^{6}\sum_{\Delta f=1}^{N}\Lambda_{i,j,\Delta f}\,\bar{b}_{i,j,\Delta f}^{\ \eta_{i,j,\Delta f}} \tag{8}$$

where as before the K's and Λ's are weighting factors; ϵ's and η's nonlinearities; $\bar{a}$ the rms value for each degree of freedom i; and $\bar{b}$ the correlation coefficient for each pair of directions are subdivided into octave bands, Δf. Insufficient data has been obtained to date to evaluate this model.

Application

The following simple example will serve to illustrate the application of the model to establish design criteria for a

§As before the amount of data dictated the use of only a limited number of terms.

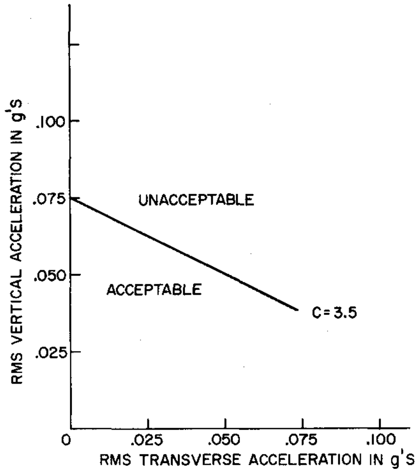

Fig. 6 Effect of vertical and transverse accelerations on ride acceptability (assuming values of pitch, roll, yaw, and longitudinal accelerations exceeded <10% of the time).

stability augmentation system to improve the ride quality of an aircraft.

An examination of flight records of the aircraft mentioned previously shows that the atmospheric characteristics and the normal control characteristics of these aircraft are such that (when taken together) motions in the longitudinal, roll, pitch, and yaw modes are small contributors to discomfort relative to motion encountered in the vertical and transverse directions. The problem then is to improve the aircraft stability in these latter two directions by improving the response characteristics by the incorporation of additional control equipment. The degree to which improvement should be made to insure passenger comfort is a critical factor since the cost of the improvement will be strongly dependent on it. Criteria for motion limits acceptable to passengers are then very important.

The answers can be found through appropriate applications of Eq. (4). As a first approximation appropriate values can be selected for the pitch, yaw, roll, and longitudinal amplitudes based on the analyses of flight data. As an example, taking values from our experimental flight program such that the actual amplitudes are less than these values 90% of the time, and eliminating them from Eq. (4), a single equation relating the transverse acceleration, $\bar{a}_T$, and the vertical acceleration, $\bar{a}_V$, is obtained. Using our data and $C = 3.5$ to represent the limit of acceptance we get

$$\bar{a}_V = 0.5\bar{a}_T + 0.075 \tag{9}$$

Figure 6 shows a plot of the result. Additional curves for arbitrarily selected values of C can be obtained from Eq. (4), and the inclusion of the cross correlation terms can be easily accommodated if desired. The designer thus needs to make provision for maintaining aircraft motion below the limiting line for a percentage of the flight time selected in conjunction with a study of normal frequency of encounter records to keep excursions above the line few in number over the stage length of the flight.

Conclusions

The need and capability for establishing meaningful criteria for passenger ride quality acceptance has been established. The present work indicates a method for computing the relative comfort of a ride with preliminary guidelines for establishing acceptable limits of motion. Models presented give good correlation with the presently available data, but should be expanded and tested using additional data involving an increased number of variables and an enlarged test group.

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