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APPLICATION OF RIDE QUALITY TECHNOLOGY TO PREDICT

RIDE SATISFACTION FOR COMMUTER-TYPE AIRCRAFT

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SUMMARY

A method has been developed to predict passenger satisfaction with the ride environment of a transportation vehicle. This method, a general approach, has been applied to a commuter-type aircraft for illustrative purposes. Here the effect of terrain, altitude and seat location were examined. The method predicts the variation in passengers satisfied for any set of flight conditions. In addition several non-commuter aircraft were analyzed for comparison and other uses of the model described. The method proposed has advantages for design, evaluation, and operating decisions.

INTRODUCTION

The purpose of this paper is to provide a method of assessing passenger satisfaction with the ride quality on transportation vehicles. The method is applicable to both existing systems as well as future ones, and can be used for evaluation, design and decision making. Basically it relates the environment in which the vehicle must be used and the performance character-istics of the vehicle to determine the probability of satisfying the passenger.

This analysis is based on previous work by the authors in assessing vehicle ride quality for the air mode. In refs. 1 and 2, a model of passenger comfort and satisfaction with a ride as a function of the motion of the vehicle was developed. This model coupled with standard techniques for analyzing a vehicle's motion allow us to examine such variables as: vehicle type, input forcing functions, operating characteristics, etc.

The method will be applied to commuter-type aircraft and variations in passenger satisfaction due to terrain, altitude, equipment and location in the vehicle described. Other uses of the technique are also suggested.

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SYMBOLS

a   acceleration

C   comfort rating

f   joint probability density function

L   length scale for turbulence spectrum

S   percent of passengers satisfied with ride

V_0 velocity of vehicle

v_g turbulence gust velocity in transverse direction

w_g turbulence gust velocity in vertical direction

μ mean

ρ correlation coefficient

σ standard deviation for accelerations, rms for turbulence quantities

ϕ power spectral density

ω frequency

$\underline{\omega}$ angular velocity

Subscripts:

a_y transverse rms acceleration

a_z vertical rms acceleration

x   longitudinal direction

y   transverse direction

z   vertical direction

METHOD

Description

The method of analysis is shown in figure 1. A vehicle forcing function is converted into motion cues to the passenger using the appropriate transfer

functions for the system being analyzed. Typical forcing functions are illustrated in table I along with the important properties of the transfer functions for several vehicles.

Table I

Vehicle	Primary Forcing Function	Characteristics of Transfer Function
Airplane	Atmospheric Turbulence	Aerodynamics, Mass Properties
Train	Rail Profile	Suspension System, Wheel Configuration, Mass Properties
Bus, Automobile	Road Surface	Suspension System, Wheel Configuration, Mass Properties
Ship	Sea Surface	Hydrodynamics, Mass Properties

In most cases the vehicle engines also contribute to the motion experiences (e.g. vibrations) however their amplitudes and frequencies compared with the primary forcing function shown above are usually negligible.

Vehicle functions generally depend on frequency; thus, both amplitude and frequency information of the input; or, the input power spectrum is necessary for the analysis. In addition the inputs can and usually are statistically varying quantities so that a probability density function for each of the inputs is necessary. In fact, as will be seen below, the method described allows for isolating components of the forcing function which contribute most to passenger dissatisfaction. In some cases this information may be used to find ways to improve the ride environment (e.g. treatment of roadways or active ride smoothing on the vehicle).

Vehicle motion can take the form of velocities, accelerations and rates of change of acceleration in each of six-degrees-of-freedom. Not all of them are appropriate for the ensuing analysis and only those needed in the subjective transfer function must be determined. In general the passenger's comfort will be functionally related to the motion parameters of angular velocity and linear acceleration and their derivatives

$$C = f(a_x, a_y, a_z, \omega_x, \omega_y, \omega_z, \dot{a}_x, \dot{a}_y, \dot{a}_z, \dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z) \tag{1}$$

where C is the subjective comfort rating, a_x, a_y, a_z linear accelerations in the longitudinal, lateral and vertical directions respectively, and ω_x, ω_y, ω_z angular velocities about the longitudinal, lateral and vertical axes respectively. The · denotes a time derivative, thus $\dot{a}_x$ is the longitudinal jerk, etc. The comfort model can be a simple function of rms motion variables through a more complex frequency-dependent psychophysical model (see e.g. ref. 2). In the "real world" other factors also contribute to the passenger's comfort (e.g. noise, temperature, etc.) however these will be neglected here. A more complete analysis should include them.

The mathematical procedure for arriving at the comfort rating is straight-forward but somewhat tedious to perform. The joint probability density function for the motion variables, $f(a_x, a_y, a_z, \ldots)$ is integrated over motion space to arrive at a probability function for the passenger's comfort level. That is, the probability that the comfort rating is less than or equal to some value C' is given by

$$P(C \leq C') = \int_{\dot{\omega}_z=0}^{C'-\bar{C}_{\dot{\omega}_z}} \int \cdots \int_{a_x=0}^{C'-\bar{C}_{a_x}} f(a_x, a_y, a_z, \ldots, \dot{\omega}_z) da_x \, da_y \, da_z \cdots d\dot{\omega}_z \quad (2)$$

where $\bar{C}_i$ is the value of the associated motion variable given by the comfort equation, each one being eliminated as the integration progresses. Since the motion can vary with location in the vehicle, the above analysis must be repeated at each station of interest.

The last step in the analysis relates the derived comfort rating to a value judgement. This value judgement is taken to be passenger satisfaction with the ride which is related to comfort rating. The percentage of passengers satisfied, S, is a simple function

$$S = f(C). \quad (3)$$

Thus for any comfort rating the value judgement transfer function transforms C to S by the above equation. The actual decision process is much more complex, being dependent on other variables as well as competing modes. These have been neglected in this analysis, assuming that if a passenger were dissatisfied a sufficient number of times he would seek an alternate means of reaching his destination.

The remainder of this paper will apply this method to a particular vehicle type--commuter aircraft--however it is important to note that the method is by no means restricted to this mode. At the present time this is the only mode for which data were available.

Application to Commuter-Type Aircraft

Input Forcing Function

For aircraft the input forcing function is atmospheric turbulence, which can be characterized by velocity power spectra in all six-degrees-of-freedom, longitudinal, lateral, vertical, pitch, roll, and yaw. However, since previous work (refs. 1 and 2) has shown that the comfort models require only vertical and lateral linear accelerations, only these components of the turbulence field will be considered. The amplitude probability as well as the frequency content are functions of terrain, altitude, and weather. Typical examples are shown in figure 2, where the variation in vertical, σ_{w_g}, and lateral, σ_{v_g}, rms gust intensity is seen versus altitude for mountain terrain (refs. 3 and 4). Similar curves are available for water and flat terrain. The power spectra for these are given by a Dryden model

$$\phi(\omega) = \sigma^2 \frac{L}{\pi V_0} \frac{1 + 3(\frac{L\omega}{V_0})^2}{\left[1 + (\frac{L\omega}{V_0})^2\right]^2} \tag{4}$$

where V_0 is the aircraft velocity, ω, the frequency, σ the rms gust intensity and L, the length scale which is a function of altitude (ref. 4). A typical power spectrum is shown in figure 3.

Vehicle Transfer Function

Aircraft transfer functions are a function of aerodynamics and mass properties and can be found in many references (see e.g. ref. 5). Here we assume a rigid body model (no structural bending) and neglect gyroscopic effects. The particular vehicle first considered is the deHavilland Twin Otter aircraft, which was selected because of the abundance of data available concerning its aerodynamic characteristics. It is regrettable that functions for the aircraft suitable for potential use in the commuter market are not readily available.

Motion Spectra of Vehicle

The outputs of interest for the comfort model to be used below are the rms accelerations in the vertical and lateral directions. These can be obtained by integrating their power spectral densities over frequency space which are given by

$$\phi_{a_z}(\omega) = \left|\frac{a_z}{w_g}\right|^2 \phi(\omega) \tag{5a}$$

$$\phi_{a_y}(\omega) = \left|\frac{a_y}{v_g}\right|^2 \phi(\omega) \tag{5b}$$

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where $\phi_{a_z}(\omega), \phi_{a_y}(\omega)$ are the power spectral densities for vertical and lateral accelerations, and $\left|\dfrac{a_z}{w_g}\right|$ and $\left|\dfrac{a_y}{v_g}\right|$ are the transfer functions for these accelerations relating them to the turbulence field. For the Twin Otter, the rms acceleration cumulative probability distribution is shown in figure 4 for a typical case. Typical spectra for these accelerations are given in figure 5.* As can be seen in figure 6 the acceleration in the vertical direction closely approximates a normal (Gaussian) distribution. The same behavior can be seen for actual flight data in reference 6. Transverse acceleration behaves similarly. This allows us to write the probability density functions for each separately and for both combined using a normal distribution. From flight data (refs. 2 and 6) the cross correlation between vertical and lateral accelerations is 0.8 thus the joint probability distribution function is given by

$$f(a_y, a_z) = \frac{1}{2\pi\sigma_{a_y}\sigma_{a_z}} \cdot \frac{1}{\sqrt{1-\rho^2}} \exp\left\{ -\frac{1}{2(1-\rho^2)}\left[\left(\frac{a_y - \mu_{a_y}}{\sigma_{a_y}}\right)^2 - \frac{2\rho(a_y - \mu_{a_y})(a_z - \mu_{a_z})}{\sigma_{a_y}\sigma_{a_z}} \right.\right.$$
$$\left.\left. + \left(\frac{a_z - \mu_{a_z}}{\sigma_{a_z}}\right)^2 \right] \right\} \tag{6}$$

where μ_{a_y}, μ_{a_z} are the mean rms accelerations, $\sigma_{a_y}, \sigma_{a_z}$ are the standard deviations of rms accelerations, and ρ is the correlation coefficient between accelerations. The values for the μ's and σ's for different terrain, altitude and vehicle location can be found by computing values of the motion variables for $P(a) = .5$ and .84 respectively.

Subjective Transfer Function

A subjective comfort model has been developed (ref. 2) based on extensive field data taken on commercial airlines (refs. 6, 7, 8) and in-flight simulator (ref. 9) experiments. This model relates the subjective comfort response to rms vertical and transverse accelerations in g's as

$$C = 2 + 11.9a_z + 7.6a_y \text{ when } a_z \geq 1.6a_y, \tag{7a}$$

and

$$C = 2 + a_z + 25a_y \text{ when } a_z < 1.6a_y, \tag{7b}$$

_____

*The contribution to the rms acceleration for the vertical direction can be divided into two frequency regimes—below and above 1 rad/sec. The region above 1 rad/sec contributes 88 percent of the total power and is thus more important in determining comfort.

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where C is restricted to values 2 through 5, with the following descriptors:

$$C = 2 \quad \text{comfortable}$$
$$= 3 \quad \text{neutral}$$
$$= 4 \quad \text{uncomfortable}$$
$$= 5 \quad \text{very uncomfortable.}$$

For motions in which vertical acceleration dominates (i.e. $a_z \geq 1.6 a_y$), subjective judgments lean more heavily toward the vertical stimulus, however transverse acceleration is more important otherwise. For pure motion in either direction these models predict twice the sensitivity to the transverse direction compared with the vertical direction.

Comfort Determination

Using equations 7 we compute the comfort rating corresponding to any given vertical and transverse accelerations. However the accelerations are described by the joint probability distribution function (given in equation 6). Thus the probability of exceeding a given comfort level C' is obtained from equation 6 using equations 7 to describe the integration space as

$$P(C \geq C') = \int_0^{a_{y_0}} \int_{1.6a_y}^{(C'-2-7.6a_y)/11.9} f(a_y, a_z) \, da_y \, da_z$$

$$+ \int_0^{a_{z_0}} \int_{a_z/1.6}^{(C'-2-a_z)/25} f(a_y, a_z) \, da_z \, da_y. \tag{8}$$

For the Twin Otter aircraft the first, μ, and second, σ, moments describing the probability distribution f are given in table II, for the center of gravity of the aircraft. Similar data have been generated for other positions within the craft.

Table II

	Terrain					
	Mountain		Water		Flat	
Altitude	152 m	3,048 m	152 m	3,048 m	152 m	3,048 m
μ_{a_z} (g's)	.055	.035	.019	.012	.048	.031
μ_{a_y} (g's)	.015	.0094	.0051	.0032	.013	.0082
σ_{a_z} (g's)	.024	.015	.0052	.0033	.019	.012
σ_{a_y} (g's)	.0066	.0041	.0014	.00088	.0051	.0032

Equation 8 is numerically integrated to determine the cumulative probability distribution for each case of interest (i.e. terrain, altitude, seat location). A typical result is shown in figure 7 which illustrates the variation due to terrain for a fixed altitude and location within the aircraft. Thus for this case there is a 90% probability that the subjective comfort rating will be less than 2.3 for flight over water, less than 2.75 for flight over flat terrain, and less than 2.9 for flight over mountain terrain. Stated alternatively the probability that the comfort rating of the ride will be less than or equal to 2.5 is 100%, 54%, and 42% for flight over water, flat and mountainous terrain respectively. Similar comparisons can be made for any set of conditions or to compare different aircraft for a single set of conditions.

Value Transfer Function

The calculated comfort judgments must now be related to a more value-oriented variable. We choose as this quantity the percentage of passengers satisfied with the ride, that is, the fraction of passengers who would willingly take another flight at least without hesitation. This quantity has been determined in previous work (ref. 1) to be related to the subjective comfort rating as shown in figure 8. As can be seen, from a statistical point of view, there are approximately 7% of the passengers who will not be satisfied with the ride environment even when the ride is rated comfortable by most of the passengers. This is seen more clearly when examining distributions of passenger responses (see e.g. ref. 2).

This transfer function, figure 8, has been applied to data on subjective comfort responses, to obtain the probability of satisfying a given percentage of the passengers. Typical graphs are given in figures 9 and 10 for the aircraft center of gravity and an extreme aft seat location as a function of terrain and altitude. As an example of using these graphs, they indicate that at the center of gravity there is a 45% probability of satisfying at least 85% of the passengers flying at 152 m over mountain terrain, while there is an 84% probability of satisfying the same number of passengers flying at 3,048 m over mountain terrain. Similarly over the same terrain at 152 and 3,048 m respectively there is a 36% and 78% probability of satisfying 85% or more of the passengers at an aft seat location. This illustrates that a) the aft seat locations are less comfortable than those near the center of gravity, and b) flying at higher altitudes increases the probability of satisfying passengers. Thus the more conservative approach would be to design to the low altitude, aft seat location results.

Comparison to Other Aircraft

Several other aircraft have been analyzed using the method described. Transfer functions were obtained from references 10 and 11. The aircraft are the Breguet 941, Douglas DC-8, Cessna 182, and an externally blown flap (EBF) aircraft still in the design stage. These aircraft have the following characteristics:

Aircraft	Weight (kg)	Approximate No. of Passengers
DC-8	91,000	200
Cessna 182	1,360	4
Breguet 941	20,000	45
EBF	122,000	270

Figure 11 illustrates the variation in percent satisfied by aircraft type for cruise at 3,048 m altitude over mountain terrain. As is seen the DC-8 is the best aircraft and the EBF the worst.

Applications of the Method

The method described can be used to assess the satisfaction of passengers with the ride environment of a given vehicle. In addition it can be used to perform sensitivity analyses of the effects of vehicle variables, through variations in the vehicle transfer function and of input variables through the forcing function. These can be used to determine maximum design payoffs in the case of the vehicle or operating conditions and surface requirements (for roadways/rail) in the case of the forcing function.

Another application would be to incorporate an optimization routine and use the method inversely to determine the optimum design under engineering constraints for a desired satisfaction level.

Lastly, the method can be applied to validation studies of models of comfort and/or satisfaction by testing over a wide range of conditions with a limited set of field data. This would be accomplished by inserting the appropriate transfer function to replace those described above.

Conclusions

A method has been developed to predict passenger satisfaction with the ride environment of a transportation vehicle. This method, a general approach, has been applied to a commuter-type aircraft for illustrative purposes. The effects of terrain, altitude and seat location were examined. The method predicts the variation in passengers satisfied for any set of flight conditions. Several non-commuter aircraft were also analyzed for comparison and other uses of the model described. The method proposed has advantages for design, evaluation, and operating decisions.

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VEHICLE FORCING FUNCTION → VEHICLE TRANSFER FUNCTION → VEHICLE MOTION → SUBJECTIVE TRANSFER FUNCTION → COMFORT EVALUATION → VALUE TRANSFER FUNCTION → SATISFACTION DECISION
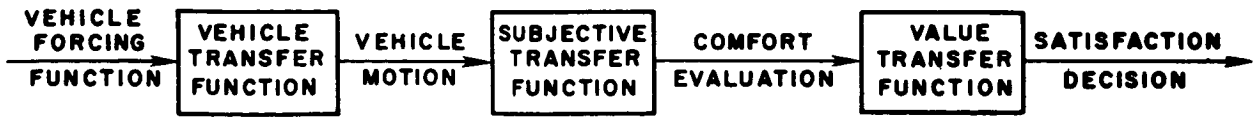
Figure 1.- Schematic for determining passenger satisfaction with ride quality.
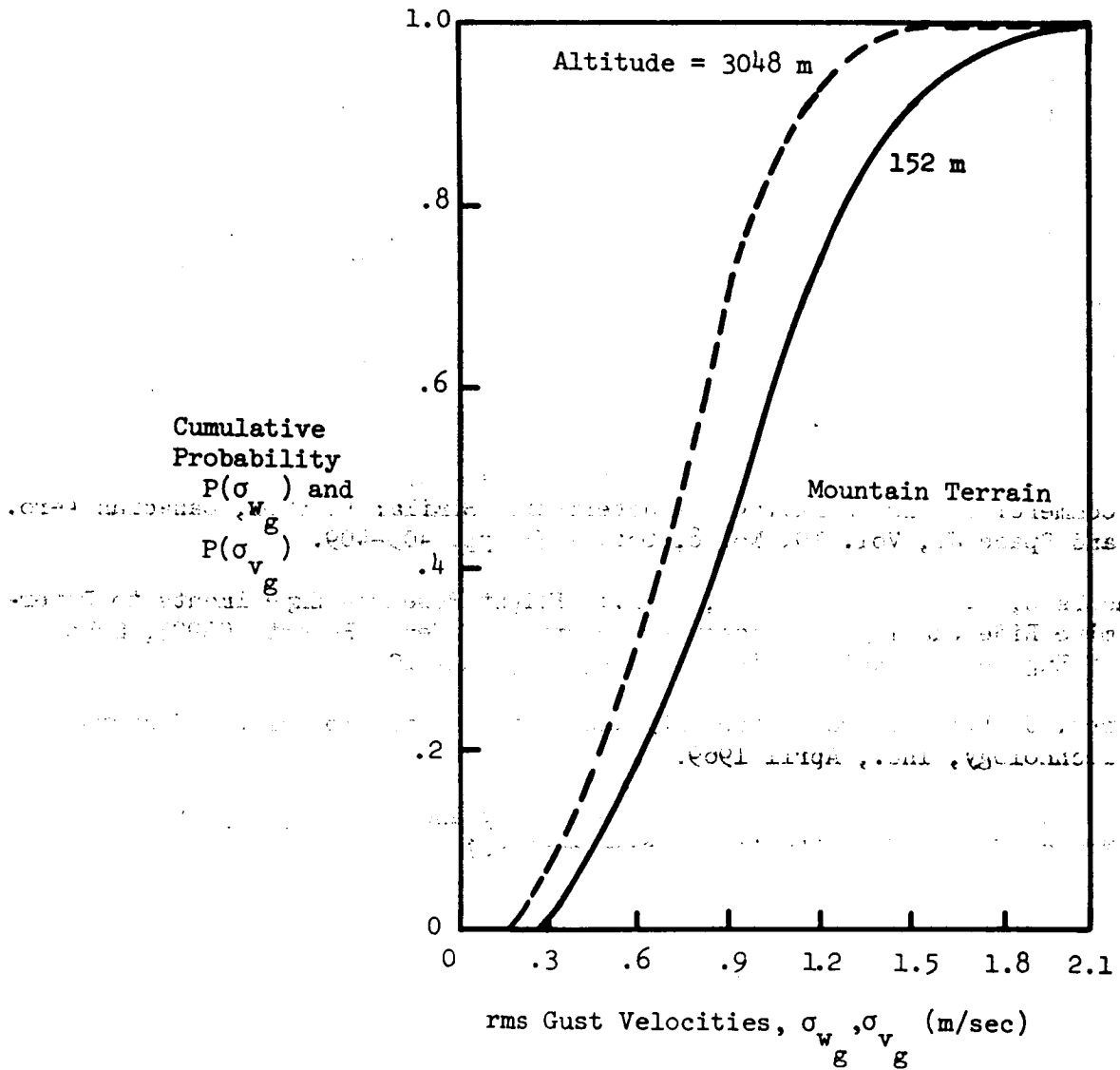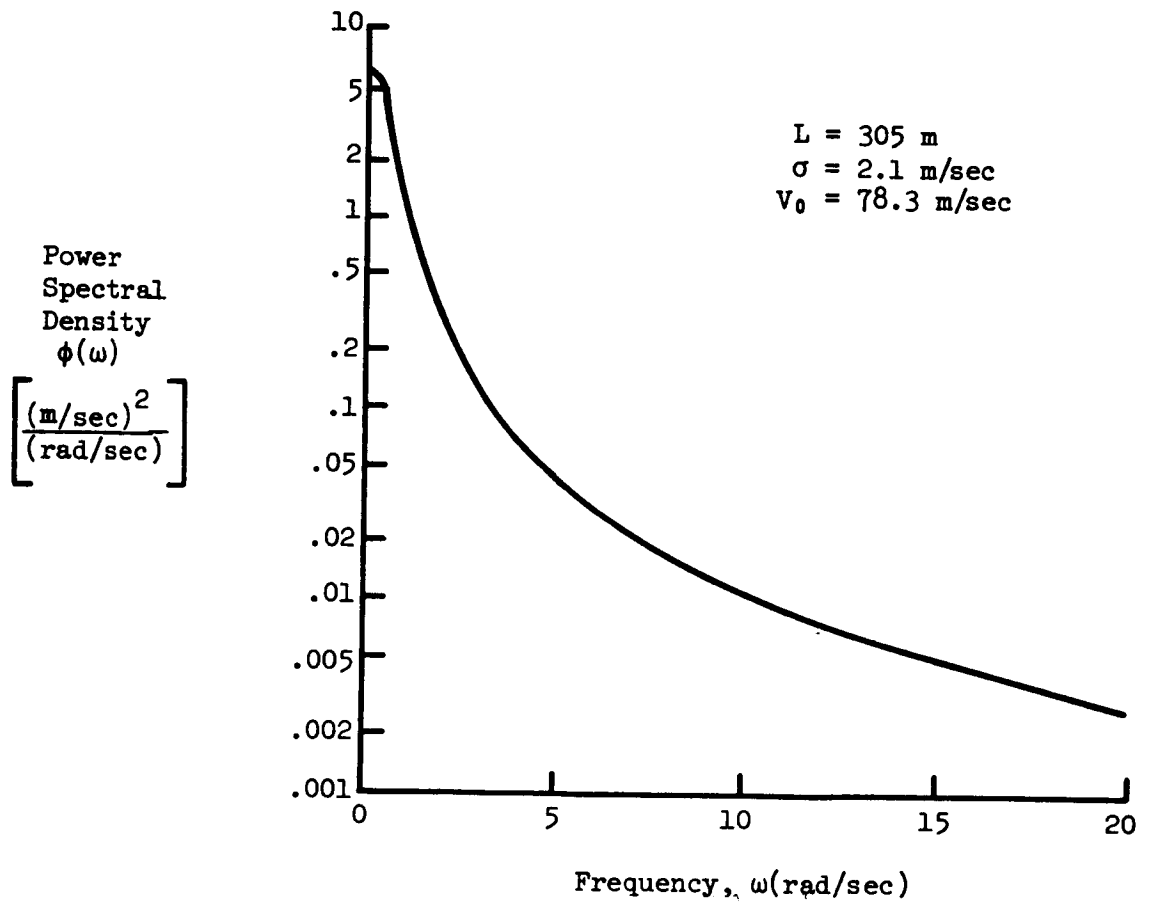

Figure 2.- Turbulence probability distribution.

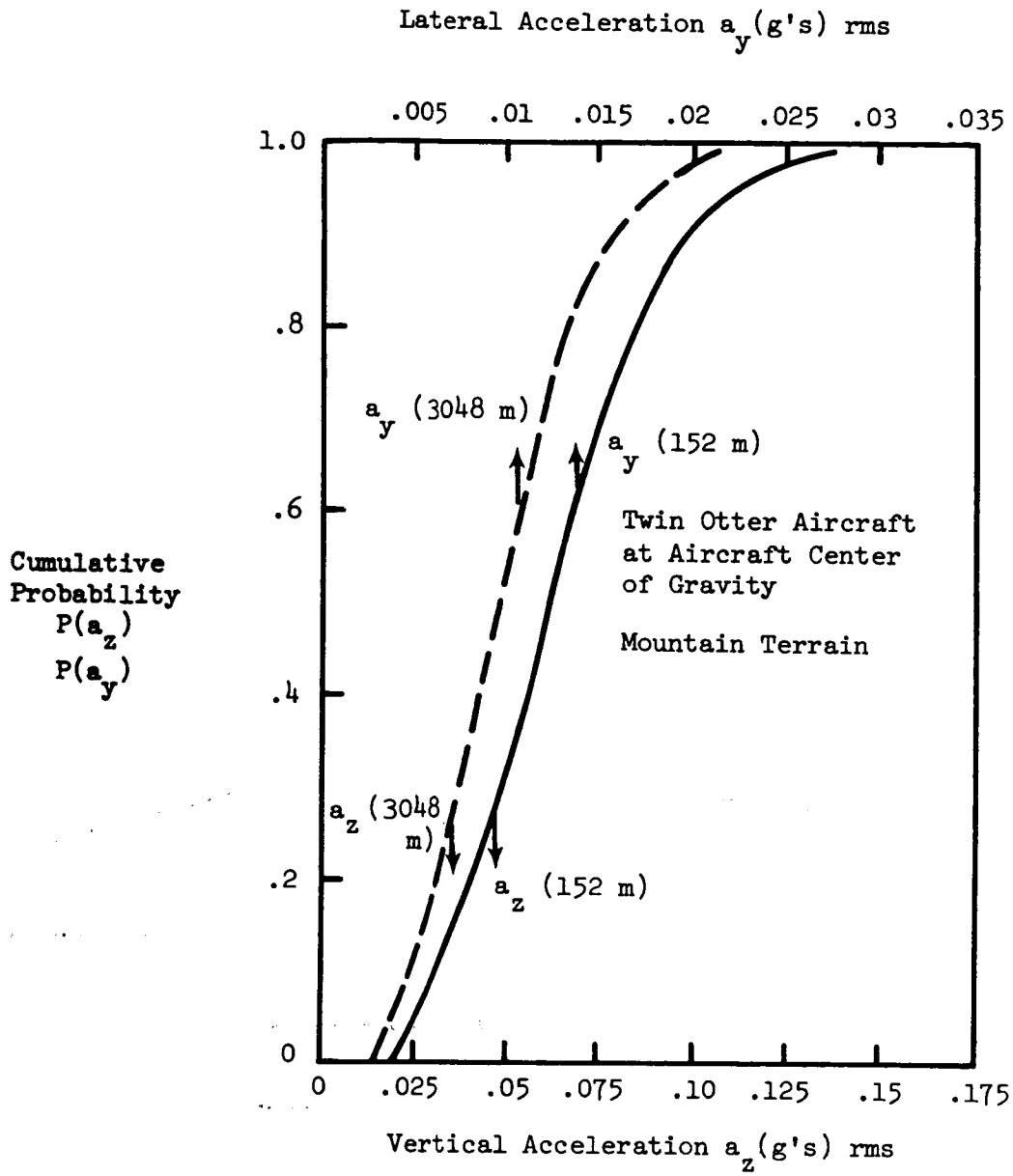Figure 3.- Turbulence power spectrum.

Figure 4.- Acceleration probability distribution.

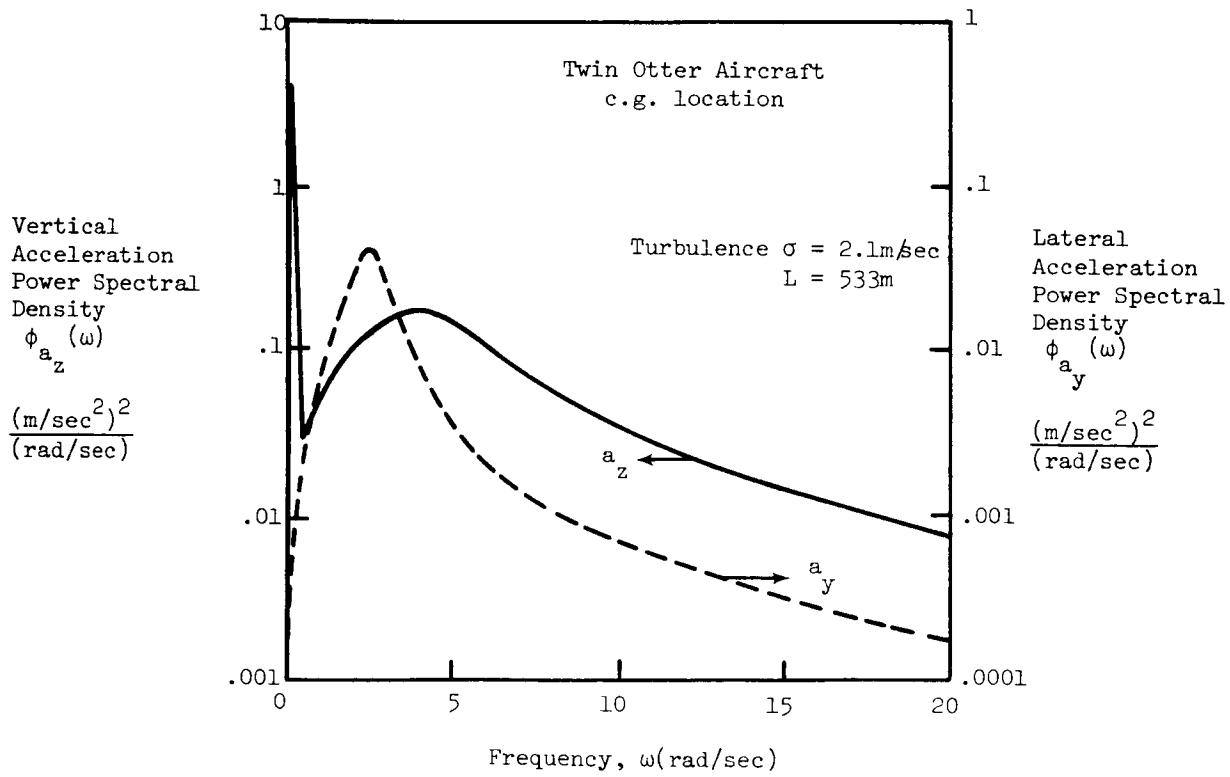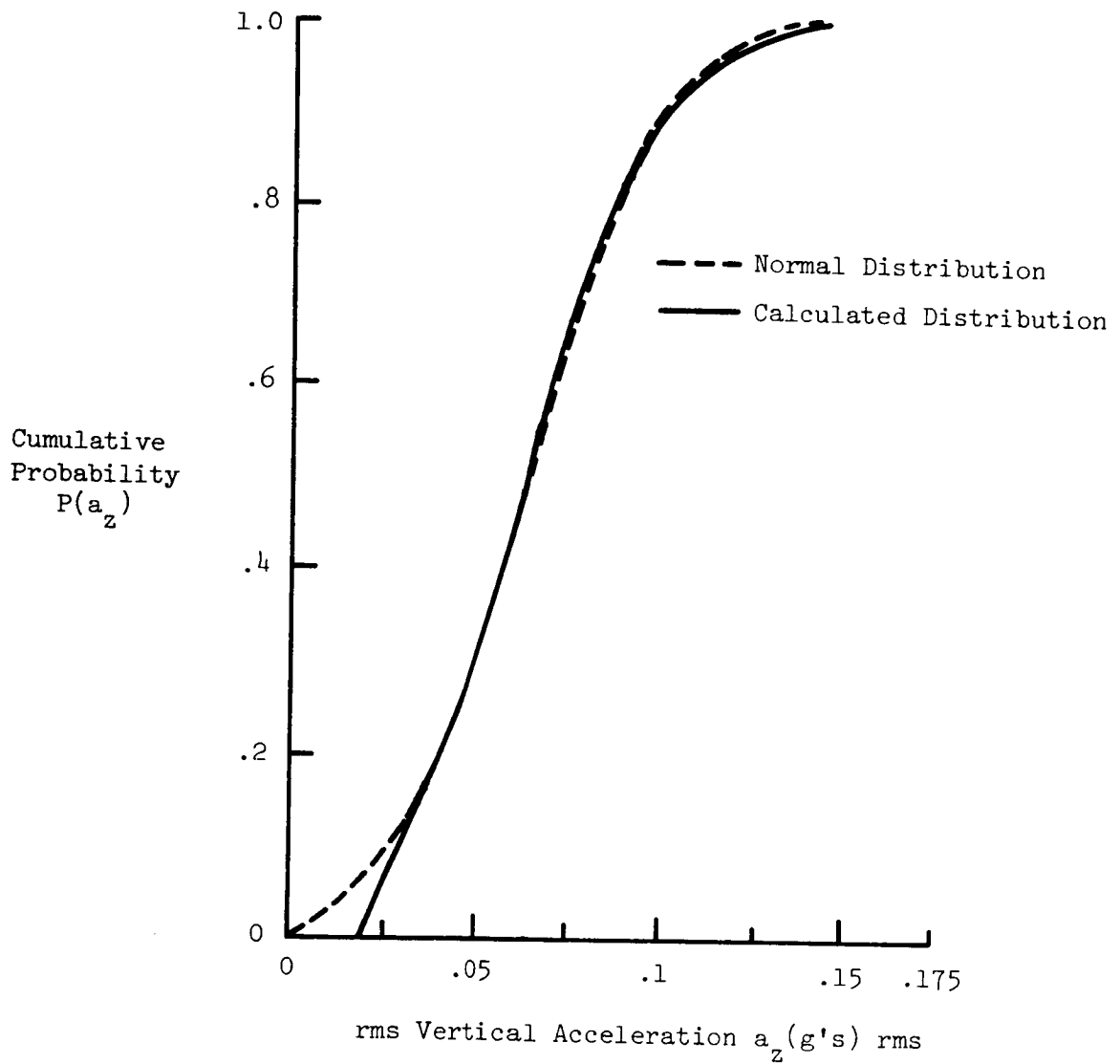Figure 5.- Acceleration power spectrum.
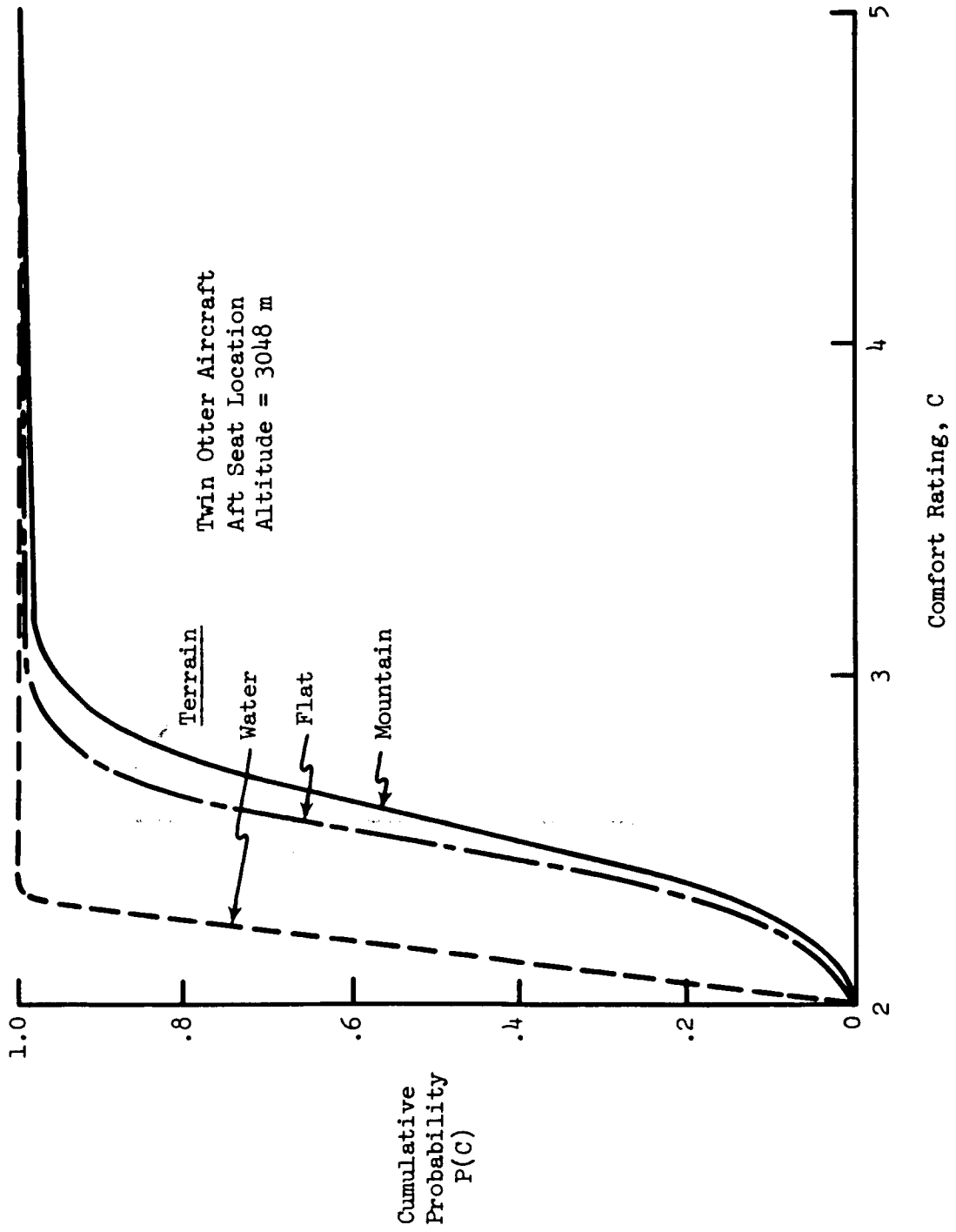
Figure 6.- Comparison of normal acceleration distribution with Gaussian distribution.

Figure 7.- Subjective rating probability distribution.
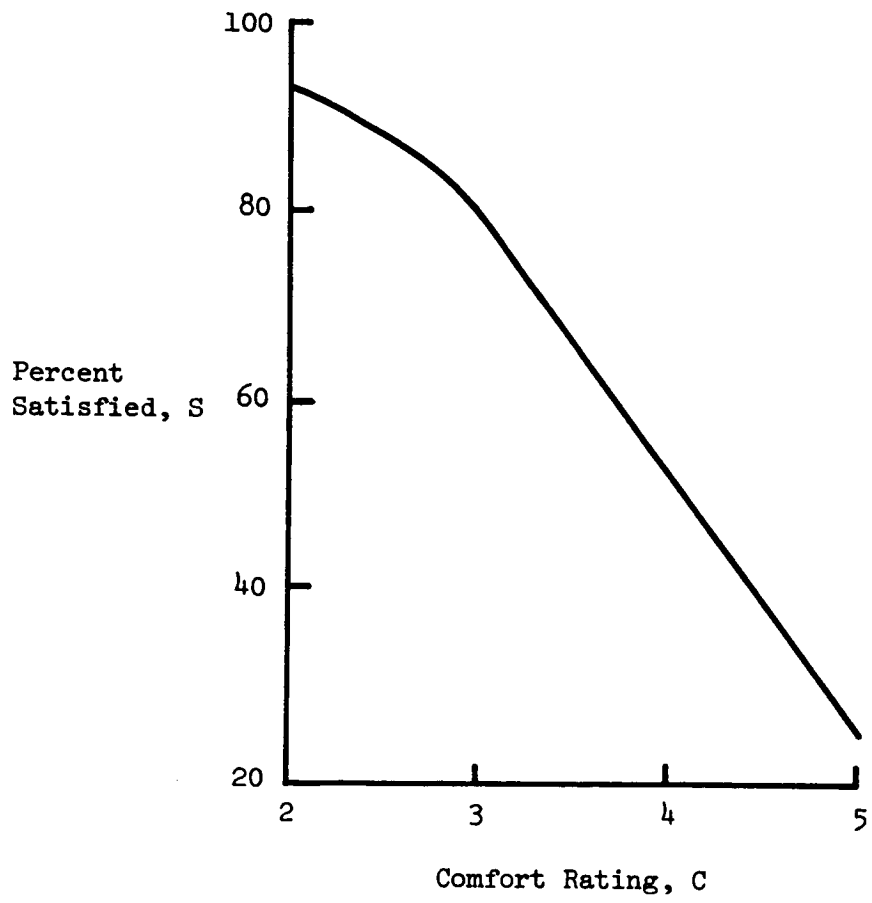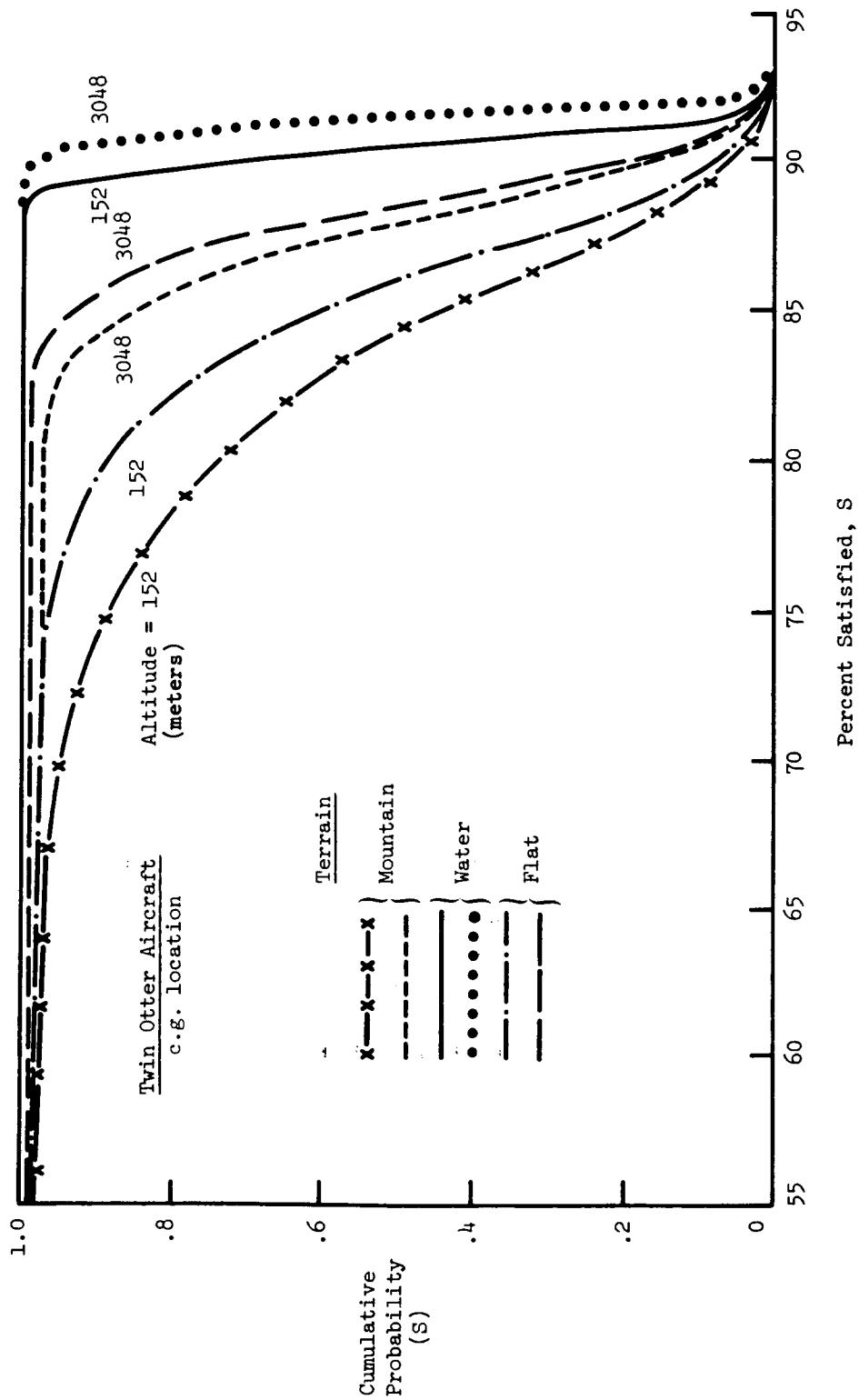
Figure 8.- Value transfer function.

Figure 9.- Satisfaction probability distribution - Twin Otter, center of gravity location.
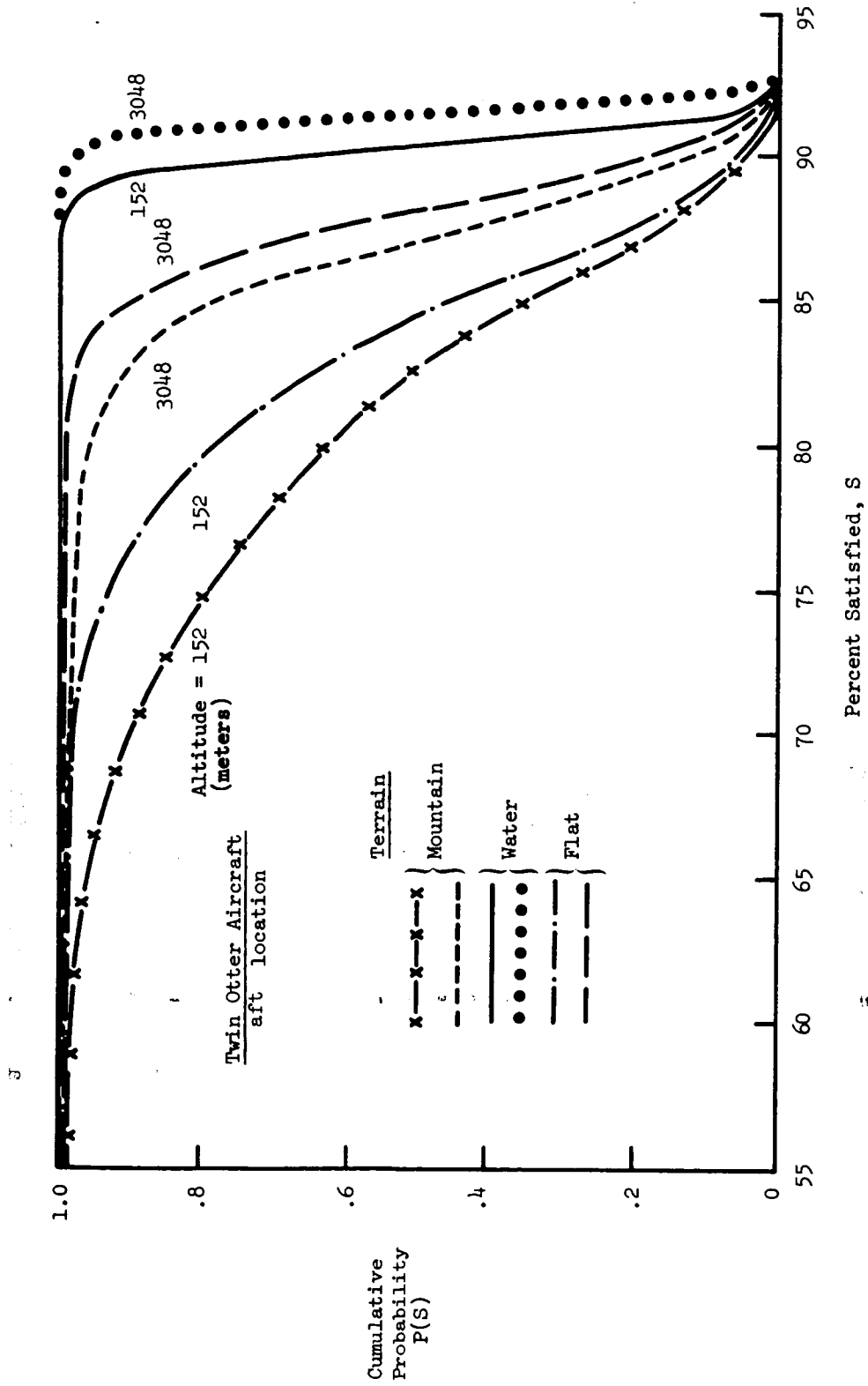
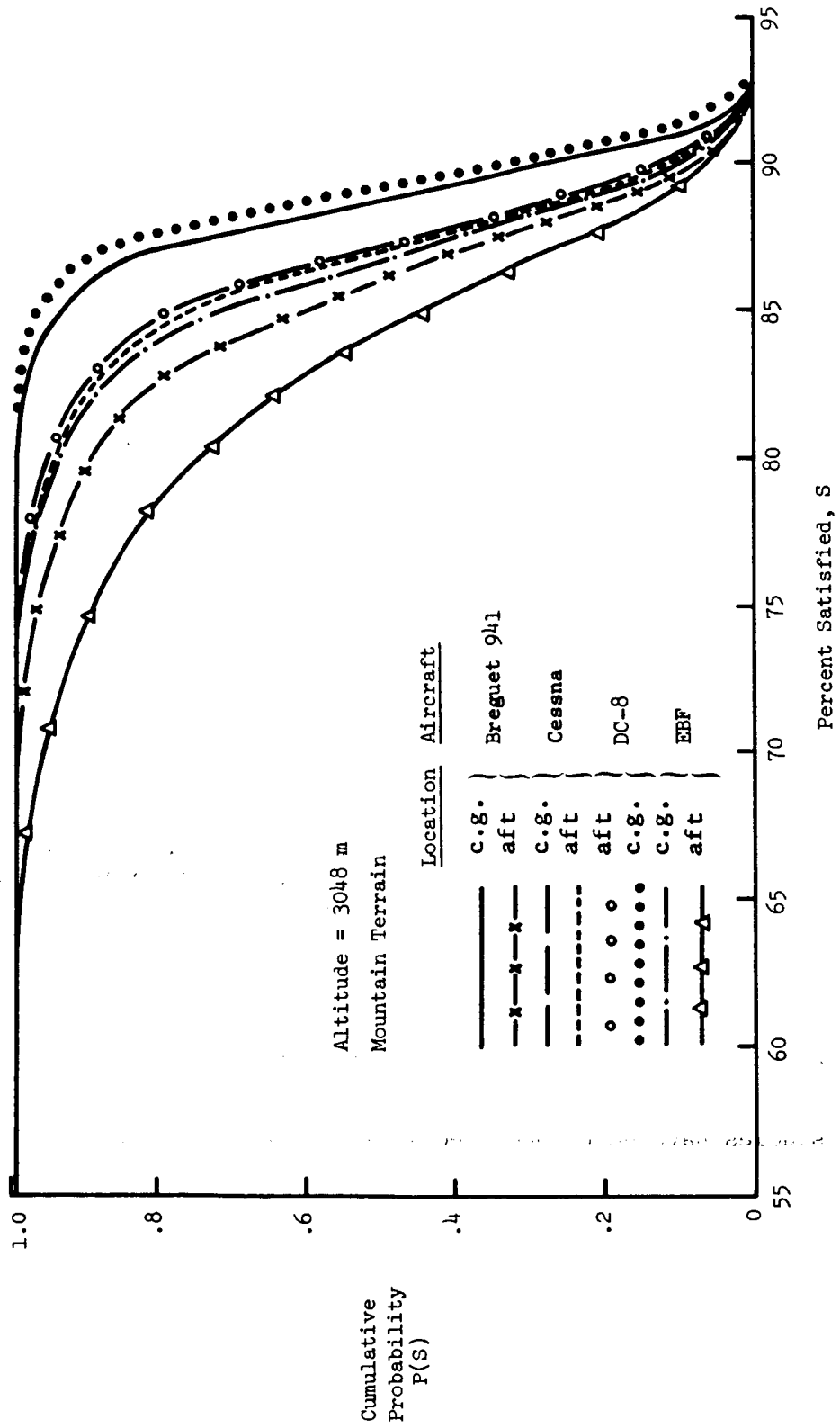Figure 10.- Satisfaction probability distribution - Twin Otter, aft seat location.

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Figure 11.- Satisfaction probability distribution by aircraft type.