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MODELS OF SUBJECTIVE RESPONSE
TO IN-FLIGHT MOTION DATA

Technical Report 403209
Short-Haul Air Transportation Program

by
A. N. Rudrapatna and I. D. Jacobson

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LIST OF SYMBOLS

$\bar{a}$ rms value of acceleration (g's)

$\bar{a}'$ $\bar{a}$ in normal form (mean = 0, standard deviation = 1)

$\bar{a}_{jk}$ square root of the crosscovariance between accelerations along X_j and X_k ($k \neq j$)

$\bar{a}_{j,k}$ rms value of acceleration along the direction X_j for the kth band of frequency (between f_k and f_{k+1} Hz)

$\bar{a}_{w_j}$ frequency weighted rms value of acceleration along the direction X_j

b_o constant in the models using rms values (both weighted and unweighted)

b'_o constant in the models using frequency split rms accelerations

b_j coefficient of the variables $\bar{a}_j$ and $\bar{a}_{w_j}$

b_{jk} coefficient of the variable $\bar{a}_{jk}$

b'_{jk} coefficient of the variable $\bar{a}_{j,k}$

C generic symbol for comfort (also used for observations)

C' predicted comfort in a normal form (mean = 0, standard deviation = 1)

$\bar{C}$ mean of the observed comfort values

f frequency expressed in Hz

f_k lower limit of the kth frequency band and upper limit of the $(k - 1)^{th}$ frequency band, used in the frequency dependent model

F upper limit of frequency used for analysis

K number of frequency bands

r^2 defined as $\sum\limits_{i} (\hat{C}_i - \bar{C})^2 / \sum\limits_{i} (C_i - \bar{C})$

LIST OF SYMBOLS (Continued)

$W(f)$ human frequency response function

$x_j(t)$ acceleration time history of channel number j

μ_q generic definition, $= E(q)$

ρ_p generic symbol for correlation coefficient between any two variables p and q

σ_q generic symbol for standard deviation of any variable q

ϕ generic symbol for the power spectral density function (p.s.d.f.)

ψ_k slope of $W(f)$ in the frequency range f_k to f_{k+1}

Subscripts

j   indicates the particular data being considered

j,k   indicates the particular variable under consideration

L   longitudinal

P   pitch

R   roll

T   transverse

V   vertical

Y   yaw

Superscripts

^   predicted value

—   averaged over time or a number of cases

ABSTRACT

Mathematical relationships between subjective comfort and environmental variables in an air transportation system are investigated. As a first step in model building, only the motion variables are incorporated and sensitivities are obtained using stepwise multiple regression analysis. The data for these models have been collected from commercial passenger flights.

Two models are considered. In the first, subjective comfort is assumed to depend on rms values of the six-degrees-of-freedom accelerations. Variations in the model for different subjects are also explored.

The second assumes a Rustenburg-type human response function in obtaining frequency-weighted rms accelerations, which are used in a linear model. The form of the human response function is examined and the results yield a human response weighting function for different degrees of freedom. In addition, an improved subjective comfort model is obtained.

Section 1

INTRODUCTION

With the advent of short-haul aircraft over the last few years,
increasing attention has been directed at aircraft ride quality inasmuch
as many of these vehicles fly at low altitudes and encounter turbulence
over a significant portion of their flights. The objective of this
study is to develop a subjective comfort model which will predict human
reaction to the six-degrees-of-freedom of aircraft motion, viz., three
linear accelerations (vertical, transverse, and longitudinal) and three
angular accelerations (pitch, roll, and yaw). The data utilized in
obtaining the models contained herein are from the first phase of a
continuing study. As future data is obtained refinements will be
reported.

1.1 Background to the Problem

Most of the work in ride quality has been done since the 1930's--
primarily in the field of automobile and railway ride comfort--and has
been operator-performance oriented, rather than passenger-comfort oriented.
The work that has been done in developing comfort criteria is summarized
by Jacobson (1). Some of the vertical acceleration criteria are shown
in Figure 1.1 and similar results for transverse acceleration are shown
in Figure 1.2.

The major portion of the experiments done to date have used ground-
based simulators although increasing attention has been directed at actual
field testing (e.g., Jacobson (3) or Koo (4)) in the last decade. Simulators
have certain advantages; one of the most important is the ability to collect
considerable data using a number of test subjects with minimal cost. Further,
there is the advantage of wider control over the acceleration input (all the

1
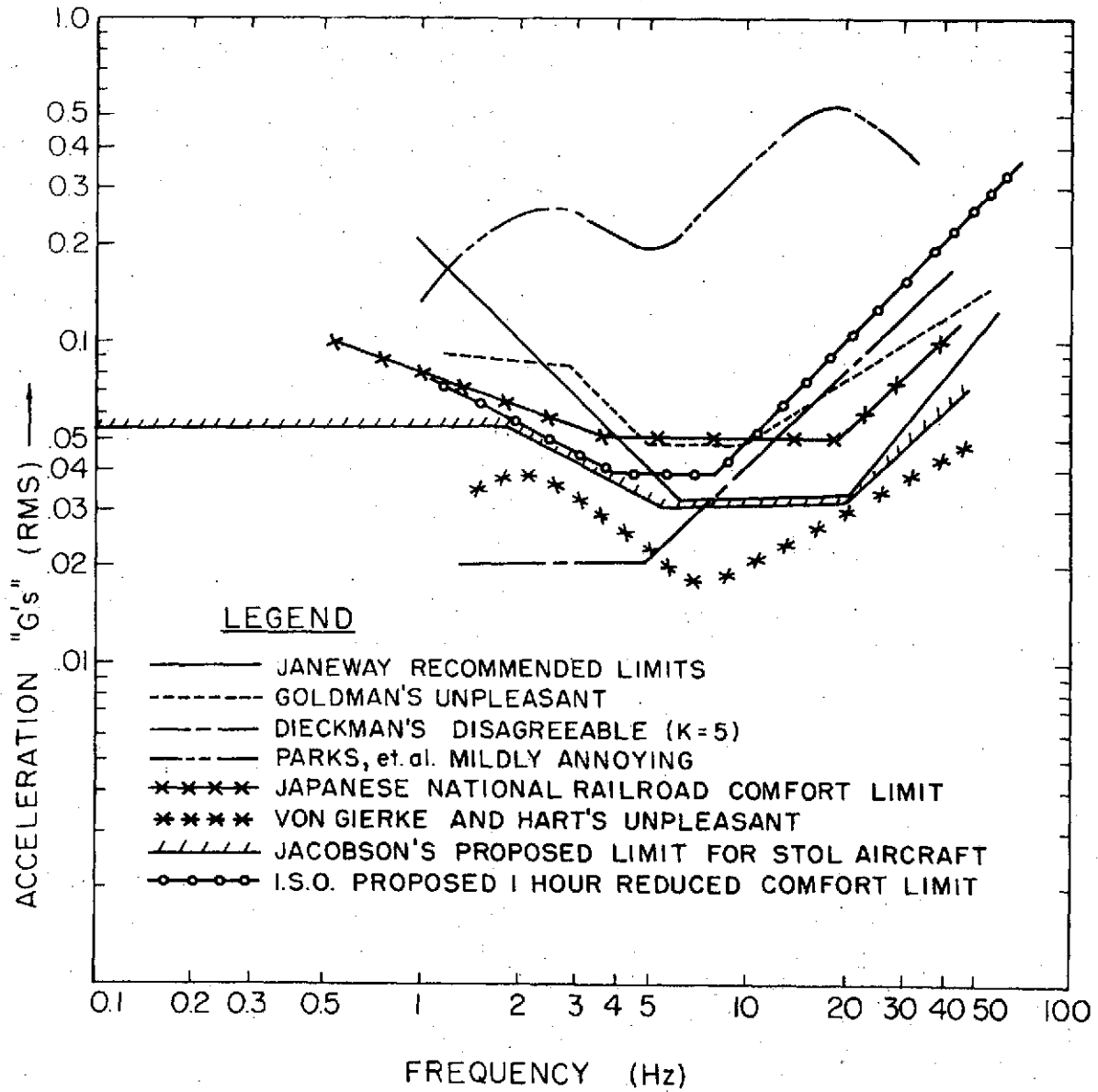
FIGURE 1.1 VERTICAL VIBRATION CRITERIA

(Taken from Jacobson (1) and Draft International Standard (2))

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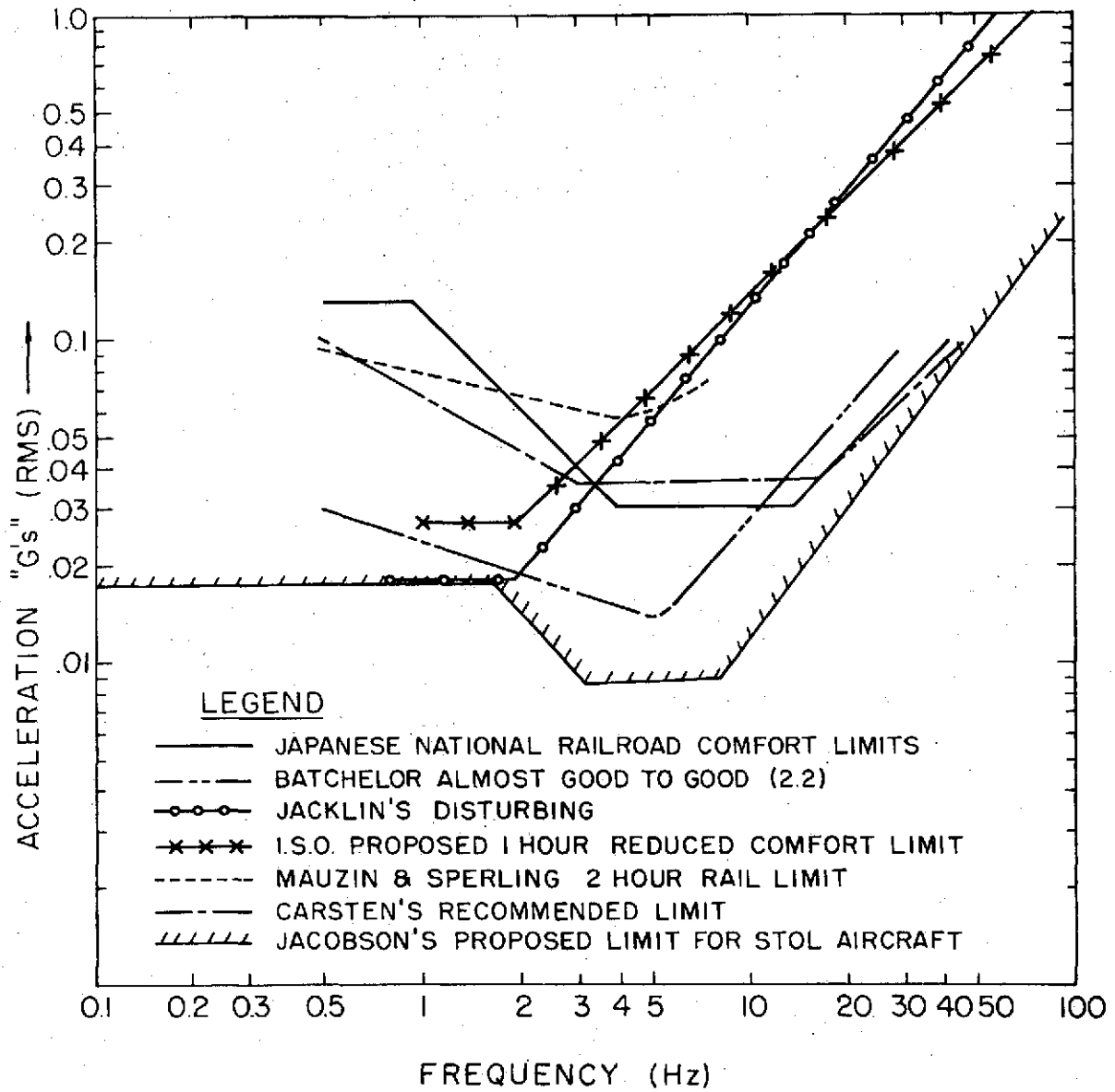
FIGURE 1.2 TRANSVERSE VIBRATION CRITERIA

(Taken from Jacobson (1) and Draft International Standard (2))

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six-degrees-of-freedom) which is essential to obtain a good mathematical model. On the other hand, ground-based simulator tests lack the ability to simulate psychological factors (e.g. anxiety and motivation) among test subjects. This is especially undesirable for aircraft comfort tests, since the anxiety factor of being airborne cannot be simulated on the ground.

Further, most previous work has involved human response to vertical acceleration only. Some recent research has been directed at other axes of acceleration such as transverse and longitudinal (e.g. ISO (2) and Koo (4)), but surprisingly little has been done on angular accelerations (e.g. Collins (5) and Clark and Stewart (6)).

In addition, most of the simulator tests have been conducted with sinusoidal oscillations at different discrete frequencies. Test subjects are generally exposed to increasing acceleration at each frequency and they rate the acceleration based on a comfort scale. The exposure limits given by the criteria are probably applicable only for pure sinusoidal acceleration in the corresponding degree of freedom. The results may not be applicable, if there is more than one frequency of acceleration occurring simultaneously (some efforts have been made in this direction-- Brumaghim (7) and O'Massey, et al. (8)), or if there are multiple degrees of freedom present (an area where hardly any work has been done at all).

Though most of the experiments were conducted under different physical environments (e.g. sitting, standing, etc.), the results indicate that humans are most sensitive to the frequency range of 4 - 8 Hz in the vertical mode, probably due to internal organ resonance. Except on this point,

there is wide disagreement on the magnitudes of acceleration for a given

semantic level (e.g. perceptible, uncomfortable, etc.). The intolerable

level of one investigator is not even mildly annoying for another (1).

Such discrepancies are found widely, and experimental and semantic

differences do not always explain the spread in results.

Table 1.1 indicates the sources of vibration with dominant

frequencies, flight phases, and durations for typical aircraft. Of the

various flight phases, cruise is the longest and the main sources of

vibration are the engine (propeller or jet), turbulence, and buffeting.

1.2   Statement of the Problem

Vibration has been found to be an important variable affecting

passenger comfort (3). Figure 1.3 shows the frequency ranges of

mechanical vibration effects on man. It is seen that most of the effect

on humans is caused by infrasonic frequency vibrations (0 to 25 Hz),

hence this study is restricted to this range.

Data was collected on regular commercial flights, with test subjects

riding as passengers, creating both the proper physical and psychological

environment as well as providing representative accelerations encountered

in regular flights.

Several models are evaluated:

a. A comfort model depending on the root mean square (rms) values

of the six measured accelerations is developed. Inter-aircraft and

inter-subject differences are explored.

b. A comfort model depending on frequency-weighted rms accelera-

tions using a Rustenburg-type human response function is developed.

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TABLE 1.1

AIRCRAFT MISSION DESCRIPTION AND PROMINENT VIBRATION SOURCES
(Taken from O'Massey (8))

Flight Phase	Approximate Time Duration	Prominent Vibration Sources	Frequency Range
Warm up	1 to 15 min.	Engine	40 and above
Taxi	5 to 10 min.	Runway Roughness and Engine	0.5 to 5 40 and above
Run up	2 to 15 min.	Engine	40 and above
Takeoff	1 to 3 min.	Runway, Turbulence[*] Engine Buffet	0 to 10 40 and above 1 to 20
Climb	3 to 30 min.	Engine Turbulence[*]	40 and above 0 to 10
Cruise	15 min. to 8 hrs.	Engine Turbulence[*] Buffet	40 and above 0 to 10 1 to 20
Descent	5 to 15 min.	Turbulence[*]	0 to 10
Landing gear and flaps down	1 to 10 min.	Flap buffet and Turbulence[*]	0 to 10
Landing	5 sec. to 2 min.	Landing impact Runway Roughness	Pulse in nature 0.5 to 5

---

[*]Here turbulence refers to both atmospheric and boundary layer turbulence.

FREQUENCY - Hz

| 0.1 | 1 | 10^1 | 10^2 | 10^3 | 10^4 | 10^5 |

Infrasonic vibrations | Audio-frequency range | Ultra-sonics

HUMAN RESPONSE

Range of vibratory sensation
Disequilibrium (high intensities)
Motion sickness
Major body resonances
Blurring of vision
Disturbance of speech
Interference with manual tasks
Discomfort/pain (high levels)
General stress/"fatigue" effects
Damage risk to spine*
Gastro-intestinal disorders*
Vibration syndrome (hands)*

←SCOPE OF
ISO
LIMITS →

*   Cumulative occupational hazard

-----   uncertain ranges

FIGURE 1.3   APPROXIMATE FREQUENCY RANGES OF PRINCIPAL
EFFECTS OF MECHANICAL VIBRATION ON MAN

(Taken from Broderson and Von Gierke (9))

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c. A comfort model depending on frequency-weighted rms accelerations is determined. This model yields human sensitivity as a function of frequency for each degree of freedom.

Section II

DATA ACQUISITION AND REDUCTION

2.1 Introduction

A theoretical approach to the prediction of subjective comfort

level, given six-degrees-of-freedom of motion, has been ruled out

because of the lack of understanding of the complex interaction of

biodynamic, physiological, and psychological characteristics of humans.

The only recourse is to employ empirical techniques which require a

large amount of data collection.

Past ride quality studies have used a variety of comfort scales

(1), most having 3 to 7 levels of comfort. Since people prefer not

to use end points, the 3-level scale is inadequate. For the present

work, a 5-level comfort scale has been adopted:

    1. Very comfortable

    2. Comfortable

    3. Neutral

    4. Uncomfortable

    5. Very uncomfortable

No performance measures have been associated with these levels since

test subjects might be misled in evaluating performance measures rather

than comfort.

2.2 On-Board Data Recording

The measuring and recording system, designed and fabricated by

NASA Langley Research Center (shown in Figure 2.1), consists of battery
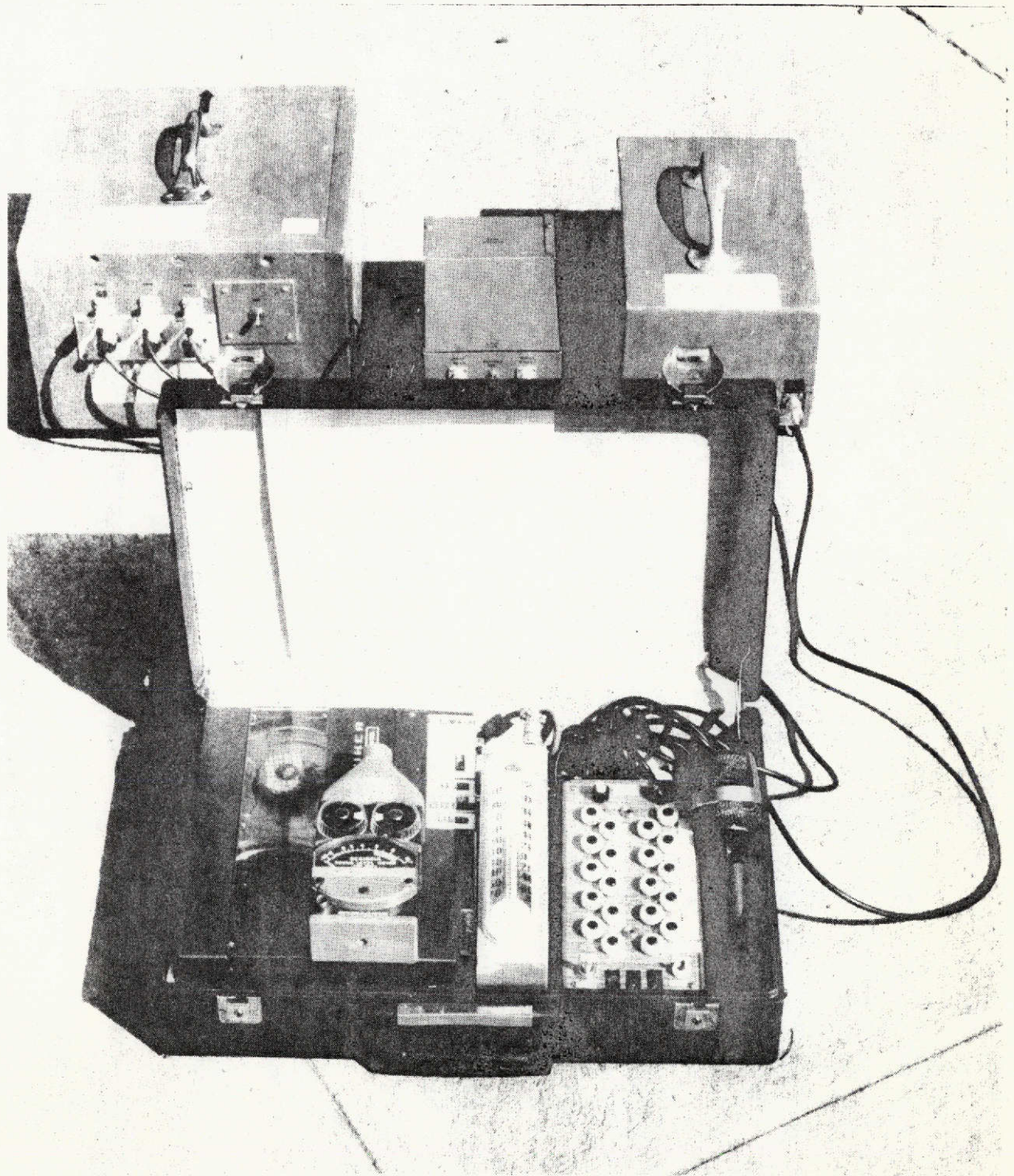
FIGURE 2.1 PORTABLE INSTRUMENT PACKAGE
AND RECORDING EQUIPMENT

operated sensors and recording equipment weighs a total of 30 pounds.
Linear accelerations to $\pm$ 1/2 g in each of three mutually-perpendicular
directions (vertical, longitudinal, and transverse), angular accelerations
to $\pm$ 2 rad/sec^2 about three mutually-perpendicular axes (pitch, roll,
and yaw), subjective response, and reference frequency signal are all
recorded on a two-channel 1/4" magnetic tape recorder (AM)--one channel
of FM multiplexed data, the other voice. A functional block diagram
of the measuring and recording system is shown in Figure 2.2. The
voltage-controlled oscillator (VCO) for each of the recorded variables
corresponds to standard inter-range instrumentation group (IRIG)
frequencies (10), (11), and (12). The reference frequency signal is
used during data reduction to compensate for tape speed variations.

The accelerometers are placed on the floor of the vehicle, at the
foot of the subject's seat. The subject indicates his comfort level by
depressing the appropriate comfort box button, corresponding to one of
the semantic levels described above, when evaluating the ride over a
period of approximately 30 seconds, in 2-minute intervals during flight.

2.3 Data Recovery

A functional block diagram of the data recovery system is shown
in Figure 2.3. The multiplexed data processed through discriminators
has an output which is directly proportional to the input signal
frequency and hence to the amplitude of acceleration.

During playback, the reference frequency is used by a compensation
module which detects deviations due to tape speed changes and applies an
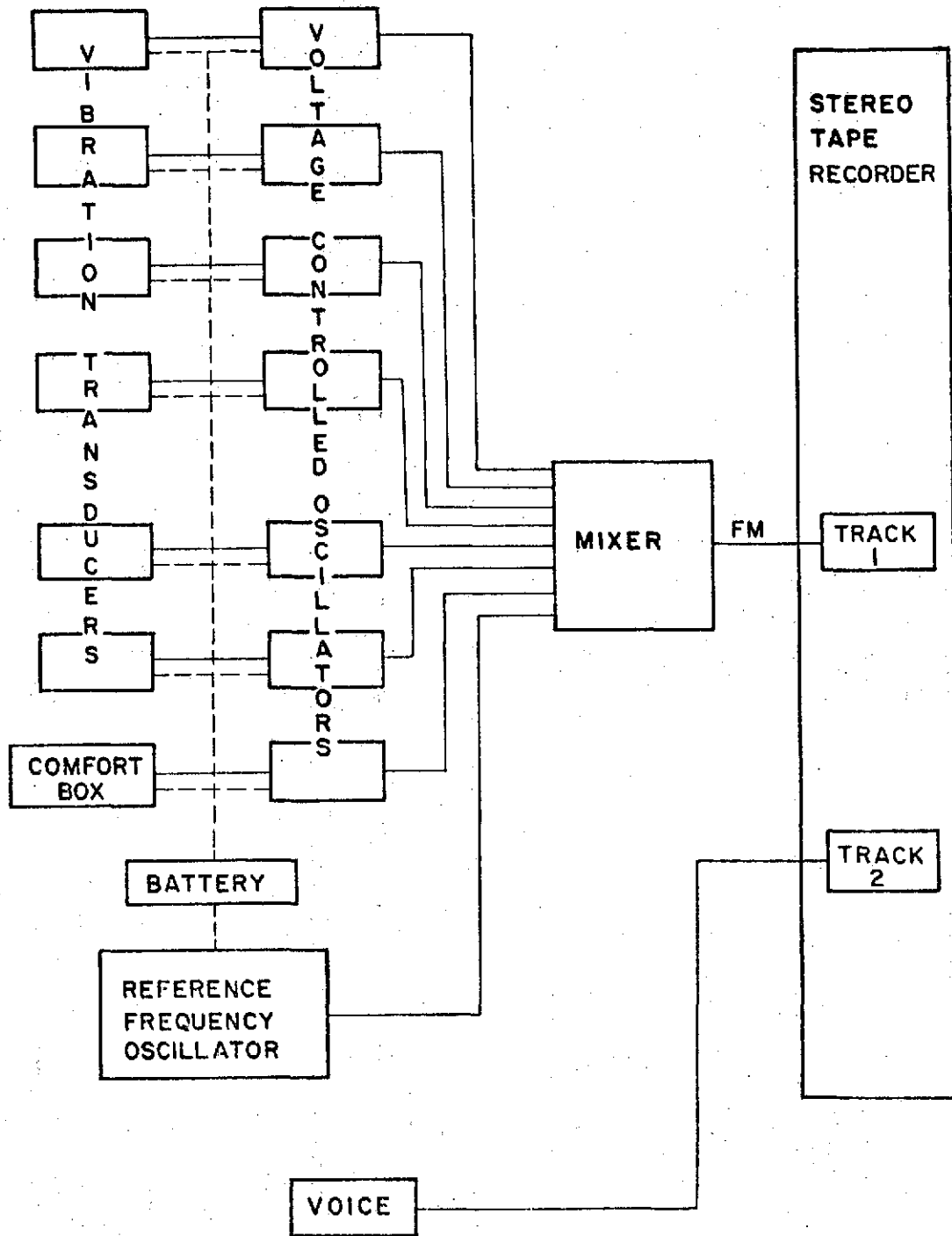inverse percentage compensation, considerably reducing errors. Each

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FIGURE 2.2   FUNCTIONAL BLOCK DIAGRAM OF MEASURING
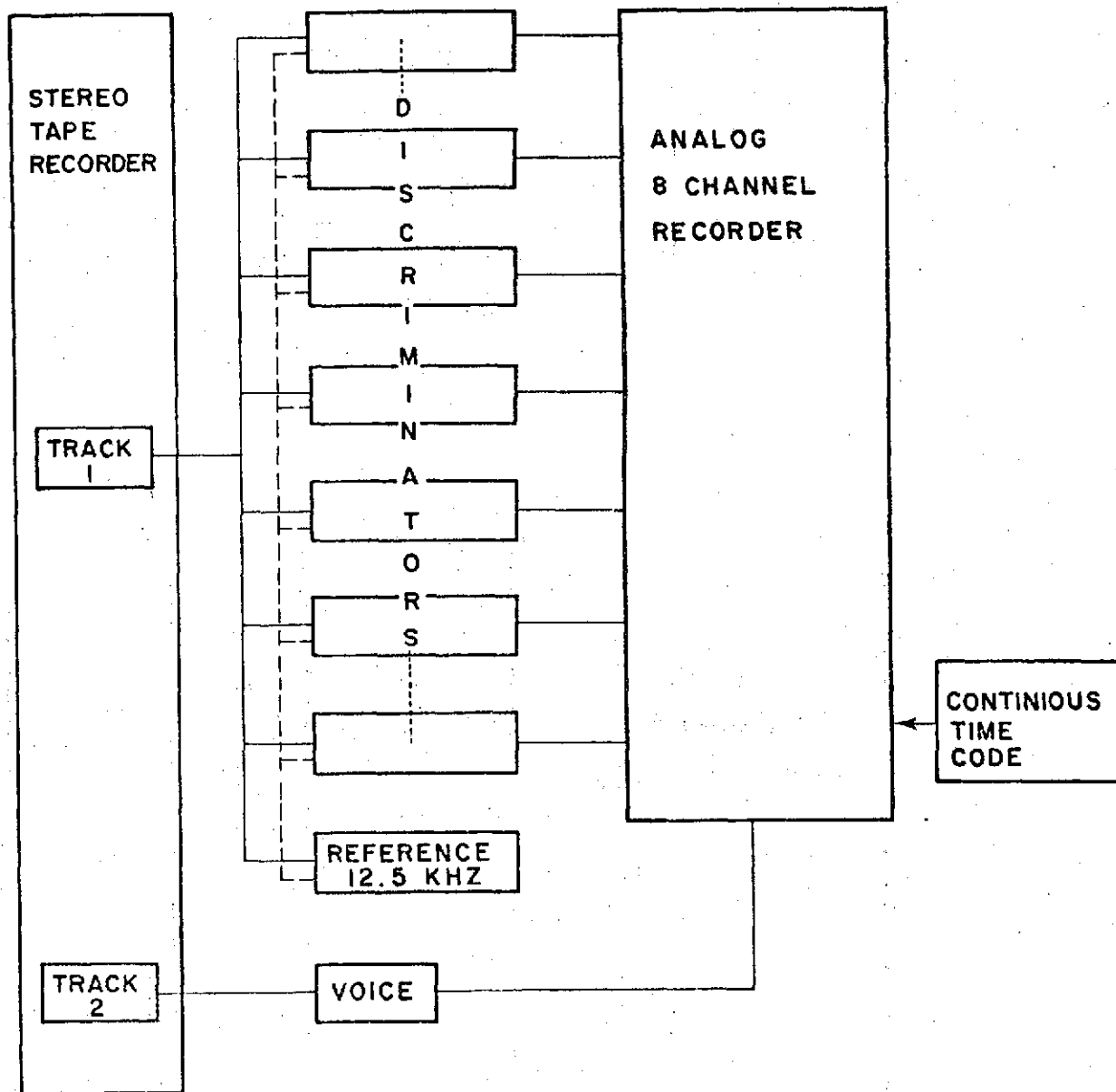AND RECORDING SYSTEM

FIGURE 2.3 FUNCTIONAL BLOCK DIAGRAM OF DATA
          REDUCTION SYSTEM

channel of data is recorded on an eight-channel wide-band FM tape with
carrier frequency (6.75 KHz) along with a continuous time code. This
time code becomes the primary reference in the data analysis. An
oscillograph record of all measurements complete with the time code,
subjective responses, and acceleration signals is obtained simultaneously.
A typical output, less the time code, is shown in Figure 2.4. The
recovered data is processed through a digitizer, sampled every 0.02
second (each channel), and written on a standard digital tape.

2.4 Data Reduction

It is nearly impossible to use acceleration time histories alone
to arrive at a subjective response model. The data must be reduced to
meaningful variables which are amenable to modelling. A Time Series
Analysis program (TSA) is utilized at the LRC computer facility for
providing various statistical quantities (13). These include the
means, standard deviations, autocovariances, crosscovariances, and
power spectral density functions for each of the six-degrees-of-
freedom. These quantities, along with a ten-digit code consisting of
the date of flight, type of aircraft, flight number, and a sequence
number uniquely identifying a given flight segment, are stored on
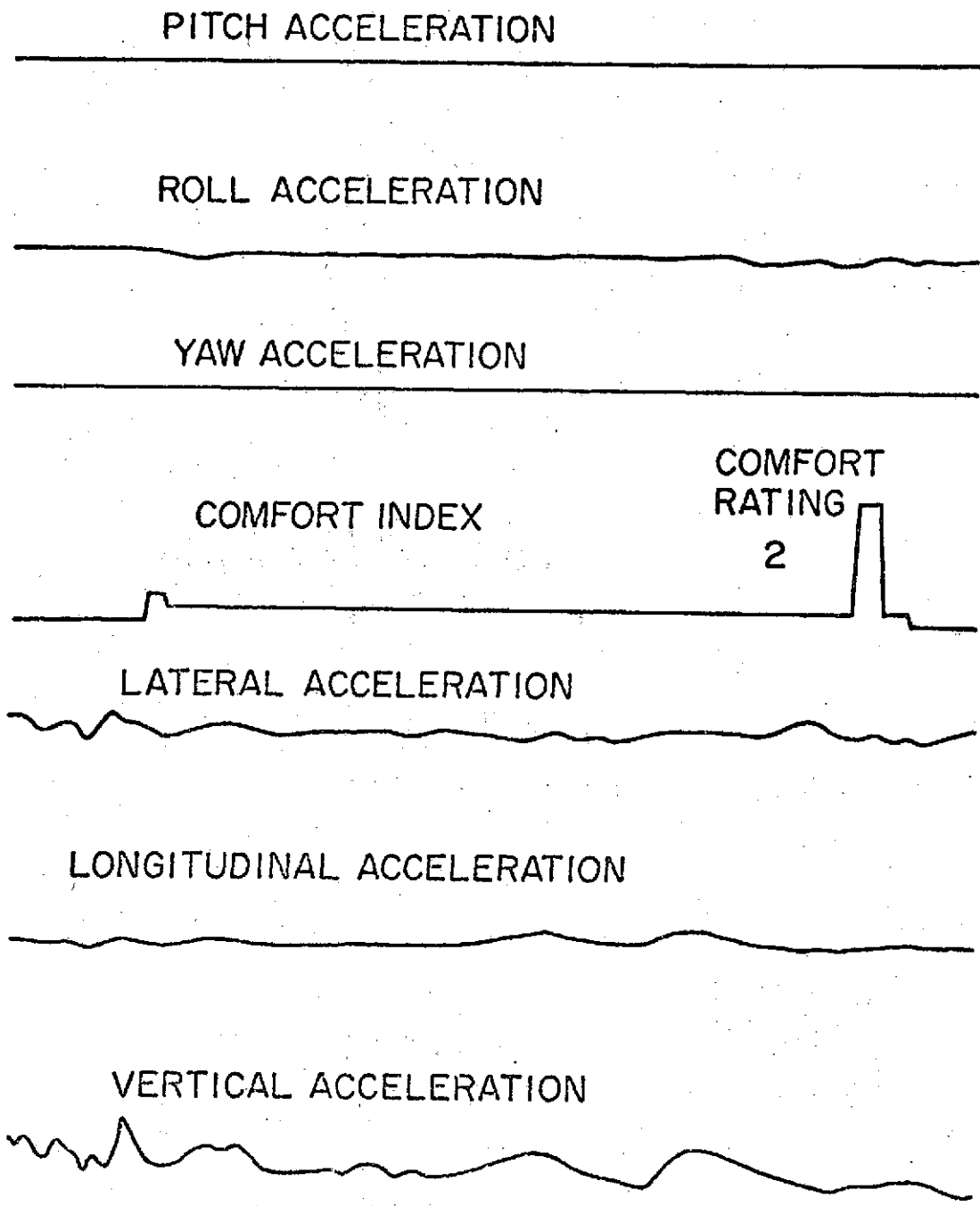magnetic tape to be used in the data analysis.

PITCH ACCELERATION

ROLL ACCELERATION

YAW ACCELERATION

COMFORT INDEX

COMFORT RATING 2

LATERAL ACCELERATION

LONGITUDINAL ACCELERATION

VERTICAL ACCELERATION

FIGURE 2.4   TYPICAL DATA OUTPUT TRACE

Section III

ANALYSIS OF DATA

3.1 Assumptions in Developing the Model

Most of the vibration experienced by the test subject is through
the seat, thus there is a discrepancy with the vibration measured by
the equipment at the foot of the test subject. For the present study,
it is assumed that the seat transfer function is the same for all the
aircraft under consideration in the frequency range of interest.

3.2 Data Collection

All the data used in this study were taken on commercial airline
flights between January and April of 1972. This involved approximately
100 flight segments flown on-board three different aircraft--F-227,
YS-11, B-737--under a variety of turbulence conditions and over
dissimilar terrain. (For aircraft details see Appendix A.) The
number of flight segments per day varied from 2 to 8, from approximately
60 miles to 250 miles in length, and from approximately 15 minutes to an
hour in duration. One or two test subjects flew on-board each flight
segment and a total of nine test subjects participated in the program.
(See Appendix A for details.)

3.3 Modelling

Regression analysis is used to develop subjective comfort models
(a detailed description of the statistical quantities used, as well as
the regression analysis can be found in reference 14) where subjective
comfort is the dependent variable and accelerations in the six-degrees-

of-freedom are the independent variables. The regression program

used is part of the UVA system library (SPSS, Statistical Package

for the Social Sciences) (16).

The first model developed uses autocovariance and crosscovariance

and has the form:

$$\hat{C} = b_o + \sum_{j=1}^{6} b_j (\bar{a}_j) + \sum_{j=1}^{6} \sum_{k=j+1}^{6} b_{jk} (\bar{a}_{jk}) \qquad (3.1)$$

where

$\hat{C}$ - predicted value of the subjective comfort

b_j, b_{jk} - constants predicted by the regression analysis

$\bar{a}_j = \sqrt{R_{X_j}(0)}$ - rms value of the acceleration $\qquad (3.2)$

$\bar{a}_{jk} = \sqrt{R_{X_j X_k}(0)}$ - zero lag crosscovariance of variables X_j and X_k. (3.3)

Hence, from Equations (2.5) and (2.7):

$$\bar{a}_j^2 = \frac{1}{T} \int_0^T X_j^2 (t) \, dt, \qquad (3.4)$$

and

$$\bar{a}_{jk}^2 = \frac{1}{T} \int_0^T X_j(t) X_k(t) \, dt. \qquad (3.5)$$

With appropriate modification nonlinear terms such as square roots can

also be incorporated in the above model.

The second type of model uses a Rustenburg-type (17) human response

function to compute frequency-weighted rms accelerations. It is necessary

to obtain a human equal sensation curve; this is not easy, however,

because existing data have large scatter as is seen in Figures 1.1 and

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and 1.2. Since most of the available data is for subjects exposed to vertical vibration, a human equal sensation curve has been adopted based on that data and is shown in Figure 3.1. (Taken from Jacobson (1).) The human frequency response function, W(f), is obtained by inverting the equal sensation curve as is shown in Figure 3.2. W(f) indicates the relative weight at frequency f that subjects use in evaluating comfort, and is normalized over the entire range of frequencies of interest.

An assumption made in this model is that the response function W(f) is valid in all six-degrees-of-freedom. This assumption is inherently weak as can be seen in Figures 1.1 and 1.2, but is used in the hope that it will indicate trends.

The frequency-weighted rms acceleration (of X_j) is given by:

$$\bar{a}^2_{W_j} = \int_o^F W^2(f)\ \phi_{X_j}(f)\ df \qquad\qquad (3.6)$$

where

F - the upper limit of frequency.

To normalize W(f), $\phi_{X_j}(f)$ is set equal to 1 in Equation (3.6) and the weighted and unweighted (W(f) = 1) cases are compared, yielding:

$$\int_o^F W^2(f)\ df = F. \qquad\qquad (3.7)$$

W(f) is gotten by interpolation as:

$$W(f) = W(f_k)\ \left(\frac{f}{f_k}\right)^{\psi_k} \qquad\qquad (3.8)$$

for $f_k \le f \le f_{k+1}$

where ψ_k is the slope between the break points of the W(f) curve.
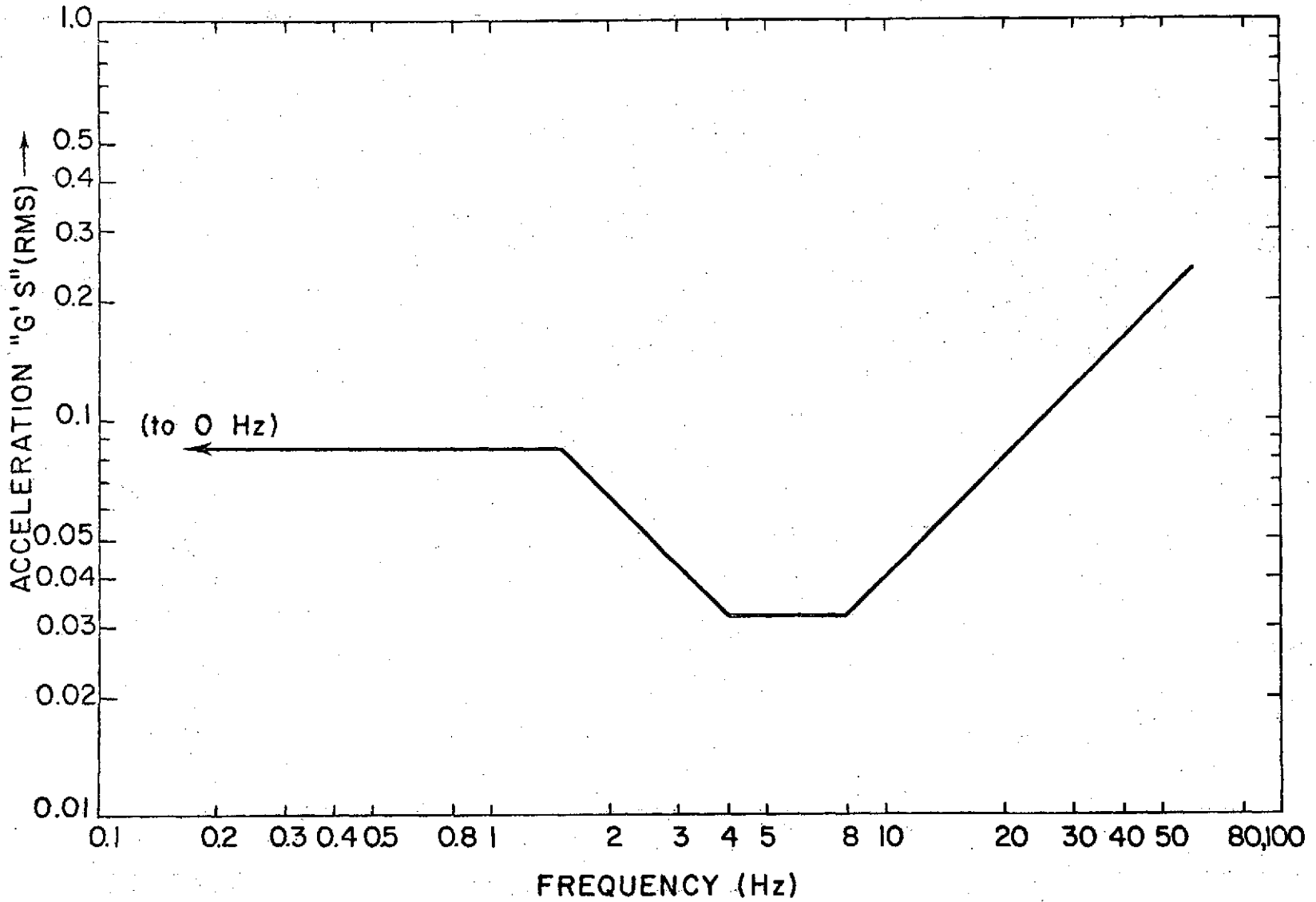
FIGURE 3.1   EQUAL SENSATION CURVE

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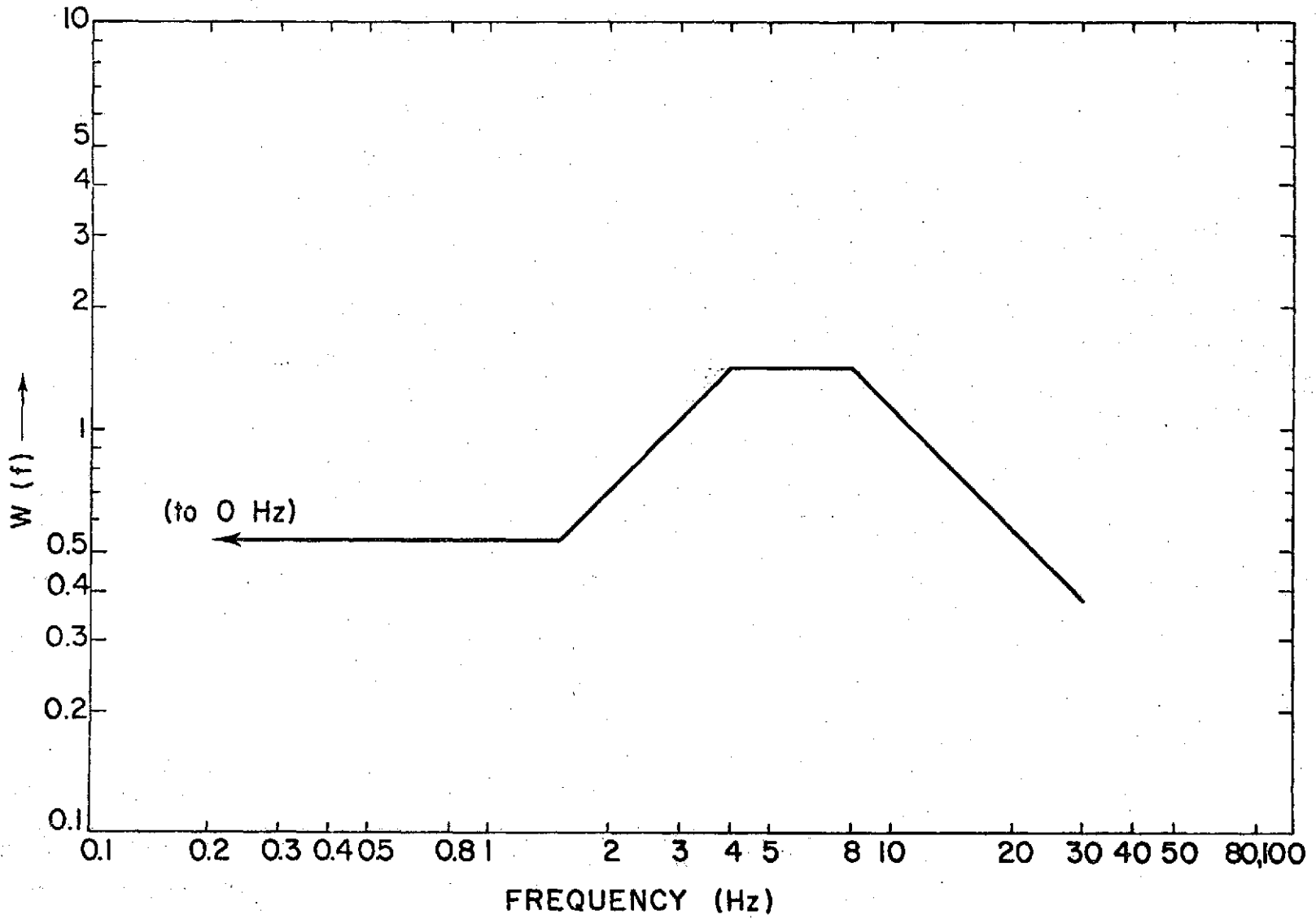
FIGURE 3.2 THE HUMAN FREQUENCY RESPONSE FUNCTION [W(f)]

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Table 3.1 tabulates the values of ψ_k used for the model:

$$\hat{C} = b_0 + \sum_{j=1}^{6} b_j (\bar{a}_{W_j})$$ (3.9)

TABLE 3.1

SLOPES OF THE HUMAN RESPONSE FUNCTION, W (f)

Range of Frequencies (Hz)	Slope ψ_k
0 to 1.5	0
1.5 to 4	1
4 to 8	0
8 to 30	-1

The final model considered for analysis is frequency dependent, and has the form:

$$\hat{C} = b_0' + \sum_{j=1}^{6} \sum_{k=1}^{K} b'_{jk} (\bar{a}_{j,k})$$ (3.10)

where

$\hat{C}$ - predicted value of comfort

b_0', b'_{jk} - coefficients predicted by the regression analysis,

and where the rms value is given by (15):

$$\bar{a}_{j,k}^2 = \int_{f_k}^{f_{k+1}} \phi_{X_j} (f) \, df.$$ (3.11)

Here

$\phi_{X_j} (f)$ - p.s.d.f. of the variable X_j

f - frequency

f_k, f_{k+1} - lower and upper limit of the frequency band, over which the rms $\bar{a}_{j,k}$ is evaluated

K - number of frequency bands used.

Suitable frequency bands are chosen in order to develop this model, yielding a frequency-dependent model and a human response function for each degree of freedom.

These three models serve as the preliminary criteria of ride quality.

RESULTS AND DISCUSSION

4.1 The Linear Model

Models are restricted to a few coefficients--about 100 data segments being needed for each. By this criterion, the largest model can have 14 coefficients at most (approximately 1400 data segments are available). As a first step, only the rms values derived from the autocovariances are used in a linear model, resulting in a comfort response, C, which is related to the six accelerations by:*

$$\hat{C} = 1.82 + 14.3\bar{a}_V + 0.163\bar{a}_R + 1.0\bar{a}_L + 2.3\bar{a}_T + 0.2\bar{a}_Y + 0.14\bar{a}_P. \quad (4.1)$$

Vertical is found to be the dominant and best defined variable for the following reasons:

a. Vertical acceleration accounts for the largest average contribution to the comfort value compared to the other degrees of freedom. The average contribution of each acceleration component, X_j, is computed as follows:

$$\bar{C}_{\bar{a}_j} = b_j \, \mu_{\bar{a}_j} \quad (4.2)$$

where

$\bar{C}_{\bar{a}_j}$ is the mean contribution to $\hat{C}$ by $\bar{a}_j$

$\mu_{\bar{a}_j}$ is the mean value of $\bar{a}_j$.

The average values of $\bar{C}_{\bar{a}_j}$ are:

---

*In this and ensuing models, all linear accelerations have units of rms g's and all angular accelerations rms rad/sec².

Vertical	0.92
Longitudinal	0.073
Transverse	0.048
Roll	0.051
Pitch	0.022
Yaw	0.011

The comfort scale is divided into five step function values (i.e.,
integer values of 1 to 5) implying that any degree of freedom which
on an average contributes less than 0.5 stands less than 50% chance
of altering the step response "C" by itself.* Hence all such variables
are relatively insignificant individually (in comparison with those
that contribute more than 0.5 on an average). In this sense only
vertical seems to be significant.

b. As can be seen from Table 4.1, the correlation of vertical
acceleration with the comfort rating (0.723) is the largest.

c. Further it is seen that the coefficient of variability (which
is defined as the ratio of the standard error to that of the expected
value or mean) of the predicted coefficient of vertical is low. The
variability coefficients are listed below:

Vertical	0.04
Roll	0.51
Longitudinal	1.72
Transverse	0.588

---

*Here the assumption is made that human response varies continuously
between discrete levels of C and that the crossover occurs at the
midpoint.

TABLE 4.1

CORRELATION MATRIX (SYMMETRIC)

	Comfort	Pitch	Roll	Yaw	Trans.	Long.	Vert.	$\sqrt{\text{Vert.}}$	Trans.-Vert.
Comfort	1.0	0.107	0.209	0.273	0.58	0.271	0.723	0.724	0.544
Pitch		1.0	0.836	0.366	0.2	0.123	0.031	0.018	0.12
Roll			1.0	0.442	0.351	0.181	0.164	0.15	0.207
Yaw				1.0	0.472	0.197	0.342	0.315	0.354
Transverse					1.0	0.351	0.751	0.726	0.699
Longitudinal						1.0	0.437	0.454	0.369
Vertical							1.0	0.982	0.763
$\sqrt{\text{Vertical}}$								1.0	0.729
Trans.-Vert.									1.0

Yaw	9.59
Pitch	0.96

The lower the coefficient of variability, the greater the confidence in the coefficient. Hence, the greatest confidence can be placed on the coefficient of vertical.

d. The model, Equation (4.1), can be expressed in a normalized form as follows:

$$C' = 0.71\bar{a}_V' + 0.07\bar{a}_R' + 0.02\bar{a}_L' + 0.05\bar{a}_T' + 0.02\bar{a}_Y' + 0.035\bar{a}_P'$$

$$(4.3)$$

where

$$C' = (\hat{C} - \bar{C})/\sigma_C$$

$\bar{C}$ - mean of C

$\bar{a}'$ - rms values based on autocorrelation with zero mean and unity standard deviation over the set of n data cases

σ_C - standard deviation of C.

Here each of the independent variables have zero mean and unity standard deviation. If it is assumed that all of the normalized variables have a similar probability density distribution, then the probabilities of each variable taking a given value are almost equal. Since the coefficient for $\bar{a}_V'$ is the largest, the average contribution from $\bar{a}_V'$ to C', and in turn to $\hat{C}$, is the largest, again indicating that vertical is the most dominant.

e. Finally, the r^2 value (see reference 15 for definition) indicates that most of the improvement was achieved with vertical alone in the model ($r^2 = 0.52$) versus addition of all other terms ($r^2 = 0.54$).

4.2 The Nonlinear Model

Since vertical is the dominant variable in determining subjective comfort, it is given an additional degree of freedom. C = 5 represents the highest comfort level independent of the acceleration. Thus a model which linearly increases for small accelerations and flattens out at high accelerations would be preferable. Incorporation of the additional term $\sqrt{\bar{a}_V}$, modifies the linear model to behave in the desired fashion, yielding:

$$\hat{C} = 1.33 + 5.29 \sqrt{\bar{a}_V} + 0.158\bar{a}_R + 1.0\bar{a}_L + 4.0\bar{a}_V + 2.69\bar{a}_T + 0.16\bar{a}_P$$
$$+ 0.09\bar{a}_Y . \tag{4.4}$$

The mean contributions to $\hat{C}$ in this case are:

$\sqrt{\text{Vertical}}$	1.27
Vertical	0.26
Transverse	0.056
Longitudinal	0.073
Roll	0.05
Pitch	0.025
Yaw	0.005

Once again vertical is the dominant variable. Comparing the above with the mean contributions of each variable in Equation (4.1), it can be observed that $\sqrt{\bar{a}_V}$ has replaced $\bar{a}_V$ as the term contributing most. This is encouraging, since $\sqrt{\bar{a}_V}$ rises slower than $\bar{a}_V$ and hence the model behaves better for large values of vertical acceleration.

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4.3 Model Using Vertical and Transverse Dependent Variables

From Table 4.1, it is seen that transverse has the second highest correlation with the comfort index. However, it is not the second largest contributor to $\hat{C}$. This is due to the strong correlation between vertical and transverse (0.75), which is also confirmed by Figure 4.1 showing the interdependence of vertical and transverse. The contribution of transverse to $\hat{C}$ occurs in two ways: partially through the transverse term which is independent of vertical and partially by vertical to which transverse is highly correlated.

From Table 4.1 it is seen that only transverse, vertical, and rms crosscovariance between transverse and vertical (written for simplicity as trans-vertical) have a correlation with subjective comfort of more than 0.5. Using these three variables, the model:

$$\hat{C} = 2.0 + 13.8\bar{a}_V - 3.25\bar{a}_{VT} + 4.5\bar{a}_T \tag{4.5}$$

is obtained. Here note that the coefficient for $\bar{a}_{VT}$ is negative. This implies that the presence of each degree-of-freedom masks the other to some extent. A similar effect is seen by Brumaghim (7), in his study of dual frequencies.

Depending on the application, one of Equations (4.1), (4.4), or (4.5) can be used for a criterion. Equation (4.5) is the simplest, whereas Equation (4.4) is the most accurate and complex model of the three. In most cases, Equation (4.5) should be adequate.

4.4 Rustenburg-Type Model

The second model is the Rustenburg-type (17) using frequency-weighted rms acceleration as shown in Equation (3.9) that yields:
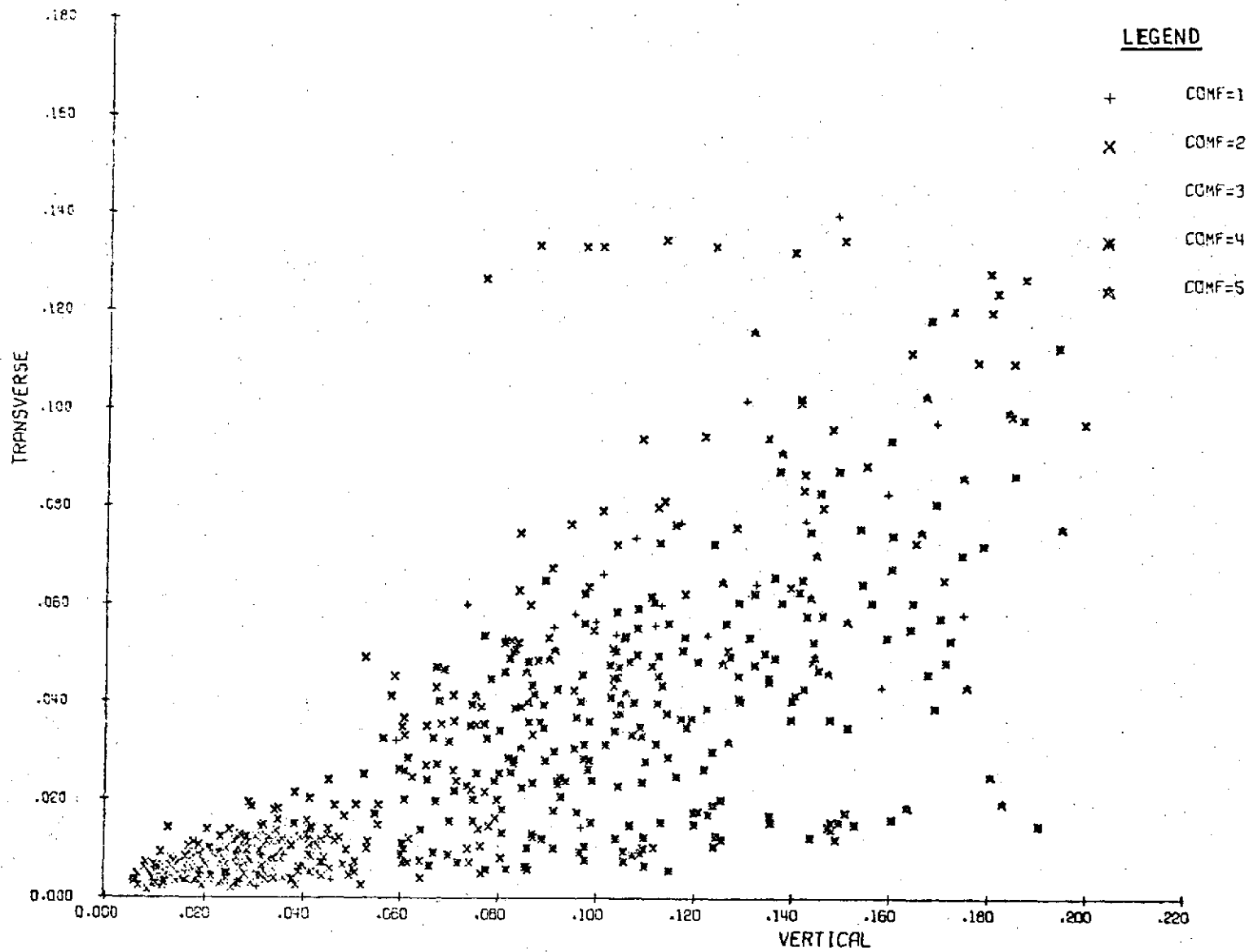
FIGURE 4.1   PLOT OF OBSERVATIONS ON VERTICAL-TRANSVERSE PLANE

$$\hat{C} = 1.31 + 6.54\ \sqrt{\bar{a}_{W_V}} + 0.46\bar{a}_{W_R} + 0.5\bar{a}_{W_L} + 5.63\bar{a}_{W_V} + 0.2\bar{a}_{W_Y}$$

$$\tag{4.6}$$

$$+\ 0.71\bar{a}_{W_P} + 0.48\bar{a}_{W_T}.$$

The mean contributions to $\hat{C}$ of each variable is:

√Vertical	1.26
Vertical	0.23
Transverse	0.0065
Longitudinal	0.005
Pitch	0.036
Roll	0.072
Yaw	0.008

Equations (4.4) and (4.6) compare favorably except for the coefficient of transverse acceleration, which has decreased considerably. This is also confirmed by comparing the mean contributions of the two models. One of the reasons for the discrepancy between the two models is that the response function (or the weighting function), W(f), is not a good description for transverse (this will be confirmed below).

Table 4.2 shows the difference in correlation coefficients, ρ, between subjective comfort and the frequency unweighted and weighted accelerations. As can be seen, the correlation between $\hat{C}$ and frequency-weighted rms accelerations is greater than the correlation with the unweighted rms accelerations in all the degrees of freedom, indicating a definite frequency dependence of the comfort model. The same conclusion is reached by comparing the standard errors (0.568 for weighted and 0.573

TABLE 4.2

COMPARISON OF CORRELATIONS, ρ, BETWEEN THE FREQUENCY UNWEIGHTED AND

WEIGHTED VARIABLES AND COMFORT INDEX

Independent Variable (X_j)	Unweighted $\rho_{C\bar{a}_j}$	Weighted $\rho_{C\bar{a}_{W_j}}$
Pitch	0.107	0.436
Roll	0.209	0.333
Yaw	0.273	0.355
Transverse	0.58	0.593
Longitudinal	0.271	0.356
Vertical	0.723	0.728
$\sqrt{\text{Vertical}}$	0.724	0.728

unweighted) and the percentages of points with error greater than 0.5 (39.6% for the weighted against 40.5% for the unweighted case).

4.5 Frequency-Dependent Model

In order to obtain a better representation of human sensitivities than that given by Figure 3.2, a general frequency-dependent model (Equation (3.10)) is used.

Only the p.s.d.f. in the range 0 to 8 Hz is used since in almost all instances, most of the energy is concentrated in this range. A three-band frequency split, 0 to 1.5 Hz, 1.5 to 4.0 Hz, and 4.0 to 8.0 Hz, is chosen.

If all degrees of freedom, each with three frequency splits, are incorporated simultaneously, the number of unknowns, 22, exceeds that which can be determined for the amount of existing data. Thus human sensitivities in each degree of freedom are considered individually.

Vertical yields:

$$\hat{C} = 2.07 + 8.0\bar{a}_{V,1} + 9.0\bar{a}_{V,2} + 20.1\bar{a}_{V,3} \tag{4.7}$$

where

$\bar{a}_{V,1}$ - rms acceleration for 0 to 1.5 Hz

$\bar{a}_{V,2}$ - rms acceleration for 1.5 to 4 Hz

$\bar{a}_{V,3}$ - rms acceleration for 4 to 8 Hz.

The coefficients of $\bar{a}_{V,3}$ and $\bar{a}_{V,1}$ imply that subjects are most sensitive to frequencies in the 4 to 8 Hz range and least sensitive to frequencies in the 0 to 1.5 Hz range. This confirms the form of W(f) shown in Figure 3.2, and also agrees in relative magnitudes.

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For transverse:

$$\hat{C} = 2.4 + 15\bar{a}_{T,1} + 47\bar{a}_{T,2} + 4.7\bar{a}_{T,3} \ . \qquad (4.8)$$

As is seen, $\bar{a}_{T,2}$ (1.5 - 4 Hz) is the most heavily weighted whereas $\bar{a}_{T,3}$ is the least weighted. This is in keeping with the data in Figure 1.2, and indicates that the response function, $W(f)$, shown in Figure 3.2 does not hold for transverse acceleration.

Other degrees of freedom are not evaluated due to lack of spread in the data, i.e. the mean accelerations in other degrees of freedom are nearly constant and hence their relationship with comfort cannot be established with any confidence.

4.6 Inter-Aircraft and Inter-Subject Differences in the Model

The data was acquired on board three aircraft--F-227, YS-11, and B-737--using 9 test subjects. Here inter-aircraft and inter-subject differences in the model are evaluated. The simplest model, using rms values based on vertical, transverse and crosscovariance between vertical and transverse, is used for the analysis.

Figure 4.2 shows inter-aircraft differences, where numbers in parentheses are the standard errors in the predicted coefficients. As is seen, the coefficients of vertical for all aircraft agree closely with the overall model. The coefficient of transverse for the overall model agrees well with that of the YS-11, reasonably with that of the B-737, and poorly with that of the F-227. Note the fact that the standard error in prediction for the transverse coefficient in the case of the F-227 is high. The same behavior is observed for the

<u>OVERALL</u>:

$$\hat{c} = 2.0 + 13.8^{(\pm 0.635)\overset{*}{}}\bar{a}_V - 3.25^{(\pm 1.89)}\bar{a}_{VT} + 4.52^{(\pm 1.29)}\bar{a}_T$$

$$\bar{c} = 2.95$$

<u>AIRCRAFT F-227</u>:

$$\hat{c} = 2.395 + 14.18^{(\pm 3.14)}\bar{a}_V + 7.27^{(\pm 8.14)}\bar{a}_{VT} - 11.14^{(\pm 7.46)}\bar{a}_T$$

$$\bar{c} = 3.25$$

<u>AIRCRAFT YS-11</u>:

$$\hat{c} = 2.01 + 13.83^{(\pm 0.68)}\bar{a}_V - 3.78^{(\pm 2.08)}\bar{a}_{VT} + 4.45^{(\pm 1.39)}\bar{a}_T$$

$$\bar{c} = 2.975$$

<u>AIRCRAFT B-737</u>:

$$\hat{c} = 1.9 + 14.29^{(\pm 2.0)}\bar{a}_V - 4.04^{(\pm 5.83)}\bar{a}_{VT} + 10.15^{(\pm 4.1)}\bar{a}_T$$

$$\bar{c} = 2.77$$

---

*Numbers in parenthesis indicate the standard error in predicted coefficient.

FIGURE 4.2   INTER-AIRCRAFT DIFFERENCES IN THE MODEL

coefficient of trans-vertical. This discrepancy is probably due to the sparsity of data taken on-board the F-227. Further we see that for the flight test conducted the F-227 appears to be the most uncomfortable ($\bar{C}$ = 3.25) and the B-737 ($\bar{C}$ = 2.77) the most comfortable among the three aircraft.

Similarly Figure 4.3 shows inter-subject differences for 3 subjects. The coefficients of vertical are similar with the exception of subject C. A large standard error resulted in the elimination of the coefficient of transverse for subject C. The overall model's coefficient of transverse compares favorably with that of subject B and reasonably with that of subject A. The coefficient of $\bar{a}_{VT}$ seems to be well behaved. The dispersion exhibited by the model for subject C is due to a sparsity of data for this subject.

Some deviations are observed for the coefficients of $\bar{a}_T$ and $\bar{a}_{VT}$, however they do not contribute significantly to the comfort model as confirmed in Figures 4.4 and 4.5.

It can be concluded that inter-aircraft and inter-subject differences are small and hence the overall model can be used to represent all aircraft and subjects.

OVERALL:

$$\hat{c} = 2.0 + 13.8^{(\pm 0.635)^{*}}\bar{a}_V - 3.25^{(\pm 1.89)}\bar{a}_{VT} + 4.52^{(\pm 1.29)}\bar{a}_T$$

$$\bar{c} = 2.95$$

SUBJECT A:

$$\hat{c} = 1.99 + 13.93^{(\pm 2.45)}\bar{a}_V - 2.34^{(\pm 7.15)}\bar{a}_{VT} + 11.24^{(\pm 5.57)}\bar{a}_T$$

$$\bar{c} = 2.98$$

SUBJECT B:

$$\hat{c} = 2.09 + 12.5^{(\pm 0.81)}\bar{a}_V - 2.09^{(\pm 2.3)}\bar{a}_{VT} + 4.08^{(\pm 1.6)}\bar{a}_T$$

$$\bar{c} = 2.97$$

SUBJECT C:

$$\hat{c} = 2.02 + 16.36^{(\pm 1.78)}\bar{a}_V - 5.91^{(\pm 6.84)}\bar{a}_{VT}$$

$$\bar{c} = 2.93$$

---

*Numbers in parenthesis indicate the standard error in predicted coefficient.

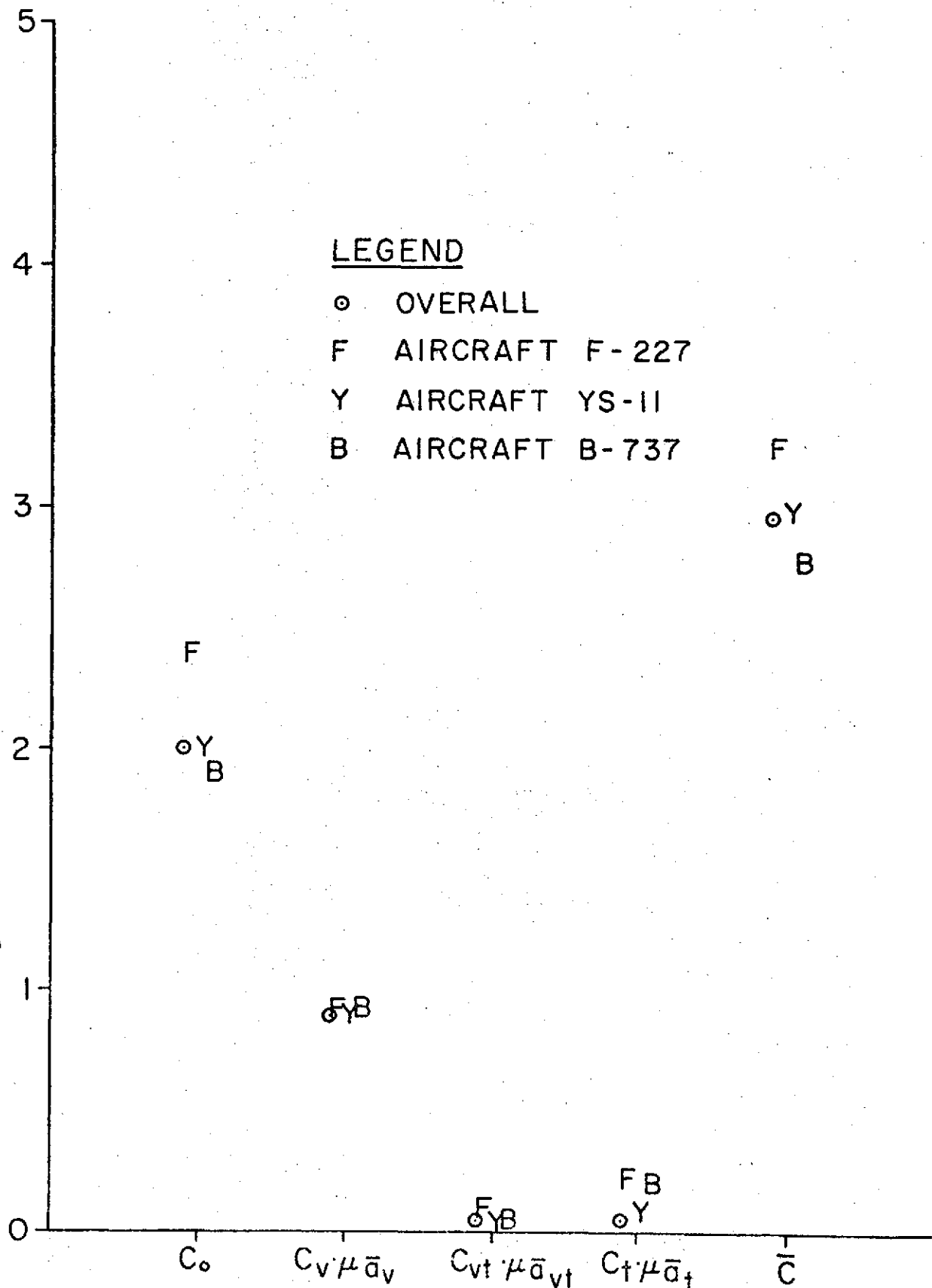FIGURE 4.3 INTER-SUBJECT DIFFERENCES IN THE MODEL

FIGURE 4.4   INTER-AIRCRAFT DIFFERENCES IN THE AVERAGE
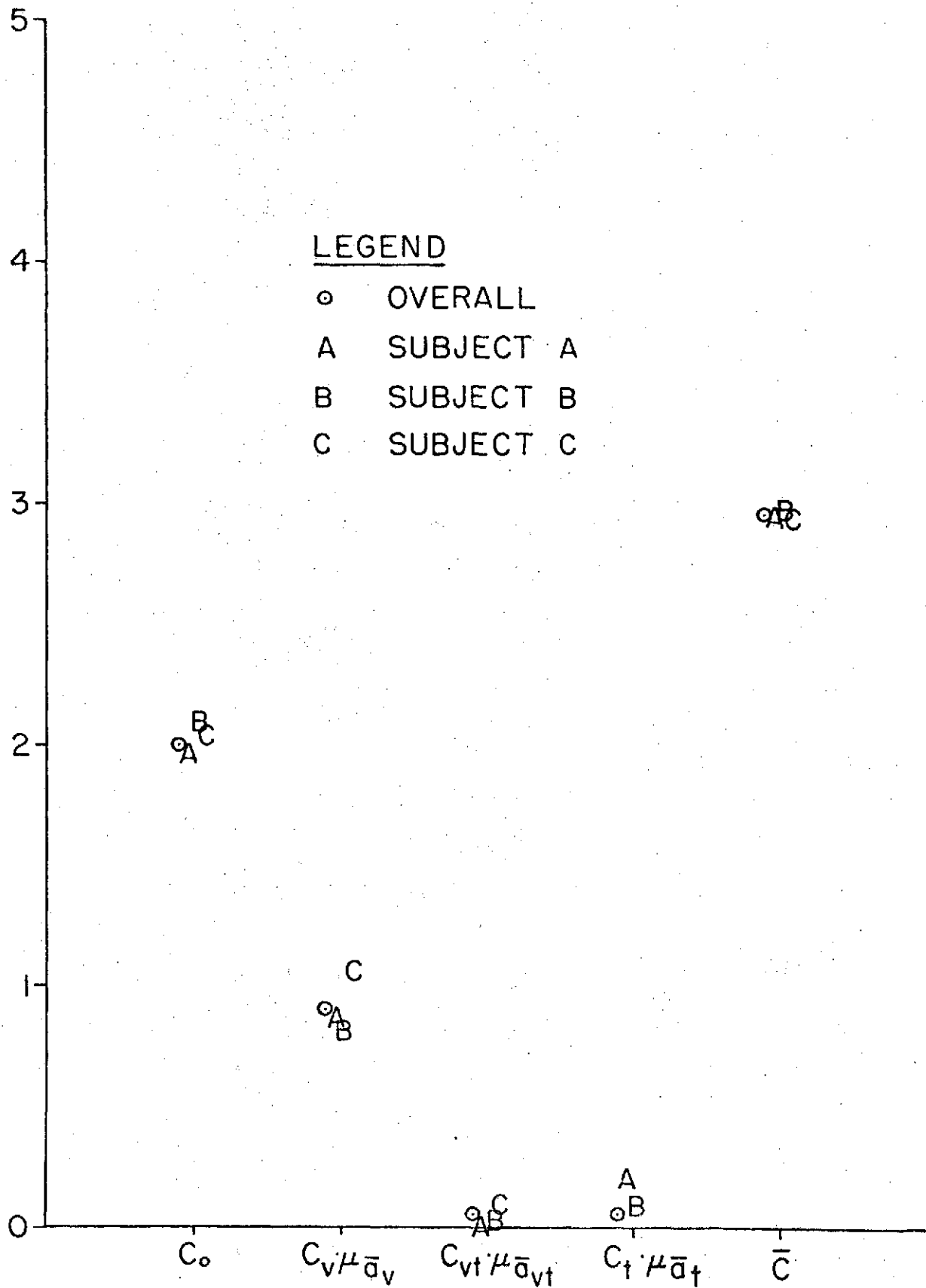CONTRIBUTION TO COMFORT "C"

FIGURE 4.5   INTER-SUBJECT DIFFERENCES IN THE AVERAGE
CONTRIBUTION TO COMFORT "C"

Section V

CONCLUSION

5.1 Some Remarks

Three types of models have been developed: models using rms acceleration; a Rustenburg-type frequency-weighted rms acceleration model; and a general frequency-dependent model.

It was concluded that human sensitivities obtained for vertical acceleration, unlike transverse, follow the general form of the response function shown in Figure 3.2. Further, it was observed that the Rustenburg-type model was superior to the rms acceleration model; however the human response function is not known for all directions, hence this type of model cannot be used to its full potential.

As a criterion, the simplest model developed, i.e., Equation (4.5), is suggested:

$$C = 2.0 + 13.8\bar{a}_V - 3.25\bar{a}_{VT} + 4.52\bar{a}_T \qquad (4.5)$$

where inter-aircraft and inter-subject differences are minor. It is cautioned that this is a preliminary model which will be refined as future data becomes available.

5.2 Applications

Among the many applications for Equation (4.5) is the evaluation of existing aircraft ride quality under various flying configurations. Those found objectionable can be modified to conform to the passenger comfort criterion. The ride criterion can also be used in designing aircraft and flight control systems.

Once a model has been selected, a suitable value of C can be chosen as the comfort boundary--one between 3 and 4 would be a good choice (18).

Taking a value of 3.5, which yields 68% passenger satisfaction (18),
Equation (4.5) yields:

$$13.8\bar{a}_V - 3.25\bar{a}_{VT} + 4.52\bar{a}_T = 1.5. \qquad (5.1)$$

The crosscovariance $\bar{a}_{VT}$ is related to the rms accelerations in vertical
and transverse by:

$$\bar{a}_{VT}^2 = \rho_{VT}\, \bar{a}_V\, \bar{a}_T \qquad (5.2)$$

where ρ_{VT} is the correlation coefficient for transverse with vertical.
The value of ρ_{VT} is obtained from Table 4.1 ($\rho_{VT} = 0.751$) yielding for
Equation (5.1):

$$13.8\bar{a}_V - 2.816\sqrt{\bar{a}_V}\,\sqrt{\bar{a}_T} + 4.52\bar{a}_T = 1.5. \qquad (5.3)$$

Equation (5.3) along with isocomfort curves for $\hat{C} = 3$ and $\hat{C} = 4$
are plotted in Figure 5.1.

Figure 5.2 shows the superposition of the comfort criterion
($\hat{C} = 3.5$) on the actual data and indicates that more than 50% of the
data lie within the acceptable range. It is also felt that the model
may not be valid for large transverse accelerations simultaneous with
small vertical accelerations, since negligible data was obtained in
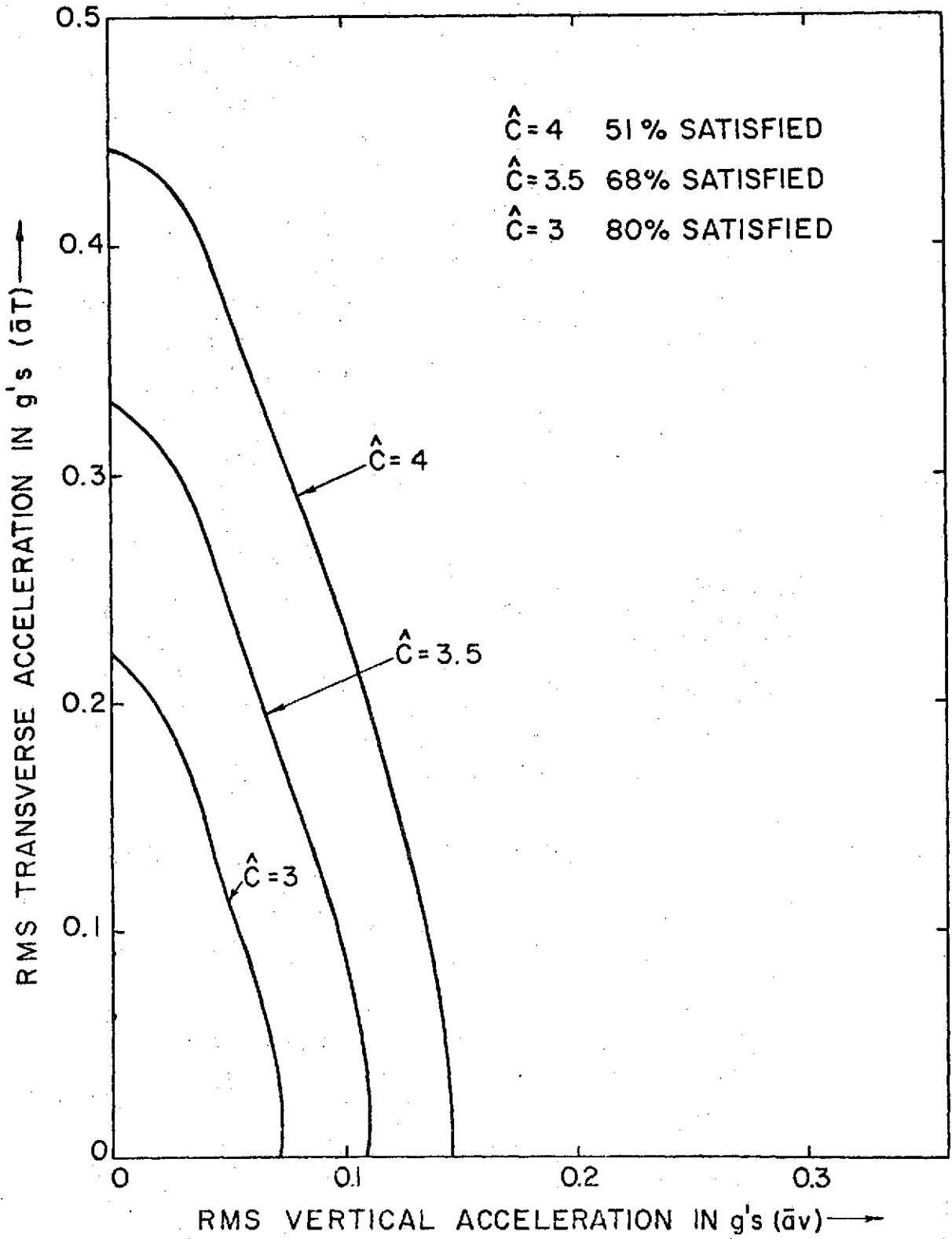that range, thus the model represents an extrapolation in this region.

FIGURE 5.1 ISO-COMFORT CURVE FOR THE MODEL
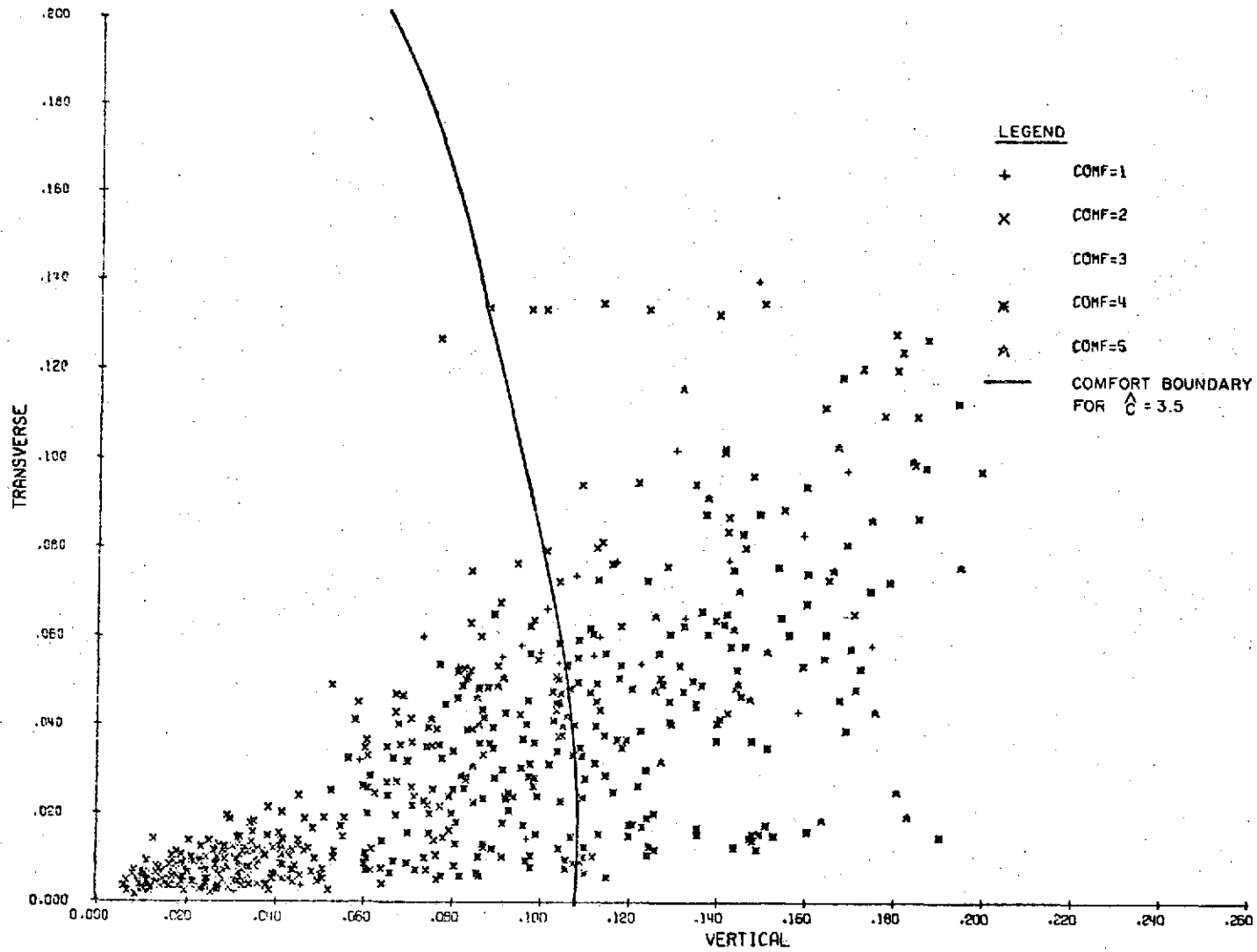$$\bar{C} = 2.0 + 13.8\bar{a}_V - 3.25\bar{a}_{VT} + 4.52\bar{a}_T$$

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FIGURE 5.2 COMPARISON OF COMFORT CRITERIA WITH ACTUAL DATA

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APPENDIX A

SOME REMARKS ON THE AIRCRAFT AND SUBJECTS USED

FOR DATA COLLECTION

This appendix lists special characteristics and conditions under which the data were collected.

Data were collected on three aircraft--FH-227B-200, YS-11A, and B-737-201 (abbreviated in the text as F-227, YS-11, and B-737, respectively). Table A.1 indicates their characteristics and pertinent conditions under which the data were obtained. As can be seen, most of the data have been collected on board the YS-11.

Table A.2 shows the subject breakdown of the nine male test subjects used. Most of the data were collected using subjects A, B, and C.

TABLE A.1

DIFFERENCES IN THE AIRCRAFT USED FOR DATA COLLECTION

Aircraft	FH-227B-200	YS-11A	B-737-201
Length (ft)	84	86	100
Wing span (ft)	95	105	93
Capacity (No. of passengers)	44	60	90
Max. wing loading (lbs/sq. ft.)	60.3	52.8	115.2
Engine	2 turbo-prop	2 turbo-prop	2 turbo-fan
Normal terrain of flight	Flat	Mountainous and Flat	Flat
Average duration of flight (min.)	17 - 55	11 - 60	20 - 52
Altitude (1000 ft.)	5 - 11	2 - 10	6 - 26
Stage length of flight (miles)	72 - 240	45 - 260	85 - 380
Cruise T.A.S. (M.P.H.)	280	280	320 - 550
Noise (db) (C_F weighted)	90 - 98	80 - 100	75 - 105
Temperature (^{O}F)	70 - 82	65 - 80	65 - 78
Seat comfort	Least leg room	Average leg room	Most leg room
No. of flight segments	10	71	14

TABLE A.2

DIFFERENCES IN THE SUBJECTS USED FOR DATA COLLECTION

Subject	Approximate Age (Years)	Occupation	Number of Flight Segments
A	30	University teaching/engineer	17
B	25	Research Engineer	82
C	25	Research Engineer	24
D	24	Research Engineer	13
E	40	University teaching/engineer	6
F	40	University teaching/engineer	4
G	30	University teaching/mathematician	2
H	52	University teaching/engineer	2
I	30	University teaching/engineer	1

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