FLIGHT RESEARCH EXPERIMENTS
ON RIDE QUALITY

Technical Report
National Aeronautics and Space Administration
Grant No. NGR 47-005-202

Technical Report 403907
Short-Haul Air Transportation Program

Submitted by:

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RESEARCH LABORATORIES FOR THE ENGINEERING SCIENCES

UNIVERSITY OF VIRGINIA
CHARLOTTESVILLE, VIRGINIA 22901

Report No. ESS-4039-105-75
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Introduction

This report documents the results and analysis of several flight research experiments in ride quality. These tests were carried out aboard the NASA Flight Research Center, JetStar Aircraft equipped with the General Purpose Airborne Simulator; and aboard a specially instrumented Boeing 747 flown in actual commercial flight. The data has been analyzed to determine appropriate models for subjective reaction to the motion environment. Specifically, vertical and transverse acceleration inputs and aircraft bank angle have been studied along with duration of exposure. Other experiments were conducted during this study on the effects of spectral content and subjective reaction time, however these have been reported elsewhere (1,2) and are omitted here.

Description of Experiment

The basic experiment on the JetStar aircraft is described in reference 3 and is repeated here.

The aircraft, shown in Figure 1, is a Lockheed JetStar modified to carry the GPAS system. In addition to the "normal" control surfaces, the aircraft is equipped with direct lift flap control (dlc) surfaces and side force generator (sfg) surfaces. The use of these surfaces for the current study allow a wide range of vertical and transverse accelerations to be obtained.

A typical flight is shown in Figure 2 where a segment consists of a predetermined motion signature for a duration of 1 minute--runs 1 and 3 are used to evaluate vertical and transverse accelerations while runs 2, 4, and 5 indicate the effects of turns. Runs 1, 2, and 3 were constant altitude (20,000 feet) and runs 4 and 5 were descending turns. The elapsed time from take-off to landing is 60 minutes. In addition to the flight engineer, pilot and copilot, two subjects who continuously indicated their

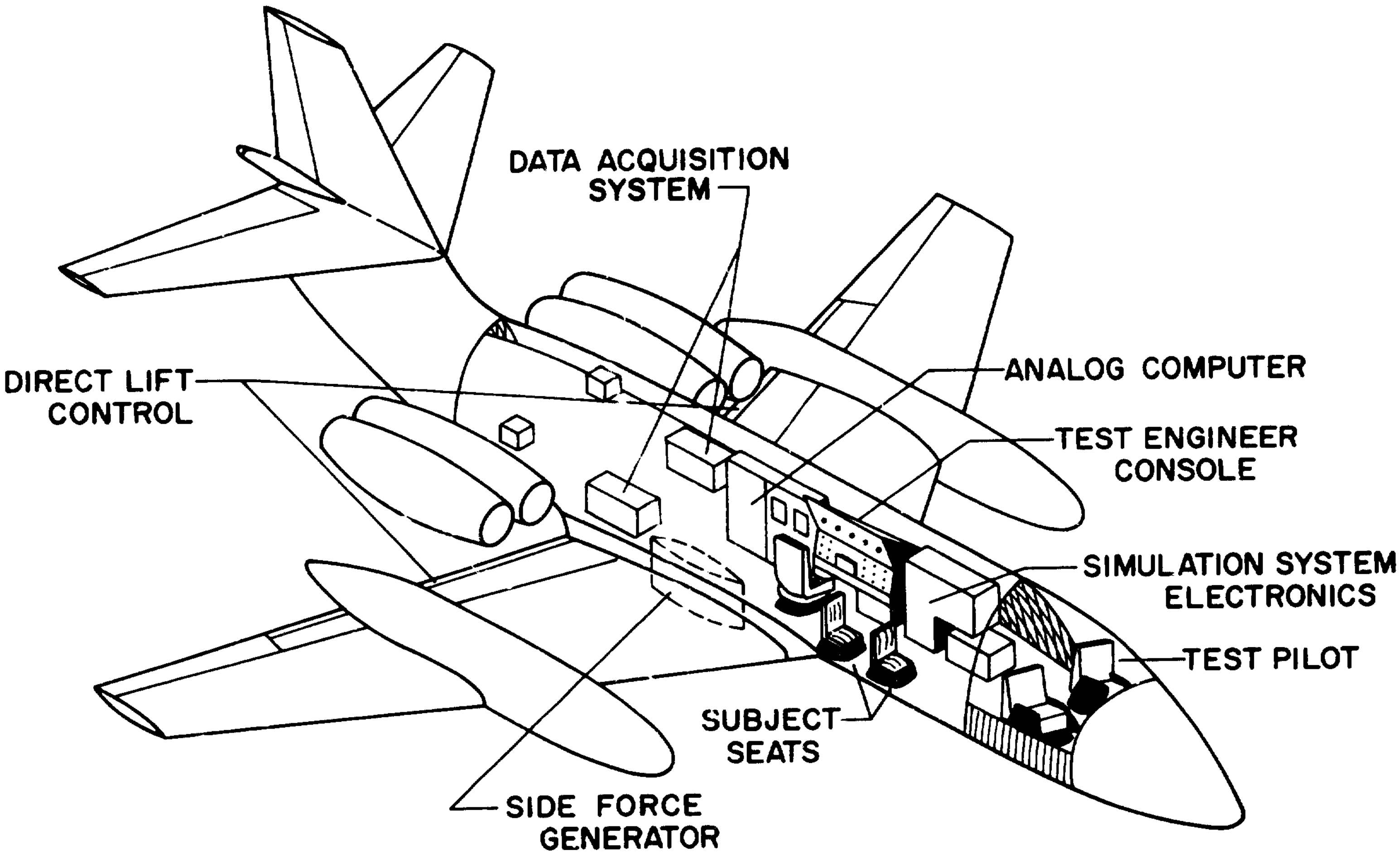

FIGURE 1. NASA General Purpose Airborne Simulator (GPAS)

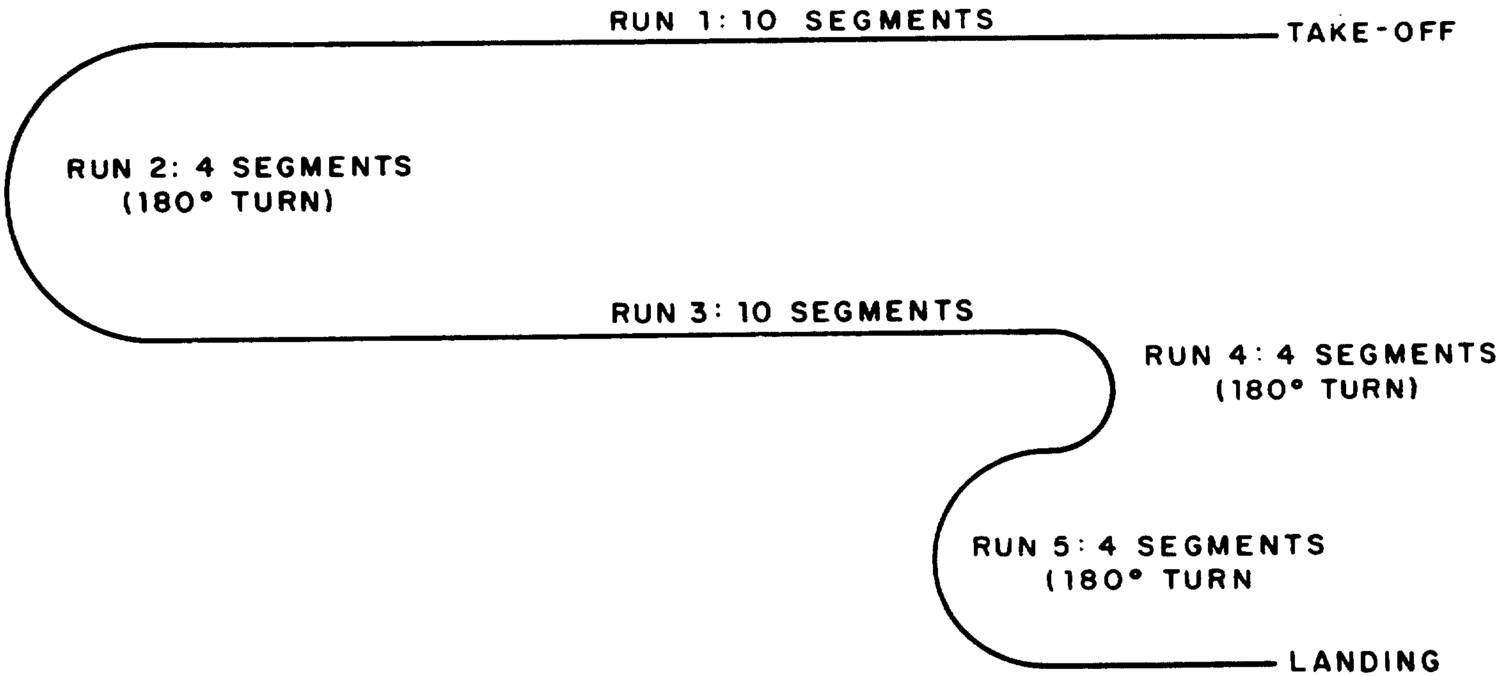

FIGURE 2. Typical Flight Pattern

comfort were on board. A five-point comfort scale was used with the following designations:

1 - Very comfortable
2 - Comfortable
3 - Neutral
4 - Uncomfortable
5 - Very uncomfortable

Each subject was given instructions on the use of the comfort scale prior to flight. The responses were automatically recorded along with the aircraft's motion variables.

The commercial aircraft data has been collected+ on board a Boeing 747 flying both transcontinental and transpacific with flight times lasting a maximum of four hours. As in the JetStar flights a five-point comfort scale was used for subjective judgements. The subject was located in the aft seat of the passenger cabin for all tests.

For both sets of tests the following data were obtained at five second intervals for each flight.

1. Vertical rms acceleration, or simply vertical acceleration, $\bar{a}_v$ ("g's")
2. Vertical mean acceleration, v ("g's")
3. Transverse rms acceleration, or simply transverse acceleration, $\bar{a}_t$ ("g's")
4. Transverse mean acceleration, t ("g's")
5. Comfort rating, C
6. Bank angle, ϕ (degrees)
7. Absolute time (seconds)

The mean and rms of vertical and transverse accelerations and bank angle are averaged over every five-second interval for which the subject responds, giving his/her assessment of the comfort.

+This data was collected by Continental Airlines under contract to NASA Flight Research Center. For a description of this program, see NASA CR-127492-P. W. Kadlec and R. G. Buckman, Inflight Data Collection for Ride Quality and Atmospheric Turbulence Research, Dec. 1974 (Ref. 4).

Data Reduction

The data was digitally recorded in-flight and later reduced using standard numerical techniques on the NASA FRC Cyber-70 computer system. In addition to mean values and standard deviations of aircraft motion variables, representative power spectra were obtained.

Analysis of Data

JetStar Data: Several models have been generated using the JetStar data. Here, subjective response is correlated with transverse and vertical accelerations. A summary of each of the models follows.

Model 1: Linear

$$C = 1.9 + 3.0\bar{a}_v + 20.9\bar{a}_t \qquad \bar{a}_v \leq 1.6\bar{a}_t \qquad \text{(a)}$$

$$C = 1.7 + 10.4\bar{a}_v + 11.0\bar{a}_t \qquad \bar{a}_v > 1.6\bar{a}_t \qquad \text{(b)}$$

where C is the subjective response and $\bar{a}_v$ and $\bar{a}_t$ are the vertical and transverse rms accelerations, respectively. The correlation coefficients and F-statistic for (a) and (b) are $f_a = .5$, $F_a = 85$ and $r_b = .6$, $F_b = 464$. Both models are significant at better than the .001 level. A composite of these is drawn in Figure 3 smoothing the transition at $\bar{a}_v = 1.6\bar{a}_t$.

Model 2: Nonlinear

$$C = 2 + 5.3\bar{a}_v + 17.4\bar{a}_t - .15\sqrt{\bar{a}_v\bar{a}_t}$$

Here the correlation coefficient is .39 and the F-statistic, 136. This model is not as accurate as the two linear models and thus will not be further analyzed.

Model 3: Psycho-physical

$$C = .9 + 3\bar{a}_t^{.25} + .9\bar{a}_v^{.5}$$

or for pure vertical motion

$$C = 6.76\bar{a}_v^{.39}$$

and for pure lateral motion

$$C = 4.47\bar{a}_t^{.17}$$

The correlation coefficients for these models are .51, .47 and .23, respectively. These models are not as good as the linear

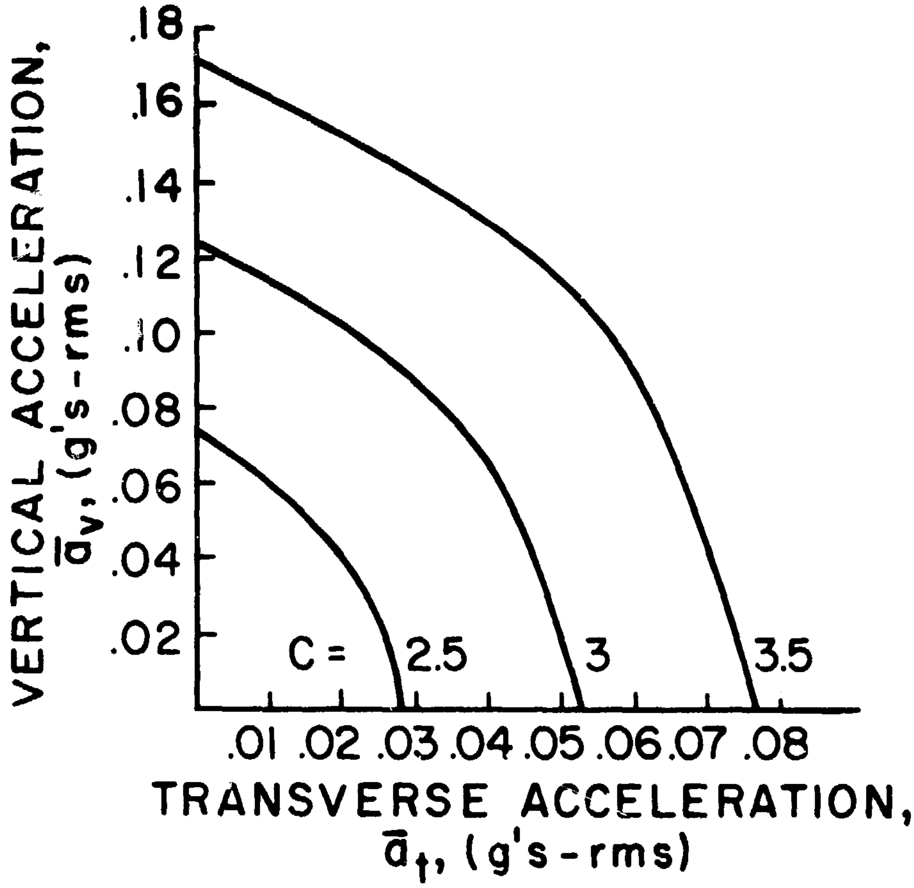

FIGURE 3. Equicomfort Contours

relationship. The models predict a threshold value, C=1, for the vertical and transverse directions as shown in Table I, where the two-variable model yields different values than the single degree-of-freedom models.

TABLE I. Acceleration Thresholds

Direction	Threshold		Miwa's Results
	2-DOF	1-DOF	
Transverse	1.2×10^{-6}	1.5×10^{-4}	8×10^{-4}
Vertical	1.2×10^{-2}	7.4×10^{-3}	2×10^{-3}

Here we can see that the predicted threshold for vertical is higher than Miwa's, however the threshold for lateral is lower. It should be kept in mind that Miwa's results are for subjective sensation, not comfort, and are in a laboratory situation.

Model 4: Biodynamic

Since the human body can be modelled by a mechanical analogue (see Figure 4) with resonances at various frequencies--mainly 4 to 8 hertz--in the vertical direction, a regression model related to this analogue was undertaken. The results given here are somewhat disappointing with a correlation coefficient of only .19. This would seem to indicate that a simple mechanical analogue does not adequately represent the psycho-physical decision in the subjects' assessment of comfort. The equations for each of displacement and velocity variables are:

$$C = 2.6 + 5 \times 10^{-5} (\text{Displacement})^2 + .012\ (\text{Velocity})^2$$

It is not felt that an adequate variance is accounted for in this model.

Bank Angle Data

The bank angle data have been analyzed to determine the effect of bank angle and its contribution to subjective comfort when in the presence of vibratory motion. Figure 5, a composite of all bank angle data, shows the effect on comfort rating.

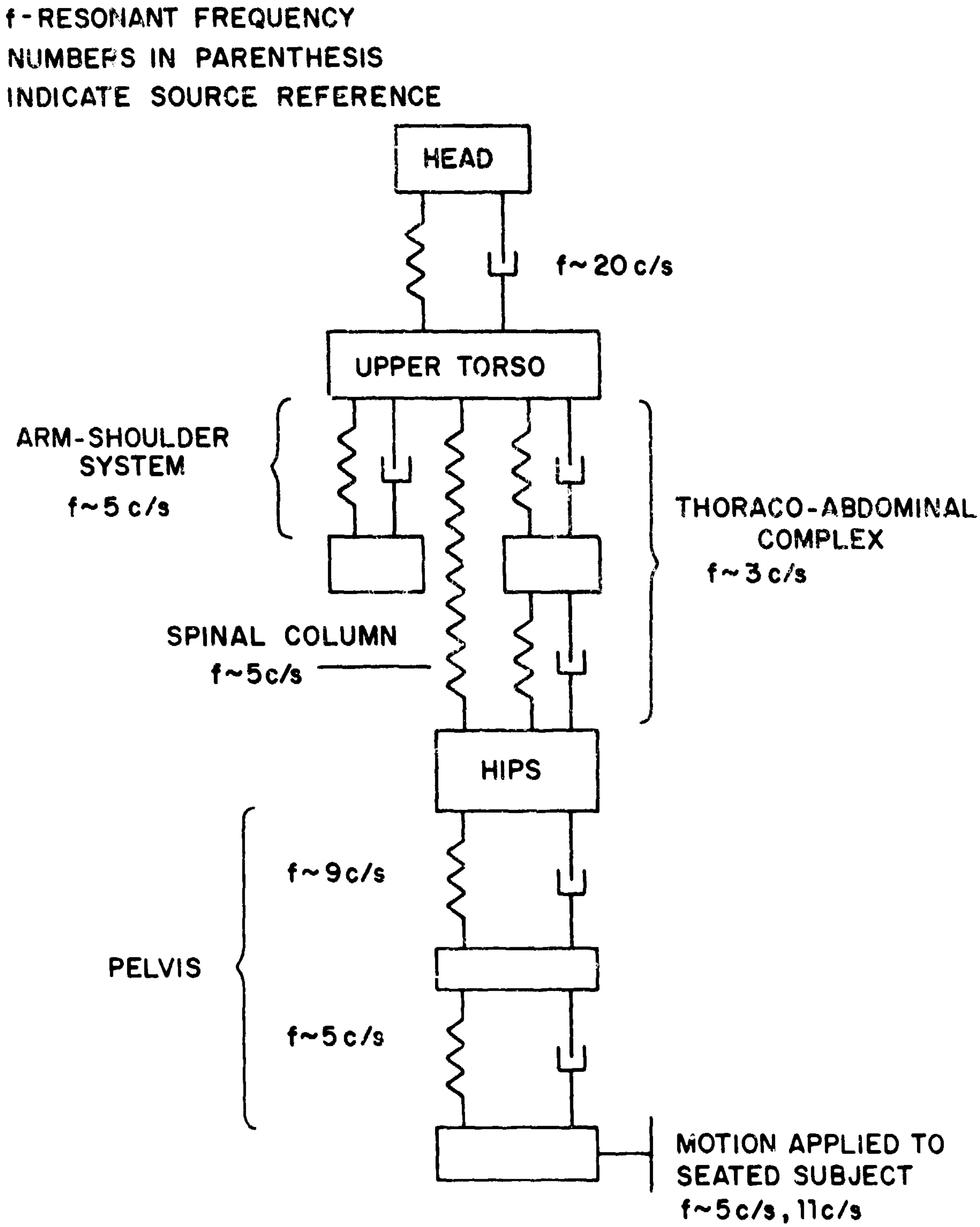

FIGURE 4. Analogue of the Human Body

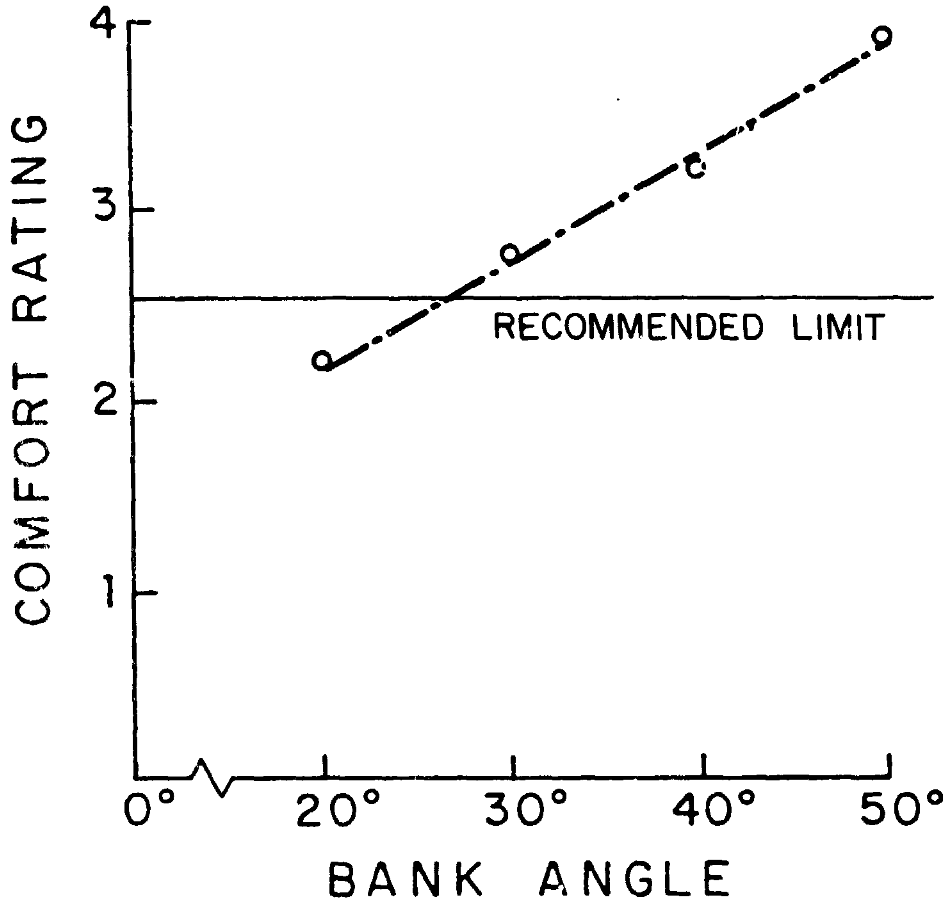

FIGURE 5. Passenger Responses to Bank Angles

Here a linear relationship is evident and based on previous studies (5), a limit of 27° is recommended (this corresponds to a C of 2.5).

Figure 6 indicates the proportion of passengers for which a given bank angle degrades their comfort level. Here it can be seen that banked flight is always worse than unbanked flight for 30 to 40 percent of all subjects; and high bank angles (i.e. > 35°) degrades subjective comfort for the majority of subjects.

In addition, the JetStar aircraft seating was configured so that during positive bank angles the passenger had a view of the ground, however during negative bank angles there was no reference for the subject. At low bank angles (i.e. < 30°) the negative angles showed a consistent trend to being less comfortable than the positive angles. It should be noted that no attempt was made to ascertain the coordination level of the turn.

Commercial Flight Data

Data Range

Figures 7 through 11 show the present data plotted in vertical-transverse (or lateral) axes, where each plot represents one value of subjective comfort. Five separate plots, are shown--one for each subjective response level, to enhance clarity. As can be seen, the data are limited to the range 0.06 to 0.16 g's in the vertical direction and 0.01 to 0.06 g's in the transverse direction. The data is distributed similarly for each value of comfort. Table 2a shows the distribution of vertical and transverse acceleration. Table 2b is the two-dimensional distribution in vertical-transverse space. 1541 segments out of 4519, or roughly 1/3 of the data, are within the narrow band of 0.005 to 0.01 g's $\bar{a}_t$ (rms transverse acceleration) and 0.07 to 0.08 g's $\bar{a}_v$ (rms vertical acceleration).

Table 3 presents a summary of the acceleration data and comfort responses, by flight, comfort response level, and hour

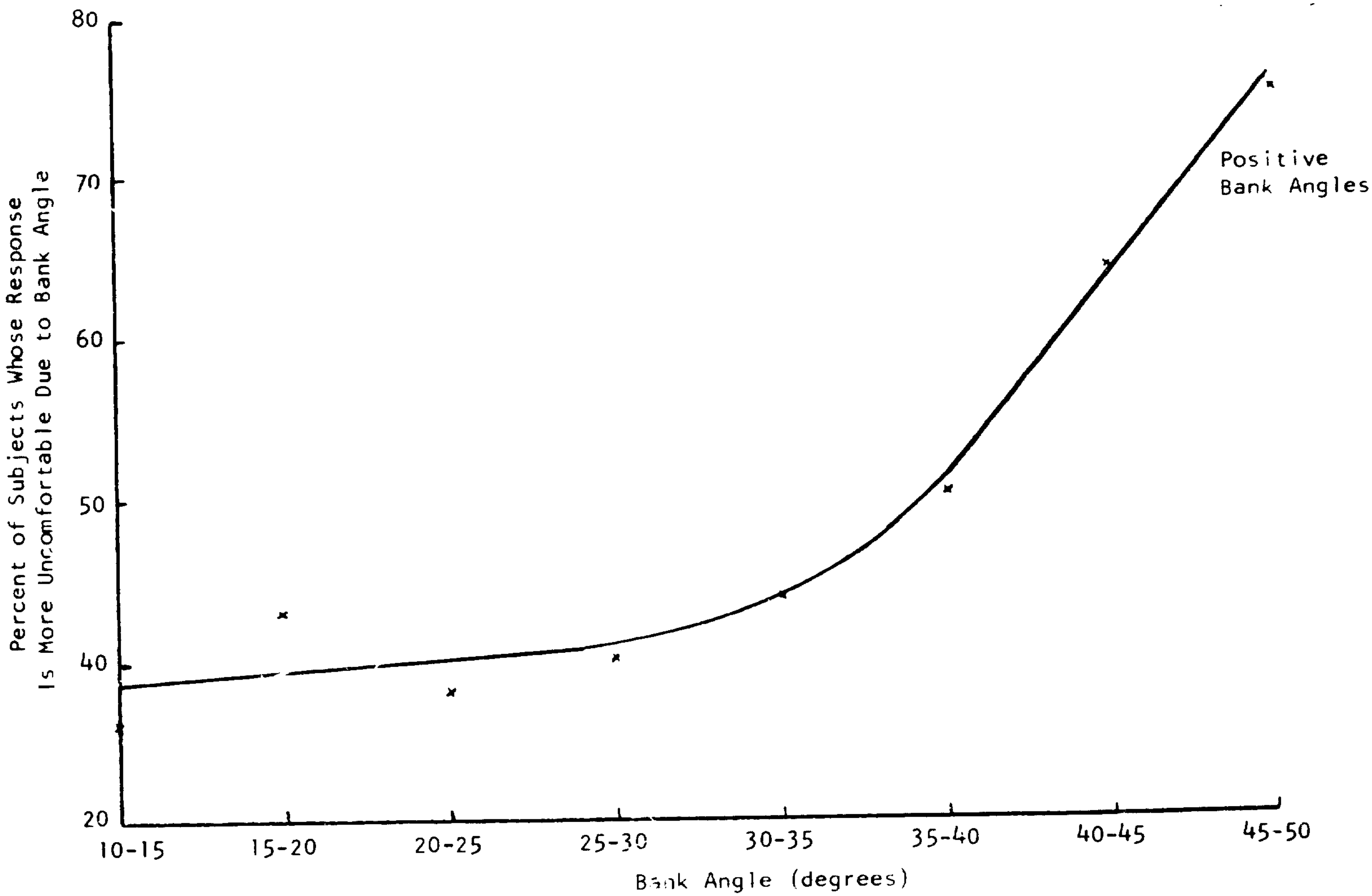

FIGURE 6. Degradation of Comfort due to Bank Angle

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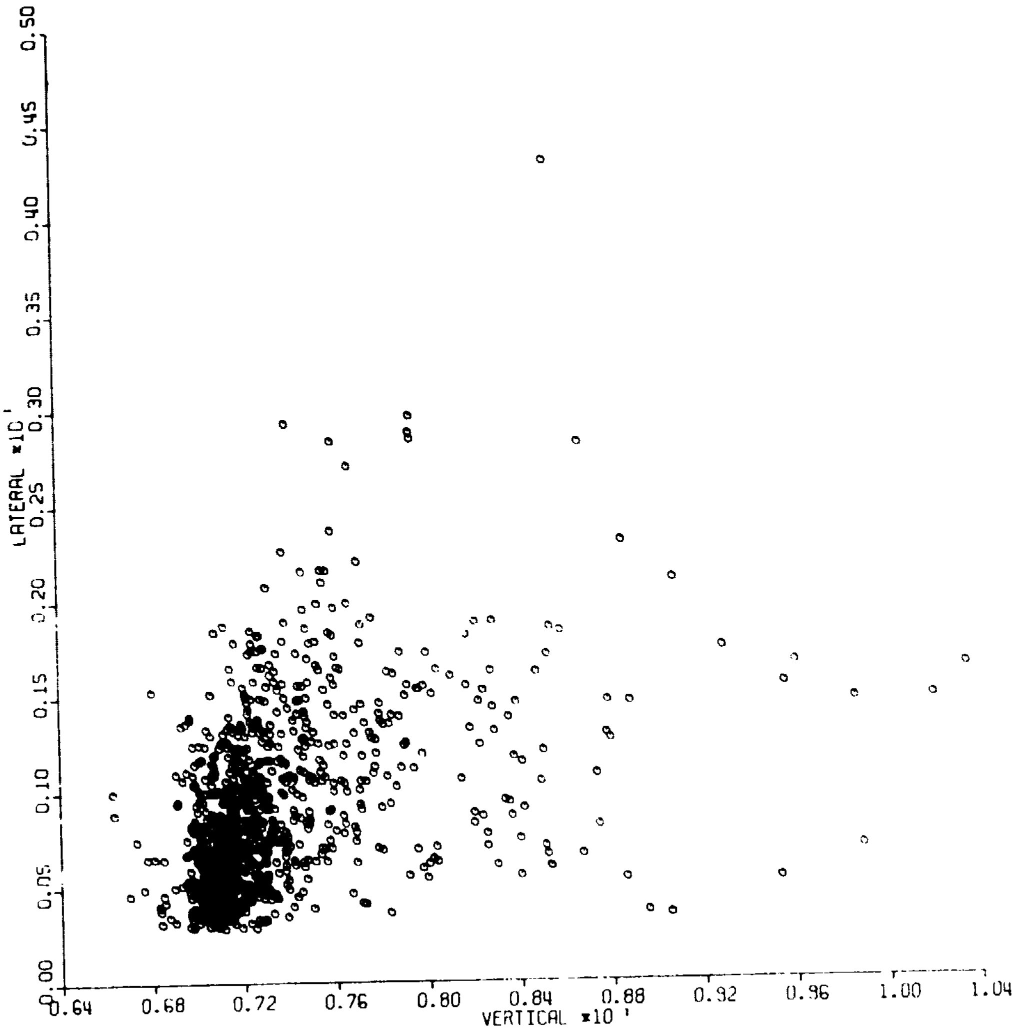

FIGURE 7. Plot for all data: C=1

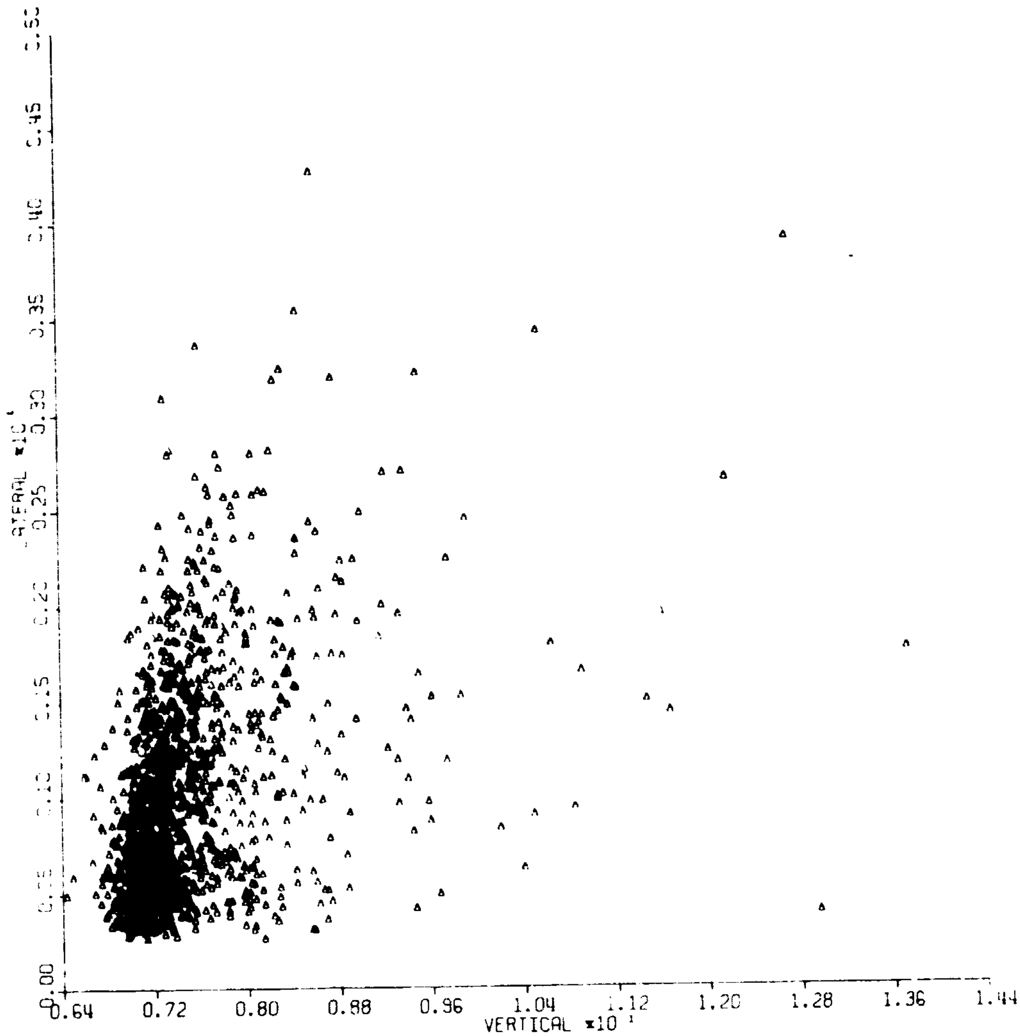

FIGURE 8. Plot for all data: C=2

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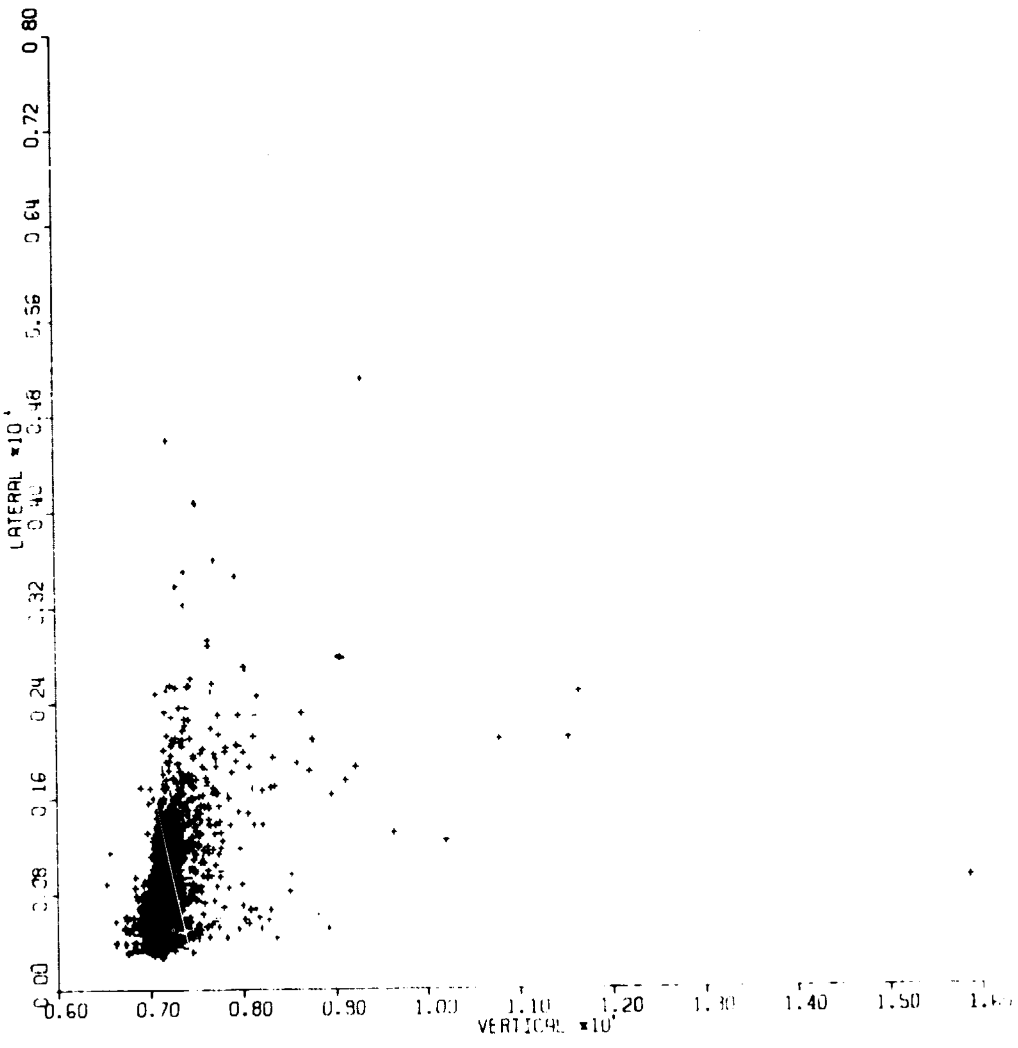

FIGURE 9. Plot for all data: C=3

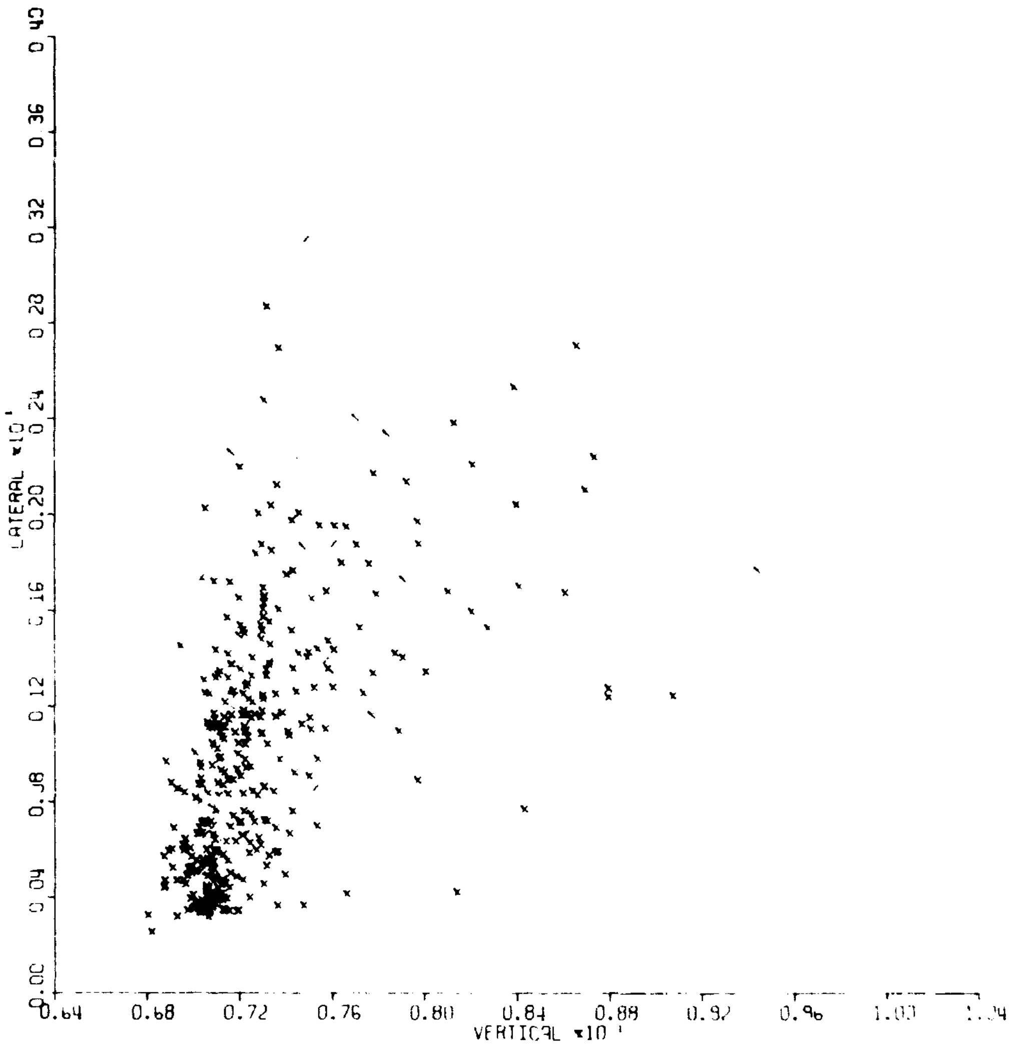

FIGURE 10. Plot for all data: C=4

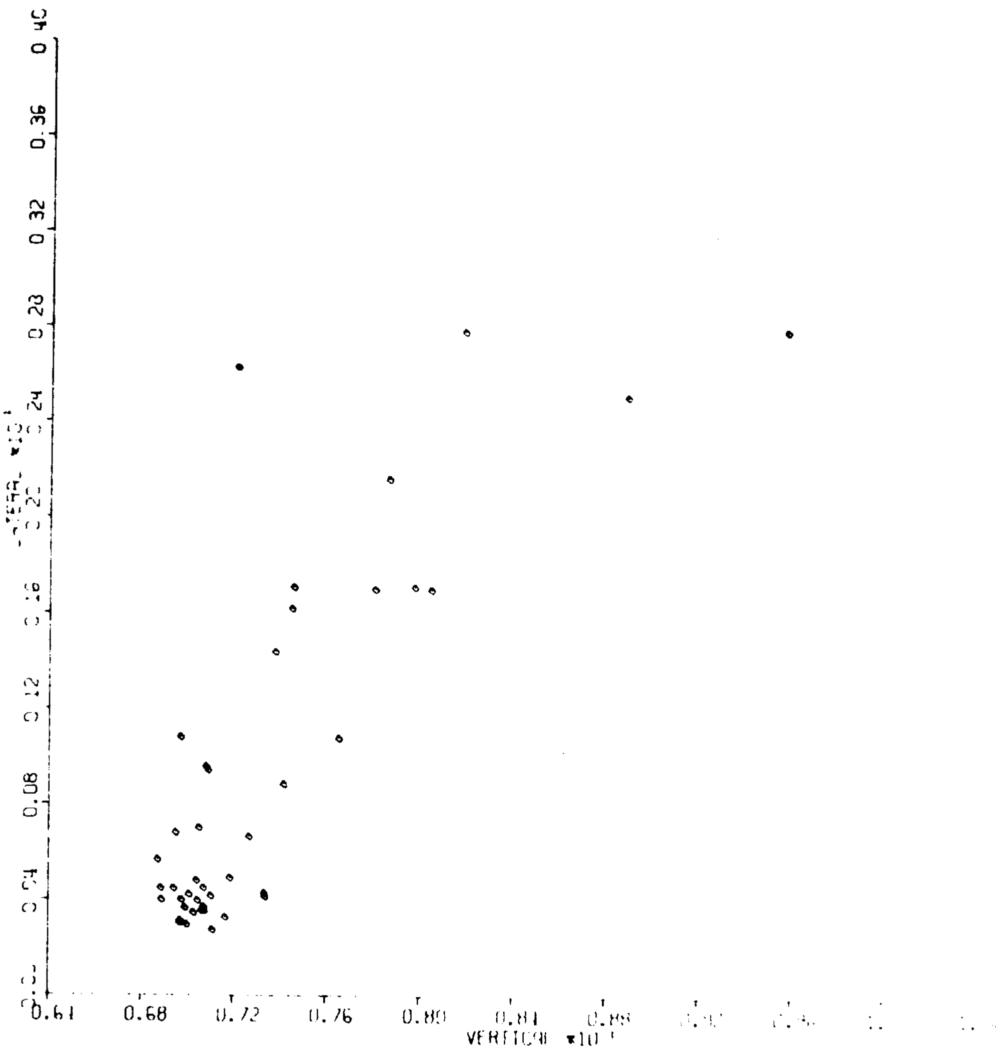

FIGURE 11. Plot for all data: C=5

TABLE 2. Distribution of Data

TABLE 2A

Number of Points per Band

VERTICAL		LATERAL	
≤ .02	0	≤ .01	2899
≤ .04	0	≤ .02	1429
≤ .06	0	≤ .03	170
≤ .08	4212	≤ .04	16
≤ .10	286	≤ .05	4
≤ .12	16	≤ .06	1
≤ .14	4	≤ .07	0
≤ .16	1	≤ .08	0
≤ .18	0		
≤ .20	0		

TABLE 2B

Number of Points per Band

LATERAL \ VERTICAL	.06-.07	.07-.08	.08-.09	.09-.10	.10-.11	.11-.12	.12-.13	.13-.14	.14-.15	.15-.16
≤.005	175	891	19	3	0	0	1	0	0	0
≤.010	191	1540	68	6	4	0	0	0	0	1
≤.015	30	912	57	9	2	1	0	0	0	0
≤.020	6	334	61	11	3	2	0	1	0	0
≤.025	0	95	23	5	1	2	0	0	0	0
≤.030	0	28	11	4	0	0	1	0	0	0
≤.035	0	6	4	1	1	0	0	0	0	0
≤.040	0	2	1	0	0	0	1	0	0	0
≤.045	0	1	2	0	0	0	0	0	0	0
≤.050	0	1	0	0	0	0	0	0	0	0
≤.055	0	0	0	1	0	0	0	0	0	0
≤.060	0	0	0	0	0	0	0	0	0	0

TABLE 3

Inter-comfort, Inter-flight and Inter-hour Comparison Data

	Comfort (C)		Vertical ($\bar{a}_v$)		Transverse ($\bar{a}_t$)	
	μ	σ	μ	σ	μ	σ
All Data (4519)	2.3	0.9	0.07	0.005	0.009	0.005
Comfort (957) 1	-	-	0.07	0.004	0.009	0.005
(1745) 2	-	-	0.07	0.006	0.009	0.005
(1398) 3	-	-	0.07	0.004	0.009	0.005
(377) 4	-	-	0.07	0.004	0.01	0.005
(42) 5	-	-	0.07	0.005	0.009	0.007
Flight # (953) 1	2.8	0.7	0.07	0.003	0.006	0.004
(880) 2	1.6	0.8	0.07	0.005	0.01	0.005
(710) 3	2.5	0.8	0.07	0.007	0.01	0.006
(281) 4	1.4	0.5	0.07	0.005	0.009	0.005
(703) 5	2.3	0.7	0.07	0.005	0.009	0.005
(754) 6	2.7	1.0	0.07	0.002	0.009	0.004
(238) 7	2.0	0.5	0.07	0.007	0.01	0.005
Hour of Flight (1572) 1	2.3	1.00	0.07	0.003	0.008	0.005
(1487) 2	2.4	0.9	0.07	0.004	0.009	0.005
(949) 3	2.3	0.9	0.07	0.005	0.009	0.005
(511) 4	1.9	0.6	0.08	0.008	0.01	0.006

of flight. It can be seen that for all data the means for vertical and transverse acceleration are respectively, $\mu_{\bar{a}_v} = 0.07$ and $\mu_{\bar{a}_t} = 0.0009$.

The following correlations are obtained for the present data and past studies (ref 5):

	$\rho_{\bar{a}_v}, C$ (correlation between C and $\bar{a}_v$)	$\rho_{\bar{a}_t}, C$ (correlation between C and $\bar{a}_t$)
Previous study (ref. 5)	0.723	0.58
Present data	-0.07	0.04

This clearly indicates that the correlation coefficients are unsatisfactory. The major cause of lack of correlation is the limited range of the data ($\bar{a}_v$ and $\bar{a}_t$). That is, when subjects are exposed to a narrow range of accelerations, they use other criteria in assessing comfort.

Inter-flight/Inter-subject differences

As mentioned previously only one subject responded during each flight hence inter-flight and inter-subject differences cannot be separated.

From Table 3, it can be seen that μ_C varies from 2.8 to 1.4 for flights #1 and #4, respectively, even though the means of vertical acceleration ($\mu_{\bar{a}_v}$) are equal (.07 g's) and the means of transverse acceleration ($\mu_{\bar{a}_t}$) are 0.006 and 0.009, respectively. This indicates a negative correlation between μ_C and the rms acceleration means, implying inter-subject differences. Hence, based on $\bar{a}_v$ and $\bar{a}_t$ only, the subject of flight #6 is on the average more comfortable than the subject on flight #1. Similarly, looking at flights #6 and #7, the σ_C are 1.0 and 0.5, respectively. However, their associated rms acceleration variations are $\sigma_{\bar{a}_v} = .002, .007$ and $\sigma_{\bar{a}_t} = .004$ and $.005$, respectively. This indicates that the subject on flight #6 is more sensitive to changes in acceleration than the subject on flight #7.

Table 4 lists the distribution of comfort for different flights. For most flights, the subjective comfort response is centered around a value of 2 or 3. Only flights #2 and #4 have a maximum of responses for a comfort value of 1. In fact, for flight #4 there are no responses for comfort values of 4 or 5. In addition the mean error is relatively constant between flights for each comfort response (σ_ε are very small).

Duration of Exposure Effect

In this section, the effect of duration of flight on subjective responses are investigated [each flight lasted between two to four hours]. Figure 12 illustrates the effect of flight time on average subjective response.

These results do not indicate any fatigue effect. In fact, subjective responses seem to get better towards the end of the flight. This might be due to subjects getting used to the acceleration environment and hence becoming more tolerant to the stimulus. The effect observed is only slight and no strong conclusion can be reached.

Stimulus-Response Effects

In this section, the effect of change in acceleration environment on the change in subjective response is investigated. Stimulus-response properties as a function of ΔC for these data were analyzed. There appears to be no clear cut relationship between ΔC and "means" of $\Delta\bar{a}_v$, $\Delta\bar{a}_t$, Δv, Δt and τ (duration of flight).

The following correlations were observed:

$$\rho_{\Delta C \cdot \Delta\bar{a}_v} = 0.41$$

$$\rho_{\Delta C \cdot \Delta\bar{a}_t} = 0.52$$

$$\rho_{\Delta C \cdot \Delta v} = 0.01$$

TABLE 4. Comfort Distribution with Flight #

Comfort	Flight #						
	1	2	3	4	5	6	7
1	9	520	36	156	75	142	10
2	330	240	385	110	356	105	219
3	439	95	230	6	254	371	3
4	168	20	48	0	12	126	3
5	7	5	11	0	6	10	3
TOTAL	953	880	710	281	703	754	238

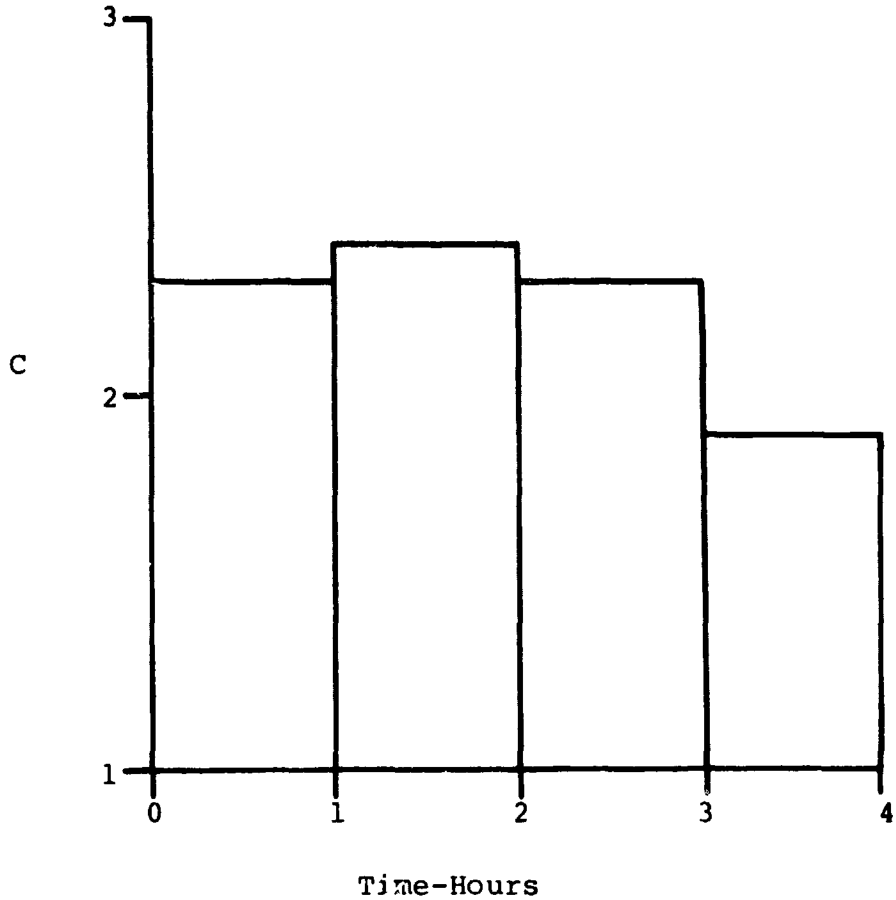

FIGURE 12. Histogram of comfort vs. time of flight

$$\rho_{\Delta C \cdot \Delta t} = 0.07$$

$$\rho_{(\Delta C/\Delta \bar{a}_v) \cdot \tau} = 0.03$$

$$\rho_{(\Delta C/\Delta \bar{a}_t) \cdot \tau} = 0.036$$

where v - vertical mean, t - transverse mean, and τ - time from start of flight (sec.). As can be seen among all these correlationa only $\rho_{\Delta C \cdot \Delta \bar{a}_v}$ and $\rho_{\Delta C \cdot \Delta \bar{a}_t}$ seem to be significant indicating the stimulus-response relationship should be between ΔC and $\Delta \bar{a}_v$ and $\Delta \bar{a}_t$.

The following regression equation was obtained between ΔC and Δa_v and Δa_t as dependent variables

$$\Delta C = 0.104 + 70.5 \Delta \bar{a}_v + 37.1 \Delta \bar{a}_t$$

with a correlation coefficient of 0. . This equation gives the stimulus-response relationship between changes in acceleration and changes in comfort.

From Table 5 it can be seen that the duration of exposure has very little effect on $\mu_{\Delta C}$ (except in $\mu_{\Delta \bar{a}_v}$, $\mu_{\Delta \bar{a}_t}$ and $\rho_{\Delta \bar{a}_t \cdot \Delta C}$. But, $\rho_{\Delta \bar{a}_v \cdot \Delta C}$ constantly increases for each successive hour. $\rho_{\Delta \bar{a}_t \cdot \Delta C}$ is not as consistent as $\rho_{\Delta \bar{a}_v \cdot \Delta C}$.

TABLE 5. Stimulus - Response Properties as a Function of Duration of Flight

	All Data	HOUR 1	2	3	4
$\mu_{\Delta C}$	0.013	0.04	-0.039	0.12	-0.44
$\mu_{\Delta \bar{a}_v}$	.002	≃ 0	≃ 0	≃ 0	≃ 0
$\mu_{\Delta \bar{a}_t}$	.001	~ 0	≃ 0	≃ 0	0.002
μ_T	6000	1672	5109	9243	11290
$\rho_{\Delta \ddot{a}_v \cdot \Delta C}$	0.41	0.24	0.5	0.54	0.59
$\rho_{\Delta \bar{a}_t \cdot \Delta C}$	0.52	0.44	0.68	0.68	0.43

Conclusions

This analysis has led to the following conclusions:

1. A linear regression model for subjective response appears superior to other types.
2. A biodynamic model does not adequately represent the complex subjective judgement of comfort.
3. Bank angles degrade comfort. A maximum bank angle of 27 degrees is recommended.
4. For transcontinental (long duration) flights subjective reaction is a function of changes in acceleration levels -- not the levels themselves.
5. Duration effects (fatigue) have not been seen for flights of up to four hours.

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