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RIDE QUALITY SENSITIVITY TO SAS CONTROL LAW AND TO HANDLING QUALITY VARIATIONS

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SUMMARY

State variable techniques are used to generate the vertical and lateral fuselage loadfactor distributions for the B-52H and B-1 bombers. A comparison of loadfactors resulting from cruise turbulence excitation, reveals that ride quality is not significantly improved by increasing the control law complexity. Control law complexity is meant to imply rate feedback in comparison to full state feedback. Handling quality parameterizations show pronounced effects on the loadfactors. Finally variations under relaxed static stability implementation show that the ride quality is degraded by restoration of handling characteristics to original short period values.

INTRODUCTION

Control Configured Vehicle (CCV) technology is just beginning to affect the design and manufacture of aerospace vehicles. Current technology aircraft like the F-16 fighter and B-1 bomber are utilizing concepts such as ride control, Relaxed Static Stability (RSS), and fatigue reduction. Future vehicles will certainly incorporate active controls, maneuver load control, direct lift, flutter mode control, and gust load alleviation concepts. These future vehicles will be optimized under many manifolds to include Ride Quality (RQ).

The objective of this paper is to discuss the RQ trends which large flexible aircraft exhibit under various parameterizations of control laws and handling qualities. The information was generated as a data base for research supported by NASA Dryden Flight Research Center under grant NSG 4003. The ultimate aim of the project is delineation of handling qualities specifications for highly flexible CCV vehicles. This paper contains a summary of the assumptions and solution technique, a control law parameterization review, a discussion of ride sensitivity to handling qualities, and finally the RQ effects generated by implementing relaxed static stability configurations.

SYMBOLS

A' Transpose of the A matrix

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$\bar{c}$	Mean aerodynamic chord length
cg	Center of gravity
E{ }	Expected value
HQ	Handling Qualities
ℓ_x	Distance from cg along fuselage centerline, positive forward
$\bar{\ell}_t$	Distance between the tail and wing-body aerodynamic centers
$N_{z,y}$	Loadfactor at a particular body station; z denotes vertical y denotes lateral
rms	Root mean square
RQ	Ride Qualities
RSS	Relaxed static stability
S	Wing planform area
S_t	Tail planform area
U_0	Averaged Steady State Flight Velocity
u	Control(s) vector; elevator, aileron, and/or rudder
$\bar{V}$	Tail volume coefficient
x	State vector; usually associated with physical outputs in this paper
α	Perturbation angle of attack
β	Perturbation side slip angle
ζ	Damping value
η	Scalar unit white noise
θ	Perturbation pitch angle
ξ_i	ith elastic mode generalized displacement
$\phi_i(\ell_x)$	ith orthogonal elastic mode shape value at body station ℓ_x
ϕ	Perturbation roll angle

ψ Perturbation yaw angle

ω Natural frequency

PROBLEM FORMULATION

Equations of Motion for Flexible Vehicles

Time domain representations for the flexible vehicles were decoupled into longitudinal and lateral state variable formats. The Gaussian white noise representation of turbulence was modeled as a state vector system as suggested in reference 1. The gust state vector was appended to the vehicle state equations resulting in the familiar control form (1).

$$x(t) = Ax(t) + Bu(t) + G\eta(t) \tag{1}$$

where:

x	$(n+p) \times 1$
u	$m \times 1$
n	number of physical vehicle states
m	number of controls
p	number of gust states
G	$(n+p) \times 1$
A	$(n+p) \times (n+p)$
B	$(n+p) \times m$

Loadfactor Expression

The major contributions to vertical and lateral loadfactors at cruise conditions can be represented by equations (2a) and (2b).

$$N_z(\ell_x,t) = \frac{1}{g}[U_0(\dot{\theta}-\dot{\alpha}) + \ell_x\ddot{\theta} - \sum_{i=1}^{K} \phi_i(\ell_x)\ddot{\xi}_i] \tag{2a}$$

$$N_y(\ell_x,t) = \frac{1}{g}[g\phi - U_0(\dot{\beta}+\dot{\psi}) - \ell_x\ddot{\psi} - \sum_{i=1}^{K} \phi_i(\ell_x)\ddot{\xi}_i] \tag{2b}$$

where: K is the number of elastic modes included in the model.

Throughout this paper the standard right hand stability axis system is utilized with the x axis positive forward from the cg as shown in figure 1.

The sign conventions for the vertical and side bending elements are shown in figures 2 and 3.

The loadfactor expressions can be reformulated as functions of the physical state variables by simple substitution.

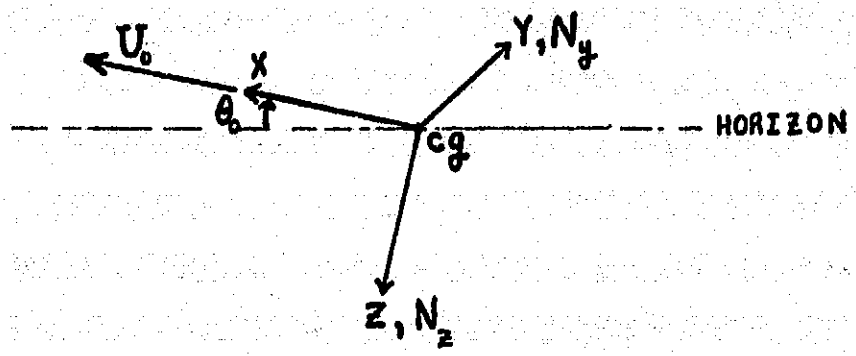

Figure 1: Stability Axis Sign Convention

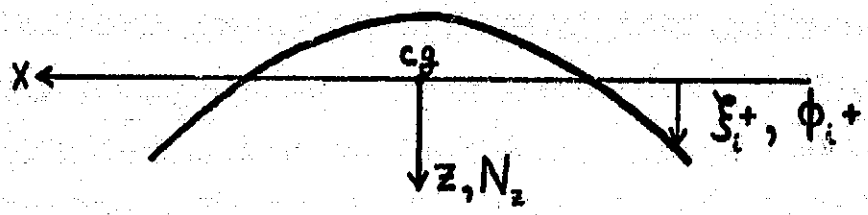

Figure 2: Fuselage Vertical Bending Sign Convention

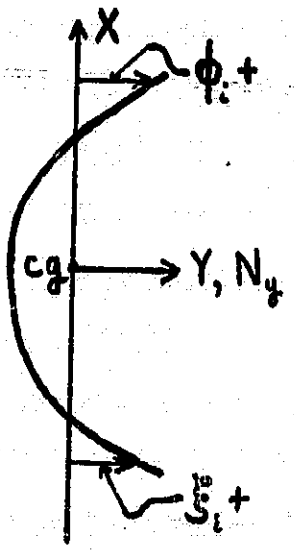

Figure 3: Fuselage Side Bending Sign Convention

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$$N_z(\ell_x,t) = P_z\ x_z(t) \tag{3a}$$

$$N_y(\ell_x,t) = P_y\ x_y(t) \tag{3b}$$

The 1X(n+p) row vectors, $P_{z,y}$ are deterministic for a given vehicle equation of motion set, specific control, and specified gain value. Equations (3) can be manipulated into a mean square value expression for the loadfactor.

$$E\{N^2_{z,y}\} = P_{z,y}\ E\{xx'\}_{z,y}\ P'_{z,y} \tag{4}$$

Assuming a stationary, zero mean process for the state differential system (1) leads to an algebraic matrix Riccati equation. This equation can be solved for the symmetric covariance matrix, $E\{xx'\}$. Utilizing one algorithm suggested by Gelb in reference 2, convergence can be obtained within 35 seconds on a CDC 6500 for a 16X16 Riccati system. A simple matrix multiplication routine completes the solution utilizing equation (4).

Study Vehicle Descriptions and Flight Conditions

The B-52H and B-1 were chosen for this study because they exemplify the trend toward more elastic structures for future large vehicles. The B-52, and commercial derivatives thereof, was a member of the first generation of elastic vehicles. Since that era, improved structural design techniques and composite materials have made possible vehicles like the highly elastic B-1.

The flight conditions were chosen because they represent cruise conditions which are mission essential and because turbulence encounters at low altitudes must be included in future design considerations.

The B-52H is used by the US Air Force as a long range bomber. It is 47.55 meters long and has a wing span of 56.4 meters. Originally designed as a high altitude bomber, it must now cope with penetration problems by combined high/low altitude profiles. Table 1 describes the flight condition for the B-52H.

Mass = 158,757 kilograms (350,000 lbs.)
Mach = .55
Velocity = 185.56 meters/sec (608.8 fps)
cg at 25% mean aerodynamic chord
Altitude = 609.6 meters (2000 ft)

TABLE 1: B-52H Flight Condition

The B-1 is currently being test flown in a major pre-production effort by Rockwell International and the USAF. It is designed as the replacement vehicle for the aging B-52 fleet. The advanced structures and integrated technology make this vehicle an outstanding example for loadfactor

contributions due to elasticity. The overall length of the B-1 is 46 meters. The reference wing span utilized at the flight condition in Table 2 is 41.8 meters.

Mass = 103,315 kilograms (227,770 lbs)
Mach = .85
Velocity = 289.4 meters/sec (949.45 fps)
cg is at fuselage station 40.67 (meters)
Altitude = 30.48 meters (100 feet)

TABLE 2: B-1 Flight Condition

CONTROL LAW VARIATIONS

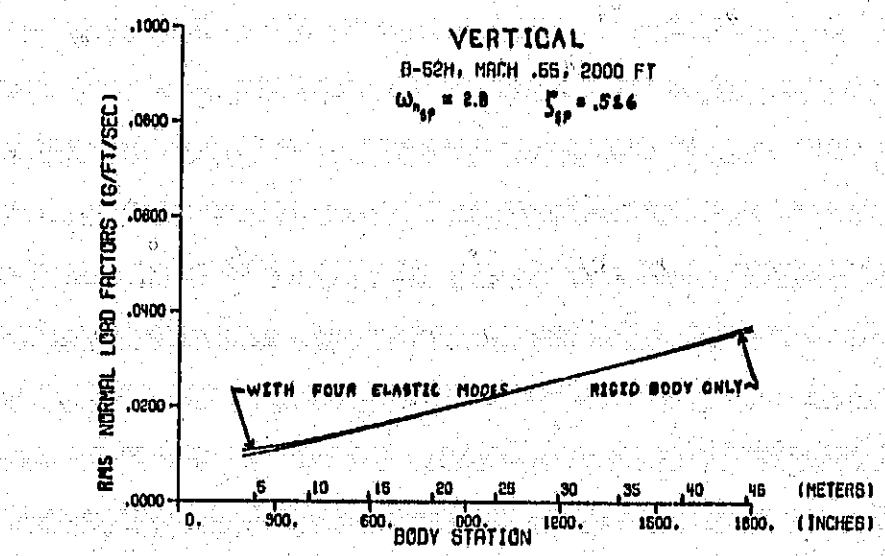
Both vehicles were modeled as stable, unaugmented systems in the vertical and lateral cases with the exception of the B-52H which required a small roll subsidence mode stabilization before proceeding. Each vehicle model was theoretically modified utilizing pitch rate, yaw rate, pitch rate/pitch attitude, blended pitch rate with acceleration, and full state feedback control laws. No significant differences in RQ were generated by these variations for identical (or nearly equivalent) handling quality values.

It should be mentioned here that the B-1 Structural Mode Control System was purposely not included or utilized because this study is involved with general control design parameterizations and not the specific RQ optimization of the B-1. For both aircraft studies, only the primary control surfaces (elevator, rudder, and aileron) were used for RQ determinations.

To establish a basis for comparison, the unaugmented vehicle loadfactors were computed for .3048 meter/sec (1 fps) rms (root mean square) gust velocities.

Figure 4 depicts the loadfactor curves for the unaugmented B-52H. The nearly linear loadfactors labeled "rigid body only" include all terms except the summations in equations (2a) and (2b). Hence any interactive rigid body and elastic dynamics from the Riccati solution are included in this output. The second line which has a more pronounced curvature includes all the modes that were utilized in the model. For the B-52H at this flight condition, the maximum elastic contribution to vertical loadfactors is about 15% of the total. (The lateral fuselage modes used in this data were primarily aft-body modes. Hence the rise in elastic effects near the tail.)

Figure 5 shows an impressive increase in the elastic contribution to vertical loadfactors on the unaugmented B-1. The discerning reader will immediately note the changes in vertical scale in figures 4 and 5. The different flight conditions and elastic contributions to ride on the separate vehicles dictated these scale changes.



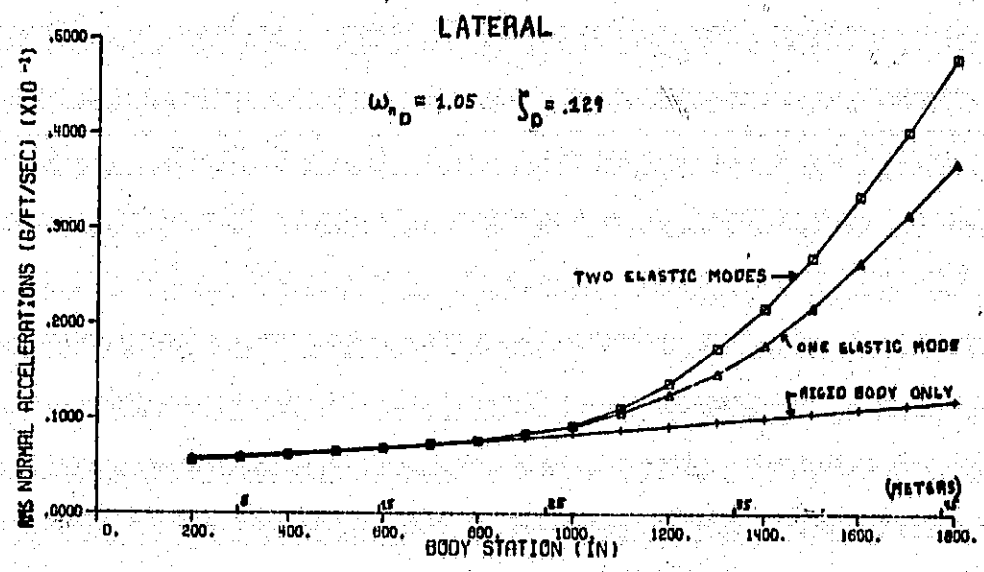
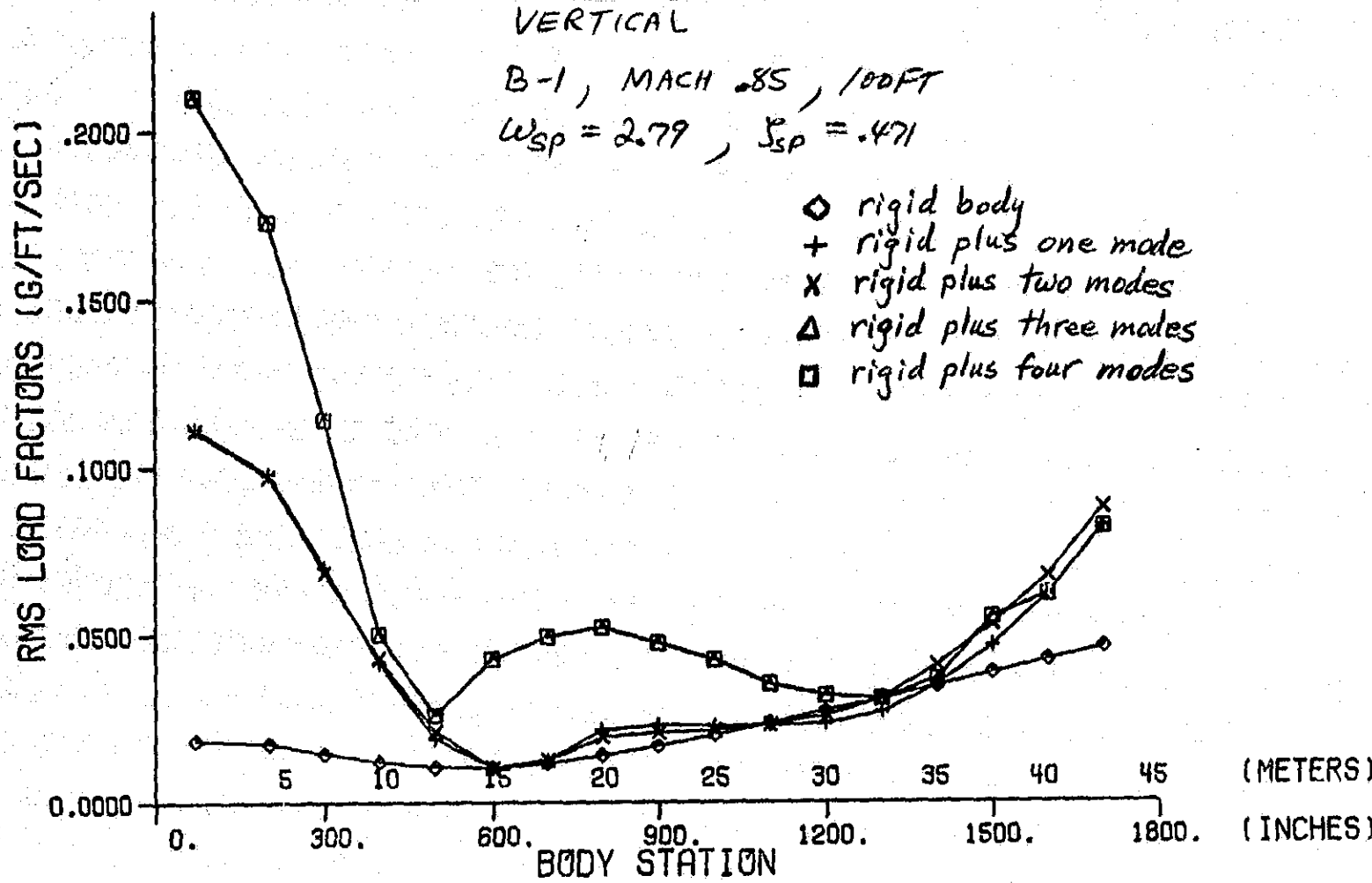


Figure 4: B-52H Unaugmented Loadfactors

RQ SENSITIVITY TO HANDLING CHARACTERISTICS

Under each control law studied, the gains were changed so that a range of handling characteristics and their resulting loadfactors could be cataloged. The values used for the handling characteristics were restricted to the acceptable ranges given in MIL SPEC 8785B. Hence the following boundaries:



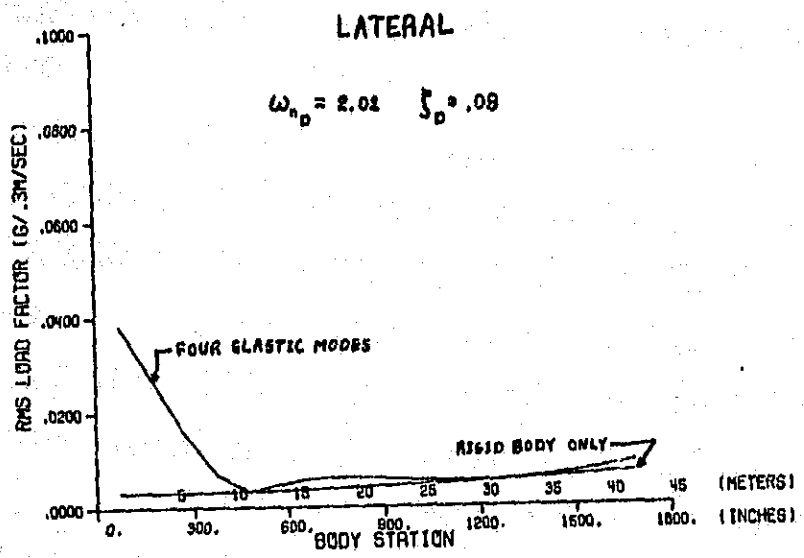


Figure 5: B-1 Unaugmented Loadfactors

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Longitudinal Short Period $\begin{cases} .3 \leq \zeta_{sp} \leq 2.0 \\ 2.0 \leq \omega_n \leq 10.0 \end{cases}$

Lateral Dutch Roll $\begin{cases} .08 \leq \zeta_D \\ .40 \leq \omega_n \end{cases}$

It is important to reiterate at this juncture that the study goal was RQ sensitivity to feasible controls, not the design of an optimal control for either vehicle.

Pitch Rate Feedback (B-52H)

Figure 6 shows the percentage change in loadfactor for various handling characteristics. The baseline in all these cases is the unaugmented vehicle loadfactors from figures 4 or 5, whichever is appropriate. As shown, the increase of damping and frequency for higher stabilizing feedback gains produced better RQ.

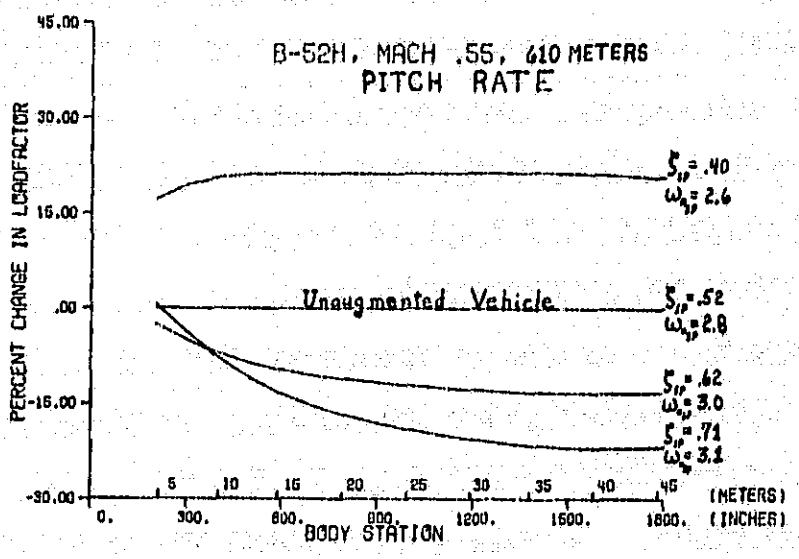

Figure 6: Pitch Rate SAS Changes

Yaw Rate Feedback (B-1)

Figure 7 shows the loadfactor curves for the B-1 lateral dynamics. Notice the effect is similar; increased damping produces better RQ.

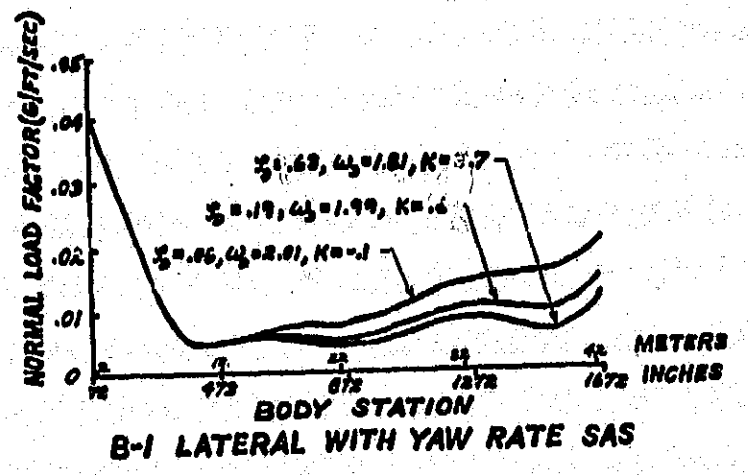

Figure 7: B-1 Yaw Rate SAS Loadfactors

Blended Pitch Rate and Acceleration (C*) (B-1)

Figure 8 shows the percentage changes in loadfactor under the C* control policy with variations in handling characteristics. Again the same general trends appear.

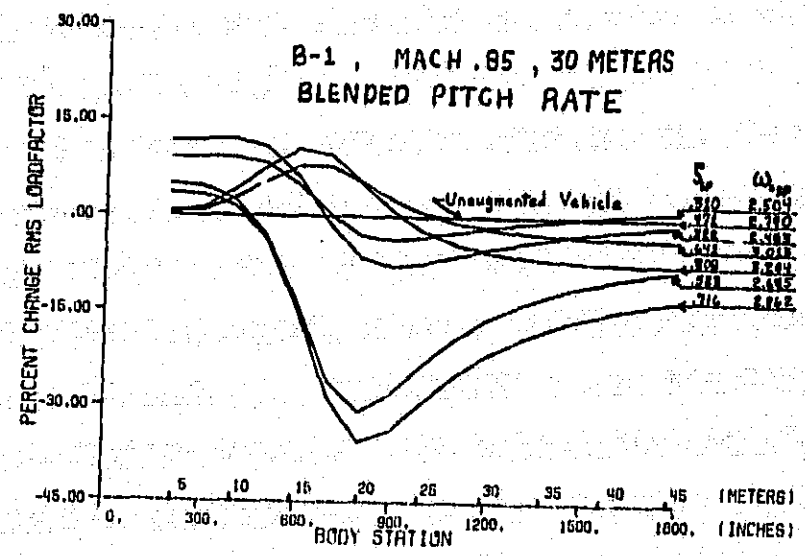

Figure 8: B-1 C* SAS

Full State Feedback (B-52H)

The trend expected by control experts would show that higher frequency and higher damping beget better RQ. This expectation was validated using full state feedback pole placing capacility. Figure 9 shows the results as percentage changes in loadfactor compared to the unaugmented vehicle. The forward fuselage percentage changes were distorted by relatively low baseline loadfactor values. Hence the higher damping/frequency loadfactor curves represent better rides overall. The asterisk cases in figure 9 deserve special mention. In these two cases the elastic mode damping was artificially increased through the elevator feedback control policy. Note that both cases generated appreciably worse RQ. This occurred because of the increased elevator excitation of the rigid body parameters in equations (2). Breakdowns of the elastic contributions to the loadfactors showed the three elastic modes chosen for increased damping actually did contribute less to the rms loadfactor.

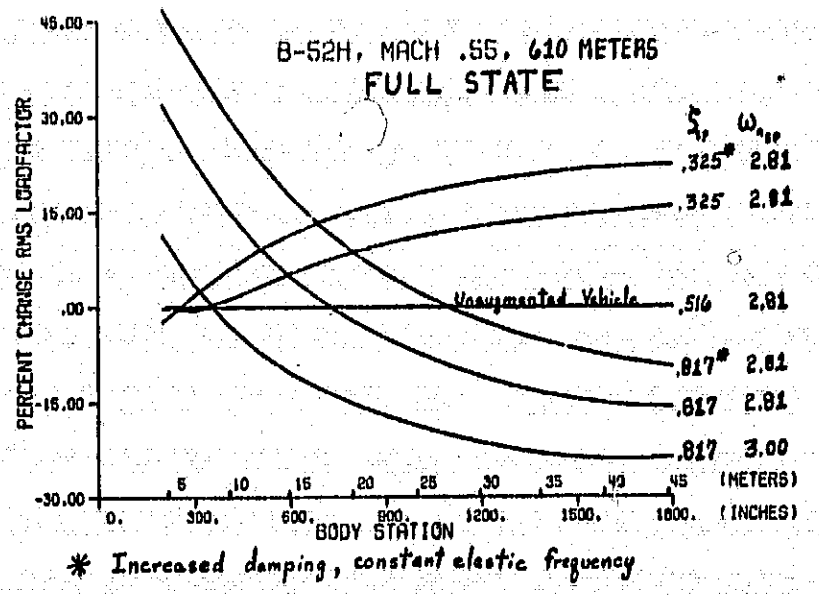

Figure 9: B-52 Full State SAS

This result prompted a theoretical attempt to parametrically plot loadfactor versus frequency and damping. Using a transfer function approach and the Dryden power spectral density for vertical gusts, the loadfactor mean square value was computed as an integral over the frequency domain. The results support the numerical analysis shown in figure 9.

As frequency increases, the RQ gets better. Likewise damping value excursions from the coupled elastic mode eigenvalue at constant frequency will adversely affect the loadfactors. A numerical example was run for the B-52H and is shown in figure 10 for two increased short period frequency cases. The elastic mode increased damping was not included in these cases.

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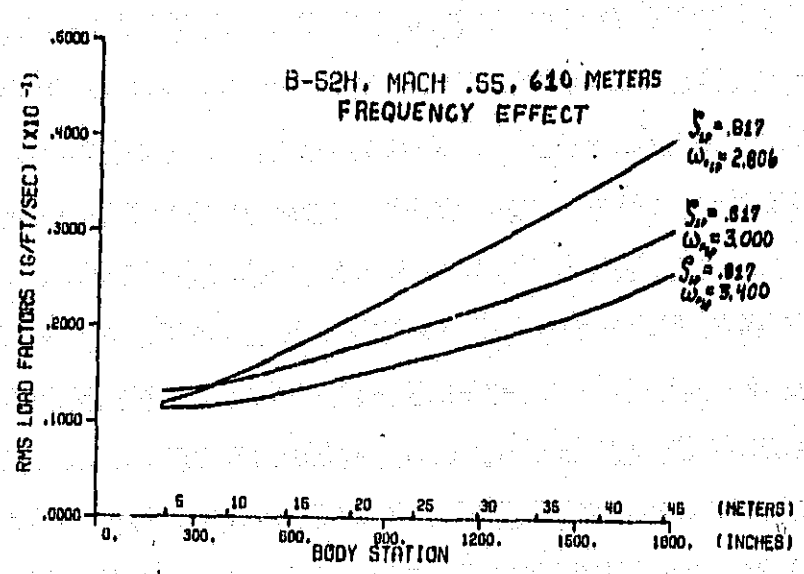

Figure 10: B-52H Increased Short Period Frequency Effect

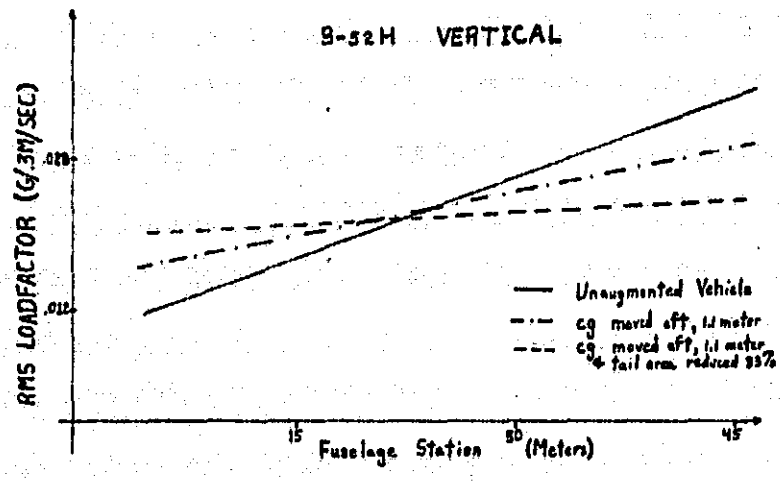

Figure 11: B-52H Rigid Body Relaxed Static Stability

RELAXED STATIC STABILITY (RSS)

Two methods were used to simulate this effect on the study vehicles. First the tail volume coefficient, $\bar{V}$, was reduced.

$$\bar{V} = \frac{\bar{\ell}_t \; S_t}{\bar{c} \; S} \tag{5}$$

This has the effect of shifting the vehicle aerodynamic center toward the center of gravity. Static stability is thereby reduced. The second method involves an artificial cg shift toward the tail. This is the more practical of the two methods, as it has already been incorporated as a fuel transfer or management activity on a test vehicle (CCV B-52).

Figure 11 shows the effect of RSS on vertical ride for the rigid body B-52H vehicle. Essentially pitching moment effects are reduced until at neutral stability the loadfactors are constant and due only to the vertical accelerations. This would logically follow from the definition of the neutral point. The question now arises, what rides are induced by restoring the original handling characteristics of the unaugmented vehicle with an active control system? Figure 12 shows these results in terms of percent loadfactor change. In general the restoration resulted in degraded RQ.

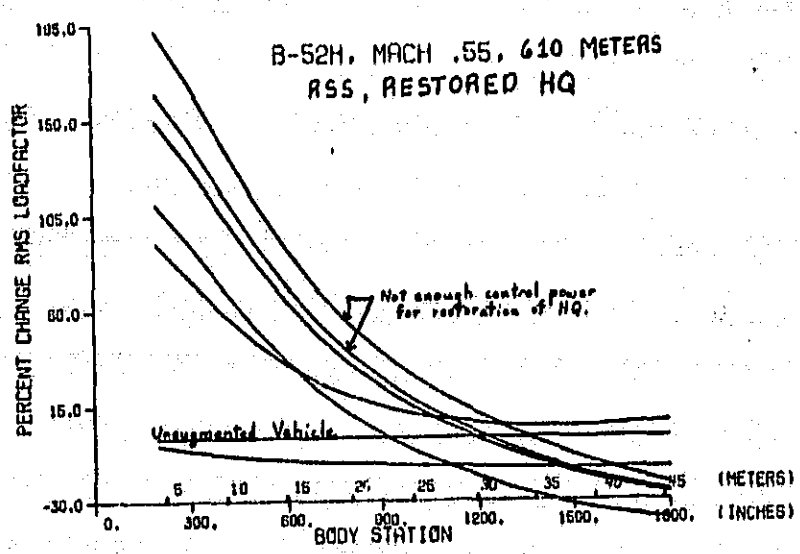

Figure 12: B-52H RSS, Restored Handling Qualities

CONCLUSIONS

1. Ride quality is particularly sensitive to the handling characteristics specifications.

2. Except in optimizing a particular vehicle's control capabilities, ride quality is not dependent on the type of control law chosen.

3. Relaxed Static Stability has a favorable effect on B-1 ride quality in that less pitch acceleration and/or velocity contribute to the loadfactor.

4. Relaxed Static Stability with restored handling qualities generates higher loadfactors on the B-52H and B-1 at the flight conditions studied.

REFERENCES

1. Heath, Robert E., II: State Variable Model of Wind Gusts, Air Force Flight Dynamics Laboratory Technical Memorandum, AFFDL-FGC-TM-72-12, Wright-Patterson AFB, Ohio, July 1972.

2. Gelb, Arthur, et al.: Applied Optimal Estimation, MIT Press, Cambridge, Mass., 1974.

3. Swaim, R. L., et al.: An Analytical Method for Ride Quality of Flexible Airplanes, Proceedings of the 3rd AIAA Atmospheric Flight Mechanics Conference, Arlington, Texas, June 1976.