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Flight Test Evaluation of an Advanced Stability Augmentation System for B-52 Aircraft

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Results and comparisons with theoretical predictions are given for a flight test performance evaluation of an advanced stability augmentation system (SAS). The new SAS, developed for installation in the B-52G-H fleet, provides control of low-frequency structural modes as well as the conventional control of airplane rigid body motions. Flight test results are presented showing the SAS performance in terms of mode damping, fatigue damage rates, maximum expected stress, and ride quality for flight through turbulence. Comparisons are made between theoretically predicted and experimental results. The flight test results show significant reductions in dynamic response to turbulence with the advanced stability augmentation system. Reductions in response of the low-frequency antisymmetric structural modes and the Dutch roll mode were obtained with SAS. Lateral loads on the fin and aft fuselage during flight through turbulence were reduced by more than 20%. Fatigue damage rates due to turbulence were reduced more than 50% for these same structural locations. The flight control system configuration and test procedures used to evaluate the SAS performance are presented.

Introduction

AN Air Force sponsored study was conducted by The Boeing Company during 1964 and 1965 to determine the changes to the B-52 flight control and stability augmentation systems that would provide meaningful improvements in the airplane structural life and in aerodynamic and structural stability in severe turbulence. This study was conducted as a part of a continuing program to provide B-52 fleet longevity and effectiveness to meet Air Force requirements during the next decade. The results of the study program, available in August 1965, indicated that significant reductions in structural fatigue and peak loads could be expected if an advanced stability augmentation system were installed on the B-52.

Development of the prototype stability augmentation system was accomplished during 1966 and 1967. Reference 1 summarizes SAS analyses and synthesis. Structural analyses conducted and a summary of the analytical results obtained are presented in Ref. 2. The system selected for development included both pitch and yaw stability augmentation.

A prototype model of the advanced SAS was designed, fabricated, and installed on a B-52H flight test airplane. Flight testing of the prototype SAS was completed in 1967 to optimize and demonstrate the SAS performance in terms of reducing peak structural loads and fatigue damage rates. The optimization was accomplished within the boundaries of adequate handling qualities and dynamic stability of the airplane.

The following sections present a general description of the flight control system configuration, the flight test approach, and results obtained. The flight test included flutter, SAS optimization, and performance testing. Performance testing included evaluation of handling qualities (Ref. 3) and dynamic response to atmospheric turbulence. General results obtained during gust response testing are described in this paper, including comparisons to analytical predictions.

Prototype SAS Configuration

A general description of the existing B-52 fleet flight configuration, which includes a yaw damper, is given in Ref. 2 along with study ground rules, SAS variations considered, and the SAS configuration selected for prototype flight testing. The two axis SAS consists of structural and rigid body motion sensors, and hydraulic actuators to position the elevator and rudder. These same hydraulic actuators also position the control surfaces on command from the primary flight control system and autopilot.

The yaw SAS functional configuration, illustrated in Fig. 1, utilizes a yaw rate gyro located at Body Station 695 (wing rear spar to body intersection) and a lateral accelerometer located at Body Station 1719 (stabilizer rear spar to body

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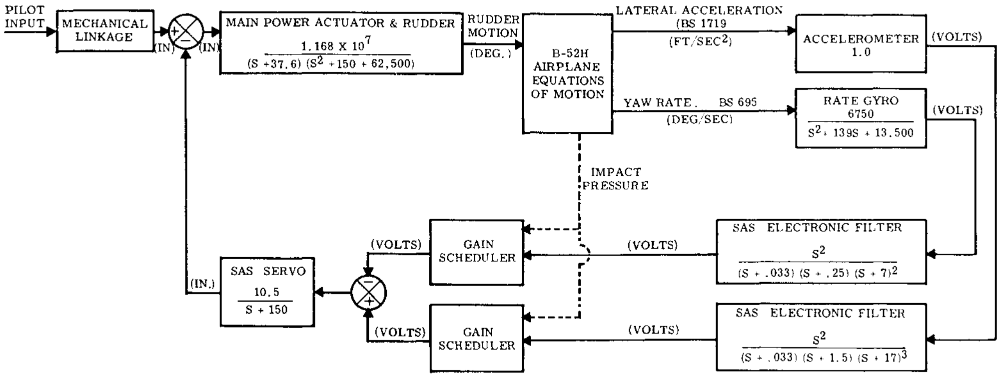

Fig. 1 Yaw SAS block diagram.

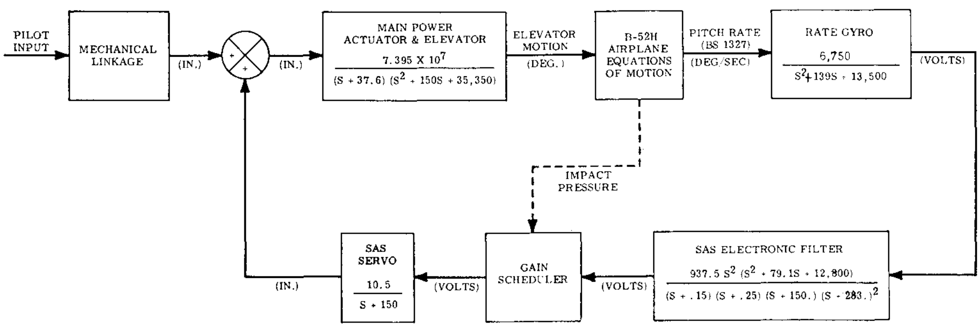

Fig. 2 Pitch SAS block diagram.

intersection). Separate gain functions, scheduled as a function of impact pressure, and separate filters are used for the rate gyro and accelerometer signals. The two channels are summed after filtering and gain scheduling operations, and the combined signal drives the SAS servo which posi ions the rudder through the hydraulic actuator.

The pitch SAS, illustrated in Fig. 2, utilizes a pitch rate signal derived from a rate gyro located at Body Station 1327 (located between the wing and empennage). This pitch rate signal is shaped through a filter and gain scheduled as a function of impact pressure. This channel then drives a SAS servo which positions the elevator through the hydraulic actuator.

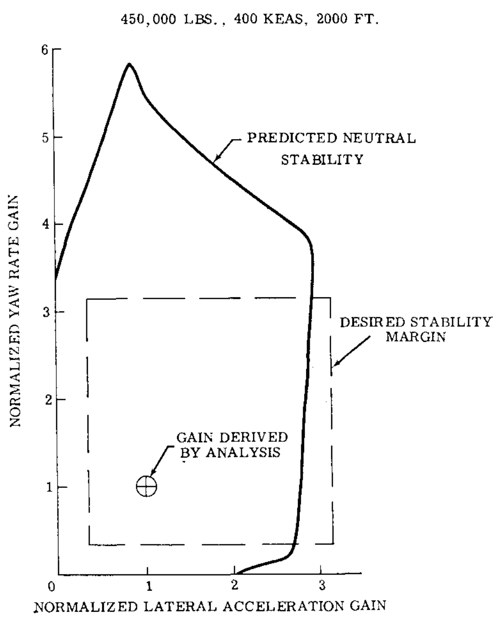

Fig. 3 Predicted stability boundaries.

Flight Testing

Flight testing of the prototype SAS was initiated in January 1967 to evaluate performance in terms of airplane dynamic response to turbulence. The evaluation was designed to determine dynamic load reduction for the new system. Flight flutter testing was necessary to establish stability boundaries prior to demonstrating the system. Testing in smooth air was accomplished to optimize the SAS configuration. The discussion of flutter and optimization testing in the following paragraphs is generally restricted to the yaw axis; however, similar techniques were employed for the pitch axis.

Flutter

Conventional flutter test techniques, using airplane response to pulse control inputs, were employed to establish stability margins as a function of SAS gain. Theoretical studies indicated that the advanced SAS could provide significant dynamic loads reduction if the desired stability margins existed as illustrated in Fig. 3.

Test stability boundaries were determined by initially setting the rate and acceleration gains to approximately 70% of nominal analysis values, and disturbing the airplane with

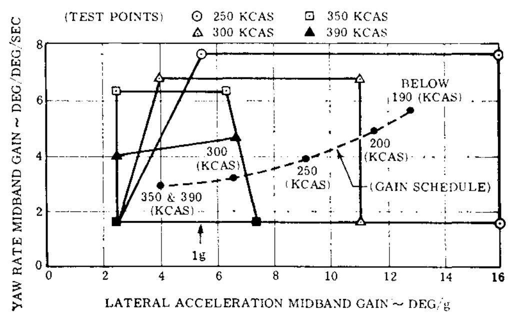

Fig. 4 Demonstrated stable gain points for a range of gross weights.

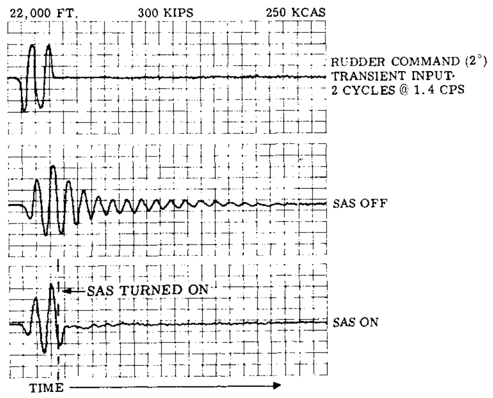

Fig. 5 Transient response for aft body elastic bending moment at BS 973.

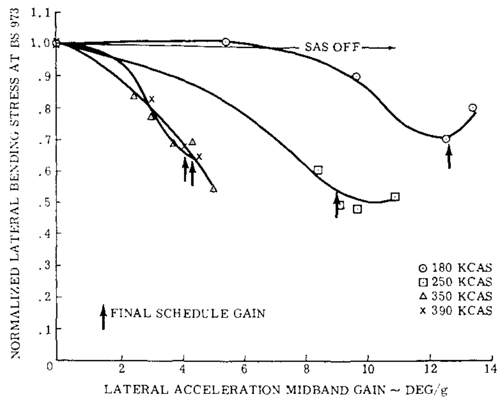

Fig. 7 Lateral bending peak stress optimization.

pulse control surface inputs. The gain in each loop was individually incremented until twice nominal gains were demonstrated or until structural vibration mode damping was degraded by 20% from the unaugmented value. This variation was continued until a stability region was defined which was considered acceptable for additional SAS performance testing. Note that the test stability boundaries represent a maximum of 20% degradation in structural mode damping rather than neutral stability.

Test boundaries obtained for the yaw SAS are shown in Fig. 4. Each point represents the least stable weight configuration for a range of gross weights between 220–450 klb. Comparison to the theoretical gain schedule in Fig. 4 demonstrates this concept achieved the desired stability. Although direct comparisons of analysis and test stability boundaries are not applicable, predicted stability margins of approximately three provided adequate margin for design of the system.

Optimization

SAS gains were optimized with respect to loads reduction within gain stability boundaries established by flutter testing. To determine the optimum gain value for each channel, the airplane was excited with a repeatable and carefully calibrated control surface sinusoidal transient at the appropriate rigid body or elastic mode frequencies. Initially a frequency search was conducted with the system "off." Frequency and amplitude of the control surface excitation were varied in a band about the predicted frequency of modes of interest to determine the frequency at which maximum response occurred. The excitation amplitude was adjusted for each flight condition and mode so as to obtain control surface deflections within the linear operating range of the system. A sinusoidal duration of two cycles was used to provide adequate frequency selectivity.

After determination of excitation frequency and amplitude, the system performance (frequency, damping, and peak loads) was measured for selected modes. The system was off during the two cycles of control surface excitation and engaged automatically as the feedback error signal passed through zero command to the control surface. This minimized and standardized the transient due to system engagement. Figure 5 gives a typical example of an elastic mode transient response. Frequency, damping, and peak loads were evaluated for various system gains.

Figures 6 and 7 illustrate improvements obtained for peak stress responses at Dutch roll and aft body mode frequencies,

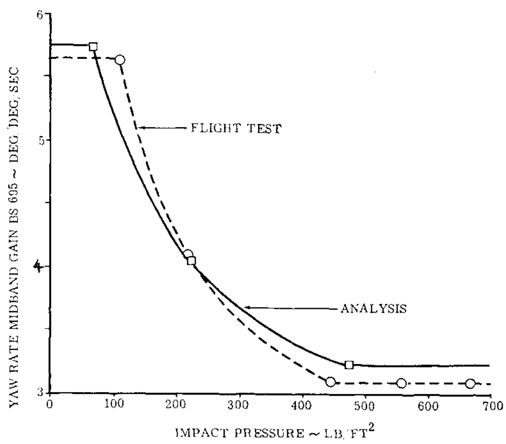

Fig. 8 Yaw rate gain schedule comparison.

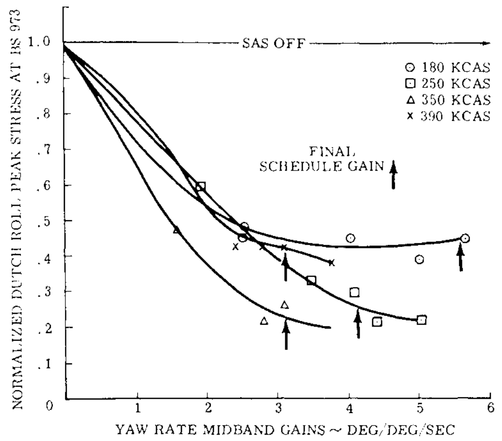

Fig. 6 Dutch roll peak stress optimization.

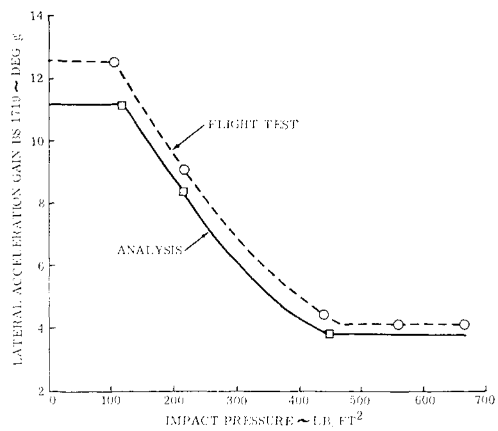

Fig. 9 Lateral acceleration gain schedule comparison.

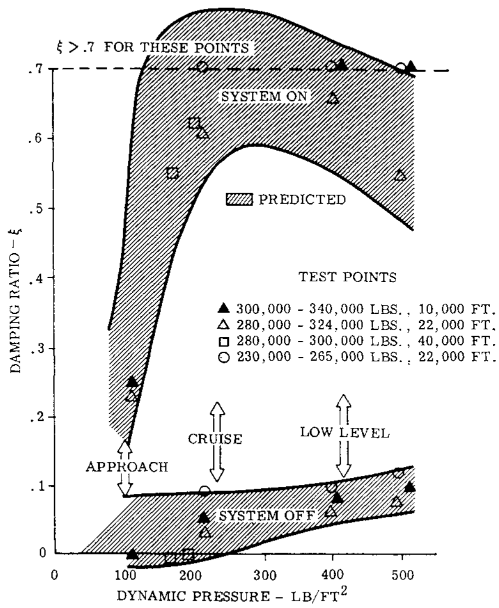

Fig. 10 Comparison of test and analysis, dutch roll mode damping ratios.

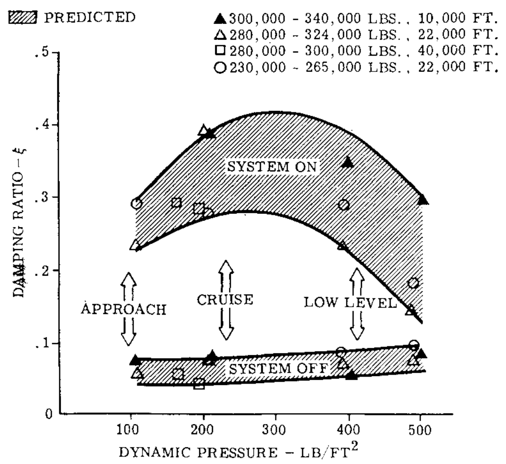

Fig. 11 Comparison of test and analysis, aft body elastic mode damping ratio.

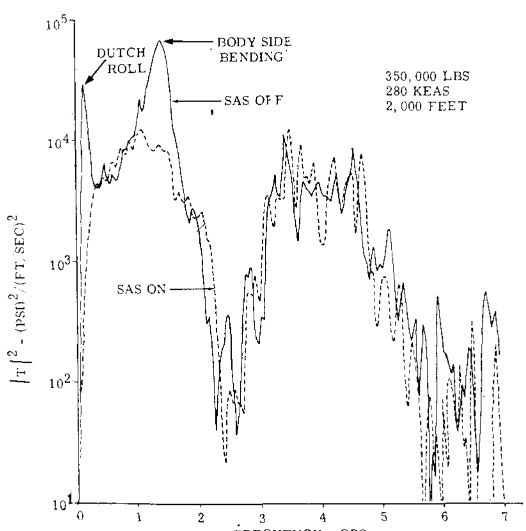

Fig. 12 Fuselage stress transfer function comparison—experimental.

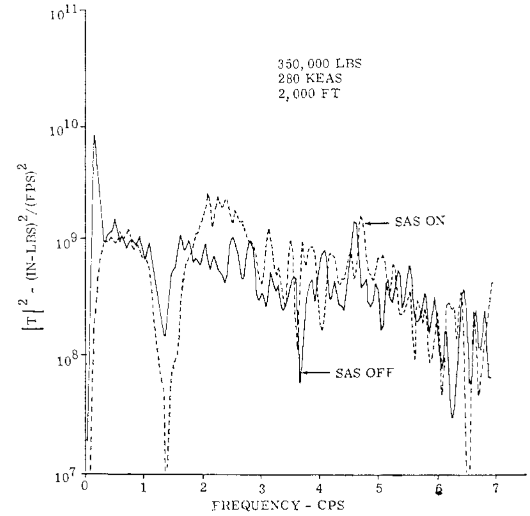

Fig. 13 Vertical tail moment transfer function comparison—experimental.

respectively. For the yaw SAS, optimum gain values were based primarily on damping and reduction of peak stress associated with aft body bending for the Dutch roll and elastic modes.

Based on gain optimization tests, predicted gain schedules were shown to be close to optimum values obtained from flight test as illustrated in Figs. 8 and 9.

A comparison of predicted and measured Dutch roll damping ratios is shown in Fig. 10 for the scheduled gain values, and a similar plot for the aft body elastic bending mode is presented in Fig. 11. These plots illustrate that the selected yaw SAS configuration met or exceeded all damping performance predictions.

Performance

The evaluation of the final SAS configuration performance was accomplished by recording dynamic response and gust velocity data during flight through atmospheric turbulence. The general test approach described in Ref. 4 was also used in the performance evaluation of the prototype SAS. Because of the random nature of atmospheric turbulence, statistical techniques using generalized harmonic analysis were used in the interpretation of the test results. The flight test demonstration was designed to provide data for direct comparisons to the theoretical predictions. Ten-

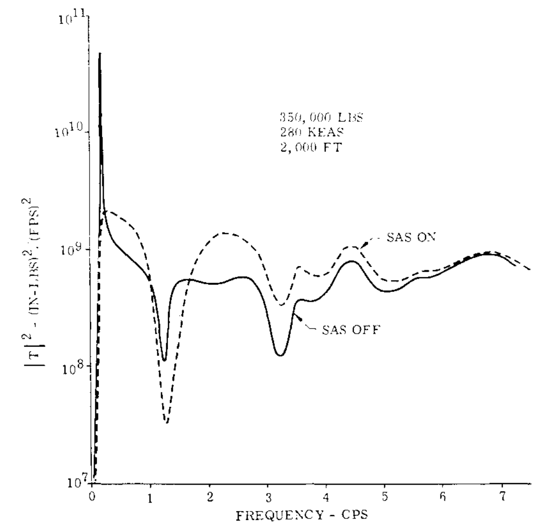

Fig. 14 Vertical tail moment transfer function comparison—theoretical.

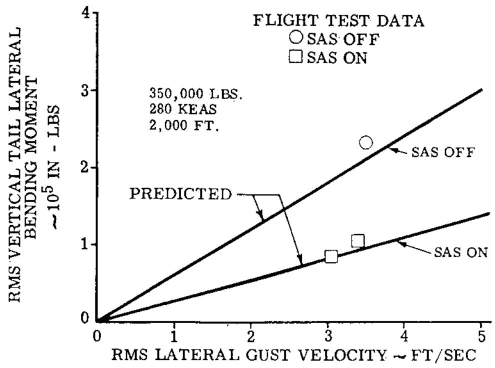

Fig. 15 Comparison of test and analysis, vertical tail bending moment.

minute data samples were recorded for SAS-on and-off conditions at two gross weights (250,000 and 350,000 lb) and at two airspeeds (280 and 350 KEAS) during low-altitude flight. The SAS-off conditions are representative of the unaugmented airplane. Some of the significant flight test results are described in the following paragraphs.

Transfer functions

Time histories of the vertical and lateral components of gust velocity along with various loads, stresses, and accelerations were recorded during the test conditions. Both vertical and lateral gust time histories were used with various responses to calculate experimental transfer functions by cross spectral methods.

Experimental gust response transfer functions are presented in Fig. 12 showing the effects of the prototype SAS-on stress in the aft fuselage upper longeron due to lateral gusts. The prototype SAS provides a significant reduction in fuselage stress for both the Dutch roll mode and the fuselage first side bending mode. The effect of modal suppression is clearly shown in these experimental frequency response functions.

Similar results are presented in Fig. 13 showing the effects of the prototype SAS-on vertical tail side bending moment. These results indicate that a significant load reduction was obtained at the Dutch roll mode with some increase in the response at about 2 cycles / sec. For comparison the corresponding theoretical transfer functions are shown in Fig. 14 indicating very similar trends.

RMS response

The root mean square response per unit root mean square gust velocity was calculated for loads, stresses, and accelerations to obtain a measure of the prototype SAS effect on peak loads, peak stresses, and aircraft ride quality.

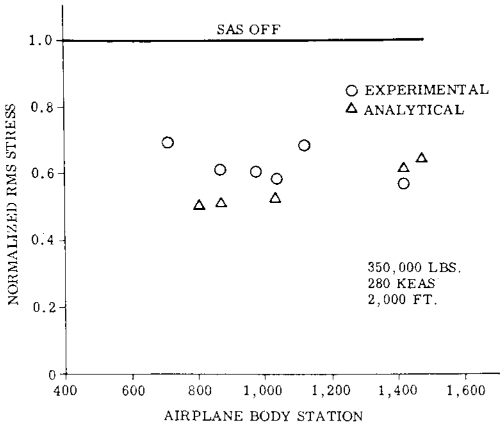

Fig. 16 Improvement in fuselage stress with advanced SAS.

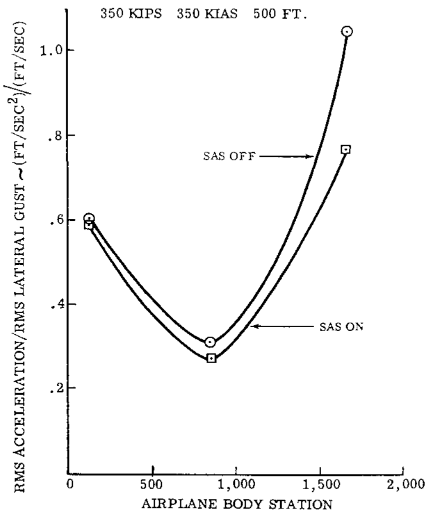

Fig. 17 Lateral acceleration per unit gust.

A comparison of the rms vertical tail side bending moment vs rms gust velocity is given in Fig. 15. These results indicate a significant reduction in vertical tail loads due to the prototype SAS and good agreement between theory and test.

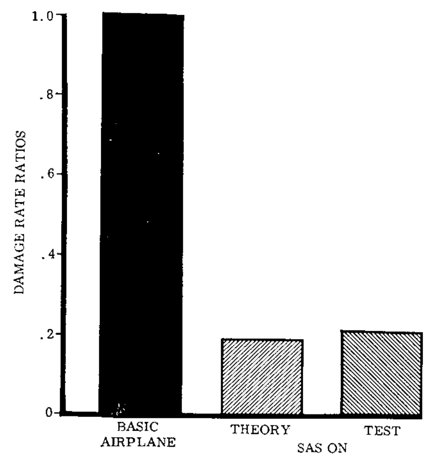

Fig. 18 Relative fatigue damage, low-level turbulence, fuselage station 1412.

The normalized rms stress (ratio of SAS-on to SAS-off) in the fuselage upper longeron vs airplane body station is presented in Fig. 16. The test results indicate that fuselage longeron stress is reduced by 30 or 40% by the prototype

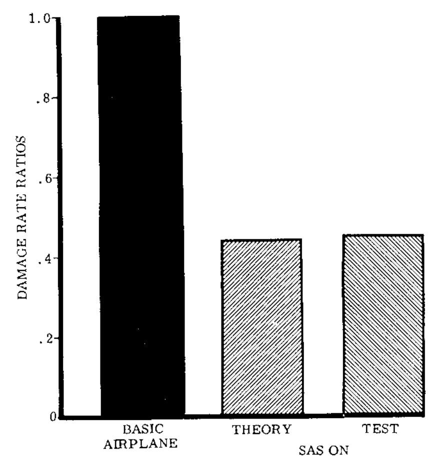

Fig. 19 Relative fatigue damage, low-level turbulence, wing station 859, Stringer No. 3 lower surface.

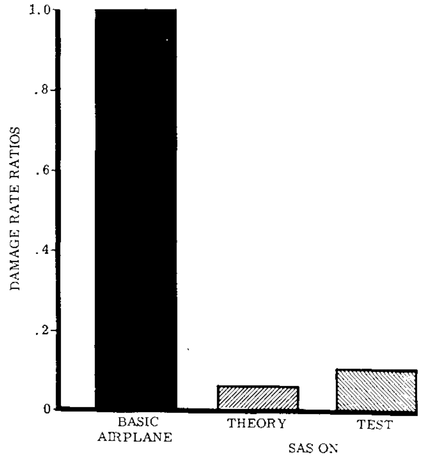

Fig. 20 Relative fatigue damage, low-level turbulence, vertical fin station 135, main spar.

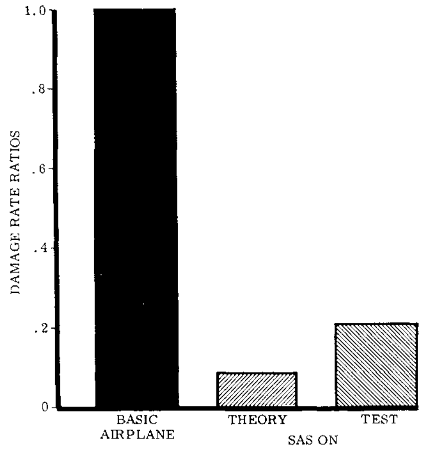

Fig. 21 Relative fatigue damage, low-level turbulence, horizontal stabilizer, buttock line 56.

SAS, slightly less than that predicted by the theoretical analysis.

The effect of the prototype SAS-on rms lateral acceleration is shown in Fig. 17 indicating a small reduction along the entire fuselage. Using rms acceleration as a measure of ride quality, the prototype SAS provides a slight improvement.

Fatigue damage rates

A major design objective for the prototype SAS was the reduction in structural fatigue damage rate due to flight through atmospheric turbulence. The experimental response parameters obtained from the cross spectral transfer functions were combined with a definition of atmospheric turbulence to calculate stress response statistics. These were then used with fatigue allowables in terms of *S-N* curves to calculate experimental damage rates. *S-N* curves represent the number of cycles to fatigue failure vs the applied alternating stress levels. These results are compared with corresponding theoretical data in Figs. 18–21 for four structural locations. The results are presented as a ratio with SAS-on to the damage rate for the basic airplane. These ratios represent the average values for the four test conditions. The results in Figs. 18–21 indicate that major reductions in fatigue damage rates due to flight through turbulence were obtained with SAS and the largest improvements were on the empennage and fuselage. Also, generally good agreement is noted between theoretical predictions and experimental results.

Conclusions

The stability of the B-52 was improved by the increased control authority and wider band frequency response of the advanced stability augmentation system. The damping of the rigid airplane motions and the low-frequency aft fuselage vibration modes was increased by the prototype SAS.

Significant reductions in aft fuselage and empennage dynamic loads and stresses for flight through atmospheric turbulence were obtained. Reductions of more than 50% of fatigue damage rates due to turbulence were obtained for the fuselage and empennage with smaller but significant reductions in wing damage rates. Comparisons between theoretically predicted and test results indicated good agreement.

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