NASA TECHNICAL MEMORANDUM

NASA TM X-1179

NASA TM X-1179

N66-10320

(ACCESSION NUMBER)

14

(PAGES)

(NASA CR OR TMX OR AD NUMBER)

1

(THRU)

(CODE)

32

(CATEGORY)

FACILITY FORM 602

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GPO PRICE $ ________

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Hard copy (HC) ________

Microfiche (MF) ________

ff 653 July 65

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1965

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CENTAUR AC-2, AC-3, AND AC-4 VEHICLES

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SUMMARY

The structural integrity of the interstage, because of its propensity to panel flutter, was studied. A wind tunnel test program, using both individual panels and a full-scale quarter section of the adapter, was conducted at the NASA Langley Research Center to identify the flutter boundary.

The AC-2, AC-3, and AC-4 flight vehicles were instrumented to record skin oscillations. The high-frequency pressure fluctuation transducers were included in the instrumentation. Analysis of flight parameters indicated that on each of these flights the vehicle flew essentially outside the flutter boundary (i.e., no flutter); however, flight data established that a high degree of skin oscillations was encountered on each of the flights.

Further analysis indicated that these oscillations were forced by sonic and aerodynamic inputs during the flights. Structural integrity of the interstage was maintained through stage separation. It may be concluded that the existing adapter is adequate to withstand the load imposed by the vibration environment.

Author

INTRODUCTION

The interstage adapter forms the structural connection between the Atlas and Centaur stages of the Atlas-Centaur vehicle. It is a thin aluminum, 10-foot-diameter shell, stiffened internally by circumferential rings and externally by hat-section stringers. The rings and the stringers result in a large number of unsupported skin panels, which could conceivably be subject to panel flutter within the flight envelope of the Atlas-Centaur vehicle.

This suspected susceptibility to panel flutter was the cause of some concern regarding the structural integrity of the interstage adapter. A panel flutter test program was formulated by the Centaur Project Office at NASA Marshall Space Flight Center and the NASA Langley Research Center. This test program initially consisted of single flat panel specimens tested at Mach 1.63 and 1.84. Based on the data obtained from these tests, the program was expanded to include a full-scale quarter section of the adapter.

Inevitably, design changes in the flight adapter resulted in some geometric dissimilarities between the test and flight adapters. In order to extend the validity of the flutter boundary obtained from the wind tunnel tests, recourse was made to existing literature. The test and extrapolated flutter boundaries were sufficient to establish the flutter environment on each flight.

In general, flight within the flutter boundary was limited to a very few seconds. Review of skin accelerometer data, however, showed high values of skin vibrations at launch and during transonic flight. Flight data indicate that the vibrations are induced by sonic and by boundary layer noise excitation.

WIND TUNNEL PANEL FLUTTER TESTS

The initial design of the interstage adapter was such that the size of the unsupported skin panels was $6\frac{3}{4}$ by $14\frac{1}{2}$ inches. Single flat panels of this configuration and 0.032-inch aluminum skin were tested in the Langley Unitary Plan Wind Tunnel at Mach 1.63 and 1.84. The results indicated that the panel, when loaded in compression, would undergo a nondestructive flutter at aerodynamic conditions attainable within the flight range of the launch vehicle. The flutter motion was mild, and the effect of curvature of the flight adapter was expected to be stabilizing. Still, there was a possibility that a streamwise array of panels could be subjected to "cascading," an increase in flutter amplitude in each successive downstream panel. Therefore, the effect of curvature and cascading of a full-scale quarter section of the flight adapter in the thermal structures tunnel was investigated at Mach 3. The most severe environment for flutter was expected to occur at Mach 1.8. With the use of the flutter parameter, flight conditions could be simulated by other combinations of aerodynamic variables within the operating range of the 9-by 6-foot tunnel.

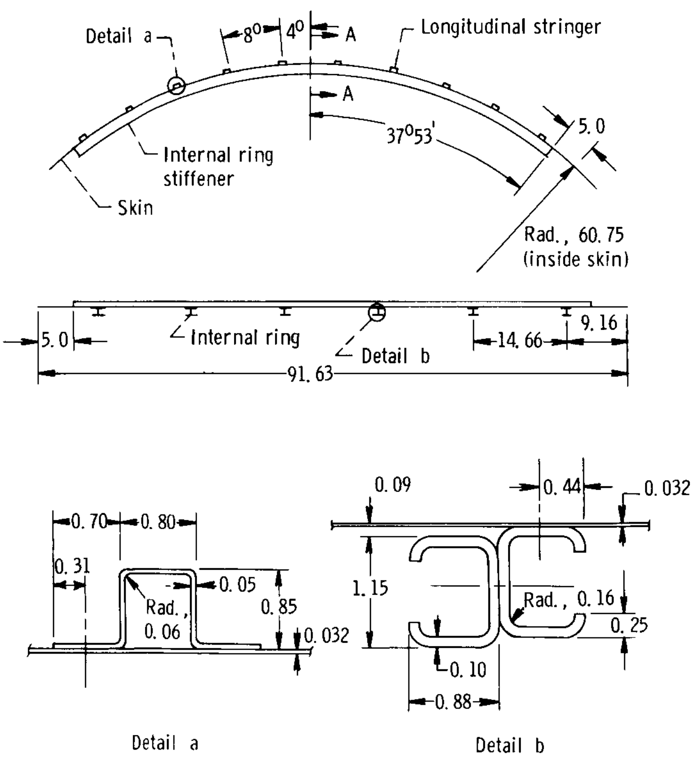


Figure 1. - Structural configuration of quarter-section Langley wind tunnel flutter test specimen.

The geometric configuration of the test specimen is shown in figure 1. It differed from the flight article in the design of the internal rings. The actual rings were Z sections; in order to reduce the depth of the test article to fit an existing fixture, the rings were redesigned as in figure 1. The stiffness of the two ring designs was approximately the same. Compressive loads were applied to the stringers by means

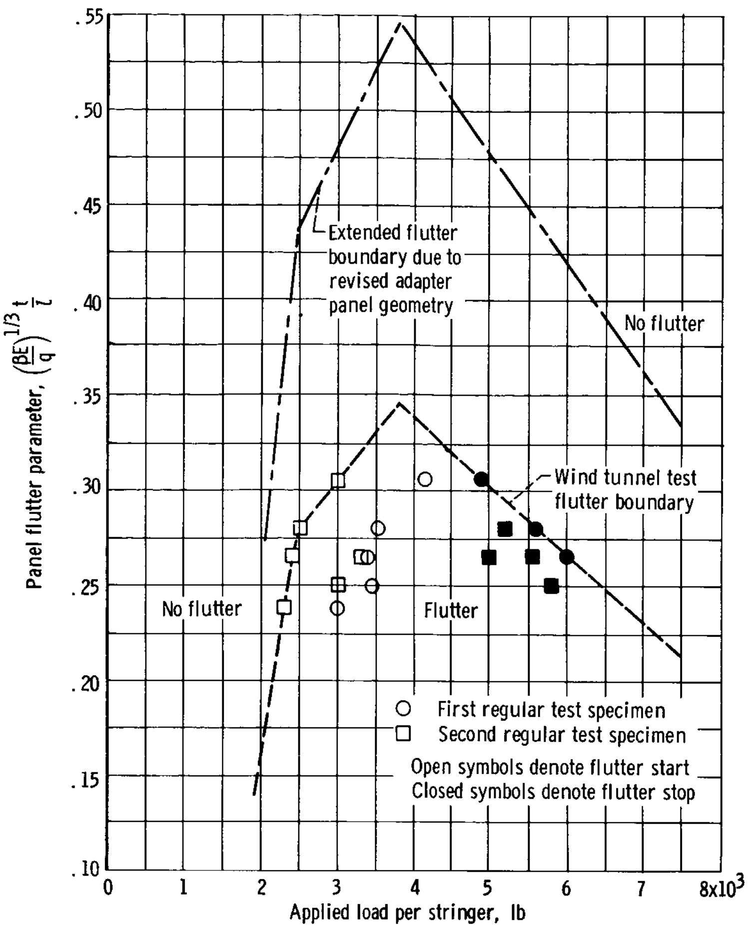


Figure 2. - Interstage adapter panel flutter boundary.

of hydraulic jacks. Data indicated that flutter was most likely to occur when the skin stress was near the point of buckling. The range of compressive loads applied to the stringers varied from zero up to initiation of flutter and further to the point where flutter stopped. This process was repeated at several values of the flutter parameter; thus a flutter boundary was established (the lower of the two flutter boundaries illustrated in fig. 2).

Before the wind tunnel tests were started, static tests were made to establish stresses in different parts of the specimens as functions of the loads on the stringers. The test specimen was extensively instrumented with strain gages and installed in the test fixture. Compressive loads to the test article were applied with the specimen edges rigidly restrained and unrestrained in the test fixture. The strain gage data indicate that centerline panels were practically unaffected by the edge restraints. The influence of edge restraint grew progressively worse in the rows of panels toward the edge. Sizable shear stress was evidenced at the edges, and diagonal buckles appeared as a result of the edge restraint. Results of the static tests showed skin buckling at a stringer compressive load of 2500 pounds.

Dummy runs were made in the wind tunnel to obtain pressure distribution data. The data showed that uniform and satisfactory flow existed over the centerline panels. Poor flow conditions existed along each side. It was surmised that these conditions were caused by shock waves from the upstream part of the test fixture which reflected off the tunnel walls and impinged on the specimen.

The flutter tests were conducted at Mach 3 and 300° F stagnation temperature over a dynamic pressure range of 1630 to 3500 pounds per square foot. The maximum flight dynamic pressure encountered on Atlas-Centaur flights was less than 800 pounds per square foot. The test values of dynamic pressure are then well in excess of a conservative 1.5 factor criterion.

Flutter results as a function of the flutter parameter

$$\left(\frac{\beta E}{q}\right)^{1/3} \frac{t}{l}$$

where

β $\sqrt{M^2 - 1}$

M Mach number

E modulus of elasticity

q dynamic pressure

t skin thickness

l streamwise panel length

and stringer compressive load for the five centerline panels is shown in figure 2. These centerline panels are considered representative of the conditions that would be encountered by the flight adapter. Data were obtained as stringer compressive load was gradually increased until flutter was initiated. The load was further increased until flutter ceased. Flutter was not initiated in all five panels at the same time. This may be attributed to slight imperfections in and differences between the various panels. The flutter boundary obtained as a result of these tests is the lower boundary in figure 2. The detailed data and discussion of the test program are contained in reference 1 and have been summarized here in the interests of completeness of presentation.

The flutter motion was not violent; no noticeable damage was incurred by the centerline panels after a total accumulated flutter time of over 1 minute. Cracks did appear in the edge panels, the region of disturbed airflow and high shear stress. Total flutter time for developing these cracks is estimated at between 1 to 2 minutes. During the tests it was observed that flutter occurred in the shear-loaded panels in the extreme outer arrays before it began in the center panels which were loaded in compression.

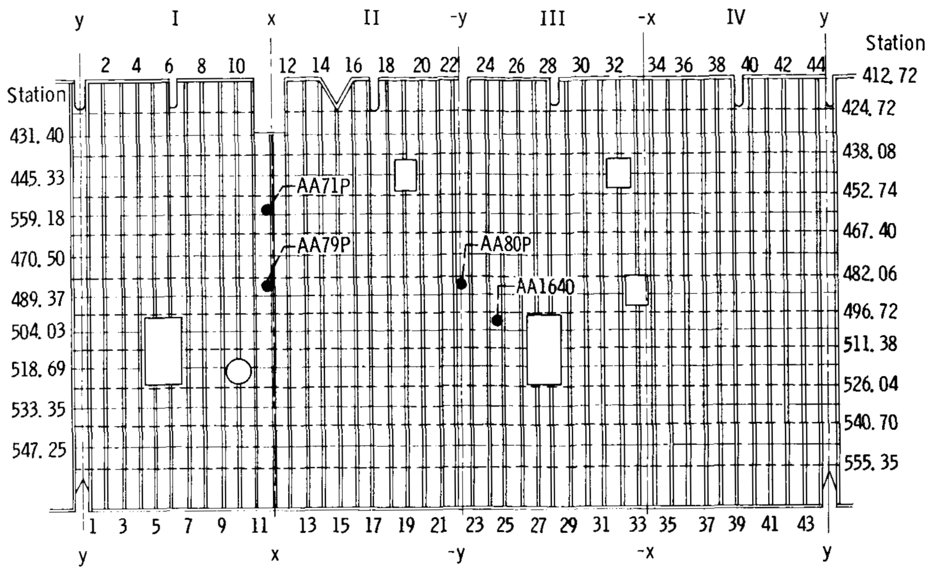


Figure 3. - Interstage adapter panel flutter instrumentation on AC-2, AC-3, and AC-4 flights. Broken lines indicate center lines of ring stiffeners, deleted on AC-4 flight. Structural configurations of AC-2 and AC-3 flights included all ring stiffeners shown.

FLIGHT ADAPTER GEOMETRY

On the earlier flights, there was some concern that crushing pressure loads would be imposed on the adapter as a result of aerodynamic venting through the openings at the interstage-Centaur interface. Thus the adapter was reinforced to obviate any possibility of in-flight failure due to unforeseen loads. This reinforcement was accomplished by reinforcing the existing rings and by adding extra internal circumferential rings between them. The longitudinal hat sections were strengthened by capping the existing stringers for a length of two bays at the forward and aft ends. Further, six stringers were added at the forward and aft ends for approximately two bay lengths. The net effect over most of the adapter was to shorten the length of each unsupported skin panel by a factor of two leaving the width unchanged. This geometry is shown in figure 3 and was used on the AC-2 and AC-3 flights. On the AC-4 vehicle the reinforcing rings were deleted and the configuration returned to essentially that of the wind tunnel test specimen.

EXTRAPOLATION OF WIND TUNNEL DATA TO BE REPRESENTATIVE OF ADAPTER FLIGHT CONFIGURATION

On the AC-2 and AC-3 interstage adapters the effect of the additional reinforcing rings was to reduce the unsupported length of the skin panel from $14\frac{1}{2}$ inches to approximately half that value. The width remained unchanged. A search through existing literature was made to establish the effect of length-to-width ratio l/w on the flutter boundary. Such data was found in reference 2 for aluminum alloy panels of geometrically similar configuration. This data indicated that decreasing the streamwise length of the panels resulted in raising the flutter boundary to higher values of the flutter parameter. The wind tunnel test boundary was ratioed based on data in reference 2. The wind tunnel and revised flutter boundaries are shown in figure 2. The upper line was used to establish the panel flutter environment for the AC-2 and AC-3 vehicles, and the lower line was used for the AC-4 vehicle.

The flutter parameter enables the test results to be extrapolated to other Mach numbers only within certain limits. In particular, the extrapolation is questionable below Mach numbers less than 1.7. On the Atlas-Centaur flights data indicated that most severe panel vibration occurred at approximately Mach 1. The absence of wind tunnel data at the lower Mach numbers made it necessary to use the flutter parameter for extrapolation down to these lower Mach numbers. The limitations of this extrapolation should be kept in mind in the interpretations of the flight data.

Thus far, flutter characteristics in only a supersonic flow field have been considered. No tests were conducted at subsonic and transonic speeds. Literature research indicated that subsonic flutter is highly unlikely; theoretical investigation appears to preclude its existence. Experimental evidence of this problem was found in reference 3. Here, attempts to initiate flutter in aluminum alloy skin panels 0.004 inch thick proved quite unsuccessful. It has, therefore, been concluded that for this investigation there is no subsonic flutter. For the transonic region, too, no experimental data were found. It may be argued that at transonic speed, panel excitation by aerodynamic buffet and boundary layer turbulence would obscure the effect of panel flutter. In view of the foregoing, it has been assumed that panel flutter would only be evidenced in the supersonic flight regime. The flutter boundaries of figure 2 were used to establish the flight period during which flutter was possible.

FLIGHT INSTRUMENTATION

On each flight one high-response accelerometer was mounted in the middle of a typical skin panel to monitor skin oscillations. Included in the instrumentation were three high-frequency pressure fluctuation transducers to monitor the fluctuating pressure excitation of the panels. The measurements were located aft of the boost pump fairing and wiring tunnel protuberances, which were the largest protusions immediately forward, and hence it was considered the region of most disturbed flow. The adapter geometry and the location of instrumentation on each flight are shown in figure 3. There were several temperature transducers on the flight adapters which are not shown in this report. The temperatures encountered during flight where panel flutter and excitation were critical were of the order of 100° F. The time of maximum heating occurred at T+140 seconds just prior to booster engine cutoff. Therefore, skin temperature was not a consideration in the study of panel vibrations. For this reason no temperature history data are presented herein.

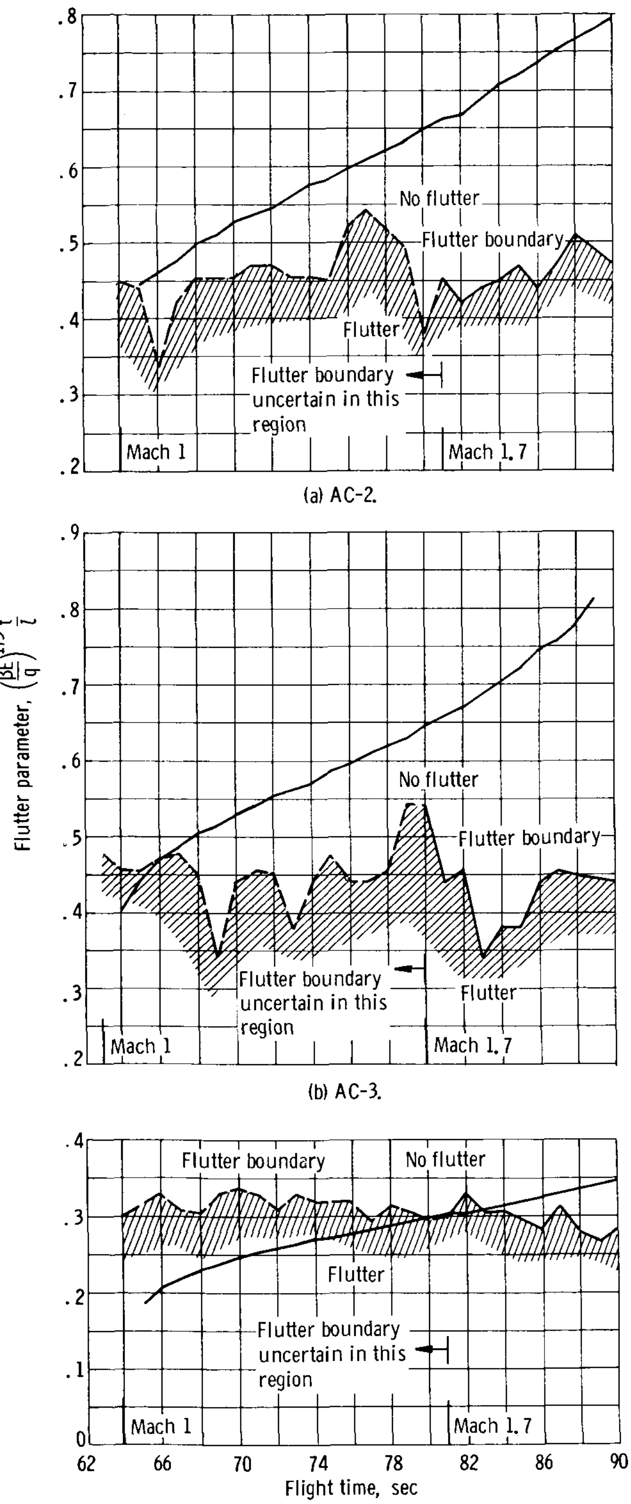


Figure 4. - Flight flutter parameter and flutter boundary history.

STRINGER COMPRESSIVE LOAD

The sources of compressive load on the stringers are the aerodynamic bending moment, drag, and longitudinal inertia loads. There is also a slight bending moment due to the center of gravity offset from the longitudinal axis of the vehicle. On each of the Atlas-Centaur flights (refs. 4 and 5), the interstage was instrumented with four longitudinal strain gages on the inner surface of the stringers. One each of the four gages was located on the positive and negative yy and xx axes. Data obtained from these gages were used to compute a peak compressive load history experienced on each flight. Because both the wind magnitude and direction change with flight time, the peak loaded stringer changes with time. Hence the skin panel most susceptible to panel flutter changes with time. The purpose here was to establish whether or not any region on the adapter fell within the flutter boundary of figure 2. The peak compressive load history, as derived from the strain gage response data, was used to establish the panel flutter boundary on each flight.

FLIGHT FLUTTER PARAMETER

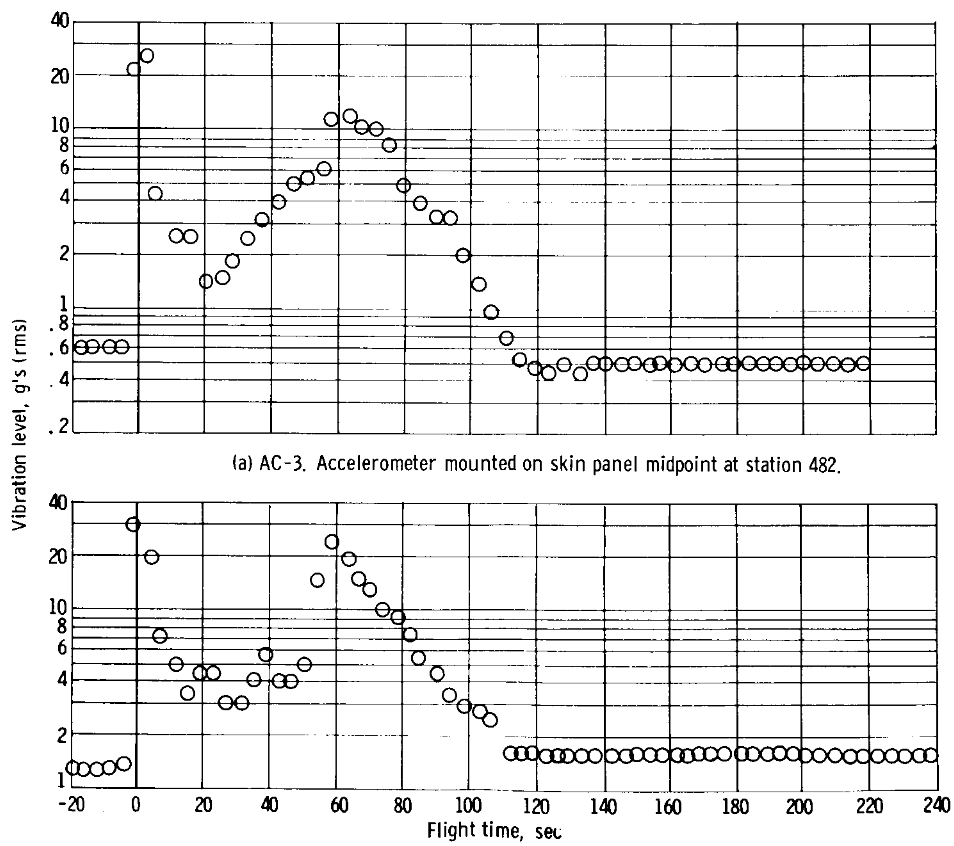
Subsequent to each flight, flutter parameter, Mach number, and dynamic pressure were calculated from trajectory reconstruction data and atmospheric properties from the Rawinsonde Balloon Sounding. The flight flutter parameter history was compared with the flutter boundary on each flight. This comparison is shown in figure 4.

On each of the Atlas-Centaur flights, the interstage was substantially outside the panel flutter regime except perhaps for a few seconds subsequent to attaining Mach 1.

During transonic flight the presence of sources of excitation such as boundary layer noise and aerodynamic buffet would obscure any self-excited oscillations of the skin panels. With this in mind, it may be concluded that little or no panel flutter was encountered on the AC-2, AC-3, and AC-4 flights. The total time of the vehicles through the atmosphere was approximately 120 seconds.

FLIGHT DATA

The preceding discussion demonstrates that on the subject flights little or no panel flutter (self-excited) was encountered. Of the three the AC-4 flight exhibited the longest dwell within the flutter boundary, approximately 18 seconds. It should, however, be borne in mind that the flutter boundary is not sharply defined. In fact, figure 2 shows that the boundary is in reality a gray area, and the true boundary for each panel will depend on minor fabrication and material difference. The boundary shown is for the extremeties of the data obtained during wind tunnel test. In all cases for the Atlas-Centaur flight, penetration of the flutter boundary was very shallow (i.e., in the gray region). Hence, from the comparison of the flight flutter parameter and the flutter boundary, it is not clear if panel flutter was indeed encountered on these flights.



(b) AC-4. Accelerometer mounted on skin panel midpoint at station 502 and y-axis.

Figure 5. - Vibration level as recorded by accelerometer (AA164φ) mounted on skin panel midpoint (data obtained from ref. 7). Transducer commutated to record for 1 second in every 4 seconds of flight; analysis band, 20 to 2100 cps.

A review of the accelerometer (AA164φ) data shows that rather severe skin vibrations were encountered on each of the flights. The g's (rms) history of these vibrations for AC-3 and AC-4 flights are shown in figures 5(a) and (b), respectively. There are two peaks in the root mean square of the response: one at launch, the other at 60 seconds (transonic) of flight. On each of the flights Mach 1 was attained at approximately 63 seconds of flight. Subsequent to attaining Mach 1, the vibration level gradually trailed off to nothing at approximately 120 seconds. At launch the peak values of g's (rms) attained on the AC-3 and AC 4 flights were 26 g's and 30 g's, respectively. Through transonic flight the levels attained were 13 and 24 g's (rms) respectively. The AC-4 vibration levels were considerably more severe than those encountered on the AC-3 flight. This is to be expected in view of the change in geometry; that is, the unsupported panel length on the AC-4 adapter panels was twice that on the AC-3 adapter for substantially the same environment.

At times of peak response, the skin panels were substantially outside the flutter boundary; hence, these vibration levels must be the result of external excitation (comparison of the corresponding curves of figs. 5 and 6). There is a correlation between the pressure fluctuations and the skin vibrations. It is suggested that the skin vibrations are being excited by the pressure fluctuations. The pressure fluctuations are the result of sonic environment at launch, boundary layer noise, and aerodynamic buffet during transonic flight. During the few seconds subsequent to Mach 1 when the skin panels are within the flutter

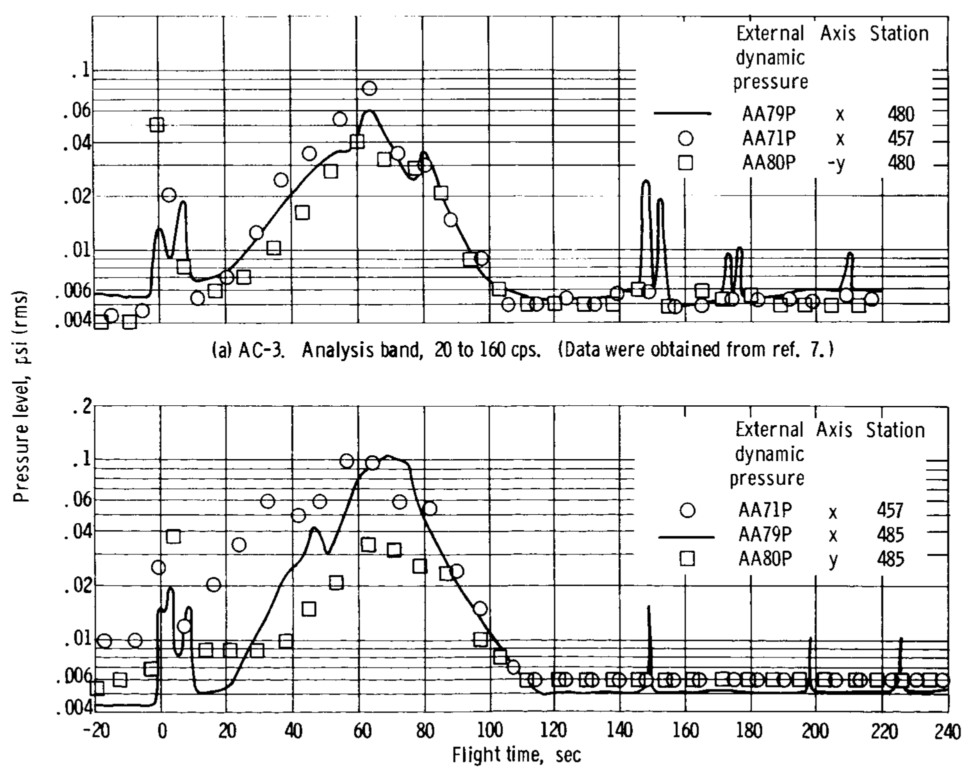
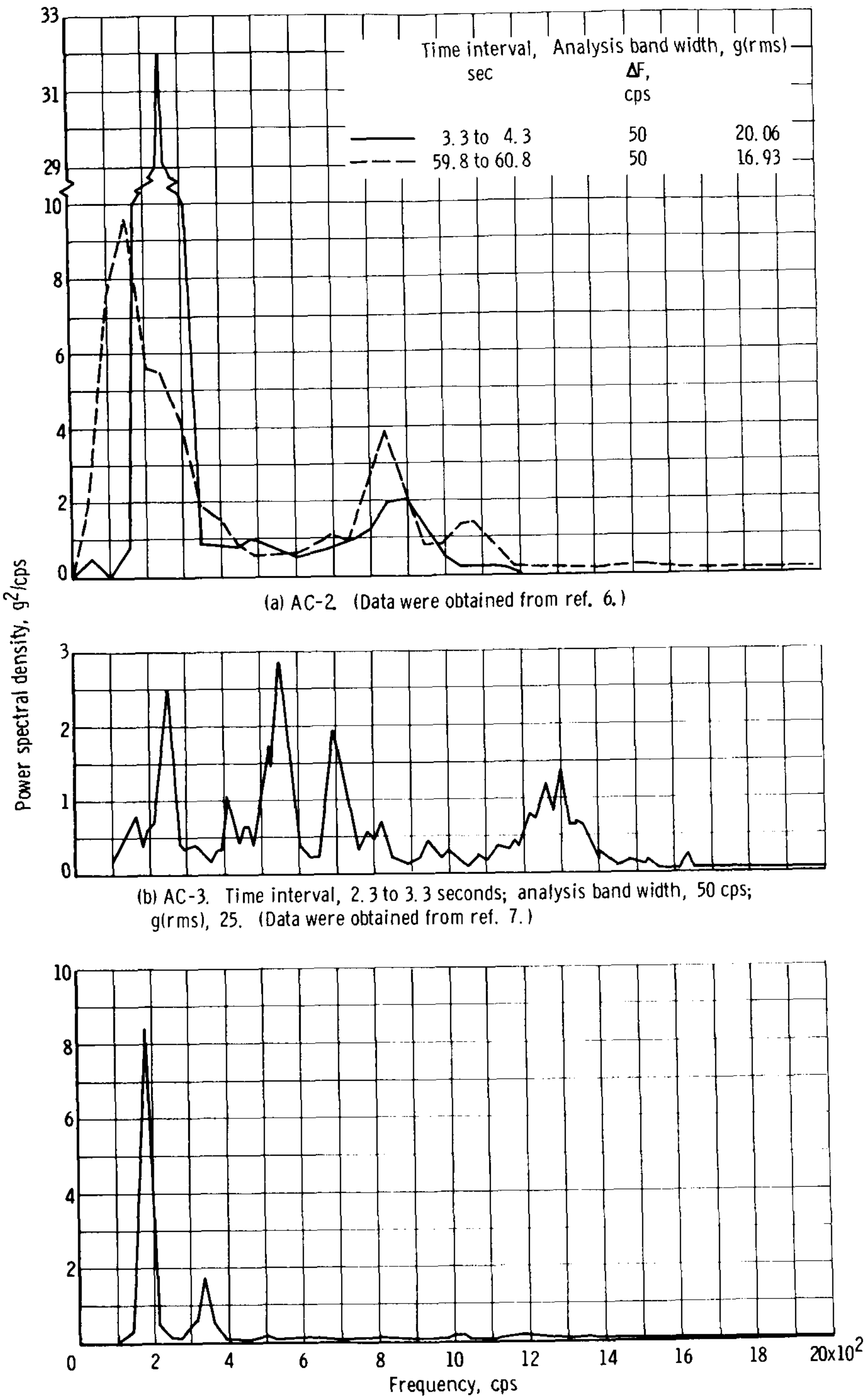


Figure 6. - Fluctuating pressure level distribution around interstage adapter. AA71P and AA80P commutated to record for 1 second in every 8 seconds of flight. AA79P analysis band, 20 to 110 cps.



(a) AC-2. (Data were obtained from ref. 6.)

(b) AC-3. Time interval, 2.3 to 3.3 seconds; analysis band width, 50 cps; g(rms), 25. (Data were obtained from ref. 7.)

(c) AC-4. Time interval, 3.3 to 4.3 seconds; analysis band width, 20 cps; g(rms), 30. (Data were obtained from ref. 8.)

Figure 7. - Flight power spectra of skin panel accelerations. Measurement number, AA164φ.

boundary and the response levels are still high, the possibility of panel flutter exists; however, from the data it is impossible to identify the contribution of panel flutter to the overall response.

When only the structure is considered, the source of the oscillations is of little consequence, whether self-excited or forced, the effect on the structure is the same. The influence of all these loads is to induce a fatigue condition in the skin panels. On all the flights under consideration, the interstage adapter performed adequately and the structural integrity was maintained through stage separation. During the wind tunnel tests at Langley Research Center, some cracks developed in the test specimen. These cracks were in a high shear stress and disturbed flow region, as was pointed out in the previous discussion. There is no way to compare the wind tunnel and flight load environment to establish susceptibility of the panels to fatigue cracks; however, the successful performance of the adapter on three flights is indicative of its structural adequacy.

In references 6, 7, and 8, spectral analyses of the raw data were performed. For completeness, these data have been extracted from the above references and presented in figure 7. The spectral plots show the concentration of energy at certain frequencies in the panel response accelerations. From the power spectrum of the response it may be possible to identify some, though not all, of the natural frequencies of the skin panels. The power spectra in figure 7 indicate that the first two natural frequencies of the AC-4 panels could be 180 and 330 cycles per second.

CONCLUSIONS

Analysis shows that on the three flights under consideration, panel flutter on the interstage adapter was highly unlikely. If any flutter did occur, it was for only a few seconds subsequent to Mach 1; however, forced excitation due to sonic, aerodynamic boundary layer noise and aerodynamic buffet environment did occur on each of the flights. The structural integrity of the adapter was maintained through stage separation. Therefore, the existing adapter is adequate to withstand the loads imposed by the vibration environment.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 5, 1965.

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