TECHNICAL NOTE

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STRUCTURAL DYNAMIC EXPERIENCES OF THE X-15 AIRPLANE

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON March 1962

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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STRUCTURAL DYNAMIC EXPERIENCES OF THE X-15 AIRPLANE*

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SUMMARY

The structural dynamic problems anticipated during the design of the X-15 airplane are reviewed briefly, and the actual flight experiences are described.

Considerable time and effort were expended in finding solutions and providing modifications to the airplane which alleviated the structural dynamic problems encountered. It is of interest to note that the modifications have been relatively simple; and a major portion of the effort has been required to determine the source of trouble and to proof-test the modification.

The flight experience of the X-15 airplane and the research initiated by the X-15 program have made a major contribution toward understanding the panel-flutter problem.

INTRODUCTION

The X-15 is the first airplane that has been designed and flight tested in which the structure was designed to operate in a high-temperature environment. In addition, it is the first airplane to make extensive use of high-temperature materials. The design, manufacture, and flight testing of the X-15 have added impetus to wind-tunnel and analytical studies that have advanced the state of the art in several fields of structural dynamics.

This paper reviews the structural dynamics problems that influenced the design of the structure and discusses the experiences that have been encountered during the flight tests.

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*This document is based on a paper presented at the Conference on the Progress of the X-15 Project, Edwards Air Force Base, Calif., November 20-21, 1961.

The areas discussed include the noise environment produced by the jet engines of the B-52 airplane and the XLR99 rocket engine, the buffet characteristics both of the B-52/X-15 combination and of the X-15 airplane alone, classical flutter, and panel-flutter experiences during the flight program. Where problems have been encountered that led to structural modifications, the modifications are shown.

SYMBOLS

C_N	airplane normal-force coefficient
$\left(\frac{E\sqrt{M^2 - 1}}{q}\right)^{1/3} \frac{t}{l}$	flutter parameter
l	panel length, ft
M	Mach number
Δp	peak-to-peak pressure fluctuation, lb/sq ft
q	dynamic pressure, lb/sq ft
w	panel width, ft

DISCUSSION

First, the experiences encountered with the B-52/X-15 combination and with the ground handling of the X-15 airplane are discussed.

Noise

Noise surveys indicated that the B-52 jet engines at 100-percent power would produce a noise environment approaching 158 decibels in the area to be occupied by the X-15 tail surfaces. These data were available at the time the design was fixed, and the fatigue life of the horizontal and vertical tails in this environment was questioned. Siren tests were initiated to determine the fatigue life of these structures. The results of these tests indicated that the fatigue life was unacceptable. North American Aviation, Inc., tested structural modifications that resulted in an appreciable increase in the fatigue life and initiated a retrofit of these modifications in the structure.

Consideration was also given to operating the B-52 jet engines next to the X-15 airplane at 50-percent power during take-off to minimize the noise environment. The measured noise levels produced by these operating conditions are shown in figure 1. The tip of the horizontal tail is exposed to a noise level of about 158 decibels and the sides of the vertical tail are exposed to a noise level of about 144 decibels. Increasing the B-52 jet-engine power to 100 percent would raise these levels by about 6 to 10 decibels.

A second noise source considered was that of the rocket engine during ground runs which was estimated to be higher than that of the B-52 jet engines. Measured noise levels produced by the XLR99 engine with the flame shield in place, shown on the right side of figure 1, are 148 decibels on the vertical tail and 156 decibels on the horizontal tail.

In order to check further on the fatigue life of the structure, additional tests were made with the B-52 jet engines as the source of the acoustic load. These tests were made with the engines at reduced take-off power, as shown in the left-hand drawing of figure 1, and no failures were found even in the original construction after 20 hours of exposure. The results of these tests indicated that the original construction had an acceptable fatigue life in the noise environment of the B-52 jet engine at reduced power. Take-off with reduced power on the engines next to the X-15 airplane was not desirable, however, from an operational standpoint. Calculations indicated that the modified structure would have an acceptable fatigue life in the noise environment produced at 100-percent power; therefore, 100-percent power has been used on all engines for take-off throughout the flight program.

The modifications made to the vertical tail for acoustic fatigue are shown in figure 2. On the left is the original construction, and on the right is the modified construction. The modifications consisted of increased rivet diameter, incorporation of dimpled-skin construction rather than countersunk rivets, and an increase in the gage of the corrugated ribs along the edge where they are flanged over to attach to the cap strip. Modifications to the horizontal tail consisted of increased rivet diameter and dimpled construction.

Initial captive flights were made with the original construction before retrofit of the modifications was accomplished. Structural failures were found in the upper vertical tail after the third captive flight. The failures, which were similar to those that occurred during the siren tests, consisted of failure of the corrugated ribs where they are flanged over to attach to the cap strip. The most extensive failure was a complete separation of the rib from the flange for approximately 18 inches on the side away from the B-52 jet engines. Subsequent investigation showed, however, that the failures were largely a result of a previously unsuspected source - the turbulence created by the X-15 pylon and the B-52 wing cutout.

Figure 3 shows the upper vertical tail located in the cutout of the trailing edge of the B-52 wing. On the left is the upper vertical tail in the wing cutout, as viewed over the upper surface of the B-52 wing. On the right is a rear view of the upper vertical tail in the wing cutout. The X-15 pylon and the blunt surface ahead of the X-15 upper vertical tail should be noted. Pressure measurements were made on the sides of the B-52 wing cutout to measure the environment of the vertical tail. These results are shown in figure 4. The magnitude of the pressure fluctuations Δp plotted against dynamic pressure increases with dynamic pressure and has a value of about 40 percent of dynamic pressure and a frequency of about 100 cps. These pressures converted to equivalent noise levels have a value of about 160 decibels at a dynamic pressure of 300 lb/sq ft and 154 decibels at a dynamic pressure of 150 lb/sq ft. Estimates of the fatigue life of the modified construction indicated an acceptable fatigue life in this environment. The modified tail is still subjected to the high-turbulence environment during captive flight and no further difficulty has been experienced to date.

Buffeting

Another area in which the B-52/X-15 combination was of concern was the effect of the X-15 airplane on the buffet characteristics of the B-52 airplane. Wind-tunnel tests indicated that the buffet characteristics of the B-52 airplane would be essentially unaffected by the addition of the X-15 airplane and would not be a problem. Flight experience has shown this to be true. The B-52 limit buffet boundary in terms of normal-force coefficient C_N plotted against Mach number is shown in figure 5. It was originally planned to launch the X-15 airplane at $M \approx 0.78$ at an altitude of 38,000 feet, and initial launches were made within the lower shaded area of the figure. In order to increase the performance of the X-15 airplane and for safety considerations, the launch conditions have been raised to Mach numbers greater than 0.8 at an altitude of 45,000 feet. Subsequent launches have been made, therefore, within the upper shaded area shown in figure 5. The launch conditions currently used are just below the flight-determined buffet boundary for the B-52/X-15 combination, and no problems due to buffeting have been encountered even though the buffet boundary has been penetrated slightly with the X-15 airplane aboard.

The remainder of the paper is devoted to some of the problems and experiences with the X-15 airplane alone. The buffet boundary established for the X-15 airplane is shown in figure 6 in terms of normal-force coefficient C_N plotted against Mach number. The data were taken from the normal acceleration at the airplane center of gravity and represent the onset of buffeting.

At subsonic and transonic speeds, the X-15 buffet boundary is similar to that of other low-aspect-ratio, thin-winged airplanes. The X-15 airplane usually penetrates the buffet boundary slightly during round-out after launch before accelerating to supersonic speed and usually encounters some mild buffet after completing the supersonic portion of the flight. Buffeting has not been a problem in the X-15 flights, but flight within the buffet region is generally avoided.

Throughout the flight program the airplane has experienced vibration from various sources. Although these vibrations have been felt by the pilot and have been referred to as buffeting, they have been attributed to causes other than aerodynamic buffeting. Early in the flight program, panel flutter of the fuselage side fairings caused a heavy vibration throughout the airplane. The stability-augmentation system has also been responsible for heavy vibration due to structural feedback from the horizontal tails. The flight records have also indicated a mild vibration at many regions throughout the flight envelope at a frequency which approximately corresponds to the horizontal- and vertical-tail natural frequencies. It is anticipated that a planned modification to the control system consisting of incorporating a pressure-differential feedback valve to the control-surface actuators will alleviate this problem.

Classical Flutter

The components in which flutter considerations influenced the design of the X-15 are shown as shaded areas in figure 7 and include the horizontal and vertical tails and landing flaps. Adequate wind-tunnel tests were made on the various components to provide proof tests to 30 percent above the design dynamic pressure of 2,500 lb/sq ft. No indication of flutter has been experienced in X-15 flights.

Panel Flutter

Panel flutter, on the other hand, has occurred in flight and has required modification of extensive areas of the fuselage side fairing and vertical tails which are shown as shaded areas in figure 8. The side-fairing panels consisted of a series of flat rectangular panels stiffened by a corrugated inner skin with the corrugations oriented normal to the flow. This orientation was chosen to allow thermal buckling and thus minimize thermal stresses, but of course it is not desirable from a panel-flutter standpoint. With respect to the vertical tail, the skin panels were unsupported over a length of about 60 inches with a rib spacing of about 6 inches. This resulted in long narrow panels having length-width ratios of about 10.

At the time that the structural design of the X-15 airplane was fixed, some information was available in regard to panel flutter. Application of the available results to determine the flutter characteristics of long narrow panels and corrugation-stiffened panels, such as those found in the vertical tail and the side fairing of the X-15, respectively, was uncertain. Thus, the initial design was not influenced by panel-flutter considerations.

Panel flutter of the fuselage side-fairing panels was experienced early in the flight program, however, and resulted in a severe vibration felt throughout the airplane. Strain gages were installed on the side-fairing panels, and panel flutter was detected at dynamic pressures as low as 650 lb/sq ft and identified as the source of vibration. Wind-tunnel tests on a full-scale side-fairing panel were initiated in the Langley Unitary Plan wind tunnel. During these tests, the panel flutter that was measured was in good agreement with the flight measurements. At the completion of these tests, cracks were found which originated at drain holes in the corrugations and extended outward to the base of the corrugation. Inspection of the airplane revealed several panels which had similar fatigue cracks. Previous wind-tunnel and analytical studies had indicated that a simple modification would be effective in preventing panel flutter on this type of panel. The modification, shown in figure 9, consisted of a hat-section stiffener riveted to the corrugations and extending in the streamwise direction. This modification was installed on the test specimen and tested in the Langley Unitary Plan wind tunnel. These tests served to clear the airplane for flight up to dynamic pressures of 2,000 lb/sq ft. Proof tests were later conducted in the Langley 9- by 6-foot thermal structures tunnel under conditions of aerodynamic heating at dynamic pressures up to 3,250 lb/sq ft and cleared the airplane for flight to dynamic pressures of 2,500 lb/sq ft. A total of 38 side-fairing panels, ranging in size from 12 by 15 inches to 23 by 34 inches, were stiffened in this manner on each X-15 airplane for panel flutter.

Panel flutter of the vertical tail also became of concern during proof tests to clear the airplane for classical flutter. Consequently, a second series of tests on the vertical stabilizer was planned to investigate panel flutter. Tests were made in the Ames 9- by 7-foot tunnel at a Mach number of 1.7 and dynamic pressures up to 1,300 lb/sq ft. Flutter was obtained on the skin panels with a length-width ratio of 10 and also on the closure rib. As a result of these tests, the affected panels were stiffened by North American Aviation, Inc., and flights with the stiffened stabilizer were restricted to dynamic pressures no greater than 1,500 lb/sq ft at Mach numbers up to 3.0.

Additional tests were then conducted on full-scale ventrals in the Langley 9- by 6-foot thermal structures tunnel and were to be culminated by proof tests. These tests disclosed other areas of the external skin also susceptible to panel flutter within the flight environment of the X-15 airplane. The additional skin areas included both unstiffened panels and corrugation-stiffened panels similar to the side-fairing panels.

Results of these and other investigations have led to the establishment of the panel-flutter envelope, reproduced from reference 1, shown in figure 10. In this figure the flutter parameter $\left(\frac{E\sqrt{M^2 - 1}}{q}\right)^{1/3} \frac{t}{l}$ is plotted as a function of length-width ratio l/w. The area under the curve is the flutter region and the area above the curve is free of flutter. The results of panel-flutter measurements in flight made on the flat rectangular panels on the vertical tail of the X-15 airplane are also shown in the figure. It is interesting to note the agreement between the flight data and the previously established envelope.

More recent unpublished experimental data tend to move the flutter boundary upward for a wide range of length-width ratios. The flutter results for the corrugation-stiffened panels indicate that correlation for such orthotropic panels on the basis of equivalent isotropic plates is still uncertain. Attempts to correlate the flutter characteristics of these orthotropic panels have been made on the basis of an effective thickness and width, but correlation has not been satisfactory because of the uncertainties in the determination of the effective values.

The modifications made to the vertical tail for panel flutter are shown in figure 11. The modification consists of J-section stiffeners riveted longitudinally on the inner surface of the skin at the centerline of the panel. In addition, lateral stiffeners were riveted to the skin near the panel centers and tied into the longitudinal stiffeners. Tests have shown that lateral stiffeners are ineffective in preventing flutter unless they are firmly restrained against rotation about the line of attachment to the panel. Other areas of the vertical tail in which panel flutter was experienced were on the corrugation-stiffened panels, similar to the side-fairing panels. The modification consisted of a single, light-weight hat section riveted to the backs of the corrugations along the longitudinal centerline. Proof tests were made on a full-scale ventral incorporating all modifications for panel flutter. These tests were made at a Mach number of 3.0, a dynamic pressure of 3,250 lb/sq ft, and a stagnation temperature of 660° F, with no evidence of flutter.

During the remaining flights of the X-15, in which dynamic pressures as high as 1,600 lb/sq ft have been achieved, no further panel-flutter problems have been encountered.

CONCLUDING REMARKS

The structural dynamic problems anticipated during the design of the X-15 airplane have been reviewed briefly, and the actual flight experiences have been described.

Considerable time and effort were expended in finding solutions and providing modifications to the airplane which alleviated the structural dynamic problems encountered. It is of interest to note that the modifications have been relatively simple and that a major portion of the effort has been required to determine the source of trouble and to proof-test the modification.

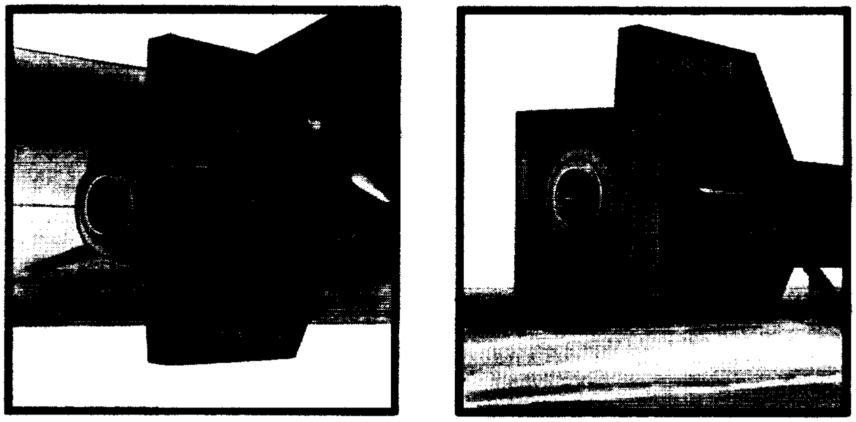
For future vehicles it is desirable to have theoretical methods for prediction of panel flutter or experimental means for defining prototype characteristics on the basis of model test results. Theoretical prediction of panel flutter is still uncertain, particularly for long narrow panels and corrugation-stiffened panels. The flight experience of the X-15 airplane and the research work initiated by the X-15 program have, however, made a major contribution toward understanding the panel-flutter problem.

Flight Research Center
National Aeronautics and Space Administration
Edwards, Calif., November 20, 1961

REFERENCES

1. Kordes, Eldon E., Tuovila, Weimer J., and Guy, Lawrence D.: Flutter Research on Skin Panels. NASA TN D-451, 1960.

MEASURED NOISE ENVIRONMENT



B-52 ENGINES AT 50% POWER

XLR99 ENGINE WITH FLAME SHIELD

Figure 1

STRUCTURAL MODIFICATIONS FOR ACOUSTICS

ORIGINAL CONSTRUCTION

MODIFIED CONSTRUCTION

Figure 2

VERTICAL TAIL IN B-52 WING CUTOUT

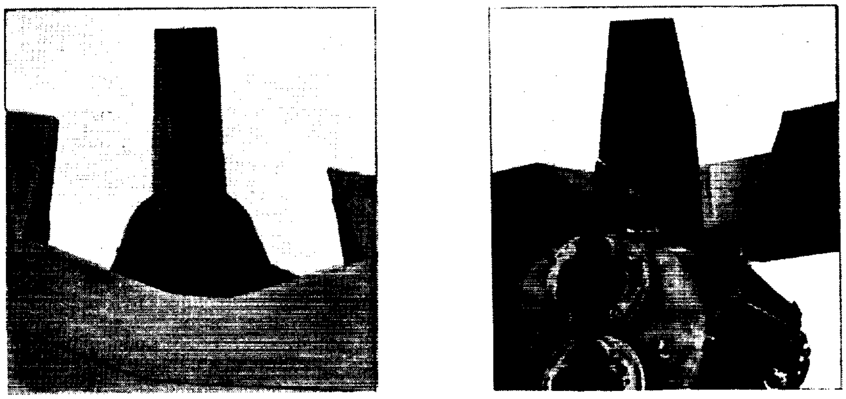


Figure 3

FLUCTUATING PRESSURES IN B-52 WING CUTOUT

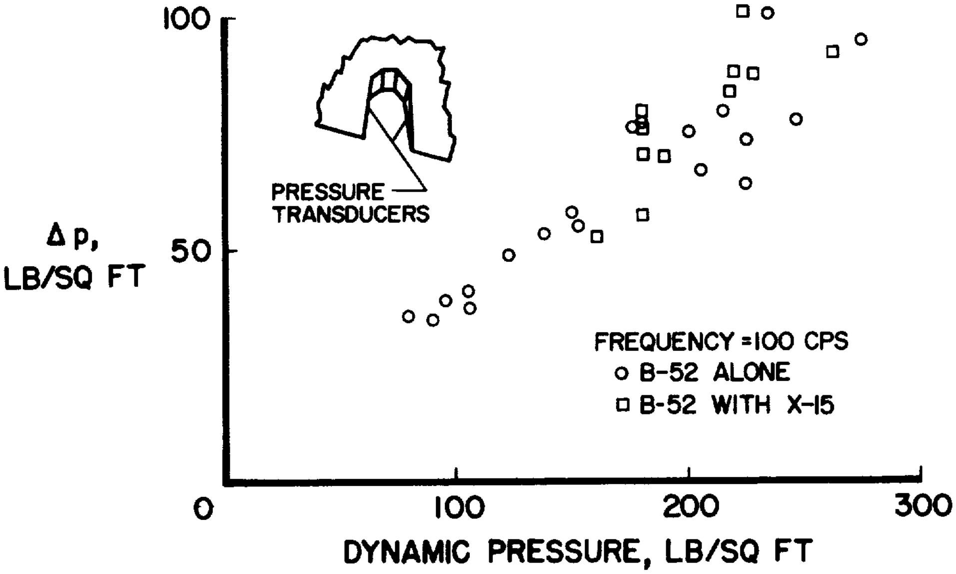


Figure 4

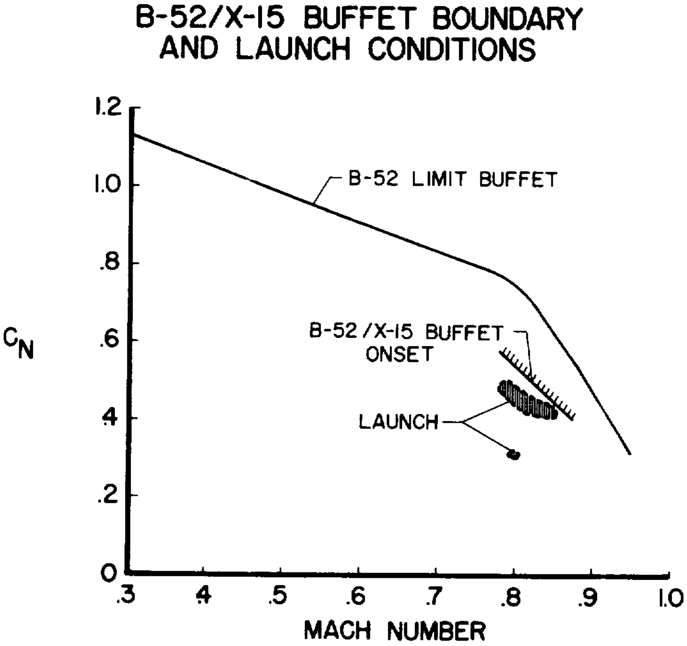


Figure 5

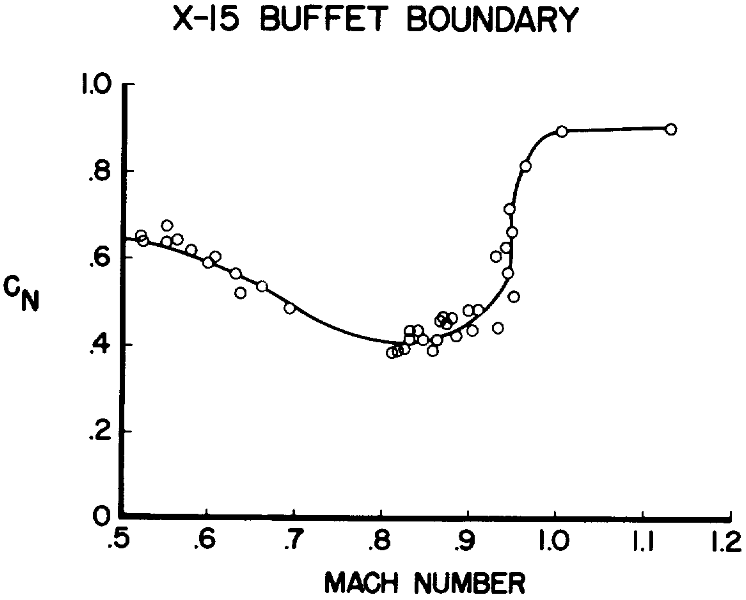


Figure 6

COMPONENTS DESIGNED BY FLUTTER CONSIDERATIONS

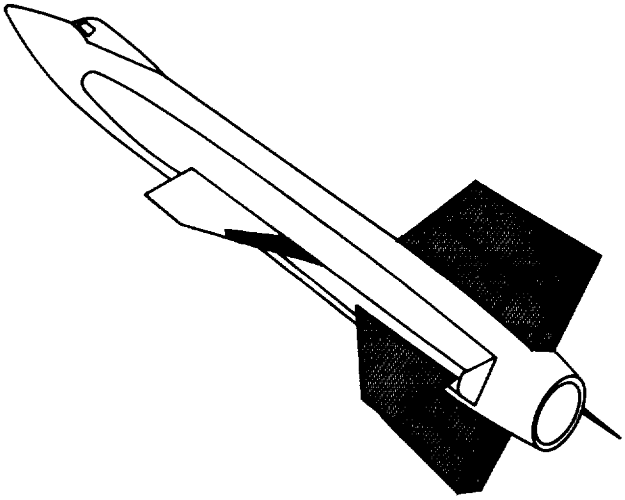


Figure 7

AREAS AFFECTED BY PANEL FLUTTER

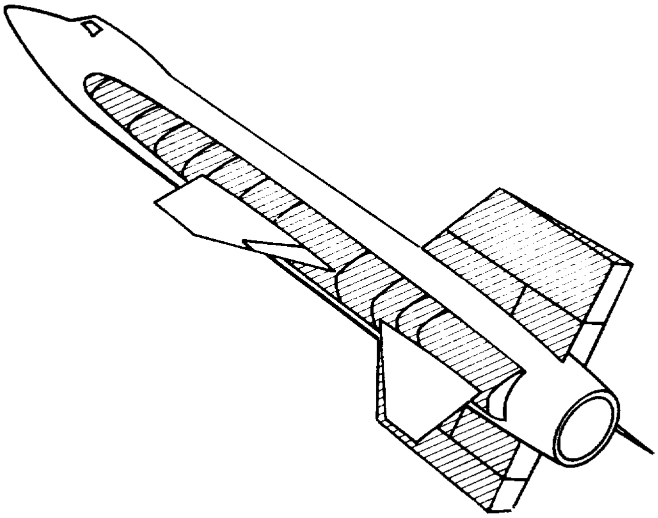


Figure 8

STRUCTURAL MODIFICATION FOR PANEL FLUTTER

SIDE FAIRING

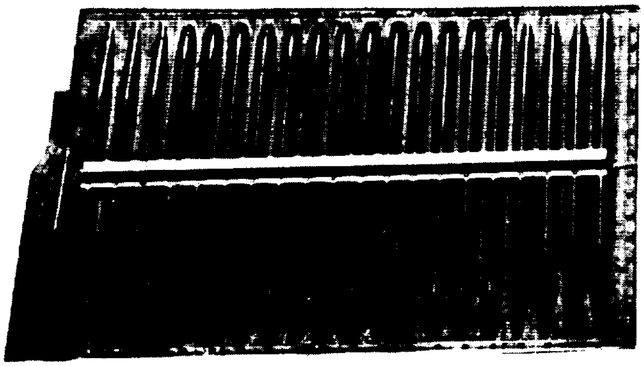


Figure 9

PANEL FLUTTER

FLAT PANELS

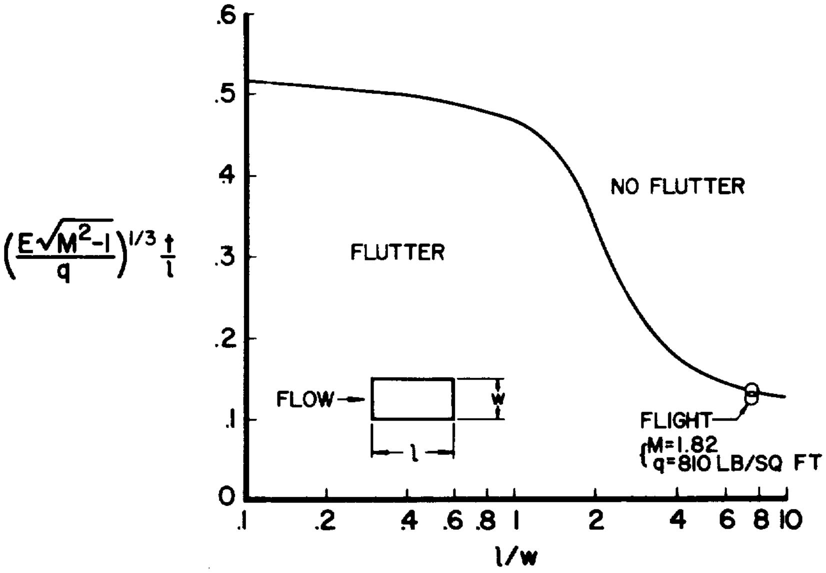


Figure 10

STRUCTURAL MODIFICATION FOR PANEL FLUTTER

VERTICAL TAIL

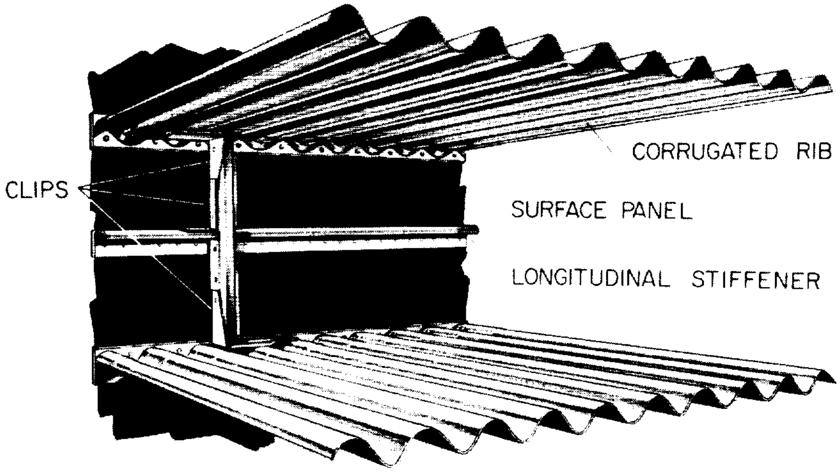


Figure 11

NASA-Langley, 1962 H-281