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UNSTEADY AERODYNAMICS

By

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SUMMARY

This study briefly describes some of the problem areas in the Saturn launch vehicle development program that are related to unsteady phenomena. The two principal types of unsteady phenomena are self-excited phenomena and externally excited phenomena. Self-excited phenomena consist of panel flutter, body flutter, and fin flutter. Studies conducted in this area show that strong influences are exerted by the boundary layer. Concurrently, studies are being made to calculate the nonlinear and the linearized inviscid flow over pulsating and stationary wavy-walled surfaces.

The following three methods have been initiated for predicting aerodynamic damping: a linearized unsteady potential equation based upon a generalized Adams-Sears iteration process; a linearized method of characteristics solution for slowly oscillating pointed bodies of revolution that are of arbitrary profile and that are in supersonic flow; and a nonlinear method of characteristics solution.

Externally excited phenomena consist of buffeting loads, noise problems, and meteorological environment, such as wind gusts and atmospheric turbulence. Research to determine the power-spectral characteristics of various buffeting regions is in process. Theoretical studies are also being made on the relative contribution of regions of high-entropy production in the exhaust stream to the overall intensity, propagation, and directivity characteristics of the radiated acoustic energy.

I. INTRODUCTION

Unsteady aerodynamics are airflows that are time dependent and that may produce a dynamic response of the vehicle structure or control system. A characteristic feature of these response problems is that comparatively small aerodynamic forces may produce a very large or even catastrophic dynamic response. Aircraft wing flutter and the Tacoma Narrows Bridge failure are typical examples.

Unsteady phenomena can be divided into the general classes of self-excited and externally-excited phenomena. Self-excited phenomena shall consist of:

- (a) Panel flutter.
- (b) Body flutter.
- (c) Fin flutter.

Externally excited phenomena shall consist of:

- (a) Buffeting loads.
- (b) Noise problems.
- (c) Meteorological environment, such as wind gusts and atmospheric turbulence.

The primary objective of this study is to describe the efforts to provide an accurate description of unsteady aerodynamic forces to be used to furnish input information to the structures' and control systems' designer. No established procedures exist for determining an unsteady aerodynamic environment in connection with space vehicles or missiles. Therefore, this study is primarily of a research nature. However, these research results should be converted into useful design information as soon as possible.

II. PANEL FLUTTER

Panel flutter is the self-excited oscillation of a panel in a flow under the action of aerodynamic forces generated by the panel motion. The possibility of panel flutter was suspected in the early phases of the V-2 development. Since then, experiments have shown conclusively that flutter of surface skin panels can exist. Wind-tunnel tests showed that a traveling, wave-type, flutter condition caused panel failure within a period of a few seconds [1]. Recently, panel flutter occurred on the X-15 airplane as shown in Figures 1 and 2. In general, structural nonlinearities tend to limit the flutter amplitudes and, therefore, cause the modes of structural failure to be related to

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fatigue rather than to the explosive fracture of the skin surface. However, it is quite dangerous to regard panel flutter only as a fatigue problem. Tests of the corrugation stiffened X-15 panels, e. g., revealed that flutter was very sudden and very severe. The panels failed unless flutter was stopped within a period of a few seconds.

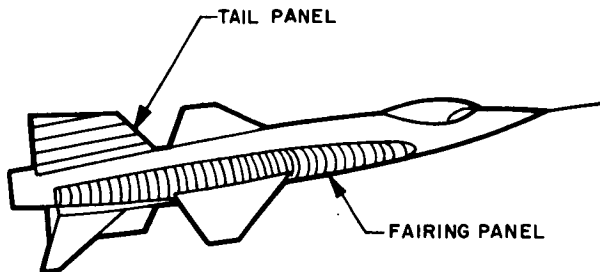


FIGURE 1. REGIONS OF X-15 RESEARCH AIRCRAFT AFFECTED BY PANEL FLUTTER

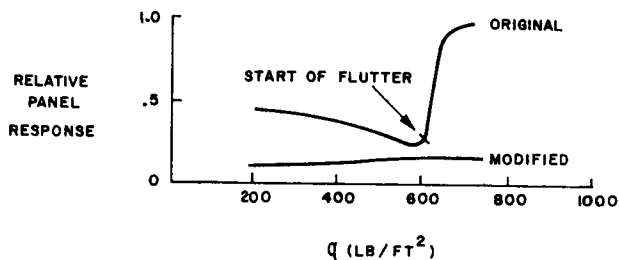


FIGURE 2. VARIATION OF PANEL-RESPONSE ENVELOPE WITH DYNAMIC PRESSURE OBTAINED FROM FLIGHT MEASUREMENTS ON AN X-15 SIDE-FAIRING PANEL

For this reason, it was considered necessary by the Aero-Astrodynamics and the Propulsion and Vehicle Engineering Laboratories to test the hat sections of the Saturn-IC stage. These tests, which were carried out by Boeing personnel in the Ames Research Center (ARC) 2- and 11-foot (0.61- and 3.35-m) tunnels, demonstrated the strong influence exerted by the boundary layer.

Theoretical flutter calculations are based upon inviscid linearized flow theory. Only recently has the need for taking into account the effect of the viscous boundary layer been recognized. For this reason, the Unsteady Aerodynamics Branch has initiated a cooperative research program with ARC

and Georgia Institute of Technology to study the influence of the boundary layer on panel flutter. A decision was made to first explore the stationary flow over wavy-walled surfaces for varying boundary layer thicknesses. The first test in this program was scheduled for January 1966 at the ARC 2-foot (0.61-m) tunnel. The Mach number range to have been explored was $0.8 < M < 1.6$. Concurrently, theoretical inhouse studies are being carried out to calculate nonlinear and linearized inviscid flow over pulsating and stationary wavy-walled surfaces [2].

III. AERODYNAMIC-DAMPING STUDIES

As a result of the increased flexibility of the launch vehicles in the Saturn class, it has become necessary to investigate the aerodynamic damping characteristics of these vehicles during flight in the first three bending modes. Theoretical approaches to predict the aerodynamic damping are especially important because the simulation of elastic vehicle response in a wind-tunnel test is very complicated, and the results of this expensive test may be of limited value because of the wind-tunnel noise and the model-mount interference. Another factor in favor of the theoretical approach is that the elastic model usually necessitates a lead time of 1 year. Consequently, the test results become available when the vehicle design has been frozen.

For these reasons, the Unsteady Aerodynamics Branch tried to formulate theoretical approaches to predict the aerodynamic damping. These theoretical approaches had to be based upon inviscid attached flow concepts in order to make the problem mathematically tractable. So far, the following results have been obtained:

- (a) A solution of the linearized unsteady potential equation has been worked out based upon a generalized Adams-Sears iteration process. This work is now complete [3] and Figure 3 shows one result that demonstrates the influence of body shape and Mach number upon the pitch damping coefficient.
- (b) A linearized method of characteristics solution is presently being investigated for slowly oscillating pointed bodies of revolution that are of arbitrary meridian profile and are in supersonic flow. This method is an extension of the Oswatitsch-Erdmann characteristics method. Preliminary results for the steady case show a wide applicability [4].

(c) A nonlinear method of characteristics solution is being investigated by the Massachusetts Institute of Technology (MIT). This approach is based upon the superposition of small time-dependent angle of attack perturbations on a nonlinear axisymmetric flow field that is determined by the method of characteristics. Good results have been obtained for the oscillating cone [5].

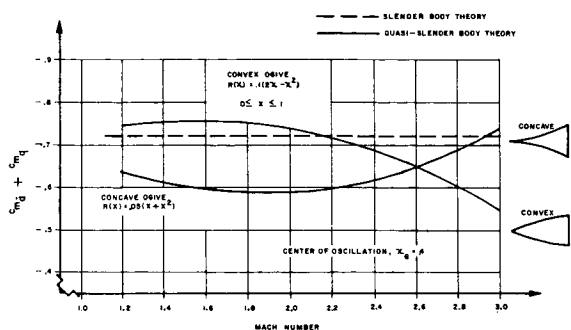


FIGURE 3. EFFECT OF MACH NUMBER ON FIXED AXIS DAMPING IN PITCH MOMENT COEFFICIENT FOR CONVEX AND CONCAVE PARABOLIC OGIVE OF THICKNESS RATIO 0.1

Calculation of damping characteristics, which are based upon attached flow concepts, are not sufficient for most of the current launch vehicle configurations. Blunt nose cones and steep interstage flares, which have become characteristic of space boosters, produce large regions of flow separation that dominate the aerodynamic loading over the vehicle in the transonic and the supersonic speed range, as shown in Figure 4. As a result, it has become necessary to take into account separated flow effects upon aerodynamic damping. The success of an analytical and experimental method of dynamic analysis of the Atlas-Able launch vehicles [6] suggested a possible adaptation to the Saturn launch vehicle configuration. This method is based upon the assumption that the total lift force on any part of the vehicle consists of the following components:

- (a) Local lift, which is lift due to local motion at time t .
- (b) Induced lift, which is lift induced by the wake created at the nose at time $t - \Delta t$.

This suggests that local lift is always in phase with the lateral vehicle motion and that induced lift is out of phase by the time lag Δt . These two assumptions make it possible to determine aerodynamic damping from static wind-tunnel tests thus eliminating

expensive elastic model tests. This procedure is being applied to the various Saturn launch vehicle configurations.

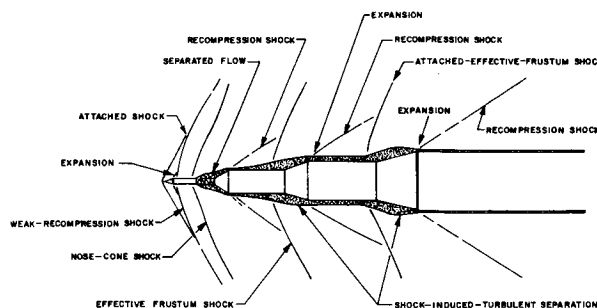


FIGURE 4. FLOW FIELD ABOUT TYPICAL SATURN SERIES VEHICLE

IV. BUFFETING

Buffeting is the pressure oscillation caused by separated flow. The launch vehicle interstage areas may cause intensive fluctuating pressures, and, consequently, severe structural loads as shown in Figure 5. In the separated flow region shown in Figure 5, a slowly circulating reverse flow exists, overlain by a free-shear flow. The highest fluctuating pressure levels are found to occur at the point of flow separation and reattachment. Current research is devoted to the determination of the power-spectral characteristics of these buffeting regions. The Unsteady Aerodynamics Branch has several research programs to analyze this problem. Perhaps the most significant program in this field is the protuberance wind-tunnel test which is being carried out in cooperation with ARC. This program is currently in the data reduction process and the results should be available in the near future.

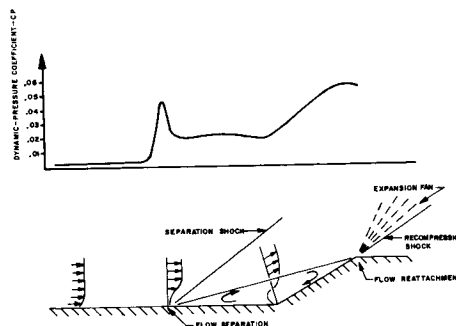


FIGURE 5. TYPICAL FLUCTUATING PRESSURE ENVIRONMENT FOR VEHICLE INTERSTAGE TYPE GEOMETRIES

V. ENGINE-GENERATED NOISE

Research in the field of engine-generated acoustics has been directed towards the determination of the predominant noise generation mechanisms in high-temperature, rocket exhaust flows. Present investigations include theoretical studies of the relative contribution of regions of high entropy production in the exhaust stream to the overall intensity, propagation, and directivity characteristics of the radiated energy. This work is being supplemented by experimental rocket exhaust studies using a substitute gas to simulate the predominant flow characteristics of the H-1 engine at a considerably lower temperature, thus allowing measurements to be made in the flow.

VI. GROUND-WINDS PROBLEM

A launch vehicle erected on the launch pad before liftoff is exposed to surface winds that may generate large dynamic loads under certain circumstances. Downstream from the body, a wake flow is created that is Reynolds number dependent and has characteristics which are difficult to describe mathematically. In certain cases, the well known Karman vortex street is obtained. At the higher Reynolds numbers, the vortex shedding is very dependent upon the type of flow in the vicinity of the body (laminar or turbulent boundary layer). Therefore, a distinction must be made between subcritical and supercritical flow regimes. Insufficient understanding of the mechanisms involved and lack of reliable calculation methods force most investigators to extract the aerodynamic forcing function from an analysis of the aeroelastic response of various launch vehicle configurations. The Unsteady Aerodynamics Branch has initiated an extensive wind-tunnel program on the different Saturn I, IB, and V configurations. Most of these tests are conducted at the Langley Research Center (LRC) and require aeroelastic models of about 5-percent scale. Unfortunately, for the Saturn V configuration, a full-scale Reynolds number cannot be simulated, thus introducing a further degree of uncertainty. Typical vehicle responses are shown in Figures 6 and 7. In both figures the vehicle base bending moment, because of steady drag, dynamic drag, and dynamic lift, is plotted versus the wind velocity. A typical noncritical response is shown in Figure 6, while a typical critical response due to dynamic lift at a specific wind velocity is shown in Figure 7.

The critical response is of primary concern to the vehicle designer since it may impose exceedingly high loads upon the vehicle. Unfortunately, the reason for the occurrence of such a critical response is little understood. The possibility for self-excited vibrations cannot be excluded at this time. Therefore, a cooperative research program between LRC, MSFC, and the Martin Company was formulated to investigate the aerodynamic forces on oscillating two-dimensional cylinders. These tests were conducted recently at LRC and the data are in the process

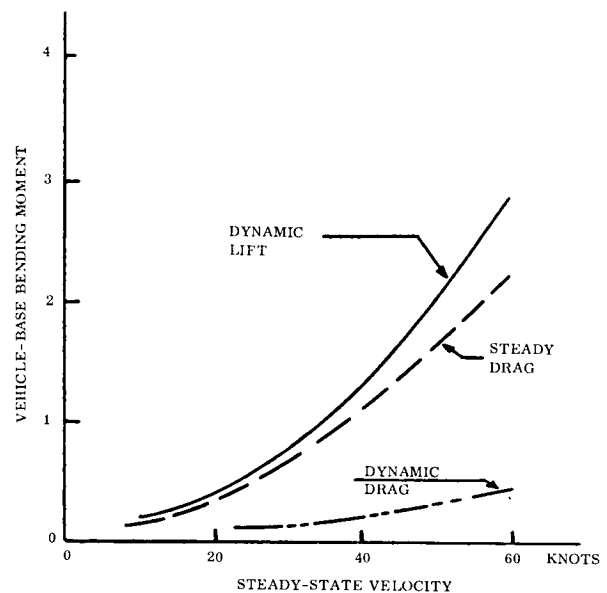


FIGURE 6. TYPICAL NON-CRITICAL RESPONSE

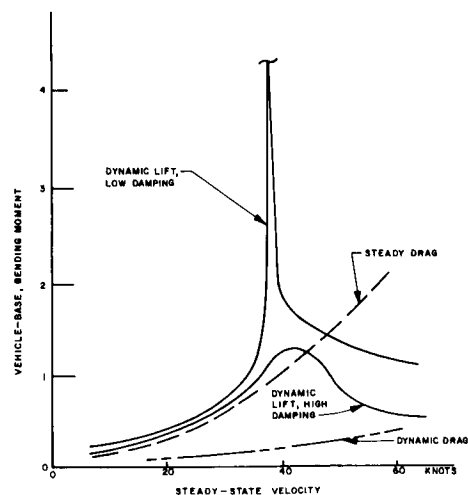


FIGURE 7. TYPICAL CRITICAL RESPONSE

of evaluation. This experimental program is being supplemented by an analytical studies program that should provide a better understanding of the basic flow-field characteristics.

Unsteady aerodynamic effects present the launch vehicle designer with a series of important and challenging problems. Since these phenomena are little understood, a continuous and vigorous research effort is required.

VII. CONCLUSIONS

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