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COMPUTATIONAL UNSTEADY AERODYNAMICS FOR AEROELASTIC ANALYSIS

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Summary

This report summarizes the status of computational unsteady aerodynamics methods for aeroelastic analysis and makes recommendations for future research activities. The flight conditions for which various types of flows exist are described and the aeroelastic phenomena that can occur in those flight regimes are discussed. Some important aeroelastic problems of current interest are described, and the aerodynamic methods needed to analyze them are presented. The capabilities and limitations of existing unsteady aerodynamics methods are discussed. Computer resources required to perform aeroelastic analysis of various flight vehicle configurations are presented. Recommendations for future research are made, and schedules for completion of proposed research tasks are presented.

Introduction

Computational aerodynamics is rapidly becoming an important tool in the design of flight vehicles. It allows computer simulation of flows past configurations that previously would have required large budget and personnel resources to determine the flows experimentally. In addition, many design options can be examined using computational methods. To model the flow past flight vehicles, today's engineer must choose from a range of options based upon available computer capacity and budget. The choices range from the calculation of the flow past a relatively complete description of the entire aircraft using lower order approximations to the equations of fluid flow to the calculation of the flow past less complex representations of the vehicle, such as the wing only, using higher order flow equations.

Flow models can be grouped into lower order potential flow models--full potential (FP) and transonic small disturbance (TSD) potential--and the higher order models typified by various approximations to the Navier-Stokes equations--the parabolized, thin layer, and Reynolds averaged approximations. The intermediate Euler equations flow model is obtained from the Navier-Stokes equations by neglecting the viscous terms.

This paper presents some current aeroelastic problems of interest to the aerospace community and the computational aerodynamics methods available for simulating flow fields and analyzing aeroelastic phenomena. This is followed by a discussion of the capabilities of existing methods and the computer resources required to use those methods for aeroelastic analysis. Finally, recommendations for future research directions and schedules for completion of proposed tasks are presented.

Current Aeroelastic Problems

This section describes some of the aeroelastic phenomena that have been observed on modern aircraft and the nature of the flows involved. The aerodynamic methods necessary to analyze each type of aeroelastic response are discussed.

Figure 1 shows the characteristics of attached, mixed, and separated flow for complete aircraft at free stream Mach numbers between 0 and 2.0. In region I, the flow is predominantly attached. To obtain optimum performance and to avoid the drag penalty associated with flow separation, design cruise conditions for aircraft typically are located in region I, near the boundary of region II (mixed flow).

As speed and/or angle of attack increases, a transition region of mixed flow (region II of fig. 1) is encountered. For rigid structures, this region is typified by the onset of localized regions of flow separation which may exhibit significant aerodynamic unsteadiness. For realistic, flexible structures, the aeroelastic response of the structure interacts with the airflow to induce much more complicated situations. Structural vibrations can cause the flow to alternately separate and reattach at flow conditions where a rigid structure would support attached flow. The associated highly unsteady aerodynamic loading can interact with the structural dynamic response to cause unusual aeroelastic phenomena which may restrict the vehicle flight envelope.

With further speed and/or angle of attack increases which are encountered under maneuvering conditions, stable separated flow conditions emerge (region III of fig. 1). Leading-edge vortex flows and shock-induced separated flows are of this nature. At still higher angles of attack, vortex bursting is encountered. Within such regions, the flow is highly unsteady, requiring careful attention to turbulence modeling.

While predictive methods for attached flows are reasonably well developed, the picket fence in fig. 1 emphasizes the difficulty in predicting aeroelastic phenomena in the mixed and separated flow regions. It also symbolizes novel features that are being encountered in transonic flutter testing. Modern high performance aircraft are capable of maneuvering at transonic speeds, leading to a much enlarged parameter space for flutter clearance. Wing/store loading, speed, angle of attack, wing shape, altitude and wing sweep all must be considered, and the traditional flutter boundary parameterization of dynamic pressure at flutter versus Mach number may need to be augmented to adequately describe aeroelastic stability boundaries. For instance, flutter tests give some indication that these additional parameters affect the detailed aeroelastic stability condition near the flutter boundary. Thus, the pickets of the fence in fig. 1 represent isolated regions of instability and low damping that may be encountered.

Key Aeroelastic Problems

The mathematical formulation that is used to model the flow is determined by the problem that is to be solved. The flow may be modeled using a velocity potential equation, the Euler equations, or a form of the Navier-Stokes equations. Problems of current interest include (1) aircraft operating at maximum speed at design conditions, (2) aircraft operating in attached/mildly separated flow conditions, and (3) maneuvering, high-performance aircraft where vortex/shock-induced separated flows at high dynamic pressures define the flutter-critical conditions.

To impact the design of modern aircraft, new methods should provide accurate predictions of nonclassical flutter features such as those observed near the edge of the flutter envelope, and vortex flow interactions with vertical tails which severely limit structural lifetime. These methods also should provide a means for modeling the effects of active controls. Enhancing the computational aeroelastic analysis capability will result in opportunities to examine key aeroelastic problems, including the minimum in flutter boundaries usually observed at transonic speeds (the transonic "flutter dip"), the DAST ARW-2 nonclassical aeroelastic response, wing/store limit amplitude flutter, vortex induced oscillations of the B-1 wing, and vertical tail buffet on twin-tailed fighters.

Figure 2 shows a traditional flutter boundary of dynamic pressure at flutter versus Mach number. The boundary tends to decrease with increasing Mach number for subsonic speeds, reaching a minimum in the transonic speed range, followed by a rapid increase. Such boundaries are usually established for straight and level, trimmed flight conditions. The boundary shown in fig. 2 represents "hard" flutter conditions typified by divergent structural oscillations that lead to structural failure. For subsonic speeds, attached flow conditions prevail (region I, fig. 1) and linear aerodynamic methods have been used quite successfully. As speed increases into the transonic regime, the flutter boundary deviates from that predicted with linear methods, which can become unconservative. The minimum of the flutter boundary is associated with the formation of shock waves and the onset of flow separation, typical of flow in region II. This minimum is a critical condition for flutter analysis and represents a primary challenge for computational aeroelastic analysis. A key question is the level of flow model required to predict this minimum flutter speed accurately. It is very likely that many cases may be treated using an inviscid flow method (i.e. a potential or Euler equation code) coupled with a viscous boundary layer method.

The nonclassical aeroelastic response of the DAST ARW-2 is illustrated in fig. 3. This is a region of high dynamic response at constant Mach number encountered at dynamic pressures well below those for which flutter was predicted. The motion is of the limit-amplitude type, and the response is believed to be associated with flow separation and reattachment over the supercritical wing, again a region II flow condition. Interacted viscous/inviscid methods may treat the types of flows associated with this response and may be used in the aeroelastic analysis.

Wing/store limit amplitude flutter is experienced by modern, high performance aircraft under various loading and maneuvering conditions at transonic Mach numbers, resulting in vehicle placards on performance. The conditions for which this response occurs are shown in fig. 4. The flow is characterized by mixed flow--region II-- over portions of the wing surfaces. Thin layer Navier-Stokes methods can model the flows characteristic of region II and may be required to calculate wing/store limit-amplitude flutter.

Vortex-induced oscillations observed on the B-1 wing occur for high wing sweep angles, during wind-up turn maneuvers. The flow is of the type in region III. The instability is of the first wing bending mode type and occurs over a wide Mach number range (0.6 - 0.95) at angles of attack 7-9 degrees. The range of conditions for which this phenomenon occurs is shown in fig. 5. A Reynolds-averaged Navier-Stokes method can model the stable, separated flows associated with this instability and may be used to calculate the vortex-induced oscillations.

Tail buffet on twin-tail fighters occurs when a vortex encounters downstream lifting surfaces, horizontal and vertical tails, causing structural fatigue. This type of aeroelastic response occurs when aircraft operate in flows characteristic of region III. Figure 6 shows the operating conditions for which tail buffet occurs. Buffet of horizontal tails can occur at intermediate angles of attack and is a result of an unburst vortex encountering a lifting surface. As angle of attack increases, the location of vortex bursting moves upstream in the wake. Loss of lift is associated with the burst location reaching the vicinity of the aircraft, and vertical tail surfaces located in such regions experience severe dynamic loads. Typically, this occurs at angles of attack of approximately 30 degrees. Navier-Stokes methods with more sophisticated turbulence models than are currently available are needed to analyze these responses. This is because the burst vortex phenomenon involves massive separation and large-scale unsteadiness. Current turbulence models are not valid for such flows.

Aerodynamic Methods

Various aerodynamic methods are available to analyze the aeroelastic phenomena discussed above. They range from potential flow codes for complete aircraft to Navier-Stokes methods for airfoils and wings. Table I provides a summary of current research activities in computational unsteady aerodynamics at the NASA Langley Research Center (LaRC). The discussion below details the methods and the types of problems to which they are applicable.

Potential Flow Methods

These methods provide a realistic opportunity to develop design and analysis capabilities for complete aircraft. They are applicable only to aircraft operating in attached flow (region I). Current potential flow capability includes the XTRAN3S (ref. 1) and CAP-TSD (Computational Aeroelasticity Program-Transonic Small Disturbance) (ref. 2) codes. The XTRAN3S code solves the transonic small disturbance (TSD) potential equation and was developed for analysis of isolated wing configurations. Extensive modifications to the code have enabled the analysis of either wing/fuselage or wing/canard (tail) configurations. The CAP-TSD code was developed by the Unsteady Aerodynamics Branch (UAB) at Langley and can be used for aeroelastic analysis of complete aircraft. As an example, ref. 2 gives the details of modeling an F-16 aircraft, including the wing, strake, tail, fuselage, tip launcher, and tip missile.

Methods based on TSD theory are valid for thin bodies at small angles of incidence undergoing small amplitude unsteady motions. In addition, the flow equations are derived assuming that the free stream Mach number is near unity. Thus, full potential (FP) methods are being explored. The state-of-the-art differencing method for calculating unsteady full potential flows was developed by UAB personnel with two university researchers (refs. 3-5). This method is based on differencing the flux function. It is an improvement upon previously-used methods since the flux-differencing method (a) accurately tracks sonic conditions and requires no empirical constants to specify the amount of artificial viscosity, (b) produces no velocity overshoots at shock waves, allowing for larger time steps and increasing computational efficiency for unsteady calculations, (c) produces well-defined shock waves with a maximum two point transition between upstream and downstream states, and (d) dissipates expansion shocks, ruling out solutions with such nonphysical characteristics. Flux differencing was implemented in an approximate factorization algorithm to yield a two-dimensional unsteady full potential code (ref. 5). This algorithm and the algorithm used in CAP-TSD are similar.

It has been shown that when shock waves are in flow fields modeled using potential flow methods, the calculated loads can be highly inaccurate and even multivalued (refs. 6-9). This is because the entropy generated by shock waves is not modeled in the isentropic formulation of potential flow aerodynamics. Methods have been developed to modify isentropic potential theory at the 2-D and 3-D TSD levels (refs. 8,9) and at the 2-D FP (ref. 5) level. Calculations of attached flows with strong shocks indicate that the modified potential methods improve the accuracy of and extends the range of validity of potential flow solutions (refs. 5,8,9). The method used in ref. 5 for 2-D FP calculations can be applied in three dimensions.

Euler/Navier-Stokes Methods

Navier-Stokes methods are needed to analyze aeroelastic phenomena that occur in mildly separated (region II) and fully separated flows (region III). Steady flow codes have been developed by the Analytical Methods Branch at Langley. The CFL2D code (ref.10) is used for 2-D flows, and the CFL3D code (ref. 11) is used in three dimensions. The CFL2D and CFL3D codes are the most efficient and stable of existing codes for solving the Navier-Stokes equations. These codes use upwind differencing with flux-vector splitting to achieve unconditionally stable algorithms. Solutions of the Euler equations are obtained from the Navier-Stokes codes by neglecting the viscous terms. Although viscous effects are neglected, which limits applicability to region I, the Euler equations can accurately model flows containing curved shock waves and vorticity convection. Recently, the CFL2D and CFL3D codes were modified to allow the calculation of time-accurate unsteady solutions. Euler calculations for oscillating airfoils and wings have been obtained (ref. 12). These unsteady codes are available to be used in aeroelastic analysis.

Interacted Viscous/Inviscid Methods

Since inviscid flow methods--potential and Euler--are limited to the attached flow regime, it is necessary to interact the solutions with viscous boundary layer methods to allow analysis of mildly separated flows. Coupling viscous boundary layer methods with inviscid flow codes results in a capability for more accurately resolving some aeroelastic phenomena. In particular, accurate definition of the transonic "flutter dip" and calculation of the nonclassical aeroelastic response observed for the DAST ARW-2 are among the problems that may be treated with this capability. Available boundary layer methods include one with which mildly separated flows can be modeled (ref. 13). This method has been tested, in a quasi-steady manner, in the 2-D unsteady TSD code XTRAN2L (ref. 14). Implementation in CAP-TSD, in a quasi-steady, 2-D strip fashion, is underway. These methods also can be coupled with full potential and Euler methods. Coupling Euler and viscous methods provides a means for calculating separated flows, for some cases, as well as attached and mildly separated flows. For some cases, it may be necessary for a vortex tracking method to be coupled with the flow solver.

A contracted effort supported by UAB to develop a finite difference computer code for solving the unsteady 3-D boundary layer equations is nearing completion. When complete, it will provide a 3-D viscous boundary layer method (ref. 15) that is more accurate than those currently available.

Vortex Flow Methods

The development of methods for treating leading edge vortex flows is being supported by UAB with a university grant. A hybrid vortex method (ref. 16) that can be used to predict vortex flows arising from leading edge separation on wings at high angles of attack has been developed. In this method, the full potential equation is solved over most of the flow field using integral equation methods. Regions of the flow containing strong shock waves or vortices are treated by solving the Euler equations.

Euler methods may be used for the analysis of vortex flows arising from separation at sharp edged wings at moderate angles of attack. In order to predict the separation line on round-edged wings, solutions of the Navier-Stokes equations are required. Research in these areas is being pursued under a university grant supported by UAB (ref. 16).

Computer Resource Requirements

This section discusses the computer resources required to analyze aeroelastic phenomena using various aerodynamic methods. The resources required for analysis of a complete aircraft and a wing/body/canard configuration are presented.

The computer resources required to calculate a single flutter point for a complete aircraft using TSD and Navier-Stokes methods are shown in Table II. The required resources are presented as central processing unit (CPU) time on the Control Data Corporation VPS-32. Required CPU times are obtained assuming that a flutter point can be determined by calculating a steady, loaded condition and three aeroelastic responses at varying dynamic pressures to determine neutral stability and that the steady condition and each response can be calculated in 1000 time steps. The time for the TSD calculation is obtained using the computation speed for actual CAP-TSD calculations--2.7 microseconds per grid point per time step. This works out to 2.3 hours of CPU time per flutter point. This problem requires approximately 30 million of the 32 million words of memory available with the VPS-32. When calculating symmetric aeroolastic responses, a half-span model can be used, with a proportional decrease in required memory and CPU time. For run times of this length, turnaround times on the VPS-32 can be expected to be quite long. Thus attention to ways of automating the calculation of flutter points is needed. One such method has been developed at UAB and implemented with a 2-D TSD method (ref. 17). Use of a FP method would increase the computer resource requirements by 50-100 percent, while Euler methods are approximately 2-5 times more expensive than FP methods. The time for the Navier-Stokes analysis in Table II is calculated from the following relationship

$$\text{TIME} = (\text{GRID PTS}) \times \frac{\text{OPS}}{(\text{GRID PTS} \times \text{ITER})} \times (\text{ITER})/(\text{OPS/SEC})$$

Computer speeds of 100 million floating point operations per second (MFLOPS) and 1000 operations per grid point per time step are assumed. For Reynolds number of 10 million, 77.8 hours of VPS-32 time is required to calculate a single flutter point. This points out that routine aeroelastic analysis of complex configurations using Navier-Stokes aerodynamics is not feasible using the VPS-32.

Table III shows the CPU times required to calculate a flutter boundary for a wing/body/canard (tail) configuration with increasingly complex aerodynamic methods. The boundary is assumed to consist of flutter points at ten Mach numbers with each point requiring the calculation of a steady, loaded condition and three aeroelastic responses. The steady condition and each response can be calculated in 1000 time steps. The computation speed on the VPS-32 is assumed to be 100 MFLOPS, and that on the NAS is taken to be 250 MFLOPS. Computational grids for the TSD, full potential, and Euler calculations are assumed to have 750 000 points, and its estimated that a grid with 14.5 million points is required for the Navier-Stokes calculations. Also, it is assumed that the TSD calculations require 200 operations per grid point per time step, the full potential calculations require 300 operations per grid point per time step, the Euler calculations require 600 operations per grid point per time step, and the Navier-Stokes calculations require 1000 operations per grid point per time step. The times shown for the TSD and full potential calculations are 180 percent of the inviscid flow times. The 80 percent increase in run time (compared to inviscid calculations) has been observed for potential flow coupled with boundary layer methods (ref. 13). Coupling a boundary layer method with an Euler solution increases the required CPU time by approximately 30 percent. Thus the times shown in Table III for the Euler solutions are 1.3 times the inviscid Euler requirements. Because of the differences in the multiplicative factors--1.8 versus 1.3--the ratio of required times for Euler and TSD solutions decreases. The TSD method with boundary layer can be used for problems in region I and for some problems in region II. Using this flow model, 30 hours and 12 hours on the VPS-32 and NAS, respectively, are required to define a flutter boundary. Full potential with boundary layer also can be used in regions I and II. Estimated CPU requirements are 45 hours on the VPS-32 and 18 hours on NAS. An Euler method with viscous modeling can be used in regions I and II and for some problems in region III. Sixty-five hours of VPS-32 time and 26 hours of NAS time are required to define the flutter boundary using this flow model. Navier-Stokes methods can be used in regions II and III. At a Reynolds number of 100 million, 1611 hours on the VPS-32 and 644 hours on NAS are required to calculate the flutter boundary. Sufficient experience with NAS has not been obtained to make a judgement on turnaround time, but it is expected to be significantly better than that experienced with the VPS-32. However, for the simplest of flow models, the computer requirements will not allow routine analysis of complex aircraft configurations. Future generation supercomputers are required to predict aeroelastic responses of complex configurations.

Recommendations

The development of computational aeroelastic methods should proceed on two fronts--at the Euler/Navier-Stokes level and at the potential flow level. The CFL2D and CFL3D codes for solving the unsteady 2-D and 3-D Euler/Navier-Stokes equations are available in the NASA Langley Computational Fluid Dynamics Laboratory. The CFL2D code (Navier-Stokes option) presently is being used to correlate with unsteady pressure data measured at transonic speeds, cryogenic temperatures, and Reynolds numbers up to 35 million (ref. 18). Results from the unsteady CFL3D code (Euler option) are being compared with results from unsteady TSD codes.

RECOMMENDATION: INCORPORATE THE AEROELASTIC ANALYSIS METHODS INTO AVAILABLE EULER/NAVIER-STOKES CODES.

Since the aerodynamic codes are available, this effort should proceed immediately. This will allow analysis of some aeroelastic phenomena where vortex and separated (mixed) flows are important. Such problems of current interest include the DAST ARW-2 nonclassical flutter response, wing/store limit amplitude flutter, and B-1 vortex-induced oscillations. There will be limitations of the resulting method. One of the most important is the limitation of turbulence models. Present turbulence models yield poor results for flows in which 3-D effects are important and do not do a good job in regions of massive separation, large-scale unsteadiness, and transition from laminar to turbulent flow. Aeroelasticians are dependent upon aerodynamicists to develop turbulence models that are valid in these regions. Until this is accomplished, aeroelastic phenomena such as those due to vortex bursting cannot be modeled accurately using existing Navier-Stokes methods. Problems of current interest that fall into this category include vertical tail buffet of twin-tail fighters.

Euler/Navier-Stokes codes currently are too expensive to use for routine aeroelastic analysis. For a large class of problems, potential flow or potential flow/boundary layer is adequate. An effort is needed to determine when the Euler/Navier-Stokes methods are needed. The only way to accomplish this is to construct a full potential code for evaluation purposes.

RECOMMENDATION: DEVELOP AN AEROELASTIC ANALYSIS CAPABILITY BASED ON THE FULL POTENTIAL FLOW EQUATIONS.

A logical step is to extend the FP method discussed above to three dimensions. It would be an improvement upon TSD methods because of improved accuracy of the calculated aerodynamic loads. Full Potential methods can be used for analysis of thick, blunt bodies such as blended wing/fuselage configurations that are characteristic of Advanced Technology Fighters. Because grids used in unsteady FP methods can follow the vehicle motion, body boundary conditions are applied at the instantaneous surface locations. In TSD methods, the boundary conditions are applied on mean surfaces that must not be much different than the actual surfaces. Thus, FP methods should be useful in predicting aeroelastic responses that involve larger amplitude motions.

This should be done by developing a CAP-FP code that, initially, treats isolated wings. The resulting code can be used to evaluate the advantages of FP over TSD methods without developing a complete aircraft code. If it is determined that those advantages warrant further development of FP methods, a code for complex configurations should be developed. This capability should be developed in conjunction with the development of Euler/Navier-Stokes aeroelastic analysis capability.

RECOMMENDATION: COMPLETE DEVELOPMENT OF TRANSONIC SMALL DISTURBANCE CODE FOR COMPLETE VEHICLE AEROELASTIC ANALYSIS.

This code will provide the first capability for complete vehicle computational aeroelastic analysis. The initial goal should be to use the TSD code for analysis of vehicles in level flight at maximum speed. At such conditions, aircraft operate in attached flow (region I) or attached flow with mildly separated regions (region II).

The TSD and FP methods should be augmented by including nonisentropic effects. In addition, the inviscid flow methods (potential and Euler) should be coupled with direct and inverse boundary layer methods.

A list of activities directed at accomplishing these recommendations is shown in Table IV. Correlation of CFL2D with transonic cryogenic data is underway. This will serve to validate this higher equation level code for unsteady flow about oscillating airfoils. In parallel with this effort, initial calculation of flutter of an isolated wing using Navier-Stokes aerodynamics is proceeding. In addition, a full potential code for the analysis of isolated wings is under development which will be used to evaluate the utility of such a code for more complex configurations. The initial version of CAP-TSD (Version 1.0) including nonisentropic and vorticity corrections is available, and a version with viscous boundary layer modeling (Version 2.0) is under development.

Conclusions

The status of computational unsteady aerodynamics methods for aeroelastic analysis is summarized and recommendations for future research activities are made. Aeroelastic problems of current interest are discussed. These include (a) the minimum flutter speed, (b) the nonclassical aeroelastic response of the DAST ARW-2, (c) wing/store limit amplitude flutter, (d) vortex-induced oscillations on the B-1 wing, and (e) tail buffet of twin-tail fighters. The aerodynamic methods available to analyze various aeroelastic phenomena and the computer requirements to use those methods are discussed. The requirements for aeroelastic analysis of complex configurations using even relatively simple flow models are quite restrictive. Recommendations for future research activities include (a) incorporating aeroelastic analysis methods into available Euler/Navier-Stokes codes, (b) developing a pilot full potential code, and (c) completing development of a transonic small disturbance code for complete vehicle aeroelastic analysis.

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TABLE I. CURRENT LaRC ACTIVITIES IN COMPUTATIONAL UNSTEADY AERODYNAMICS

CONFIGURATION / EQUATION LEVEL	AIRFOIL	WING	WING/BODY	COMPLETE AIRCRAFT
TRANSONIC SMALL DISTRUBANCE		X	X	X
FULL POTENTIAL		X	X	
EULER/NAVIER-STOKES	X	X		

TABLE II. COMPUTER RESOURCE REQUIREMENTS TO DETERMINE FLUTTER POINT AT A SPECIFIED MACH NUMBER

(4000 TIME STEPS PER FLUTTER POINT)

CONFIGURATION	FLOW MODEL	GRID POINTS	CPU HOURS (VPS-32)
COMPLETE AIRCRAFT	TSD	0.75M	2.3*
COMPLETE AIRCRAFT	FULL NAVEIR-STOKES (RE = 10 MILLION)	7.00M	77.8**

*BASED ON ACTUAL CASES

**ASSUMES COMPUTATIONAL SPEED OF 100 MFLOPS

TABLE III. COMPUTER RESOURCE REQUIREMENTS FOR FLUTTER BOUNDARY

WING/BODY/CANARD CONFIGURATION
10 MACH NUMBERS (40 CASES) PER ANALYSIS

$$\text{TIME} = (\text{GRID PTS}) \times \frac{\text{OPS}}{(\text{GRID PTS} \times \text{ITER})} \times (\text{ITER}) / \left(\frac{\text{OPS}}{\text{SEC}}\right)$$

FLOW REGION	FLOW MODEL	VPS-32 (100 MFLOPS)	NAS (250 MFLOPS)
I, MAYBE II	TSD WITH 2-D STRIP BOUNDARY LAYER	30 HOURS	12 HOURS
I, MAYBE II	POTENTIAL WITH 2-D STRIP BOUNDARY LAYER	45 HOURS	18 HOURS
I, II, MAYBE III	EULER WITH 2-D STRIP BOUNDARY LAYER	65 HOURS	26 HOURS
II, III	NAVIER-STOKES ($RE = 10^8$)	1611 HOURS	644 HOURS

TABLE IV. ACTIVITIES IN COMPUTATIONAL UNSTEADY AERODYNAMICS

- CORRELATION OF NAVIER-STOKES AND TRANSONIC CRYOGENIC PRESSURES
- NAVIER-STOKES FLUTTER ANALYSIS
- FULL POTENTIAL (ISOLATED WINGS)
- FULL POTENTIAL (CONFIGURATIONS)
- CAP-TSD (LEVEL 1.0)
- CAP-TSD (LEVEL 2.0)

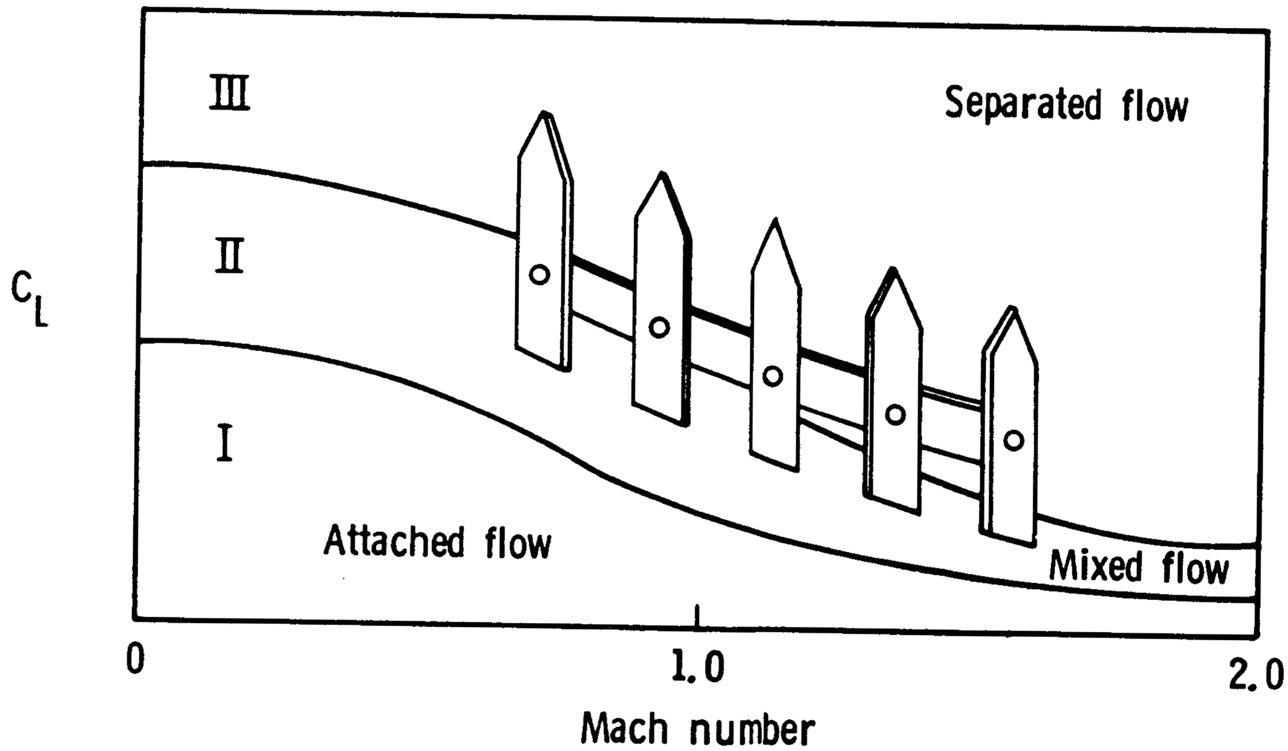

Figure 1. Characteristics of attached and separated flow for complete aircraft.

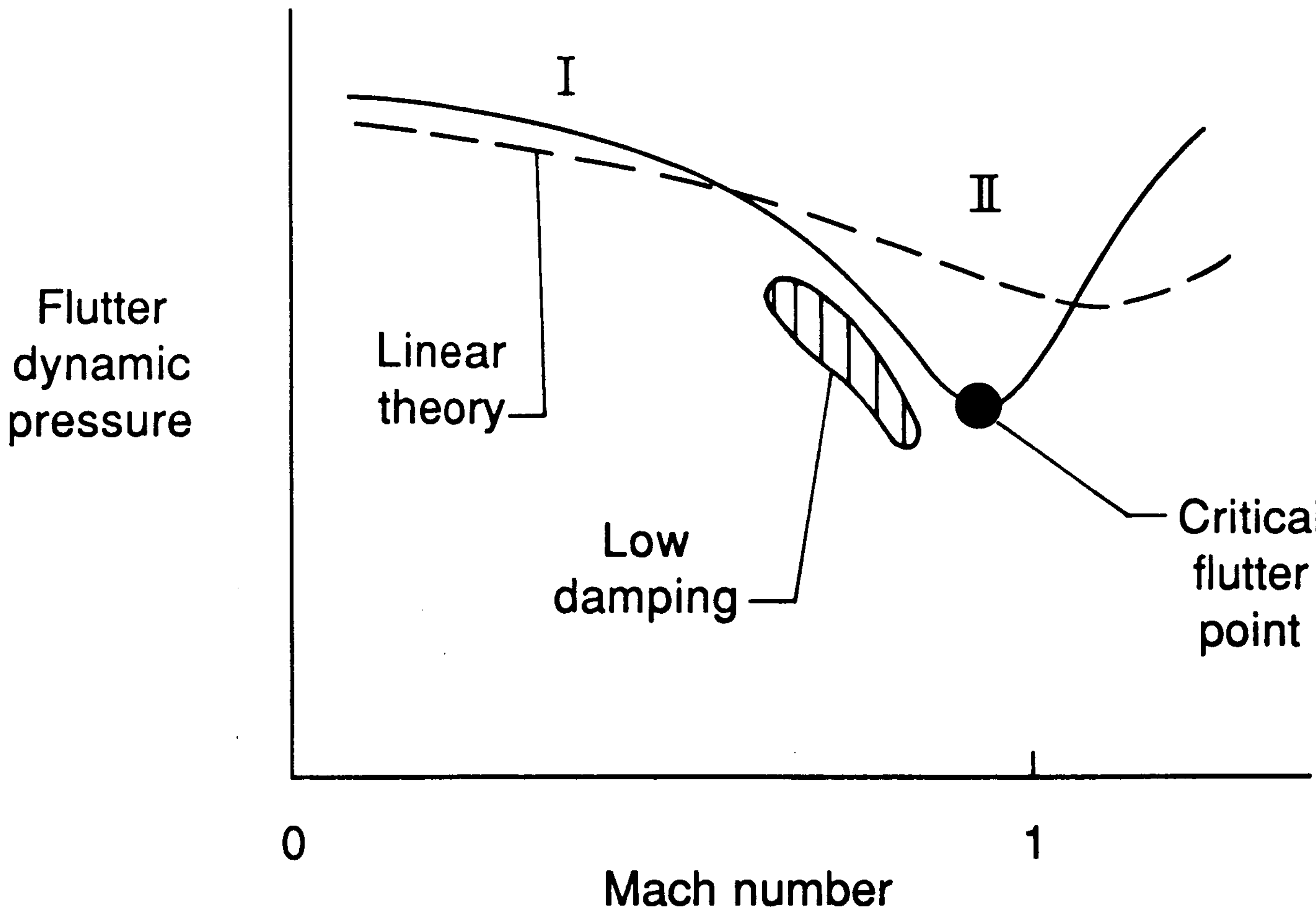

Figure 2. Features of transonic flutter.

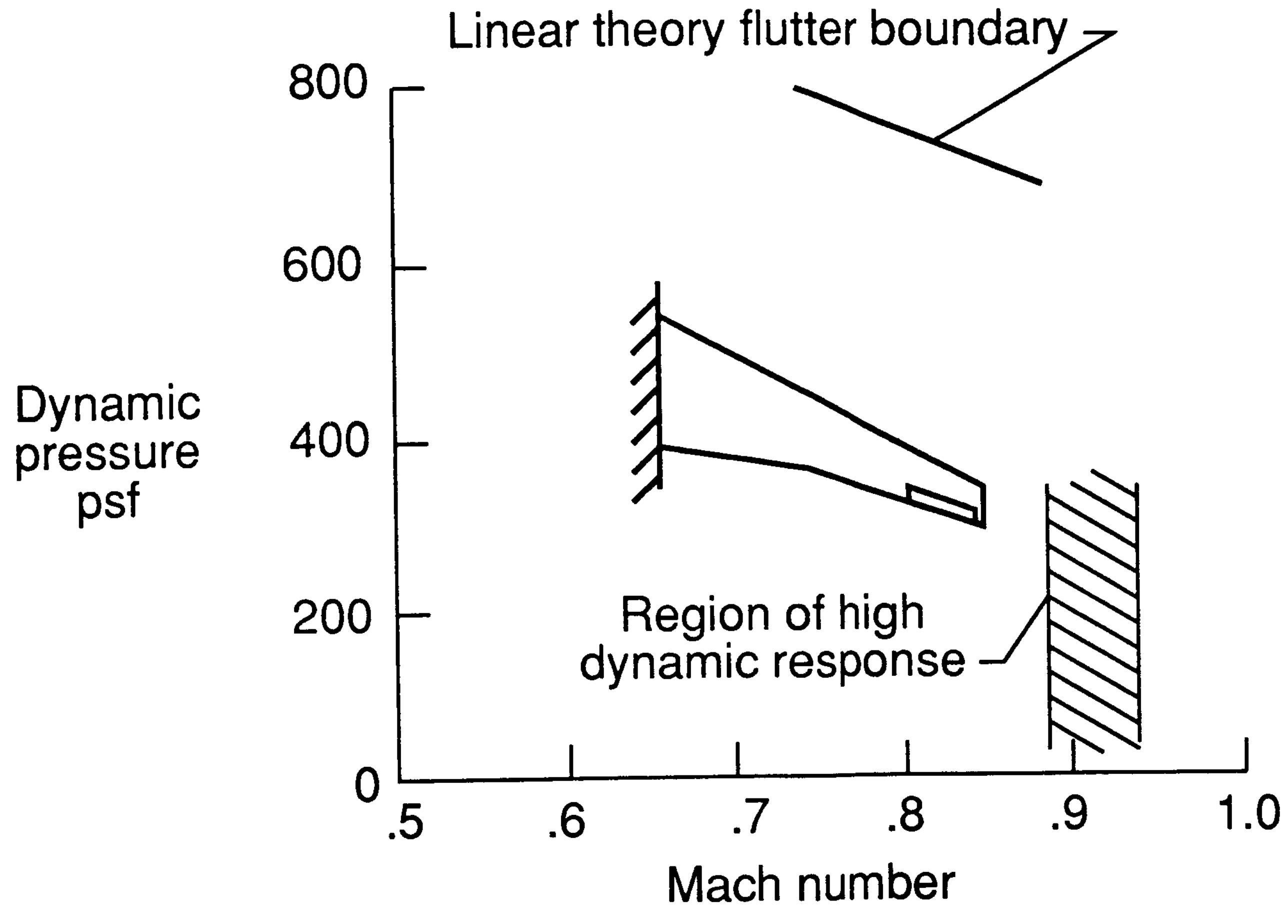

Figure 3. DAST ARW-2 shock-induced instabilities.

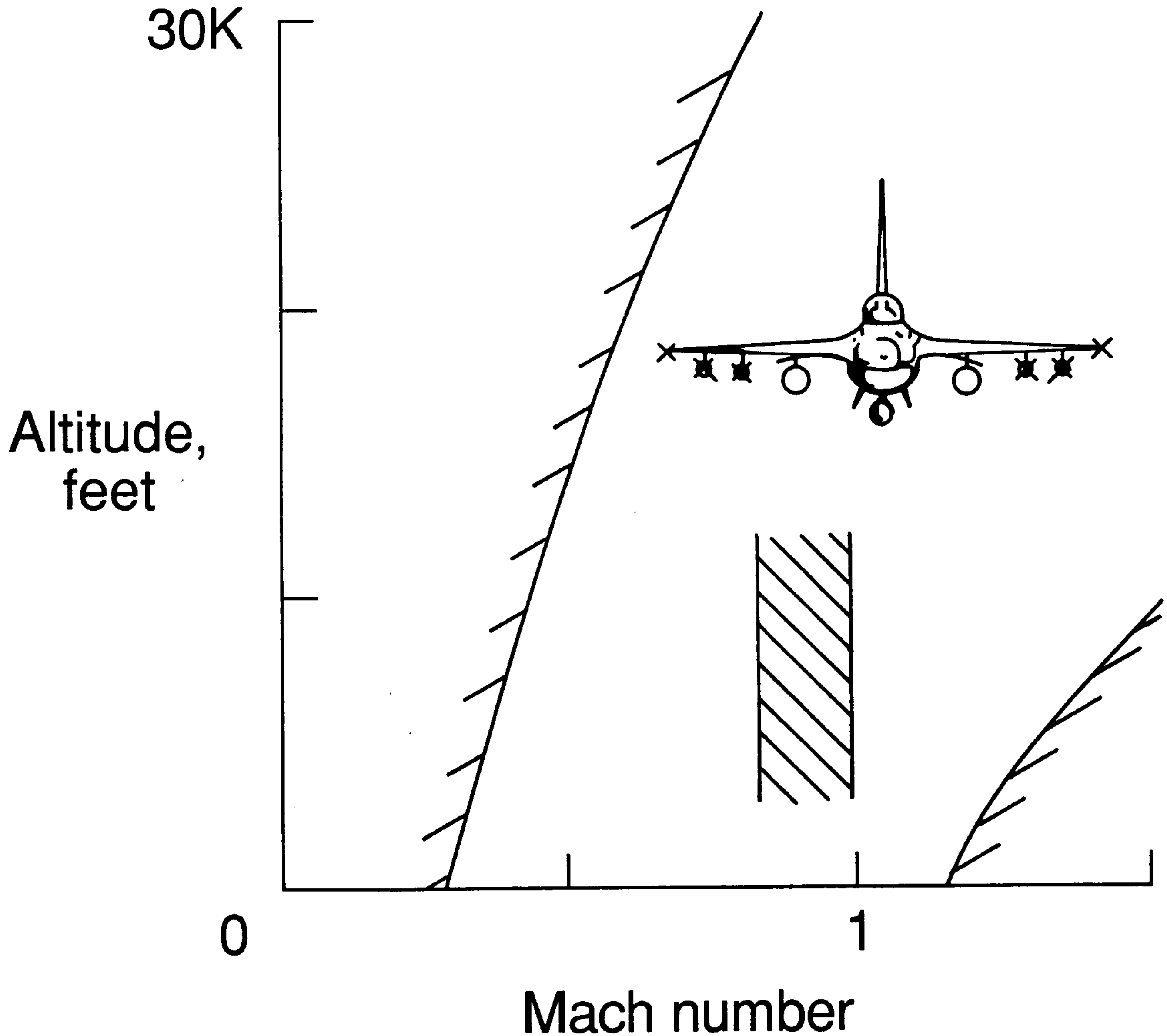

Figure 4. Wing/store limit amplitude flutter.

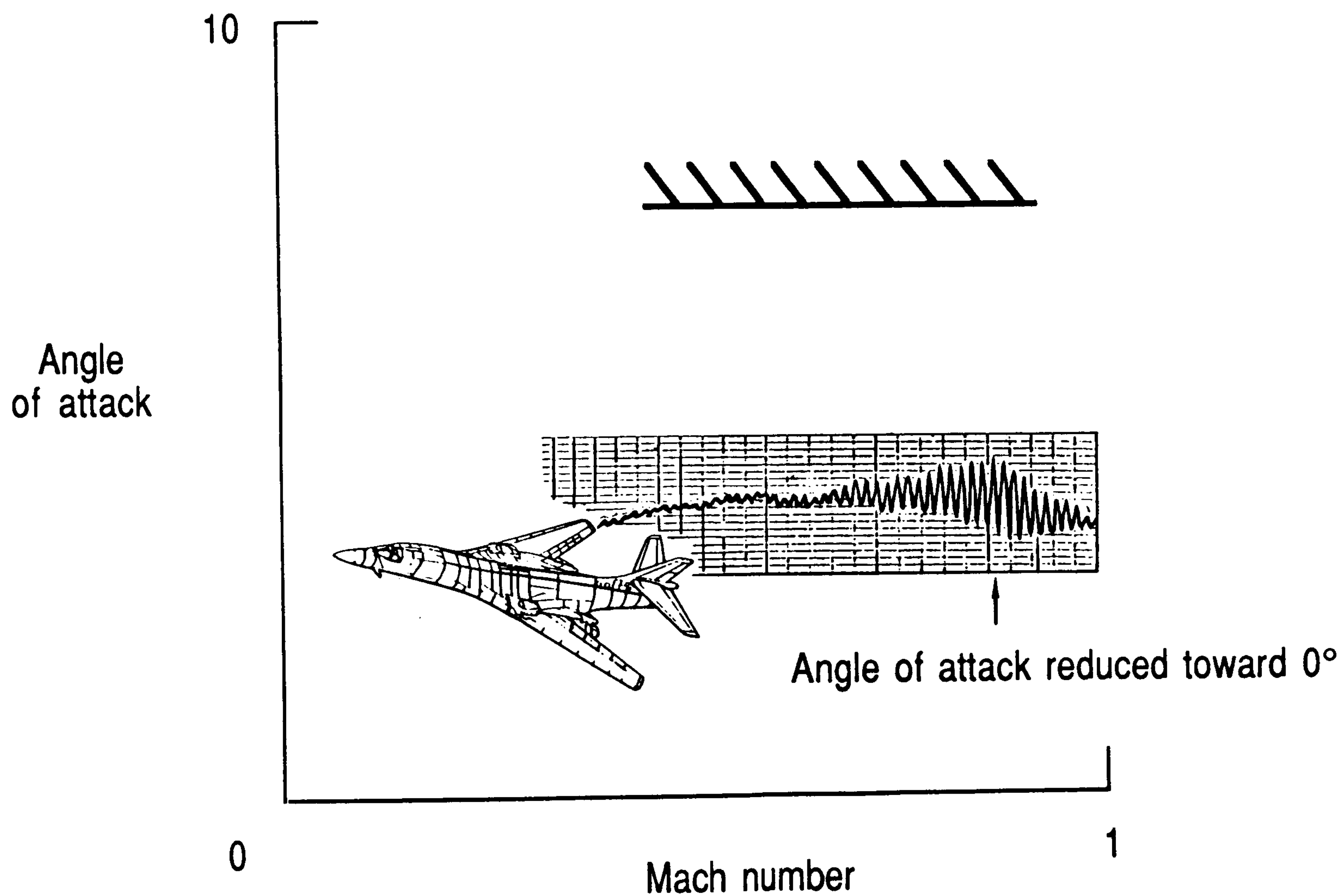

Figure 5. B-1 vortex-induced oscillations.

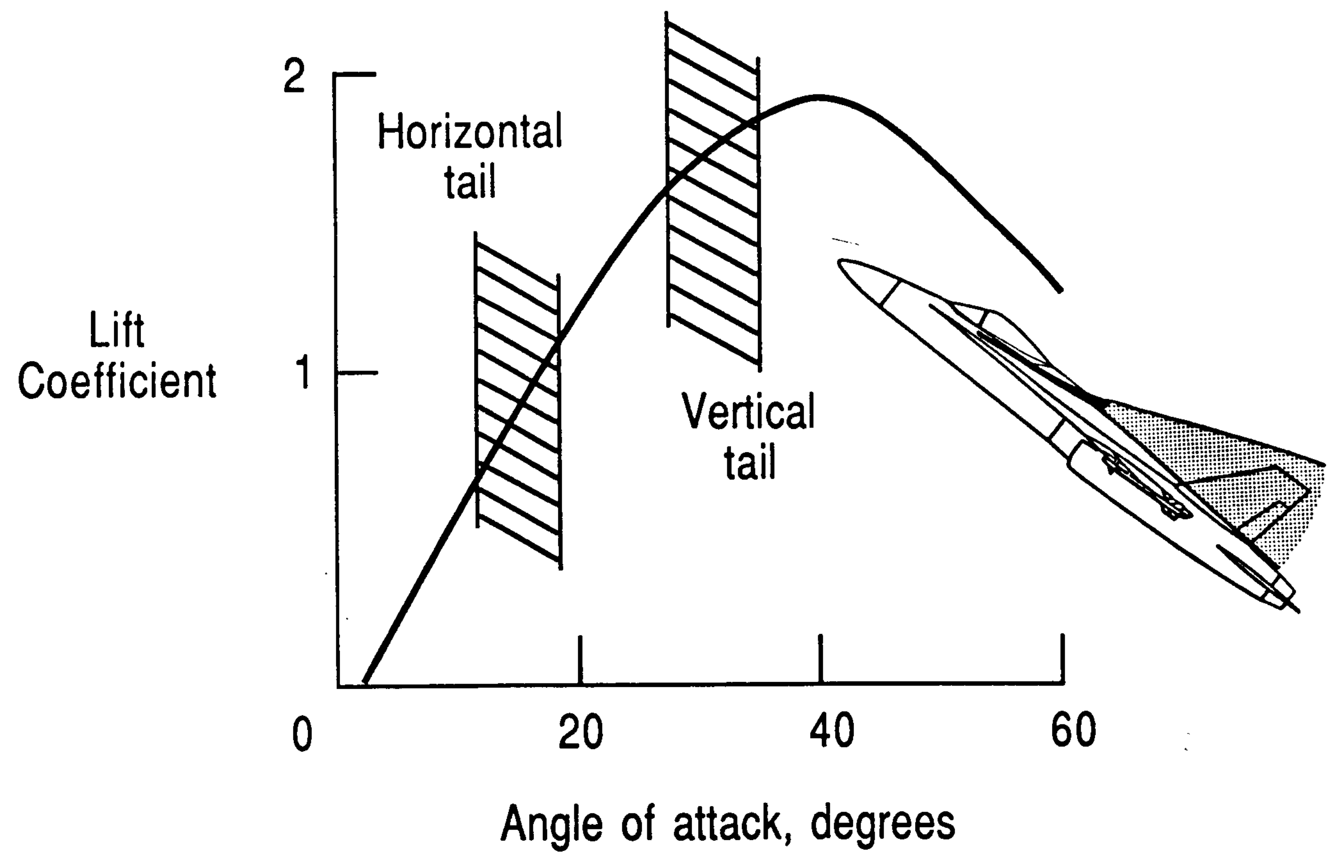

Figure 6. Vortex-induced buffet loads.

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15. Supplementary Notes

16. Abstract

This report summarizes the status of computational unsteady aerodynamics methods for aeroelastic analysis and makes recommendations for future research activities. The flight conditions for which various types of flows exist are described and the aeroelastic phenomena that can occur in those flight regimes are discussed. Some important aeroelastic problems of current interest are described, and the aerodynamic methods needed to analyze them are presented. The capabilities and limitations of existing unsteady aerodynamics methods are discussed. Computer resources required to perform aeroelastic analysis of various flight vehicle configurations are presented. Recommendations for future research are made, and schedules for completion of proposed research tasks are presented.

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