13th Von Karman Lecture

Aeroelasticity—Frontiers and Beyond

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Introduction

IN 1972 I had the privilege of giving the Fifth Biennial von Karman Memorial Lecture in Israel on the topic "Perspectives in Aeroelasticity" aimed at indicating achievements of the preceding decade. The opportunity to honor von Karman's memory has again been given on this occasion. Again, the encompassing scientific and technical discipline of aeroelasticity is my topic. A tradition has evolved for the von Karman lectures to be broad in scope and of general interest, yet pointed to specialists; a rather difficult goal to attain. I hope this lecture will not stray from that goal.

Aeroelasticity deals with the behavior of an elastic body or vehicle in an airstream wherein there is significant reciprocal interaction or feedback between deformation and flow. In this sense it clearly includes many such problems in liquids; that is, hydroelasticity. While dramatic instabilities may often be featured, it may be stressed at the outset that control of subcritical response behavior of a vehicle is as important as removal of such critical speeds from the design or flight envelopes. Thus, the main problems of aeroelasticity are determination of both the response and the stability problems. In the sense that aeroelasticity deals with interaction of internal and external sources of energy it may include servo-aeroelasticity not only in aircraft, but also in launch vehicles ascending the atmosphere and, in an extended sense, many structural feedback problems of spacecraft as well. Thus, by intention, the word "beyond" in the title of this paper takes on partly the meaning of space that it has in von Karman's autobiographical book *The Wind and Beyond.* Another meaning of "beyond" may be inferred by going beyond aerospace to some problems which have arisen in industrial fields, for example, in nuclear reactors in the flow of liquids or gases past plates, or in more prosaic, but no less important problems in civil engineering, as the wind response of bridges, chimney stacks, buildings, and transmission lines.[1] It is of interest, for example, that viscoelastic damping between floors has been designed into skyscrapers to reduce wind response; and that the response of glass and panels in large buildings has led to costly lessons in architecture. The galloping of electric transmission lines under icing and wind conditions is by now a classical aeroelastic problem. Trends in transmission line design have veered toward bundles of conductors with spacers and are leading to new classes of oscillatory wake and flutter problems.

Of the many sides of von Karman's personality and humanism, the scientist, engineer, mathematician, teacher, creative scholar, organizer, and prime mover, I will recall only a few relevant bits. Much of von Karman's creative life's work developed within the fields of structures and aerodynamics, hence his deep interest in aeroelasticity—a field combining both disciplines. Von Karman also imparted that interest to many of his students. In 1940, together with M.A. Biot, he wrote the pioneering textbook *Mathematical Methods in Engineering*, which set a new penetrating educational style, stressing insight and problem formulation, a style well worth emulating but unfortunately neglected in most textbooks. Von Karman and J.M. Burgers in the Durand Aeronautics Series (Vol. II) presented the first basic developments on the aerodynamics of flapping flight, related to nonstationary or oscillating air forces and to the im-

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He has taught courses for the University of Virginia Engineering Extension and George Washington University; he served for one year as Hunsaker Professor of Aeronautical Engineering at MIT. He gave the Minta Martin Lecture (1957), as well as many AGARD lectures, and was von Karman Lecturer in Israel (1972). He was editor of the AIAA Selected Reprints volume *Aerodynamic Flutter*, and has served as an associate editor of the *AIAA Journal*. Mr. Garrick served as NASA representative to the Division of Mathematical Sciences of the National Academy of Sciences and is on an advisory council for the Air Force Office of Scientific Research. He has been a member of various advisory committess on applied mathematics, space vehicle structure, structural dynamics, and vibration and flutter. Among his awards and honors are NASA Exceptional Service Award (1964) Langley Scientific Achievement Award (1965), and AIAA Sylvanus A. Reed Award (1973). He is a Fellow of the AIAA.

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memorial problems of the flight propulsion of birds and the locomotion of fish.

Von Karman's sense of humor, which was remarkably appropriate to a given occasion, has become legendary. Recoginzing that the poor structures engineer was usually held accountable for structural integrity, he quipped "The aerodynamicist assumes everything but the responsibility." When appointed to a commission made up of "concrete and steel" people to investigate the spectacular destruction in 1940 in moderate winds of the majestic Tacoma Narrows Bridge, he stated that he alone in the commission did not represent concrete and steel but represented "only the wind." When a bridge designer protested to him "you don't mean, Dr. von Karman, that elastic models of future bridges should be tested in wind tunnels" he said, "that is exactly what I mean."

On a personal note, to repeat two anecdotes that I have related previously,[2] I first met von Karman in 1938 at the Fifth International Congress for Applied Mechanics where I spoke on the Fourier transform, or Laplace transform, relationships between indicial (transient) and oscillatory aerodynamics. Von Karman inquired where I had learned these subjects and I replied "in the books." His response was "ah so, they are still the best teachers." Some dozen years later at the Langley Laboratory when he learned I had just been made head of a division he said to me, rather prophetically, "it is a sad event when one goes from research to management."

It has been gratifying to me to observe that in major aerospace industry the aeroelastician is no longer the stepchild he once was. From an almost parochial isolated specialist, he is now the generalist who tends to pull together the separate efforts in structures, aerodynamics, stability and control, and propulsion, even in early design stages. Yet, there are still human problems such as one-way communications and barriers between departments as well as physical problems that are often so recondite and difficult that aeroelastic problems may slip through the cracks.

This paper is intended as a survey of the current scene and the frontiers along which aeroelasticity is expanding, viewed from the perspective of interpretive comments on some selected topics. References given for topics are indicative rather than complete, and may serve as guideposts to the wider literature. The topics presented are:

Orientation and Overview of Some Current Problems
Active Control of Aeroelastic Response
Unsteady Aerodynamics of Arbitrary Configurations
Aeroelasticity and the Space Shuttle
Verification of Flight Aeroelastic Behavior

Orientation and Overview of Some Current Problems

Some Threads of History

Flexibility is generally associated with light weight so that phenomena and problems of aeroelasticity were encountered from the earliest days of flight. Since large deformations are also associated with high loads or high dynamic pressures, problems continue to arise in the design of all high-performance vehicles, and sometimes in their operation. Let us recall just a few threads of history for orientation and insight, and also give a brief overview of some current considerations.

We may recall that the Wright Brothers made favorable use of flexibility in the lateral control of their aircraft by wing warping, and that they were aware of the adverse effect of torsional deformations on the thrust of a propeller. This latter divergence effect (increase of the effective angle of attack) led in later years to the phenomenon of propeller stall flutter. Elevator flutter of a World War I bomber (1916) was eliminated by the great British pioneer, Lanchester, by introducing a carry-through structure rod, connecting right and left elevator panels, thus greatly increasing the torsional stiffness. Lanchester thus also established a precedent for the years of excellent British work on flutter. Pioneers in the Netherlands could eliminate early control surface flutter by dynamic mass balance, in which the products of inertia about two axes, the control surface hinge line, and a relevant vibration nodal line is reduced so that a decoupling of the interacting modes occurs. In the Netherlands too, there was established a tradition for excellence in aeroelastic work that continues to the present day.

Thus by 1922 the two basic remedies for flutter problems, increased stiffness and mass balance, were already framed and together with damping mechanisms, are still the basic elements that must be properly incorporated into the vehicle structure to avoid aeroelastic instabilities.

Since the aerodynamics also contributes in a major way to the stiffness, damping, and inertial characteristics, knowledge of air forces is basic to understanding the phenomena of aeroelasticity, and for converting palliative remedies into cures. It is pertinent to mention briefly two other pioneers. Theodorsen at Langley in 1934 developed in an exact way the simplest theory of flutter that contained the essential parameters. He thus removed a large domain of oscillatory (nonstationary) aerodynamics from the sting of empiricism, then associated with hydraulics as a "science of variable constants." Kussner at Gottingen in 1940 laid the foundation for general nonstationary wing surface theory, which has found its unfolding and utliization by modern computing machine methods, of which more later.

By World War II adverse effects of aeroelasticity in stability and control had been encountered, such as the loss of aileron effectiveness at high speeds by aileron reversal wherein the wing twists in a way to reduce or completely reverse the aileron control effects. Recognized also at an early date was the importance of flexible modes, along with rigid body modes, in determining structural response and fatigue of the aircraft due to repeated loads in rough air or turbulence. However, the aeroelastic regimes of interest for stability and control involved mainly rigid body airplane modes, while response to gusts included in addition the very lowest structural modes, and for flutter they involved also still higher frequency modes, thus these regimes were then mainly noninteracting. This situation has been changing especially for the large high-performance aircraft with long slender fuselages in the direction of creating greater overlapping and interaction of the regimes, while effects of static aeroelasticity have become more pervasive.

After supersonic flight had been reached, it was observed that the transonic speed range tended to produce the most severe requirements for stiffness to avoid flutter (due in part to increased slopes of the lift curve in that range and to center-of-pressure shifts, as well as to aerodynamic phase shifts) and that stiffness, or moduli of elasticity, rather than levels of strength dominated the requirements for some aerodynamic surfaces. Moreover, several varieties of instabilities, particularly for control surfaces, could occur in this speed range such as one designated buzz and associated with oscillating shock waves. Interestingly, criteria for the level of control surface stiffness (basic frequency of oscillation) for avoidance of buzz resemble closely the empirical criteria for avoidance of propeller stall flutter originally formulated by A.A. Regier.

Concern for the flutter of structural panels arose with supersonic flight for both aircraft and launch vehicles. In the mid-50's, for example, a fighter airplane was lost in a test flight because of failure of a hydraulic line which had been attached to a panel that fluttered. Another group of fighter aircraft that was unbearably noisy in the cockpit was quieted when the problem was traced to panel flutter. For this type of problem aeroelasticity is encroaching on its cousin domain of aeroacoustic response, and indeed analysis of acoustical noise effects which arise from fluctuating airloads utilizes the same theoretical base as oscillatory aerodynamics.[3] Early V-2's of World War II were said to have been broken up by flutter of panels located near the nose of the missile. The panel flutter problem was also quite bothersome for the Saturn V-Apollo launch vehicle and required much detailed consideration. Other aircraft and missile problems include the problem of providing enough stiffness and avoiding flutter for all-movable wings, a concept introduced to provide sufficient control effectiveness at the higher speeds.

A survey made in 1958 indicated that in the decade 1947-57 more than 100 different flutter incidents occurred in the U.S. for civil and military aircraft, mostly of control surfaces and tabs, some wings carrying external stores, and one case of a T-tail airplane. Military aircraft in particular, face a great many problems in the arrangements of external stores. It is interesting to note that the flexible swept-wing B47 bomber pioneered in static aeroelasticity of swept-wing airplanes, and that the 707 transport, an outgrowth of it, employed the location of the engine pods to diminish aeroelastic effects and increase the flutter speed margin. And, in fact, all modern transports in their development must undergo combined programs of analysis, ground vibration tests, wind-tunnel, and flight test of aeroelastic response. As cited by C.D. Perkins,[4] one of the chief reasons for abandonment of Boeing's early SST variable-sweep configuration was that no practical solution could be found for its aeroelastic problems.

Now that general-aviation aircraft have markedly increased in number and types, and in performance, their aeroelastic problems have become increasingly of concern. The special needs of the industry are for clear, simplified, noncostly procedures and programs to anticipate and overcome these problems. "We can't afford these flutter guys" was stated by an aerospace executive with respect to the aeroelastic analysis costs in development of a small STOL aircraft. Even large aerospace projects have foundered on the costs and long time cycles of aeroelastic analysis; I am sure this was no small problem for the Boeing SST when the design was abruptly changed to the fixed-wing airplane.

Propeller-Whirl Flutter

In 1960, the propeller-whirl flutter of a turbo-prop airplane led to two major disasters; the phenomenon involved gyroscopic coupling of nacelles and propellers in pitch and yaw, as later special wind-tunnel studies demonstrated. Rather subtle considerations entered here, since prior damage to the nacelle-engine mounts had to be assumed to have occurred; thus the modified airplane required not only different engine support stiffness but also fail-safe supports. The investigations in this case have provided valuable lessons for rotor and V/STOL aircraft.

Rotors and Turbomachinery

Rotorcraft in general also have their full share of aeroelastic problems; they have long histories of vibration and dynamic stability problems. A purely mechanical dynamic instability of rotors, known as ground resonance, associated with fore and aft flexibility of the rotor and with pylon flexibility was demonstrated long ago and lurks in several forms. For some helicopters stall flutter may occur routinely over part of the cycle creating or attenuating possible fatigue problems. Useful accounts of aeroelasticity problems of hinged and hingeless rotorcraft may be found in Refs. 5 and 6. Aeroelastic problems of helicopters remain fertile areas for advanced work; a research airplane project to serve as a test bed for rotor research and development, designated Rotor Systems Research Aircraft is being developed jointly by NASA Langley and the U.S. Army.

Turbomachinery, compressors, fans, and turbines have newly required special attention in regard to aeroelastic problems, because of transonic and supersonic relative speeds, thinner blades and higher pressure ratios between stages. Many millions of dollars have had to be expended in the development stages to overcome these. Systematic research is difficult and mostly lacking so that the problems arise anew with each new design. Of the problems that arise many involve complex flow situations with shocks and turbulence, or separation and stall, or equivalently nonlinear aerodynamics including hysteresis effects, while others may be more related to classical potential flows. Figure 1,[7] gives a schematic indication of some of the types of instability that the operating line of the engine compressor must be designed to avoid. A discussion of these instabilities and design methods for avoiding them are given in a recent paper[8] which appears in a special issue of the *Journal of Aircraft* devoted to engine technology, and included several papers on the structural and aeroelastic problems of variable cycle and variable geometry engines.

Flying Wing—Tailless Tanker

The use of active controls in control configured vehicles is taken up as a special topic in a following section of this paper. However, in this overview it is sufficient to recognize that active controls will require new looks at old or discarded configurations. For example, the tailless or flying wing configuration will lead to interesting new aeroelastic studies.[9] In Fig. 2 there is shown a comparison of planforms for a conventional tanker and one employing active controls to achieve its stability. As given in a study by Walker[10] significant reduction in overall weight and in cost can be achieved for similar performances of the aircraft.

Oblique-Wing Transport

The unique concept of the oblique or yawed wing transport (Fig. 3) advanced by R.T. Jones of Ames Research Center merits much discussion because of its novel aeroelastic behavior, associated with its asymmetrical structure and unsymmetrical aerodynamics, however, only some brief remarks are given here mainly to illustrate the significant effects of an unrestrained vs a restrained wing analysis. It is well known that the sweptback, cantilevered wing will have a higher

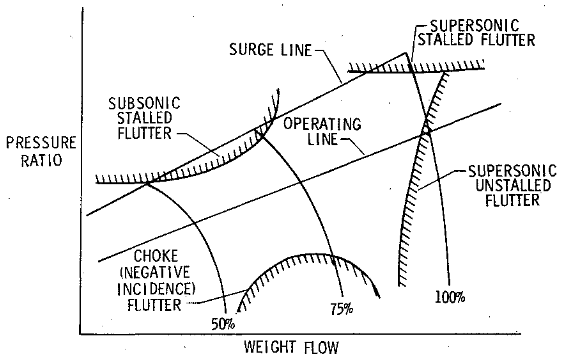


Fig. 1 Boundaries for four types of flutter of a compressor.[7,8]

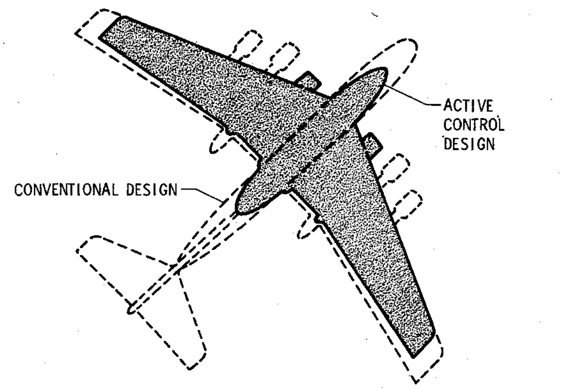


Fig. 2 Control configured flying-wing tanker vs conventional design.[10]

divergence speed (or it may not diverge at all) compared with that of a similar unswept wing. This effect may be explained by noting that, for example, an upward bending deflection of the wing, say, by a gust, tends to reduce the angle of attack or to unload the wing, and thus tends to counter the gust response. For a sweptforward, cantilevered wing the situation is reversed, the the divergence speed may be greatly reduced. However, when the fuselage is allowed to participate in the motion, and freedom to roll permitted, the situation is markedly different. Jones and Nisbet[11] indicate that the freedom of the fuselage to roll will stabilize the static divergence characteristics as will also the use of aileron controls. The main parameters for determining neutral stability boundaries are the fuselage roll inertia, distribution of mass along the wing, and the wing damping in roll. Undamped oscillations, involving coupling of bending and roll, or torsion and pitch, depending on the stiffnesses in bending and torsion, will appear at speeds in excess of the static divergence speed and will need to be resolved, as will adequacy of the available aileron power and possible control problems associated with the combined coupling effects of pitch, yaw, and roll. The classical stability analysis in which separation of longitudinal and lateral control is invoked will thus need a new look.

Mathematics and Aeroelasticity

Some main features of an aeroelastic analysis are depicted in Fig. 4, while Fig. 5 illustrates schematically the cycle of iteration from initial choice of configuration to a final design.[12] Many experimental and analytical chores need to be carried out, the responsibility for which in an aerospace company spans entire departments of structures, aerodynamics, dynamics, and loads. Yet aeroelasticity has, from the start, relied heavily on theoretical methods, and this is part of the fascination of the field for the applied mathematician as an important arena to ply his art and science. The natural application of matrices to aeroelasticity was indicated about 35 years ago by Loring in the U.S. and by Frazer, Duncan, and Collar in Great Britain. Since then the development of finite-element methods in structural analysis, as introduced by Turner and associates at Boeing and by Argyris in Europe about 1956, and of similar lattice methods in aerodynamics have multiplied the use of matrix methods manyfold. And since modern computers are adapted to naturally gobble up matrices (although some of them do choke up), the triple alliance of finite elements, matrices, and computers has led to a mountain of software codes in aeroelasticity.[13] Two of these general codes which are evolving under constant improvement, NASTRAN and FLEXSTAB, have much present usefulness and enormous potential for the future. An old aphorism that "mathematics is the art of avoiding arithmetic" has been turned into "the art of reducing everything to arithmetic for machines to handle."

The use of finite elements, matrices, and codes as implied in the foregoing, leads to so-called "math model" concepts and may be assessed as a trend toward mathematical engineering, while more traditional applied mathematics pervades aeroelasticity in a gamut of areas such as optimization, wave propagation, random processes, active and adaptive control, dynamic stability of nonconservative systems, and so forth. It has been pointed out that singular perturbation theory and matched asymptotic expansions, methods suitable for numerical solution of nonlinear problems, really began with Prandtl's boundary-layer theory. Similarly, a case can be made for the influence of aeroelasticity on mathematical application methods, and for its furnishing a wide spectrum of problems illustrating tools and concepts of applied mathematics. Mathematical analysis alone, however, is not yet a sufficient design base for mastery of diverse and detailed aeroelastic problems, largely because of nonlinear phenomena, particularly those of aerodynamic origin. Insight into such problems remains difficult to achieve and is fallible without supplementary experimental programs; thus nonlinear aerodynamics both steady and unsteady remains a major frontier.

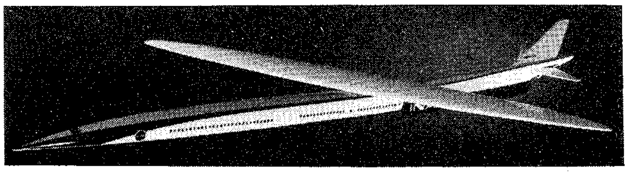


Fig. 3 Oblique-wing transonic transport (concept of R.T. Jones).

SST Follow-on Technology

After the cancellation of the contracts for the Boeing SST prototypes (1971), the FAA supported the continuation of research in several areas that had been most critical in the design and development. Prominent among these was aeroelasticity; accordingly, related follow-on activity took place in active controls and structural optimization with respect to avoiding needed increase in weight to increase stiffness. Aeroelastic optimization[14] is evolving into the popular field for analysis, and can take on many different objectives, as modifying the structural frequency spectrum, or reducing and distributing the weight subject to various constraints while keeping strength and flutter speed unchanged. A further important dimension in this effort is furnished by the selective use of composites[15] which enable the aeroelastic "tailoring" of structural elements or components, especially of control surfaces. These developments can not only lead to practical improvements but also to improved insight into design.

Recently NASA has continued support in the area of advanced computerized structural design with emphasis on

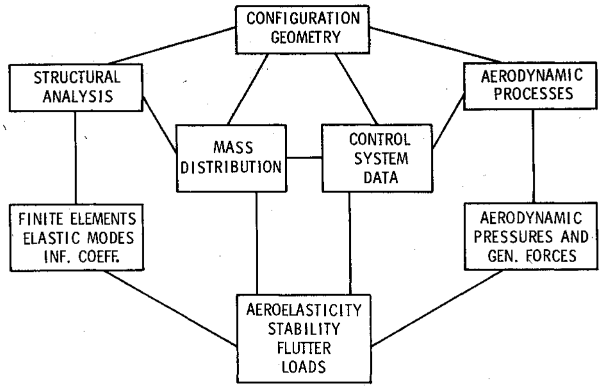


Fig. 4 Aeroelastic analysis schematic.

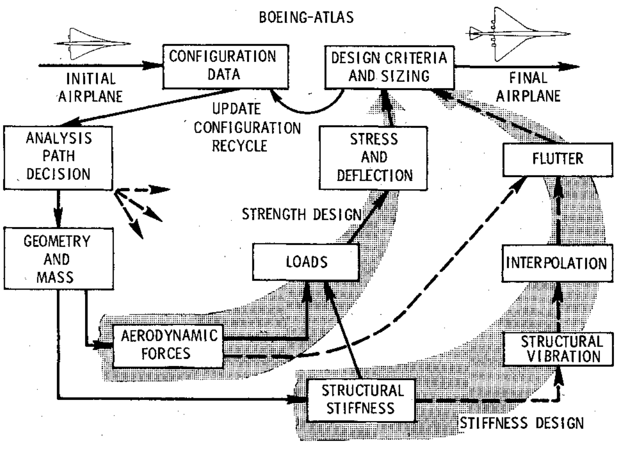


Fig. 5 Integrated aeroelastic design process.[12]

aeroelasticity. The older preliminary design procedures wherein for a chosen configuration, the aerodynamic performance and strength are first determined, then aeroelasticity and flutter checked for adequacy, followed by redesign and repeat cycles, led to long and costly time delays. Consequently, an advanced design system making use of the ATLAS and FLEXSTAB codes was developed and applied to SST configuration in which the load, mass, stress, vibration, flutter, and resize programs are integrated in the design process. The major advantages of short time to recycle between strength and stiffness in preliminary design studies was stressed and demonstrated in this study.[16] A general integrated automatic program to aid design with the acronym IPAD has been described by Heldenfels[12] and is currently the focus of considerable development on the utilization and assembly of computer codes.

Aerospace Flutter and Dynamics Council

A forward-looking event in the U.S. aerospace industry that deserves special recognition has been the organization of the Aerospace Flutter and Dynamics Council (AFDC), an outgrowth of a former Aircraft Industries Associates (AIA Panel 58), and the only technical committee among many in AIA that has survived since the 1950's. Composed of individual leaders in dynamics and aeroelasticity, it was originally set up to tie in with the former NACA Advisory Subcommittee on Vibration and Flutter, and has remained an active and dedicated forum for exchange of detailed information on the technical problems that affect safety and structural integrity of aerospace vehicles in all dynamic stability areas. It is significant that government and university specialists are regularly invited to attend their sessions.*

AGARD Activity

The AGARD Structures and Materials Panel in the NATO organization has been active for many years producing many specialist publications in aeroelasticity. A major storehouse of information for specialists is the *AGARD Manual on Aeroelasticity,* a periodically updated set of six volumes. The AGARD Flight Mechanics and Guidance and Control Panels have also become increasingly active in aeroelasticity areas. It is appropriate to recall that AGARD itself (Advisory Group for Aerospace Research and Development) is the offspring of von Karman's initiatives.

Active Control of Aeroelastic Response

A major current trend which will play a dominant role in research, development, and practice during the years ahead is the union of modern control technology and aeroelasticity; for example, in control configured vehicles (CCV). Much support for growth is being given by NASA and by the Air Force, especially through its Flight Dynamics Laboratory, so that a rapidly burgeoning literature is developing.[17,18] Although aeroelasticians and control specialists have in the past usually gone their separate ways and both fields have become quite sophisticated, in the last few years there have been attempts at real cooperation and adaptation to each other's methods so that important information has been published.

The question may be asked, however, why is this trend occurring now? After all, the concepts are quite old. In the 1950 Wright Brothers Lecture, Bollay[19] gave a comprehensive outlook on the field; and in a 20-year-old textbook[20] it is stated 'There exists an excellent possibility of improving flutter performance by somehow installing in the structure a properly designed rapidly responding automatic control system, actuated in closed-loop fashion by the motion to be stabilized.'' The answer to "why now" resides partly in the design trends having high performance and wide mission requirements and thus in the need to avoid many inherent compromises, partly in improved hardware, but largely it is psychological, the growth of confidence in the concepts and methods of active controls as gained by their general use in the space program and, recently, in broad programs for certain research aircraft, in several military development areas, and currently in the fly-by-wire YF 16 fleet.

In application active controls employ various sensors, appropriately located to detect deformations or motions, with suitable servo feedback to accomplish potentially large gains in weight savings and in increased aerodynamic efficiency for many types of flight vehicles. Figure 6 shows a simplified general schematic; there can be multiple inputs and outputs, separate or combined systems, and onboard microcircuit computers. The various applications as indicated, may be separated into two main categories: active control of stability and control, and active control of loads or stresses.

The items in the first category are mainly concerned with the rigid body behavior of the vehicle; accelerometers and angular-rate pickups will naturally sense any superposed structural motion. Some detailed understanding of the vibration modes and response of the vehicle is therefore needed, so that sensors can be properly located and filters judiciously employed to avoid interference between rigid-body and flexible modes. Items in the second category are more directly concerned with the control of the structural deformations and modes. The table indicates that among the numerous proposed applications are: stability augmentation systems (SAS), gust and maneuver load alleviation and corresponding fatigue damage reduction through modal suppression, ride quality control, of importance for low wing loading STOL aircraft, or for low-altitude flight, and (the one most far out) flutter suppression. Other applications include missile and drone vehicle control, control of external stores,

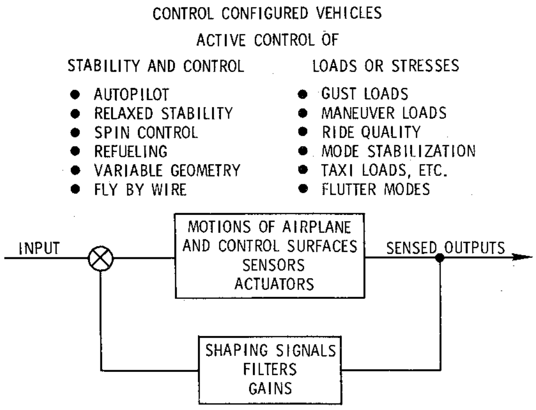


Fig. 6 Active control of aeroelastic response.

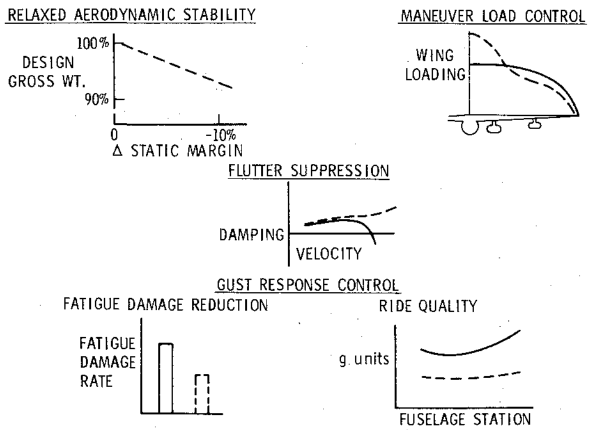


Fig. 7 Several active control concepts.

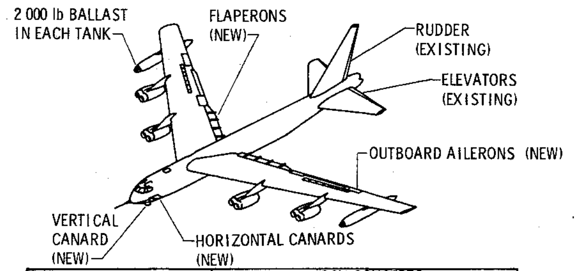
*The current chairman of the AFDC is B. Hall of McDonnell Douglas, who succeeded E. Baird of Grumman.

taxi load alleviation, automatic control of variable geometry, such as has been proposed for compressor or turbine blades, or for variable-sweep aircraft.

One may characterize the active-controls trends as resembling biological adaptation, the logical evolutionary development of the vehicle's structual and propulsive growth, or skeletal and muscular growth, to a sensory system and the beginnings of a nervous system or brain. The designer must insure that this increased sensitivity meets the tests of economy and safety. Of special significance is the rapid progress in microelectronics wherein costs have gone down and reliability increased so that onboard dedicated computers are already practical. Improvements in sensors and actuators will, no doubt, also continue to evolve further.

A few additional words may help to recall some of the advantages of these developments (Fig. 7). Relaxed aerodynamic stability refers to the design approach that meets stability and handling criteria by stability augmentation rather than by inherent stability, and may lead to reduction in weight as well as the lowering of the trim drag. For example, there is a large normal rearward shift of the aerodynamic center for a supersonic transport as the Mach number is increased from subsonic to supersonic speeds. This wide travel of the aerodynamic center relative to the c.g. may be acceptable without elaborate fuel weight shifts otherwise required. For the Boeing SST a 6000-pound weight saving and 225 naut mile increase in range were indicated. In fact, multipurpose use of the so-called hard SAS, that is systems redundant enough to be regarded as reliable as the structure, had been considered in the design of the SST.

Maneuver loads control usually means a redistribution of some of the outboard wing load toward inboard in order to reduce bending moments and thus structural material, or to yield greater fatigue life. A major program for the C-5-A designated Active Lift Distribution Control System (ALDCS) has demonstrated the concepts to be used in the fleet.[21]



SURFACES	CCV CONCEPTS RCS	FMC	MLC	AS	FR
RUDDER				X	
ELEVATOR			X	X	X
FLAPERON		1 SEGMENT	X		
OUTBOARD AILERON		X	X		X
HORIZONTAL CANARD	X				
VERTICAL CANARD	X				

Fig. 8 B-52 CCV control surfaces.[22]

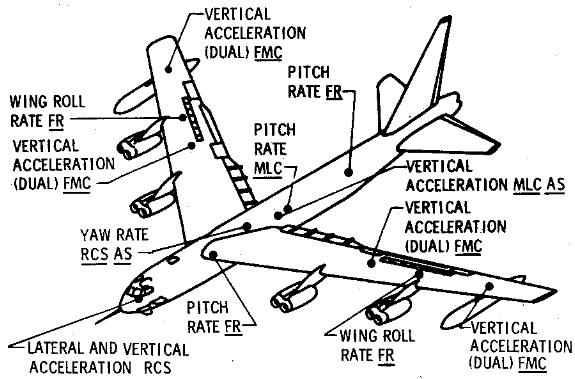


Fig. 9 B-52 CCV sensors (see table in Fig. 8).

Two concepts are involved in alleviating response to atmospheric turbulence or gusts: fatigue damage reduction by reducing stresses in gust critical areas; and ride quality control or ride smoothing by reducing aircraft motion not only for passenger and crew comfort, for example, in STOL aircraft but also for relief of pilot and crew fatigue in military missions. Active control techniques are being used in the B-52 fleet as a result of the LAMS (Load Alleviation and Modal Suppression) program for routine control of repeated loads in rough air or in low-altitude flight by servo-control of rigid and flexible modes. Rudders and aileron are used in the lateral-directional system and elevators in the longitudinal system. The system provides at least a 50% reduction in damage rate. The canard surfaces on the B-1 are to be used for similar purposes.

Active flutter suppression, a technique for damping flutter modes using aerodynamic surfaces, is considered the most radical of these concepts, yet recent progress has been very promising. The benefits may be large structural weight savings and the removal of flight envelope restrictions such as flutter speed placards. It is, of course, necessary to insure that adverse effects, if any, are negligible. Three such flutter programs, having varied points of interest, will be briefly described.

B-52 Active Control Program

A comprehensive CCV program for the B-52-E airplane including flutter mode control (FMC), initiated by the Air Force Dynamics Laboratory and the Boeing Company, Wichita Division,[22,23] is indicated in Fig. 8; also shown are the control surfaces utilized for a ride control system (RCS), maneuver loads control (MLC), augmented stability (AS), and for fatigue reduction (FR). The supplementary Fig. 9 indicates the types of sensors proposed for each system.

The flutter mode control system was demonstrated in a pioneering flight program and supplemented by a parallel wind-tunnel study at the Langley Research Center which employed a 1/30-scale aeroelastic model[24] (see Fig. 10). Flutter was induced in the normal flight envelope by ballasting the added tip tanks, and control was achieved by special outboard ailerons and flaperons as shown in Fig. 8. The wing flutter mode was symmetric at 2.4 Hz with a gradual onset. Flight, wind-tunnel, and analytic results expressed as damping vs airspeed may be compared in Fig. 11. Differences of the order of 10% remain in the flutter speeds between the various approaches, and although differences in the damping levels exist, the damping trends for subcritical speeds are similar. It is noted, however, that in each case a significant improvement is indicated between the open and closed-loop results. Improvements such as better simulation for the nacelle support

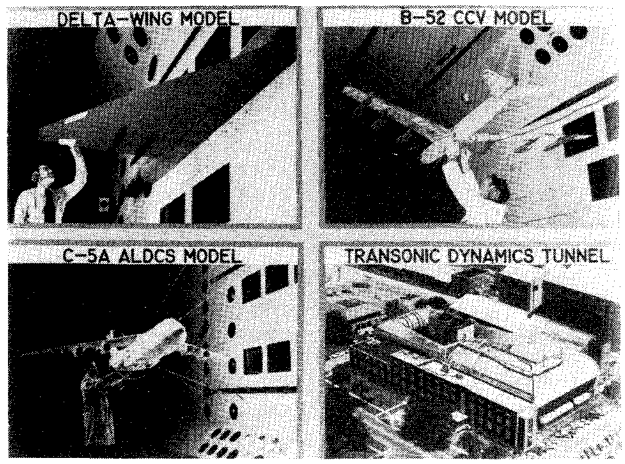


Fig. 10 Aeroelastic models in the Langley Transonic Dynamics Tunnel.

system and better estimation of the structural damping are recognized as needed to bring the results into better alignment. The degree of validation of flight trends, however, is promising for the use of both aeroelastic analysis and wind-tunnel models in the future developments for control configured vehicles.

Flutter Control Based on Aerodynamic Energy Methods

The Boeing SST delta wing has served as a focus for several special flutter studies. One such study initiated a Langley employed a wind-tunnel model (Fig. 10) and was aimed at demonstrating the use of an aerodynamic energy concept of Nissim,[25] wherein both leading- and trailing-edge control surfaces are used to control bending-torsion wing flutter. The objective was to develop a control law involving both of these surfaces that would prevent work being done by or energy being drawn from the airstream enough to overcome the inherent damping of the structure, that is, to cause flutter. A short explanation of the concepts involved may be based on the opposite quantity, the work $\bar{W}$ done by the wing per cycle as it undergoes oscillations in bending $h=h_0{}^{i\omega t}$ and in torsion $\alpha=\alpha_0{}^{i\omega t+i\phi}$, where h_0 and α_0 are amplitudes and ϕ is the phase difference between bending and torsion. The expression for $\bar{W}$ is a quadratic of the form

$$\bar{W}=B_1h_0^2+B_2\alpha_0^2+B_3\alpha_0h_0$$

where B_1 represents damping in bending, B_2 damping in torsion, and B_3 is a cross-coupling damping. These terms also contain the contributions of the control surfaces embodied in the chosen control law. By a linear transformation of h_0 and α_0 the cross-coupling terms clearly may be made to vanish so that $\bar{W}$ may become a principal quadratic form

$$\bar{W}=\lambda_1h_1^2+\lambda_2\alpha_1^2$$

The terms λ_1 and λ_2 for given geometry and location of the sensors may be studied as a function of the frequency of oscillation and the choice of the control law. If λ_1 and λ_2 are both positive, $\bar{W}$ must be positive, hence work is being done by the wing on the airstream, and flutter is not possible in the assumed modes. Moreover, since the requirement λ_1 and λ_2 positive is sufficient but not necessary, optimum values requiring minimum control power, may be sought. Nissim has shown that these concepts carry over to an arbitrary number of degrees of freedom. He has also applied the method to a trailing edge and tab arrangements.[26] The wind-tunnel study[27] demonstrated the validity of these concepts. Increases in flutter speed as obtained by use of several control laws or strategies and as verified by test are shown in Fig. 12. Also shown is a time history for one of the cases showing the damping effect of turning on the suppression system. The study indicated the need to improve the accuracy of the control surface aerodynamics especially of the leading-edge surfaces.

We may note that aerodynamic energy or work concepts were used by Carta[28] in 1967 to investigate and gain insight into the flutter instability of complex turbojet rotor systems caused by interactions between unsteady air loading and coupled vibration modes of a rotating blade-disk-shroud system. Carta shows both by potential flow theory for low angles of flow incidence, and by empirical data for high angles, that under certain conditions of vibration coupling, which are to be avoided, energy can be transferred from the air to give rise to flutter. A fuller development of this approach has appeared in 1975[8] and evolved into a design and development tool for modern rotor technology, which has been used with empirical data even for some stall and separated-flow flutter problems.

It is of interest to observe that the aerodynamic energy concepts, which had their early use by von Karman and Burgers in 1934 for determination of propulsion in flapping flight, have evolved under Lighthill's master touch into new fields in natural philosophy, as given in a recent volume, *Mathematical Biofluiddynamics.*[29]

Flutter Control of Aircraft with External Stores

A series of thoughtful reports by Triplett and associates[30-33] has considered the problem of control of wing/store flutter by active means. The problem is of special concern for military aircraft carrying external fuel tanks, missiles, or other stores. One may predict that the routine application of active flutter control is most likely to occur first for wing-external store applications. Indeed, the B-52 airplane demonstration of flutter control in flight was really an airplane-store flutter control demonstration in view of the added ballast tank. The number of signficant parameters that may arise through variation of stores and their supports is exceedingly large, and thus the problem demands versatile solutions. Active control with sensors on the main aerodynamic surfaces, rather than on the stores, with the possible use of adaptive gains, was the solution sought. The analytically predicted flutter boundary for the F4 airplane carrying a 370-gallon external tank at the

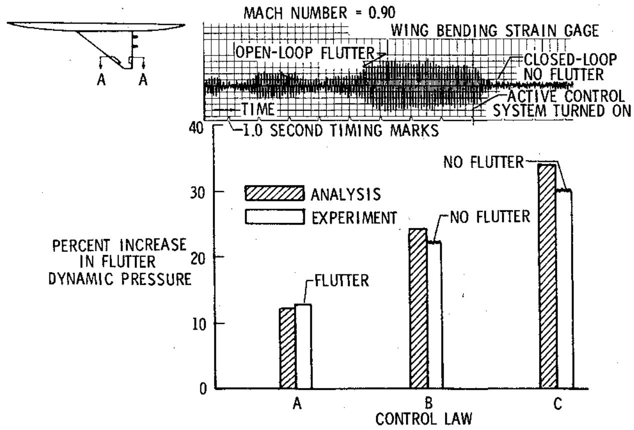


Fig. 12 Active flutter control of SST type delta wing in wind tunnel; also showing time history for one of the control laws employed.

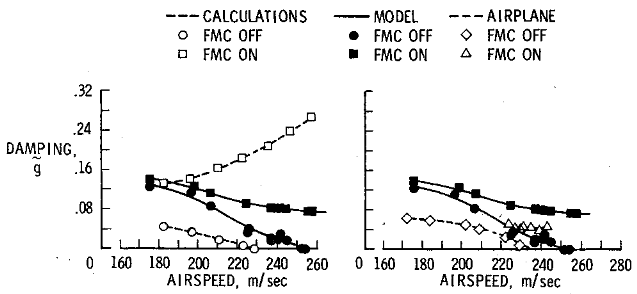


Fig. 11 Active flutter control of modified B-52 airplane showing results of model tests and analysis and of model flight tests.

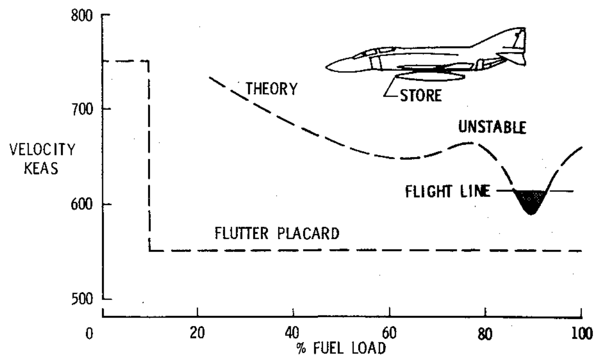


Fig. 13 Airplane/store flutter boundary (F-4 with 370-gal tank).

outboard store station is shown in Fig. 13. Also shown is the flutter encounter line determined by flight test, and the flutter speed placard line. Although the program was limited to a feasibility study, it has identified the design, performance, and hardware for an adaptive system to accomplish active flutter suppression of the F4 wing-store problem. Plans have been given for a wind-tunnel and flight verification program. A study[32] was made of various adaptive control techniques as is indicated in Fig. 14. These techniques clearly bring to the fore nonlinear control methods in general, including concepts of saturation, conditioning, multiple gains, growth and decay, hysteresis and lag, and emulation of nonlinearities arising in nature.

Remarks on the Mathematical Treatment of Active Controls

A brief overview or outline of some of the methods employed (which go back many years) may be of interest. Basic equations of aeroelasticity may be expressed symbolically as

$$\mathcal{S}(q) - \mathcal{A}(q) - \mathcal{I}(q) = Q \tag{1}$$

where $\mathcal{S}$, $\mathcal{A}$, and $\mathcal{I}$ represent structural, aerodynamic, and inertial operations on the (generalized) displacements q, and Q is an applied system of disturbance forces. A damping force operator may also be added. The operators may be linear or nonlinear combinations of algebraic, difference, differential, or integral operations.

By assuming linearity of all operators, the vibration equations about a nominal flight condition may be written as a matrix equation

$$([S] - [A] - [I])\{q\} = \{Q\} \tag{2}$$

For an aircraft represented as a discrete system of finite elements these matrices may be of extremely high order. More commonly for dynamical problems the order is greatly reduced by employing continuous modal representations. In either case the equation can be grouped into the form

$$[B_{ij}]\,[q_j\} = \{F_i\} \tag{3}$$

where

$$B_{ij} = (m_{ij} + a_{ij})p^2 + (r_{ij} + b_{ij})\ p + (k_{ij} + c_{ij}) \tag{4}$$

and where p may be considered to be the operator $\mathrm{d}/\mathrm{d}t$ or as the Laplace transformed (algebraic) variable. In Eq. (4) the individual terms are shown separated into structural and aerodynamic parts and into a sum of mass, damping, and stiffness terms. The forcing function F_i must take account for active controls of the contribution of each mode q_i to the response of the various sensor elements, and hence through

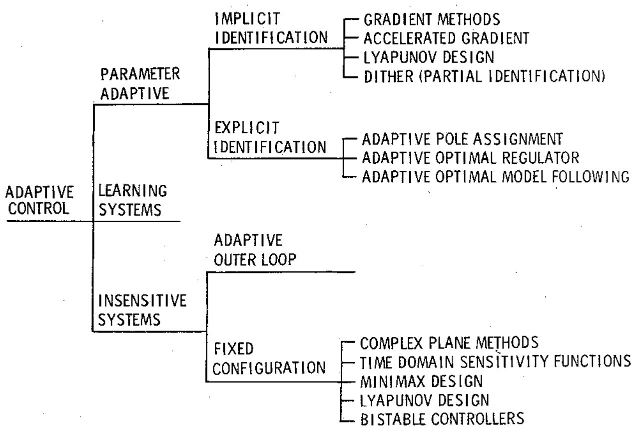


Fig. 14 Some adaptive control techniques (discussed in Ref. 32; attributed to C.F. Price and W.D. Koenigsberg).

the chosen control law or transfer functions to their output response. In order to simplify the analysis, the control transfer functions are usually chosen to be simple fractions of polynomial functions of p (such as Padé approximants).

The aerodynamic terms a_{ij}, b_{ij}, and c_{ij} are not constants (as was assumed in the early British work on flutter around 1928) but contain heredity terms that depend on the wake and are generally found from lifting surface or strip theory as functions of the harmonic frequency ω, or of the reduced $k = \omega l / v$ (where l is a length and V the velocity) rather than of p, and can be grouped into a complex term $A(ik)$. However, by assuming analyticity of all aerodynamic terms the variable ik is converted to the variable $p = \lambda + ik$, and λ conveniently written as γk (where γ is the ratio of damping to critical damping of an equivalent viscous damping system). This step for the two-dimensional incompressible case has been the subject of much controversy during the early 1950's because of a logarithmic singularity in the use of the Theodorsen function $C(k)$ for $k=0$ (and pecularly associated with decaying oscillations rather than growing oscillations, since such oscillations were treated as infinitely large in remote time). However, for wings of normal aspect ratio the singularity seems to be extremely weak and does not seem to affect numerical results.[34] Moreover, the aerodynamic treatment of the oscillating wing as a causal system suddenly started from rest will also avoid the problem.

(The question of the behavior of $C(k) = F(k) + iG(k)$ for k negative has always seemed to me to be essentially a moot one. For, the change of the convention of choice of $e^{i\omega t}$ to $e^{-i\omega t}$ ab initio, would require directly that $C(-k) = F(k) - iG(k)$ so that $F(k)$ is an even function of k and $G(k)$ an odd one. These requirements must also be carried along when various polynomial approximations are introduced for $C(k)$ and as often happens spurious roots arise.)

The use of a structural damping "g" concept in flutter analysis wherein the structural stiffness terms are multiplied by factors $1 + ig$, has both simplified and obscured the picture. This concept of damping has legitimacy only for sinusoidal oscillations, and originally could be interpreted to represent approximately the exponential factor $e^{ig} \approx 1 + ig$, and which implied an elliptic hysteresis-loop type of damping. The factor $1 + ig$ has the virtue of leading to algebraic rather than transcendental characteristic (eigenvalue) equations. Solutions for the flutter speed appear in the form of a relation between v, g, and k; and only when g is actually equal to the nominal value of the structural damping, often taken as zero, does the combination represent a true flutter solutions. Thus in the g, v, k plots, the g values are artificial, representing the structural damping necessary to allow harmonic motion, and in fact are mainly determined by the aerodynamic terms. Thus for a more realistic interpretation of damping and subcritical response, conversion from g, v to γ, v plots is indicated. For the $M=0$, 2-D case, the Theodorsen function $C(k)$ and its Laplace transform, the Wagner indicial function $k_1(s)$, where s represents the number of chords traveled can be approximated by functions convenient for control system analysis.[35] Equation (3), in its differential equation form, can then be solved for arbitrary motion with the use of the indicial functions and convolution. In the general case for arbitrary M and 3-D, where aerodynamic results are given numerically rather than analytically, it is necessary to employ various devices, such as representing the generalized harmonic aerodynamic forces by appropriate approximations in ω or k for a range of frequencies of interest.

Figure 15 taken from Hassig[36] illustrates differences that may arise in certain anomalous cases between g, v, and λ, v representations; Hassig supplies additional background references. A bonus in the p approach is that converting from the frequency (stability) domain to the time history domain by the inverse L- transform methods is relatively straightforward. In the time history domain one can more readily introduce appropriate nonlinearities of servomechanical actuator system as corrections.

An alternative approach for treatment of interaction of active controls and aeroelasticity, which although well known in optimal control theory, is just beginning to receive attention, employs state space methods. In this procedure the original differential equation in the form

$$[A]\{\ddot{q}\}+[B]\{\dot{q}\}+[C]\{q\}=\{F(t)\} \tag{5}$$

may be transformed to the state space canonical form

$$\{\dot{x}\}=[E]\{x\}+\{G\}$$

where

$$\{x\}=\begin{Bmatrix} q \\ \dot{q} \end{Bmatrix} \tag{6}$$

$$[E]=\begin{bmatrix} 0 & I \\ -A^{-1}C & -A^{-1}B \end{bmatrix}$$

and

$$\{G\}=\begin{Bmatrix} 0 \\ A^{-1}F(t) \end{Bmatrix}$$

$[E]$ defines the system and $\{G\}$ the input.

For multivariable inputs the equation takes on the standard form of linear optimal control theory

$$\dot{\underline{x}}=\underline{A}\underline{x}+\underline{B}\underline{u} \tag{7}$$

where matrix $\underline{A}$ represents the system characteristics and $\underline{B}$ the shaping matrix of the control variables $\underline{u}$. If a quadratic performance index is introduced, say, for minimum control movement or minimum power required, the standard methods lead to a Riccati matrix differential equation for solution.[37-39]

Unsteady Aerodynamics of Arbitrary Configurations

The goal of conveniently obtaining analytical or numerical unsteady flow aerodynamics for arbitary configurations, even in unseparated flows, is still far off, yet in the past few years much progress has been made along the road. An indication of some of the current developments, admittedly highly selective and incomplete, is given here.

First, a brief look back will be helpful for orientation, and to begin with consider only potential flow. It has been shown that the exact equation for compressible isentropic unsteady potential flow can be cast into the form of a *local* wave equation, wherein the velocity potential propagates with the local speed of sound and is convected with the local velocity. Local linearization methods, analogous to a piecewise linear treatment of the differential equations that have been used for the approximate treatment of transonic flows, rest on this property. The linearized forms of the equation for small disturbances for subsonic and supersonic flows reduce to the standard equations of aerodynamics or acoustics for a moving stream. Basic solutions of the equations could be found from classical methods utilizing Green's theorem, methods which applied to the classical wave equation lead to Huyghen's principle and Kirchoff's formulas associated with the superposition of waves in optics and acoustics. The transonic and hypersonic regimes remain inherently nonlinear.

Concepts of H.G. Küssner (1940) for general lifting surface theory led in the linearized case to an integral equation relating known normal velocity (downwash) to the unknown lift or pressure distribution by means of a so-called kernel function, the integration being taken over the mean lifting surface. The kernel, a highly singular function, represents the normal downwash associated with a unit point load and is a kind of influence function or Green's function due to a doublet. Some 15 years elapsed before it was reduced to a form suitable for solution. By 1965 more than half a dozen computer codes has been developed for lifting surfaces, utilizing various kernels which depend on whether the acceleration or velocity potential is used and where the integrations are taken over the lifting surface along, or over both lifting and wake surfaces. To include effects of thickness and inteference, it is necessary to employ the nonplanar forms of the kernel functions, which actually are less singular than the planar forms.

Numerical approaches for successful solution of the integral equations have included both discrete and continuous (modal) methods. The discrete approaches may be termed aerodynamic finite-element methods being quite analogous to the finite-element methods in structures; one such method, the subsonic doublet lattice method of Rodden and coworkers is prominently used in industry because it is systematic and adaptable.

Since about 1970 many applications and refinements for wing-body configurations, interfering surfaces as T-tails, and control surfaces have been developed. A review (1972) by Ashley and Rodden[40] has cited more than a hundred references. Many additional works are cited in Ref. 13. These will alleviate the need for numerous specific citations in this discussion. A systematic approach for wing-body steady flow aerodynamics is that of Woodward; an application is

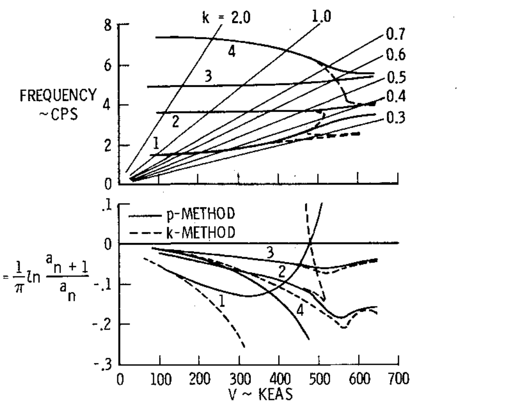


Fig. 15 Comparison of responses by a "p" method and by a "k" method for twin-jet transport.[36]

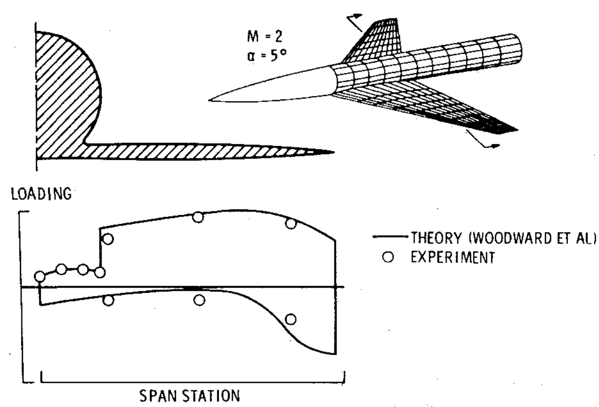


Fig. 16 Wing-body calculation and experiment (steady flow).

illustrated in Fig. 16. The method has been incorporated into the FLEXSTAB static aeroelasticity and stability programs.[14] Currently, a major effort is going into NASTRAN to improve its capabilities for unsteady flow aeroelastic analysis.

Analytical methods for obtaining aerodynamics of steady and oscillating control surfaces have taken on much greater significance because of the contemplated uses of active controls. The shortcomings of potential flow solutions, because of boundary-layer and separation effects are quite apparent in this realm. Nevertheless, potential flow methods for arbitrary control surfaces need to be more fully developed first. A large step in this direction utilizes kernel function methods, with allowance for local velocity effects due to thickness, and is given in Ref. 42, where partial span leading- and trailing-edge control surfaces with sealed gaps have been treated. Fig. 17, taken from this reference, shows results for a partial span flap deflection of a tapered swept wing in steady flow. An oscillatory flow calculation and comparison with experiment for an outerspan flap configuration is shown in Fig. 18.

Among recent work that of Morino is very promising for future development and application.[43-45] Morino has given a general systematic treatment for the nonlinear unsteady potential equations which he arranges as an iteration procedure, wherein the linearized equations are to be solved first. Boundary conditions are taken at the wing surfaces consistent with the order of iteration, rather than at the mean surface. An interesting aspect of Morino's approach is that it is completely classical, in that it is a direct application of Green's theorem, wherein the theory of distributions and the use of generalized functions facilitates demonstration of the validity of the results. An end result[45] is an integral relation in space and time variables (entirely similar to the one in Huyghen's principal) between the surface normal velocity and the velocity potential which Morino terms a "generalized" Huyghen's relation. Reversing the usual procedure of eliminating the time first, by discretizing the space variables first and then eliminating time by Laplace transforming to the s variable, Morino is able to express the transformed velocity potential explicitly as a transfer matrix times a transformed downwash matrix, which can be calculated in terms of the known boundary conditions at the surface. The effect of the wake is obtained with the usual assumption that it remains where it is formed, although higher order approximations can account for wake motion and interference. Morino shows excellent agreement with other numerical methods and indicates that the integrations over the wake for nonstationary flows may be greatly truncated without significant loss of accuracy. Thus the method has several advantages that may lead to its more widespread use: it may be applied to oscillatory or transient flows; boundary conditions are taken at the actual surface position (akin to this respect to the classical approach of J.L. Hess and A.M.O. Smith for $M=0$ flow); apparent versatility for time or frequency domain analysis; capable of systematic higher order improvements. However, very little has been performed as yet beyond the first step in the iteration process.

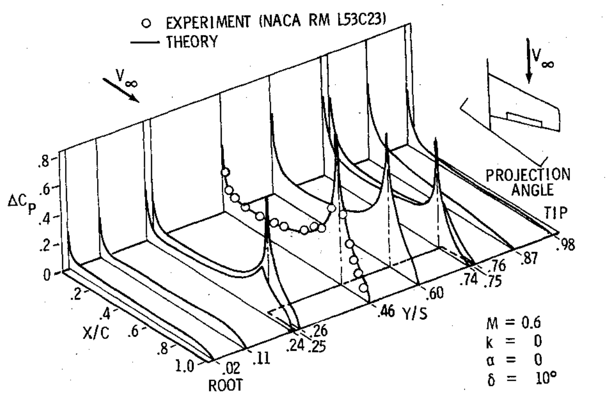


Fig. 17 Predicted and measured pressure distributions for a partial-span flap in steady flow.[42]

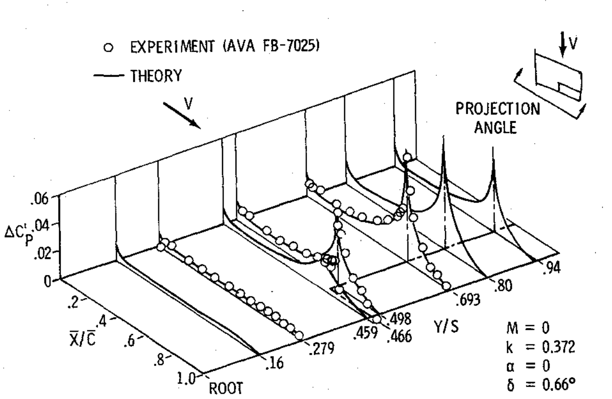


Fig. 18 Predicted and measured in-phase pressure distributions resulting from sinusoidal motion of an outer-span flap. (Ref. 42 also gives the out-of-phase results.)

Transonic Flow Consideration

The transonic speed regime has usually been critical for aeroelastic problems for several reasons. Often the dynamic pressure q is at or near a maximum and the flutter speed index in terms of q may have a significant dip in this regime; in addition, transonic shock characteristics may lead to local flow sensitivities and to separated flow, buffet, and buzz of control surfaces.

The supercritical wing (Whitcomb)[46] successfully postpones the transonic drag rise; the question of its aeroelastic effects is still quite open. Comparison of two similar elastic wings, one with a supercritical airfoil configuration, the other conventional, indicated relatively small differences with respect to wing flutter. Such a comparison may not be a valid one really since the supercritical wing permits thicker wings of higher aspect ratio and lower sweep to accomplish similar performances. Because of the aft chordwise loading of the supercritical wing section one may, however, expect significant differences for control surface, and for wings wherein chordwise camber modes are more involved in its vibration spectrum.

The work of Garabedian and associates at New York University[47] on the theoretical design of supercitical shockless airfoils has been based on the hodograph variables and the brilliant use of the mathematics of "complex characteristics." The behavior of the design airfoil at off-design conditions is, of course, also needed and was accomplished by numerical solution of the partial differential equations by finite difference methods, with innovations to speed the numerical convergence by Jameson.

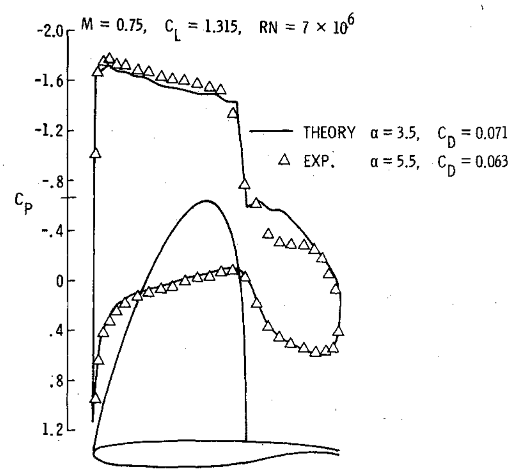


Fig. 19 Off-design pressure distribution for supercritical airfoil.

A calculation on an early Whitcomb configuration is shown in Fig. 19; a semiempirical correction for the boundary-layer displacement thickness has been included. Comparison of experiment and calculations for the relatively high C_L value of 1.3, and for the drag rise with Mach number in general, shows relatively good agreement. Applications have also been made to compressor blades and to the Jones oblique wing as an early instance of extending the work to include some three-dimensional flow effects.

Methods for unsteady flow perturbations in the transonic regime require knowledge of the baseline solutions for steady flow. With these solutions as input, the "local" wave equation referred to earlier becomes a linear one with variable coefficients. Several approaches now exist; some references are described by Bland.[48] Singled out mention may be made of numerical finite-difference schemes used by Ehlers and by Magnus and Yoshihara; local linearization methods given by A.M. Cunningham and be Stahara and Spreiter. Need for much additional development, simplfication, and assessment of accuracy remains.

Computational Fluid Dynamics

Advanced methods in both structures and aerodynamics require large investments in numerical computation. The speed and potential of the very latest generation of computers such as the CDC STAR, is such that many more numerical operations (such as a 64-bit number addition) can be done in a second than there are seconds in a year! The most rapidly advancing area in fluid dynamics, indeed, seems to be in the computational field. The proceedings of two recent conferences illustrate well the scope of problems tried and solved.[49,50] Important progress was shown on calculations in two and three dimensions of some Navier-Stokes problems involving boundary-layer transition, separated and reattaching flows, wall interference, even turbulence modeling. Other numerical problems have treated arrow wings in transonic and supersonic flows with leading- and trailing-edge interacting vortex flows, internal flows, and nonequilibrium and reacting flows. Much of this is, however, in a quite early stage as far as unsteady flow effects are concerned, for example, on dynamic stall effects and the aerodynamics of lifting rotors. It must be cautioned that numerical approaches should, of course, not necessarily mean purely numerical work (which can be abhorrent to many analysts) but should include sufficient analysis for insight and perspective.

Aeroelasticity and the Space Shuttle

A monumental decade of man in space and on the Moon ended for the U.S. with the launching of the last of the Saturn vehicles in July 1975. A new start will take place with the reusable space shuttle in the 1980's. Advanced technology and "focused" research in many diverse fields have been involved in the development of the shuttle; a comprehensive description of these fields and of the pivotal technical issues were given by Love in the 1972 von Karman Lecture.[51] The intention here is to dwell briefly on some of the problem areas related to aeroelasticity and the methods for resolving them.

A view of the shuttle showing the external tank (ET), the solid rocket boosters (SRB), and the orbiter (O) is given in Fig. 20. Potential problems in dynamics and aeroelasticity, which involve, to one degree or another, details of the vibrational characteristics of the shuttle or its components, are indicated in two figures borrowed from Love and

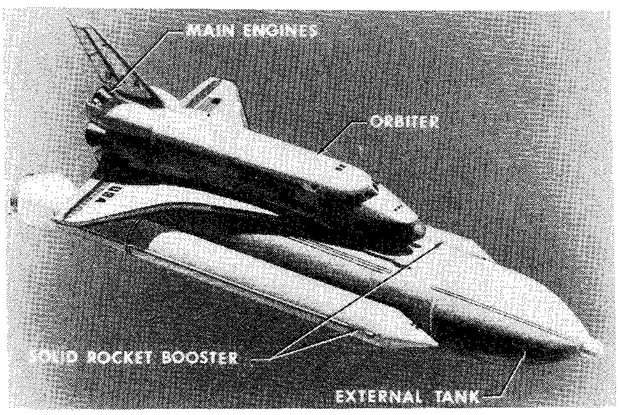


Fig. 20 Space Shuttle.

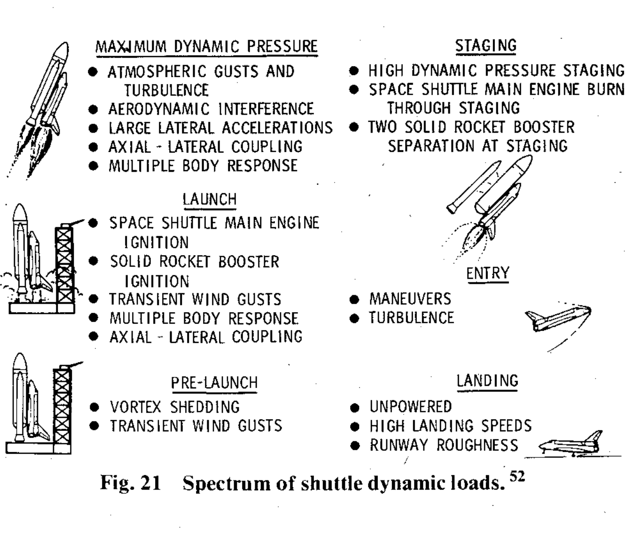


Fig. 21 Spectrum of shuttle dynamic loads.[52]

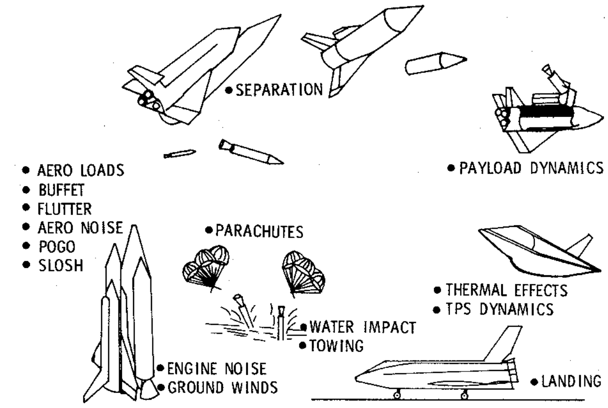


Fig. 22 Problem areas of the space shuttle in dynamic loads and aeroelasticity.

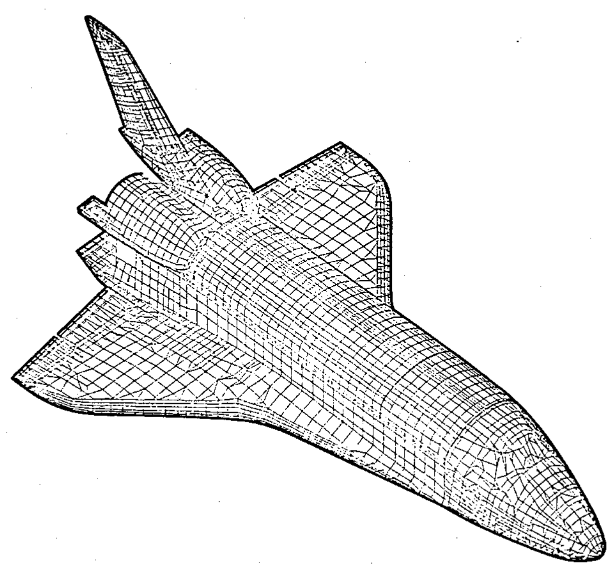


Fig. 23 Computer generated orbiter based on finite elements.

Thompson[52] (Figs. 21 and 22). It is recognized that the system with its large offset components is a highly complex one, involving marked lateral-longitudinal mode couplings.

A view of the orbiter as generated by structural finite elements on a computer is shown in Fig. 23; the individual elements are beams, rods, torque tubes, various plates, and shells. To develop knowledge of the behavior, with respect to loads and dynamics, of the components of the shuttle, and of the combined system, great reliance is being placed on the finite-element "math" models involved and on their continual updates. This is accomplished by the interaction of analysis, test hardware, simply and complex vibrational models, and finally some full-scale testing.

A relatively inexpensive early research model of the shuttle of ⅛ scale has been under study by Langley over the past several years to help define the couplings and modal interactions (Fig. 24). It is noted that previous experience with the use of elastic models of launch vehicles evolved with the development of the Saturn vehicles. Both simulated and near replica models have been used and have played important roles in development.[53] An elastic model had a prime role in the development of the Titan III for which no full-scale dynamic test vehicle was actually employed. Figure 25 shows several of these models.

As indicated in Fig. 26, a ¼-scale partially replica dynamic model is being assembled (at Rockwell International Space Division). The analytical activity for prediction of the characteristics of the model is of great importance in the development process as it will mean the tying together of the math models for the various components which are being designed, built, and analyzed by different contractors. It will also mean that proper reliance can be placed on the math model of the assembled full-scale vehicle system. In this process the methods of *substructuring,* based on finite-element analysis, and of *modal synthesis,* based on component mode analysis, which have seen major developments in the past decade (although still in need for much improvement) are being greatly relied on, and essentially replace lumped mass-and spring-model methods.[54-56]

Substructuring methods require independent structural analysis of component substructures of an assembly, in which the substructure is defined by its stiffness and displacement forces acting on it and on its boundary. Combining or integrating substructures is their joining at common boundaries to yield total system stiffness characteristics. Modal synthesis methods are aimed at synthesizing coupled modes of a complete assembly in terms of modal characteristics of components with due regard to compatibility and restraints at junctions. With inertial characteristics considered as included in substructuring methods, modal synthesis methods may be regarded as also incorporated. These concepts are still evolving and there is need for development of more efficient and less tedious methods.

Some features of the shuttle that have required very special study and treatment are indicated in Fig. 27. The pogo problem which from a mild to possibly violent degree, has arisen for all large launch vehicles is a longitudinal transient

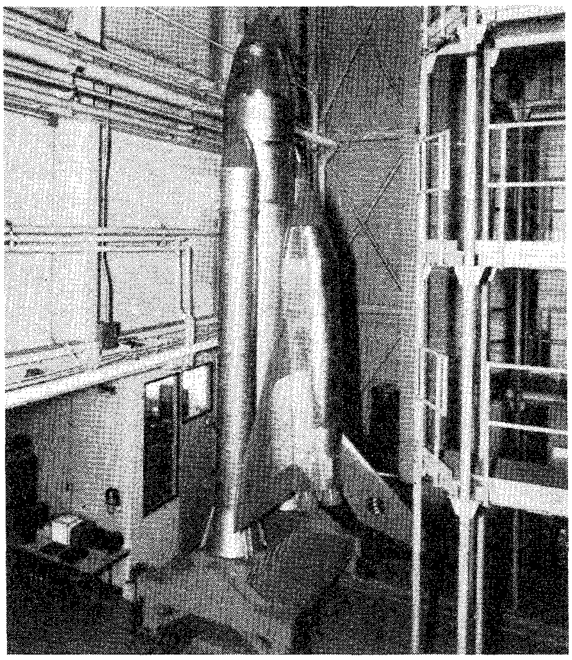


Fig. 24 ⅛-scale vibration model of the shuttle.

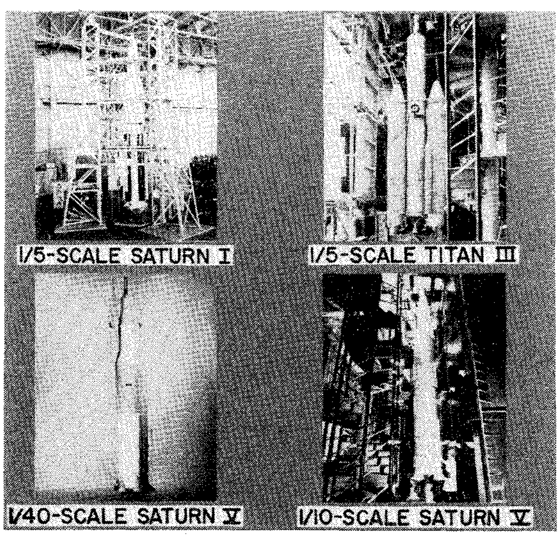


Fig. 25 Several elastic models of launch vehicles.

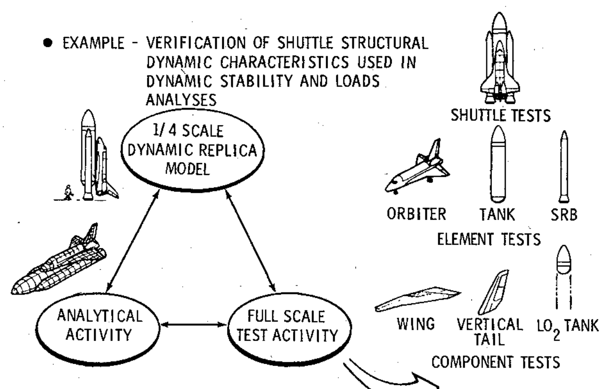


Fig. 26 Substructuring approach via analysis and elastic model to shuttle structural dynamics.

PROPULSION/STRUCTURAL COUPLING (POGO)

- AXIAL - LATERAL COUPLING DUE TO ASYMMETRY
- LONG LIQUID OXYGEN LINES CAUSES CLOSELY SPACED LINE NATURAL FREQUENCIES
- LATERAL SEGMENT OF PROPELLANT FEED LINE ENHANCES EFFECTS OF AXIAL - LATERAL COUPLING
- HIGH CHAMBER PRESSURE, TWO STAGE PUMP MAIN ENGINES
- POSSIBLE POGO/FLIGHT CONTROL COUPLING

LIFTING SURFACE FLUTTER

- AERODYNAMIC INTERFERENCE DUE TO MULTIPLE BODIES

CONTROL SYSTEM STABILITY

- AXIAL - LATERAL COUPLING DUE TO ASYMMETRY
- HIGH MODAL DENSITY OF CONFIGUTATION

Fig. 27 Features of potential instabilities of the shuttle.[52]

oscillation associated with the feedback between structural and propulsion system dynamics. Physical and loop elements of the basic pogo problem are indicated in schematic Fig. 28. The regenerative feedback is associated with the changes in the vehicle modal characteristics as fuel is depleted (recall that fuel weight is 80% of the lift-off weight) and the hydroelastic interaction with the fuel feedline and pump characteristics; thus, thrust variations and longitudinal vibrations may mutually enhance one another. For the shuttle, the problem is complicated by the long feedlines with many turns and organ-pipe modes, the longitudinal-lateral vibration coupling between components, the possibilities of higher interaction modes, and the more complex coupling between control and guidance systems.[57,58] The analytic problem of determining transfer functions between the elements of the system is not yet state of the art and requires empirical data especially for the pump and feedline characteristics. Consequently, much reliance will be placed in techniques to decouple the structural and propulsion systems by means of a gas accumulator acting as a soft spring within the system. The most effective location for the accumulator has been estimated by analysis using experimental data for the pump compliance to be the inlet to the high-pressure line in the liquid oxygen line. Similarly to avoid pogo the Titan-Centaur vehicles employed in the Viking-Mars Mission was very successfully fitted with an accumulator in its oxydizer line ahead of the pump.

Instead of using ablation concepts for its thermal protection, the shuttle will employ a thermal protection system (TPS) of insulation of the main load-bearing structure by a system of ceramic tiles mounted on a so-called strain isolation pad. An illustrative view of such tiles undergoing combined aerodynamic pressure and thermal tests is shown in Fig. 29. The thickness of the tiles will be tailored to fit the predicted thermal and dynamic load environment of its position on the structure. The structural integrity of the tiles and their reuse or refurbishment are problems of much concern. It would appear that the aeroelastic panel flutter problem will be avoided provided approach to any local buckling conditions can be avoided, so that the thermal and pressure loads will dominate the requirement. Thus the avoidance of local hot spots is important and solution of the gap impingement problem of the adjacent separated tiles takes on importance. Considerable theoretical work on flutter of sandwich panels and layered nonhomogeneous panels has been accomplished as a consequence of these TPS problems, while much ingenuity has gone into the covering materials. Of special interest is the use of a *compliant* material cover for areas where very thin tiles would be required. Compliant cover material has also been proposed in other applications since aerodynamic evidence exists of significant reductions in turbulent skin-friction drag ("dolphin-porpoise" effect). The aeroelastic behavior of such surfaces has not been thoroughly investigated.

Problems arising from separated flows are of great importance for the shuttle. Because of its rather blunt geometry, wide ranges of speed, flight attitudes, and angles of attack, buffet problems on exit and stability problems on entry are of special concern. For example, the orbiter fin rudder has presented a buffet problem arising from separated flow near its hinge position. Another more extensive buffet problem occurs in the transporting of the orbiter, for which the B-747 airplane will be used in a carrier mode (Fig. 30). The effect of buffeting flow from the orbiter on the tail of the B-747 may severely reduce its fatigue life. Several remedies are being considered at this moment of writing, as increasing the strength of the tail, employing attachable dual split tails, employing aerodynamic vanes to de-energize or reduce the buffet region, and using an afterbody cover for the rear of the orbiter.

Air launch from the carrier airplane will be employed to study landing entry and approach problems, and at higher dynamic pressures, to gain such modal identification information that may help confirm ground-based test and analysis and avoid the necessity of exploring the boundaries of the complete flight envelope.

The shuttle must be able to sustain design ground winds of 70 knots. The winged configuration complicates the nature of the response to wind excitation. Several of the problems have been discussed by Reed.[59] An aeroelastic model may play a significant role in the design of the restraints and dampers of the shuttle on the launch pad.

Interference and interaction aerodynamics associated with the proximity of wings and bodies represents an important consideration for the shuttle. Analysis based on unsteady nonseparated potential flow has indicated relatively small effects on flutter,[60] however, separated flow analysis which is necessarily semiempirical has indicated some low or negative damping at supersonic speeds for low-frequency modes affecting the dynamic stability. The degree of separation associated with the plume induced flowfield and the damping characteristics need further resolution.

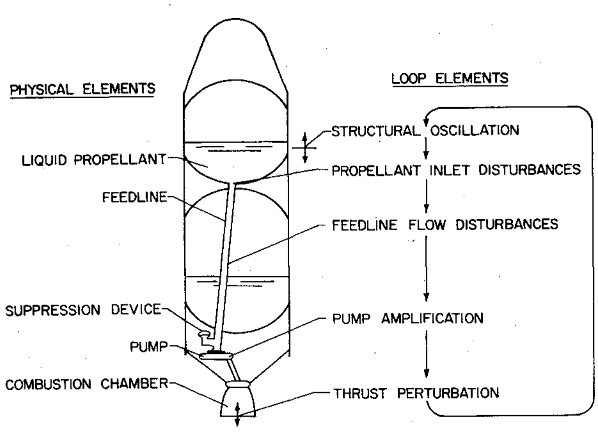


Fig. 28 Elements of the pogo problem.

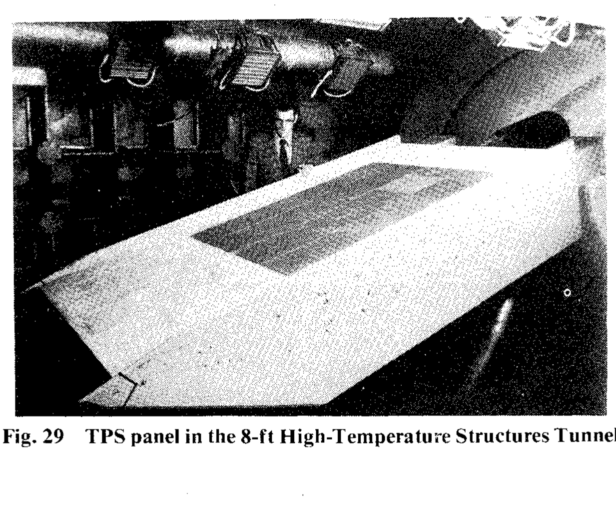


Fig. 29 TPS panel in the 8-ft High-Temperature Structures Tunnel.

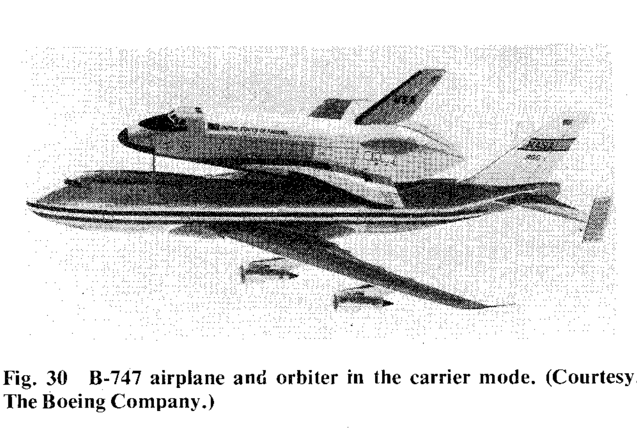


Fig. 30 B-747 airplane and orbiter in the carrier mode. (Courtesy, The Boeing Company.)

Verification of Flight Aeroelastic Behavior

Although the roles of analytical methods in design and development of a flight vehicle such as the use of finite elements and the math model have increased greatly, there remains the vital role of flight confirmation of aeroelastic effects. Brief comments on progress in this field, especially on flight flutter testing, make up this final topic.

Analytical methods of static aeroelasticity, it is recalled, must be relied on in design to yield configurations having the proper jig shapes during construction that will take on the desired cruise shapes in flight. Moreover, the significant effects of aeroelasticity on the slope of the lift curve and center of pressure must be correctly evaluated. (The author was informed by Poisson-Quinton of ONERA that because of aerothermoelastic effects in accelerated flights to altitude and to supersonic cruise, the Concorde may exhibit in different flights a two-degree elevator trim-angle change, an effect that it monitored, computed, and adjusted continuously in flight.) Evaluation of the effects of aeroelasticity on stability and control under various loading conditions involves the extracting of stability derivatives from carefully controlled flight tests. The fields of system identification and parameter identification—the identifying of the coefficients of the differential equations (usually linear although sometimes nonlinear) that define the system or parameters of the system —through suitably measured data have been the subjects of many recent papers and synposia.[61] (See also Refs. 34 and 41.)

Figure 31 indicates features of system identification by model matching. The method involves three main parts shown shaded: 1) the input corresponding to the excitation and flight test techniques; 2) the various instrumentation and flight test techniques; and 3) the analysis of the flight test data by an iteration scheme. The measured input as a time history is fed to the analytical model and the resulting computed output is compared with the measured output. The difference error is used to modify and to updata through a computational algorithm the a priori or previous estimate of the parameters of the model so as to reduce errors to a minimum.

Aeroelastic models in the wind tunnel may also yield valuable information in this domain, for example, Fig. 32 taken from Reed[62] shows the agreement achieved with flight measurement of aileron effectiveness for a large cargo transport at $M=0.75$ and its aeroelastic flutter model. Reed has also proposed the use of the aeroelastic model on a unique cable-mount system (Fig. 33) to extract free-flight stability and control derivatives under various loading conditions. The analytical method is essentially a parameter identification scheme utilizing measured responses to known inputs. The cable-mount system has also been used, together with gust generating vanes, to obtain gust response information, such as the frequency response of the B52 flutter model for comparison with flight.

The Langley Transonic Dynamics Tunnel utilizes as its medium air or freon or a mixture of both to achieve its Mach number and dynamic pressure characteristics. A major new laboratory, The National Transonic Facility, is being designed which when built at Langley will be operated by NASA and the Air Force. It will utilize the cryogenic properties of nitrogen to achieve very high realistic Reynolds numbers at transonic speeds. Although it is primarily intended for investigations of aerodynamic performance, consideration is being given to the special requirements that will arise for aeroelastic models.

Flutter in flight of an approved type aircraft is, of course, a rare event—flutter is expected to be eliminated by design. Nonetheless, cases occur; for example, flutter has been known

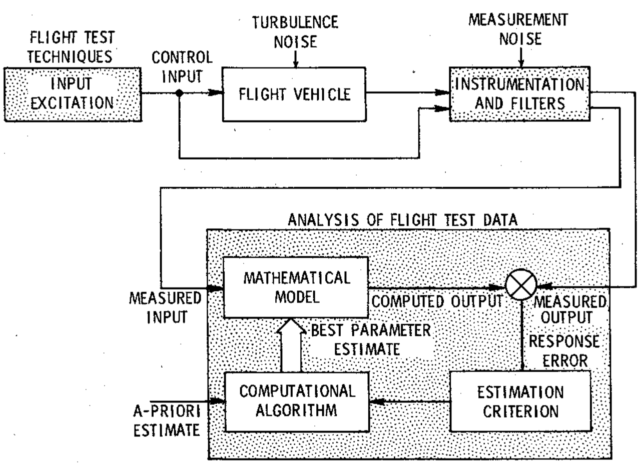


Fig. 31 System identification by model matching.[61]

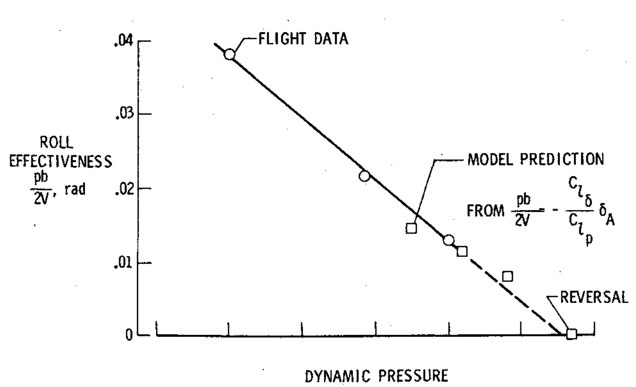


Fig. 32 Comparison of flight measurements and model-predicted aileron effectiveness.[62]

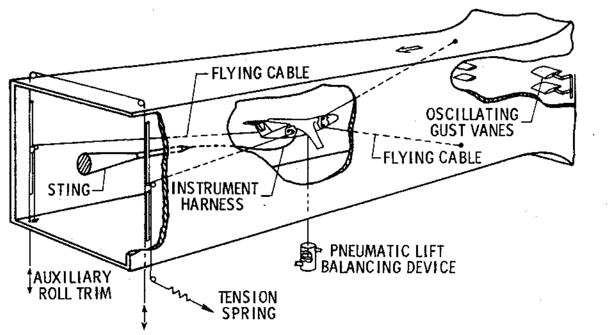


Fig. 33 Novel features for aeroelastic model testing in the Langley Transonic Dynamics Tunnel.

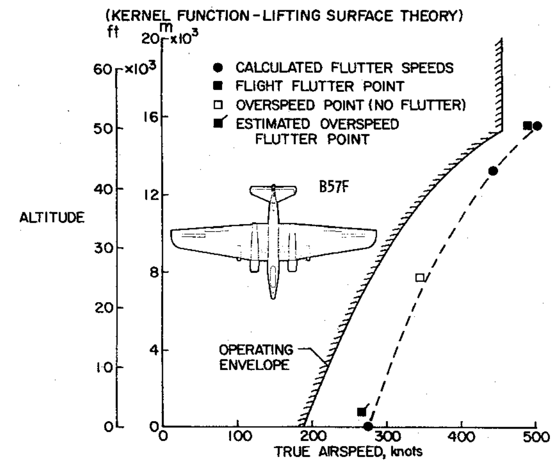


Fig. 34 Flutter speeds measured in flight and calculated by the Kernel Function Method (from R. Peloubet, General Dynamics Corp., Fort Worth, Texas).

to have been induced in general-aviation aircraft by the painting of lifting surfaces, accumulation of water or ice internally, by free play in controls, by loss of balance weights, or by lack of maintenance of dampers. Figure 34 shows a low-altitude flutter point of the aircraft depicted which unintentionally entered an overspeed condition outside of its normal flight envelope. A subsequent flight study and kernel function calculations gave the results and agreement shown. Figure 35 applies to the flutter of a newly developed missile whose canard wings came off at $M=1.7$ within its flight operating boundary. A wing of shorter span, redesigned on the basis of a piston theory analysis, performed satisfactorily as indicated.

Flight flutter testing is the search for exposing low damping regions of flight, hopefully averting negative damping. An art, a product of experience and ingenuity, and a science, a product of experiment and theory, it is the most sophisticated type of flight testing. In general, it encompasses the practice of detecting major response frequencies and obtaining damping of these modes at successive increments of speed.[63] Because flutter modes may arise rather suddenly and explosively, flight flutter testing must be carefully planned and cautiously pursued.

Two major conferences[64,65] specifically devoted to subcritical flight flutter testing have been held, one in 1958 and the other in 1975. It is of interest to remark on the changes that have occurred in the interim. Continuous improvements, in great measure due to the space program, in flightborne and ground-based computers have profoundly altered the balance of test and analysis. Analog methods have given way to digital ones; real-time test and data analysis have greatly reduced the duration and number of flight required. Active control places new emphasis on the analysis of nonlinear domains, distinctions between mild and violent flutter, and analysis of subcritical response and its correlation with effective damping concepts.

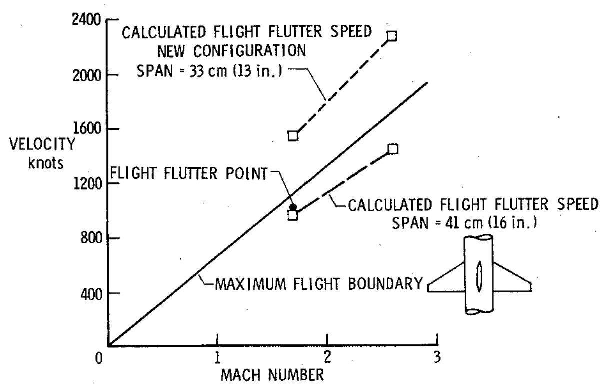


Fig. 35 Flutter of missile wings at $M=1.7$.

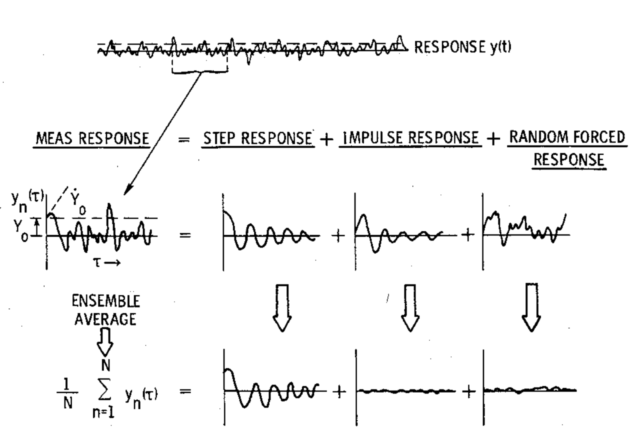


Fig. 36 Randomdec method concepts.[68]

Methods of excitation of aircraft in flight have included all manner of types, steady state, transient, pulsed and random, the latter including natural turbulence. Excitation of aerodynamic vanes has become widely employed since the induced inertia forces are small, and sinusoidal sweep has been used to decrease time durations and to maintain uniform flight conditions. With respect to determination of damping from noise-free, noise-contaminated, or noise-excited records many methods have been discussed by Houbolt,[65,66] such as standard peak and width of resonance or spectral density curves, vector plots of responses (Kennedy-Pancu method), differential sweep effects, correlation, cross correlation, spectrum and cross-spectrum methods to yield system characteristics with minimum noise, truncation or special weighting of portions of the time history or frequency records, iterative correlation and truncation, ensemble averaging and the random decrement ("randomdec") method. Despite the many methods, separation of closely spaced modes amidst noise remains very difficult and requires combined methods and ingenuity.

The randomdec method mentioned, due to Cole,[68] has the virtue of deriving the step-function response of a system from response to excitation by noise by very simple procedures that can be automated. The method is based on enhancing the signal and reducing the noise by procedures indicated in Fig. 36. The step-function response at amplitude levels y_0 to zero-mean noise, it may be noted, is the result of ensemble averaging of segments of the record at levels y_0, wherein the impulse response to the slopes y_0' and the response to noise average out to zero.

A good application of randomdec to data for the B-52 aeroelastic model at about 3% of the speed below flutter speed gave results shown in Fig. 37. Note the original noisy

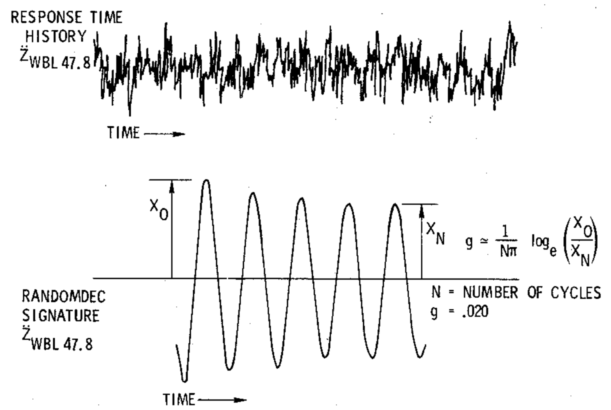


Fig. 37 Damping near flutter obtained from a noisy record by the randomdec method.

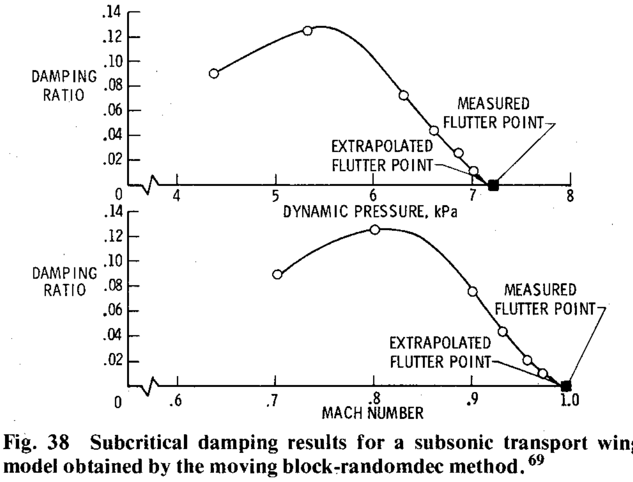


Fig. 38 Subcritical damping results for a subsonic transport wing model obtained by the moving block-randomdec method.[69]

record and the clean damping response obtained. A shortcoming of randomdec is that it is limited basically to the response of a single degree of freedom in a noisy field; it also has the requirement of adding together values from a large number of record segments. However, several variations of randomdec have been developed that may be successfully applied to records with many degrees of freedom, and with transient rather than random excitation. For example, Hammond and Doggett[69] have employed randomdec concepts but with transient superposed excitation and a "moving block" method (developed at Lockheed) to deduce frequencies and damping of a many mode system. An application to subcritical testing of a transport aircraft model in the wind tunnel led to the clean damping data shown in Fig. 38 both against dynamic pressure and Mach number.

A digital method of system identification employing sampled response data, difference equations of motion and their Z-transforms (the discrete analog of the L-transform) has been used by Grumman in their recent flight programs[67] and has had good success.

The flight flutter program[65] for the F-15 airplane, it may be noted, led to the detailed study of at least 13 different combinations of modes, mainly of the empennage, that gave flutter margins from the 15% margin, required for military vehicles, to 30% indicating achievement of a very weight efficient aeroelastic design.

It should be noted that flight flutter testing in the traditional sense is not feasible for the space shuttle. On launch the shuttle reaches its maximum dynamic pressure (650 psf) at $M=1.45$ in 80 seconds and passes through the transonic range at about three-fourths maximum dynamic pressure. Some of the control surfaces on the orbiter may be in locked positions on exit so that the milder reentry conditions will be significant for these controls. Although flutter margins are expected to be sufficient, it will be desirable or necessary to collect system identification data in the horizontal flights of the orbiter from the carrier aircraft, and possibly from the vertical flights by short bursts of pulsed or turbulence-excited responses. The vertical flights will be carried out, at first, at lower maximum dynamic pressures. Moreover, some data for damping and for system identification should be available from an aeroelastic model of the orbiter. Clearly, several approaches and considerable ingenuity will be required to obtain meaningful data.

Concluding Remarks

This survey of the reaches of aeroelasticity has been made by a sampling of current topics, rather arbitrarily selected. It is apparent that problems, methods, and solutions for both the theoretical and experimental aspects are becoming more computerized and sophisticated. Configurations are more varied and complex; aeroelasticity has merged with stability, flight mechanics, and performance and its methods apply to launch and space vehicles and to nonaerospace areas; active controls have added a new dimension, as has also the use of composite materials. Substructuring methods utilizing finite elements and math models need more development and more efficient procedures. Aerodynamics of unsteady potential flows need to be further developed for arbitrary configurations and for control surfaces, while nonpotential flows of many types need further breakthroughs. Through it all the need persists for simpler and less costly methods. Especially, the aeroelastician must develop insight into the physics of a problem so that the wide use of computers and black boxes can be a real blessing rather than a reliance on black magic. It is heartening that, although an old subject, aeroelasticity still breeds new applications and worthy challenges to equal or exceed any of those in the past.

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