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Aeroelasticity of Nonconventional Airplane Configurations—Past and Future

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At the end of the first century of manned, powered flight, it is worthwhile to look backward to understand how innovation in airplane design required developments in aeroelasticity and how aeroelasticity has played a role in shaping the first 100 years of aircraft design. The insights gained will help to predict how and where aeroelasticity and aeroservoelasticity will influence the future development of efficient, more capable, innovative air vehicles, and define the needs for technology and tools to enable this future. By definition, all new aircraft begin as unconventional to a certain extent. Designs that never see universal use remain curiosities, but still help our quest for better vehicles and guide the development of analysis, design, and testing tools. Innovative, nontraditional designs affected by aeroelastic considerations have included oblique wing aircraft, forward-swept wing aircraft, X-wings, flying wings, and large joined wings. Designs that were unusually innovative at the time of their introduction but later became widespread include the swept-back wing jet, the T-tail, and the fly-by-wire control configured vehicle. Control and exploitation of aeroelasticity depends on the continued development of new materials, new structural and aerodynamic concepts, sensors, actuators, and active control techniques. Such developments must be accompanied by proper integrated analysis/design tools, and, most importantly, by the same human inquisitiveness and creativity that has driven aircraft design for over a century. This paper uses the history of nonconventional airplane configurations to review some of the steps taken during the past century to establish aeroelastic effects as integrated design features that must be anticipated, controlled, and exploited. The paper goes on to discuss the potential impact of past lessons on emerging airplane configurations currently in various stages of study and development.

Introduction

AS aircraft development enters its second century, aeronautical engineers can look back with pride to see how far they have come in terms of their abilities to understand, model, and control the diverse effects necessary to make aircraft operate in the wide variety of operational environments required for service. These environments range from low subsonic speeds to hypersonic speeds and altitudes from sea level to the outer reaches of our atmosphere. These flight vehicles carry small payloads and large payloads of diverse types, from global passengers and cargo, delivered safely and efficiently, to ordnance, delivered precisely, and sensors for communication and surveillance of wide areas. These operations

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Fig. 1 XB-47 (Courtesy of NASA).

are done reliably, routinely, and with small cost compared to the extraordinary value that they add to our economy and national security.

With every step of increased capability, there have been technical and societal roadblocks. These roadblocks were successfully overcome by advances in human creativity, scientific theory, computational excellence, advanced testing, and technological capability. These same features will also lead us into the second century of flight, and, if there is an absence of progress in one of these areas, the others will suffer.

Discoveries are seldom planned. In his story of the engineering effort that led to the Boeing XB-47 (Fig. 1), William H. Cook describes the discovery that body deflections and their effect on horizontal tail incidence angle countered the negative effect on longitudinal stability caused by swept-back wing flexibility. "The emotional relief I felt is hard to describe. Without this unexpected answer, we all would have been looked at as the stupidest of engineers, as this was exactly the type of problem the theoreticians had been afraid of, and it could have killed the whole project. . . ." (Ref. 1).

Dick Rutan, describing the development and record-breaking flight of the Voyager (Fig. 2), which flew around the world nonstop and without refueling in 1986, writes about the effect on him of the encounter with flutter:

> It was the only airplane I had ever been afraid of. I had never gotten used to the flailing wings. . . . When we flew at the heavier weights, the flapping became serious. . . . Unless the pilot or autopilot stopped it, the wings would literally flap themselves off in about ten or twelve seconds. If you let go of the stick, this airplane would come apart.[2]

With its twin-boom high-aspect-ratio wing and canard configuration the Voyager is still considered a unique machine. The XB-47, the ancestor of transonic jet transports flying today, seems from our current perspective quite conventional. Body freedom flutter, however, which in the Voyager's case was caused by coupling between motion of the whole vehicle and low-frequency wing bending oscillation of the fuel-loaded flexible wings, is well known and quite "conventional" now. It is easy to forget, after almost 50 years of dominance of the swept-back high-aspect-ratio jet transport airplane with its wing-mounted engines and long and flexible fuselage, how unique and unconventional this configuration was at the time of its introduction.

The integration of aerodynamic, structural, and mechanical technologies plays a vital role in aircraft development, and aeroelasticity is at the heart of this multidisciplinary integration. At the beginning of the first century of flight, aeroelastic effects were ignored during the design process. Later, when catastrophic failures in high-speed flight occurred (in the case of early aircraft, high speed was only 60–80 miles per hour) it was given new prominence, and theories and testing were developed to eliminate problems. Eventually aeroelasticity became a required part of safety-check procedures for new designs, forcing modifications that were considered by designers to be aeroelastic penalties. Over the last 30 years aeroelasticity has progressed from a problem area to become one the first areas to use integrated technologies to turn problems into opportunities and harness aeroelastic interactions to improve airplane performance.

Even when unconventional configurations of the past become the conventional configurations of the present, complacency must be avoided. The past has taught us that even with familiar, conventional designs, we must always be on guard, conducting analysis, design, and testing with great care, watching for new failure modes and any unusual behavior. This paper presents a selective survey of past experiences with the aeroelasticity of nonconventional configurations. These experiences are linked to key emerging new airplane configurations, their potential aeroelastic problems, relevance of past experience, and the required analysis, design, and testing technologies that are required to move into the future.

The aeroelastic experience on a multitude of airplane configurations spanning a 100 years of flight is too vast to be discussed in a single paper. The number of emerging future airplane configurations discussed in the aeronautical literature is large too. By focusing on a few key developments, the discussion presented here intends to contribute to the education of aeroelasticians of the future, add to the experience and awareness of current aeroelasticians and airplane designers, and contribute to research and technology developments.

Treatment of subjects in the paper will not follow a historical timeline, but rather proceed by association to link aeroelastic lessons of the past with emerging technologies, including technologies motivated by such aeroelastic lessons. Discussion in the present paper will be limited to airplanes.

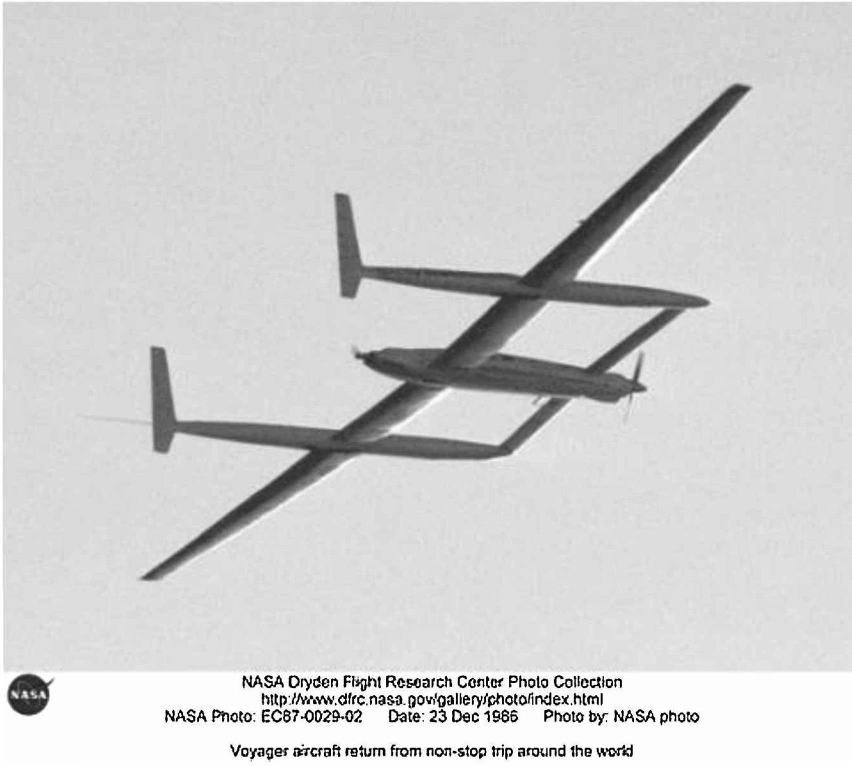

Fig. 2 Voyager (Courtesy of NASA).

Unconventional-Configurations and Aircraft-Configuration Development Trends

The specific meaning of the words “conventional” and “unconventional” (Ref. 3) depends on the disciplinary context. From an aerodynamic perspective the overall shape of the vehicle, the flow regimes in which it operates, and details such as high-lift devices and flow-control determine whether the configuration is conventional or unconventional. For the structural designer conventional refers to the types of materials used, the geometry of the structural layout, the thermal environment, and design details such as actuation and shape control mechanisms. From the controls perspective the level of complexity of a configuration and the degree to which it departs from past designs will depend on sensing, actuation, and controls technologies used, including analytical foundation, software, and hardware of control law mechanization. New, innovative propulsion concepts compared to established propulsion technology determine whether an airplane is conventional or unconventional from the propulsion engineer’s point of view. Aeroelasticity and aeroserevoelasticity involve all of the preceding considerations.

In the commercial or military transport arena swept-wing jet passenger and cargo airplanes will dominate the airways for many years to come, closely resembling the Boeing 707s of the 1950s. Yet, development in structures and materials technology, or controls, or propulsion can make them very different. Accepting that most subsonic commercial aircraft are likely to look the same in 2030 as they do today, at least on the outside, advances in electronics and avionics can drastically change the inside of the airplane and have far-reaching effects on operations and logistics, including safety. Advances in aerodynamic shaping and aerodynamic control, through the use of new airfoils, wing-tip devices, high-lift devices, and flow control, must be accompanied by careful aeroelastic modeling, analysis, and testing. The same applies to changes in scale. With the giant Airbus A380 in development, new challenges in the aeroelasticity of very large airplane design must be met.[4]

Configurations such as the Boeing Blended Wing Body (Fig. 3) as well as Joined-Wing (Fig. 4) and Box-Wing configurations considered by NASA, the U.S. Air Force, and a number of

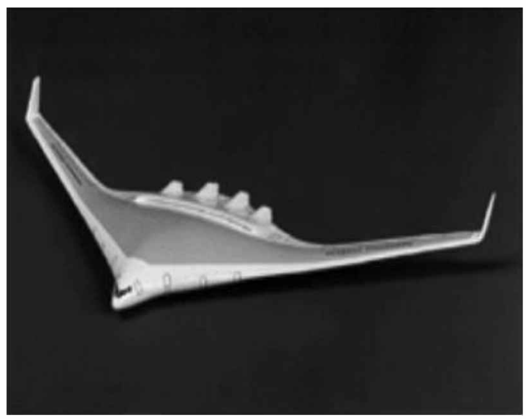

Fig. 3 Boeing BWB Transport (Courtesy of NASA).

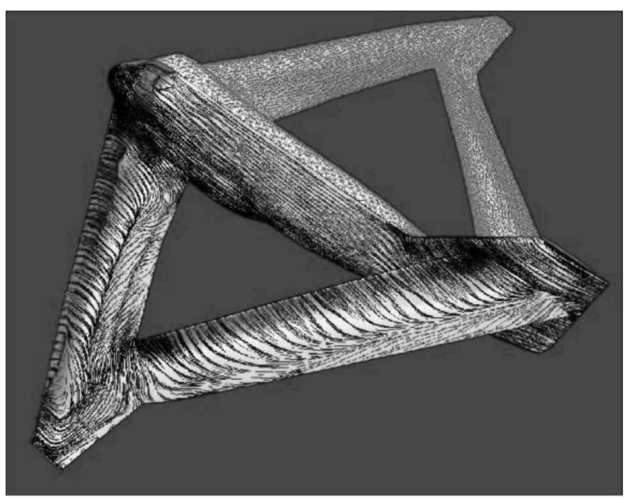

Fig. 4 Flow lines on a joined-wing configuration (Courtesy of NASA).

companies are also examples of aircraft that are designed for efficiency and specialty uses.

Military aviation, at least for manned operations, faces a similar outlook. The primary development of the F22 Raptor and Joint Strike Fighter is finished. It is likely that these are the last major fighter programs for the United States for the next quarter century.

A major thrust of future aircraft design, which promises to generate a multitude of new configurations, is in the area of unmanned air vehicles (UAVs). These vehicles can be radically different than conventional designs because UAVs are not bound by the constraint of enclosing a pilot and can be used for unconventional missions. Proposed military UAVs come in all sizes and shapes, ranging from large aircraft such as the Global Hawk and notional designs such as unmanned sensor-craft. Sensor-craft require a lightweight composite-wing structure and antennas integrated to form multi-functional structures. Aerodynamic and electromagnetic considerations affect the overall shape.

Current operational UAVs have missions primarily dedicated to observation. Recently the observation mission has been augmented by weaponizing the Predator UAV to add the ability to eliminate small targets. An intense effort to develop unmanned combat aerial vehicles is already underway.

Some UAVs have several features that require attention to aeroelastic effects. First of all, the operation of high-altitude aircraft requires highly efficient wings and airfoils and particular attention must be paid to reduced-weight design schemes. The operational features of efficient high-altitude flight drive the aircraft speeds into the transonic range, even though the flight speed itself might be relatively low. Second, the absence of the pilot and the requirements to carry sensors and ordinance of various types leads to configurations that are unusual and for which component structural vibration and the motion of the entire aircraft cannot be conveniently uncoupled. Because of the design complexity, it is wise to model such vehicles as accurately and as soon as possible because the past does not offer reliable guidelines.

In the following sections we will survey key aeroelastic lessons learned on past nonconventional airplane configurations and link these to what we see as emerging needs in the area of aeroelasticity/aeroservoelasticity of the new configurations in the near future.

Importance of Rigid-Body Degrees of Freedom

In at least two cases involving nonconventional configurations, flutter analysis that neglected rigid-body motion of the complete vehicle was found to produce grossly inaccurate results (Refs. 5–7). In the cases of the forward-swept wing (FSW; Fig. 5) and the oblique wing (OW; Fig. 6) configurations, common wisdom of the time suggested that the aeroelasdtic mode of failure would be aeroelastic divergence caused by the well-known tendency of cantilevered forward-swept isotropic high-aspect-ratio wings to become statically unstable at high speed (Ref. 5, p. 13).

In both cases the result of the aeroelastic stability analysis changed drastically when rigid-body degrees of freedom were included. Rigid-body pitch for the symmetric FSW and rigid-body roll on

Fig. 5 X-29 forward-swept wing research fighter (Courtesy of NASA).

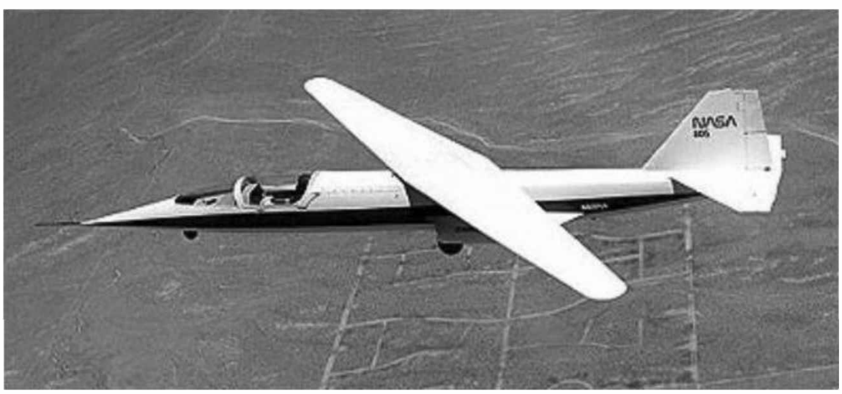

Fig. 6 NASA oblique wing research vehicle (Courtesy of NASA).

Fig. 7 Aerovironment high-altitude Pathfinder in flight (Courtesy of NASA).

the OW (Refs. 8–18) changed both the dynamic pressure and the type of instability encountered.

The importance of including rigid-body degrees of freedom in aeroelastic analysis of complete vehicles was well recognized in the 1940s (see Ref. 6, Section 5.1.2) and was well within the aeroelastic knowledge base already in the 1950s (Ref. 5). Flutter analysis progressed from focusing on cantilevered wings to the utilization of free-free natural mode shapes of free-free vehicles. Yet, in many cases in the last 40 years only the free-free elastic modes were used, and the rigid-body (zero frequency) modes were not included. This had a minor effect on the modeling of classical flutter mechanisms involving bending/torsion motions of lifting surfaces or wing/control-surface interactions.

Rigid-body motion of the aircraft provides relief with respect to the case of cantilevered boundary conditions because aeroelastic deformation leads to changes in total lift and total moments and hence affects the rigid-body motion of the complete vehicle. Additionally, because divergence tendency of an aeroelastic system leads to reduction of coupled aeroelastic vibration frequencies with increasing dynamic pressures wing frequencies on FSW configuration (such as the X-29, Fig. 5) can decrease to the point where they become quite close to typical flight mechanics rigid-body frequencies of the vehicle.

When the frequency separation between rigid-body and elastic motions becomes small, the traditional fields of aeroelasticity and rigid-body flight mechanics cannot be separated, and the flight mechanics of the deformable airplane, covering motion in all degrees of freedom, must be treated in an integrated manner.

Coupling between rigid-body and elastic motion of deformable flight vehicles is found on other configurations. Examples include aeroelastic behavior when wings are loaded with heavy external stores or tip missiles[18] and the case of very high-aspect-ratio wings loaded with fuel. Tailless airplanes with relatively low rigid-body pitch inertias can have relatively high short period frequencies that interact with vehicle elastic deformations. Examples include the B2 bomber[19,20] and the blended-wing-body (BWB) configurations.[21,22]

There are cases where configurations include both high-aspect-ratio/low-bending-frequency wings and low rigid-body pitch inertias. Lightweight high-aspect-ratio sailplanes such as the German SB13 (Ref. 23) or high-altitude high-aspect-ratio airplanes such as the Aerovironment Pathfinder (Fig. 7) are such examples.

Rigid-body flight mechanics/aeroelastic interactions can also be expected on joined-wing configurations.[24–27] In this case two effects become important. The tail sections are swept forward. Additionally, the tail sections are under compression. When the design is optimized for minimum weight, buckling/divergence and flutter caused by reduction in effective stiffness of the tail sections can become critical. Geometric stiffness becomes significant in the tail surfaces even when overall deformation is not too high, and nonlinear structural dynamic analysis must be carried out. Even without the effects of compression and geometric nonlinearity, body freedom flutter of joined-wing configurations had been found based on completely linear structural and aerodynamic analysis.[27]

With the coupling of flight mechanics and aeroelastic behavior interactions in analysis comes the need for an integrated approach to design. Synthesis of flight control systems must take all modes of dynamic behavior into account. The flight mechanics/aeroservoelasticity of deformable actively controlled airplanes is discussed in a subsequent section.

Finally, in the case of lightweight wings of very high aspect ratio flight mechanics behavior might be influenced by nonlinearities of aeroelastic behavior and by aeroelastic drag effects. With very large deformation geometric nonlinearities might affect the effective stiffness of the wing, leading to variation of natural frequencies under load[28–32] and to limit-cycle oscillations involving coupled rigid-body/elastic motion of the complete vehicle.

Coupled Flight Mechanics/Aeroelastic Behavior: Effect of Static Aeroelasticity

Even when structural dynamic frequencies of the airplane are well separated from its rigid-body frequencies, aeroelasticity still can have a significant effect on flight mechanics via the contribution of static aeroelastic (quasi-static) deformation to stability and control derivatives.[33–38] The upward bending of high-aspect-ratio wings in flight adds to the effective dihedral of a configuration. Bending of swept-back elastic wings as well as rear fuselage/tail/elevator

Fig. 8 Victor.

Fig. 9 C-141 (Courtesy of NASA).

assembly affects neutral point location and the resulting longitudinal stability of an airplane.[1,34]

Among nonconventional configurations of the past, the T-Tail configuration has presented significant challenges to the aeroelastician. In July 1954 a British Handley Page Victor bomber (Fig. 8) was lost because of severe T-tail flutter. Extensive work on T-Tail flutter commenced leading to better modeling techniques, understanding, and design guidelines.[39–41] As it turns out, static aeroelastic effects are extremely important in this case, changing the dihedral of the horizontal stabilizer on top of the tail, and in turn, through the effect of dihedral on aerodynamic rolling moment caused by sideslip motion, affecting the generalized aerodynamic forces in a way that might reduce flutter speeds.

The need to evaluate accurately unsteady aerodynamic forces on a configuration that has significant interference between lifting surfaces, such as the T-Tail, was one of the motivations for the development of the doublet-lattice method[42–46]—still the unsteady aerodynamic building block of practically all subsonic aircraft flutter clearance procedures.

The T-Tail problem is complicated by coupled structural dynamics, where the horizontal tail affects bending/torsion motions of the vertical tail. T-Tail flutter problems were encountered on a number of jet flying boats developed for the U.S. Navy. The C-141 (Fig. 9) transport's T-Tail was designed with a streamlined fairing to smooth flow at the vertical and horizontal tails' juncture. It was found that, at transonic speeds, this fairing caused shock-induced flow separation over the aft portion of the fin-stabilizer juncture, affecting transonic flutter characteristics of the entire tail surface. A redesign included a new shape and a blunt boat tail, as well as vortex generators on the fin to eliminate the adverse pressure gradients that led to separation.

Two other aeroelastic problems were encountered during the development of the C-141. An unstable oscillation of the horizontal tail was experienced during high-altitude flight tests and was eliminated by increasing the elevator mass balance. The C-141 also suffered aileron reversal, similar to the experience with the XB47 (Ref. 33).

Aileron reversal is one of the most serious static aeroelastic problems affecting flight mechanics,[5,33,47–49] and it still has a major impact on wing design and the resulting wing weight. On supersonic fighter and transport aircraft with thin wings and relatively low torsional stiffness, aileron effectiveness can decrease dramatically with dynamic pressure unless the wing is stiffened considerably. A supersonic transport such as the Boeing 2707 SST (Ref. 33) could have aileron effectiveness decrease to zero before Mach 1 if the ailerons were placed toward the wing tips. On a modern supersonic fighter aileron effectiveness for the wing flaperons can decrease to 15–20% of the rigid wing value at high dynamic pressures, and the control system uses antisymmetric differential horizontal tail motions to augment roll power at high dynamic pressures to achieve desired roll rates.

Aeroelastic tailoring and aeroelastic optimization in its early phases were developed in part to address the aileron effectiveness problem and to obtain by design required effectiveness with a minimum of weight penalty. In the mid-1980s the active-aeroelastic-wing (AAW) concept was introduced as a means to eliminate any weight penalty caused by aileron effectiveness requirements. These will be discussed subsequently.

The growing power of computational tools for unsteady aerodynamics and the growing power of computer simulation made it possible to solve large systems of ordinary differential equations efficiently. This began to allow, starting in the 1970s, a better integration of flight mechanics and aeroelasticity. Aerodynamic tools for the estimation of dynamic stability derivatives on flexible aircraft also became available.[50] With modern structural dynamic and aerodynamic capabilities in place, it became possible to create mathematical models of complete deformable aircraft in flight, including rigid-body and elastic motions as well as flight control system in the loop. Aeroservoelasticity now grew to encompass flight mechanics and flight controls of flight vehicles, in both analysis and synthesis of such systems.[50–56]

Active Control of Coupled Flight Mechanics/Aeroservoelastic Flight Systems

The appearance during the 1970s of unstable control configured vehicles such as the YF16 (Fig. 10) and the shift in such vehicles from mechanical controls to fly by wire was accompanied by the development of electrohydraulic servoactuators and the resulting actuation of airplane control surfaces with bandwidth that was substantially wider than the bandwidth of previous cable-rod flight control systems. That is, with more advanced actuators and without the low-pass filtering effect of mechanical linkages and cable systems, the flight control system became faster and more powerful.

"Spillage"—control system undesirable effects in frequency bands higher than what the mathematical models used for controls synthesis covered—became a problem immediately. In the case of actively controlled aircraft, control systems developed for the rigid airplane following standard procedures showed undesirable, even dangerous, interaction with structural dynamic modes in frequencies well above those associated with rigid-body motion.[57–78]

The YF16 case[65–67] is a typical example of such an aeroservoelastic instability. Rigid-body six-degree-of-freedom simulations with flight control system engaged (with static aeroelastic corrections to stability derivatives) indicated no problem. Ground tests of the airplane with input signals to each of the control surfaces and output measurements over a range of frequencies at each control loop also indicated what was believed to be enough attenuation to prevent any aeroservoelastic instability. In addition, an aeroservoelastic analysis was conducted at one high subsonic Mach number at low altitude, flight conditions believed to be critical, as it was in the controls-off flutter case. Nevertheless an aeroservoelastic instability with a YF16 carrying tip missiles was encountered during flight tests. This involved coupling between antisymmetric missile pitch (at 6.5 Hz) and first wing bending (at 8.0 Hz) modes. The cause of the instability was found to be the roll channel of the control system, and it was sensitive to the overall gain in the roll channel—the actual control system gain times the aeroelastic aileron effectiveness. Thus, interestingly, at low-altitude high dynamic pressures, where aileron effectiveness was low, it had the effect of reducing the overall gain in the roll channel. At higher altitudes and lower dynamic pressures, where the instability actually occurred, aileron effectiveness was higher, thus adding to the overall gain in the roll channel. The solution of the problem was based on reducing the control system roll channel gain and adding a notch filter centered around 6.5 Hz, providing additional gain reduction at that frequency.

Lessons from the YF16 aeroservoelastic instability incident are applicable to all deformable modern actively controlled aircraft. Aeroservoelastic stability and response analysis must be carried out with the flight control system in the loop at multiple flight and loading conditions. Rigid stability derivatives obtained from computation or wind-tunnel tests using rigid models must be corrected for static aeroelastic effects. This correction must be adjusted so that when a set of vibrations modes is used for aeroservoelastic analysis static aeroelastic corrections must account for only the residual flexibility effect—that flexibility not captured by the modes used.[66]

With careful placement of sensors (at nodal points or points of zero rotation of structural modes) and with notch filters, the effect of structural dynamic response on the actively controlled flexible airplane can be minimized. On the other hand, notch filters add time lags and can degrade the performance of a control system designed without proper accounting for structural dynamics. Moreover, in configurations where the range of frequencies required for rigid-body motion and structural dynamics overlap rigid-body flight mechanics and dynamic aeroelasticity cannot anymore be separated, and controls synthesis must consider the complete aeroservoelastic system.[66–78]

The importance of aeroservoelastic clearance and the synthesis of control systems to meet both flight mechanics and aeroelastic constraints is expected to grow. This is particularly true of modern fighters carrying heavy external stores, forward-swept and joined wings, where frequencies decrease with dynamic pressure toward the flight mechanics frequency range. It is also true in the case of large supersonic transports or bombers with their slender fuselages or high-aspect-ratio long-endurance UAVs—all employing high authority active control systems.

The future is expected to bring control systems synthesis techniques for ensuring stability and desired response, for meeting handling qualities and ride comfort criteria, and reducing vibration levels and dynamic stresses caused by gusts and other dynamic inputs. The fields of flight mechanics and rigid vehicle flight control and the field of aeroelasticity/aeroservoelasticity will have to be unified for many of the flexible, actively controlled configurations of the near and far future.

For active flutter suppression—the use of active controls for structural weight benefits as a result of elimination of the flutter "penalty"[59,64,73,74]—concerns about reliability and safety and

Fig. 10 YF-16 control-configured prototype vehicle (Courtesy of NASA).

unknown tradeoffs between structural gains and added weight of redundant, failsafe control and actuation systems will continue to prevent this technology for materializing on a large scale in the near future. The well-known case of the F/A-18 Active Oscillation Control (Refs. 77 and 78) might just be a case of actual active flutter suppression.[78] In that case "unacceptable 5.0–6.0 Hz oscillation at low altitude and high speed"[78] was observed with some external store configurations. The existing flight control system (FCS) was modified to suppress the vibration through the ailerons using the existing FCS fuselage lateral acceleration accelerometer. As Ref. 78 describes, however, the F/A-18 experiences a number of aeroelastic mildly unstable or neutrally stable oscillations with various external stores configurations. Obtaining an acceptable operational flight envelope for each of these configurations might depend on utilization of active control.

Control Surfaces and Wing/Control Surface Flutter

The F/A-18 case provides an example of the effects of leading-edge control surfaces on flutter. Usually in flutter analysis of a configuration, a set of low-frequency modes is selected as a reduced basis for modeling the structural dynamic behavior. The cutoff frequency, where modes with higher frequencies are considered to be too removed from the frequencies range of interest, is usually taken to be two times or higher than the highest response frequency of interest. In the case of the FA/18 leading-edge flaps, natural modes with significant flap participation had very high natural frequencies, above 70 Hz, whereas the flutter frequency of the configuration was about 5 Hz. Yet, exclusion of these high-frequency modes from the flutter analysis led to erroneous results and missed the actual flutter mechanisms involved. Because of their tendency to diverge, leading-edge modal frequencies, even if they are high for the zero-speed case, can decrease dramatically with increasing flight dynamic pressure. As speed increases, frequencies of the associated aeroelastic leading-edge control surface modes decline and cross into the range of wing bending/torsion frequencies, affecting the flutter stability of the whole wing/control surface configuration (Fig. 11, and Refs. 79 and 80).

Control surface and coupled wing/control surface flutter problems are some of the most commonly encountered in the development of new aircraft.[81–88] With new configurations, new actuators, and new control surface structural and aerodynamic designs, extreme care must be taken to model control surfaces accurately. Attention must be paid to stiffness and inertial characteristics, details of the attachment to the wing, actuator, and actuator attachment, including stiffness of the local backup structure. Nonlinearities as a result of free-play or support structure and mechanisms are also extremely important and are expected to affect every new aircraft design.[89–95]

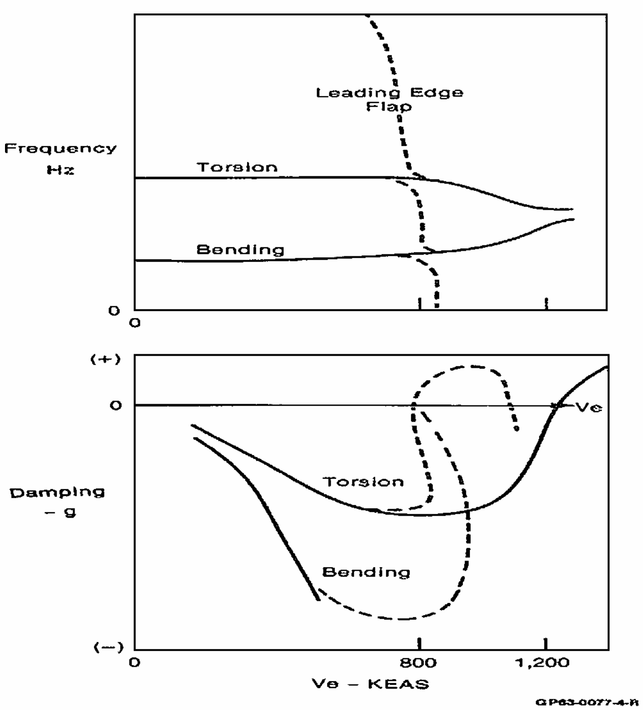

Fig. 11 Effect of leading-edge flaps on wing flutter.[79]

Other Nonlinearities

Structural and actuator nonlinearities in control surfaces are but one factor in the general nonlinear aeroelasticity of airplanes.[96–100] The transonic "dip"[47,96–100] as well as stall flutter (Ref. 47, Chapter 5) in wings at high angles of attack are well known. A number of other nonlinear effects have already been described in this paper, namely, the geometric stiffness effect in lifting surfaces loaded in plane or subject to significant deformation. Aerodynamic nonlinearities can be caused by interference, separation, and vortex shedding,[101–110] rolling up of wakes,[109] or shock oscillations in the transonic regime.[19,20]

Emerging computational-fluid-dynamic (CFD) and computational-structural-dynamic (CSD) numerical capabilities[102–105,111–113] for complex structures undergoing large rigid-body and elastic motions will make the analysis of nonlinear aeroelastic effects on complex new configurations flying in all flight regimes more feasible. For the near future, however, the preparation of mathematical models (via meshing and discretization) and the simulations themselves are so computationally intensive that nonlinear CFD–CSD will probably be used only for checking a few critical designs at a small number of critical flight conditions. Integration of advanced CFD–CSD nonlinear aeroelastic simulation into the early stages of the airplane design process is still years away.

The continuous improvement of CFD–CSD simulation tools is expected to make an impact on airplane design by allowing more nonconventional configurations to be studied. It will become possible to address the aeroelasticity of thick wings, such as on the BWB configuration, low-aspect-ratio wings of fighters and supersonic transports at high angles of attack, close-coupled canard/wing configurations,[114] or joined wings in a more complete and rigorous manner. The same observations apply to aeroservoelasticity, where better modeling of the flow nonlinearities as a result of control surface motions has the promise of removing a major element of uncertainty in aeroservoelastic analysis and design.

Aeroelastic Tailoring

That geometry of the structural layout and the sizing and anisotropy of its members can be used to control aeroelastic characteristics of design has been known to designers and aeroelasticians since the early days of aviation. The divergence problem of the Fokker D-8 airplane[5] was caused by government requirement to change the original wing design so that the front and rear spars would be similar, thus shifting the elastic axis rearward. Careful material distribution in a wing structure designed to have desirable stiffness and inertia characteristics while keeping weight to a minimum has always been a key to successful airplane design. The emergence of fiber composite materials, where the structural design space allows different stiffness and strength in different directions, allows significant aeroelastic benefits.

The history of airplane structural materials and concept development is well documented in many books and articles.[115] Intensive work to develop analysis and design tools for the synthesis of airplane structures using fiber composites started in the 1960s and matured significantly in the 1970s and 1980s. The 1960s and the 1970s were also the years in which the foundations of structural synthesis[116,117] were laid. It was only natural to integrate composites structural analysis with structural optimization to create what is known today as modern tailoring of composite structures.

In a the structural tailoring process the thicknesses of skin layers with different fiber directions and the directions themselves are determined in some optimal way to meet a set of constraints representing various failure criteria including manufacturing requirements and additional requirements on such measures as stealth and cost. The structural design space can be expanded to also include geometry and topology of the inner spar and rib structure. Pioneering work at General Dynamics, Fort Worth, Texas, led to the development of the TSO code[118–120] for the optimal aeroelastic tailoring of wings. The code was evaluated using F-111 and F-16 wings to study potential benefits and possible improvements with composite tailoring technology. In what turned to be the most famous utilization of the code, it was used to synthesize forward-swept wings[121,122] and showed that tailoring could overcome the "divergence penalty" of such wings. In time this led to the development of the X-29 (Fig. 5).

Today, aeroelastic tailoring in the context of aeroelastic design optimization can be commonly used, and several commercial design optimization computer codes are available for this purpose.[64] The extent to which tailoring is used to its full potential is not clear. Concerns about manufacturing cost and structural reliability and some resistance as a result of engineering conservatism are some of the inhibitors.

Full aeroelastic tailoring, as part of an overall design optimization process of airplane structure, is destined to grow in importance in the coming years. Most of the mysteries involved have been long removed, and the potential benefits are too great to ignore.

AAW Concept

Combined action of leading-edge and trailing-edge control surfaces has been used for years to adapt wing camber to maneuver requirements.[123–128] The structural penalty in wing design required to sustain acceptable aileron effectiveness is one of the most well-known problems of aeroelasticity. It has long been recognized, however, that the loss in roll power as a result of to aeroelastic nose-down twist of wing sections is characteristic of trailing-edge control surface effects. With leading-edge control surfaces aeroelastic twist of the wing will actually increase aeroelastic rolling efficiency. Research in Russia during the 1960s examined the combined use of leading-edge and trailing-edge control surfaces on elastic wings and demonstrated that the loss of effectiveness of the trailing-edge controls could be compensated by the addition of leading-edge controls.[125,126] This research effort also examined small control surfaces mounted forward of the wing leading edge on wing-tip booms (Fig. 12).

Leading-edge control surfaces do not come free. They tend to diverge at high speed, and special attention has to be paid to adequately stiff hinges and effective actuators. The hinge moments on leading-edge control surfaces are difficult to predict. Excessive rotation of these surfaces can also lead to flow separation over the entire wing, especially in the case of thin wings. This introduces uncertainty into the aeroservoelastic analysis of configurations where leading-edge control surfaces are actively utilized.

On aircraft such as the F16 and F18 leading-edge (LE) flaps were used together with trailing-edge (TE) flaps and flaperons to create variable camber. In the case of the F18, LE control surfaces are also used to augment roll.

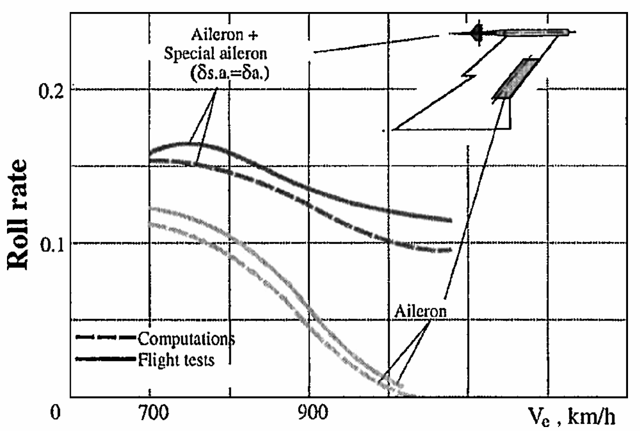

Fig. 12 Aeroelastic effectiveness of trailing-edge and forward-mounted control surfaces.[126]

Fig. 13 F-18 AAW research aircraft (Courtesy of NASA).

If LE and TE control surfaces could operate in harmony, if this could be taken advantage of during the design process, if Aeroelastic optimization of the wing itself could be combined with optimization of the schedules of the control surfaces, and if enough control surfaces were available to the control system to manipulate, then significant weight savings in wing design would have been possible, and the costly aileron effectiveness weight penalty could be eliminated.

With the growing power of aeroelastic optimization tools and improvements in power and reliability of actuators and control systems, this concept, known as the active aeroelastic wing, could be designed. A major effort in the mid-1980s involving industry, the U.S. Air Force, and NASA[129–133] demonstrated the feasibility of the active aeroelastic wing, and subsequently a flight demonstration program commenced (Ref. 131, and Fig. 13). It is a matter of historic curiosity that the airplane selected for flight tests was an F18 restored to the original development configuration found during development tests to be inadequate from aeroelastic roll effectiveness perspectives. That led to major stiffening of the production wings.

In an AAW airplane trailing-edge surfaces can actually reverse at high speed. The control system, through the scheduling of LE and other surfaces, will compensate so that the airplane will not lose rolling control.

The AAW concept is a natural outcome of an integrated aeroservoelastic design optimization approach to wing synthesis.[54,64,134] The complex problem of sizing inner structure, sizing the skins, and selecting the proper rotation angles for all control surfaces at all flight conditions while protecting against flutter and stress failure modes or control system limitations can be formulated as a constrained optimization problem.

When this optimization is carried out in an automated process, it becomes clear that it is not that important whether control surfaces become ineffective or reversed in some flight conditions as long as no failure occurs and as long as the roll rates achieved through actions of other control surfaces combined with the aeroelasticity of the wing and controlled by a high authority control system meet requirements. This is the integrated aeroservoelastic design optimization approach in such design codes as the LS-CLASS code in the mid-1980s,[64] and later incorporated into ASTROS.[64] In the work described in Refs. 64 and 134, optimization tools were developed for scheduling of control surfaces (whether reversed or not, as long as there is enough controllability) together with optimizing structure, aerodynamics, active flutter suppression, gust alleviation, and ride quality control. In practice, optimization had already been used to set the control surface scheduling (as a function of flight conditions, etc.) on the AAW test vehicle.[129] When structural, aerodynamic, and dynamic control system design variables are added to the mix, integrated multidisciplinary design optimization (MDO) makes it possible for future vehicles to benefit from the full potential of the AAW concept.

Variable Sweep and Variable Camber

Shape variation to adjust and control airplane performance for different maneuvers and flight conditions has been a major part of airplane design since the early days of aviation. These design features include wing warping, aileron rotation, trailing-edge and leading-edge flap high-lift systems for takeoff and landing, and improved roll control. Airplane shape variation techniques can be categorized according to the extent of the shape change, the authority of the control systems used, and the speed at which the shape change is carried out (bandwidth).

Significant planform shape variation can be found on variable-sweep aircraft,[135–137] such as the American F-111 (Fig. 14), F-14, and B-1 bomber, the Panavia Tornado, and the Soviet Sukhoi Fitter, Mig-23, and Tu-22M3. Variable anhedral angles of the North American XB-70 supersonic bomber could change from 0 to 65 deg (Fig. 15) for improved directional stability at transonic and supersonic speeds. Variable camber for performance improvement using leading-edge and trailing-edge control surfaces has been widely used for fighter aircraft. Its potential for load redistribution and gust alleviation has been extensively investigated.[127,128,138] The mission-adaptive-wing (MAW) concept was developed and tested on a AFTI F-111 research vehicle[139–141] to create smooth camber shape variations to avoid flow separation and buffeting caused by the effect of geometric discontinuities on hinge lines of conventional articulated control surfaces.

Whenever configuration shape variations lead to significant changes in stiffness, inertia, and aerodynamic distributions, the aeroelastic analysis, testing, and flight clearance efforts become substantial. Aeroelastic analysis has to address all flight conditions and maneuvers and all possible configuration shape variations. The additional need to cover all fuel conditions, and, in the case of attack/fighter aircraft, all external store configurations, makes the aeroelastic clearance task formidable.

A possible flutter mechanism not usually found on conventional configurations involves the fore-aft motion of a variable-sweep wing on its pivot. The fore-aft mode shapes of variable sweep wings, sensitive to local stiffness in the wing pivot mechanism, can be also

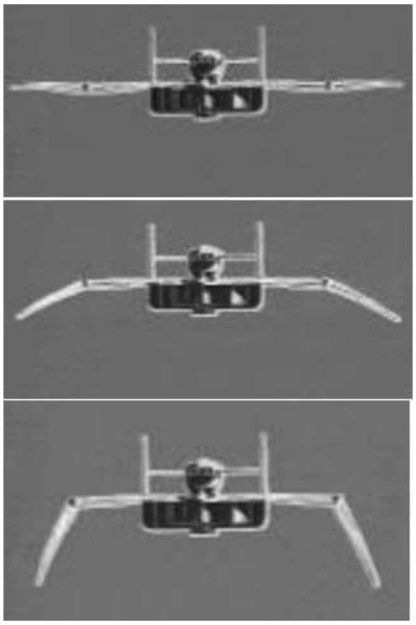

Fig. 15 Variable wing-tip anhedral on the XB-70 supersonic bomber.

Fig. 14 F-111 variable-sweep wing aircraft (Courtesy of NASA).

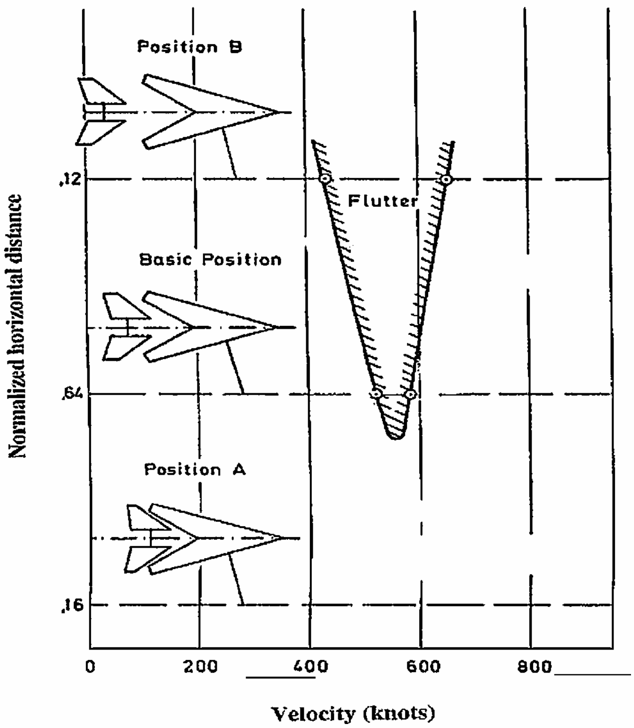

Fig. 16 Effect of aerodynamic interference on flutter.[136]

influenced by heavy external stores under the wings. The resulting coupled fore-aft/torsion motion of the wing can couple with other more conventional out-of-plane wing bending or torsion modes to create flutter.[134–137]

The discussion of flutter contributions of fore-aft wing modes (known in helicopter aeroelasticity as lead-lag motions of rotor blades) calls here for the mention of such effects in another case—the flutter of very high-aspect-ratio flexible wings. Forward-aft motion of the long wings couples with drag forces to affect flutter mechanisms on such vehicles. The reader should consult Refs. 142–144.

Of special interest in the case of variable-sweep airplanes is the aerodynamic interference between all major parts of the airplane. Available unsteady aerodynamic methods of the early 1960s did not allow for aerodynamic interference between surfaces and were limited to one lifting surface at a time. This led to erroneous results when used to analyze flutter on variable-sweep wing/tail configurations.[136] With the appearance of more advanced lifting surface methods, such as the doublet-lattice method,[42–45] and assumed-pressure-distribution collocation methods for interfering surfaces,[145–149] aerodynamic interference could be addressed, and a major source of flutter analysis error was removed. Aeroelastic analysis needs on variable-sweep wing configurations with tails were among the drivers (as was the T-tail problem) for better unsteady aerodynamics prediction methods including interference.

Interference effects could lead in some cases to counterintuitive results. For instance, as Ref. 136 shows, when the horizontal tail of a coupled variable-sweep wing/tail configuration is moved aft and away from the swept-back wing, flutter speed can actually decrease (Fig. 16).

A major driver in unsteady aerodynamics methods development in the 1970s was the need to evaluate unsteady aerodynamic forces on control surfaces and due to control surfaces accurately. The motivation for this development was to support aeroservoelasticity and active flutter suppression analysis and studies. This is as important today because active LE control surfaces are used often. If smooth wing camber variation on wings becomes a feasible and economical alternative to articulated control surfaces, the importance of capturing accurately the unsteady aerodynamic effect of complex wing camber shapes will not diminish, especially when local shape changes are introduced in the leading-edge area. Such cases present a challenge not only to linearized theories, but also to nonlinear unsteady aerodynamic CFD methods, where meshing and modeling of viscous effects must be done carefully and accurately.

Reconfigurable Morphing UAVs

Development of new structural materials, structural concepts, actuation methods, and multi-input/multi-output control systems during the past two decades are stimulating research and development of new, shape-changing airplanes called morphing aircraft or reconfigurable aircraft.[150–159] The intent of this new aircraft concept is to create air vehicles that operate efficiently in diverse, wide-ranging mission environments. These environments have one or more extreme requirements, such as long loiter time, that can dominate the design to the detriment of others, or, worse yet, preclude a satisfactory design solution. Morphing resolves this dilemma by enabling an aircraft to efficiently change its shape at will.

The morphing aircraft philosophy is aimed at producing new concepts whose performance will go far beyond current aircraft with traditional shape-changing mechanisms such as variable-sweep, variable camber, or high-lift flap systems. The last century of flight has seen the development of numerous devices that enable aircraft with conflicting mission requirements to reconfigure or "morph" themselves in flight. An excellent example is the wingtip droop designed into the XB-70 wing in the early 1960s and illustrated in Fig. 15. Other morphing devices include flaps and slats to generate high lift at low speeds, retracting and extending landing gear to reduce drag at high speed, increasing wing sweep for supersonic drag reduction, and drooping the nose of the Concorde to get better visibility during landing while preserving supersonic cruise performance. These capabilities are usually accompanied by increased mechanism weight and the cost to design and manufacture a more capable shape-changing vehicle. However, the value added to the system and the weight reductions elsewhere are so compelling that this added cost is accepted or even embraced.

During the past decade, there has been a strong, renewed interest in the development of military UAVs, particularly for intelligence, surveillance, and reconnaissance, the so-called ISR missions. This interest has been spawned primarily by the need for more information about battlefield or prebattlefield conditions and the ever-increasing ability to transmit and process massive amounts of data and fuse it into useful information for commanders in the field. The acceleration in UAV capabilities has been caused by improvements in technologies ranging from high-speed computers and processors, sensors, lightweight materials, and low-cost airframe manufacturing. In the near future morphing vehicle technology development will focus on such small autonomous or semiautonomous UAVs, with weights of the order of several thousand pounds.

There are two reasons for focusing efforts on smaller UAVs. The first is the new capabilities that such small aircraft offer. These capabilities involve ease of operation and persistence inside hostile areas at low cost. The second reason to focus on small size is that current morphing devices are more suited for controlling air loads required for flight and maneuvers on such vehicles.

The technical impetus for morphing aircraft comes from the historical conjunction of several different research activities conducted at diverse locations around the world, as well as the ongoing refocusing of military needs. The primary technical leadership for the morphing activity originated at NASA Langley Research Center in the mid-1990s (Ref. 153). The NASA efforts identified technologies to change the shape of aircraft using adaptive, smart structures and materials.[154] Adaptive or smart materials are capable of changing shape, including length and volume, in response to external stimuli such as controlled heating and electric field. Although the changes envisioned by the NASA morphing group were small in comparison to most existing reconfiguration devices used today, their project began the shape-changing challenge.

To be successful, reconfigurable, morphing aircraft need the following technology components: materials with ability to support flight loads and still undergo high strain without creep; actuators with exceptionally low power and ability to generate substantial forces and displacements, but still fit inside a small volume; and flight controls and mission objectives that exploit the ability to undergo drastic shape changing. These can lead to new flight regions such as the ability to take off and land at low speed with minimal effort and even conduct asymmetrical operations leading to maneuverability not possible today.

In December 2002, the Defense Advanced Research Projects Agency's (DARPA) Defense Sciences Office launched its own Morphing Aircraft Structures (MAS) program by requesting proposals for reconfigurable aircraft wings that changed shape radically. This led to a DARPA program that formally began in January 2003. The purpose of this $2\frac{1}{2}$ year program is to develop design paradigms and technology for integrated, actuated structural systems in which controlled shape change will generate new capabilities for air vehicles: from static structures to lightweight, actively controlled structural systems. DARPA's concept of a morphing aircraft is a multirole aircraft that 1) changes its state/shape substantially to adapt to the mission environment; 2) provides superior system capability not possible without reconfiguration; and 3) uses integrated design of materials, distributed actuators, effectors and mechanisms to reconfigure in flight.

The DARPA vision and focus, conceived through collaboration with a number of universities and companies, is only slightly different from NASA's. The biggest difference in the two approaches is that the DARPA program envisions incorporating very large changes in shape, such as wing sweep, and using small shape changers, such as adaptive materials and small specialized devices, to control the flowfield in regions disrupted by the large shape change. An example of this approach is designing a telescoping wing in which induced drag is reduced by extending wing tips, but requires active devices control parasite drag in the disrupted connecting region where the wing chord changes dramatically.

Three major contractors submitted proposals that were chosen for the DARPA program: Lockheed–Martin; Raytheon missiles, Tucson, Arizona; and HyperComp/NextGen. The Lockheed–Martin design is shown in Fig. 17.

The MAS goal requires the identification of notional, multiple-role aircraft concepts and the subsequent creation of active aerostructural designs with efficient devices and materials to enable shape change. The success of the DARPA program also depends on the design and construction of lightweight designs with reasonable weight that fit into a reasonable volume, operate at relatively high speed with low power levels, illustrate construction simplicity, and have demonstrated links to aircraft or system performance.

To develop radical shape-changing aircraft, there are at least two issues that require resolution. The first issue is define what new capabilities these aircraft will produce. To be successful, these shape changers must not do the same old things with new expensive complex technology.[155] The second issue is how we assemble, in an effective manner, the myriad of new technologies required for efficient shape changing and take advantage of the leverage that aeroelasticity provides to advanced systems. There are at least two high-risk portions of this effort. The first is that there is not established design process to select and integrate the technologies involved. Given the high premium on design weight and power, how does one select and position actuators and size a structure that will successfully move from one form to another in an optimal manner?

The second high-risk item is the influence of aeroelasticity, the coupling between airloads and structural deformations, and the ability to accurately predict the dynamic behavior of the actuated wing as it changes form. The use of adaptive materials to control aeroelastic effects such as dynamic response, aerodynamic performance, flutter, and divergence has been extensively investigated by many researchers.[156–159] The structures controlled did not change their form. As shape-changing actuators operate and mechanisms latch and unlatch, will there be unexpected dynamic response or even instabilities as a result of stiffness changes and geometrical changes? We do not yet have the ability to predict the answer to this question reliably.

The requirements for efficiency of the powered controls will likely lead to harvesting energy from the airstream to assist in the operation of control mechanisms. Concepts like the active aeroelastic wing are strong candidates to be contributors. Multidisciplinary optimization plays a key role in guiding designers in their efforts to identify actuator/sensor combinations that work in harmony with a structure on an aircraft with limited power and volume. The extreme shape changes coupled with time-dependent stiffness changes, occurring over relatively short times, will also tax current aeroelastic analysis and test capabilities.

Supersonic Vehicles

Research work continued in the United States on technology for supersonic commercial flight in the 1970s after the cancellation of the Boeing Supersonic Transport (SST), followed by renewed research thrust in this area in the 1990s, under the U.S. NASA High Speed Civil Transport (HSCT) initiative. Still struggling today with the major structural and aeroelastic design challenges presented by the quest for low-weight economical supersonic airframes for such vehicles, we can only admire the engineering effort that led to the development of large supersonic airplanes in the late 1950s and the 1960s, such as the North Americam XB-70 Mach 3 strategic bomber (Fig. 15), the Anglo-French Concorde (Fig. 18), and the Russian Tupolev Tu-144 (Refs. 160–171).

Very little was published on the aeroelasticity and flutter clearance of the Concorde and the Tu-144. It is clear, however, that these configurations presented aeroelastic analysis and certification challenges well beyond the aeroelastic experience of the time, which was focused on high-aspect-ratio wing designs and structural beam/unsteady-aerodynamic strip modeling theories.

The supersonic configurations had large plate-like wings and required more advanced structural and aerodynamnic modeling techniques such as equivalent plates and finite elements together with lifting surface unsteady aerodynamics. Both finite element structural technology and lifting surface aerodynamics were in the early stages of their development in the 1960s. The XB70, Tu-144, and Concorde all had long slender fuselages attached to the wing along long wing root chords. Strong coupling between fuselage bending and wing camber modes added complexity to flutter interactions. Ride comfort problems as a result of structural response at the cockpit and along the fuselage to excitation by atmospheric turbulence were significant, making it necessary to consider active suppression of fuselage vibrations through the activation of canard or forward mounted vanes. Because of the need to minimize supersonic drag, the wings were thin, leading to reduction in aeroelastic effectiveness of ailerons and elevons.

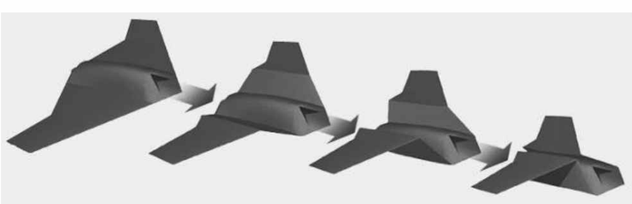

Fig. 17 Morphing UAV concept (Courtesy of Lockheed–Martin).

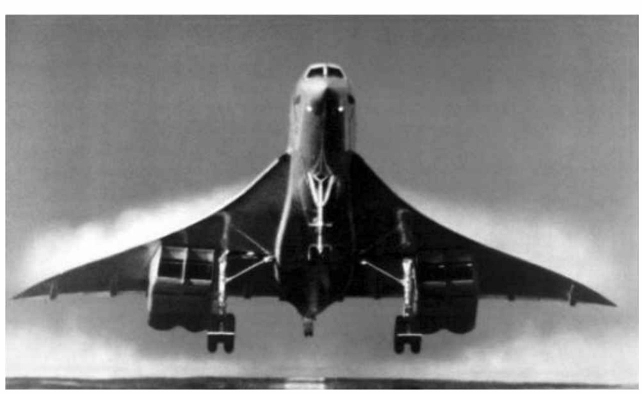

Fig. 18 Anglo–French Concorde.

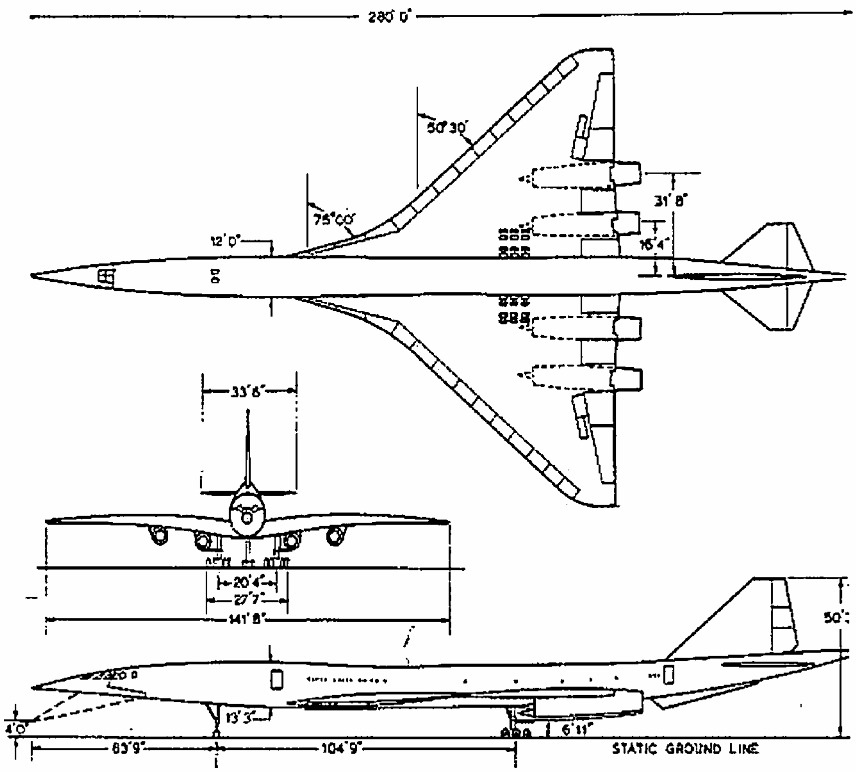

Fig. 19 Boeing SST.

In the case of the Concorde, aerodynamic heating created a discrepancy between predicted and actual deformed shape in flight because of neglect of heating effects in the static aeroelastic analysis.[160] This made it necessary to deflect control surfaces to compensate and achieve desired lift/drag ratios. As the airplane heats up, during flight elevon rotation differences of up to 2 deg can be required to trim the vehicle.[8]

The variable-anhedral wing tips of the XB-70 added complexity to the aeroelastic clearance task. Wing shapes like these were a major driver of unsteady aerodynamic lifting surface theory in the 1960s and 1970s. Work on three-dimensional lifting surface configurations continued well into the 1980s. Although the subsonic three-dimensional lifting surface problem was practically solved in the 1970s by the doublet-lattice method and some alternative techniques, the Mach–Box method, one of the first supersonic lifting surface unsteady aerodynamic methods to appear in the 1960s, proved quite inadequate for handling the highly swept leading edges of the supersonic low-aspect-ratio wing designs of the large supersonic airplanes. The supersonic three-dimensional case took a while longer to be resolved.[80,149]

Surveys of Boeing work on the aeroelasticity of the American SST in the 1960s are given in Refs. 164–166, Fig. 19. Aeroelasticity became one of the most severe problem areas for the Boeing SST, and the failure to resolve many structural and aeroelastic difficulties, including flutter issues, led to the cancellation of the program. Major weight penalties were incurred to stiffen wing structure and engine/wing mounting beams to prevent flutter. The proper positioning of the engines toward the trailing edge of the wings and away from the fuselage and the appropriate structural interface with the wing proved to be tricky from a flutter standpoint. Ballast masses mounted on forward-extending wing-tip booms were tried as passive flutter suppressors, unsuccessfully. The airplane had a severe aileron effectiveness problem.[33] Russian designers of supersonic transports were struggling with the same problem.[125,126]

The drive to reduce structural weight is so critical in the case of supersonic transports that the use of aeroelastic optimization becomes an absolutely necessary part of the design tool ensemble. Some of the first attempts to use finite element modeling, lifting surface aerodynamics, and numerical optimization for the structural/aeroelastic design task were on the Boeing SST (Ref. 164).

Even though supersonic designs require thin wings, and hence might lead to the expectation that transonic shock formation over the wing will not be as aeroelastically important as in the case of thick supercritical wings, still transonic effects on thin-wing SST configurations can be important. A significant transonic flutter dip on the Boeing SST measured in wind-tunnel tests suggests the existence of important transonic effects. Follow-on research work in the area of unsteady aerodynamics of SST-type "arrow" wings is reported in Refs. 167–169.

Work on the HSCT in the 1990s revealed that the problems just described are still major challenges today: aeroelasticity of slender thin wings, wing/fuselage structural dynamic interaction and aerodynamic interference, engine locations and structural mounting, control effectiveness, aerodynamic center shifts caused by aeroelasticity, passenger and crew ride comfort. Aeroelastic and integrated aeroservoelastic optimization,[64] where structure, controls, and aerodynamic shaping will be optimized simultaneously, are expected to play key roles in any new HSCT development.

Hypersonic Flight Vehicles

The rocket-propelled X-15 research airplane (Fig. 20) made a major impact on the design of American hypersonic launch vehicles. Over more than 10 years of ground and flight tests, the X-15 was used to study hot structures, aerodynamics, aerothermodynamics, flight mechanics, aeroelasticity, and aeroservoelasticity, as well as a multitude of other subjects associated with hypersonic flight at the edge of the atmosphere.[172–174]

Aerothermoelasticity—the aeroelastic interactions in the presence of significant heat transfer into the structure caused by hypersonic flight—adds complexity and difficulty to the aeroelastic clearance of "hot" vehicles. High temperatures lead to thermal stresses in the structure and to changes in material properties.[175–179] Both effects lead to variation of stiffness. Flight trajectory becomes important as it determines the rate at which the structure heats up. Different materials are used for different areas of the structure depending on the heating of these areas. Local failure in the form of panel buckling or panel flutter can be caused by combinations of thermal stresses, maneuver load stresses, and the interaction of outside panels with the airflow.

Fig. 20 X-15 hypersonic research rocket airplane (Courtesy of NASA).

Fig. 21 Lockheed SR-71 (Courtesy of NASA).

The development of piston theory in the 1950s (Ref. 180) was a breakthrough that made possible the flutter analysis of supersonic and hypersonic vehicles. Flutter analysis of the X-15 relied on piston theory for unsteady aerodynamic characterization. The large tail surfaces were more flutter critical than the wings, and correlation of flutter prediction with wind-tunnel test results at Mach numbers between 3.5 and 6.86 was found to be good.

The X-15 used segmented leading edges to reduce thermal stresses. Panel flutter on the vertical tail and side fairings made it necessary to stiffen panels and reduce their size. Acoustic fatigue over a wide range of Mach numbers and dynamic pressures was investigated, and this effort led to the development of panel design criteria that were later used in the U.S. space program.

It is not clear to what extent the X-15 aeroelastic experience influenced aeroelastic design and clearance of the Lockheed SR-71 (Fig. 21). Capable of sustained higher than Mach 3 flight, the SR-71 (or the YF-12; Refs. 181 and 182) incorporates a number of aerothermoelastic design features, including a high-temperature titanium alloy structure with high-emissivity surface coating, thermal-stress relief joints and skin panels designed carefully to avoid panel flutter. Several problems caused by thermal expansion during flight testing of the prototype A-12 vehicle were solved by redesign. These included nonuniform cooling of the engine and nacelle that created nacelle shrinkage during cooling, and caused contact with the hot engine compressor blades.

Reference 182 describes a more recent flutter analysis of a SR-71 carrying an aerospike experiment. It offers a rare opportunity to learn about critical flutter mechanisms for the original SR-71 including body freedom flutter involving first fuselage bending and the short period, outer wing bending/torsion coupling, and bending/torsion coupling on the all-movable rudders. Finite element NASTRAN structural modeling and doublet-lattice aerodynamics used for the Ref. 182 flutter studies together with rational function approximations of the unsteady generalized aerodynamic forces and state-space root locus stability analysis techniques provide an accurate characterization of the vehicle. Finite elements and the capacity to calculate structural/thermal behavior of complex structures were only in their infancy in the 1950s. Available current technology for the aeroelastic analysis of hypersonic vehicles includes structural-thermal finite elements codes and unsteady aerodynamics modeling tools for wing/body configurations over Mach numbers from subsonic to hypersonic, such as the ZAERO capabilities described in Ref. 80.

Aeroelastic and structural dynamic aspects of the space shuttle design development are described in Ref. 183. In addition to aerothermoelastic problems just discussed, the space shuttle faces critical flutter design points in the transonic flight regime. Because of its installation on its booster fuel tanks and rockets, aerodynamic interference between wings and bodies is a major factor in the prediction of unsteady aerodynamic loads. If a two-stage-to-orbit approach is adopted for future launch vehicles, with one vehicle carrying another to altitude for launch into space, similar interference between the vehicles will have to be addressed, and both vehicles will have to be cleared aeroelastically in their separate and joined modes of flight. The modern aerothermoelastic analysis and design problem,[184–197] based on finite elements and CFD, is especially challenging because structural analysis has to be combined with thermal analysis and hypersonic viscous flow analysis—all requiring detailed modeling of structure and flow, leading to large mathematical models. If MDO is used, then the computational resources needed for the repetitive analysis and sensitivity analysis of coupled structure-aerodynamic-thermal systems will be larger. The technology for integrated hypersonic vehicle optimization subject to aeroelastic and aeroservoelastic constraints, including modeling capable of capturing both global and local effects in the structure, is not mature yet. Any development of future hypersonic flight vehicles will depend on advances in aerothermoelastic analysis and design technology, on experience gained with new materials and new structural/cooling concepts, and on optimization of large integrated systems that cover structures, aerodynamics, heat transfer, flight mechanics, trajectory optimization, and control. The overall shape of the ramjet and scramjet vehicles is part of the propulsion system, leading the flow into the engine, and shaping the exhaust jets. Integration with propulsion, then, becomes necessary.[194–196]

National Aerospace Plane research and a number of hypersonic research vehicles led to renewed interest in aerothroelasticity and aerothermoelastic design optimization. A new NASA drive to develop technology for successor reusable launch vehicles to the space shuttle is currently underway. Aerothermoelasticity research efforts now focus on the development of advanced CFD/CSD aerothermoelastic analysis tools[197] and associated optimization and testing capabilities. Panel flutter and acoustic fatigue[198–200] will continue to serve as a prototype aerothermoelastic problem for analysis and numerical tools development, in addition to its importance in devising design criteria for panels on advanced design concepts. This work will continue in the coming years and will add to the knowledge base that will make it possible to develop reusable launch vehicle replacement of the space shuttle and future hypersonic transport vehicles.

Asymmetric Configurations

We have already discussed the aeroelastic behavior of the oblique wing. It was postulated in Ref. 201, in the context of addressing flutter clearance for aircraft/external-stores configurations, that a flutter speed for an asymmetric configuration will be higher than the flutter speed of the two corresponding symmetric configurations. A physical argument was brought up, that if the symmetry of an airplane is broken in some manner, then the mechanism of vibration energy flow between port and starboard sides can be substantially interrupted compared to cases of symmetry and the symmetric or

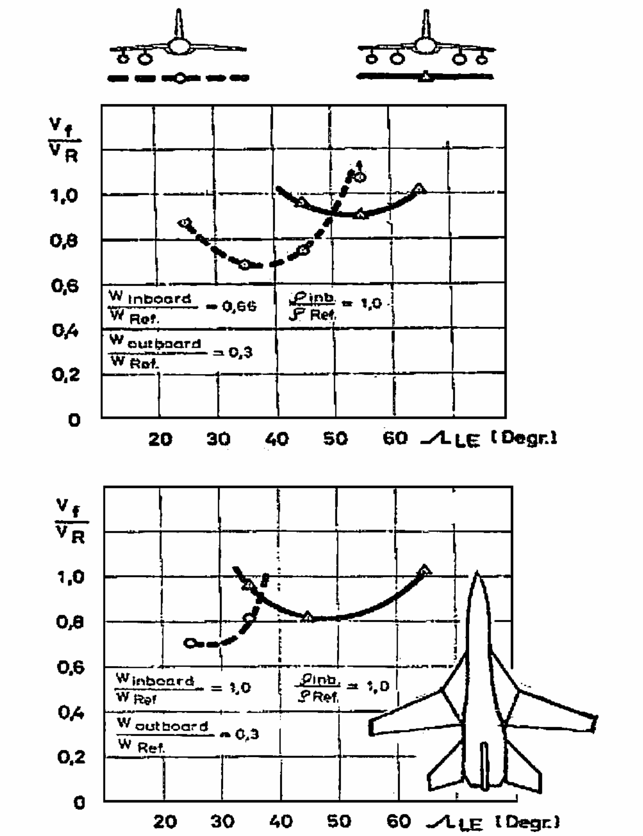

Fig. 22 Flutter of symmetric and asymmetric external store configurations on a variable-sweep airplane.[206]

antisymmetric oscillation energy transfers associated with them. This idea has led to two patents. In Ref. 202, asymmetric mass distribution on an airplane is used to raise flutter speeds. In Ref. 203, it is the tuning of engine pylons to have different stiffnesses on the right and left sides of an airplane.

As Refs. 204 and 205 show, however, for the case of a variable-sweep airplane with external stores, there can be asymmetric external stores configurations that are more flutter critical than their associated symmetric ones, Fig. 22. The aeroelastic analysis and clearance of asymmetric configurations must be carried out carefully, using the mathematical model (and wind-tunnel models, if necessary) of the full vehicle.

Conclusions

Aeroelastic technology development has been significantly influenced by challenges created by nonconventional airplane designs, as have new nonconventional designs become possible once advanced aeroelastic analysis and design capabilities became available. Selected key nonconventional airplane configurations of the past were surveyed in this paper and their aeroelastic characteristics examined: the swept-back modern jet, the T-tail, the high-aspect-ratio sail-plane/long-endurance airplane, the forward-swept wing, the oblique wing, the control configured fly-by-wire airplane, the variable-sweep/variable camber airplane, the slender supersonic transport, the hypersonic space plane, the flying wing, and the aeroelastically tailored and optimized airplane. Emerging designs currently in various stages of research and development that were discussed include the active aeroelastic wing concept, morphing airplanes, joined wings, modern supersonic and hypersonic design concepts, sensor-craft, very large transports, and blended-wing-body configurations.

On the centennial year of the airplane, it is instructive to reflect on past experiences in the area of aeroelasticity of nonconventional airplane configurations and to examine aeroelastic challenges of emerging new airplane designs. As another generation of aeroelasticians gradually retires, it is important to document its contributions and lessons learned for the benefit of the generation that will lead aeroelastic technology development in the coming decades.

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