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Historical Perspective on Analysis and Control of Aeroelastic Responses

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I. Introduction

FROM the very first human attempt to fly, throughout the history of aeronautics adverse aero-structure-contrd interaction of flexible flight vehicles has been a major concern in the aeroelasticity and control research. The study of aeroelasticity and control of aeroelastic responses involves many diverse disciplines and deals with problems such as wing flutter, buffeting, divergence, control-surface effectiveness, reversal and buzz, and gust load. Among these, flutter is the most feared dynamic instability, where wing mode oscillations extract energy from the airstream leading to sudden catastrophic failure. Divergence is a static instability, where excessive aerodynamic forces caused by elastic deformation lead to structural failure. The static and dynamic influence of elastic deformations of the structure on the distribution of steady and unsteady aerodynamic forces can also lead to unacceptable vibration, self-induced oscillation, ride-quality deterioration, and fatigue failure.

Over the past century, numerous inventors and researchers in aerodynamics, structure, material, and control, as well as dauntless flyers, have made life-long contributions towards the investigation and solutions to these problems. In this paper a brief history of this progress is presented, as a tribute to these pioneers. The early history of aeroelastic analysis and its foundations in solid mechanics, fluid mechanics, and control theory are reviewed first. This is followed by a review of some significant contributions towards the control of aeroelastic responses.

In fact, aeroelastic divergence might have played a pivotal role in the structural failure of the Samuel P. Langley's (1834–1906) flying machine, only weeks before the Wright brothers' historic flight at Kitty Hawk. Langley chose a catapult launch to speed his manned craft to 60 miles per hour. Figure 1 shows one of the launches on Potomac River. The stress of the catapult launch damaged this lightweight wood-framed fabric-covered airplane during the first attempt on 7 October 1903. During the second launch, a month later, the rear wing and tail completely collapsed. The pilot Charles Manley nearly drowned in the ice-covered Potomac River. Langley could have been the first but for the suspected aeroelastic divergence or possibly dynamic load failure. A few weeks later Orville Wright made his historic flight.[1]

On Monday, 14 December 1903, Wilbur made a successful takeoff, but the left wing hit the sandy hillside and swung the plane around, breaking several parts. They quickly made the repair and prepared for the next flight. Figure 2 shows one such preflight preparation. Three days later, on 17 December 1903, Orville made his historic flight that lasted 12 s and went over 120 ft. It was the first controlled, sustained flight, which also made effective use of wing flexibility by warping it for roll control. The brothers flew three more times that day, covering more distance as they gained experience to stabilize the flyer. The final flight of the day carried Wilbur 852 ft in 59 s. By all accounts,[1] Wright brothers were not only accomplished specialists in structures, controls, aerodynamics, propulsion, manufacturing, and flight test, but they also understood beneficial effects of aeroelasticity. An ingenious cable control system was used to twist or warp the flexible wing tips for roll control. Wright brothers' wing-warping technique is being rediscovered after a century, in the F/A-18 Active Aeroelastic Wing research[2] at U.S. Air Force Research Laboratory (AFRL) and NASA.

In 1910, Glenn H. Curtiss (1878–1930), risking an infringement of the Wright Brothers' patent, built an improved airplane and successfully flew 152 miles from Albany to Manhattan Island. Curtiss[3] pioneered many inventions now common in modern aircraft, foresaw their commercial and military applications, and is considered the father of modern naval aviation. Figure 3 shows Glenn Curtiss and Henry Ford at Hammondsport, New York, in 1913. Langley, Wright brothers, Curtiss, and many early aviators and inventors built their crafts based on the theoretical development of solid mechanics, fluid mechanics, and control sciences, which started several centuries ago. Let us now briefly recall this history.

II. Early History

Solid Mechanics

The theoretical foundation of fluid–solid interaction was built by our prodigal pioneers, Newton, Leibnitz, Hooke, Galileo, the Bernoulli family, Euler, Coulomb, Lagrange, Hamilton, Navier, Stokes, Cauchy, Green, Poisson, Kelvin, and Saint-Venant, to name a few. A superb account of this history was presented by Fung,[4] who also wrote the textbook *An Introduction to the Theory of Aeroelasticity*[5] in 1955. Timoshenko[6] in his classic textbook *Theory of Elasticity* referred to mathematician and historian Todhunter and Pearson[7] for this fascinating history first published in 1886. In brief, Galileo Galilei (1564–1642) was probably the first to develop the equations of strength of beams and columns. In 1660, Robert

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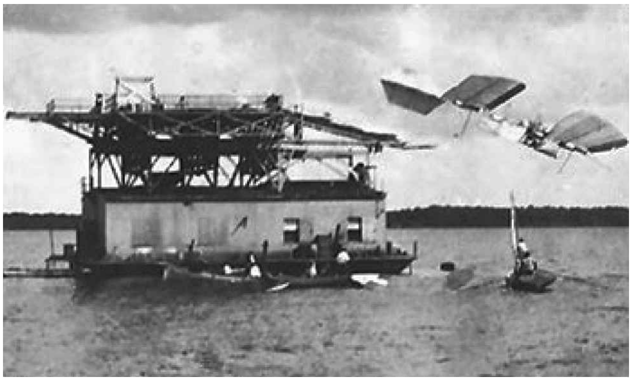

Fig. 1 Langley flier on Potomac River, 1903.

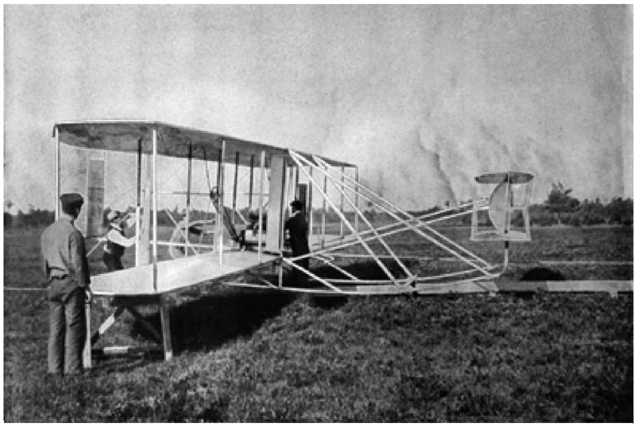

Fig. 2 Wright brothers: preparing for flight, 1903.

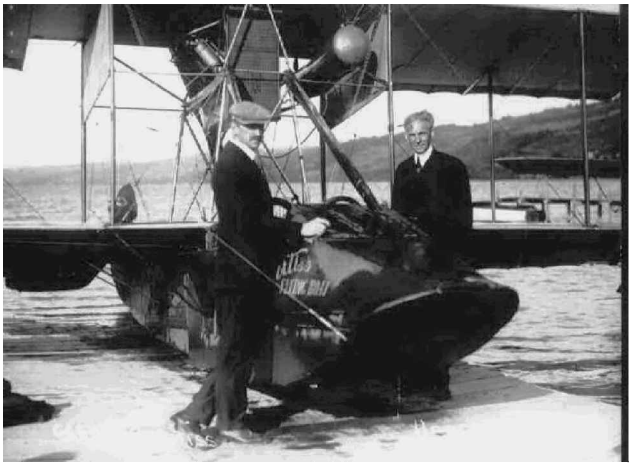

Fig. 3 Glenn Curtis and Henry Ford, Hammondsport, New York, 1913.

Hooke developed the Hooke's law relating material stress and strain. Jacques Bernoulli (1654–1705) introduced the linear elastic beam theory. His nephew Daniel Bernoulli (1700–1782) established basic equations of fluid flow and the kinetic theory of gases. His student and collaborator Leonhard Euler (1707–1783) developed the Euler-column buckling formula, as well as the Euler's equations for inviscid fluid flow. Charles Augustine Coulomb (1736–1806) developed the material failure criteria as well as the famous Coulomb's law for electrical current flow. Joseph Louis Lagrange (1736–1813) derived the equations that govern the area of analytical mechanics and bear his name. He also derived the equations for bending and vibration of plates, which are essential elements of aeroelastic analysis.

Fluid Mechanics

By 1821, Louis M. H. Navier (1785–1863) had succeeded in formulating the general equations of the three-dimensional theory of elasticity. Austin L. Cauchy (1789–1857) developed the concept of stress and strain. Simone D. Poisson (1781–1840) developed a molecular theory of elasticity and arrived at the same equation as those developed by Navier. Both Poisson and Navier based their analysis on Newtonian conception of the constitution of bodies and assumed certain laws of intermolecular forces. Cauchy's general reasoning however made no use of the hypothesis of material properties. In 1827, Navier[8] derived the equations of motion of viscous fluid flow. George Stokes[9] (1819–1903) simplified these equations in 1845 and obtained the famous Navier–Stokes equations for viscous fluid flow. With the contributions of George Green (1793–1841), George Stokes, and Lord Kelvin (1824–1907), the mathematical theories of both solid mechanics and fluid dynamics were established. Navier and Poisson also provided numerical applications of their general theory to many special problems. Barre de Saint-Venant (1798–1886) developed practical solutions for torsion and bending of prismatic bars. These fundamental developments in solid and fluid mechanics are of great importance to aeroelasticity and general engineering.

Control Theory

Modern aeroelastic analysis involves solid mechanics, fluid dynamics, and control theory. This multidisciplinary union can be traced to the prodigal pioneers who developed the theory of solid and fluid mechanics. The mathematics used in the dynamics and control theory were developed with significant contributions from Newton, Leibniz, Bernoulli family, Riccati, Lagrange, Hamilton, Laplace, Fourier, Cauchy, Maxwell, Routh, and Lyapunov, to name a few. Let us now briefly remember this history as described by Lewis.[10]

The theory of differential equation was developed in late 1600s and early 1700s. Isaac Newton (1642–1727) and G. W. Leibniz (1646–1716) are considered founding fathers of modern mathematics. J. F. Riccati (1676–1754) solved nonlinear differential equations used in optimal control theory. J. L. Lagrange (1736–1813) and W. R. Hamilton (1805–1865) established many applications of differential equations in analyzing the motion of dynamical systems. Johann Bernoulli (1667–1748), younger brother of Jacques Bernoulli, first mentioned the principle of optimality in connection with the Brachistochrone problem in 1696. This problem was solved by the Bernoulli brothers and also by Newton. During this era, various optimality principles were also investigated, including the minimum-time principle in optics of P. de Fermat and Hamilton's principle that a system moves in such a way as to minimize the time integral of the difference between the kinetic and potential energies.

In the early 19th century the development Laplace transform by P.-S. Laplace (1749–1827) and Fourier transform by J. Fourier (1768–1830), with significant contribution by A. L. Cauchy (1789–1857), facilitated the solution of many complex mathematical problems. By 1868, J. C. Maxwell[11] (1831–1879), who also developed the famous Maxwell's equations of electromagnetism, conducted the first systematic study of the stability of linear feedback control system. He showed that the system is stable if the roots of the characteristic equation have negative real parts. E. J. Routh[12] (1831–1907) provided a numerical technique for determining when a characteristic equation has stable roots. A. M. Lyapunov[13] (1857–1918) studied the stability of nonlinear differential equations using a generalized notion of energy. For a complete, fascinating account of this early history of the pioneering mathematicians, see data online at http://www-gap.dcs.st-and.ac.uk/~history/. The Lyapunov equation and the Riccati equations constitute the backbone for stability analysis and design in modern control theory. These fundamental equations are briefly described next.

Fundamental Equations

For aeroelastic analysis, structural mechanics and fluid mechanics are united in a common set of equations with judicious engineering approximations. The basic solid-mechanics equations, in the

Lagrangian coordinate tensor notation, can be written as follows[14]:

Stress equilibrium:

$$\sigma^{ij}_{,j} + F^i = 0 \qquad i, j = 1, 2, 3 \tag{1}$$

Strain displacement:

$$\varepsilon_{ij} = \tfrac{1}{2}\left(w_{i,j} + w_{j,i} - w^k_{,i} w_{k,j}\right) \tag{2}$$

Constitutive relations (Hooke's law):

$$\sigma^{ij} = E^{ijkl}\varepsilon_{kl} + k^{ij}(T - T_0) \tag{3}$$

where the force tensor F^i acting on the continuous elastic body can include inertia force, external applied force, and body force (gravity). These forces along with temperature differential $(T - T_0)$ result in displacement w_i, strain ε_{ij}, and stress σ^{ij}. When the body is immersed in a fluid, the external pressure and friction forces also depend on the deformed shape and motion of the body and can be computed from the solution of fluid-mechanics equations. In fluid mechanics stresses depend on strain rate $\dot{e}_{ij}$, and the coefficient of viscosity μ is analogous to the elastic property tensor E^{ijkl}. For a viscous fluid in motion, the components of stress tensor τ_{ij} can be expressed in the Eulerian coordinate tensor notation as[14]

$$\tau_{ij} = -pg_{ij} + \lambda\dot{\vartheta}g_{ij} + 2\mu\dot{e}_{ij} \tag{4}$$

$$\dot{e}_{ij} = \tfrac{1}{2}(v_{i,j} + v_{j,i}) \tag{5}$$

where $\dot{\vartheta} = v^k_{,k} = g^{kl}\dot{e}_{kl}$, p is the hydrostatic pressure, g_{ij} is the fundamental tensor, $\dot{e}_{ij}$ is the strain rate, v_i is fluid particle velocity, and $\lambda = -(\frac{2}{3})\mu$ from the simplifying assumption by Stokes that in viscous fluid the mean pressure $p = -(\frac{1}{3})g_{ij}\tau^{ij}$ as in an ideal fluid. This simplification led to the famous Navier–Stokes equations for ideal viscous fluid flow.

In a most general aeroelastic analysis, Eqs. (1–5), along with the equations for free-body motion, conservation of fluid mass, momentum, energy, and appropriate boundary conditions at the fluid–solid interface and far field need to be solved in order to determine the motion of a flexible vehicle moving through fluid. For analytical formulation the equations of motion are generally linearized and expressed in terms of modal deflections and generalized modal forces and moments. The linear equations of motion for a flexible flight vehicle can be written in matrix notation using the generalized mass, damping, stiffness matrices $[\boldsymbol{M}_s]$, $[\boldsymbol{D}_s]$, $[\boldsymbol{K}_s]$, and the unsteady aerodynamic-force-coefficient polynomial matrices $[\boldsymbol{Q}_s(\bar{s})\ \ \boldsymbol{Q}_c(\bar{s})\ \ \boldsymbol{Q}_g(\bar{s})]$ in the Laplace $\bar{s}$ domain, as shown in Eq. (6).

$$\left[[M_s]\bar{s}^2 + [D_s]\bar{s} + [K_s]\right]\{\xi_s\} + [M_{sc}]\bar{s}^2\{\xi_c\} + q[Q_s(\bar{s}) \quad Q_c(\bar{s}) \quad Q_g(\bar{s})]\begin{Bmatrix}\xi_s\\ \xi_c\\ \xi_g\end{Bmatrix} = \{0\} \tag{6}$$

Here, $\bar{s}$ is the Laplace variable; q is the dynamic pressure $\frac{1}{2}\rho V^2$; V is the freestream velocity; and ξ_s, ξ_c, and ξ_g are the generalized displacements of the structural modes, control-surface deflection, and normal gust component, respectively. The control-surface inertia coupling is denoted by $[\boldsymbol{M}_{sc}]$. For aeroservoelastic analysis using modern control theory, Eq. (6) along with the unsteady aerodynamics, actuator dynamics, gust dynamics, and sensor output signals $\boldsymbol{y}$ can be approximated and transformed into a larger set of first-order state-space equations [Eq. (7) and (8)]. Here, the augmented state vector $\boldsymbol{x}_s$ includes structural, aerodynamic, actuator, sensor, and gust states and their derivatives.

$$\frac{d\boldsymbol{x}_s}{dt} = \boldsymbol{F}\boldsymbol{x}_s + \boldsymbol{G}_u\boldsymbol{u} + \boldsymbol{G}_w\boldsymbol{w} \tag{7}$$

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x}_s + \boldsymbol{v} \tag{8}$$

Here, $\boldsymbol{w}$ and $\boldsymbol{v}$ are Gaussian white-noise processes with intensity $\boldsymbol{R}_w$ and $\boldsymbol{R}_v$, respectively. Using variational principles, it can be shown that the optimal full-state feedback gain $\boldsymbol{C}_0$ that would minimize the steady-state expected value of the weighted quadratic-state responses $\boldsymbol{x}_s$ and control activity $\boldsymbol{u}$ represented by the scalar cost function in Eq. (9)

$$E\left[\boldsymbol{x}_s^T\boldsymbol{Q}_1\boldsymbol{x}_s + \boldsymbol{u}^T\boldsymbol{Q}_2\boldsymbol{u}\right] \tag{9}$$

is given by

$$\boldsymbol{u} = -\boldsymbol{C}_0\boldsymbol{x}_s$$

where

$$\boldsymbol{C}_0 = \boldsymbol{Q}_2^{-1}\boldsymbol{G}_u^T\boldsymbol{S} \tag{10}$$

and $\boldsymbol{S}$ is the unique symmetric positive-definite solution of the nonlinear matrix Riccati Eq. (11) for selected symmetric-positive definite matrices $\boldsymbol{Q}_2$, $\boldsymbol{R}_v$ and symmetric positive-semidefinite matrices $\boldsymbol{Q}_1$, $\boldsymbol{R}_w$

$$\boldsymbol{F}^T\boldsymbol{S} + \boldsymbol{S}\boldsymbol{F} + \boldsymbol{Q}_1 - \boldsymbol{S}\boldsymbol{G}_u\boldsymbol{Q}_2^{-1}\boldsymbol{G}_u^T\boldsymbol{S} = 0 \tag{11}$$

Because all of the states $\boldsymbol{x}_s$ are not available for feedback, the minimum variance-state estimates $\boldsymbol{x}_c$ (Kalman filter) based on the sensor measurement Eq. (8) are used for output feedback controller shown in Eqs. (12) and (13):

$$\frac{d\boldsymbol{x}_c}{d\boldsymbol{t}} = \boldsymbol{F}\boldsymbol{x}_c + \boldsymbol{G}_u\boldsymbol{u} + \boldsymbol{B}_0(y - \boldsymbol{H}\boldsymbol{x}_c) \tag{12}$$

$$\boldsymbol{u} = -\boldsymbol{C}_0\boldsymbol{x}_c \tag{13}$$

where the Kalman filter gain matrix $\boldsymbol{B}_0$ is given by

$$\boldsymbol{B}_0 = \boldsymbol{P}\boldsymbol{H}^T\boldsymbol{R}_v^{-1} \tag{14}$$

and $\boldsymbol{P}$ is the unique positive-definite solution of the nonlinear matrix Riccati Eq. (15):

$$\boldsymbol{F}\boldsymbol{P} + \boldsymbol{P}\boldsymbol{F}^T + \boldsymbol{G}_w\boldsymbol{R}_w\boldsymbol{G}_w^T - \boldsymbol{P}\boldsymbol{H}^T\boldsymbol{R}_v^{-1}\boldsymbol{H}\boldsymbol{P} = 0 \tag{15}$$

The nonlinear matrix Riccati equations shown in Eqs. (11) and (15) are special forms of Lyapunov equations for the closed-loop system. With modern supercomputers equations similar to Eqs. (1–15), along with additional compatibility equations and corresponding boundary conditions, can be solved analytically and numerically for many complex aeroelastic phenomena. Let us now briefly recount the history of development of the theoretical foundation that made the solution of these analytical and computational aeroservoelastic equations possible.

Aerodynamics Theory

An excellent account of early history of aerodynamics theory was presented by Anderson.[15] For another detailed analytical history, see Giacomelli and Pistolesi.[16] Sir George Cayley (1773–1857) is sometimes called the father of aeronautics, and Otto Lilienthal (1848–1896) is credited for establishing foundations of experimental flight and aerodynamics. Ludwig Prandtl[17,18] (1875–1953) pioneered the application of fluid mechanics to engineering and technology from its domain in pure mathematics. He was professor of applied mechanics at the University of Göttingen and established the most important fluid dynamics laboratory at the beginning of the 20th century. The famous DLR Institute for Aeroelasticity at Göttingen has continued his legacy. In 1904, he developed the famous boundary-layer theory and its practical solution.[19] This was one of the most influential findings in the history of fluid mechanics. During his lifetime career at Göttingen, Prandtl molded the likes of von Kármán, Munk, Schlichting, Busemann, Pohlhausen, and Tollmien. Some of his own associates migrated to America, most notably Kármán and Munk, but Prandtl stayed at Göttingen.

Prandtl's student, Theodore von Kármán (1881–1963), was one of the few truly giants of aeronautics and made fundamental contributions to the theory and practice of aerodynamics, structural mechanics, and aeroelasticity. He was professor and head of the Aeronautical Institute at the University of Aachen, and later head of Caltech

Fig. 4 Tacoma Narrows suspension bridge just before collapse, 1940.

Guggenheim's Aeronautical Laboratory at Pasadena, California. His theoretical contributions include solid mechanics, nonelastic buckling, periodic vortex flow past cylinders (Kármán vortex), stability of laminar flow, turbulence, airfoil theory in steady and unsteady flow, boundary-layer theory, and transonic and supersonic aerodynamics. His lectures, both at Aachen and Caltech, were legendary. He was a key member of the Tacoma Narrows Bridge failure investigation committee. On 7 November 1940, at approximately 1100 hrs, the first Tacoma Narrows suspension bridge collapsed as a result of wind-induced vibrations. Figure 4 shows the spectacular torsion oscillation seconds before the collapse. Fung[5] discussed the investigation into possible resonant response from periodic Kármán vortex or torsion stall flutter. Dowell pointed out that Robert Scanlan, author of textbook *Aircraft Vibration and Flutter*, first published in 1951, provided some compelling evidence that this failure was the result of self-excited torsion flutter caused by negative lift-curve slope rather than a result of resonant response (see Ref. 20). One of von Kármán's famous remarks about catastrophic structural failure as a result of flutter instability was, "Some fear flutter because they do not understand it. And some fear it because they do."

Max M. Munk (1890–1986) started his work with Ludwig Prandtl at Göttingen, but was one of first of a long series of aerodynamicists to leave Germany to work at NACA. He designed and built the first NACA variable-speed pressurized closed-circuit Wind Tunnel. This historical technology is still preserved at NASA Langley. His work helped the design and development of the NASA Langley Transonic Dynamics Tunnel, where the majority of aeroelastically scaled models of aircraft, rotorcraft, and launch vehicles are tested.

Unsteady Aerodynamics and Flutter

In the early 20th century the unsteady aerodynamic theory of a moving airfoil in potential flow had been developed by a number of authors, in particular, Birnbaum,[21] Wagner,[22] Kussner,[23] Glauert,[24] and Theodorsen.[25] In their famous paper von Kármán and Sears[26,27] showed that the lift and moment acting upon an airfoil in the two-dimensional case can be calculated directly from simple physical considerations of momentum and moment of momentum. Von Kármán wrote in the introduction, "The theory of non stationary motion around airfoils has important applications, perhaps the most significant problems involved being flutter and the forces experienced by airplanes flying through gusts." The general results were applied first to a case of an oscillating airfoil and then to the problem of a plane airfoil entering a sharp-edged gust. Von Kármán and Sears made airfoil theory of nonuniform motion accessible to engineers by showing the physical significance of the various steps of the complex mathematical deductions and presented the result of the theory in a form suitable for immediate application to certain flutter and gust problems.

Theodorsen and Garrick

On 17 July 1917, NACA Langley Memorial Aeronautical Laboratory was established. At Langley, pioneering research on unsteady aerodynamics and flutter was led by the legendary Theodore Theodorsen from 1930 to 1946. The NACA advisory board members at that time included luminaries such as Joseph S. Ames, Vannevar Bush [Vice President of Massachusetts Institute of Technology (MIT) and later Chairman), Charles G. Abbott (Secretary, Smithsonian Institute), John H. Towers (Admiral U.S. Navy, later U.S. Senator), Jerome C. Hunsaker (founder of MIT Aeronautics and astronautics department), and Orville Wright. An AIAA special publication edited by Earl H. Dowell[28] titled *A Modern View of Theodore Theodorsen, Physicist and Engineer* provides an excellent first hand account of Theodorsen's lifetime contribution to the understanding of unsteady airfoil aerodynamics and mechanism of flutter.[25] Reference 28 also contains critical essays by I. E. Garrick, Holt Ashley, Donald Hanson, Anthony Peery, and Robert Scanlan. Theodorsen (1897–1978) joined the newly formed NACA at the request of Ames, then President of Johns Hopkins University and Chairman of NACA Advisory Committee. Theodorsen set to work on the oscillatory airfoil instability (flutter) quite independently of Birnbaum,[21] Wagner,[22] Bairstaw,[29] Lamb,[30] and Glauert.[24] In 1935, he completed the manuscript of NACA TR 496 (Ref. 25), one of the most disseminated and quoted reports from NACA. This remarkable report constitutes the centerpiece of Theodorsen's contribution to aeroelasticity. In NACA TR 496 Theodorsen laid the foundation for flutter analysis and control by establishing a set of complex frequency-response functions connecting vertical translation (or bending), angle of attack (or torsion), and aileron (control surface) rotation angle as "inputs" with unsteady lift, pitching moment, and aileron hinge moment (control force) as "outputs." This famous Theodorsen's function, corroborated by the parallel work of Küssner and others, has been used in countless practical calculation of flutter susceptibility of aircraft lifting surfaces in subsonic flow up to Mach numbers as high as 0.65 even up to the present day.

Edward Garrick, an associate and coauthor of much of Theodorsen's work,[28,31] demonstrated the Fourier Transform relationship of Theodorsen's function to the Wagner's function, defining the evolution of circulatory lift following an impulsive change in airfoil angle of attack, and to the Küssner's function, describing the lift evolution of the airfoil penetrating a vertical gust wall. Sears[27] described the force evolution on a thin airfoil penetrating a sinusoidal vertical gust and demonstrated its relation to Theodorsen's function. Thus, the four famous functions of motional airfoil incompressible lift theory developed by Wagner, Küssner, Theodorsen, and Sears were shown to be generically related. A great collection of reprints of 17 classical papers on aeroelasticity were republished in 1969 as a AIAA Selected Reprint Series, *Aerodynamic Flutter*, edited by I. E. Garrick.[32] This publication also contains an extensive supplementary bibliography.

III. Classic Reviews and Books on Aeroelasticity

In 1937, Alexander Klemin,[33] Chairman of Daniel Guggenheim School of Aeronautics, New York University, compiled abstracts of research reports, published from 1916–1937, for the U.S. Works Progress Administration. This rare limited distribution bibliography listed over 250 papers on divergence, reversal, flutter, and buffeting involving wings, tails, and control surfaces. The early beginning of experimental research on vibration and flutter by F. W. Lanchester, W. J. Duncan, R. A. Frazer, H. Glauert, A. R. Collar, Max M. Munk, H. G. Küssner, Manfred Rauscher, T. Theodorsen, and many other pioneers across the world were reported. At that time, although the static aeroelastic effects such as wing-torsion divergence and control-surface reversal were well understood, a dangerous instability called "flutter" was a major concern. The effect of fuselage flexibility on stability and control also received significant attention. However, the term "aeroelasticity" was not used at that time.

In 1946, Collar[34] described the interaction between elastic, inertia, and aerodynamic forces as aeroelasticity, using his famous Collar's Triangle diagram, shown in Fig. 5. He described expansion of the aeroelastic field into areas such as flutter of wings carrying engines, mass balancing and flutter-prevention devices, aerodynamic force calculation, divergence, loss and reversal of aileron and elevator, gust load, vibration, buzz, antisymmetric flexure-torsion flutter in roll, and wing design stiffness criteria. During the development

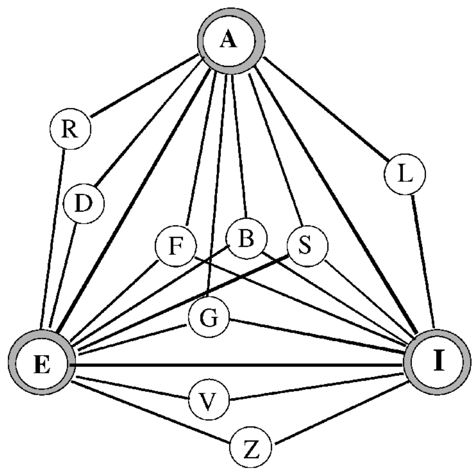

Fig. 5 Collar's aeroelasticity triangle, 1946: A, aerodynamic forces; B, buffeting; D, divergence; E, elastic forces; F, flutter; G, gust load; I, inertia forces; L, loading; R, reversal of control; S, stability and control; V, vibration; and Z, impact.

of supersonic research vehicle X-15 and the winged reentry vehicle X-20, ancestor of Space Shuttle, aerodynamic heating effects added another dimension to the Collar's Triangle, as described by Garrick.[35] For thin supersonic wings the panel-flutter phenomena became important and required significant analysis and design considerations as described by Dugundji.[36]

In 1976, Garrick[37] reported the enormous progress in aeroelasticity research made in the previous 75 years, in the 5th Biennial von Kármán Memorial Lecture. This excellent paper titled "Aeroelasticity-Frontiers and Beyond" described the entire spectrum of theoretical and experimental research, including historical background, propeller whirl flutter, rotor and turbomachinery, flying wing-tailless tanker, oblique-wing transport, and mathematics of aeroelasticity, along with the activity of Aerospace Flutter and Dynamics Council and the AGARD Structures and Materials Panel. Garrick's paper also contains detailed description of extensive research on active control of aeroelastic response, including the B-52 control configured vehicle program for load alleviation and modal suppression, flutter control based on aerodynamic energy methods, flutter control of aircraft with external stores, and the mathematical treatment of active control research. The progress in the analytical and numerical treatment of unsteady aerodynamics of arbitrary configurations and transonic flow considerations was reported. The dynamic load and aeroelasticity issues of the emerging space shuttle were also described in detail. Garrick's vision of the future applications of state-space modeling, optimal control theory, and the benefits of research on aeroservoelasticity was extraordinary. He also predicted the importance of rotorcraft aeroelasticity. For a recent historical overview of rotary-wing aeroelasticity, see Friedmann[38] and Yeager and Kvaternik.[39]

In 1981, I. E. Garrick and W. H. Reed[40] presented a detailed technical and historical account of the early history of aeroelasticity. The authors described interesting anecdotes and landmark contributions in flutter research from 1903–1919, post-WWI–1930, 1930–WWII, and important up-to-date advances. This paper listed 81 prime references, 36 critical survey papers, and 8 classic books on flutter and aeroelasticity. The authors also presented an interesting account of their own investigation into the possible role of divergence in the failure of Langley's flyer.

Bisplinghoff and Ashley

A complete technical history of aeroelasticity was presented by Raymond L. Bisplinghoff, Holt Ashley, and Robert L. Halfman, in their pioneering classic textbook *Aeroelasticity*,[41] first published in 1955. They trained numerous aeroelasticians, and the class notes resulted in this book and their second book *Principles of Aeroelasticity*,[42] which explained the complex mathematics of structural analysis, steady and unsteady aerodynamics, and their analytical solution techniques. A first-hand account of the Bisplinghoff's dedication to aeroelasticity research and teaching was given by Holt Ashley, in the Foreword "Some Memories and Some Notes from a Recent Survey of Aeroelasticity" at the Raymond L. Bisplinghoff Memorial Symposium, organized by Prabhat Hajela.[43] In 1950, Bisplinghoff (1917–1985) took over the directorship of the MIT Aeroelasticity and Structures Research Laboratory from Manfred Rauscher. Bisplinghoff along with Holt Ashley, John Dugundji, Theodore Pian, James Mar, Earl Dowell, and their students have continued to make original contributions to the state of the art. In 1956, Ashley and Zartarian[44] developed the piston theory for panel-flutter analysis at high Mach number. Dugundji[45] helped to develop the Mach box scheme for flexible delta-wing flutter analysis at supersonic speeds. Pian[46] pioneered the research on finite element methods (FEM), notably hybrid elements, that played a central role in future computational structural mechanics and aeroelasticity.

In 1970 and 1986, Ashley[47,48] presented two comprehensive reviews of mathematical advances in aeroelastic analysis. The second review paper[48] contained over 200 key references and detailed discussion of active control of aeroelastic phenomena, transonic flutter and associated computational fluid dynamics, and rotating machinery. In the section "people of aeroelasticity," he paid tribute to these pioneers and noted the passing of three contemporary "giants" I. E. Garrick in 1981, H. G. Küssner in 1984, and Bisplinghoff in March 1985. On a personal note, as a student of Dugundji at the MIT Aeroelasticity and Structures Research Laboratory, I met Bisplinghoff in 1972, during his regular visit to the aeronautics and astronautics department. Professor Halfman taught us dynamics, but Ashley had moved to Stanford University by then. I remember Ashley routinely returning to MIT (once at Christmas time, dressed as Santa Claus) and delivering enthusiastic accounts of his new findings to the eager audience. In February 1986, Prabhat Hajela[43] organized the Raymond L. Bisplinghoff Memorial Symposium at the University of Florida. Ashley along with his colleagues at Stanford and MIT, including Charles Stark Draper and many of their former students, gathered at Gainesville to pay their tribute. At this symposium Draper was scheduled to give the keynote address. In spite of his frail health, his indomitable spirit and confident smile still intact, the "father of inertial guidance" had come to pay his respect to Raymond L. Bisplinghoff.

The analytical capability to predict potentially catastrophic instability caused by aerodynamic-structural-control interaction was extended to cover all flight regimes into three dimensions, into nonlinear regime, with modern high-speed computational fluid mechanics. Dowell[20] and noted experts in these areas described these recent advances in aeroelastic analysis techniques for aircraft, rotorcraft, and turbomachinery in their excellent textbook on aeroelasticity. From Collar's triangle to the present, the ever-expanding domain of aeroelasticity virtually engulfs most topics in mathematics and engineering problems, as shown in Fig. 6, and has undergone a renaissance in recent years. In 1999, Friedmann[49] described this renaissance in an extensive review paper. In addition to covering the progress in aeroservoelasticity, computational and nonlinear aeroelasticity research over 15 years since Ashley's review,[48] he also reported new advances made in adaptive control, rotary-wing aeroservoelasticity,[38] and application of smart material in active aeroelastic wings and rotors. The paper also contains critical technical discussions and 169 valuable references.

IV. Classical and Modern Control

The classical and modern control theory and its applications were developed by pioneers like Black, Nyquist, Bode, Nichols, Evans, Bellman, Pontryagin, Wiener, Kalman, Draper, and Battin, among many others. Let us now briefly remember this history, described eloquently by Lewis.[10]

Classical Control Theory

At Bell Laboratories, Black[50] first demonstrated the stabilization of repeater amplifiers using negative feedback. Nyquist[51] derived

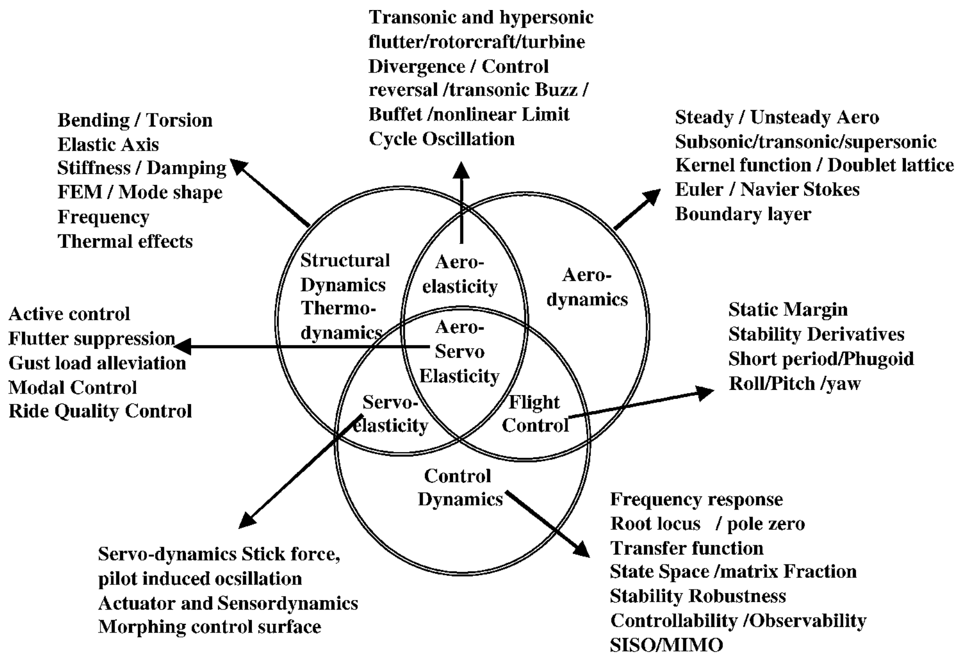

Fig. 6 Ever-expanding domain of aeroelasticity, 1963.

the Nyquist stability criterion, based on the polar plot of a complex function. In 1938, Bode[52] investigated closed-loop stability margins using the notion of gain-and-phase margin from magnitude-and-phase plots of frequency response functions. Much of the research in applied control during the 1940s came out of the MIT Radiation Laboratory. In 1947, Nichols[53] and his coworkers developed the Nichols Chart for the design of robust feedback systems. With the design approaches based on the transfer function, the block diagram, and frequency-domain methods, the theory of linear servomechanism was firmly established. Evans[54] developed the root-locus technique, which is widely used to determine migration of closed-loop poles with feedback gain. Subsequently, much of the active aeroelastic control design utilized these methods developed by Nyquist, Bode, and Evans, in order to obtain desirable closed-loop stability and response characteristics.

Modern Control Theory

In 1957, Bellman[55] applied dynamic programming to the optimal control of discrete-time systems, demonstrating that the natural direction for solving optimal control problems is backwards in time. His procedure resulted in closed-loop, generally nonlinear, feedback schemes. By 1958, Pontryagin et al.[56] had developed the maxima principle, which solved optimal control problems relying on the calculus of variations developed by Euler in the 18th century. In 1960, Kalman[57] developed optimal filtering and estimation theory, thus providing the design equations for the discrete system state estimation. In 1961, Kalman and Bucy[58] also developed the continuous-system linear filtering and prediction theory. Thus, in the period of a year the major limitations of classical control theory were overcome, important new theoretical tools were introduced, and the era of modern control theory began. Kalman formalized the notion of optimality in control theory by minimizing a quadratic generalized energy function. In estimation theory he introduced stochastic notions that applied to nonstationary time-varying systems, thus providing a recursive solution, the famous Kalman filter, for the least-squares approach first used by C. F. Gauss (1777–1855) in planetary orbit estimation. The Kalman filter is the natural extension of the Wiener filter for nonstationary stochastic systems, developed by the MIT mathematician Norbert Weiner.[59] In the early 1950s, Charles Stark Draper invented the inertial navigation system, which used gyroscopes and accelerometers to provide accurate information on the position of a moving ship, aircraft, missile or spacecraft. Thus, precision sensors and computers appropriate for autonomous navigation, guidance, and control of aircraft, spacecraft and missiles were developed. In 1981, Draper[60] presented an excellent history of this incredible progress in inertial guidance. An additional first-hand account of this history and evolution of space guidance was presented by his colleague Battin.[61]

Union of Classical and Modern Control Theory

The classical frequency-domain techniques provide a great deal of insight during control systems design, yet a good design requires extensive experience. By contrast, modern optimal control theory provided feedback control laws with guaranteed performance, through formal matrix Riccati and Lyapunov equations shown in Eqs. (7–15). However, guaranteed performance obtained by solving matrix design equations often yielded a control system design that works in theory without providing any engineering intuition about the problem. Moreover, many feedback control systems can become unstable because of the presence of unknown dynamics, disturbance, and measurement noise. With a frequency-domain approach robustness to uncertainty can be built in through gain-and-phase margin. In the 1970s, Rosenbrock,[62] and MacFarlane and Postlethwaite[63] extended classical frequency-domain stability criteria to multivariable systems, using notions like the characteristic locus, diagonal dominance, and the inverse Nyquist array.

In 1981, Doyle and Stein,[64] Safonov et al.,[65] and Lehtomaki et al.[66] extended the research on the guaranteed robustness properties of the linear-quadratic-Gaussian-based multivariable control designs. Doyle and Stein[64] developed an asymptotic robustness recovery technique for the state-estimator-based controller shown in Eqs. (12) and (13). They also showed the importance of the matrix singular value analysis in frequency domain for robust multivariable design. Using the singular value concept, many of the classical frequency-domain techniques can be incorporated into modern optimal control design. Thus a new robust control design technique, which blends the best features of classical and modern control theory, was born. In 1987, Dorato[67] presented an excellent review of this modern control theory.

Classic textbooks on the fine art of classical and optimal control that trained generations of control engineers were written by many well-known educators like Blakelock,[68] Franklin et al.,[69] Dorf,[70] Kwakernaak and Sivan,[71] and Bryson and Ho.[72] Doyle[73] and associates developed the concept of structured singular values, which combined the best of classical and optimal control theory. This technique, also known as μ synthesis, can be used for providing both stability and performance robustness to structured perturbations in an uncertain dynamic system and is especially suited for aeroservoelastic controller design. Doyle is perhaps one of the most innovative mathematicians of the modern time.

In the 1980s, with the introduction of desktop computers and a better understanding of the modern control theory, many commercial software programs for control systems design were developed, such as ORACLS, CC, DIGICON, Control-C, Matrix-X, Easy5, and notably Matlab,[74] by MathWorks—pioneered by another visionary mathematician Cleve Moler. Thus, practical application of classical and modern control theory, particularly for analysis and control of aeroelastic responses, became widespread among control engineers.

V. Analysis of Aeroelastic Responses

A complete analysis of aeroelastic response requires a unified formulation of structural deformation and unsteady aerodynamic forces [e.g., Eqs. (1–5)], combined with the vehicle dynamic equations. Generally, for aeroservoelastic analysis and application of optimal control theory the unsteady generalized forces are approximately linearized and integrated with controller dynamics and gust spectral models and transformed into linear state-space equations, similar to those shown in Eqs. (6–8).

Unified Aeroelastic Equations

Using a tensor/dyadic approach, Ashley was first to report a unified formulation of complete aeroelastic equations of flexible flight vehicle,[42,43] which also permitted large rigid-body motion. Rodden[75] developed equations of motion of a quasi-steady flexible flight vehicle utilizing restrained static aeroelastic characteristics. Albano and Rodden,[76] along with Johnson,[77] were the driving forces in developing and improving the "subsonic doublet lattice" method and the aeroelastic analysis module in NASTRAN,[77] which has now become an industry standard for FEM and aeroservoelastic analyses. In a series of papers, Schmidt[78] and his coworker developed general equations of motion in a global inertia coordinate system and applied it for a flexible hypersonic aerospace vehicle.

Unsteady Aeroelastic Forces

In 1977, Edwards et al.[79] investigated unsteady aerodynamic modeling for arbitrary motion of a two-dimensional airfoil with control surface using direct Laplace transform of potential flow equations. Morino[80] applied Green's theorem to obtain an integral relation in space and time variable between the surface normal velocity and the velocity potential. Morino et al.[81] advanced the theory and computation of oscillatory subsonic and supersonic aerodynamics around complex configurations using panel aerodynamics, applicable to vortical flow and helicopter dynamics. Morino and his associates[82] also expressed the Laplace transformed velocity potential explicitly as a transfer matrix times a transformed downwash matrix. Librescu[83] provided the formulation for unsteady supersonic aerodynamics of planar lifting surfaces undergoing arbitrary time-dependent motion. Research in this fertile area is continuing.

State-Space Equations for Aeroservoelastic Analysis

For aeroservoelastic analysis the generalized linear oscillatory aerodynamic force matrices $[\boldsymbol{Q}_s \;\; \boldsymbol{Q}_c \;\; \boldsymbol{Q}_g]$ in Eq. (6) are generally computed by the doublet-lattice method[76] for a set of prescribed structural vibration modes at their natural frequencies. To transform Eq. (6) into the linear state space Eqs. (7) and (8) for arbitrary motion, Roger[84] devised a rational function approximation method to represent unsteady aerodynamic forces in the Laplace $\bar{s}$ domain. Assuming an analytical continuation from the frequency domain to the Laplace $\bar{s}$ domain, Roger used a second-order polynomial in s plus a summation of first-order lag filters called aerodynamic lag terms. This procedure was later improved by Tiffany and Adams[85] and by Karpel[86] for better curve fitting of numerical oscillatory aerodynamic results[76] and conversion of the equations of motion to the state-space form with minimal number of states $\boldsymbol{x}_s$ in Eqs. (7) and (8). Once the state-space equations are available to represent the aeroservoelastic system dynamics with reasonable accuracy, modern control theory can be used to obtain robust flutter-suppression control laws,[87] in conjunction with numerical optimization techniques.[88]

Computational Aeroelasticity

One critical area in aeroelasticity is the transonic region, at which wings generally exhibit the lowest flutter velocity. At transonic speeds shock waves on the wing surface can also result in buffeting, limit-cycle oscillation, aileron buzz, and shock-boundary-layer interaction. Computational fluid dynamics (CFD) methods in this transonic speed regime have been developed extensively over the past two decades. Significant advances have been reported by many authors, particularly Edwards et al.,[89] Batina et al.,[90] Guruswamy and Tu,[91] and Love and associates,[92] to integrate CFD with FEM structural dynamics for aeroelastic load computation and flutter analysis, including boundary-layer effects.[93] Development of unstructured mesh by Batina[94] for computational aeroelasticity was another significant contribution. In an excellent survey paper Bennett and Edwards[95] described the recent advances in computational aeroelasticity. Recently Huttsell et al.,[96] presented the state-of-the-art review and comparison of the latest computational aeroelasticity codes for loads and flutter. This paper also included results from analyses of the F-15 flutter, a nonlinear aeroelastic residual pitch oscillation in the B-2, limit-cycle oscillation in a B-1 like configuration, the transonic buzz phenomenon in Global Hawk, and the Hypersonic National Aerospace Plane wing flutter.

Aeroservoelastic Optimization

Ashley[97] presented one of the earliest papers providing an extensive review of state of the art of optimization in aerospace. Pioneering developments of computational tools for optimization of multidisciplinary aeroelastic design were done by Vanderplaats[98] and Sobiezczanski-Sobieski and Haftka.[99] D'Vari and Baker[100] reviewed the present state of the art in aeroelastic loads optimization and sensitivity analysis. In 1999, in an excellent review paper Livne[101] presented the status, direction, and recent progress in integrated aeroservoelastic optimization. Livne listed 301 valuable references by subject. Chen[102] and associates at Zona Technologies are developing commercial software with aeroservoelastic analysis and optimization capabilities, in collaboration with Johnson and Venkayya[103] at the U.S. Air Force Wright Aeronautical Laboratory. Walsh and associates[104] described another software development for multidisciplinary high-fidelity analysis and optimization of flexible flight vehicle, including static aeroelastic effects.

VI. Control of Aeroelastic Responses

Significant volume of sustained research on aeroservoelasticity,[105] active modal control, flutter suppression, and robust control design[106] were conducted and supported by the Air Force Wright Aeronautical Laboratory. Flutter is a major concern in military aircraft, which fly faster with multiple wing-mounted armament and store, often at the edge of flight envelope, and must undergo extensive flutter testing. Kehoe[107] presented an excellent historical overview of flight flutter testing and techniques at NASA Dryden Flight Research Center. For large bombers one must also deal with adverse aeroelastic effects on ride quality and pitch and yaw stability. For fighter/attack aircraft multiple aeroelastic instabilities of wing-store combinations must be suppressed. A brief history of a few such aeroservoelastic control programs is presented next.

XB-70 Modal Suppression

In the 1960s John Wykes at North American Rockwell pioneered in active control of adverse aeroelastic effects on ride quality and pitch and yaw stability of vehicles with long slender fuselage, such as the XB-70, B-52, B-1, and B747. In an excellent paper Wykes[108] described in detail their approach to XB-70 modal-suppression system using classical design techniques. A flight investigation of a structural mode-control system termed identical location of accelerometer and force (ILAF) was conducted on the XB-70 airplane. Figure 7 shows the XB-70 taking off from NASA Dryden Flight Research Center. The deflected canard near the pilot station, used for active modal suppression, can be seen clearly. During the first flight test, the ILAF system encountered localized structural vibration problems requiring a revision of the compensating

Fig. 7 XB-70 taking off from Dryden Flight Research Center, 1967.

Fig. 8 X-29 forward-swept actively controlled wing, 1987.

network. After modification, successful structural mode control that did not adversely affect the rigid-body dynamics was demonstrated. The ILAF system was generally more effective in supersonic than subsonic flight because the conditions for which the system was designed were more nearly satisfied at supersonic speeds. The results of a turbulence encounter at a Mach number of 1.20 and an altitude of 10,000 m indicated that the ILAF system was effective in reducing the vehicle's response at this flight condition. An analytical study showed that the addition of a small canard to the modal-suppression system would greatly improve the automatic control of the higher-frequency symmetric modes.

X-29 Forward-Swept Wing

The forward-swept wing design in the X-29 vehicle, shown in Fig. 8, improved flight performance and agility significantly, but exhibited lower divergence speed and aeroelastic instability called body-freedom flutter. Fundamental research in solving this problem by aeroelastic tailoring of wing stiffness was done by Weisshaar,[109] Weisshaar and Ryan,[110] and Dugundji.[111] A sophisticated computerized digital flight-control system along with a special composite wing with aeroelastically tailored stiffness property was used to solve this problem. The flight-control also used a series of notch filters to eliminate undesirable flexible mode interaction with flight-control system. In 1985, Chipman[112] and associates at Grumman presented this success story of active and passive aeroservoelastic control of the X-29.

Decoupler Pylon

A fighter/attack aircraft carries a large array of external wing stores and munitions at different wing locations and are susceptible to multiple aeroelastic instabilities that must be suppressed. Wilmer H. Reed, III, a colleague of Garrick[40] and a prolific innovator relating to flutter and aeroelasticity of aerospace vehicles, developed a quasi-passive concept, referred to as the decoupler pylon,[113]

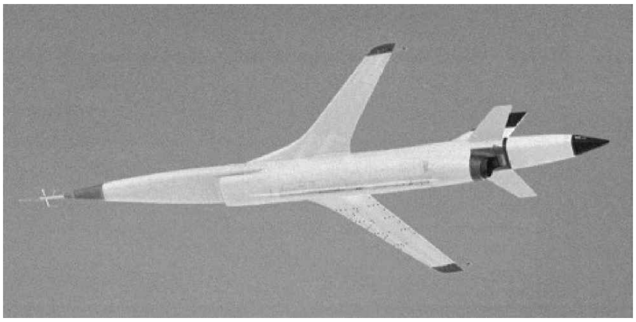

Fig. 9 Drone for aeroelastic and structural testing in flight, 1984.

which combines desirable features of conventional passive method and advanced active control method. Analysis and wind-tunnel tests indicated that the decoupler pylon provides substantial increase in flutter speed and is virtually insensitive to inertia and center-of-gravity location of the store. In 1988, Reed[114] conceived the Flutter Exciter, now used worldwide in flight flutter testing[107] of new or modified aircraft designs, including the F-16XL, the F/A-18, and the F-22. During flight test, systems identification procedures are used to process the sensor signals from the excited structural modes for prediction of robust flutter margins as described by Lind and Brenner.[115]

Active Flutter Suppression

The extensive research effort in advanced aerodynamics and active controls during the 1980s was presented in a NASA conference publication.[116] During this time, at the NASA Langley Transonic Dynamics tunnel many aeroservoelastic models with miniature servocontrols were developed and tested, including a supersonic transport-type delta-wing research model[117] and a DC-10 type transport wing.[118] A set of remotely controlled flying testbeds named "Drone for aeroelastic and structural testing" with modified instrumented wings, shown in Fig. 9, was used extensively for active flutter-suppression research.

Abel and Noll[119] described this research and applications in aeroservoelasticity from 1979–1988 at the 16th Congress of the International Council of the Aeronautical Sciences, Israel. During this time, research teams at Honeywell, NASA Langley, and NASA Ames Research Center were developing analytical techniques for better modeling of flutter dynamics and practical flutter-suppression control law development. An aerodynamic energy method by Nissim and Abel[120] and optimal control methods by Newsom et al.[121] were used to design robust feedback control laws for flutter suppression. Generally, for a multimode, high-fidelity flutter analysis the state-space model shown in Eqs. (6) and (7) is very large in order. Consequently, the full-order optimal output feedback control laws shown in Eqs. (11) and (12) are also very large in order and therefore very difficult to implement. So a set of numerical constrained optimization methods were developed[122–125] to reduce the order of the controller and then improve the multiloop system robustness based on matrix singular values[126,127] at the plant input and output, while keeping the control surface activity within the allowable limits. For a comprehensive account of testing of active control of aeroelastic response at the NASA Langley Transonic Dynamics Tunnel, see the recent survey paper by Perry et al.[128]

Active Flexible Wing

During the 1970s, aeroservoelastic interactions were of great concern to the aircraft designers because of their adverse effects on vehicle stability and performance. Examples of adverse aeroservoelastic interactions included the YF-16 and the F-18, which exhibited instabilities in flight. The YF-18 and X-29 were predicted to be unstable, resulting in flight-control-system modifications prior to first flight. The developments of structural and control system optimization procedures in the 1960s and 1970s and the continual enhancement of these techniques in the 1980s and 1990s into highly integrated multidisciplinary optimization methodologies has resulted in

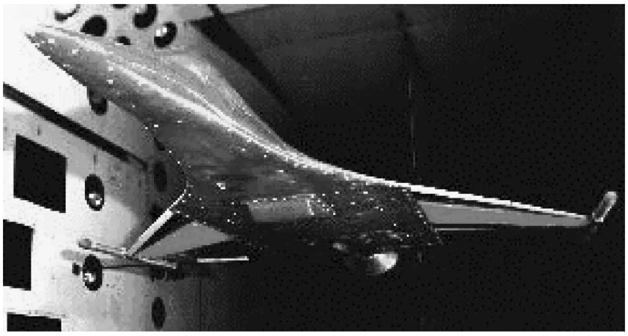

Fig. 10 Active Flexible Wing aeroservoelastic model in Langley Transonic Dynamics Tunnel, 1992.

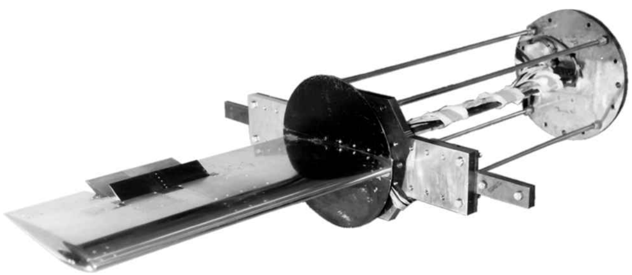

Fig. 11 BACT wing with two active control surfaces on the pitch-and-plunge apparatus for active flutter-suppression research, 1995.

innovative options for improving the capabilities of highly flexible next-generation flight vehicles.[129] To demonstrate the benefits available through the use of these techniques and use of active controls, the Active Flexible Wing (AFW) program[130] was conducted jointly by Rockwell International (now Boeing), U.S. Air Force Wright Laboratory, and NASA. Figure 10 shows the AFW aeroservoelastic model in the Langley Transonic Dynamics Tunnel. Both symmetric and antisymmetric flutter suppression, as well as dynamic load alleviation with rapid roll maneuver below and above open-loop flutter boundary, were demonstrated successfully.[130] A new online singular value-based stability margin evaluation technique for multivariable aeroservoelastic system was also demonstrated.[131]

Benchmark Active Control Technology

The Benchmark Active Control Technology (BACT) research project was conducted at NASA Langley, in collaboration with related research from Duke University, Texas A&M, University of Minnesota, Vanderbilt University, University of Florida, University of Nevada, Boeing, and Honeywell. A standard instrumented wing model with the NACA 0012 airfoil section that was mounted on a specially designed pitch-and-plunge apparatus, as shown in Fig. 11, was tested in the Langley Transonic Dynamics Tunnel.

Test objectives of the BACT project were to 1) measure, record, and archive unsteady aerodynamics data in the transonic flow regime and 2) design robust control laws and actively control several critical transonic flutter instabilities. This collection of data was used for verification and validation of CFD data and flutter-suppression control law synthesis methodologies. For flutter-suppression control laws a wide variety of design techniques[132–135] (e.g., classical, minimax, H-infinity, robust passification, structured singular value, μ-synthesis, and neural network) was used. These robust control laws were implemented digitally and tested successfully for active flutter suppression in the wind tunnel using trailing-edge flap and a midchord spoiler.

Smart Wing Program

Following the lead of the Wright brothers wing-warping technique, researchers in the smart wing program[136] sponsored by NASA/Defense Advanced Research Projects Agency/Air Force Research Laboratory have investigated the use of fully integrated adaptive material actuator systems for performance-enhancing shape control of wing because these devices offer a significant advantage over a hinged control surface. Typically, smart structure actuators are shape memory alloys, piezoelectric and electrostrictive ceramics, magnetostrictive materials, and electro- and magneto-rheological fluids and elastomers. The Northrop Grumman Smart Wing program[137] is one such effort addressing the development and demonstration of a smart wing. The overall objective of the Smart Wing program is to demonstrate seamless actuation systems for flutter suppression, dynamic load alleviation,[138] and flight control, in order to improve the aerodynamic and aeroelastic performance of military aircraft. Because such wings would require fewer moving parts for controlling flight, they could be made thinner, lighter, and more aerodynamically efficient than today's wings and thus allow for greater range, payloads, and fuel efficiency.

Fig. 12 F/A-18A Active Aeroelastic Wing, 2000.

Active Aeroelastic Wing

The Active Aeroelastic Wing (AAW) research[139,140] is rediscovering the advantage of natural warping in future jet fighter aircraft, just as it was used by the Wright Brothers a century ago.[2] AAW technology employs multiple leading-edge and trailing-edge control surfaces as tabs activated by highly sophisticated flight-control software in conjunction with a modified F/A-18A wing shown in Fig. 12, which actually bends and twists to maneuver and enhance performance. Jointly supported and managed by Boeing Phantom Works, NASA, and the U.S. Air Force, AAW project goals include investigating the use of the lighter-weight flexible wings for high-performance military aircraft and demonstrating aircraft roll control through aerodynamically induced wing twist on a full-scale aircraft.

Nonlinear Aeroservoelasticity

Dowell and Tang[141] presented the latest assessment of work in nonlinear aeroelasticity with interesting historical perspectives. Recent advances in nonlinear aeroservoelasticity (ASE) include the following: nonlinear aeroelastic response identification,[142] high-fidelity reduced-order modeling[143] of aeroelastic systems using CFD results, limit-cycle oscillations of nonlinear aeroelastic systems,[144] system identification of vortex-lattice aerodynamic model,[145] wavelet filtering[146] for ASE robustness estimation from experimental data, and adaptive output feedback control[147] of a nonlinear two-dimensional ASE system. Dynamic inversion[148,149] is also an emerging technique that can be applied to nonlinear ASE control problems. Recently, Naidu and Calise[150] presented a detailed survey paper on application of singular perturbation techniques towards solution of nonlinear control problems.

VII. Conclusions

Brief glimpses of history of aeroelastic analysis and control of aeroelastic responses and their mathematical foundation were presented. This is a continuing story, and many excellent research works in this multidisciplinary field remain to be reviewed in future. In addition, history and recent advances in aeroelastic analysis and control of rotorcraft, turbines, jet engines, launch vehicles, missiles, spacecraft, large space structure, and nonaerospace structure were omitted. Fortunately, most unclassified publications are available through the Web-based google.com search engine.

Acknowledgments

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