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# THE CONSTRUCTIVE USES OF AEROELASTICITY (*)

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*Dedicated to Professor Wladysław Fiszdon on the occasion of his seventieth birthday*

Historical, previously-published and new material is illustrated and discussed in support of the proposition that static or dynamic structural deformations of aerospace vehicles can often be used for constructive purposes. Examples are presented chronologically in categories related to the intended function. Efficient control of flight is attainable, as by the Wrights' wing warping. Constraints can be relaxed on the performance of high-speed aircraft, fixed-pithc propellers and rotors. Accelerations and loads in rough air are diminished. Aeroelastic deformations furnish a means for primary propulsion. Prospects for the future are examined, notably the "complete aeroelastic CCV".

## 1. INTRODUCTION

Since all structural materials exhibit finite elasticity, no artifact of engineering behaves under load in a completely rigid fashion. As a rule, elastic or plastic deformation is regarded as an undesirable by-product of design, and it must be limited in some appropriate way. Thus construction codes typically constrain the deflections of such civil structures as bridges or building floors, and elongated compression members must be protected against buckling instability. It is equally obvious, however, that (reversible) flexibility can often be put to good use. Instances may be found in such tiny, homely objects as paperclips or the bistable keys of an electronic calculator. But they also include springs of all sizes, shock absorbers, arresting or landing gear, and a host of other devices that will occur to the thoughtful reader.

Static and dynamic structural deformation plays a peculiarly significant role in aeronautics, where the imperative of light weight invariably comes into conflict with requirements involving stiffness and stability. When such design conditions relate to members which sustain the heavy aerodynamic pressures of flight, the associated phenomena are called "aeroelastic". First identified during World War I, their treatment gave birth to a specialized discipline(1) that remains active

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(1) Representative early books which summarized the state of the aeroelastic art were those by FISZDON [1], FUNG [2] and BISPLINGHOFF, ASHLEY and HALFMAN [3]. Among numerous other citations that might be made, consider the recent text by DOWELL *et al* [4] and COLLAR's historical survey [5].

today, although it is gradually being absorbed into the mainstream of atmospheric vehicle design.

Despite fascinating challenges, the career of the aeroelastician has many frustrations, for he is usually cast as a "policeman". The analyses and tests which he performs, in the course of avoiding dangerous instabilities like wing flutter or excessive structural loads, are seen as penalizing flight speeds or creating unwanted and perhaps unnecessary weight increases. This is a justifiable, but sometimes inappropriate, view.

By no means universally recognized is the fact that aeroelastic behavior can be constructively employed toward improving the performance, controllability, efficiency and comfort of airplanes and related aerodynamic machines. With the aim of demonstrating this proposition—and perhaps of enhancing the "image" of aeroelasticity in an entertaining way—the authors have assembled numerous illustrative examples. Some are from the earlier history of aeronautics, others current or purely conceptual. With certain arbitrariness, a selection of these examples has been categorized in accordance with the titles of sections which follow. Each is summarized as succintly as possible, with carefully chosen pictures, graphs and references. They encompass quite different devices, a wide range of operating speeds, and varying degrees of sophistication. One hopes that unity is achieved on the theme of "constructiveness".

## 2. IMPROVED CONTROL AND STATIC STABILITY

In his appreciation of the engineering achievements of WILBUR and ORVILLE WRIGHT, COOMBS [6] identifies about half a dozen which he judges especially original and important. One of these was really effective control about the airplane's roll axis—something they accomplished with the aeroelastic technique of "wing warping".

The outlines of this scheme are depicted in Fig. 1 by means of two phantom views of the 1903 Wright "Flyer" wing taken from CULICK's excellent article [7]. In the upper sketch one sees that diagonal bracing wires which stiffen the force and aft truss structures between the wings are omitted from the two outer aft bays nearest each wingtip. Thus the outboard trailing edges are made more flexible, so that they can be twisted antisymmetrically up and down by the control wires shown in the lower sketch. Lying prone in the "cradle", the pilot could move his hips sideways toward the wing which he wished to depress. From all reports, versions of this system employed on all the later Wright gliders and airplanes made it a simple matter either to keep the wings level or to bank for turning, as necessary, in proper coordination with rudder control. Only with the 1909 adoption of the aileron by FARMAN [8] was wing torsion supplanted as the best way to do the job.

Wing warping made its appearance again in a very modern context as part of the lateral-directional control system for the successful man-powered aircraft, "Gossamer Condor" and Gossamer Albatross". The functioning of this system is explained ny LISSAMAN [9], and its mechanical realization is detailed in BURKE's excellent summary [10] of the Condor designs. Figure 2 is a closeup photograph of the Albatross in flight. Barely visible are some of the bracing wires which run diagonally from the base of the vertical king post out to various stations along the wingspan. These wires are part of the primary structure, but one pair of them was cleverly arranged to twist the tips antisymmetrically in response to the pilot's stick actuation.

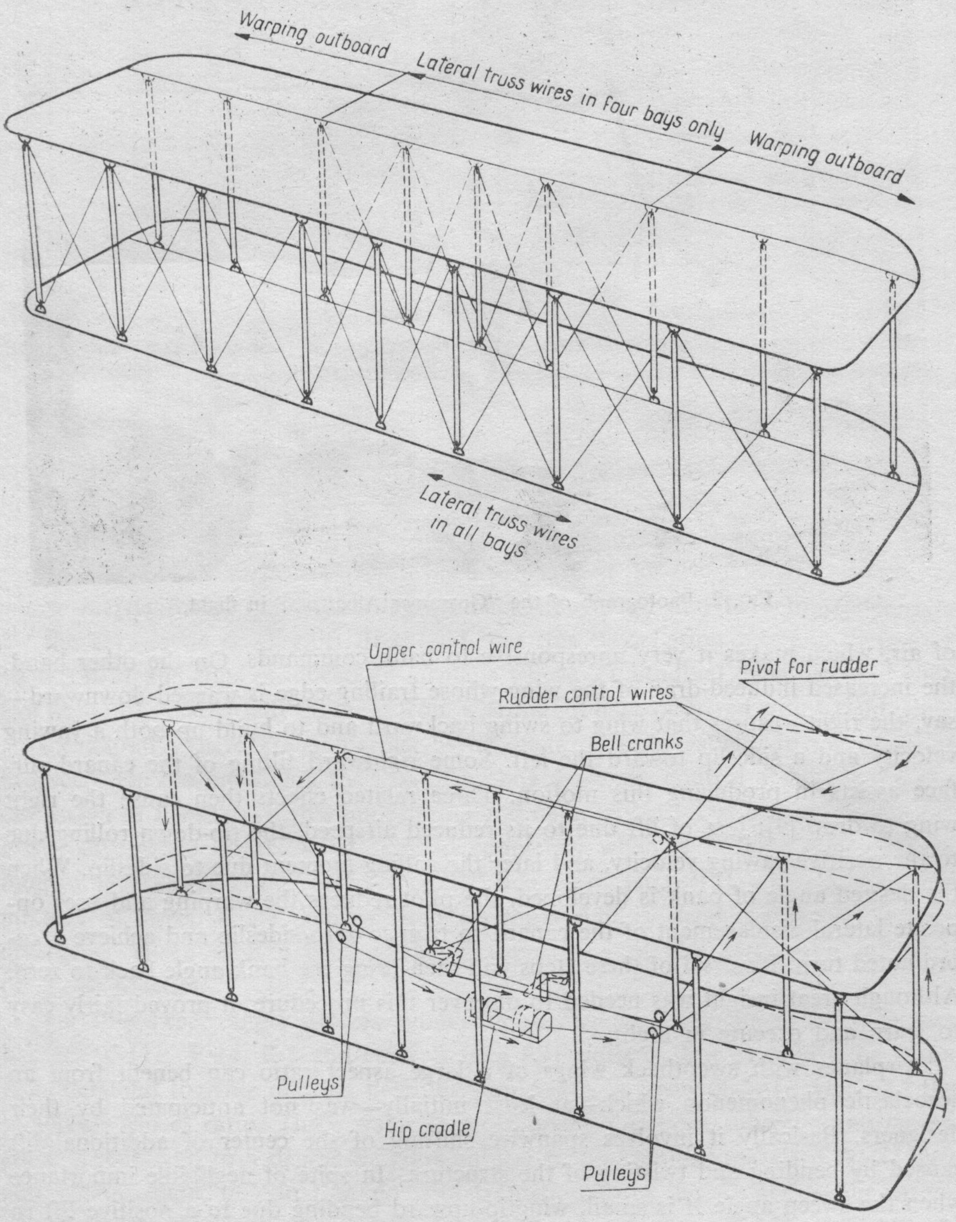

FIG. 1. Two simplified sketches of Wright Flyer wing boxes. Lower picture shows rigging from prone pilot's hip cradle to warp the wingtips. (From Ref. [7]).

A remarkable feature of the Condor system is that, by intent, a given wing leads to opposite turning from what occurred on the Wright Flyer. This is because the very light, wide Condor lifting surface carried with it in roll a huge virtual mass of air, which makes it very unresponsive to bank commands. On the other hand, the increased induced-drag of the wing whose trailing edge is warped downward—say, the right—causes that wing to swing backward and to build up both a yawing velocity and a sideslip toward the left. Some rightward tilting of the canard surface assists in producing this motion. Three related effects then cause the right wing to drop [9]: loss of lift due to its reduced airspeed, the tip-down rolling due to the positive yawing velocity, and later the rolling moment due to sideslip. When the desired angle of bank is developed, the pilot reduces the warping and uses opposite lateral displacement of the canard to trim to zero sideslip and achieve a coordinated turn. Reversal of these steps will then bring the bank angle back to zero. Although great insight was needed to discover this procedure, it proved fairly easy to learn and execute in flight.

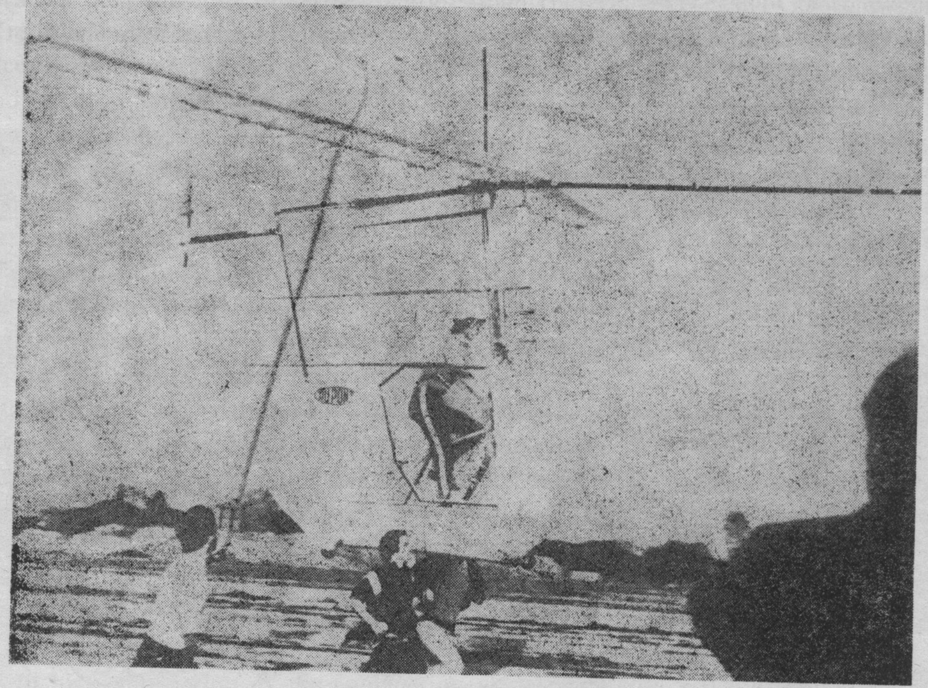

FIG. 2. Photograph of the "Gossamer Albatross" in flight.

Airplanes with sweptback wings of a large aspect ratio can benefit from an aeroelastic phenomenon which—at least initially—was not anticipated by their designers. Basically it involves spanwise shifting of the center of additional lift caused by bending and twisting of the structure. In spite of negligible importance when the sweep angle $\Lambda$ is small, wingtip-upward bending due to a positive lift increment when $\Lambda > 15$ or 20 degrees can reduce effective angles of attack near the tips, thus moving the lift center inboard and forward by a distance which depends strongly on flight dynamic pressure $q$. One consequence is a forward shift of the vehicle's aerodynamic center (A. C.) relative to where it would be if the wing were rigid. Taken from a classic paper by BROWN, HOLTBY and MARTIN [11], Fig. 3 illustrates this effect in terms of the stability derivative $dC_M/dC_L$ as it might vary with $q$ on an airplane like the B-47.

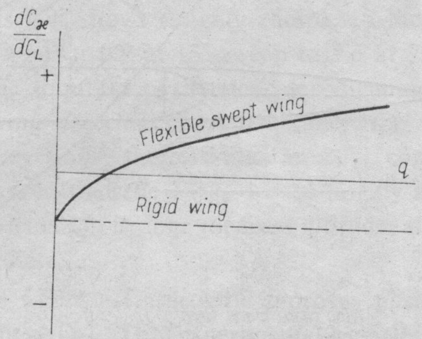

FIG. 3. Influence of flight dynamic pressure $q$ on slope of the curve of pitching moment vs. lift, as it might be measured on windtunnel models of rigid and flexible sweptback wings (Ref. [11]).

Figure 3 actually shows what one would measure on an elastically-scaled model, mounted in a wind tunnel and subjected to changes in fuselage incidence only. Fortunately for the B-47 and similar configurations of the 1940's and 1950's there are other consequences when incidence is changed in flight, as during a pull-up, entry into a turn, etc. The increased lift also causes a positive normal acceleration, whose inertia forces bend the wingtips back downward and tend to compensate for the aeroelastic A. C. shift. It is said that this cancellation was almost perfect on the B-47 and thus produced an airplane whose longitudinal dynamics and control were not substantially different from what might have occurred with a rigid wing.

Incidentally, there are numerous by-products of aeroelasticity in the presence of sweep. On the one hand, the loss of outboard aileron control at high $q$ (cf. the discussion in PERKINS [12]) is undesirable and definitely requires correction. On the other, divergence instability is avoided conpletely when $\Lambda$ is large enough. One interesting example is the "aero-isoclinic" scheme of HILL [13], whereby a proper mixture of sweep angle, bending and torsional rigidity produces exactly infinite divergence speed with a consequent disappearance of the aeroelastic influence on A. C. location.

Variable sweep angle confers significant *performance* advantages on airplanes like the F-111, F-14, B-1 and early Boeing SST designs. But care must be taken to understand the role of wing flexibility, especially in cases of large span and the structural aspect ratio. These wehicles must operate at both subsonic and supersonic speeds, and to a degree they are subject to the familiar rearward A. C. shift and greater static margin that go with transition from the former to the latter. The accompanying increase in $\Lambda$ would seem to exacerbate this shift. It turns out, however, that designers have been able to adapt the aeroelastic effect of Fig. 3 so as to keep the "open-loop" A. C. migration whithin acceptable bounds; C. G.

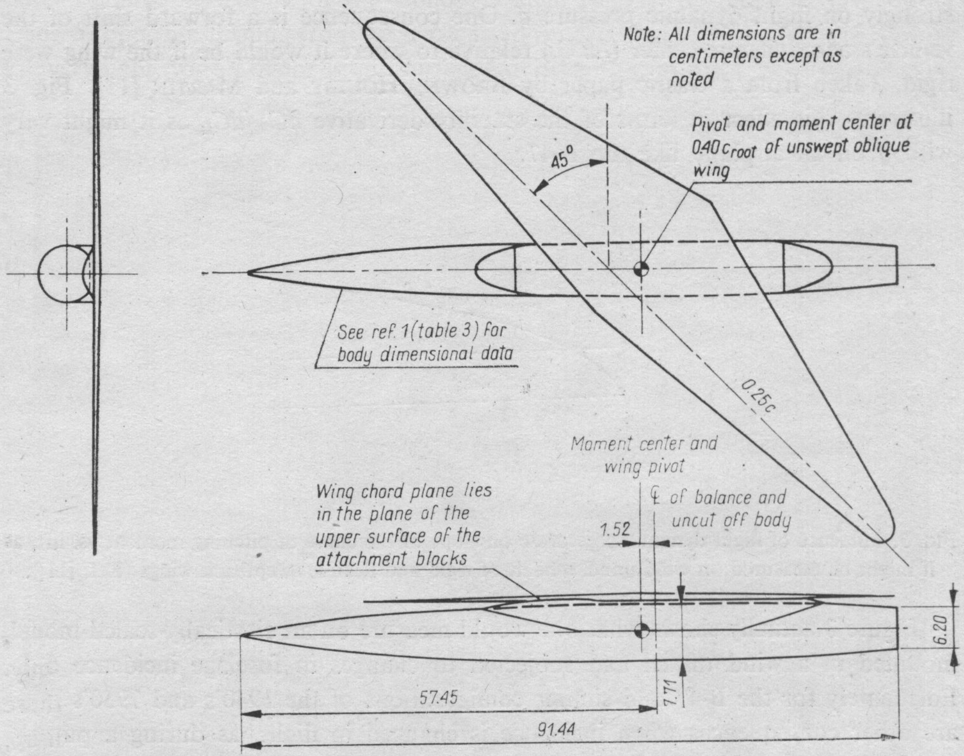

**Fig. 4.** Flexible wind-tunnel model resembling wing and fuselage of the variable-sweep AD-1. (From Ref. [16] length dimensions are in cm.).

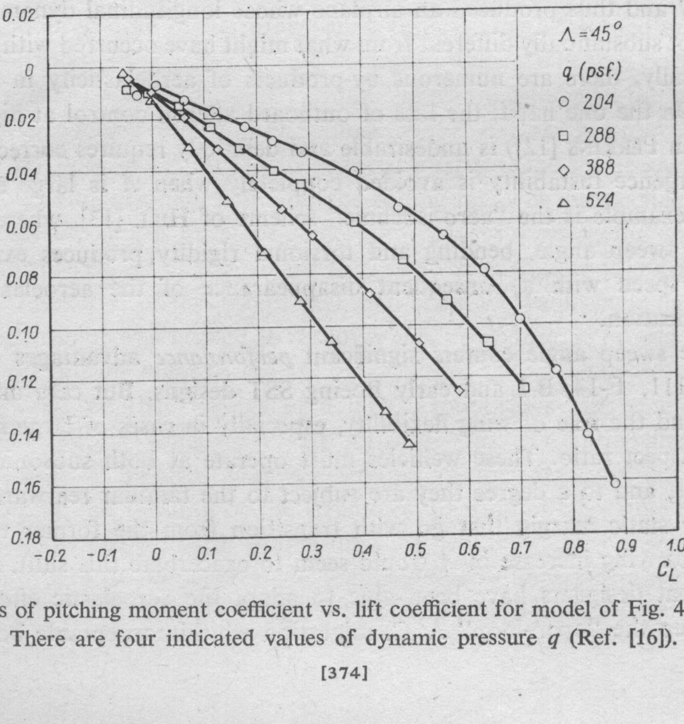

**Fig. 5.** Curves of pitching moment coefficient vs. lift coefficient for model of Fig. 4 at 45° sweep. There are four indicated values of dynamic pressure $q$ (Ref. [16]).

control by fuel transfer may also be required [12]. Published data are hard to find on these features of variablesweep aircraft. Relative to the F-111, however, R. Peloubet of General Dynamics Corporation kindly furnished a report by JONES [14], and the present authors have attempted some rough analyses which suggest a very favorable behavior. For instance, the study of pitching moment curves near the maximum-$q$ flight limits [14] shows roughly complete cancellation of A. C. shifts. Going from the Mach number 0.9 at 16° sweep to 1.5 at 72.5° causes a rigid-wing aft A. C. displacement of about 0.5 of the mean aerodynamic chord, but the *forward* displacement due to wing deformation is 0.4. Since the inertia-elastic influence on A. C. in flight is very small, there is thus an 80% compensation between the two effects. It is recognized that the F-111 would not fly at Mach 0.9 with wings full forward, but this calculation is done for fixed altitude, and similar compensation occurs also at intermediate $\Lambda$.

A more recent case where aeroelasticity improves pitching-moment characteristics is furnished by the AD-1. This experimental vehicle is intended to prove in flight the oblique-wing concept proposed by JONES [15] . In 1977, HOPKINS and YEE [16] carried out wind-tunnel measurements on an elastically-scaled aluminum model (Fig. 4) resembling the AD-1. Figure 5 presents typical plots(2) of the pitching-moment curves for this model at $\Lambda=45°$. This and other data in Ref. [16] fully substantiate their conclusion that "an oblique wing designed with the proper amount of flexibility can 'self-relieve' itself of asymmetric spanwise stalling and the associated nonlinear moment curves." As discussed in a subsequent section here, it is believed that the use of filamentary composite structural skins might be even more effective in producing such results.

## 3. BETTER PERFORMANCE OF PROPELLERS AND ROTORS

In the past five years there has been renewed attention to the aeroelasticity of propellers, stimulated by the development of large wind turbines and of high-speed, high-efficiency turboprop aircraft designs. Notably the work by Hamilton Standard Division on advanced propellers with composite blades (cf. BLACK *et al.* [17]) has rekindled interest in tailoring stiffness properties so as to increase efficiency. From a brief look into the past, however, one discovers that using flexibility to advantage in propellers was on old idea.

### *3.1. The ..Flex-O-Prop"*

The first such practical application of aeroelasticity was by Max MUNK in his patented wooden "Flex-O-Prop" [18]. Munk's propeller employed laminated wood to produce elastic coupling between bending and twisting in such a manner that a highly loaded blade would assume a shallower pitch setting as it bent forward, thereby providing for more efficient operation at the high-thrust, low-speed takeoff condition. Since thrust is diminished somewhat in cruising flight, the blades would

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(2) The two higher dynamic pressures in Fig. 5 simulate cruising and highspeed operation.

naturally return to the larger pitch settings desirable for efficient high speed operation at reduced engine rpm.

The idea (Fig. 6) for utilizing coupling between bending and twist was conceived after making the observation that the blade tip path of test propellers moved forward and backward under different throttle settings. The final design, which resulted from several years of trail-and-error testing in collaboration with engineer Eli Amanuel, employed diagonally-oriented outer laminations at approximately 45° to the spanwise axis combined with inner laminations which were radially disposed. The result was a propeller which counteracted normal undesirable twisting tendencies and produced, on a somewhat limited scale, the effects of a variable-pitch propeller.

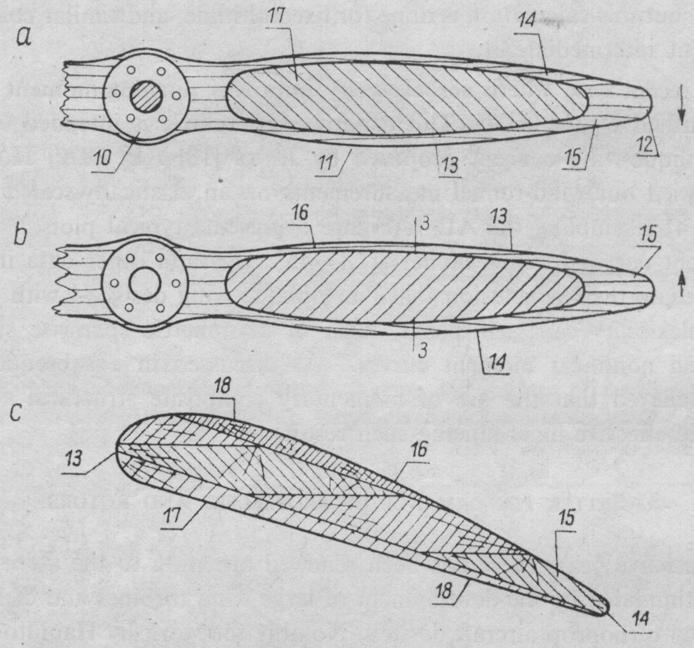

**FIG. 6. Sketch and title of Patent No. 2,484,308, by MUNK (Ref. [18]).**

**Flight tests comparing the Flex-O-Prop with an identical standard wooden propeller were performed using a Model "E" Ercoupe with an 85 hp Continental engine (HOADLEY [19]). Results included a 16% decrease in takeoff distance, a rate-of-climb increase of 13%, a maximum static thrust boost of 5%, and a speed increase of 14% at fixed cruise power setting for the Flex-O-Prop. An additional benefit noticed during flight testing was a slight decrease in vibration level, which was attributed to the "dampening" action of the diagonal laminations.**

### 3.2. *Advanced composite propellers*

A recent theoretical study (ROGERS [20]) examines the aeroelastic benefits to be derived from applying advanced filamentary composite material technology to propeller design. It was demonstrated that for a fixed-pitch "tailored" propeller an increase in efficiency of 5% at the design point and as much as 20% at off-design points can be achieved over that of a rigid design (Fig. 7). At the same time, there was shown to be a significant extension to the range of advance ratios over which efficient operation is possible. Controllablepitch propellers with composite blades were also shown to have approximately a 5% increase in maximum efficiency over rigid controllable blades.

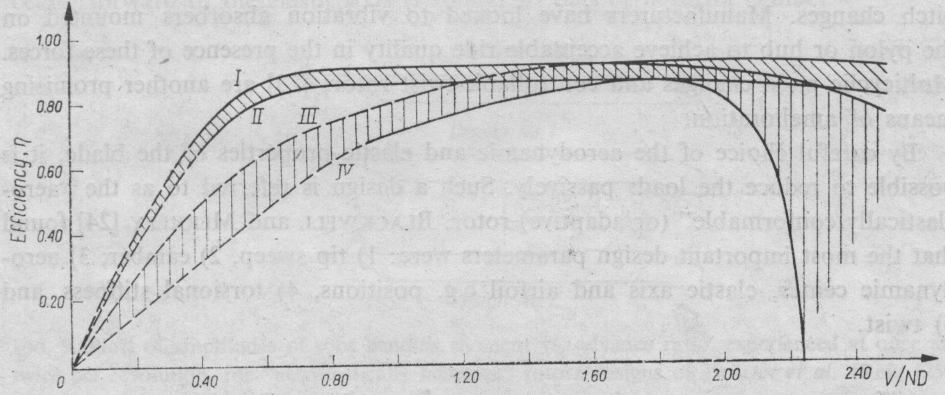

FIG. 7. Theoretical curves of efficiency ($\eta$=Thrust HP/Engine BHP) vs. advance ratio for four propeller designs (Ref. [20]). V is flight speeds, *N* and *D* the rpm and diameter of the propeller.

### 3.3. *The „Plastomatic" propeller*

Recent research on controllable, composite light-airplane propellers suitable to the general aviation market has been carried out by LARRABEE at MIT [21, 22]. His efforts produced a conceptual design for a "Plastomatic" propeller, which would use fiber reinforced plastics in a modern version of the Koppers "Aeromatic" propeller of the 1950's. In this design the feathering axis bearings are freed of centrifugal loads by introducing a tensionallystrong but torsionally-flexible tension tie member and thus allowing the blades to balance their loads against each other while equalizing the blade pitch angles. By having the locus of aerodynamic centers offset from the blade feathering axis, the equilibrium of aerodynamic, inertial, and torsional moments causes a blade angle change with airspeed such that the propeller absorbs its rated horsepower.

In fact the propeller can be designed to have two equilibrium blade angle settings; one equilibrium corresponds to a low-airspeed, high-thrust condition, and a second to a cruise-speed, cruise-thrust condition. It also exhibits approximate constant-speed characteristics about a specified design rpm but is equipped with a cruise setting override to allow efficient operation at a lower rpm as well.

Performance calculations comparing a Plastomatic design suitable for installation on a Grumman-American AA-1 airplane with a standard McCauley 7157 fixed-pitch metal propeller (71-inch dimater, 57-inch pitch) revealed a takeoffrun reduction of 28% and an increased rate of climb of 39% for the Plastomatic. Another advantage of the Plastomatic stems from its estimated weight of 10 lbs compared with 20 lbs for the solid aluminium fixed-pitch propeller.

### *3.4. Helicopter rotors*

As a helicopter increases its forward speed, the aerodynamic conditions experienced by each rotor blade begin to vary more severely with azimuthal position. The result, for a conventional blade, is a buildup of cyclic loads and vibrating hub forces. These forces cannot be effectively controlled throughout the flight envelope with the usual design parameters of twist, airfoil shape, planform and 1/rev cyclic pitch changes. Manufacturers have looked to vibration absorbers mounted on the pylon or hub to achieve acceptable ride quality in the presence of these forces. Multicyclic pitch changes and controllable-twist rotors [23] are another promising means of amelioration.

By careful choice of the aerodynamic and elastic properties of the blade, it is possible to reduce the loads passively. Such a design is referred to as the "aeroelastically conformable" (or adaptive) rotor. Blackwell and Merkley [24] found that the most important design parameters were: 1) tip sweep, 2) camber, 3) aerodynamic center, elastic axis and airfoil c.g. positions, 4) torsional stiffness and 5) twist.

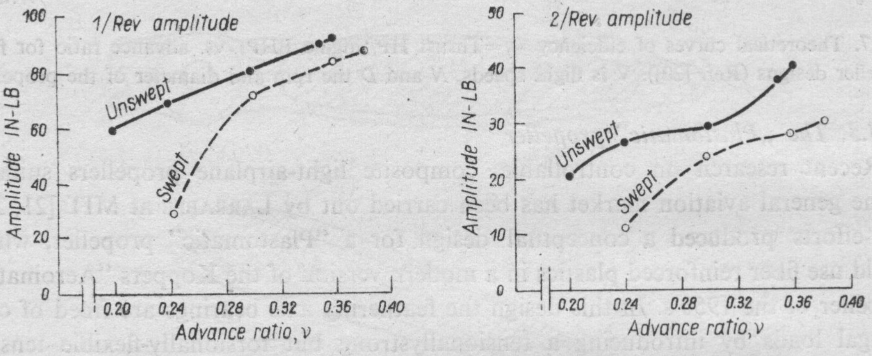

Fig. 8. Three configurations illustrating tip sweepback and reduced torsional stiffness for the "conformable" helicopter rotor of Blackwell and Merkley (Ref. [24]).

A helicopter blade's large negative twist, which distributes the lift efficiently in hover, is detrimental in high-speed forward flight where it produces a positively loaded root and negatively loaded tip on the advancing blade. It would be advantageous it in this condition the blade could be untwisted. By sweeping the blade at the tip (see Fig. 8, designs nos. 2 and 3, from Ref. [24]), a predominantly once-per-revolution (1P) twisting moment is exerted on the blade by the airloads. An aft sweep coupled with the download on the tip of the advancing blade produces a nose-up moment, which will tend to untwist the blade and reduce the negative load at the tip. This action is exactly analogous to the gust alleviation characteristics of a swept-back wing. The rotor must, of course, be suitably flexible in torsion, which makes filamentary composite blades nearly ideal.

The effect of airfoil camber is somewhat similar to that of tip sweep. By choosing a section with nonzero pitching moment $C_{m0}$, a moment (and therefore twist) dependent on the dynamic pressure can be applied to the blade. Negative camber (positive $C_{m0}$) is favorable, again because it tends to untwist the advancing blade. Wind-tunnel testing (cf. Fig. 9 from Ref. [25]) has shown that 1P and 2P flap bending is thereby reduced by about 40% and speed stability is improved with little decrease in rotor efficiency. The efficiency in hover can actually be improved by increasing the static twist of the blade [25]). The effect of having the aerodynamic center forward of the elastic axis is similar to that of negative camber.

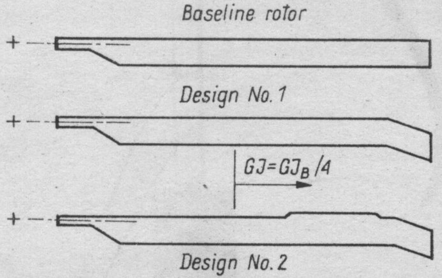

**Fig. 9. Plots of amplitudes of root bending moment vs. advance ratio, experienced at once and twice per revolution, for "aeroelastically adaptive" rotors designs of Doman *et al.* (Ref. [25]).**

### 3.5. *The Vertical-Axis Wind Turbine*

Two schemes have been analyzed and tested for realizing the simplicity and high efficiency promised by the Darrieurs wind turbine (VAWT). The first (Fig. 10) curves the blades into a shape which minimizes structural loads due to rotation. The second, whose straight, vertical blades are parallel to the axis of rotation, may require a heavier structure but offers certain other advantages. For example, the power-producing angle-of-attack oscillations which take place as the airfoil revolves in a wind-stream (see Fig. 11) can be conveniently amplified. By imagining the blade in the figure to move around a circle and studying the variation of the forward, chordwise component of the lift force $L$, one sees that higher average torque can be achieved by varying $\Delta\alpha$ in proportion to $\cos\Theta = \cos\Omega t$, where $\Omega$ is the angular velocity of rotation.

In the "Giromill" design [26], power is thus augmented by attaching the blade ends to cam supports with adjustable amplitude. An even simpler approach—one which does not require active cam control based on sensing the wind direction—would seem to involve the use of torsion springs at the points of attachement. If the effective spring elastic axis (E. A., as in Fig. 11) were placed behind the aerodynamic center of wind-induced lift, one would see how that force itself can produce the torque needed for blade-angle cycling. The system parameters would, of course, have to be adjusted to avoid resonance and to keep $\Delta\alpha$ in phase with $L$.

By means of a quasi-two-dimensional aerodynamic theory like that proposed in Ref. [27], one can predict the influence of cycling amplitude $\Delta\bar{\alpha}$ on the power coefficient

$$C_p = \frac{\text{Power output}}{\frac{1}{2}\rho A V_w^3}$$

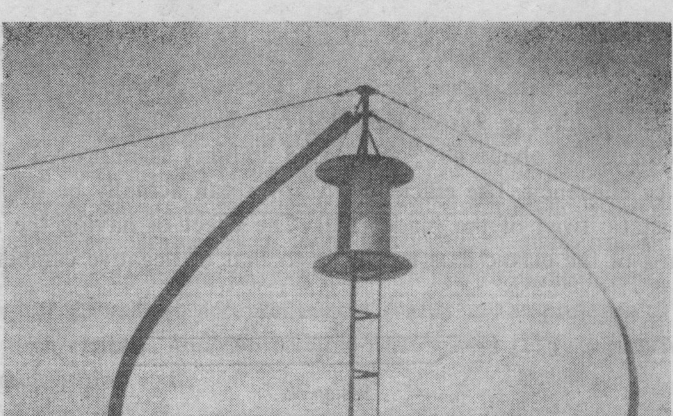

**Fig. 10.** Two-bladed Darrieus VAWT with zero-bending-moment shape note small Savonius rotors used for starting. (Courtesy National Aeronautical Laboratory, Bangalore, India).

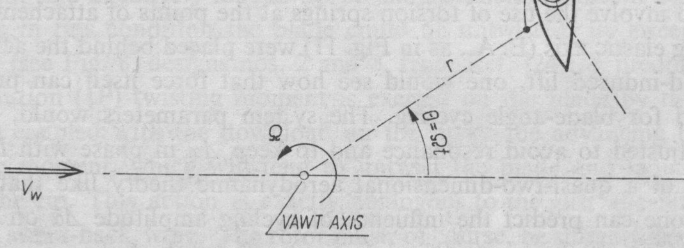

**Fig. 11.** Horizontal cross-section of straight, rotating blade of VAWT, showing instantaneous relative wind $V_W$. Also pictured is the incremental angle of attack $\Delta\alpha$ that might occur on a torsionally suspended blade due to moment of lift $L$ acting through the aerodynamic center A. C.

as it depends on the advance ratio $\Omega r/V_w$. ($\rho$ is the air density and $A$ the frontal area ewept by the machine; other symbols are defined in Fig. 11). For a design with solidity typical of modern VAWT's, Fig. 12 presents some results. Cycling at ±0.1 radian (±5.70°) appears quite practical and avoids airfoil stalling in the optimum range of $\Omega r/V_w$; yet the theoretical increase of output approaches 20%.

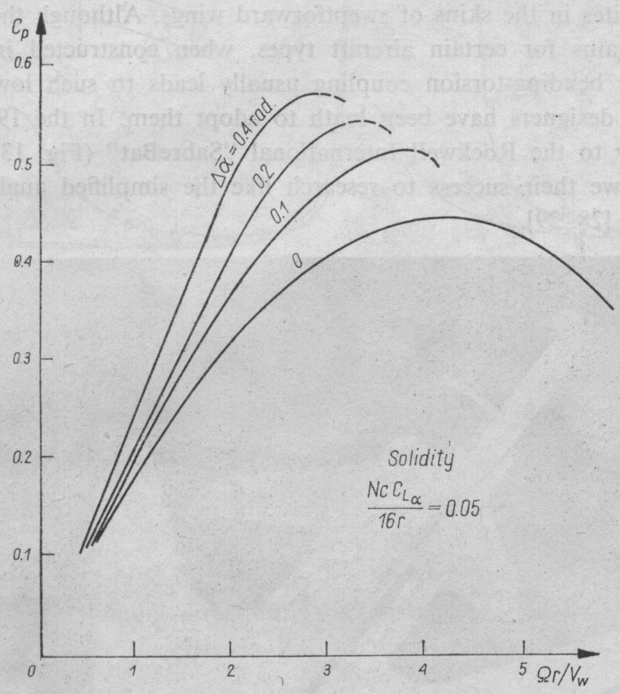

FIG. 12 Power-coefficient curves for straight -bladed VAWT, calculated by the method of Ref. [27] for four values of amplitude $\Delta\bar{\alpha}$ of cyclic angle of attack. In the definition of "solidity," $N$, $c$ and $C_{L_\alpha}$ are the number of blades, blade chord and lift-curve slope, respectively.

It is, incidentally, not unreasonable to suggest for a straight- or curved-bladed VAWT that its torsional properties might be adjusted in such a way that power augmentation occurs without any need for special blade supports. If feasible, this scheme would represent an extremely simple constructive use of aeroelasticity.

## 4. INCREASED SAFE SPEEDS, TURNING PERFORMANCE AND ENERGY MANEUVERABILITY THROUGH USE OF COMPOSITIES OR ACTIVE CONTROL

Among the most pernicious of aeroelastic manifestations are divergence and flutter—critical flight conditions above which a lifting surface or complete air vehicle experiences often-destructive static or dynamic instability due to structural deformations interacting with the airstream. It has long been a dream that active means might be found to ameliorate or eliminate these instabilities, but only in the past decade has there been practical progress toward the goal. Since it is achieved theough modifying or controlling elasticity, the results fall within the purview of this paper.

### 4.1. *Divergence*

A dramatic instance of passive "divergence control" is furnished by the skillful use of composites in the skins of sweptforward wings. Although these wings offer performance gains for certain aircraft types, when constructed in conventional materials their bending-torsion coupling usually leads to such low divergence(³) speed $V_D$ that designers have been loath to adopt them. In the 1980's, however, fighters similar to the Rockwell International "SabreBat" (Fig. 13) will soon be flying. They owe their success to research like the simplified analyses published by Weisshaar [28, 29].

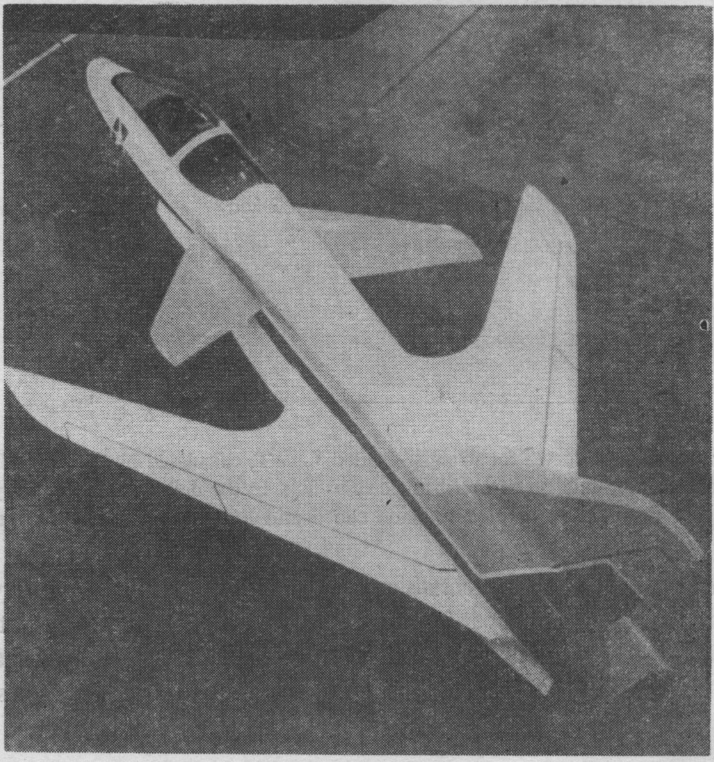

Fig. 13. Photograph of mockup of Rockwell International's "SabreBat", forward-swept-wing fighter design.

Figure 14, adapted from Ref. [28], shows clearly what the possibilities are. It relates to a cantilever of constant chord and sweep $\Lambda$, whose coupling between bending and twist is controlled by orienting the undirectional fibers in its uniform, reinforced-plastic skins. The fiber angle, $\Theta$, is measured from a reference normal

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(³) It is remarked that the worst instability may sometimes be a low-frequency flutter.

to the elastic axis; therefore, favorable values around $\Theta=100°$ correspond to reinforcement parallel to a direction 10° ahead of this axis. For an unswept and two sweptforward cases, the figure shows $\Theta$ influence on $V_D$—as referred to the speed

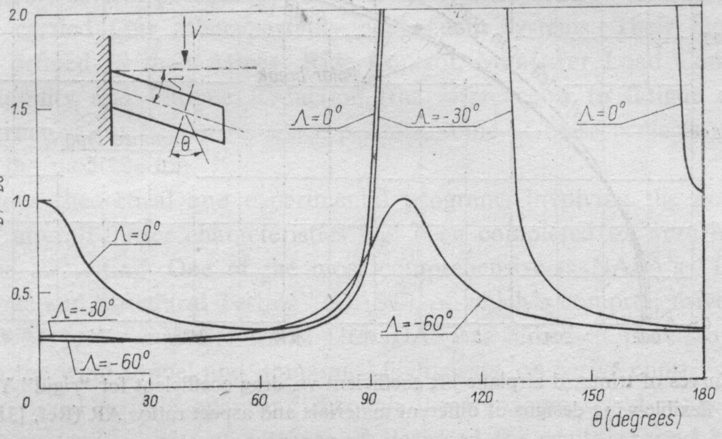

FIG. 14. Influence of orientstion $\Theta$ of composite shin plies on divergence speed of three uniform, swept cantilever wings. Note that negative $\Lambda$ means forward sweep (Ref. [28]).

$V_{D0}$ that would be observed on a wing of similar configuration at zero $\Lambda$ and $\Theta$. One sees how, even up to 60° of forward sweep, the divergence boundary can be made equal or superior to that of an acceptable reference design. On an actual airplane, other considerations obviously require that some skin plies be oriented in other than the optimum direction. It is significant, however, that about 70% of these plies run very close to $\Theta=100°$ on the wing illustrated (in mockup) by Fig. 13.

### *4.2. Tailoring*

The study in Refs. [28] and [29] represents a rather unsophisticated example of what has become known as "aeroelastic tailoring". Although more complex interactions may be employed, this concept typically involves intentional coupling between bending and twist of a lifting surface to accomplish one or more desirable effects—not unlike some of those already discussed in the preceding section. References [30] and [31] are samples from many recent documents on tailoring.

One common objective is to control the spanwise distribution of aerodynamic incidence over a wide range of maneuvering load factors. On an airsuperiority fighter, the result can be a substantial decrease of induced drag in rapid turns. The consequent increase in "energy maneuverability" or "specific excess power" could mean the difference between defeat and victory during air-to-air combat. Taken from Vol. I of Ref. [31], Fig. 15 demonstrates how (theoretical) modifications to the YF-16 wing affect its drag polar for flight at Mach 0.9 and 10,000-ft altitude. Graphite-epoxy composite skins are particularly effective; in a typical high-g turn near $C_L=0.7$ the $C_D$ reduction approximates 26% compared to the original.

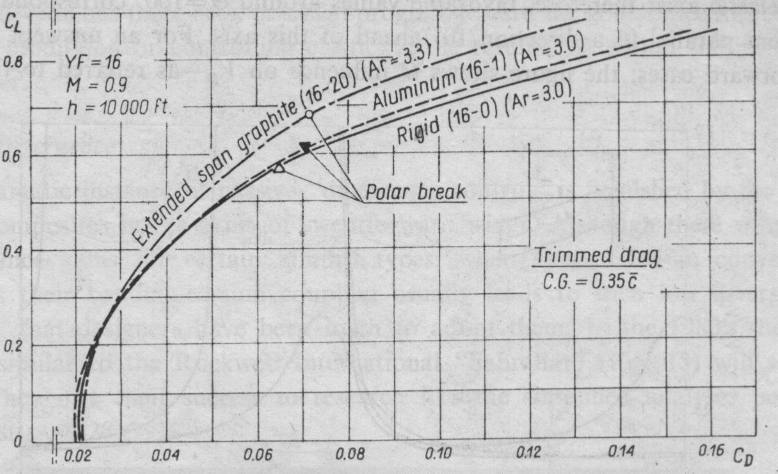

FIG. 15. Curves of trimmed airplane lift coefficient vs. drag coefficient for "rigid" YF-16 and two flexible-wing designs of different materials and aspect ratios AR (Ref. [31]).

### 4.3. Flutter

In principle, one can devise dozens of techniques for actively or passively raising an airplane's flutter speed and thereby avoiding the associated performance limitations. The passive approach, which was the only recourse unitl 1973, nearly always carries with it some sort of penalty: increased weight to enhance stiffness or to massbalance a movable surface, increased complexity for a hingeline damper, reduced range from a restriction on wing fuel distribution, or whatever. One possible counter-example, however, may be the "decoupler pylon" of Reed (see REED *et al* [32]; the use of nonlinearity to prevent excessive static deflection is discussed by DESMARAIS and REED [33]). This clever device proposes to overcome the usual flutter-speed reduction due to an auxiliary tank or weapon mounted near a fightert's wingtip by placing a relatively soft torsional spring between primary structure and the supporting pylon. Although it has not yet been adopted operationally, the decoupler shows promise of solving a serious problem for aircraft types which must carry a variety of heavy objects beneath their wings.

Active flutter control came into its own on August 2, 1973, when U. S. Air Force NB-52E No. 56-632 flew at 21,000-ft altitude 10 kts faster than its measured "open-loop" flutter supeed. The flutter mode involved was symmetrical, with the relatively low frequency 2.4 Hz. It had been driven artificially unstable within the flight envelope by means of lead ballast attached to the noses of two large wingtip fuel tanks. Nevertheless, the design and practical realization of the B-52 FMCS (Flutter Mode Control System) presages the ultimate use of this sort of reliable electronic technology on many other aircraft. The development of FMCS is summarized by HODGES [34]. Flight tests are reported in Ref. [35]. Space limitations prohibit a detailed description of the system, but it was based on rather conventional analog processing applied to signals from two pairs of wing-mounted accelerometers. The effectors consisted of symmetrically-deflected outboard ailerons and "flaperons".

The NB-52E was, in fact, a thoroughly-instrumented research airplane intended to demonstrate several potential benefits of aeroelastic control. In addition to the FMCS, it carried four other partially-independent systems. Their purposes are quite well defined by their names: Ride Control, Maneuver Load Control, Augmented Stability and Fatigue Reduction (the reference is to fatigue damage in primary structural material). As space permits, some of these projects will be discussed in the next section.

Numerous theoretical and experimental programs involving the active modification of aircraft flutter characteristics had been completed or were in progress at the time of writing. One of the most comprehensive is NASA's "Drones for Aerodynamic and Structural Testing" (DAST), of which a comprehensive summary is given in MURROW and ECKSTROM [36]. DAST is aimed at providing research data, from the wind tunnel and unmanned flight tests, on active controls for wings with supercritical airfoils operating through the transonic speed range. The first model wing resembles that of a transport designed for cruise around Mach 0.98. Its "flutter suppressor" activates small ailerons in response to signals from a pair of wingtip accelerometers, and two or more control algorithms are being tried.

FIG. 16. Photograph of DAST model in Transonic Dynamics Tunnel, with accelerometer trace showing flutter suppression by active control. (Courtesy of W. H. REED, III, NASA Langley Research Center).

Figure 16 contains a photograph of a simplified, full-scale version of half the DAST aeroelastic research wing (ARW-1), mounted from one wall of the Transonic Dynamics Tunnel, NASA Langley Research Center. The trace at the bottom of the figure reproduces the accelerometer signal from a test whereain the dynamic pressure was raised to above the uncontrolled $V_F$. The system (design reported by Abel, Newsom and Dunn [37]) is then activated, and one observes the immediate returs to a stable condition where the wing is responding only to flow turbance. One of the control syntheses investigated on this model demonstrated a 20% increase in the dynamic pressure of the flutter boundary at Mach 0.95.

Several experiments on the DAST ARW-1, carried by the modified Firebee II target drone, have subsequently been conducted at NASA's Dryden Flight Research Center. Although the vehicle and wing were partly destroyed by an accident in Summer 1980, the program is expected to continue and will involve different wing configurations. A fund of knowledge can be anticipated, which will assist in bringing constructive interaction between aeroelastic modes and active control to a routine status.

## 5. RIDE IMPROVEMENT AND ALLEVIATION OF CYCLIC LOADING

The comfort of passengers and crew during the unavoidable encounters which occur with atmospheric turbulence is a significant consideration on any aircraft and a paramount one for civil transports. The need to minimize the associated fuselage accelerations and vibration is reinforced by the fact that successful measures will often simultaneously extend the fatigue life of many structural elements. In the context of favorable aeroelasticity, it is therefore very interesting that large-aspect-ratio sweptback wings appeared in the 1940's and 1950's primarily because they enable efficient cruising at much higher speeds. Yet they also provided aviation with a "gust-alleviation" device which could have hardly been improved had that been the principal design condition.

Starting with the B-47, B-52 and first-generation turbojet airliners, sweepback has enhanced the "ride" of almost every large jet airplane. Although the literature is full of comparative data to demonstrate this point, a single example will be cited here which emphasizes that the effect is due mainly to the aforementioned angle-of-attack relief from bending deformation. Codik, Lin and Pian [38] published one of the first analyses of wingflexibility effects on the response of such an airplane to discrete gust encounters. Figure 17 is their Fig. 5.1. It relates to a vehicle with E. A. swept 34° and aspect ratio 9.43 (see the reference for other data), which encounters a "one-minus cosine" gust of half wavelength equal to 15 times the midspan semichord. Abscissa $s_0$ denotes the distance travelled from response initiation, again measured in semichords. Ordinate $K$ is the fuselage acceleration, referred to what this quantity would have been in an encounter with a "sharpedged" gust of the same amplitude, without relief due to bending or unsteady aerodynamics.

Two kinds of alleviation can be inferred from the maximum values of $K$. The drop below unity of the "rigid-wing" peak is because of the delayed buildup of wing lift and gradual penetration of the gust front due to sweepback. As for flexibility, the solid curve is the more accurate and shows a second 30% reduction from $K$=0.75 to about 0.52, which is wholly attributable to aeroelasticity.

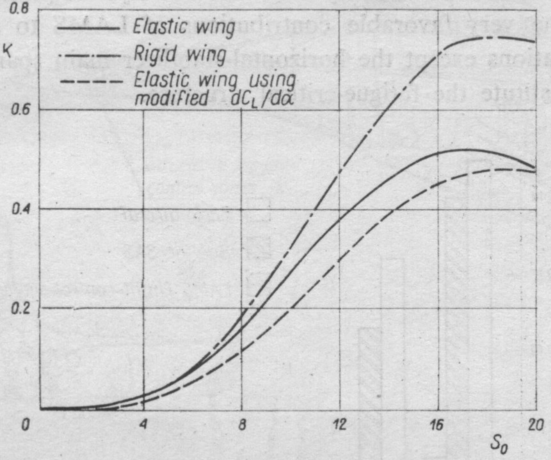

FIG. 17. Dimensionless fuselage acceleration vs. chordlengths travelled after encounter with a "one-minus-cosine" gust, plotted for three idealizations of a swept-wing airplane. (From Ref. [38] see text for definitions.

The introduction of active control- of course- provided the designer with much more versatility and freedom to choose his objectives than did the natura properties of swept wings) Extended structural life under cyclic loading—a goal by no means incompatible with increased flutter speed or ride improvement—has been the benefit sought from most systems implemented during the 1960/s and 1970/s) Such airplanes as the U-2- C-5A- F-4- F-16- and the Boeing 747 and SST concept can be cited as American examples of where the technology was employed in various ways—not all of them primarily aeroelastic) In the cases to be summarized here- however- structural deflections play a key part.

The first is the Aircraft Load Alleviation and Mode Stabilization (LAMS—cf) BURRIS and BENDER [39] system- first demonstrated on the B-52). Both the flight-test airplane and the concepts employed were- incidentally- direct precursors of the Control Configured Vehicle (CCV) described in connection with flutter stabilization (Refs 34 and 35) LAMS was developed and tested in the 1965–69 period. Although existing lateral and longitudinal movable surfaces were employed- the system modified the vehicle by adding hydraulic actuators- "fly-by-wire"- various acceleration sensors- and analog computers to implement the transfer functions required for active control Three discrete flight conditions were accounted for- chosen from a hypothetical B-52E mission profile

Figure 18- adapted from Fig. 1 of Ref. [39]- summarizes better than any other results what was proven in flight for LAMS. Assumed are 575 hours of idealized "usage" at the three combinations of vehicle weight- airspeed and altitude. Six structural analysis stations are represented- with their location numbers given

in inches from a reference origin of coordinates. According to standard methods of fatigue damage estimation due to cyclic loading by a realistic model of turbulence- the three bars compare the experience of the unaugmented B-52E wtth those predicted when the standard Stability Augmentation System (SAS) and the LAMS are activated. The very favorable contributions of LAMS to structural life are evident for all stations except the horizontal-stabilizer main spar which does not in any event constitute the fatigue-critical structure.

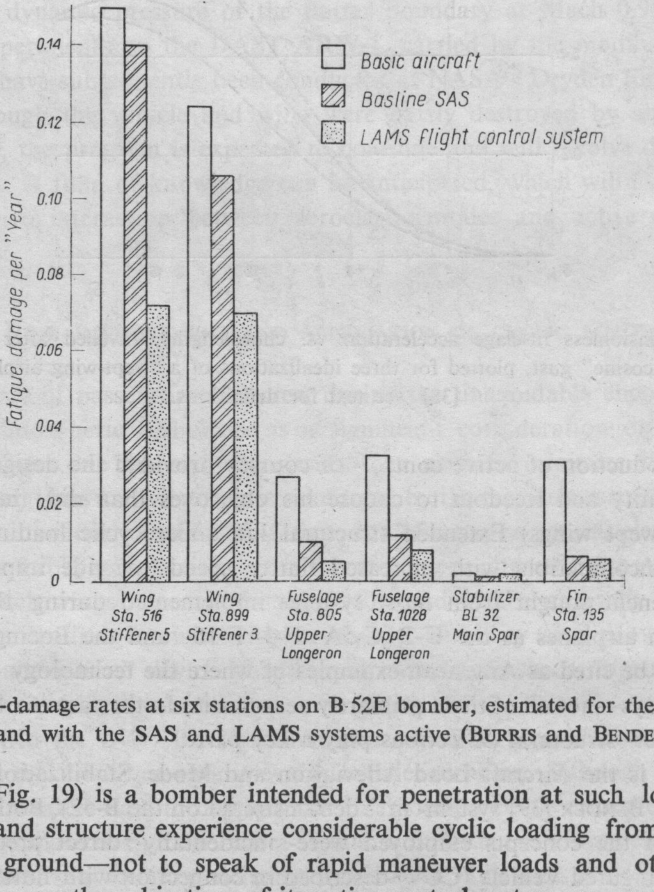

FIG. 18. Fatigue-damage rates at six stations on B-52E bomber, estimated for the unaugmented airplane and with the SAS and LAMS systems active (BURRIS and BENDER [39]).

The B-1 (Fig. 19) is a bomber intended for penetration at such low altitudes that its crew and structure experience considerable cyclic loading from turbulence rising off the ground—not to speak of rapid maneuver loads and other sources of fatigue. Among other objectives of its active control system an acceptable work environment in the crew cockpit is to be ensured. This is achieved by implementing a "Structural Mode Control System" (SMCS). SMCS is a classical realization of the ILAF (Identically-Located Accelerometer and Force) approach to motion control. Its sensors are longitudinal and lateral accelerometers mounted in the cockpit vicinity. Effectors are the vanes labelled in Fig. 19- which are installed with 30° of anhedral so that symmetric and antisymmetric rotations can generate- respectively- pure vertical and side forces at a point close to the pilot/s seat. Figures 20 and 21 (4) involve two different low-level flight conditions- comparing B-1 re-

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(4) Data supplied by courtesy of J. H. WYKES, B-1 Division, Rockwell International.

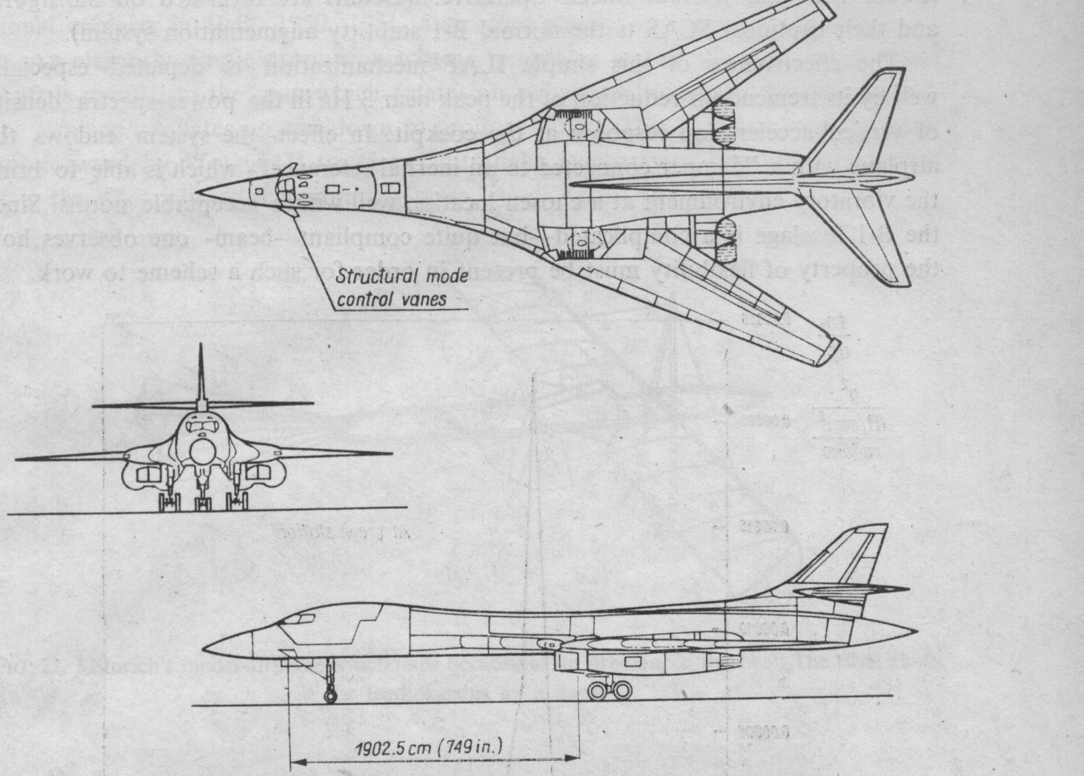

FIG. 19. Three-view drawing of B-1 bomber, showing location of vanes used by the Structural Mode Control System (SMCS).

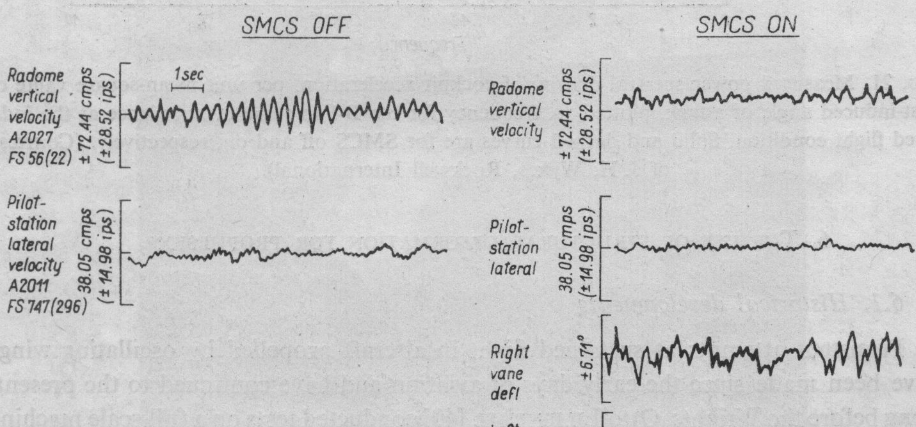

FIG. 20. Typical plots vs. time of the indicated quantities for B-1 with and without SMCS activated. (Courtesy of J. H. Wykes, Rockwell International).

sponse wtth and without SMCS operative. (Details are furnished on the figures and their captions) SCAS ts the normal B-1 stabtitty augmentation system).

The effectiveness of this simple ILAF mechanization is depicted especially well by its tremendous reduction of the peak near 3 Hz in the power spectra density of vertical-acceleration response at the cockpit. In effect- the system endows the airplane with a "damper connected to an inertial reference"- which is able to bring the vibratory environment at a chosen location well within acceptable norms. Since the B-1 fuselage is a complicated—but quite compliant—beam- one observes how the property of flexibility must be present in order for such a scheme to work.

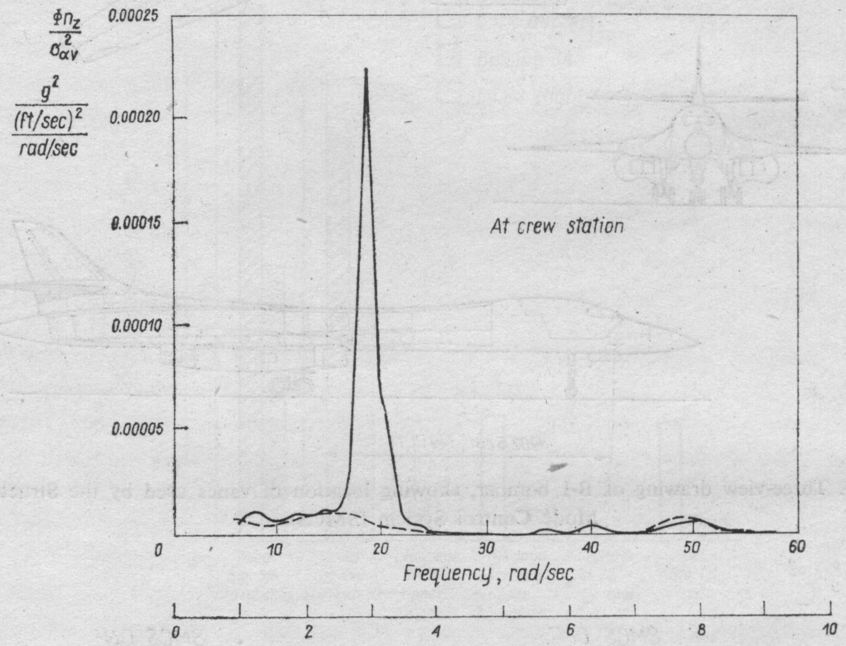

FIG. 21. Measured power spectral density of cockpit acceleration, per unit mean-square value of gust-induced angle of attack, plotted vs. frequency for the B-1 in random turbulence at the indicated flight condition. Solid and dashed curves are for SMCS off and on, respectively. (Courtesy of J. H. Wykes, Rockwell International).

## 6. THE USE OF STRUCTURAL DEFORMATION FOR PROPULSION

### *6.1. Historical developments*

Persistent attempts at sustained flight in aircraft propelled by oscillating wings have been made since the early days of aviation and have continued to the present. Long before the Wrights, Otto LILIENTHAL [40] conducted tests on a full-scale machine whose wings were made of multiple slats which "feathered" on the upstroke and closed to form a solid wing on the downstroke, but this proved much too inefficient. Fitz PATRICK [41] mentions no less than 20 other inventors who have built model or full-scale aircraft; some of these are illustrated in his paper. VASIL'EV [42] refers to an even greater number of Soviet inventors, who flew their models at national contests in 1949, 1950, 1951, and other years.

An elegantly simple propulsion scheme, presented in Fig. 22, is a motor whose shaft is parallel to the span which rotates an unbalanced mass. In reaction to this, the airplane oscillates up and down to produce thrust. This idea was recently again put forward by WOLF [43] to propel ultralight mancarrying aircraft, except that it is the pilot who is the vibrating mass.

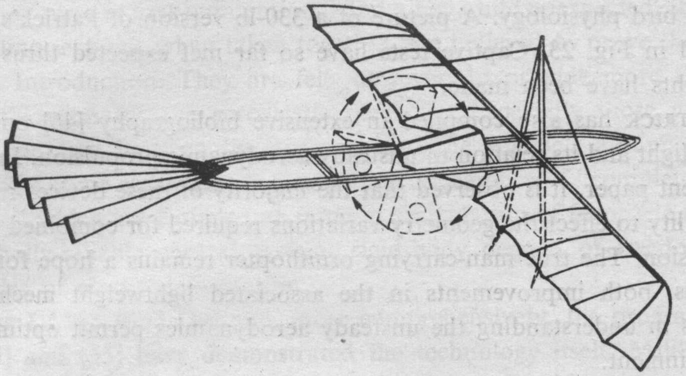

FIG. 22. Miturich's model airplane which flaps because of an urbalanced flywheel. The twist about the leading edge as it flaps.

FIG. 23. Photohraph of model ornithopter, designed, built and tested by J. L. G. Fitz Patrick (courtesy of the inventor).

The annual meeting of the Experimental Aircraft Association at Oshkosh, Wisconsin, is the gathering point for present-day inventors interested in ornithopters. Among them are P. H. Spencer of Santa Monica, who has flown gas-driven modeals. Another is J. L. G. Fitz Patrick of Staten Island Community College, who has designed and built several prototypes of a mancarrying ornithopter. These vehicles are intended to test his unique empirical theory [44], based on much personal observation of flying and swimming creatures. In fact, the patented [45] flapping mechanism of the wings is a "bird-bat analog" with the names of the parts taken from bird physiology. A picture of a 330-lb version of Patrick's ornithopter is presented in Fig. 23. Captive tests have so far met expected thrust levels, but no free flights have been made.

Fitz PATRICK has also compiled an extensive bibliography [46] on the subject of natural flight and its relation to unsteady aerodynamic propulsion. In the content of the present paper, it is observed that the majority of these devices rely on structural flexibility to effect the geometry variations required for combined sustentation and propulsion. The true man-carrying ornithopter remains a hope for the future. Nevertheless, both improvements in the associated lightweight mechanisms and recent gains in understanding the unsteady aerodynamics permit optimism regarding its attainment.

### *6.2. Aerodynamic propulsion for natural flight*

This section is completed with some words and citations on aerodynamics. One remarks that unsteady airload prediction for oscillating lifting surfaces was carried out originally in response to the needs of the aeroelastician. Its extension to the area of natural flight builds on that aeroelastic tradition, as well as the long history of observation and speculation about animal motion through air and water (cf. Ref. [44], LIGHTHILL [47], and also Ref. [48]).

The key problem involves a two- or three-dimensional wing which simultaneously executes pitching and plunging motions, represented by the quantities $\alpha$ and $h$ as functions of time. When $\alpha$ lags $h$ (positive downward) by about 90° and is of the right magnitude. the instantaneous angle of attack is minimal. It also resembles what is usually seen in nature, that is, animal propulsion is observed to have a phase angle of $-90°$. At that angle the thrust-coefficient amplitude is near minimum. But birds and fish rightly prefer to flap their wings and tails in this way because the propulsive efficiency is markedly higher than at other phase angles. According to the twodimensional theory, in fact, it can approach 100%. To compensate for the relatively small thrust, animals operate with large amplitudes. Further, one finds that the leading-edge suction is a minimum in the natural flight region. There is some doubt that the theoretical values of suction are realized in flight. Thus propulsive motion depending mostly on leading-edge suction will suffer in practice.

GARRICK [49] is believed to have written the first highly-mathematical study of chordwise forces on oscillating wings. For airfoils he estimated the average thrust due to plunging and pitching, showed its dependence on the square of the amplitude, and gave theoretical results that presage other publications more than

25 years later. OBYE [50], among others, conducted wind-tunnel experiments that validated the early theory. Important recent contributions to this difficult subject include the papers of WU [51-53], CHOPRA [54, 55], TUCK [56] and JONES [57]. The forthcoming dissertation by NATHMAN [58] contains a critical and quantitative summary of this literature, along with additional airfoil measurements and an assessment of aeroelasticity's potentially constructive role for man-made machines.

## 7. CONCLUDING REMARKS. THE FUTURE

Albeit many were at first unintentional and a few quite unexpected, the examples of the preceding sections, when taken together, are believed to prove the assertions made in the Introduction. They are felt, however, to provide more than merely a career justification for the aeroelastic specialist. Especially those which relate to dynamic coupling between the airframe and the vehicle's automatic controls permit one, with some assurance, to forecast the appearance of "complete CCV's"—that is, aircraft which are designed *ab initio* in anticipation of favorable interactions among a wholly-reliable control system, rigid-body degrees of freedom *and* important modes of elastic deformation.

Surely the LAMS B-52 [39] and, more comprehensively, the program reported in Refs. [34] and [35] have demonstrated the technology itself. Military aircraft are in the development stages with active flutter suppression and gustload alleviation. Flying operationally are devices like the F-16 longitudinal stability augmentation system [59], whose failure would cause unacceptable flyingqualities degradation yet whose record of performance contains no disastrous mulfunctions whatever. Within the state-of-the-art are small, high-powered and fast-acting hydraulic actuators. They ensure that electrical signals in the feedback path are convertible to forces and torques at structural vibration frequencies typical not only of large airplanes but of fighters as well.

It is likely that the most significant impediment to the introduction of constructive aeroelastic and "servoelastic" technology during the 1980's will be the human factor. Within the civil aviation field both the certifying authorities and conservative management of industry, concerned about the losses that may result from overoptimism, stand in the way. As in the case of several other structural and aerodynamic innovations, however, there is no doubt about potential CCV benefits in such areas as performance, efficiency and passenger comfort. The question which remains is not whether but when their promise will be fulfilled.

## ACKNOWLEDGMENTS

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J. W. Edwards, P. B. S. Lissman, W. H. Reed, III, K. Roger, and E. Amanuel. Ms. Sydney Koenig prepared the manuscript.

A special apology is due to worthy contributors to the subject of this paper whose work is *not* referenced. A complete listing would have been impossible, and unintentional oversights are unavoidable.

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## STRESZCZENIE

## KONSTRUKCYJNE ZASTOSOWANIE AEROSPRĘŻYSTOŚCI

Wnioski wynikając z omówienia historycznych i nowych danych potwierdzają pogląd, że statyczne i dynamiczne odkształcenia pojazdów lotniczych można często wykorzystać w zastosowaniach konstrukcyjnych. Przedstawiono chronologicznie przykłady zgrupowane zgodnie z przewidzianym zastosowaniem. Można osiągnąć efektywne sterowanie lotem przez sfalowanie płata Wrighta. Można też poprawić sprawność szybkich samolotów i śmigieł, ograniczyć przyspieszenia i obciążenia działające na samolot. Odkształcenia aerosprężyste mogą stać się źródłem napędu. Omówiono widoki na przyszłość.

## Резюме

## КОНСТРУКЦИОННОЕ ПРИМЕНЕНИЕ АЭРОУПРУГОСТИ

Выводы, вытекающие из исторических и новых данных, подтверждают взгляд, что статические и динамические деформации авиационных машин можна часто использовать в конструкционных применениях. Хронологически представлены примеры, сгруппированные согласно с предвиденным применением. Можна достигнуть эффективного управления полетом путем образования волны на крыле Райта. Можна тоже улучшить кпд быстрых самолетов и воздушных винтов, ограничить ускорения и нагрузки действующие на самолет. Аэроупругие деформации могут являться источником привода. Обсуждены перспективы для будущего.

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