ELASTIC SUSPENSION OF A WIND TUNNEL TEST SECTION

Russell Hacker*
Stephen Rock**
Daniel B. DeBra†

INTRODUCTION

As both military and commercial aircraft have become more complex and expensive to operate, designers have looked for ways to increase efficiency and performance. As a consequence, active control systems which influence aircraft aeroelastic behavior are receiving increased attention. These systems use attitude, position, and rate sensors to actuate a variety of control surfaces (e.g., spoilers, ailerons, elevators, flaperons, elevons, and partially inactive spoilers). Their functions include: (a) counteracting wing bending, wing torsion, and fuselage bending; (b) redistributing wing loading; and (c) avoiding flutter [Refs. 1 - 9]. An important benefit is the potential for designing lighter, less rigid structures.

Designing a successful active control system requires a fundamental understanding of an aircraft's aeroelastic behavior. The first solution for unsteady aerodynamic loading was presented in 1934 [Ref. 10] for a wing undergoing simple harmonic motion. The theory for arbitrary motion was still under investigation in 1977 [11], and complete experimental verification is still required.

A program is in progress at Stanford University in the Dept. of Aeronautics and Astronautics to provide experimental verification of the theory describing arbitrary motions of an airfoil and to develop control laws to deal with such motions. The experimental apparatus used in this program is described in this

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* Lockheed Missiles & Space Company, Sunnyvale, CA, formerly of Stanford University, Dept. Aeronautics and Astronautics

** Systems Control Inc., Palo Alto, CA

† Professor, Dept. Aeronautics & Astronautics, Stanford University

paper. It is a mechanism designed to provide two separate degrees of freedom without friction or backlash to mask the small but important aerodynamic effects of interest.

TEST SECTION DESCRIPTION

The experimental apparatus consists of a half-meter square subsonic wind tunnel with a unique airfoil suspension system, which provides two degrees of freedom (DOF) with negligible friction and no coupling of modes through the suspension.

The tunnel is constructed so that an interchangeable 1-meter-long section containing an experiment can be removed and replaced without disturbing the test specimen mounted inside, thus increasing the utilization of the tunnel. Each experiment can be installed in its own test section which is cart mounted for mobility (see Fig. 1).

The test section was designed to support a variety of airfoils. Two versions of this section have been built and, by changing airfoil suspension components, have been used for three research projects [12, 13, 14].

Airfoil test specimens used in recent investigations have been NACA profiles (e.g., 0015, 0009), typically 235-mm chord by 38-mm thickness. The specimen is fabricated with a foam interior covered with three layers of bi-directional weave fiberglass cloth and resin. The foam core consists of two slabs of foam which are grooved to fit around the wing spar (a 19-mm square aluminum tube). These three pieces are glued together and are then cut to shape with a hot-wire cutter guiding on two metal templates. These metal templates are left in place to form end ribs. The fiberglass and resin covering is then applied and final contour is obtained by sanding.

PLUNGE SUSPENSION

The suspension system is designed to provide the airfoil 2 DOF without friction. The airfoil is suspended with the spar vertical so that plunge motion is horizontal and not affected by gravity.

The plunge motion suspension is a set of four folded cantilever springs

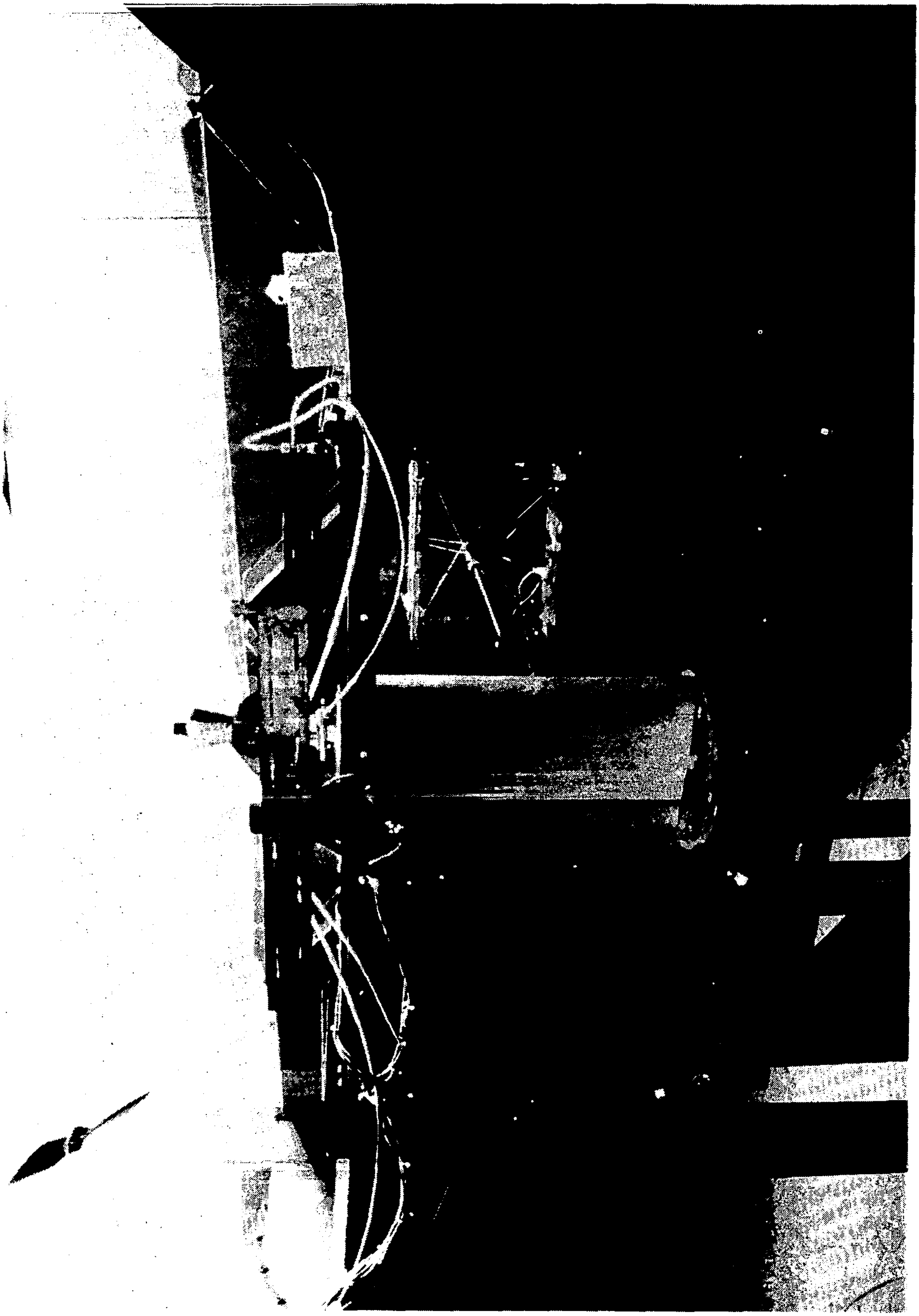


FIGURE 1 WIND TUNNEL TEST SETUP

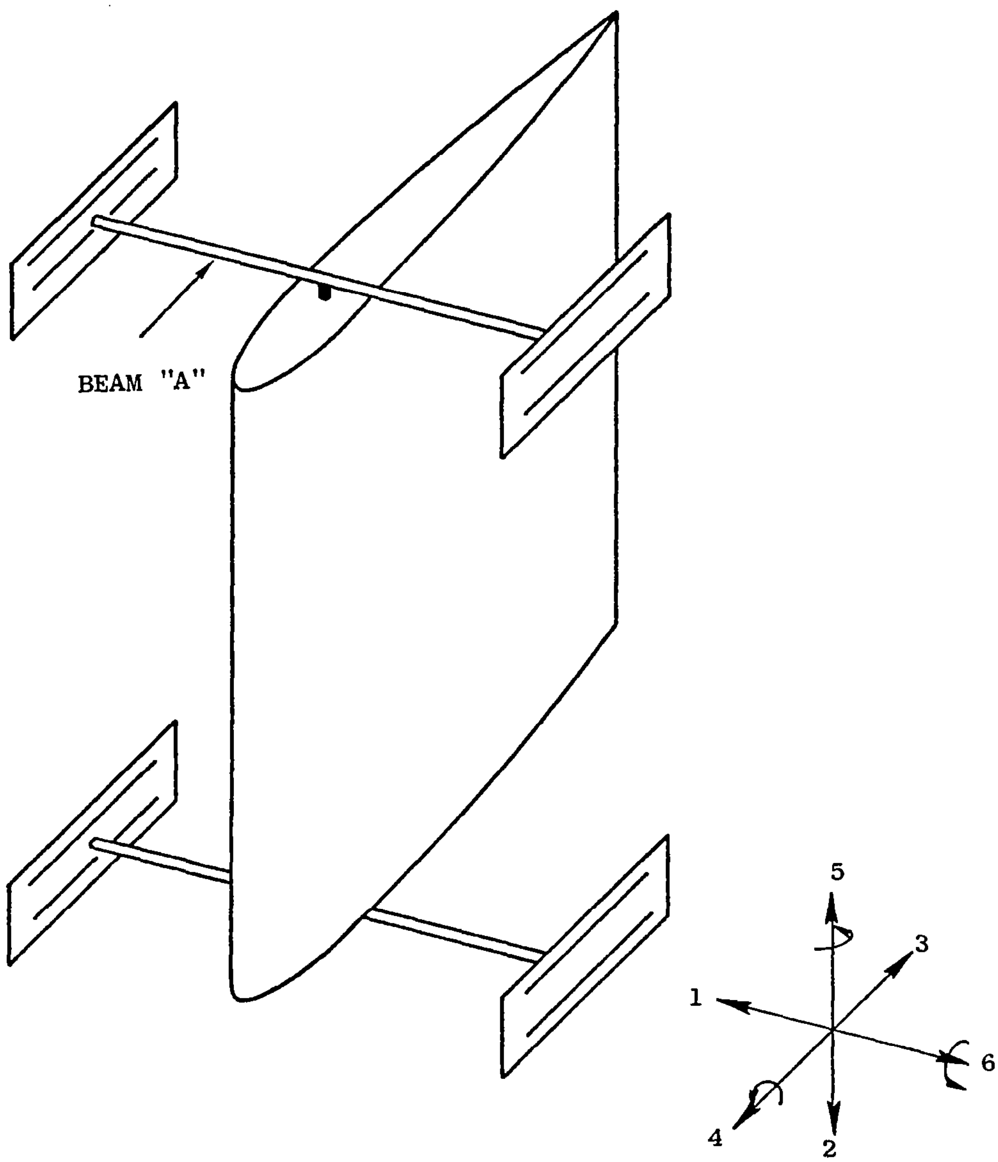


FIGURE 2 ARRANGEMENT OF FOLDED CANTILEVERS IN TWO PAIRS
[from Rock, Ref. 12]

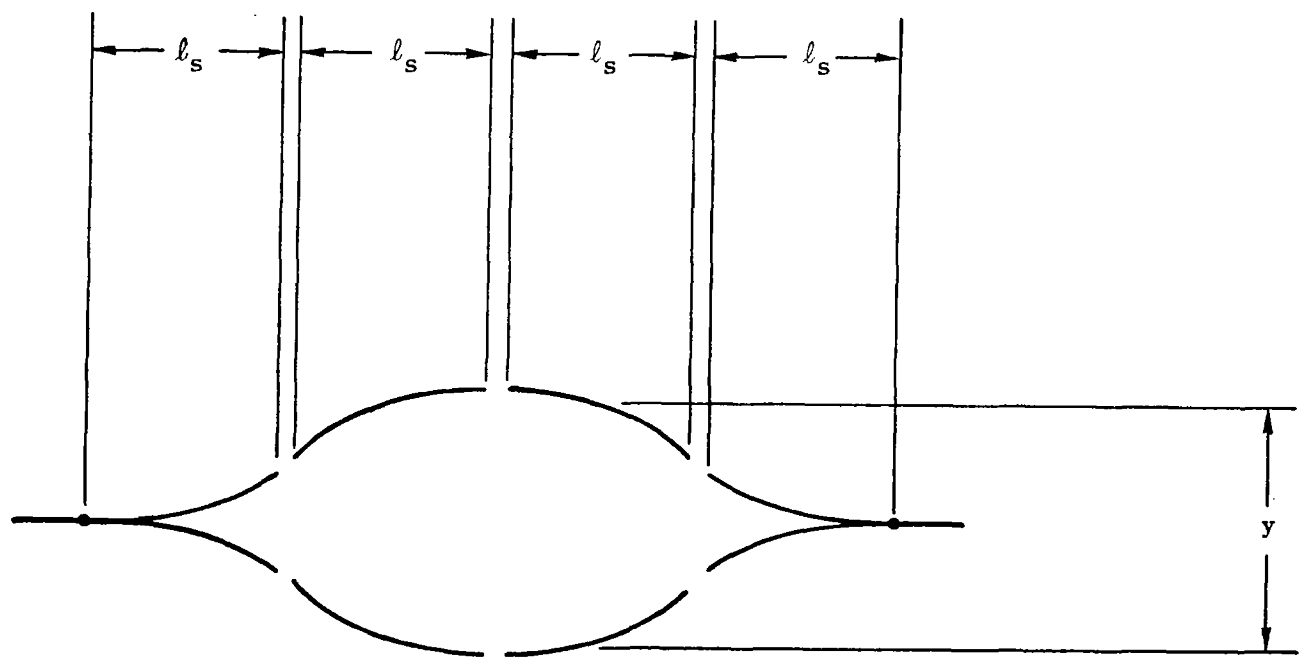


FIGURE 3 DEFLECTION OF SPRING AS A GROUP OF CANTILEVERS
[from Rock, Ref. 12]

mounted so they are stiff in the vertical direction to resist gravity and compliant in the horizontal direction to permit airfoil plunge (direction 1) (see Fig. 2).

As the wing plunges, each of the four metal springs deflects as an equivalent group of cantilever beams as shown in Fig. 3, with a spring rate given by

$$K_h = \left[\frac{3EI}{\ell_s^3}\right]\left[1 + \left(\frac{Y}{\ell_s}\right)^2 + \cdots\right]$$

where $I = w_s t_s^3/12$.

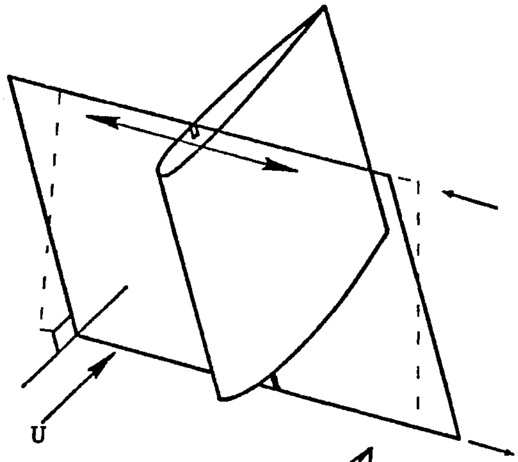
In choosing ℓ_s a tradeoff exists. It should be large to minimize the nonlinearity in the spring rate but small to minimize the compliance of the plunge suspension in directions 4 and 5 (Fig. 2). The thickness is determined by vertical strength and stiffness. The springs in current use are 2-mm-thick copper beryllium with $\ell_s = 93$ mm and $\omega_s = 14$ mm. The resulting spring rate is 10.52 kN/m.

This type of folded cantilever spring alone has compliance in directions 4 and 5 which is eliminated by connecting the springs in pairs with cross beams.

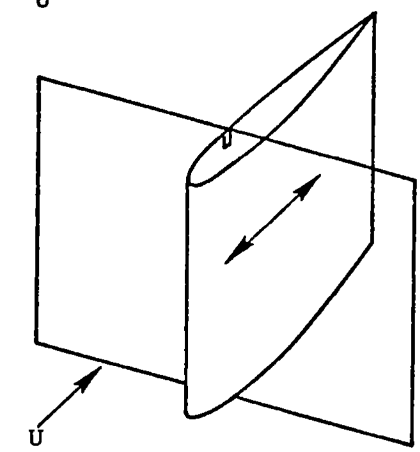
The springs are each treated as a group of cantilevers. They are designed to operate on the linear part of the force-deflection curve for the desired maximum deflection. Normally a flat spring will undergo a snap-through action when deflected through its center or zero-deflection position due to its imperfections. In addition, if the suspension is overconstrained as this one is, any imperfection in the nominal positions would require strain in the stiff direction to pass through the undeflected state. This is avoided by biasing each spring approximately $h/4l_s = 0.03$ or about 1.5 times the maximum expected motion from its center position so that in operation the spring does not pass through its zero position. Spring mounting brackets are arranged on the tunnel section to permit changes in spring sizes (widths, length, thickness).

The directions intended to be stiff have some compliance. However, motion in these DOF's can be determined experimentally and filtered electrically

(a) DIFFERENTIAL
PLUNGE MOTION



(b) CHORDWISE MOTION



(c) SPANWISE MOTION

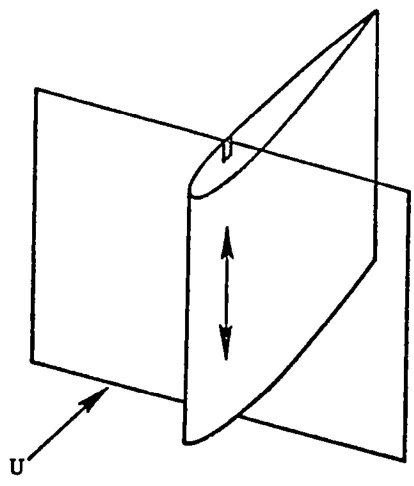


FIGURE 4 EXTRANEOUS BENDING DEGREES OF FREEDOM
[from Rock, Ref. 12].

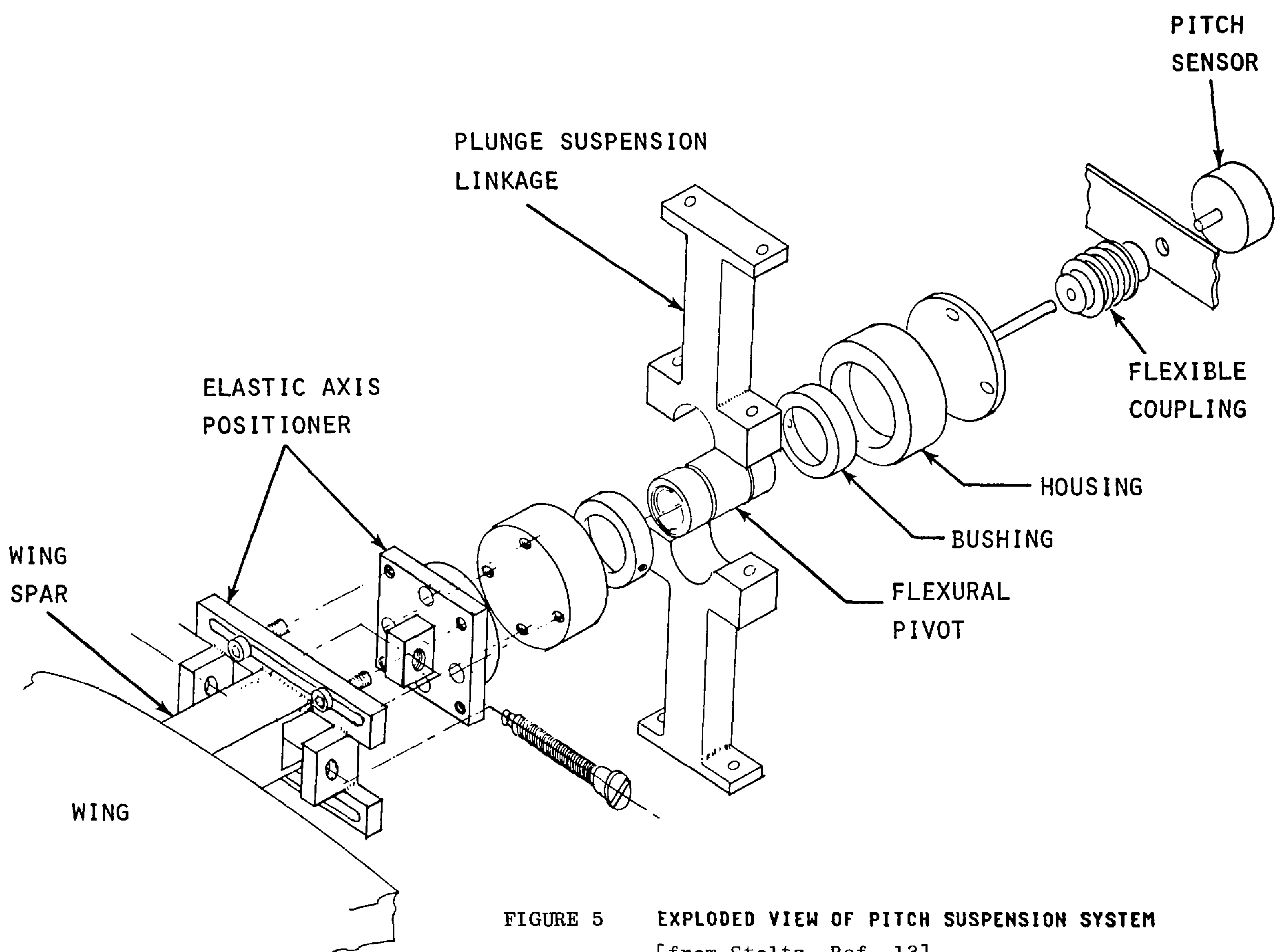


FIGURE 5 **EXPLODED VIEW OF PITCH SUSPENSION SYSTEM**
[from Stoltz, Ref. 13]

from the sensor signals. Shown in Fig. 4 they are:

1) differential motions of the wing in plunge
2) chordwise motion of the wing
3) spanwise motion of the wing

The differential plunge mode is reduced by installing a stiffening beam on the suspension, parallel to the wing spar and external to the tunnel. For experiments requiring external plunge control of the airfoil, a plunge actuator (a cast-off computer-disc-drive linear motor) is attached to the mid-point of this stiffening beam which is the approximate node of the airfoil's differential bending mode. Consequently, the differential mode is not excited by application of an external force. Plunge position is also sensed at this point so the sensor does not measure the differential mode. The transducer used is an LVDT, mounted such that it is isolated from tunnel motions.

PITCH SUSPENSION

Test specimens are permitted to rotate about a pitch axis and may be controlled about that axis by either a control actuator external to the tunnel or by some specimen-mounted device such as a trailing-edge flap.

Each end of the test specimen is attached to housings which are part of the plunge suspension system. Inside each housing there is an arrangement of bushings which accommodates various sizes of Bendix Flex Pivots. These standard commercial pivots are available with a variety of torsional spring rates and radial load capacities.

Brackets built into the spar ends allow adjustment of the wing spar in a chordwise direction relative to the flexural pivot centerline. This was done to permit studies of the effect of chordwise location of the elastic axis (see Fig. 5).

If external pitch control is desired, a control linkage and torque motor are available. A torque motor with peak torque of 2 N-m is currently used, and its mass (~2 kg) is large enough that direct attachment on the wing pitch axis would result in an unacceptable increase in the total suspended mass.

After considering drives using flexible shafts, belts, metal tape and various linkages, a four-bar linkage was chosen. The linkage is mounted in a horizontal plane under the tunnel section. As the test specimen plunges, its attachment to the plunge suspension is constrained to move in a straight line by the folded cantilever springs. The pitch linkage deflects without imparting torque to the pitch axis because the torque motor is free to rotate and translate. The motor can transmit torque to the pitch axis at any position of plunge, as shown in Fig. 6.

Friction in the linkage is avoided by using Bendix Flex Pivots at all linkage joints as well as in the torque motor since the amount of rotation is limited. Thus, known spring rates replace uncertain friction.

Sensing of pitch motion is done using various angular sensors mounted on the end of the pitch axis. To date, both resolvers and rotary variable differential transformers (RVDTs) have been used. A flexible coupling with synchronizing adjustment has been used for zero setting.

AIRFOIL-MOUNTED PITCH CONTROL

Test specimens having integral means of pitch control, such as a trailing-edge control surface, can be operated in the tunnel by removing the external pitch linkage. One such specimen has been tested. This specimen has a trailing-edge full-span flap with a chord of approximately 24% of the total wing chord (see Fig. 7).

A dc torquer mounted inside the wing at mid-span is connected to the trailing-edge flap by cables routed over pulleys (see Fig. 8).

Installation of the torque motor in the wing was accomplished by first fabricating the wing as previously described, then cutting an opening for installation of a fitting designed to carry the spar loads and house the motor. Wing contour is restored with fiberglass covers held in place with screws, all joints being sealed with putty.

Cables are attached to crank arms mounted on each end of the motor, brought out through span-wise holes in the wing, and routed along the outside of the wing end-rib to the flap hinge.

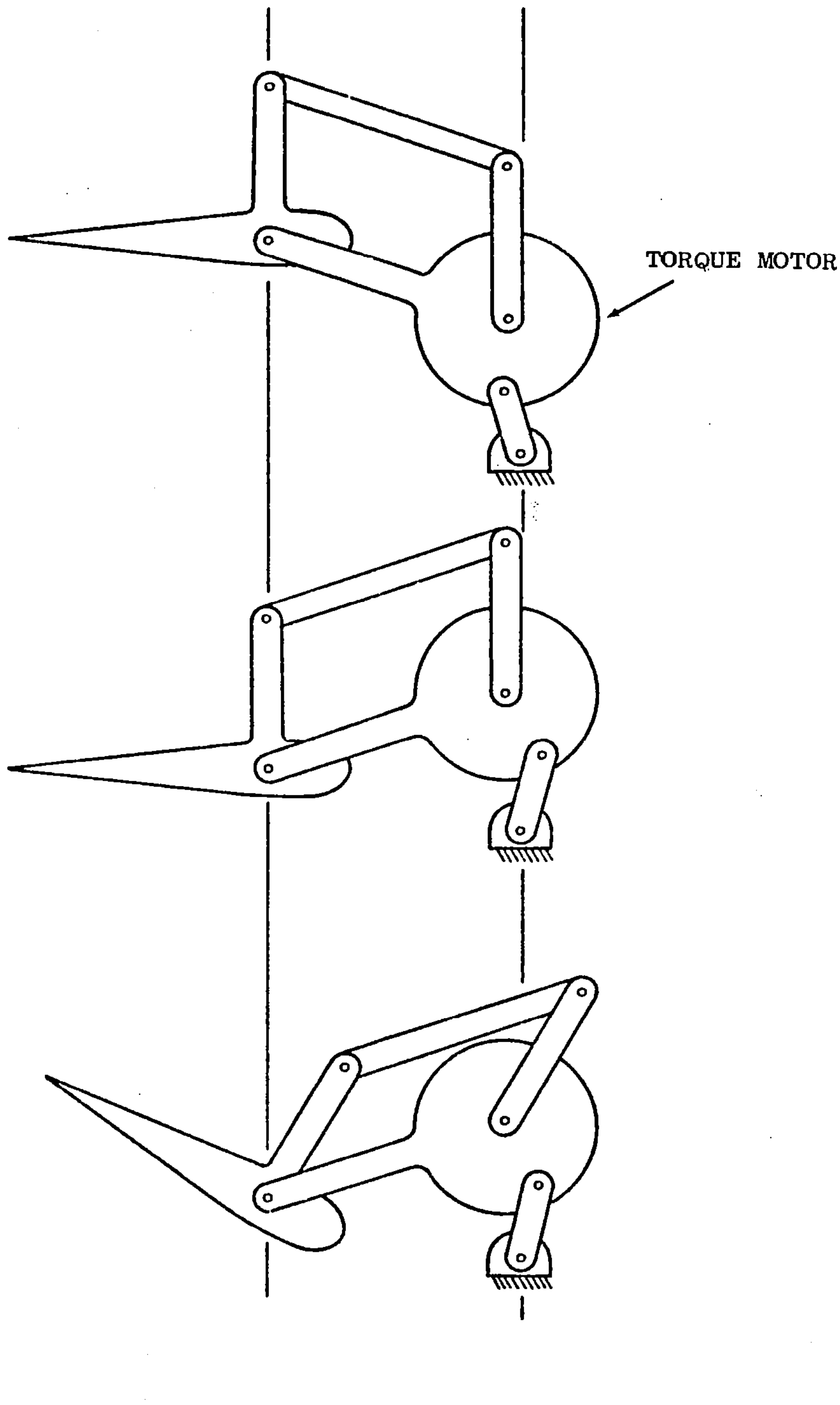


FIGURE 6 OPERATION OF FOUR-BAR LINKAGE [from Rock, Ref. 12]

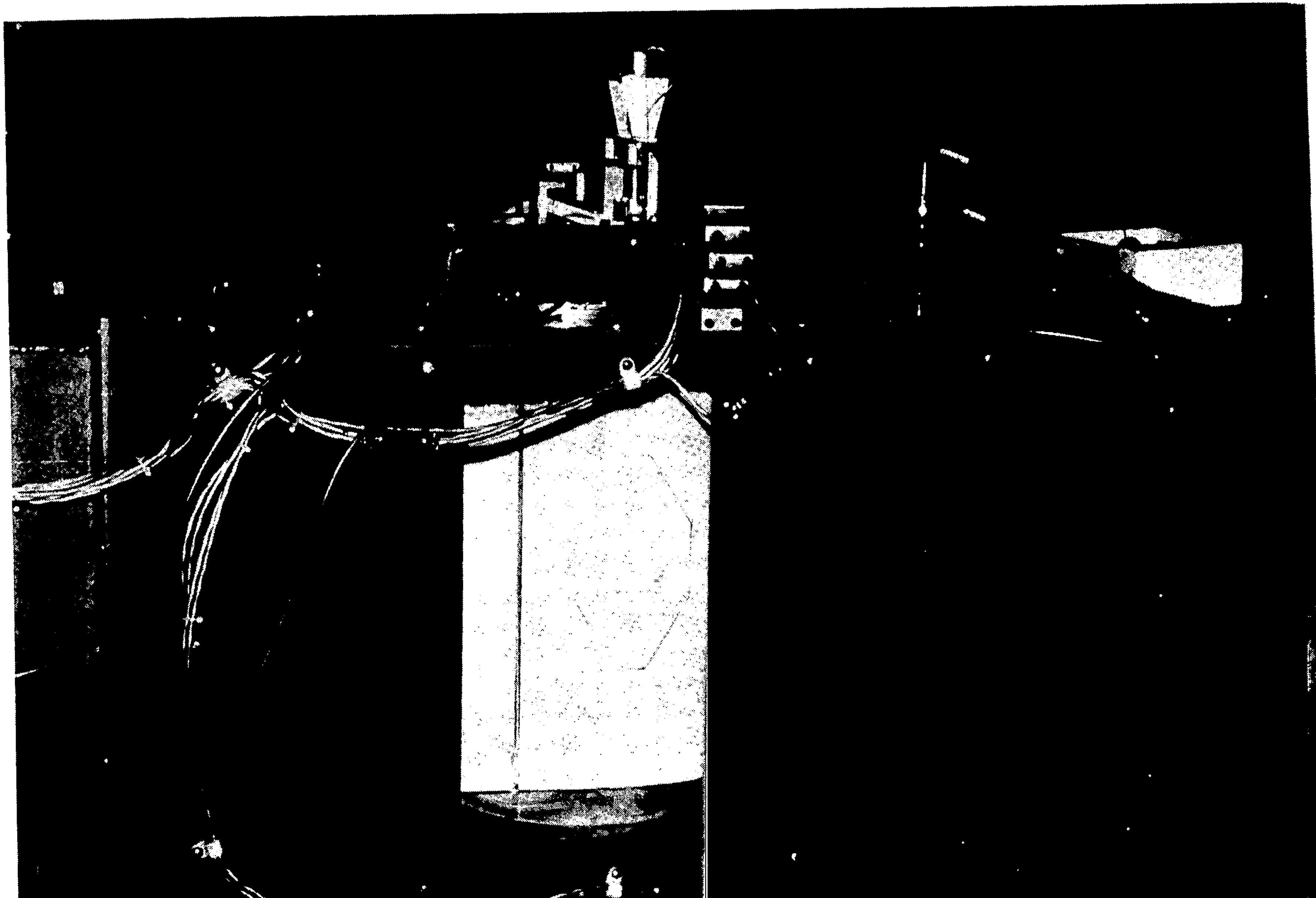


FIGURE 7 TRAILING–EDGE FLAP SPECIMEN

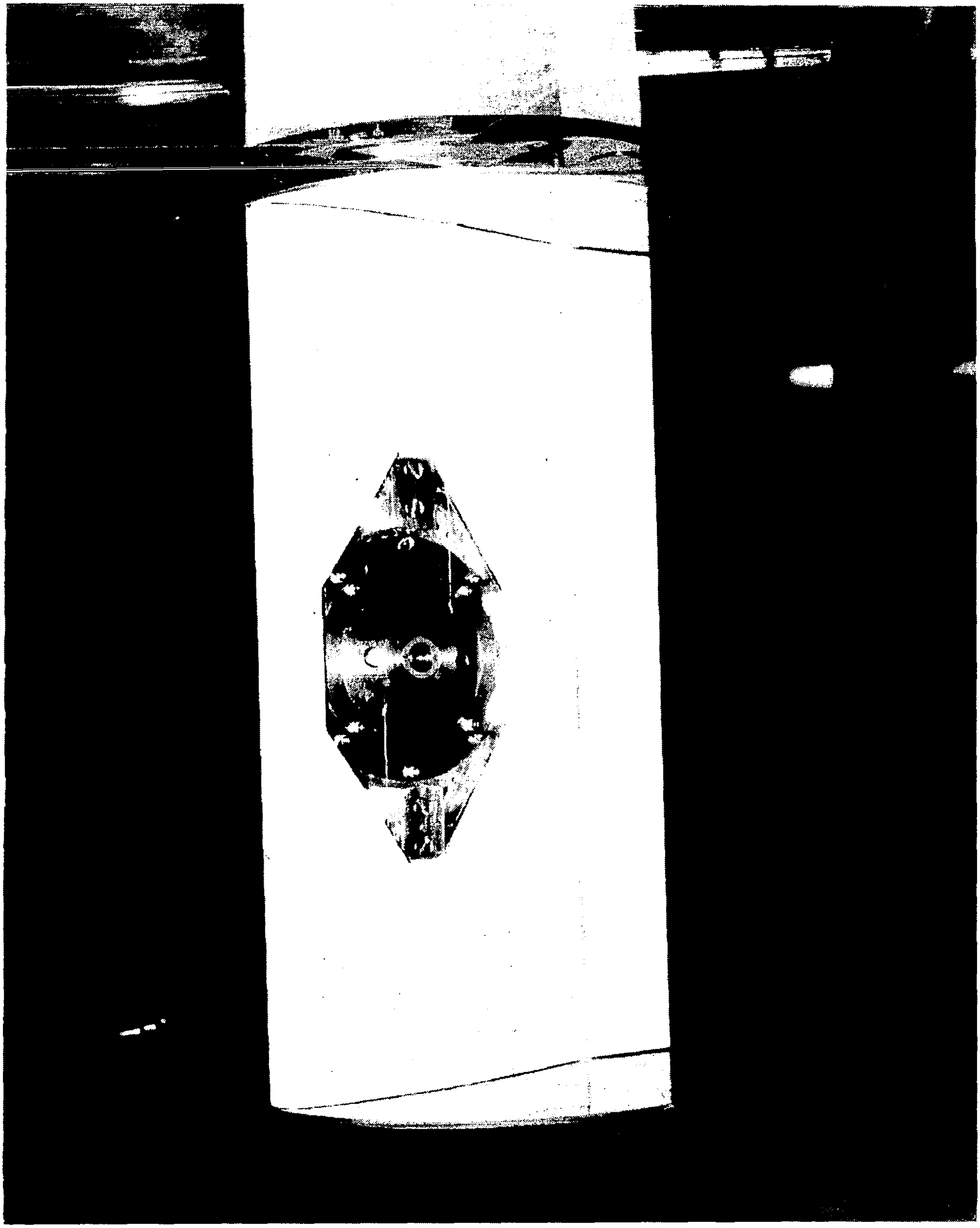


FIGURE 8 WING MOUNTED FLAP CONTROL

The hinge for the flap was designed such that the gap between the flap and the rest of the airfoil could be adjusted to minimize airflow through the gap. To achieve this, the airfoil trailing edge and the flap leading edge were designed with a concave/convex joint and the flap hinge bearings then adjusted to give a clearance of 0.2 mm (0.008 in).

The flap control was designed to provide flap excursions of $\pm$ 30 deg although in practice the motion is typically a few degrees.

SUSPENSION PERFORMANCE

The overall performance of the apparatus has been excellent. However, two complicating characteristics have been encountered. The first concerns the four-bar linkage used with the external pitch control motor. The second is excitation of differential modes.

When using the external pitch control motor, torque applied to the elastic axis of the airfoil generates an unbalanced force in the plunge DOF. This is illustrated in Fig. 9. The torque is transmitted through the linkage by axial forces and moments in its members. The motor generates torque, τ, between its case and link "A." This creates force F_1 which acts through link "B" to generate torque T about the elastic axis of the airfoil. From Fig. 9

$$T = F_1 \ell_1 = \left(\frac{T}{\ell_1}\right) \ell_1 = \tau$$

The undesired force is shown as F_2 in Fig. 9. It balances the torque acting on the case of the motor

$$F_2 = \frac{\tau}{\ell_2}$$

This force acts on the wing spar in the plunge direction. A further disadvantage of this force is that it is applied to one end of the wing, which therefore excites not only the primary plunge mode but also the differential plunge mode.

A simple technique has been used to eliminate the excitation of the primary plunge mode by the torque motor. A signal proportional to F_2 is

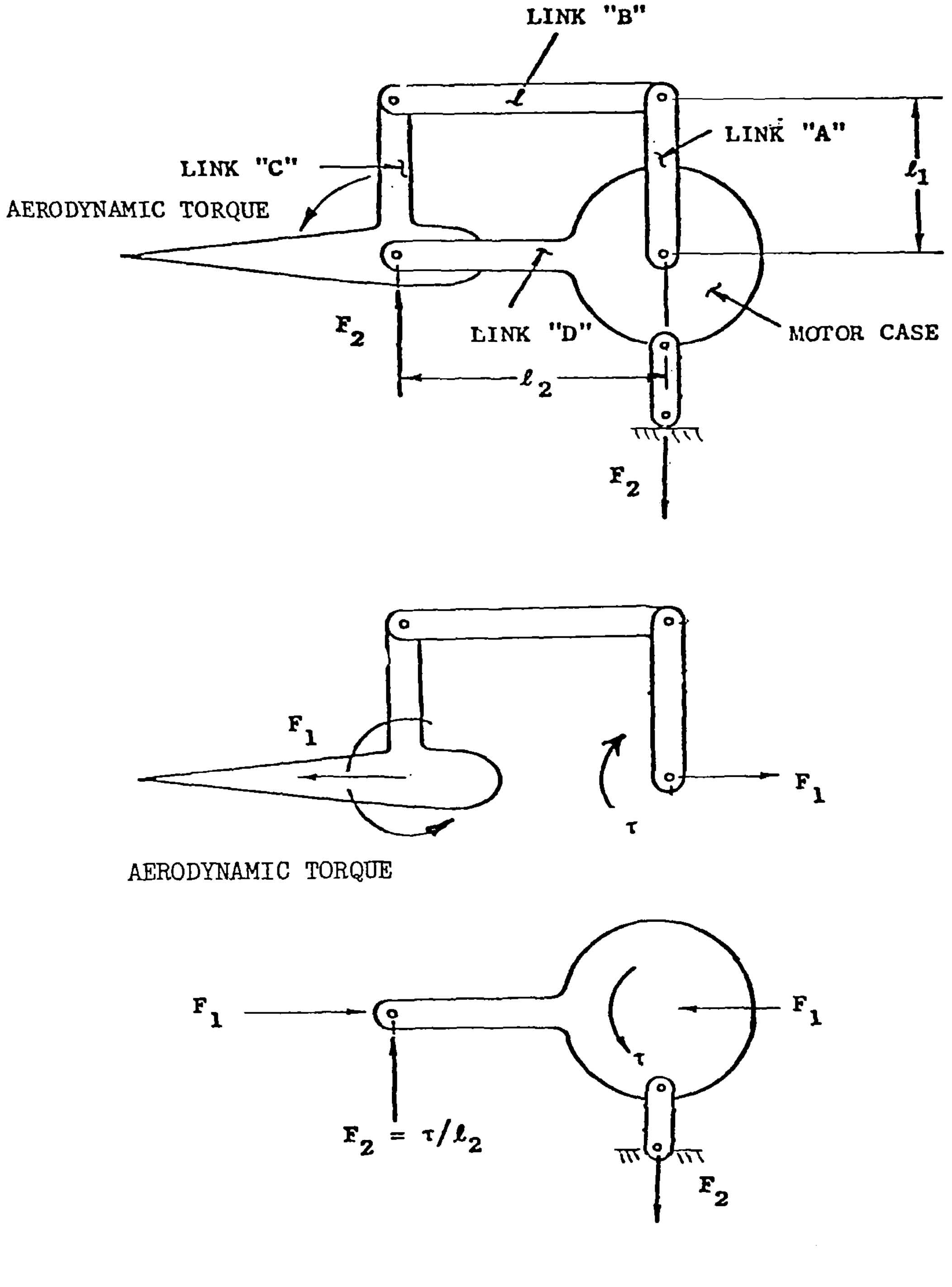


FIGURE 9 UNBALANCED REACTION FORCE IN PLUNGE DIRECTION DUE TO APPLICATION OF TORQUE [from Rock, Ref. 12].

created and summed with the command signal to the plunge actuator. The plunge actuator thus cancels F_2.

Two differential modes are excited. One is the differential plunge mode discussed above. The other is a differential twisting of the wing across its span which is excited because torque is applied only to one end of the wing. Natural frequencies are 16.5 Hz for the plunge mode and 79 Hz for the twisting mode.

In open-loop studies (sensor signals not fed back to the actuators), neither of the differential modes is a problem. These motions merely superimpose on the primary motions. They are antisymmetric and therefore do not affect the aerodynamics. Furthermore, the differential twisting mode is much faster (10:1) than system dynamics and can be ignored. The differential plunge mode is less than a factor of two faster, but is not sensed by the plunge position sensor. The only problem occurs when the amplitude of the differential plunge motion becomes large, since this can cause binding of the plunge actuator.

In closed-loop studies, it is theoretically possible to drive the differential modes unstable. This is definitely true of the twisting mode. The angular resolver is located at one end of the wing and senses motions in this mode while the torque motor acts at the other end of the wing and excites the mode. Consequently, when the resolver signal is used as negative feedback to the torque motor (to stabilize the primary mode), a destabilizing positive feedback results on the differential mode. In the experimental procedures carried out, the positive feedback was small enough that no instabilities were encountered.

ALTERNATE SUSPENSIONS

Actuation of airfoil-mounted control surfaces poses one of the more difficult problems for a wind tunnel of this size. If mounted directly in or on the airfoil, a torque motor may exceed the allowable total sprung mass, may be too large to fit within the airfoil cross section, or may not have adequate torque.

An acceptable solution to these problems would result in no unwanted forces being applied to the specimen and no friction being introduced into the system. Two linkages were considered which permit mounting the torque motor external to the test specimen.

The linkage shown in Fig. 10 has the torque motor mounted on a link permitting small fore and aft motions of the torque motor in response to pitch and plunge motions of the wing. This arrangement reduces the sprung mass of the system and is satisfactory for small angle changes of pitch and small displacements in plunge. For the investigation of larger airfoil motions the amount of pitch/plunge/flap angle cross coupling becomes excessive.

The linkage shown in Fig. 11 also permits mounting of the torque motor on an external support. Flap position is effectively decoupled from pitch and plunge. However, most of the linkage mass is mounted on the suspension system. The linkage requires two joints having 2 DOF's on link A and a universal joint on the torque tube.

Both of these linkages, although more complex than the airfoil-mounted cable system which has been used, could be used if

(a) the test airfoil were too thin for a torque motor installation,

(b) the suspended mass were large enough such that the additional mass of a torque motor were unacceptable, and

(c) if the airfoil and control surface motions were small, avoiding cross coupling.

CONCLUSIONS

Elastic elements, which are essential to avoid masking small aerodynamic effects by friction and backlash, can be incorporated in a wind tunnel model suspension. Overconstrained design is more symmetrical and convenient and leads to an acceptable configuration if all flat springs are nominally biased to avoid snap-through. Torquing can be accomplished through linkages to avoid placing a torquer on the sprung mass. A symmetrical configuration could retain independence of plunge and rotation but the duplication of components did not seem warranted. We were able to achieve decoupling by crossfeed compensation.

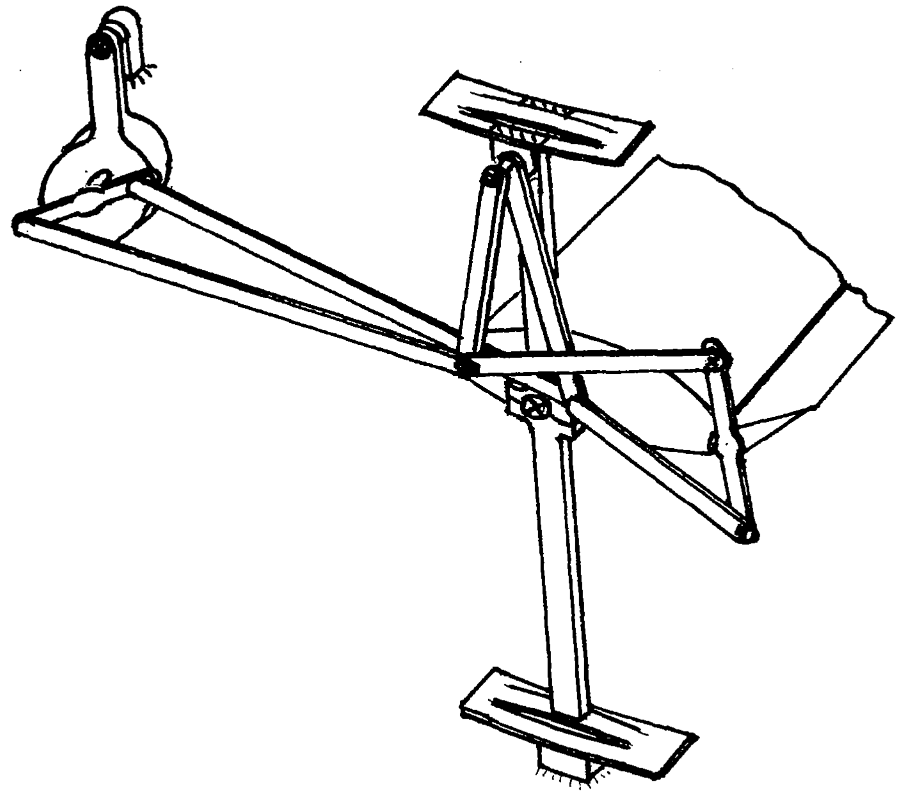


FIGURE 10 ALTERNATE LINKAGE I

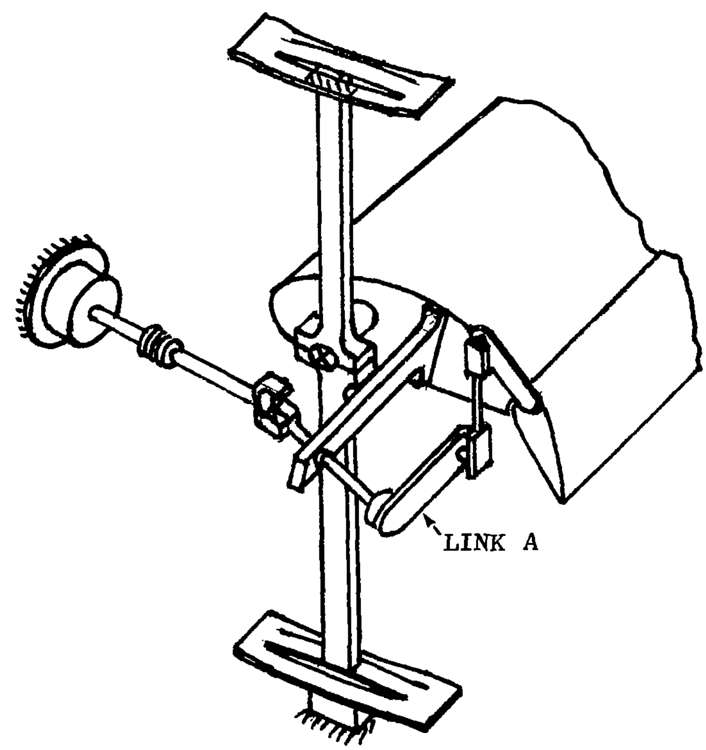


FIGURE 11 ALTERNATE LINKAGE II

ACKNOWLEDGMENTS

We gratefully acknowledge the support of NASA Dryden Flight Research Center for sponsoring the research of S. Rock and P. Stoltz, resulting in their dissertations, under contract No. NSG 4002.

Control torque motor selection, instrumentation, and all associated electric design were performed by R.A. Van Patten of Stanford University. Development and fabrication of the foam core/fiberglass airfoils were performed by Professor DeBra. Certain design requirements and valuable feedback were due to Jim Nathman and Paul Stoltz.

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Russell Hacker
Lockheed Missiles and Space Company
P.O. Box 504
Sunnyvale, California 94086

Mr. Hacker is presently a design specialist in the Structures and Mechanisms Section. During his 30 years with Lockheed, he has been involved in the design of aircraft, spacecraft, and laboratory equipment. The equipment described in this paper was designed while on loan from Lockheed to the Guidance and Control Laboratory of Stanford University. He is a registered professional engineer in California. In addition, Mr. Hacker holds a B.S. degree in Civil Engineering from Northwestern University and received his M.B.A. in 1971 from San Jose State University.

Co-authors of this paper are Mr. Stephen Rock who is affiliated with Systems Control Technology and Mr. Daniel B. Debra, a professor at Stanford University who is Director of their Guidance and Control Laboratory.