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CIRCULATION CONTROL LIFT GENERATION EXPERIMENT: HARDWARE DEVELOPMENT

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ABSTRACT

A circulation control airfoil and its accompanying hardware have been developed to allow the investigation of lift generation that is independent of airfoil angle of attack and relative flow velocity. The test equipment, designed for use in a water tunnel, includes the blown airfoil, the support systems for both flow visualization and airfoil load measurement, and the fluid-control system, which utilizes hydraulic technology. This paper describes the primary design tasks, the selected solutions, and the unforseen problems involved in the development of these individual components of hardware.

INTRODUCTION

Inherent in current lift generation methods are the constraints imposed by their dependence on free-stream velocity and angle of attack. For fixed wing aircraft to perform low-speed landings and takeoffs, complex flap systems must be used to increase the effective area of the wings to compensate for the decrease in airstream velocity. More severe limitations are demonstrated by standard rotor blade designs; here, lift generation is inhibited by the reversed relative flow experienced by retreating blades and by the eventuality, as angle of attack is increased, of dynamic stall. As a consequence of these contraints, conventional rotorcraft have been unable to achieve desired increases in forward flight speed.

The method of circulation control lift generation may remove these types of constraints. Utilized with a blunt airfoil, circulation control refers to the discharge of a jet blown tangentially over the surface of the airfoil's rounded trailing edge. The jet, by adhering to the airfoil contour, moves the stagnation point further toward the lower surface to increase the circulation, which, in turn, increases the lift generated (see Fig. 1). Hence, circulation control can provide high lift coefficients as a function of jet blowing alone, unhampered by the problems attributed to free-stream velocity and angle-of-attack dependence.

In applications to fixed wing aircraft, circulation control would negate the need for flap systems and allow for even lower landing and takeoff speeds. Application of circulation control to rotorcraft would see rotor blade sections, symmetric about midchord and possessing upper surface leading and trailing edge jets, developing high lift coefficients irrespective of relative

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*Research Engineer, NASA Ames Research Center velocity direction and without angle-of-attack stall. Control of the aircraft in both cases would be accomplished through modulation of the jet(s) blowing.

Although the potential of circulation control as a viable alternative to current high-lift generation methods is attractive, its exploitation is hindered by an insufficient understanding of the flow field surrounding the blown airfoil. Without this knowledge, accurate prediction methods for the airfoil's performance cannot be formulated. Moreover, in proposed implementation of this technology, aircraft lift control would be achieved through the periodic and transient blowing of the jets, and yet little experimental information exists concerning unsteady leading edge or transient trailing edge jet blowing.

NASA scientists have devised an experiment to obtain experimental data concerning the aerodynamics developed by a circulation control airfoil under various blowing conditions. Its primary objective is to visually define the fluid mechanical structure of the flow field for steady/unsteady leading and trailing edge blowing. To this end, water is to be used as the test medium; visualization of the flow field is facilitated by the use of dye injection or hydrogen bubble tracers, and is made more discernable because of increased time scales (one order of magnitude greater in water than in air). Also to be examined in this study is the influence of unsteady blowing on airfoil performance (forces and moments) and the influence of unsteady blowing on the movement of the leading and trailing edge stagnation-point locations. This latter complication poses a major obstacle in the development of a theoretical model.

To realize the objectives described above, NASA engineers have developed several major pieces of hardware. First, a model has been designed to capture, on a reduced scale, the characteristics of circulation control lift generation as utilized in applications to rotorcraft. Second, modifications to an existing water tunnel have been made to accommodate the model during flow-visualization studies and to provide uncontaminated airfoil load measurements. And finally, a fluid-control system has been designed to supply the model with the specified periodic and transient blowing conditions demanded in the experiment.

This paper describes the development of the hardware listed above. The details of each component design are given below individually, each preceded by the pertinent design requirements. The problems encountered during the manufacture and testing of the hardware are described collectively in the section titled PROJECT STATUS.

DESIGN

Model Design

The model is a two-dimensional representation of the circulation control methodology proposed for rotorcraft application. Designed for use in a water tunnel, the model, as shown in Figure 2, simulates rotor blade operation by blowing jets of water from the leading and trailing edge slots of a symmetrical (about midchord) airfoil. The specifics of the circulation control airfoil geometry and flow generation were defined by the Principal Researcher and are as follows:

- o Shape and Size Constraints
  - the airfoil cross section must be elliptical, with circular arc leading and trailing edges and a 10.16-cm (4.0-in.) chord.
  - the jet slots must be situated on the upper surface of the leading and trailing edges over the entire 21.08-cm (8.3-in.) length of the model.
  - the slot exit height, the narrowest point of the jet construction, must be .015 + .0013 cm (.006 + .0005 in.).
- o Flow Generation Contraints
  - the jet plenum chambers must be isolated from each other.
  - the velocity of the water leaving the jets should be 100 times faster than the velocity of the water in the plenum chambers.
- o Structural Constraints
  - the model must withstand 2.07 x 10^5 Pa (30 psi) internal pressure, 133.2 N (30 lb) lift load, 22.2 N (5 lb) drag load, and 3.38 N-m (30 in-lb) pitching moment.
  - the height of each slot cannot deflect more than .00254 cm (.001 in.) under load (i.e., the applied plenum chamber pressure).

The primary design task consisted of finding the configuration that would fulfill the geometrical contraints and yet maintain the structural integrity and desired flow characteristics of the model.

In terms of the severity of the given requirements, the jet slot proved to be the most difficult design area. Deflection of the jet slot by the pressure developed in the plenum chamber had to be minimized without drastically changing the internal features of the model. The plenum chamber height, which controls the velocity of the jet discharge, and the slot entrance area, which determines the flow field uniformity, were especially sensitive to alteration.

This design was further complicated by the positioning of the slot lip along the airfoil chord. The slot lip had to be located on the upper surface of the airfoil so that the jet discharge would exit through the minimum throat (slot) height. Adherence to design requirements necessitated that the slot lip be located along the chord at 4.708 cm (1.8537 in.) and cut to a thickness of .010 cm (.004 in.).

A specific effort also had to be directed toward assuring the integrity of the model as a pressure vessel. Material was trimmed from the model interior

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to enlarge the plenum chambers and establish a minimum flow velocity ("dead water") in the plenums. The structure of the model was further reduced to allow space to divert the water, support the wing, and isolate the plenum chambers. Hence, a maximum internal pressure of 2.07 X 10^5 Pa had to be contained with a minimum of structure.

Supplying isolated plenum chambers with independent sources of water was a difficult design task as well. Water had to flow into the plenum chambers with sufficiently slow velocity so that it would not be forced directly out the slots. However, the model size constraints would not permit increasing the diameter of the tubes bringing the water to the chambers. And decreasing the wall thickness of the tubes was undesirable since the tubes would act as the structural members supporting the model against the airfoil forces described above.

The model's final design is shown in Figure 3. Manufactured in several pieces, the model consists of two main body halves, two end pieces, a solid spar support, and two water injection pipes. The main body was sectioned so that the jet slot lip is part of the top half, while the circular arc leading and trailing edges are part of the bottom half. This allowed the jet slot area and the model interior to be easily accessed during fabrication.

The plenum chambers are isolated from each other by the solid center section of the wing halves and are supplied with water by separate water injection pipes. The large cutouts in the pipes allow the water to fill the chambers slowly. Lateral movement of the pipes is prevented by pins slotted into the bottom wing half. Plugs (not shown) welded into the ends of the pipes prevent the pipes from being ejected from the model by the pressure force.

Six support posts are evenly distributed along the length of each jet slot to prevent the deflection of the slot lip. Screws are threaded through these posts to provide increased resistance to the internal pressure. The slot lip, therefore, is constrained rather than cantilevered and the deflection of the slot lip edge is reduced; NASTRAN analysis shows this deflection to be .0023 cm (.0009 in.). In addition, the support posts allow for the adjustment of the slot height, using shims or a file, should the height deviate from .015 cm (.006 in.) for any reason. Although the posts do produce some obstruction to the flow through the slot entrance area, they are contoured into the surrounding internal geometry as much as possible to reduce this effect.

As mentioned above, the support posts aid in containing the internal pressure. The 12 screws through the posts, along with the four through the solid center section, hold the body of the wing together, while the end pieces, which slip over the solid spar and the water injection pipes, bolt into the main body to complete the pressure-vessel construction. The assembled wing is supported in the tunnel by the solid spar on the one side and the water injection pipes on the other.

Control of the slot lip deflection allowed the plenum chamber height to be maximized as a function of geometry alone. At the final design, the height measured 1.02 cm (.4 in.), 70 times the jet slot height. As a consequence, the flow through the jet slot is blown out of the airfoil at 70 times the velocity with which it enters the plenum chamber, achieving 70% of the design requirement.

Support System Design

The support system for the circulation control airfoil is the means by which the model is held in the water tunnel during the flow studies. The success of the experiment, namely how well the flow field is defined and the airfoil forces measured, depends on how well the support system fulfills the requirements listed below.

The support system must

- provide an unobstructed view of the model during flow-visualization tests;
- allow the adjustment (static) of the angle of attack prior to testing;
- contain pressurized water within the tunnel (1.03×10^5 Pa or 15 psi max.);
- conform to existing load cell and tunnel frame apparatuses;
- isolate the load path from the model to the load cells;
- comply with model movement to allow measurement of airfoil forces.

At the onset of the support system design, a decision was made to separate the flow-visualization and load-measurement phases of the experiment; the configuration of the water injection pipes made it impossible to fulfill the requirements for measuring the loads without obstructing the view of the model. Hence, two support systems were designed, one permitting flow visualization and documentation and the other permitting airfoil load measurement. In addition, a decision was made to orient the model in the test section so that it could be observed from the solid spar end. In order to supply water to the model through the water injection pipes, the fluid-control system needs to be adjacent to the model, close to the tunnel window. Consequently, the solid spar side of the model was deemed to be the "viewing side."

The subsystem designed for flow visualization consists simply of two transparent polycarbonate windows which mount into the existing test section. Cut into the water injection side window is a circular plug that may be rotated, by loosening the wing nuts holding it in place, to adjust the model's angle-of-attack. The water injection pipes extend through two holes in the plug and are sealed by O-rings to contain the water. The plug itself utilizes a gasket to prevent leaking. On the solid spar side, the window has a hole cut in it for the spar, which is sealed by an O-ring. As the circular plug and the water injection pipes rotate to bring the model to a new angle-of-attack, the solid spar need only slide in its O-ring seal. The model is held against lift, drag, and pitching moment by the 2.54-cm-thick (1-in.-thick) transparent polycarbonate windows. The water injection side window is painted black to provide a better background for laser-lighted photography.

The airfoil load-measurement support subsystem was of necessity made more sophisticated. The load cells that had been used to measure lift and drag loads in previous water tunnel tests were to be used again. Consequently, the main design effort for this subsystem was directed toward determining a method which could isolate the load path (from the model to the load cells) from the tunnel structure and windows, contain the pressurized tunnel water, and be compliant to model displacements, all within the constraints imposed by the existing structure.

The method selected for the final design, shown in Figure 4, utilizes welded metal bellows. The bellows are used as flexible connections through which the spar and water injection pipes are brought to the load cells. Able to withstand an internal pressure of 2.07 x 10^5 Pa (30 psi), the stainless steel bellows are sufficiently compliant in the axial and cantilevered directions to transfer airfoil displacements to the load cells without absorbing any load themselves. Also, the windows are cut so that the pipes and spar do not make contact with any structure on their way to the rigid load cell connections. Thus, the measurements obtained by the system are virtually uncontaiminated.

The load cell connections are designed to be completely rigid to support the model in the lift and drag directions. The bellows are torsionally very stiff and can prevent the model from rolling with the pitching moment. The pitching moment is measured by strain gages placed on the water injection pipes.

The angle-of-attack of the airfoil may be adjusted by rotating the circular plug and the attached bellows assembly on the water injection side. The solid spar is again allowed to slide in its O-ring seal so no rotation of its bellows assembly is required.

Fluid-Control System Design

The fluid-control system must develop the blowing conditions through the model that a circulation control airfoil experiences in a rotorcraft-type application. Because control of the lift developed by the model is accomplished by the modulation of the jet discharge, the blowing conditions, set by the experimenter with the fluid-control system, provide the means for correlating the data obtained during the flow-visualization and load-measurement phases of the experiment. To ensure that the information gained through this correlation be meaningful, the fluid-control system must be extremely accurate in constructing the specified test conditions.

The fluid-control system must not only be accurate, but versatile as well. The discharge of the two jets must be independently adjustable, whether the jets are blowing individually or simultaneously. The main parameter to be controlled by the system is the individual plenum pressure, which is expressable as:

$$p_i = p_i + (p_i - p_a)\ f(t);\quad i=1,2$$

where p_i = mean plenum pressure
p_a = tunnel pressure ('atmospheric')
$f(t)$ = pressure variation with time

As apparent from the above expression, the fluid-control system must maintain for each jet a mean plenum pressure and a pressure variation with time. Periodic blowing conditions are to be obtained by forcing the plenum pressure to vary sinusoidally, so that $f(t)=A \sin (wt+\phi)$. The additional parameters, frequency and phase angle, must be independently adjustable for each plenum. Transient blowing conditions are to be simulated by forcing the plenum pressure to follow a ramp function, or $f(t)=C_1 t + C_2$, which again requires that an additional paramater, the time constant for total response, be adjustable for each jet. Setting $f(t)=0$ will provide steady blowing test conditions.

From known relations between plenum pressure, p_j, jet velocity, V_j, tunnel pressure, p_a, and free-stream velocity, V_∞, and from consideration of the operational constraints of the tunnel, $V_\infty = 3$ m/s and $p_a = .01$ MPa, the following limits were placed on the test conditions to be be provided by the fluid-control system:

In general, the system must

- conserve the mass of the water used;
- provide a maximum plenum pressure of 1.38×10^5 PA (20 psi);
- deliver a maximum flow rate of .44 lps (7 gpm) to each plenum chamber (to produce the pressure given above).

For periodic blowing, the system must

- maintain a sinusoidal pressure variation in each plenum for frequencies up to 10 Hz;
- maintain a phase shift between plenum pressure variations of as much as 180°.

For transient blowing, the system must

- be capable of following a ramp (pressure variation) that reaches full amplitude in 1/40 sec.

The primary tasks involved in the design of the fluid-control system were creating a constant mass system, isolating the control of the water supplied to each plenum chamber, and determining a method or mechanism capable of accurately constructing the required pressure variations.

Creating a constant mass system and isolating the control of the fluid diverted to each plenum were simple to do in concept but difficult to implement. The conservation of mass required that the water to be blown through the model be drawn directly from the tunnel. Any excess water not supplied to the model (i.e., the test conditions demand less than the maximum flow rate) would have to be returned to the tunnel. The requirement that individual plenum pressures be adjustable could easily be fulfilled by the construction of separate water supplies for each jet. However, constructing the "closed circuit" for conservation of mass and the separate supply routes for independent fluid control proved difficult because the tunnel structure could not be modified.

The most critical design task was the determination of the means which could produce the sinusoidal and linear pressure variations accurately. Because controllability and quickness of response are necessary to such a method or mechanism, ordinary water-handling components were judged to be inadequate. Such components (i.e, check valves) were too slow or too unmanageable to meet the requirements listed above.

While the possibilty of designing a mechanism specifically for application to this system was considered, it was decided instead to adapt a readily available hydraulic component to control the water. This component, the servovalve, is capable of providing sufficiently quick response and of handling the required range of flow rates (0 to .44 lps). Operation of the valve is regulated by the amount of electric current applied to the valve; a spool inside the valve moves in proportion to the signal it receives to close or open ports which control the flow of fluid.

The servovalve provides an attractive solution to the design task described above for it permits the flow through the model to be varied according to any time function by the application of an appropriate signal. Furthermore, the valve flow follows the input signal very accurately if it is operated within a closed feedback loop; the flow through the valve is continually monitored to ensure it matches the desired flow.

However, adaptation of the servovalve to a system run with water to the extremes demanded of the fluid-control system requires that several important issues be addressed. First, flow rate is not the paramater that is controlled for the experiment as it is for the servovalves. The model plenum pressure must be modulated, and so the feedback system must be designed to measure and compare pressures. Second, the valve is designed to operate with hydraulic fluid. For use in water, the moving parts contained inside the servovalve must be protected from corrosion and excessive wear. A final consideration is the high pressure required by the valves for maximum responsiveness. A pressure of 6.9 MPa (1000 psi) should be supplied to the valves, but the model (supplied by the valves) can only withstand a pressure of .21 MPa (30 psi). Some type of protection against such extreme pressure, then, must be devised for the model.

A schematic of the fluid-control system's final design is shown in Figure 5. A constant displacement pump delivers 1.64 lps (26 gpm) at 6.9 MPa (1000 psi) to two servovalves, one to supply each plenum chamber. The regulator, located just after the accumulator used to dampen the pressure fluctuations developed by the pump, is set at 6.9 MPa; if the test conditions are such that less than 1.64 lps are allowed through the valves, pressure will build in the supply line and cause the regulator to respond to divert the excess water away from the valves. Should the regulator fail to operate, a relief valve set to blow at 8.3 MPa (1200 psi) is included in the system to prevent the pressure in the supply line from building to dangerous levels.

The accumulator situated behind the servovalves is used to dampen the pressure surges generated by the opening and closing of the valves. Contamination of airfoil load measurements from these same pressure fluctuations is prevented by utilizing flexible hose to connect the valves to the water injection pipes. Hard lines containing rupture discs are constructed in parallel to these soft lines. The discs are set to rupture at 2.07×10^5 Pa (30 psi) to provide protection for the model against all pressures greater than the design pressure.

The internal parts of the servovalves are protected from wear and corrosion by a microsealing process; the spool is impregnated with carbon to lubricate its movement through the sleeve. In addition, special seals were installed to replace those used for hydraulic fluid service. The water sent through the valve must remain extremely clean since a particle the size of $3\,\mu$m can destroy the precise valve operation. Two hydraulic filters, one $15\,\mu$m and the other $3\,\mu$m, are placed upstream of the servovalves to prevent their contamination.

As apparent from the schematic (Figure 5), the fluid-control system is indeed a constant mass system. Water, however, cannot be drawn directly from the tunnel for the pump requires a larger intake line than can be accommodated by the tunnel. Instead, a tank is used to hold water for the pump intake. The water blown off by the regulator and the overflow from the tunnel (water blown through the model) are diverted back to this tank.

The schematic in Figure 6 depicts the control loop of one of the servovalves. The desired pressure variation for each plenum is constructed by a signal generator and sent to the servovalve electronics in the form of a voltage. There, the voltage signal is converted to a current, which is then applied to the servovalve to initiate the corresponding flow rate. The flow characteristics of the model are such that the plenum pressure is directly proportional to the square of the flow rate through the plenum chamber. In a sense, then, the model converts the valve flow to plenum pressure. A pressure transducer, mounted in the model plenum, measures the pressure and feeds this voltage back to the valve electronics. By comparing this signal to the signal representing the desired pressure, an error signal is produced to correct the valve flow, which in turn, corrects the plenum pressure.

PROJECT STATUS

The circulation control airfoil entered the shop for fabrication in October 1983 and was completed in February 1984. Since that time, the model has been run in the tunnel, using the flow-visualization supports, so that its flow characteristics could be verified. It has subsequently been returned to the shop for installation of the pressure tranducers.

Few difficulties arose during the fabrication of the model. One problem that did occur, though, was that the two model halves would shift relative to one another during the contouring of the model ends. The dowel pins placed along the centerline of the model that were to hold the halves during machining did not control this problem; the slippage occured at the jet slot support interfaces and was caused by play in the screw threads. To correct this, cylindrical inserts were pressed into the support posts on one model half so that upon assembly, they fit into corresponding counterbores cut around the threads of the other half. The play in the screw threads was thus contained.

The flow-visualization support system was submitted for fabrication shortly after the model. While no difficulties were encountered during the system's manufacture, a problem did arise during its implementation when the model's angle-of-attack was to be changed. The seal developed by the gasket used to prevent water from leaking around the circular plug could not be broken easily. As a consequence, it was difficult to rotate the plug to set a new angle-of-attack. The problem was remedied in this design by fixing two pins in the plug to assist the operator in breaking the seal. All subsequent designs in which plugs are required utilize O-rings instead gaskets to avoid the problem entirely.

Fabrication of the load-measurement supports began in July 1984. The pieces have been machined and assembled (welded). The estimated installation date is May 1985.

The fluid-control system has been constructed and is being qualified for operation. Problems with the performance of the regulator have been discovered; its response to an increase in pressure in the supply line is too slow and too harsh. One solution that is to be attempted is to pump less water (.95 lps instead of 1.64 lps) through the regulator by slowing the speed of the pump. The regulator, not having to work as hard, should respond less harshly. Several more weeks of making adjustments to the fluid-control system are foreseen.

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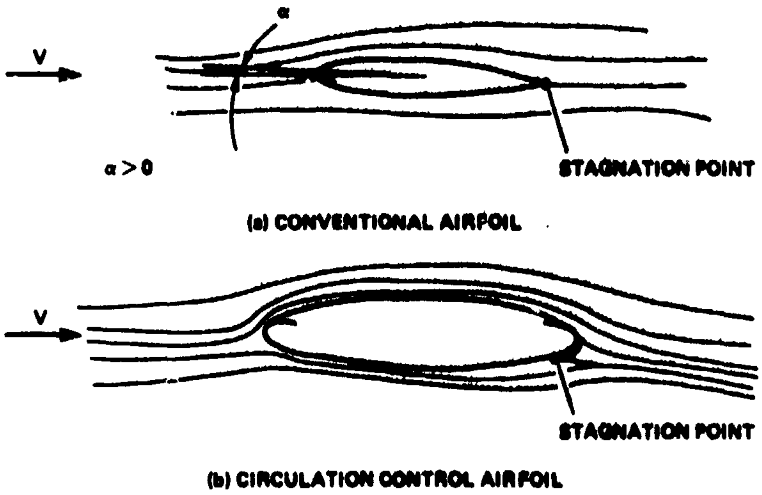

Figure 1. Lift Generation

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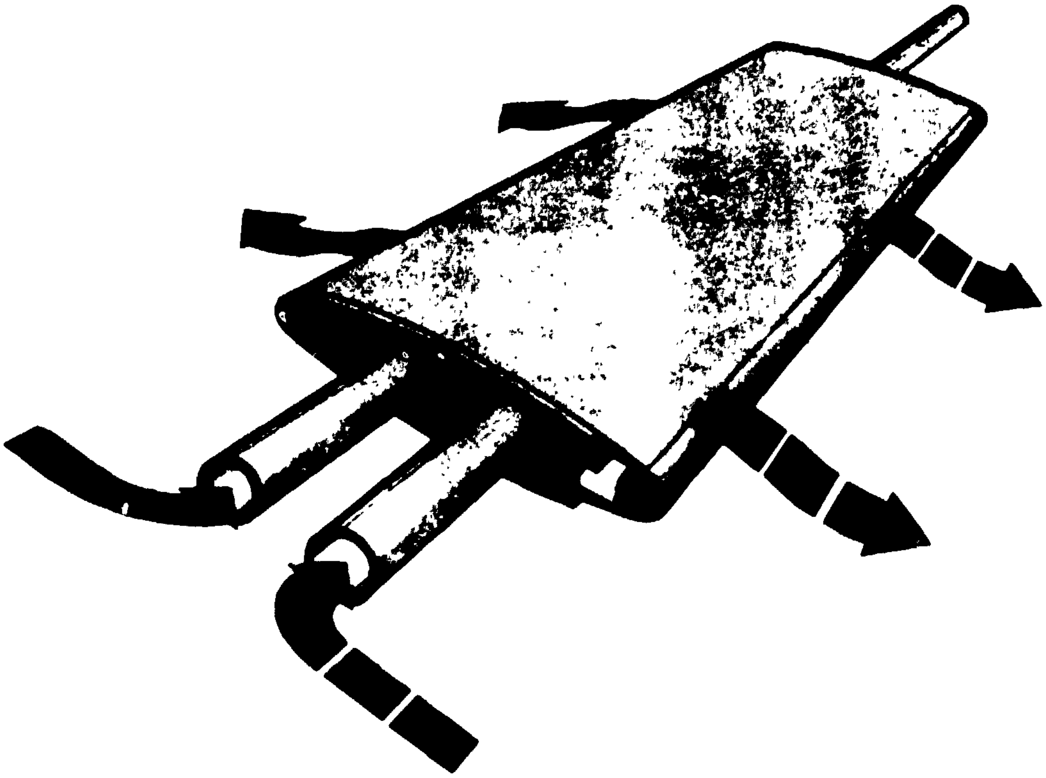

Figure 2. Circulation Control Airfoil

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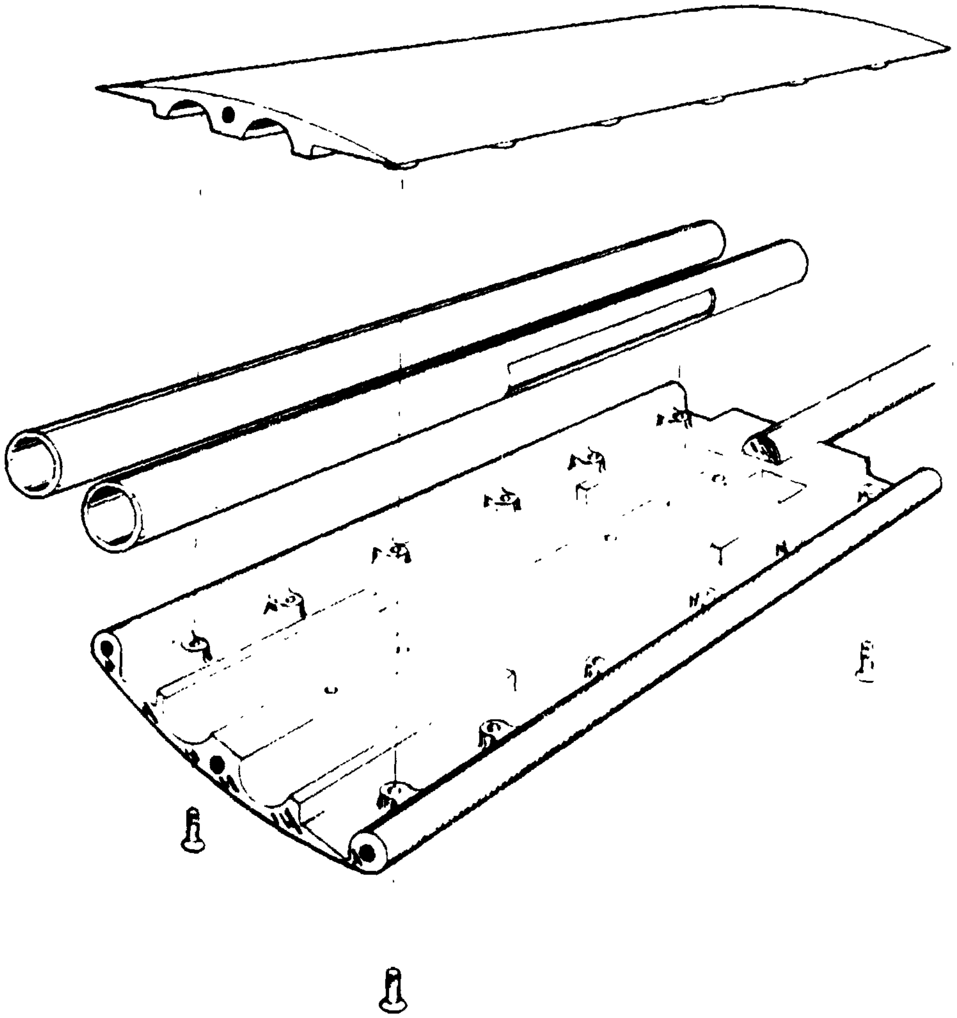


Figure 3. Airfoil Assembly

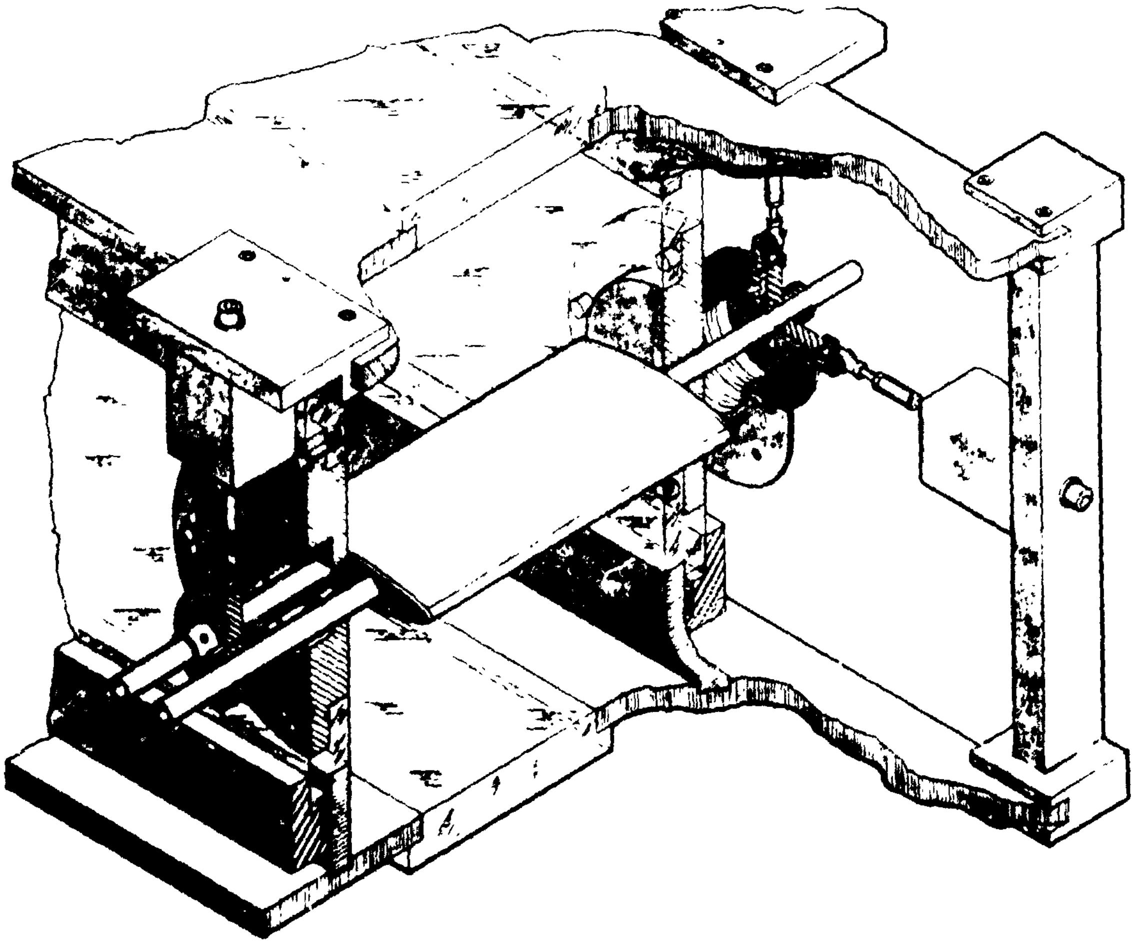


Figure 4. Load Measurement Support System
(Test Configuration)

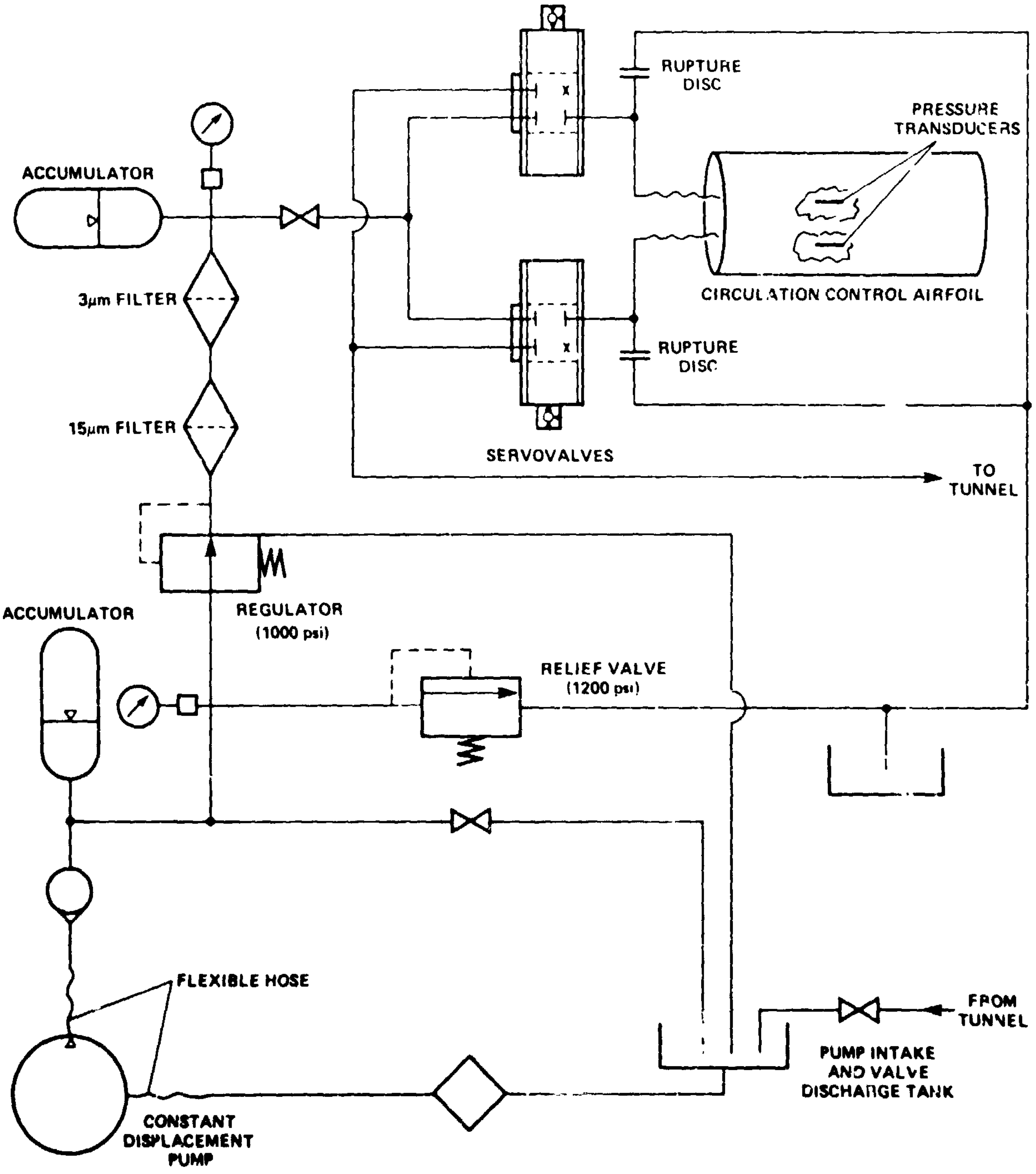
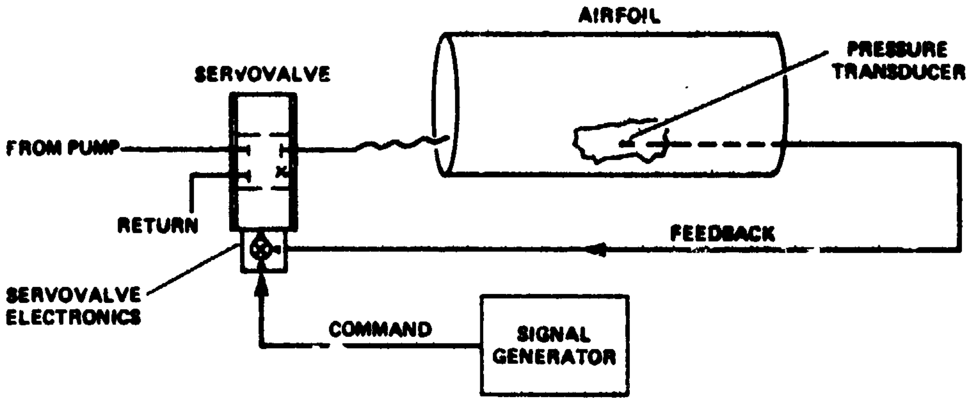


Figure 5. Schematic Fluid-Control System



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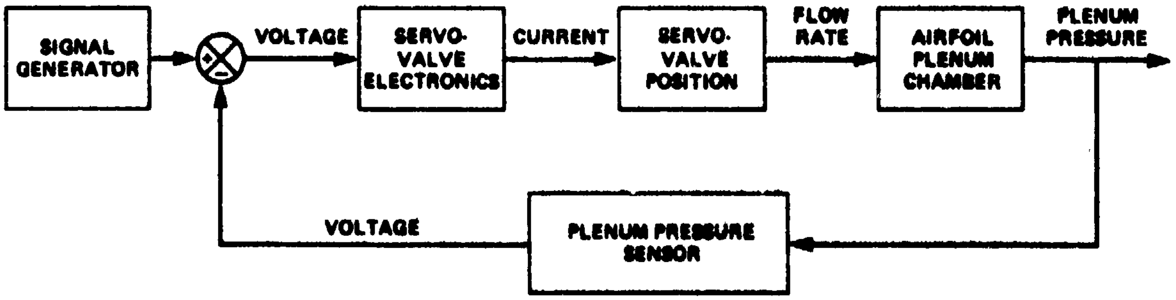

(b) SCHEMATICALLY

Figure 6. Servovalve Feedback Control