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WIND TUNNEL TESTS OF A SYMMETRICAL AIRFOIL WITH SCOOP-FED SLOTS

By Charles A. Belsterling

Prepared under Contract No. NAS12451 by
The Franklin Institute Research Laboratories
Philadelphia, Pennsylvania 19103

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

The design and wind tunnel test of a model vertical tail fin is described in this report. The model is designed to provide the aerodynamic forces necessary for lateral stabilization without moving parts or a separate source of power. It employs scoop-fed slots on both surfaces of the symmetrical airfoil. They are to be controlled differentially by means of a fluidic amplifier to implement an automatic full-time lateral stabilization system.

The results of tests show that the control of forces is stable and quite linear in various modes of operation. Significant forces were produced that can be increased as necessary by increasing slot size and scoop size. Slots can be located ahead of the conventional rudder and the scoop can be at the base of the vertical tail fin to avoid the need for major changes in conventional aircraft design.

The first phase of the work demonstrated the feasibility of no-moving-parts aircraft control. The second phase established that a practical fluidic amplifier can be built to control slot flows from fluidic signals. Recommendations are made to optimize the design of the fluidic amplifier and to characterize its dynamic response in support of further analytical studies.

INTRODUCTION

The need for a simple, low-cost, reliable lateral stabilization system (wings leveler) for general aviation aircraft has been recognized in many quarters. An acceptable system will be a valuable aid in preventing accidents and adding to the convenience of flying. The work reported here is the first phase of a program to develop a lateral stabilization system without moving parts or a separate source of power. It has the potential for satisfying all of the requirements for acceptance in the general aviation market.

A recent survey and computer study done at NASA, Langley Research Center* led to the conclusion that lateral stabilization can be achieved with a control system using the vertical tail assembly as the force-producing surface. In conventional aircraft, the rudder is the moving control surface that provides the variable side force. However, previous work by the author of this report had proved that substantial variable forces can be produced on aerodynamic surfaces without moving parts, by using span-wise slots supplied with ram air. These circumstances, coupled with other advances in the field of fluidic angular rate sensors and stable high-gain amplifiers, lead to the feasibility of a complete lateral stabilization system without moving parts or a separate source of power.

The first phase of the development covers the design and fabrication of a model of a vertical tail section with leading edge scoops feeding two rows of slots and its test in the 1.07 meter (3.5 ft) by 1.52 meter (5 ft.) wind tunnel at the Forrestal Center of Princeton University.

In the second phase the model is modified for fluidic amplifier control and more efficient scoop design. This model is retested in the wind tunnel to evaluate the amplifier and scoop, and to investigate the coupling between slots, rudder and airfoil angle of attack.

SYMBOLS

The dimensional design and test results were originally recorded in the U.S. Customary System of Units. They are presented in the International System of Units (SI) with the equivalent U.S. values in parentheses.

*"Simulation Studies of Several Lateral Stability Augmentation Concepts for Light Aircraft", H. Douglas Garner, Langley Working Paper No. —999.

WIND TUNNEL TESTS OF A SYMMETRICAL AIRFOIL WITH SCOOP-FED SLOTS

PART I-WITH LEADING EDGE SCOOP AND MANUAL CONTROL

MODEL DESIGN

The basic objective of the first phase of this program was to establish:

(1) The most practical chordwise slot location

(2) The magnitude of the forces that can be generated

(3) The required scoop frontal area

(4) The effect on drag and other aerodynamic characteristics.

To minimize cost and to avoid the need for a blower external to the wind tunnel it was decided to acquire a salvaged full-scale vertical tail section and modify it for the study. This allowed for placement of scoops in the leading edge as they were intended to be in the flight vehicle and provided a minimum of restriction to air flow through the airfoil. The vertical tail section was taken from a Cessna 177 and the rudder was replaced with a fabricated wood section as illustrated in Figure 1. A cross-section is shown in Figure 2. Note that it is a symmetrical NACA0008 airfoil. Three approximately 2.1cm (0.83 in) by 21cm (8.3 in) scoops were cut in the leading edge. A manually-controlled butterfly valve was placed just downstream of the scoops. Slots were located along approximately 55% and 75% chord lines (measured from the leading edge) and fitted with vanes to direct the flow approximately 45° from the chord line into the airstream. The end ribs were sealed against leakage and pressure probes were located as follows:

(1) static taps at each 10% chord point at mid-span top and bottom

(2) static taps inside the sealed airfoil downstream of the butterfly valve at top and bottom

(3) total probe facing into the airstream entering the mid-span scoop.

The model is shown in Figures 3 and 4 as built and undergoing

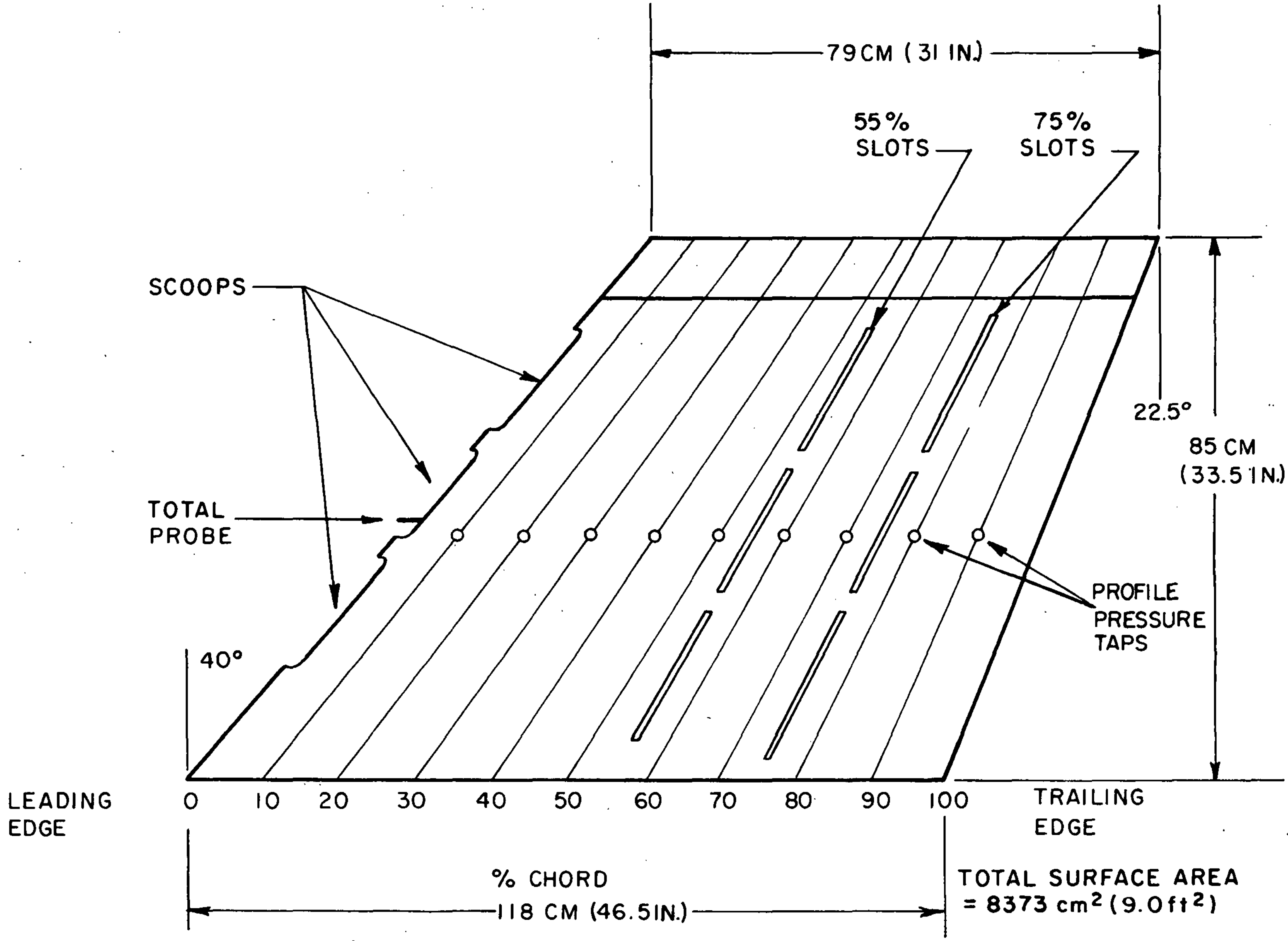

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Figure 1. Planview Sketch of Wind Tunnel Model

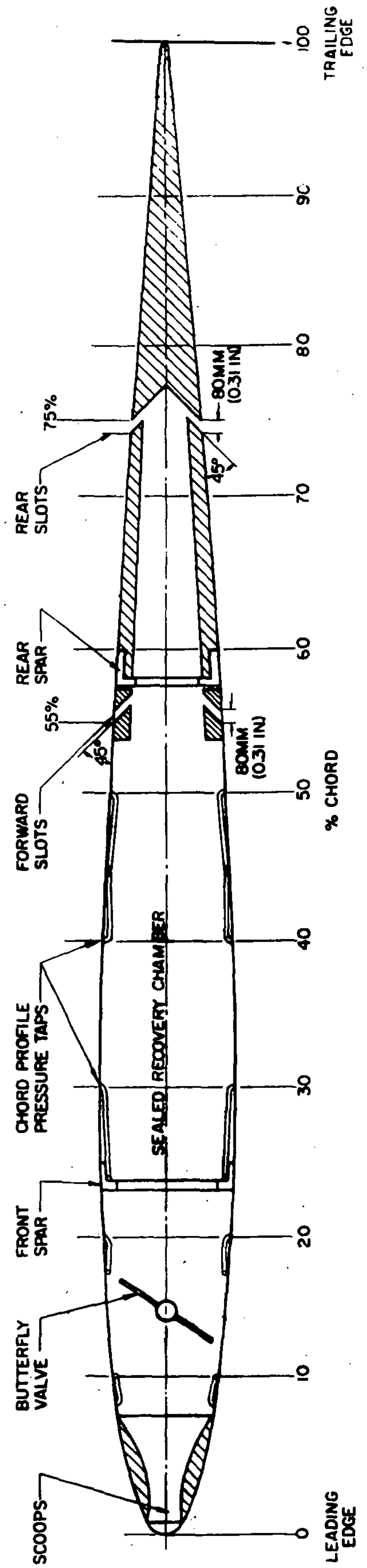

Figure 2. Cross-Section of Model Airfoil

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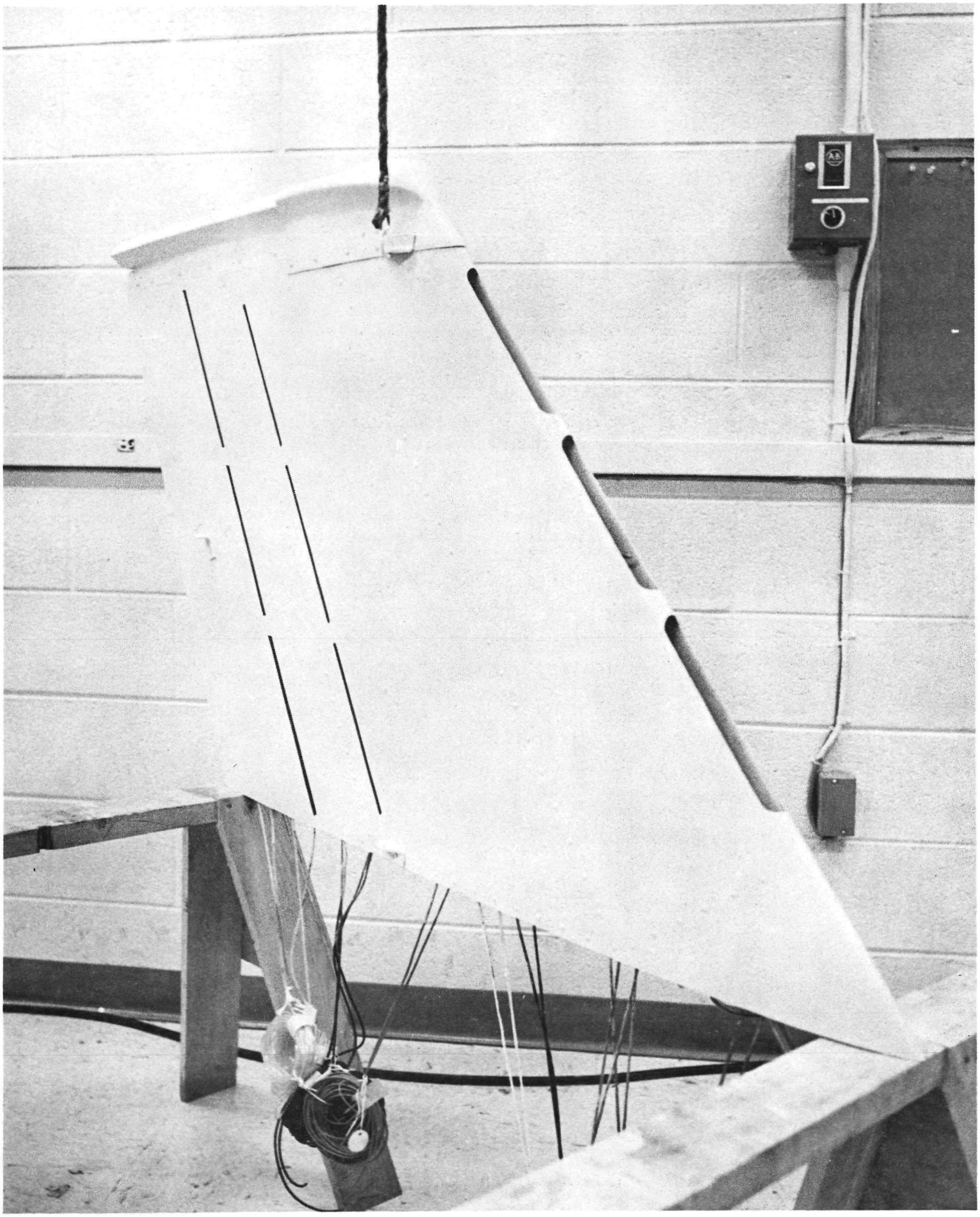
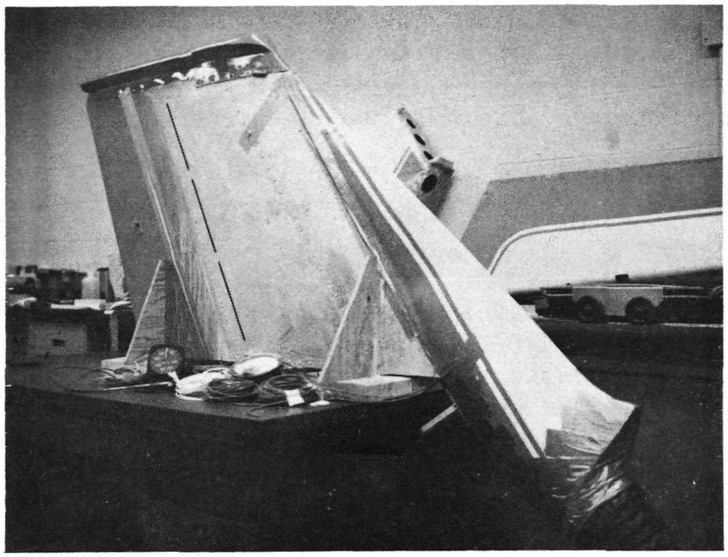


Figure 3. Wind Tunnel Model As Built



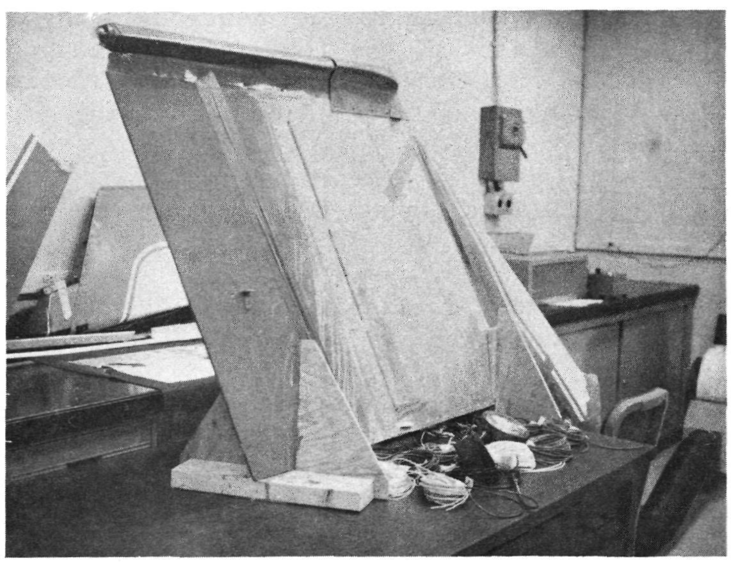


Figure 4. Model Connected to Blower for Lab Tests

laboratory tests with a centrifugal blower ducted to the leading edge scoops. When mounted in the wind tunnel it was fitted with a 61 cm (2 ft) by 152 cm (5 ft) end plate to simulate its aerodynamic configuration as mounted to the aircraft fuselage.

WIND TUNNEL DESCRIPTION

The vertical tail model described above was tested in the 1.07 m (3.5 ft) by 1.52 m (5 ft) low-speed tunnel at the Forrestal Research Center at Princeton University. An overall view of the facility is shown in Figure 5. The model horizontally mounted inside the tunnel is shown in Figure 6. Tests were run with various combinations of slots by taping over the unwanted sections.

TEST RESULTS

Early in the tests it was recognized that the scoops were not performing as expected. With the airfoil completely sealed except for the scoops in the leading edge (no flow) less than 55% of the ram pressure was being recovered inside.

A further investigation led to the conclusion that this is due to the *spanwise* angle of attack of the leading edge scoops. By fabricating a zero-angle-of-attack duct and testing it in the inboard scoop as shown in Figure 7, the hypothesis was proved by recovering more than 95% of ram pressure.

The results of the wind tunnel tests are arranged in the following figures to illustrate:

(1) The effectiveness of the slots as a function of pressure recovered inside the airfoil.

(2) The effect of slot flow on the pressure profiles across the airfoil chord.

(3) The effect of flow through the scoops on the % recovery inside the airfoil.

(4) The effectiveness of the slots when used in a differential mode as they would be when controlled by a fluidic amplifier with no center dump.

(5) The effect of the scoop-fed slot configuration on drag.

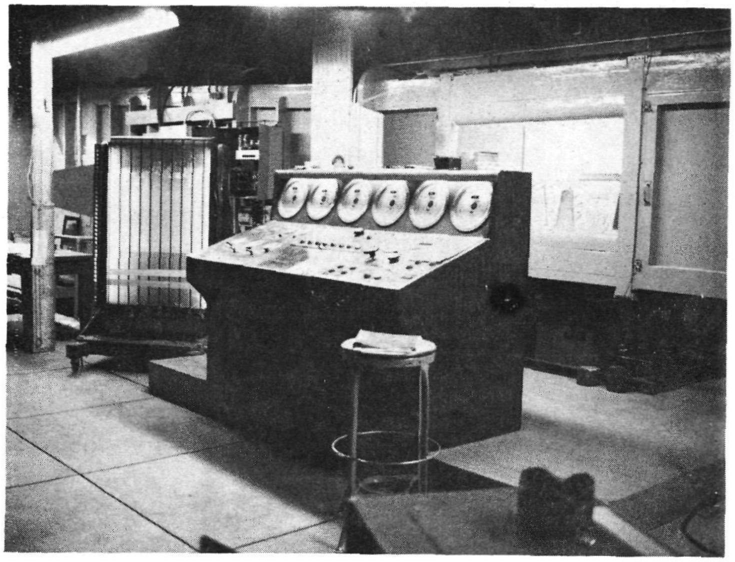
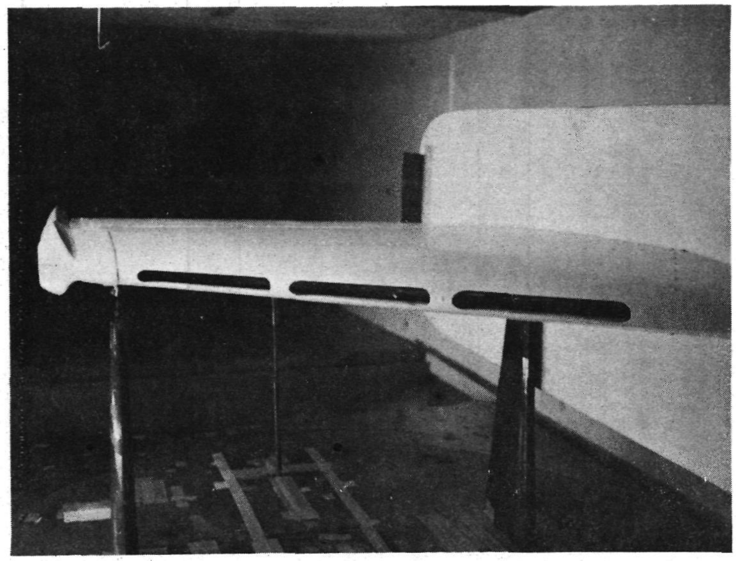


Figure 5. Overall View of Wind Tunnel Facility



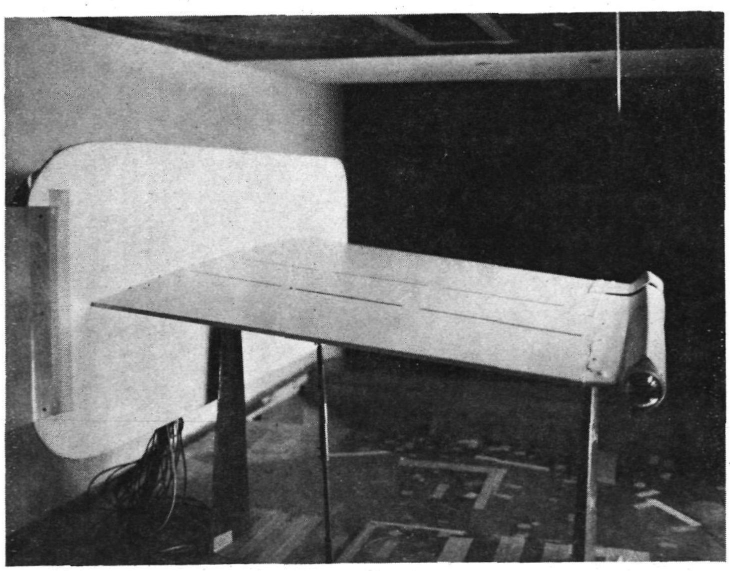


Figure 6. Model Mounted in Tunnel with End Plate

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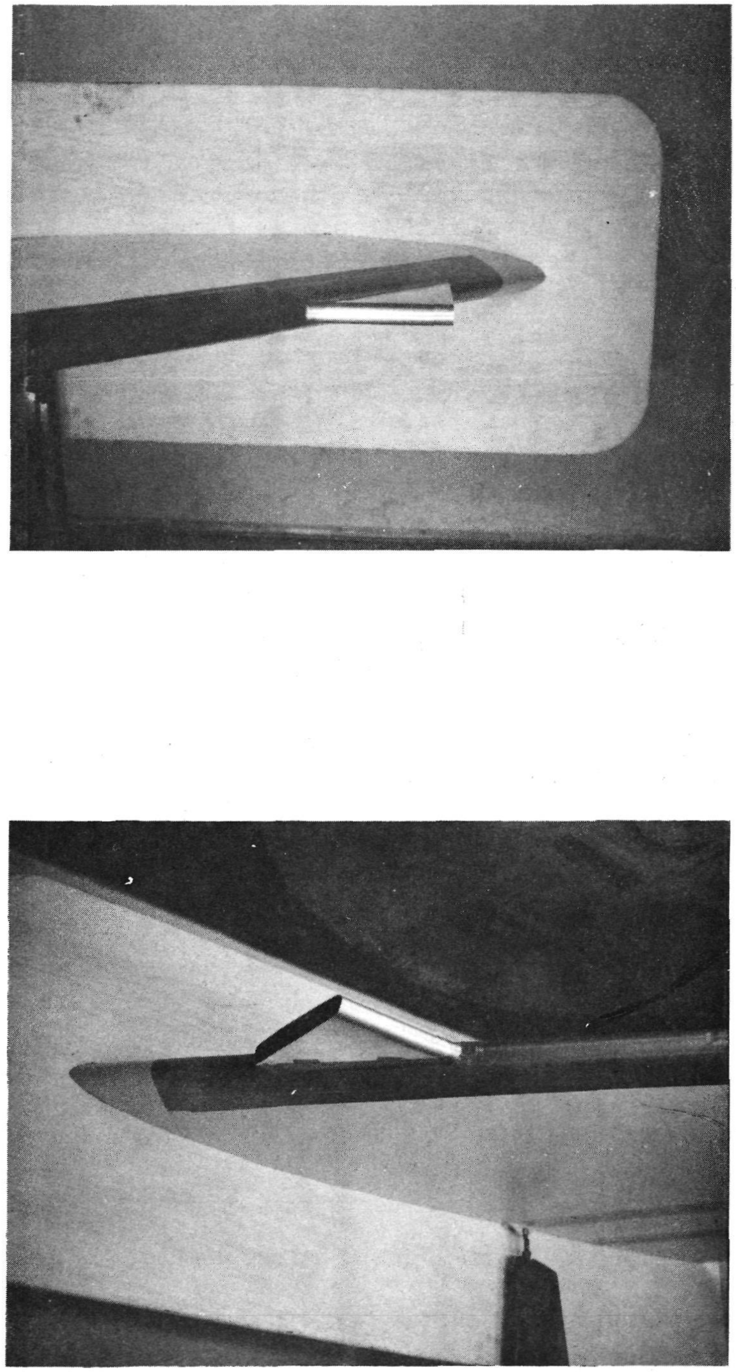


Figure 7. Model with Zero Angle of Attack Scoop

Effectiveness of Slots as a Function of Recovered Pressure

Figure 8 shows the effectiveness of the bottom forward slot (55% chord) at a free stream Q of 14.7 cm h_2O (equivalent to 110 mph). For positive angles of attack the lift of the symmetrical airfoil is very nearly a linear function of internal static pressure. For negative angles of attack the effect is more sensitive partly because the slot exits into a region of more negative pressure.

Figure 9 is a linearized comparison of the effectiveness of the 55% chord and 75% chord slots and both sets operating together. The results show that the forward sets of slots are about 90% as effective as the rear sets. They also show that front and rear slots working together produce almost the sum of the effect of the two slots alone. This is to be expected because the slot area has been doubled so there is nearly twice the momentum flow.

Pressure Profiles Over the Airfoil

Figure 10 shows the chordwise pressure profiles with the top forward slots open and the top rear slots open respectively, as compared with the unspoiled pressure profile with no slots open. It is important to note that the decrease in lifting force is due to the depression of the negative pressure profile ahead of the blowing slot in spite of the fact that there is a high peak just behind the slot where the deflected air flow again attaches to the airfoil.

Figure 11 shows the top and bottom negative pressure profiles with both forward and rear slots open. Now the depression of the profile ahead of the forward slot is doubled and there is a clear indication of reattachment of the flow behind each of the slots. It should be noted that although the unspoiled profiles are not the same top and bottom, probably because of the interference of the mounting pylons on the airflow over the bottom, the effect of slot flows is nearly identical.

Leading Edge Scoop Characteristics

Figure 12 shows the effect of flow through the scoops on the pressure recovered inside the airfoil. This plot indicates the impedance of the scoops. Since the results show that the maximum loss is approximately 30%, the scoop frontal area is well matched to the total area of the slots on one surface.

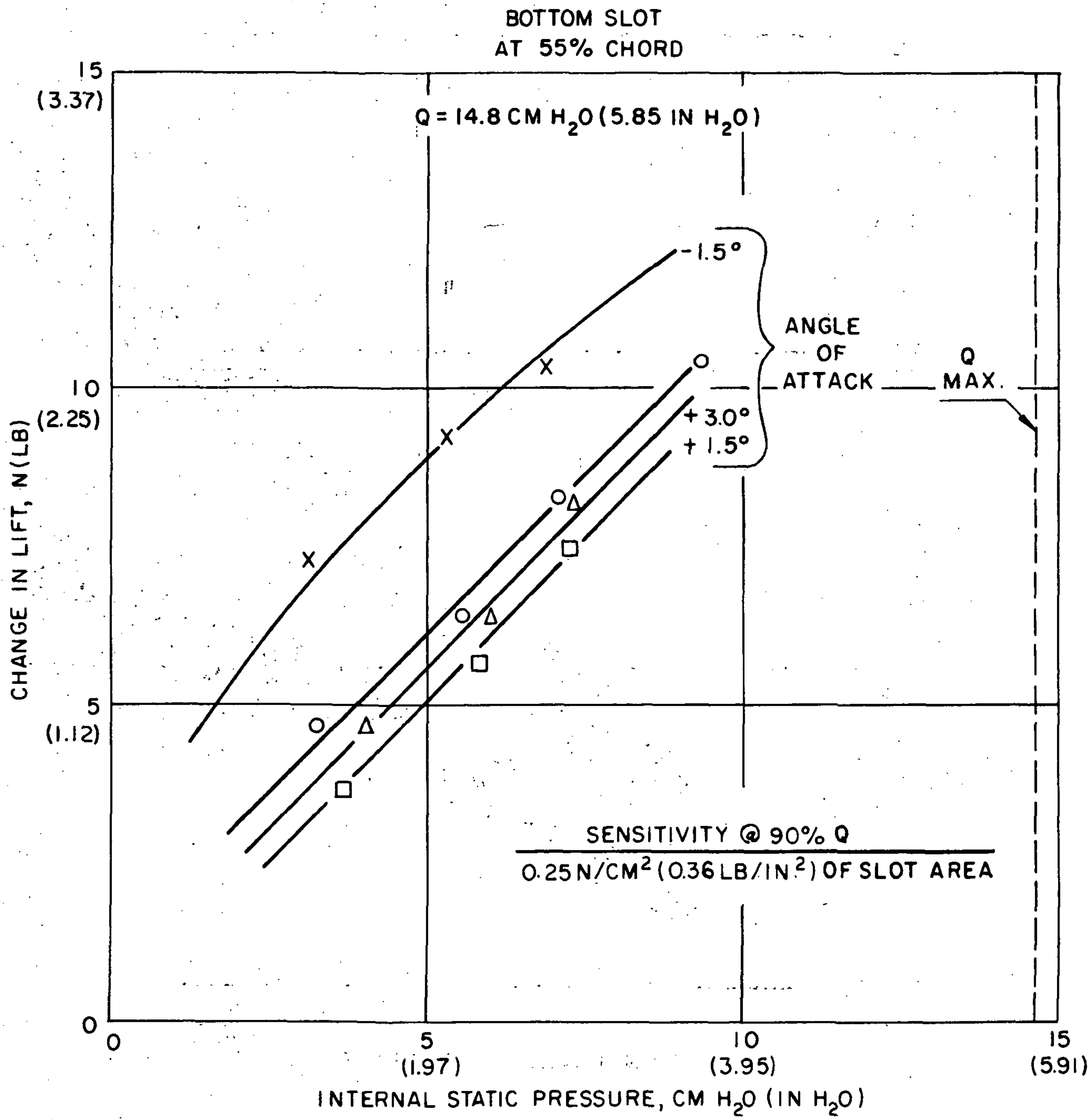


Figure 8. Effectiveness of Slot vs. Recovered Pressure

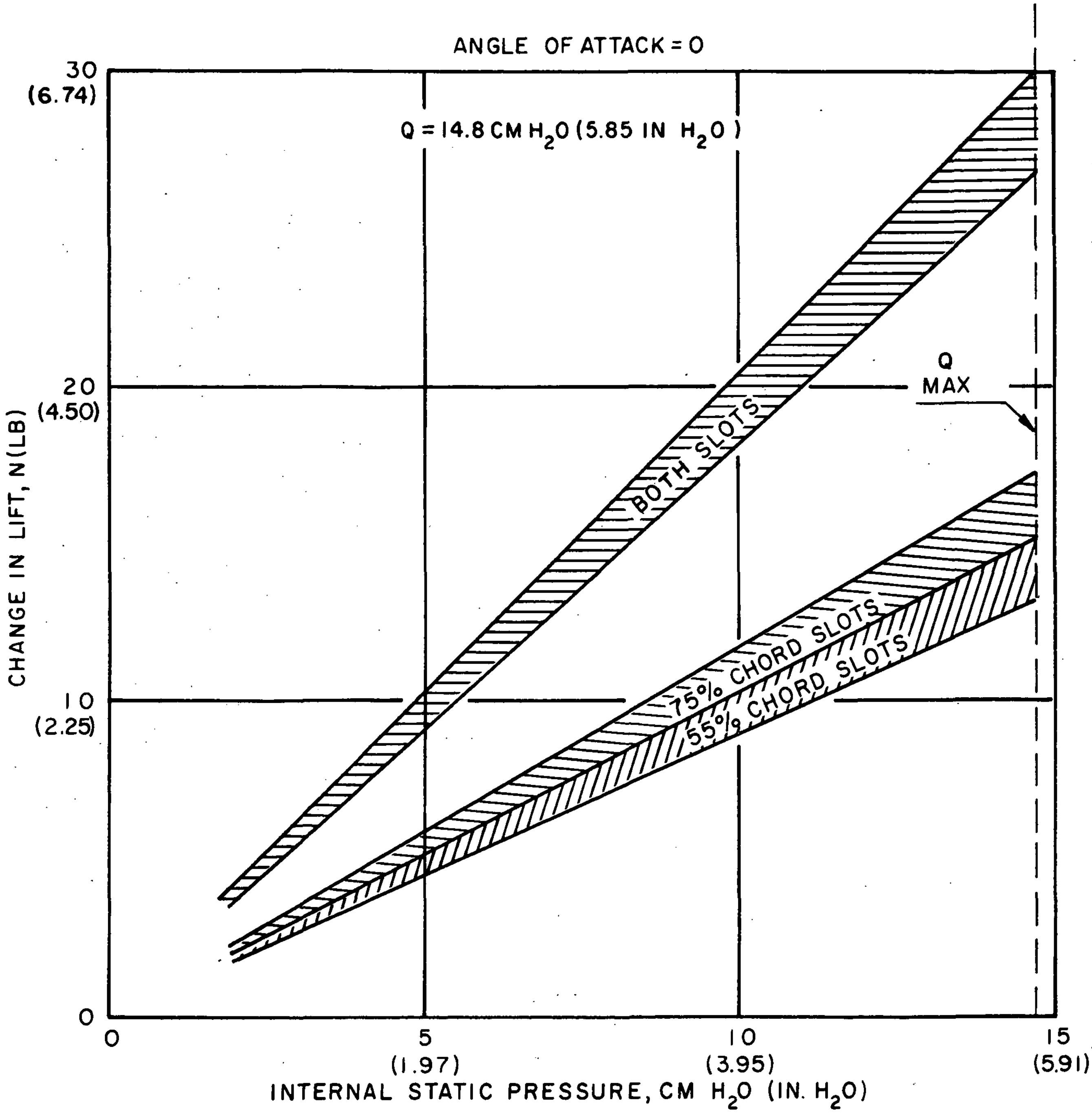


Figure 9. Comparative Effectiveness of all Slots

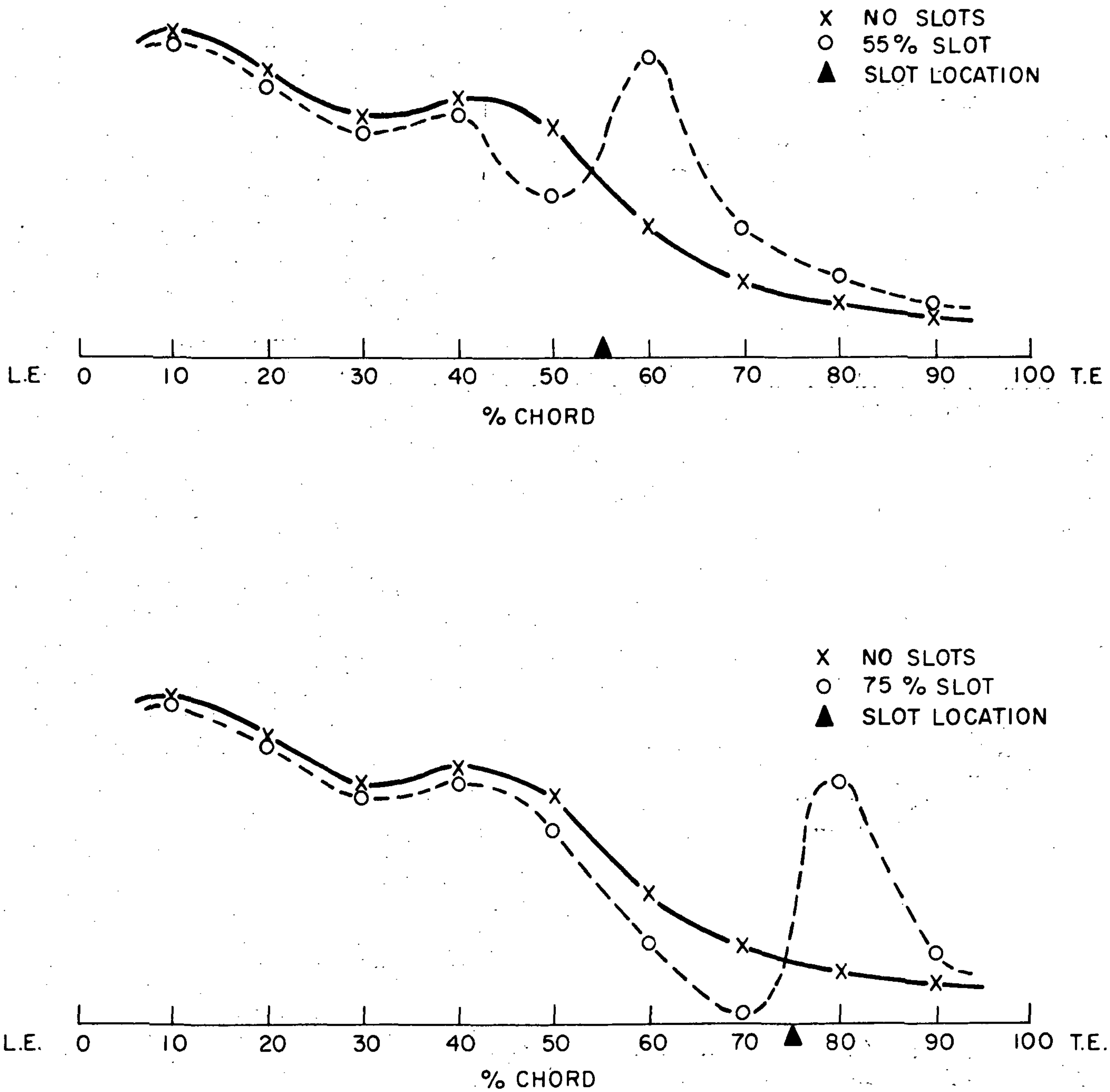
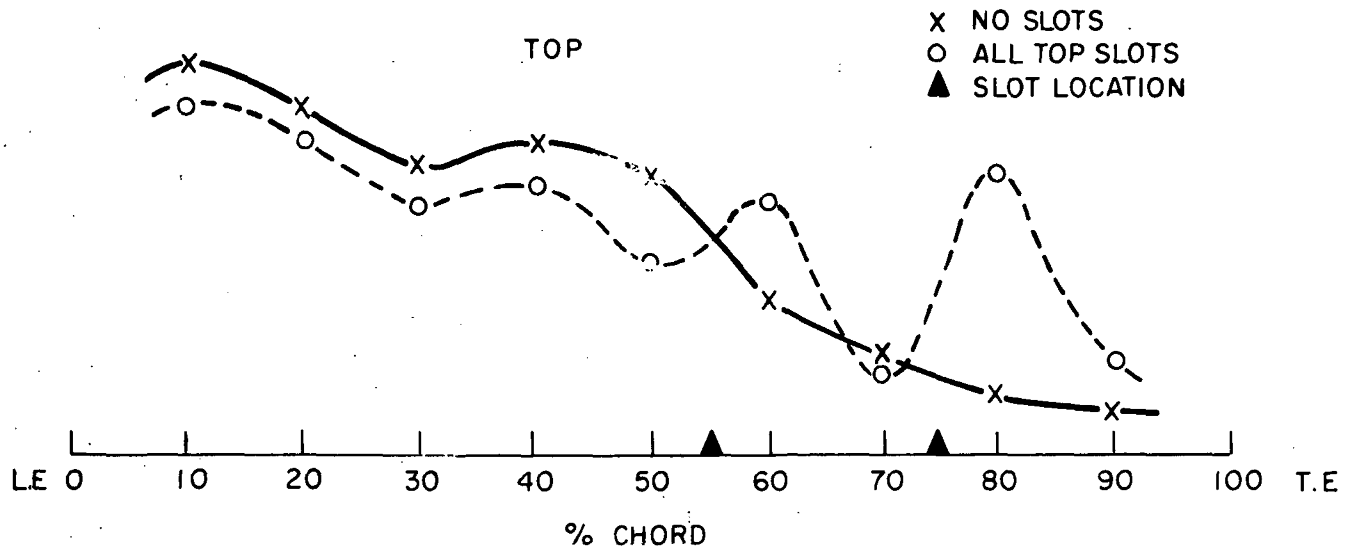


Figure 10. Chordwise Pressure Profiles - Top Slots



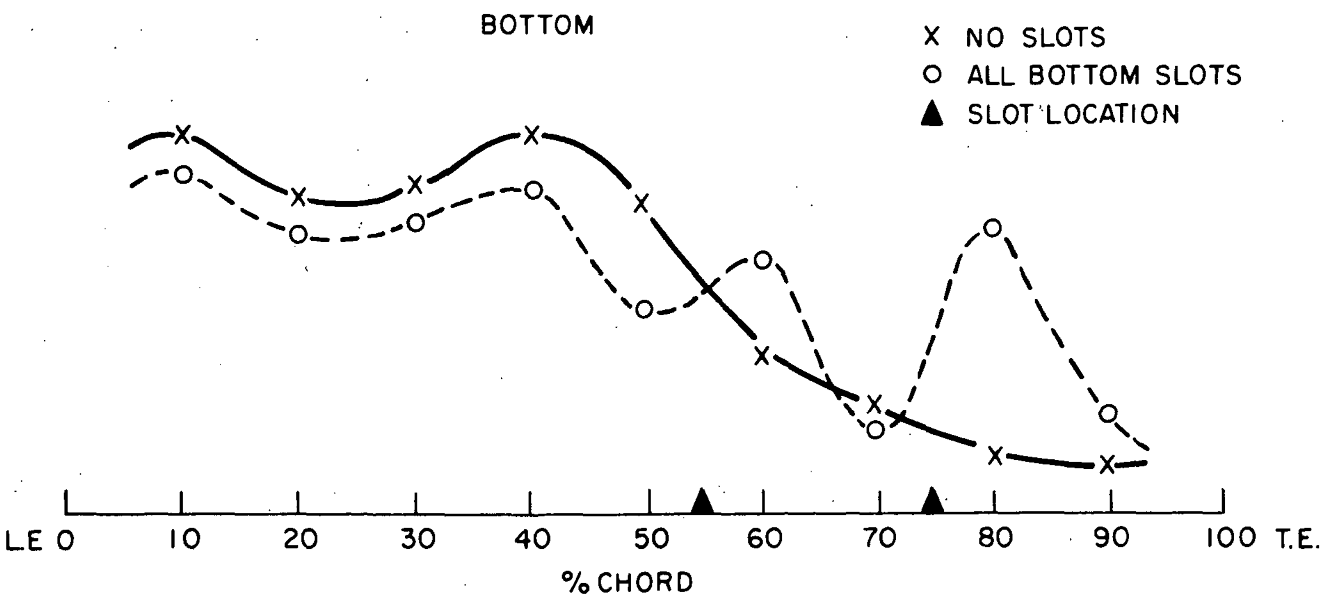


Figure 11. Chordwise Pressure Profiles - Both Slots

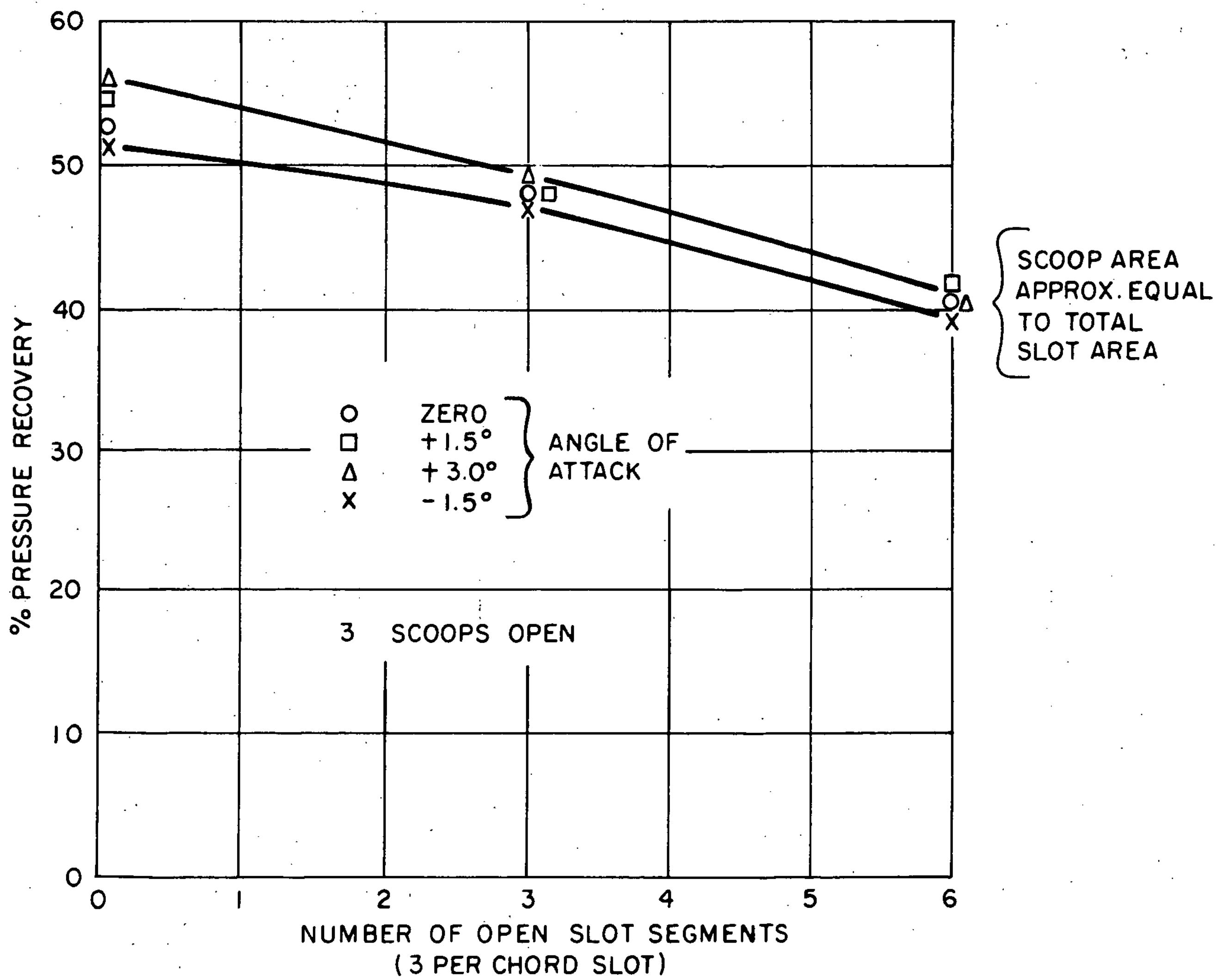


Figure 12. Effect of Slot Flow on Pressure Recovery

Differential Control of Lift

Figure 13 shows the effect of maintaining through-flow nearly constant and diverting total flow from all out the bottom to all out the top. This was done by taping over unwanted slots, keeping a constant total slot area open. This simulates the conditions that will be present when the slot flows are controlled by a fluidic amplifier with no center dump. The results show exceptional linearity and stability in the control of the net force on the airfoil. Various patterns of open sections of slots were investigated with negligible variation in effect on lift and drag.

Pitch Moment Due to Differential Control

Figure 14 is the pitch moment characteristic for the conditions defined in Figure 13.

Drag Characteristics

Finally, Figure 15 shows the drag characteristics of various configurations of the airfoil compared with the basic airfoil with all scoops and slots closed. Note that the scoops alone result in a significant increase, possibly because of their relatively unsophisticated design and the spanwise angle of attack. Single slot blowing adds only a negligible amount of drag.

DISCUSSION AND CONCLUSIONS

With reference to the foregoing graphical results each of the important points listed in the previous section can be addressed in turn.

(1) The effectiveness of the slots has been shown to be nearly a linear function of the pressure recovered inside the airfoil. It has also been shown that the effect is proportional to the slot area and that location of the slot at the 55% chord line is a practical choice. Therefore it is possible to generate the aerodynamic forces necessary to stabilize an aircraft by proper sizing of the slots without mechanical interference with the conventional rudder.

(2) It has been shown that the major effect of slot flows on the chordwise pressure distribution is to depress the negative pressures ahead of the slot. Behind the slot there is a narrow peak of pressure that indicates reattachment of the

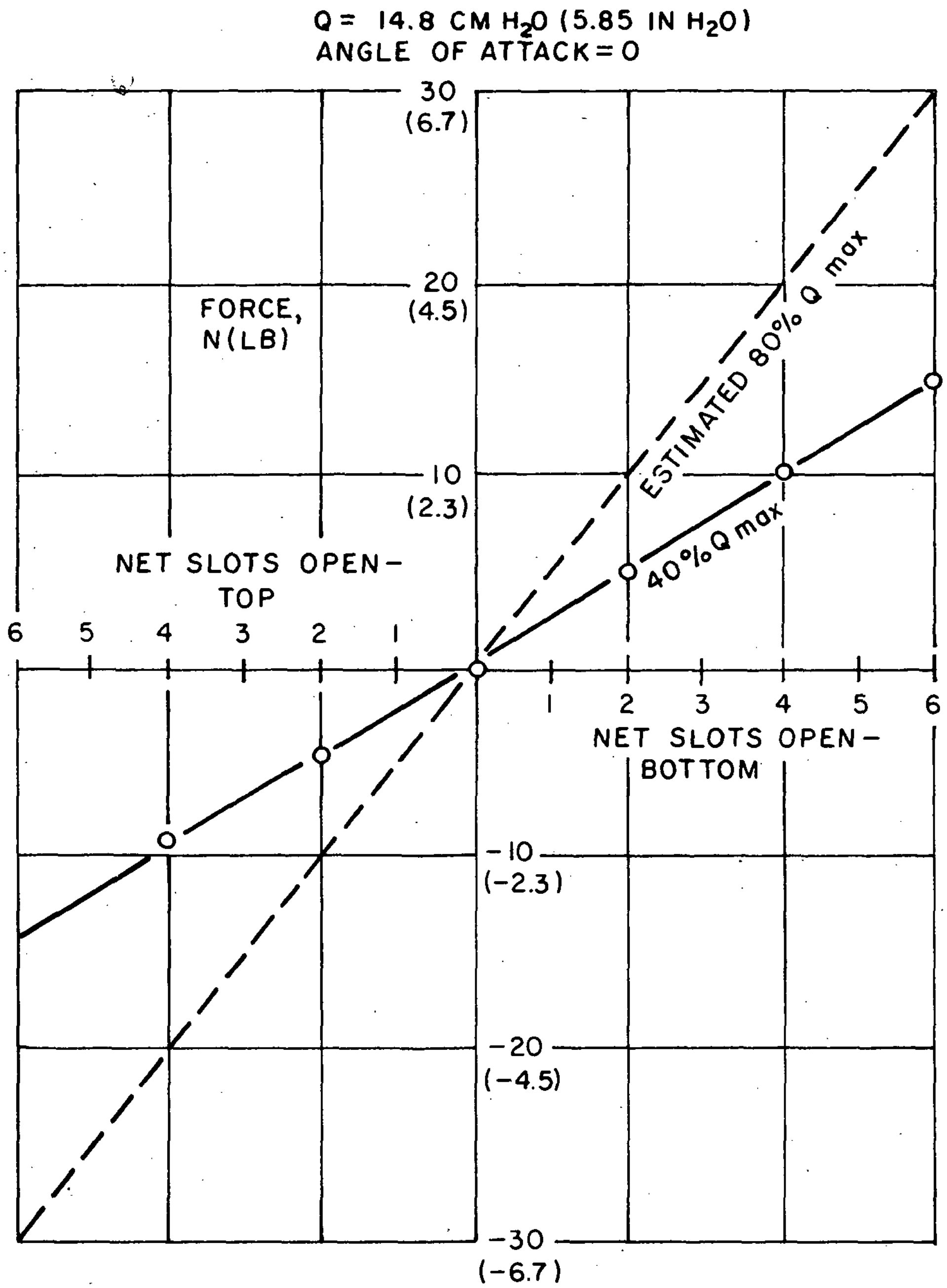


Figure 13. Differential Control with Constant Thruflow

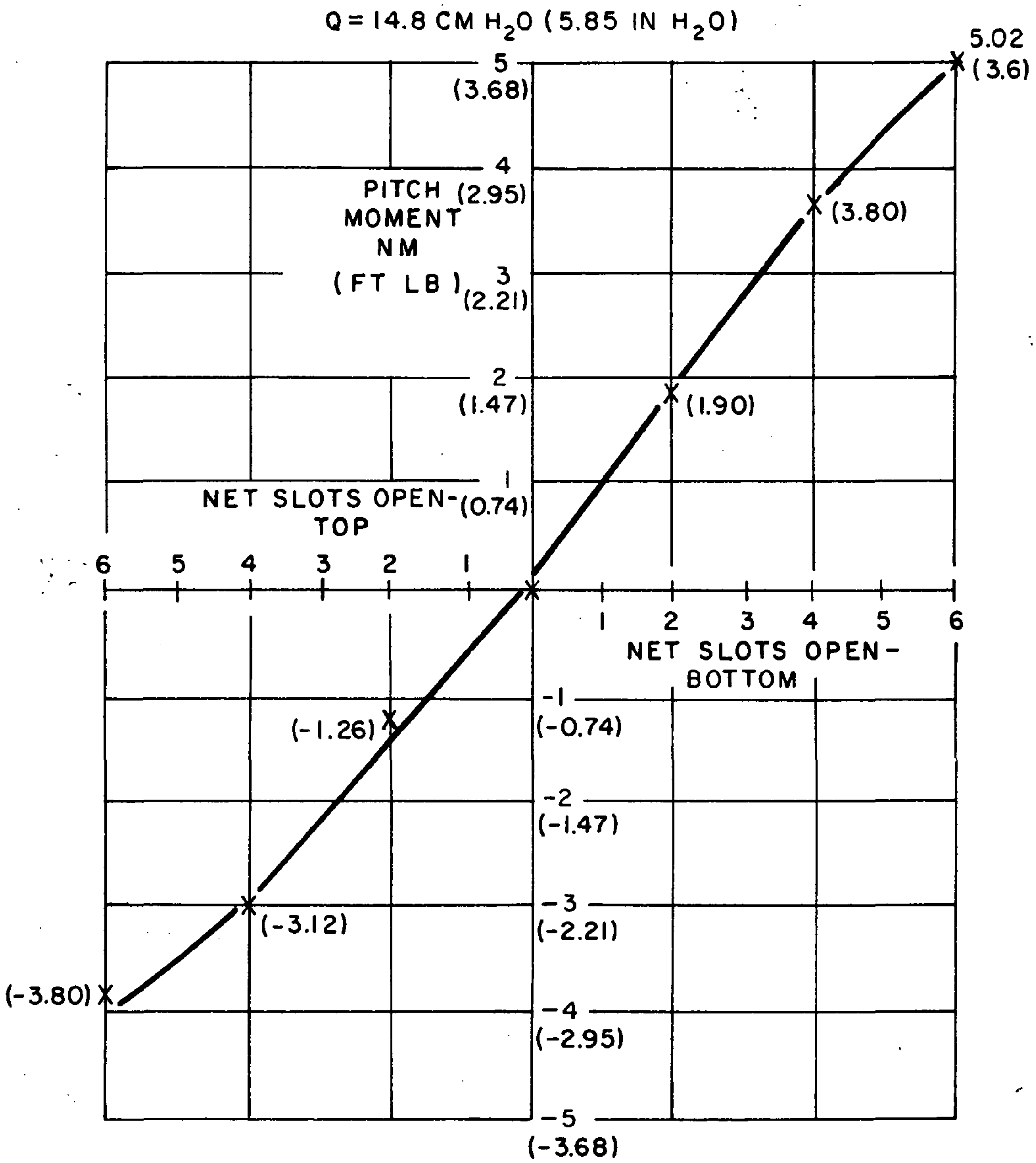


Figure 14. Pitch Moment with Differential Control

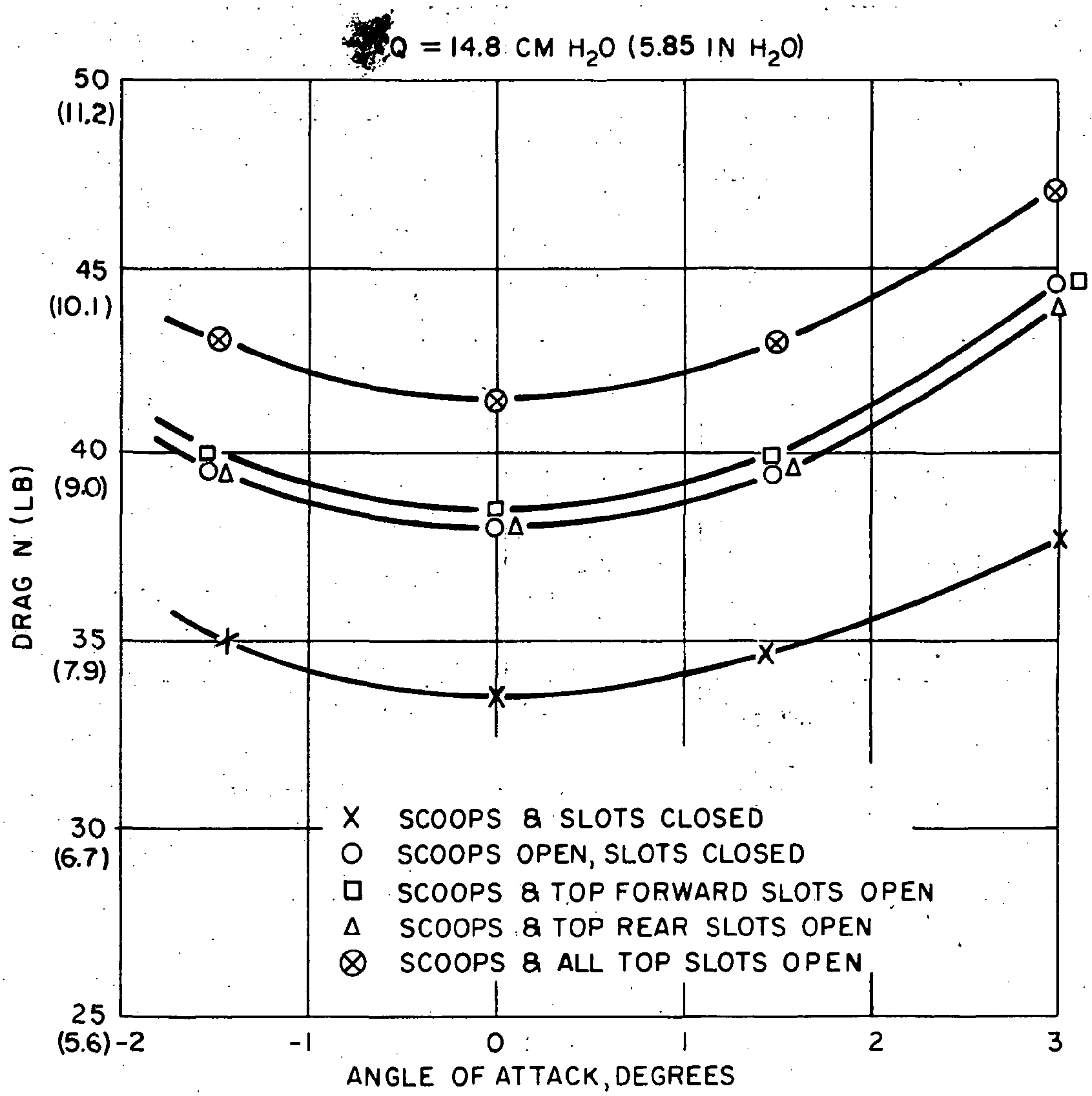


Figure 15. Drag Characteristics of Model Airfoil

normal flow. Slots at 55% chord and 75% chord work well together with predictable results. Therefore this form of lift control is a stable, repeatable phenomenon that will not interfere severely with normal operation of the aircraft nor will it lead to unstable conditions such as sudden separation.

(3) The tests measuring the pressure recovery for increasing slot flows indicate that the scoop frontal area of the model is well matched to the total slot area on one surface. When the necessary control forces for the lateral stabilization system have been defined, the slot area and the scoop area can be calculated directly from the model area ratio.

(4) Figure 13 illustrates the effectiveness of scoop-fed slots as if controlled by a simple form of fluidic amplifier. The results show that there is no negative effect of interference and that control will be quite linear with the deflection of the power stream. Details of the configuration of the fluidic amplifier should be defined, the model modified for fluidic operation and the assembly tested again in the wind tunnel. No major obstacles to success are apparent.

(5) The effect of the scoop-fed slot configuration on drag indicated a maximum increase of approximately 20%. A significant portion of this may be the result of less-than-optimum design of the scoops in the present wind tunnel model. Because of the poor pressure recovery due to the spanwise angle of attack (40°) it is recommended that the final design utilize a single zero angle of attack scoop at the base of the vertical tail. By careful attention to efficient design it is anticipated that the effect on drag can be reduced.

WIND TUNNEL TESTS OF A SYMMETRICAL AIRFOIL WITH SCOOP-FED SLOTS

PART II – WITH ROOT SCOOP AND FLUIDIC AMPLIFIER CONTROL

MODEL DESIGN

The basic objectives of the second phase of this program were to establish:

(1) the feasibility of a fluidic amplifier for slot flow control.

(2) the combination of the effect of slot control and rudder control.

(3) the tradeoff between scoop frontal area and control effectiveness.

(4) the effect of slot control at high angles of attack.

(5) the effect of slot control on rudder hinge moments.

(6) the configuration of a practical fluidic amplifier for control of slot flow.

The Phase I wind tunnel model was modified for the Phase II studies by:

(1) substituting a balanced, hinged rudder for the rigid trailing edge containing the slots at 75% chord.

(2) doubling the width of the slots at 55% chord.

(3) installing a fluidic amplifier inside the airfoil to control the flow out the slots.

(4) substituting a rectangular scoop at the root of the airfoil for the leading edge scoops. The planform dimensions of the scoop were made the same as the Phase I end-plate.

(5) installing opposed air cylinders connected to the rudder trailing edge calibrated for positioning the rudder and for measuring hinge moments.

(6) adding total probes for measuring flow out of the slots in the inboard section of the airfoil and static probes in the control chambers of the fluidic amplifier controlling the flow.

The complete Phase II wind tunnel model is shown in Figure 16. A typical cross section is shown in Figure 17 including the fluidic amplifier configuration. Ram air that enters through the scoop is distributed spanwise into the plenum upstream of the fluidic amplifier.

The Fluidic Amplifier

The fluidic amplifier is of unconventional design; an unvented, proportional, jet-interaction type with an exceptionally large aspect ratio (40:1). (Figure 18a) The power nozzle is 0.64 cm over the entire span. The amplifier is made in 3 box sections with end plates to maintain positive control of relative position of the parts. A typical section is shown in Figure 19. Note that both end plates include a manually-controlled slide-valve (see Figure 18b) that proportions flow from the pressurized plenum into the control chambers of the fluidic amplifier. The extensions of these slide valves protrude through the skin of the airfoil (see Figure 16) so manual control can be done externally.

WIND TUNNEL MOUNTING

The Phase II model is shown as mounted in the wind tunnel in Figure 20. It was mounted horizontally so the controlled force on the airfoil is measured as lift.

TEST RESULTS

The wind tunnel test results are presented in a sequence to meet the stated objectives of Phase II as follows:

(1) Fluidic amplifier control of lift at zero lift angle of attack and zero rudder deflection.

(2) The combination of the effect of slot control and rudder control.

(3) The tradeoff between scoop frontal area and the effectiveness of slot lift control.

(4) The effectiveness of amplifier-controlled slot flow at high angles of attack.

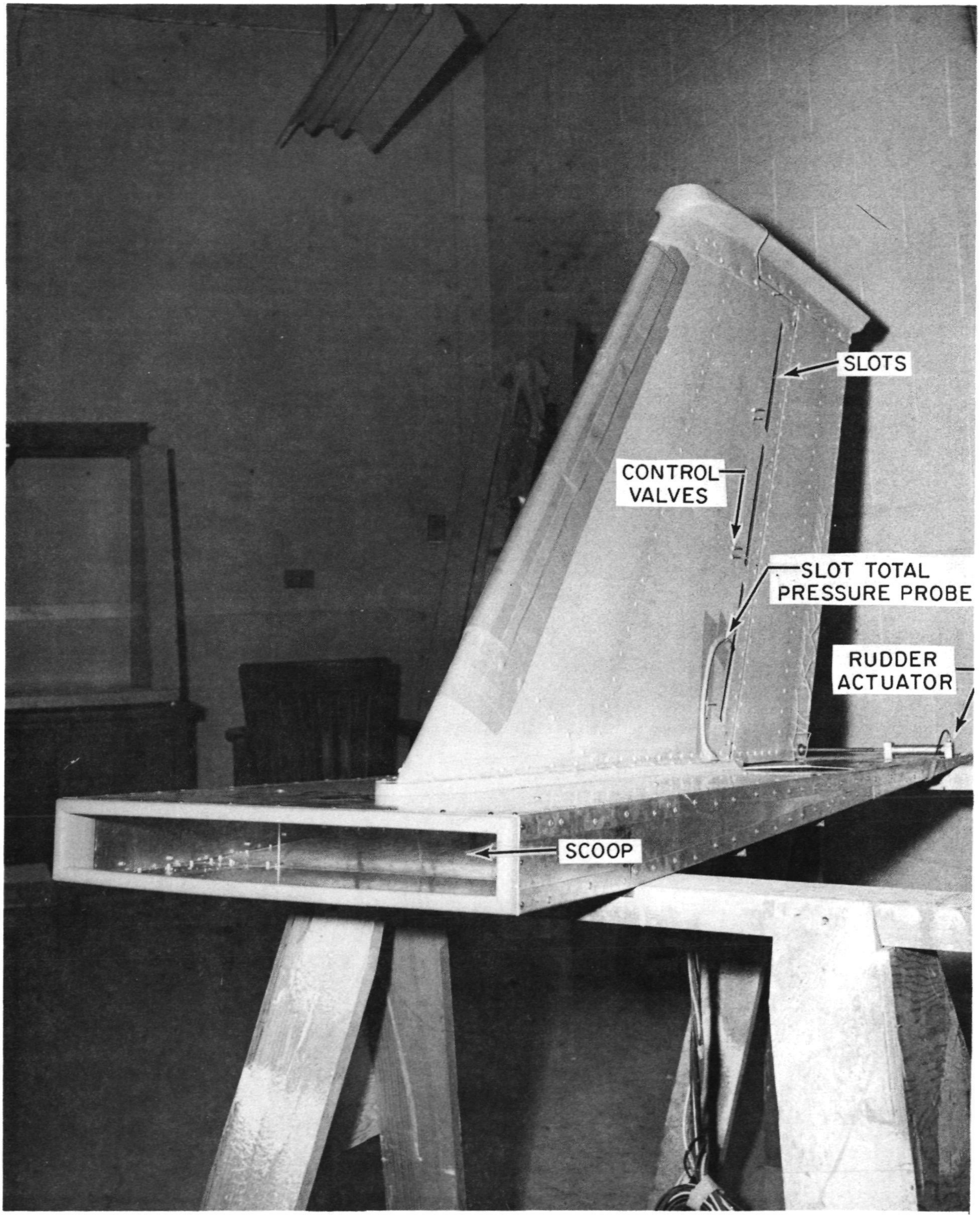


Figure 16. Phase II Wind Tunnel Model

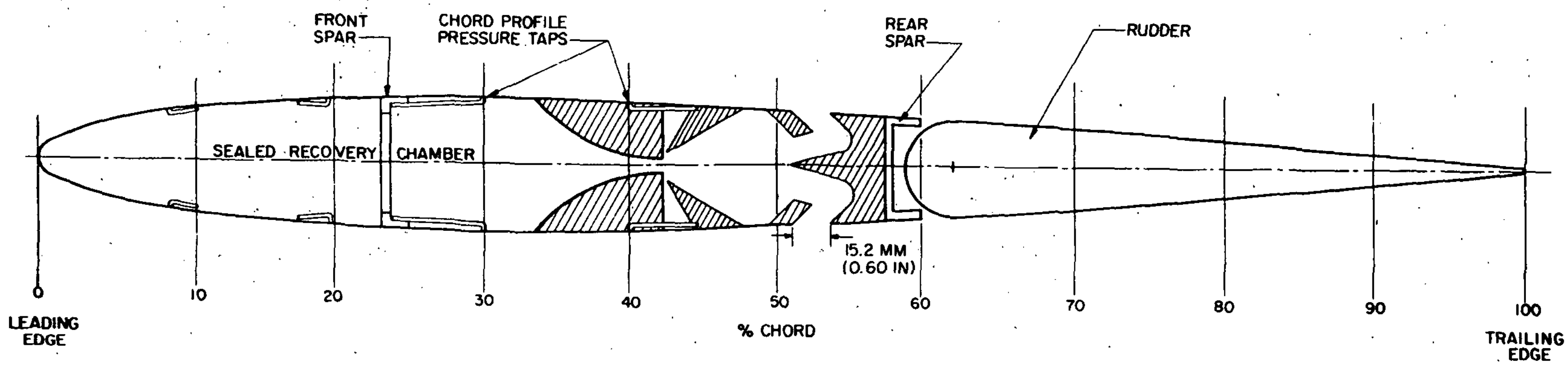


Figure 17. Cross Section of Phase II Model

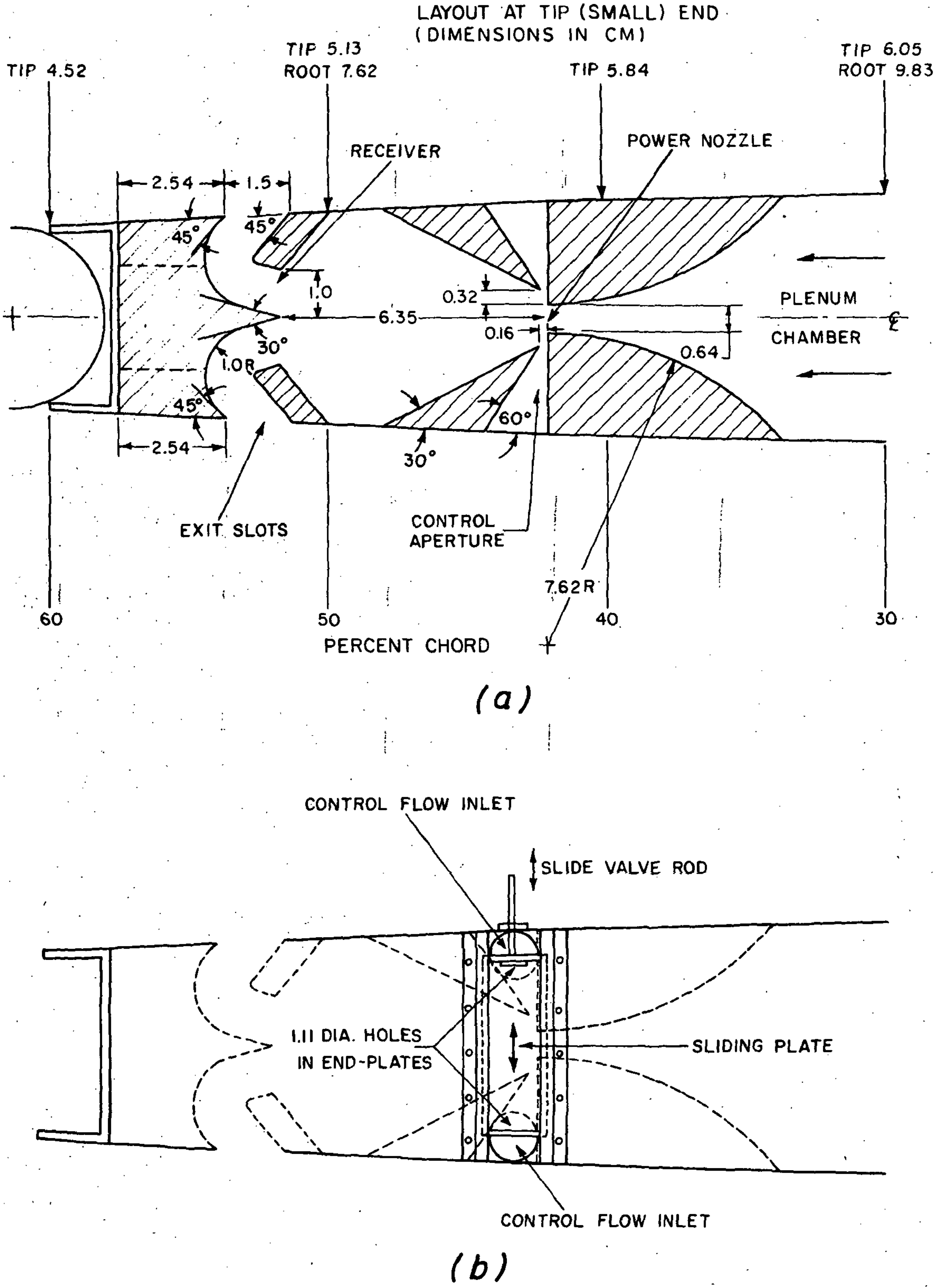


Figure 18. Details of Fluidic Amplifier

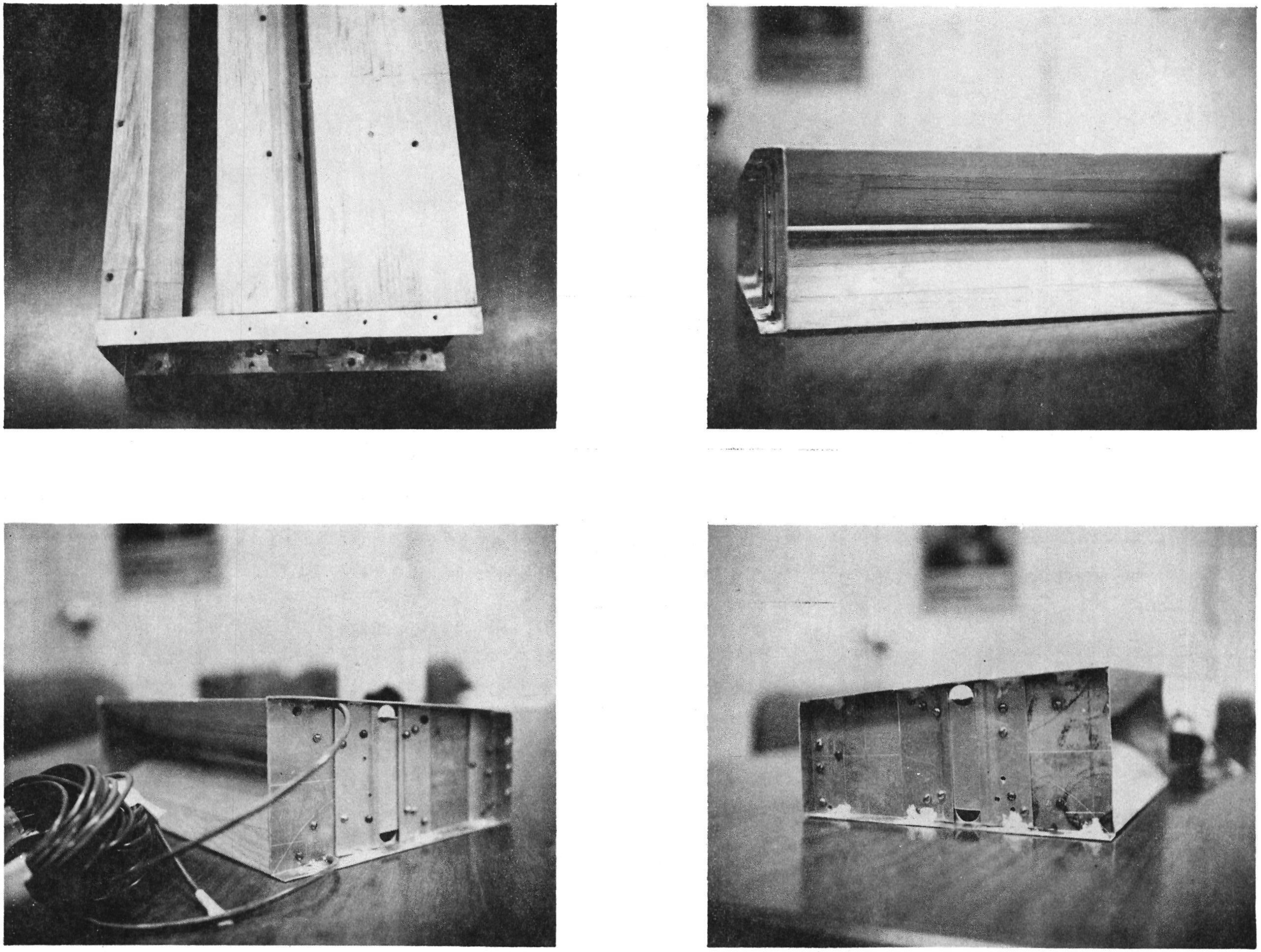


Figure 19. Typical Fluidic Amplifier Section (1 of 3)

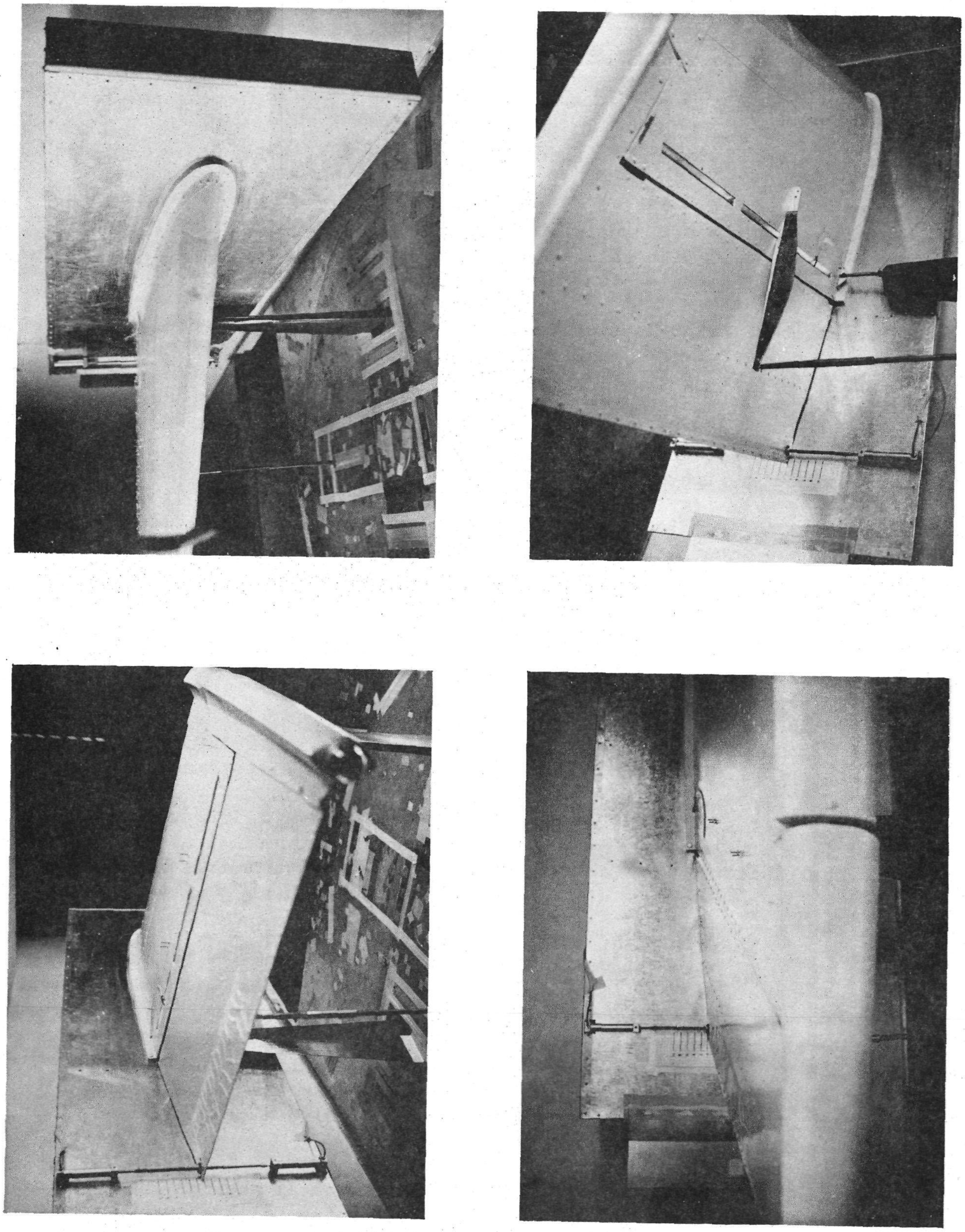


Figure 20. Phase II Model as Mounted in Wind Tunnel

(5) The effect of slot lift control on rudder hinge moments.

(6) The characteristics of the fluidic amplifier controlling slot flows.

Fluidic Amplifier Control of Lift

Figure 21 shows the variation in lift of the airfoil versus the manual position of the slide valves controlling the fluidic amplifier. The curve was measured with the rudder at zero deflection and the airfoil at the zero-lift angle of attack (-0.35°).

As a result of prior laboratory tests at FIRL it was suspected that the flow out one leg of the fluidic amplifier could never be driven to zero. To confirm this fact and to measure the maximum effectiveness of the scoop-slot configuration, test points were also measured at the extremes with the appropriate slots taped completely over, forcing zero flow from one side and total flow from the other. These test points are noted with a "T" in Figures 21 and 22.

The curves indicate two important facts. First, the fluidic amplifier <u>does</u> produce smooth, stable, proportional control of lift. Second, the fluidic amplifier <u>does not</u> completely cut off the flow from one slot at maximum deflection.

Coupling Fluidic Amplifier Control with Rudder Control

Figure 22 shows the effect of coupling slot lift control with rudder lift control. The curves indicate that the two effects add algebraically with no evidence of nonlinearity or instability. The curves also indicate that the effectiveness of the scoop-slot configuration in this model is equivalent to 1.47 degrees of rudder deflection (average), providing the fluidic amplifier cuts off the flow out one surface.

Effect of Scoop Frontal Area

Figure 23 shows the effect of scoop frontal area on the pressure recovered in the plenum chamber with full through-flow. Note that with the scoop wide open (area twice the area of the slots in one surface) we recover 86% of maximum dynamic pressure. Note also that with only half that frontal area the pressure recovery is as high as 74% maximum dynamic pressure (14% lower).

Figure 24 shows the overall effect of scoop frontal area on the control of lift. With half of the available scoop frontal area, the

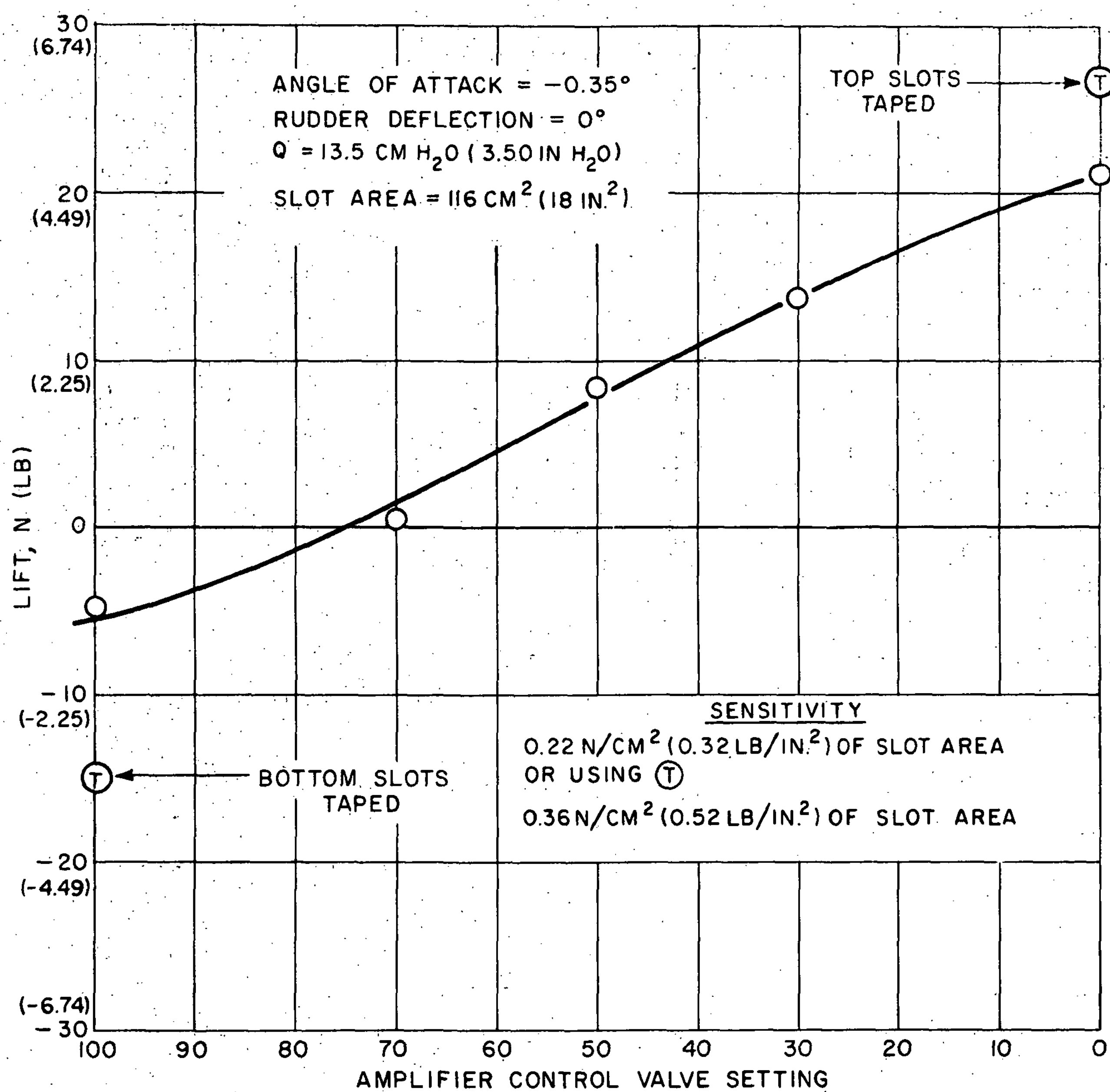


Figure 21. Lift vs. Amplifier Control

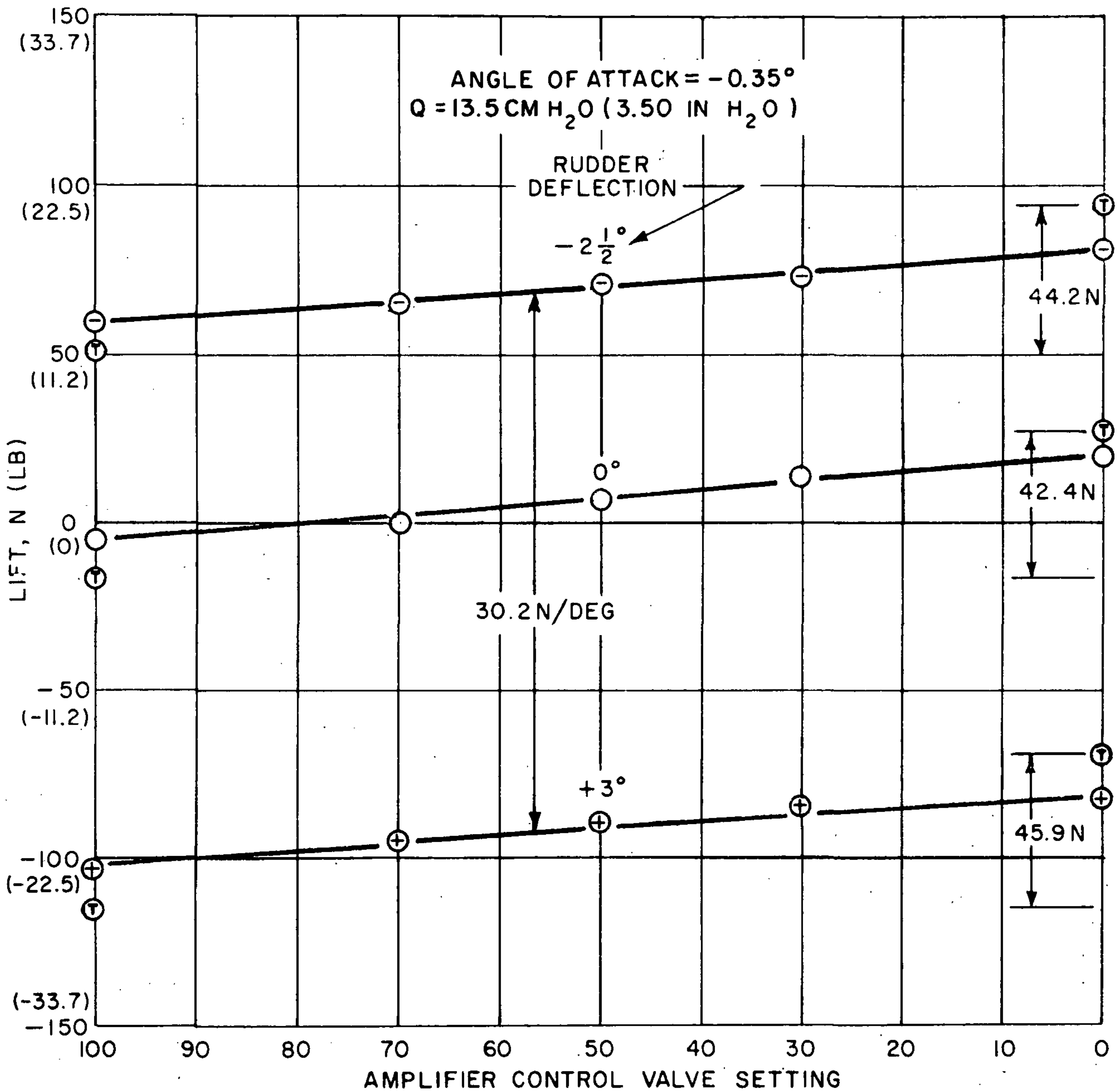


Figure 22. Amplifier Control of Lift Showing the Effect of Rudder Deflection

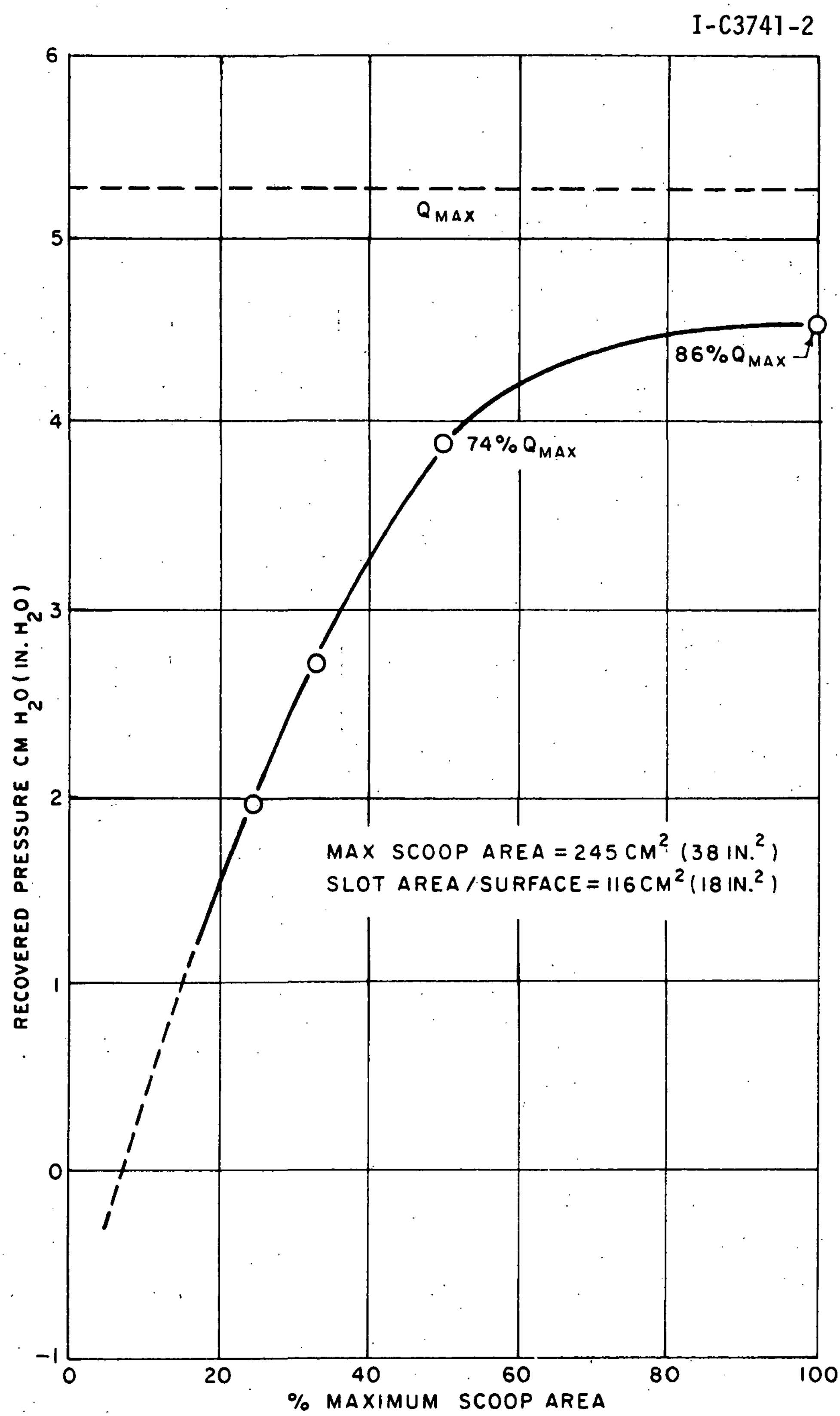


Figure 23. Recovered Pressure as a Function of Scoop Frontal Area

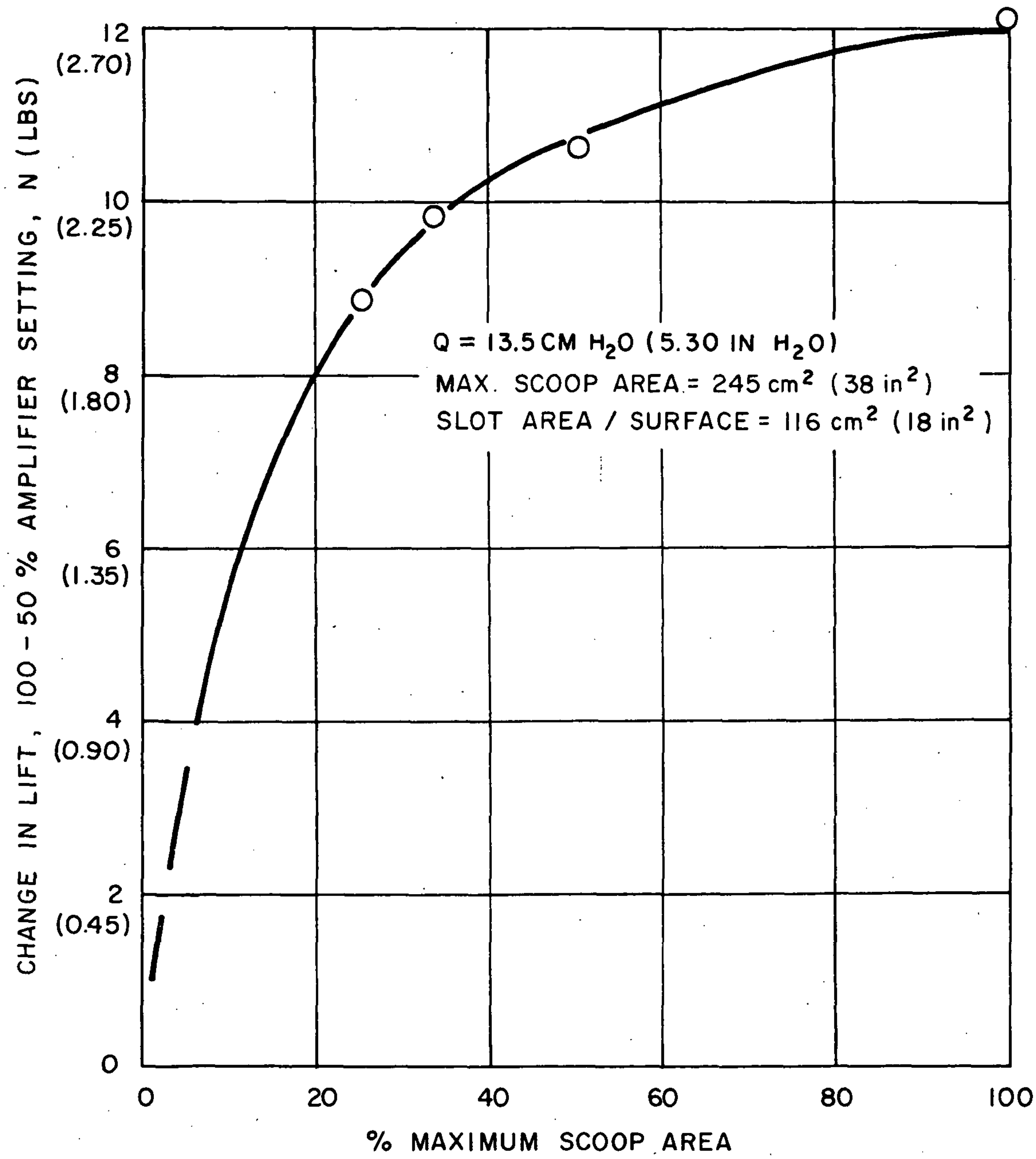


Figure 24. Slot Effectiveness as a Function of Scoop Frontal Area

change in lift produced by the amplifier-controlled slots is reduced by 1/12 or 8%. With only one quarter of the available scoop frontal area it is reduced by 1/4 or 25%. Therefore it appears that the optimum ratio of scoop frontal area to slot area (in one surface) is approximately 1.0.

Control Effectiveness at High Angles of Attack

Figure 25 shows the lift curves of the modified airfoil at angles of attack from -2° to +10° with fluidic amplifier control valve at zero, 50% (balanced) and 100%. The characteristics are normal for all conditions and do not show any tendency toward stall.

Figure 26 examines the change in lift due to slot flow in greater detail. Although the test points are rather scattered because of the difficulty in extracting small changes from high absolute values of lift, the trend indicates a fall-off of effectiveness at higher angles of attack. This is especially evident when the greater slot flow is out the surface with greater negative pressure.

Figure 27 illustrates the trend in another form of the same data smoothed with the curve in Figure 25.

Figure 28 shows how rudder control couples with slot control at higher angles of attack. The curves confirm the fall-off of slot effectiveness with angle of attack at all rudder positions and the direct addition of slot control to rudder control. Since rudder control is relatively constant at all angles of attack, these results are the first indication we have that slot control differs from rudder control.

Influence of Slot Control on Rudder Hinge Moment

Figure 29 shows the rudder hinge moments versus fluidic amplifier control positions. The curve indicates that there is a direct coupling and in comparison with the control of lift (Figure 21) the hinge moments are directly proportional to changes in lift and approximately linear.

Fluidic Amplifier Characteristics

By means of the total pressure taps located in the control chambers of the inboard amplifier and the total probes in the slots of the same amplifier, we were able to record its behavior in the flight environment.

Figure 30 shows the variation in control aperture pressures with manually-controlled valve settings. The curves show proportional control with some nonlinearity and a balanced condition nearer 60% than 50% valve position.

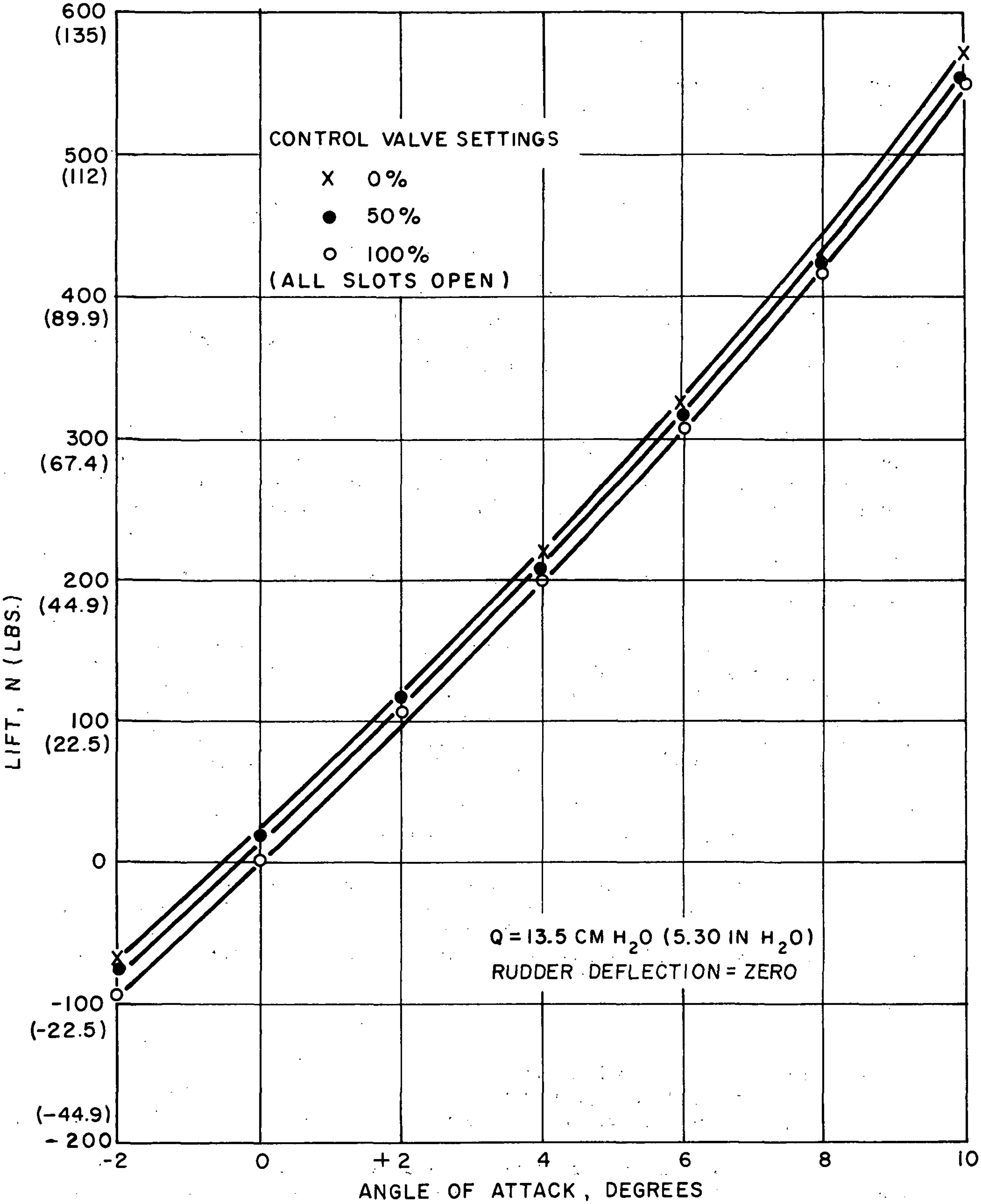


Figure 25. Lift vs. Angle of Attack Showing Effect of Slots

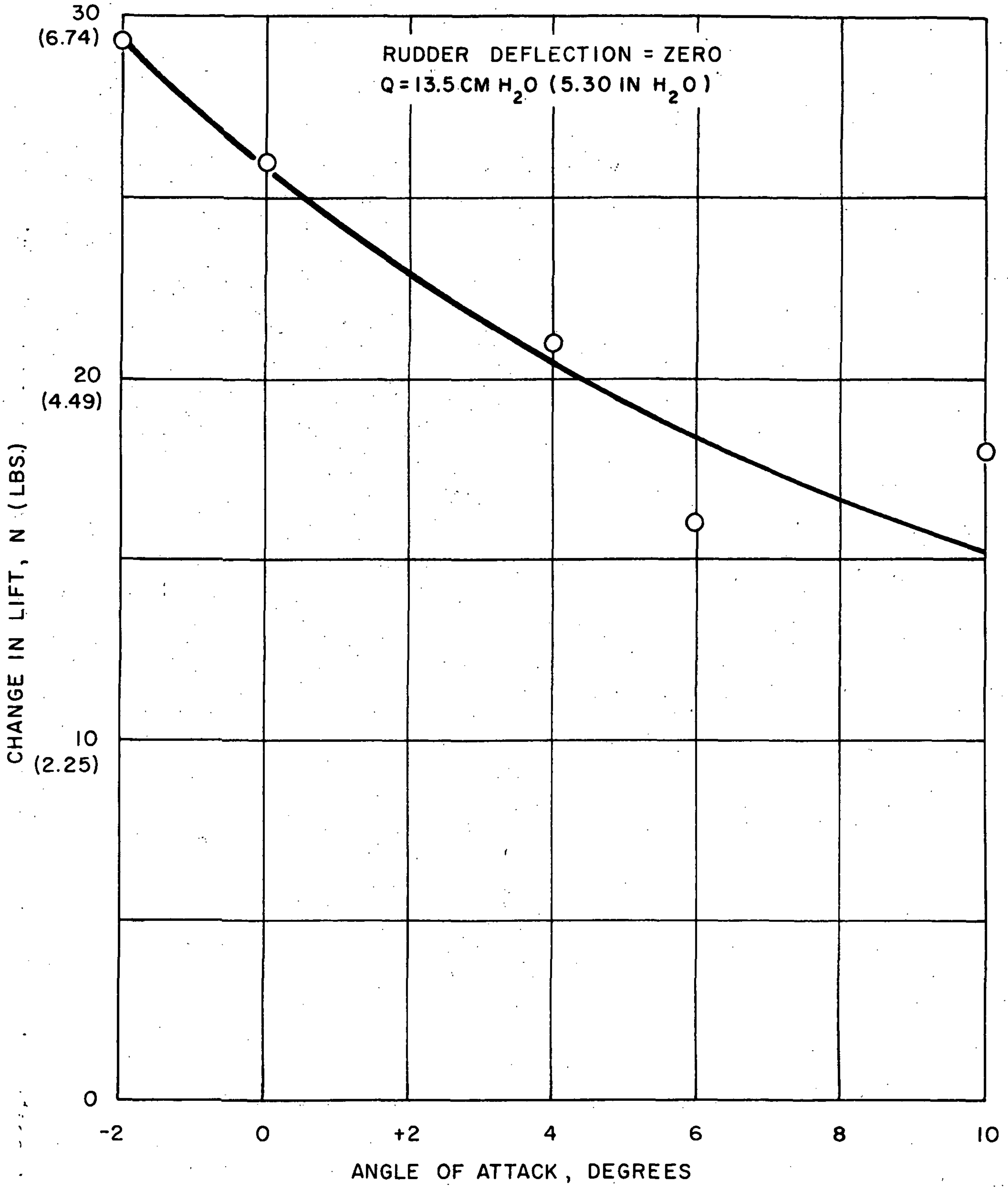


Figure 26. Change in Life vs. Angle of Attack; Zero to 100% Control Valve Settings

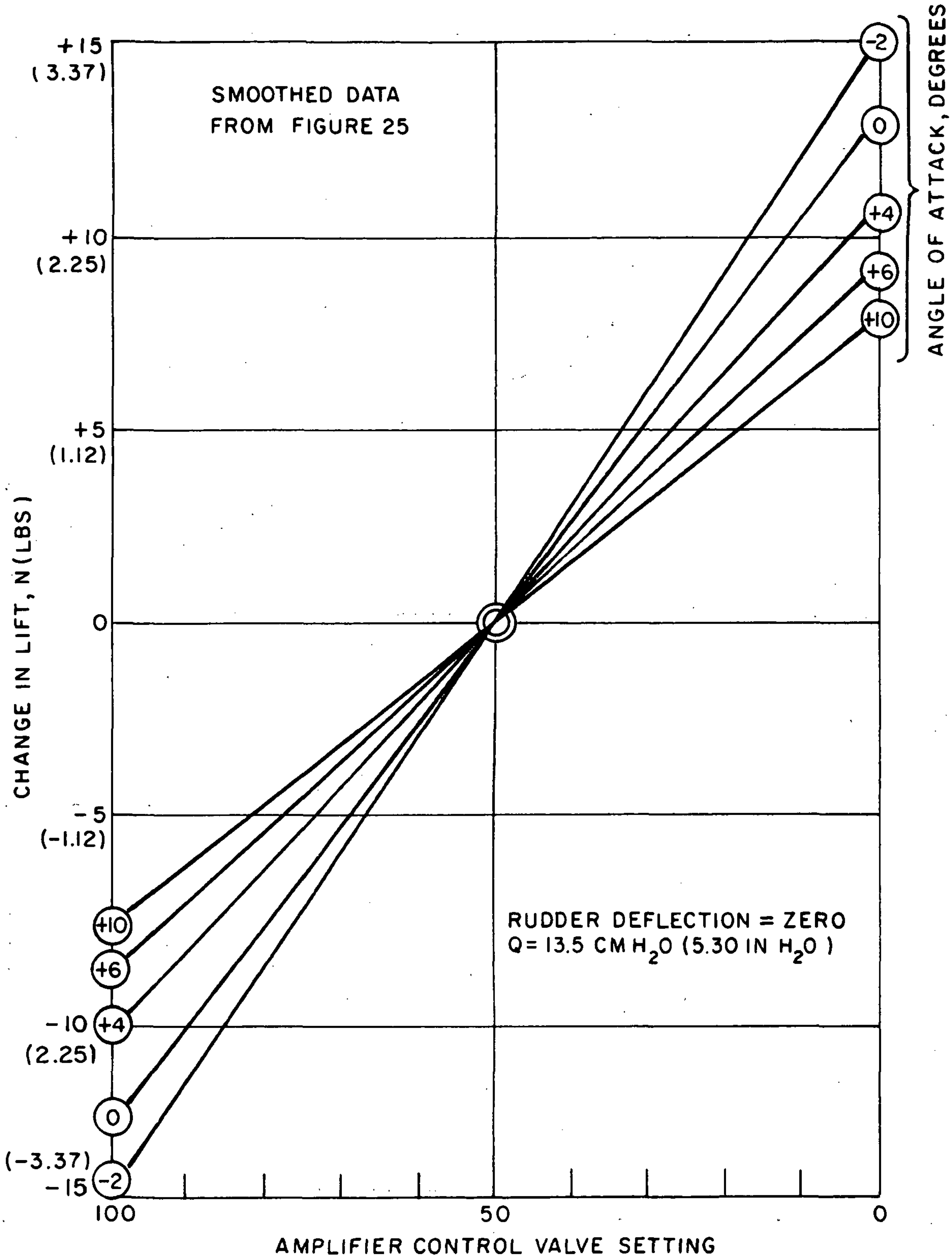


Figure 27. Effect of Angle of Attack on Amplifier Control Effectiveness

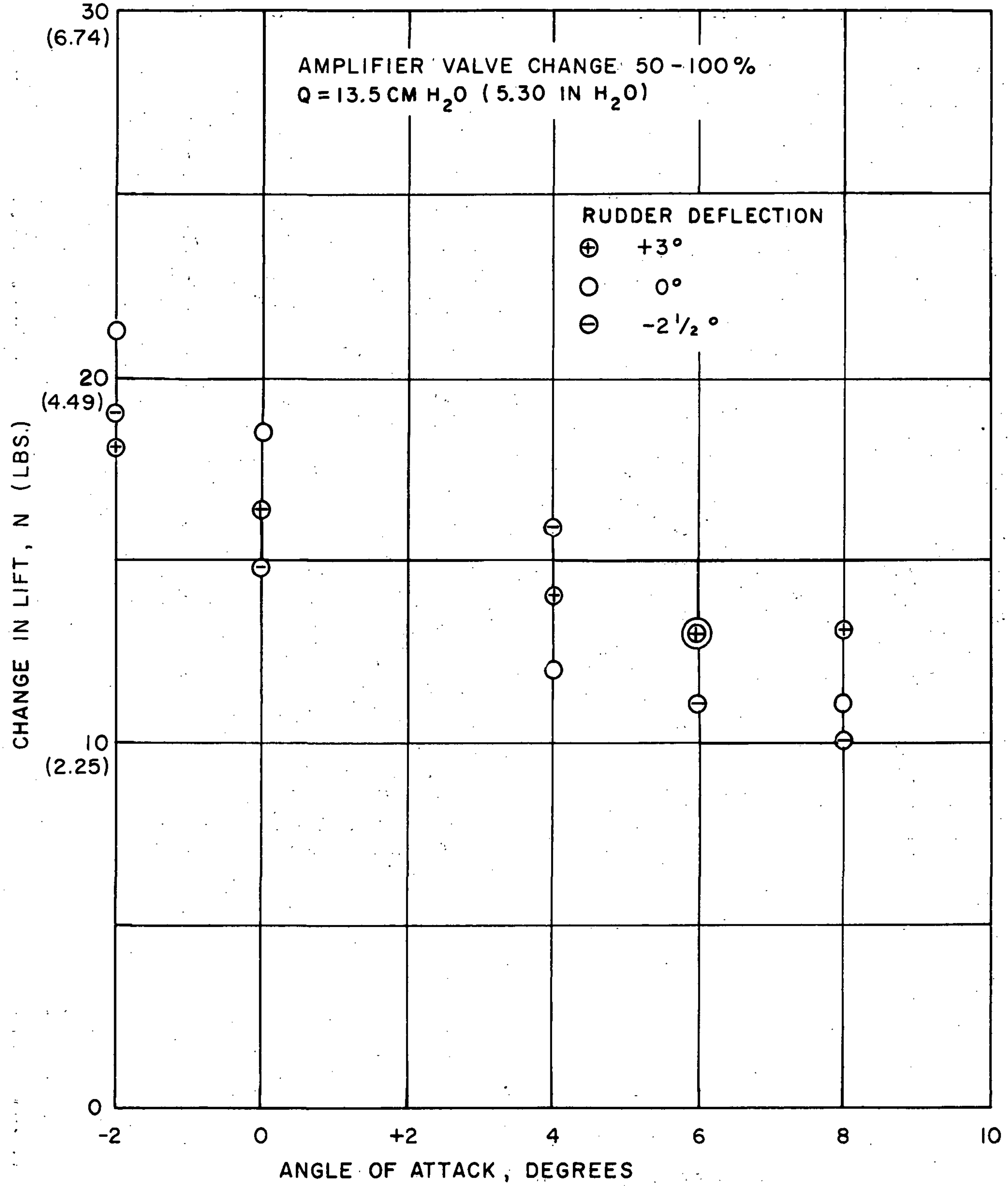


Figure 28. Change in Lift vs. Angle of Attack for Various Rudder Deflections (Spread of Raw Data)

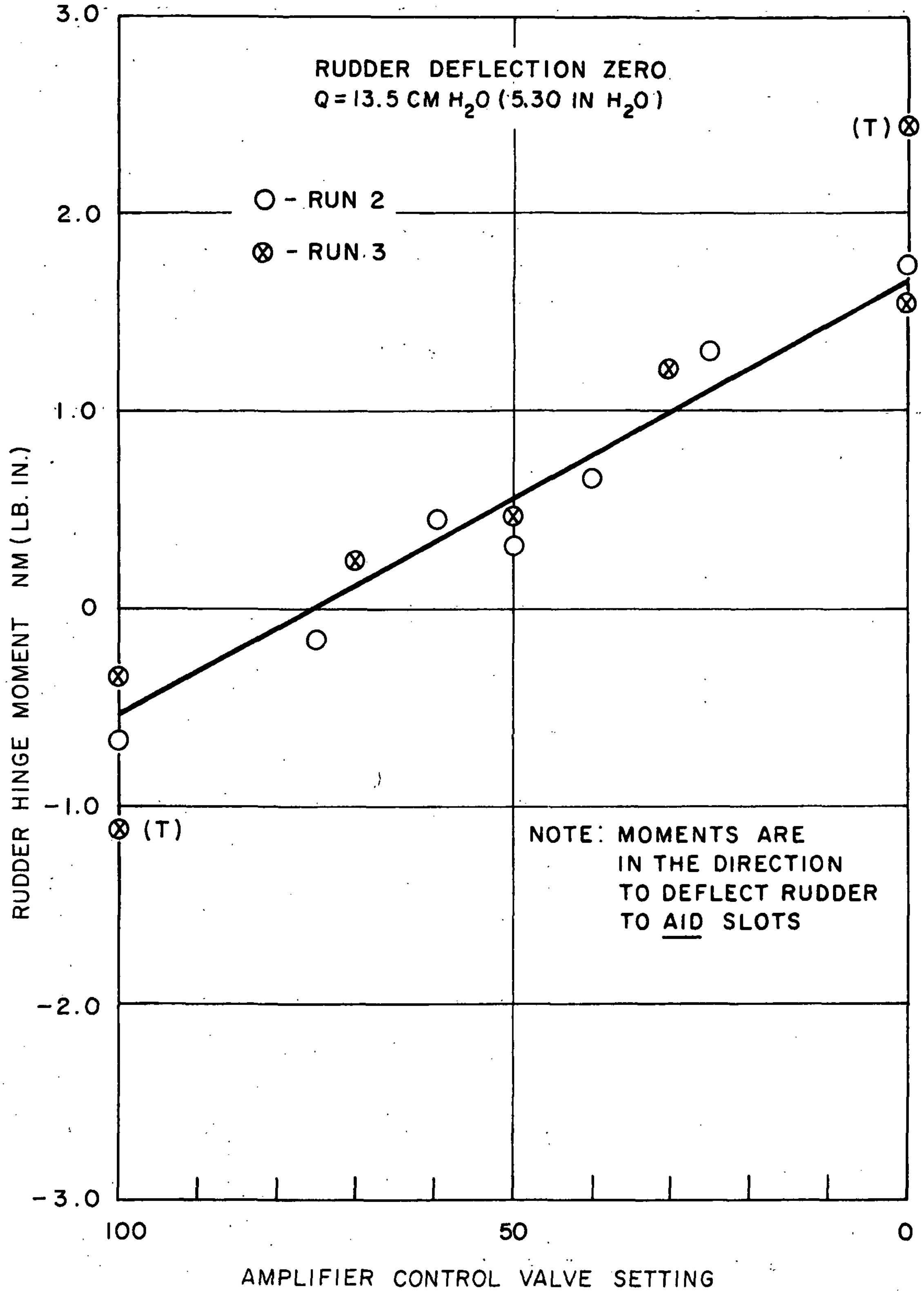


Figure 29. Effect of Amplifier-Controlled Slot Flow on Rudder Hinge Moment

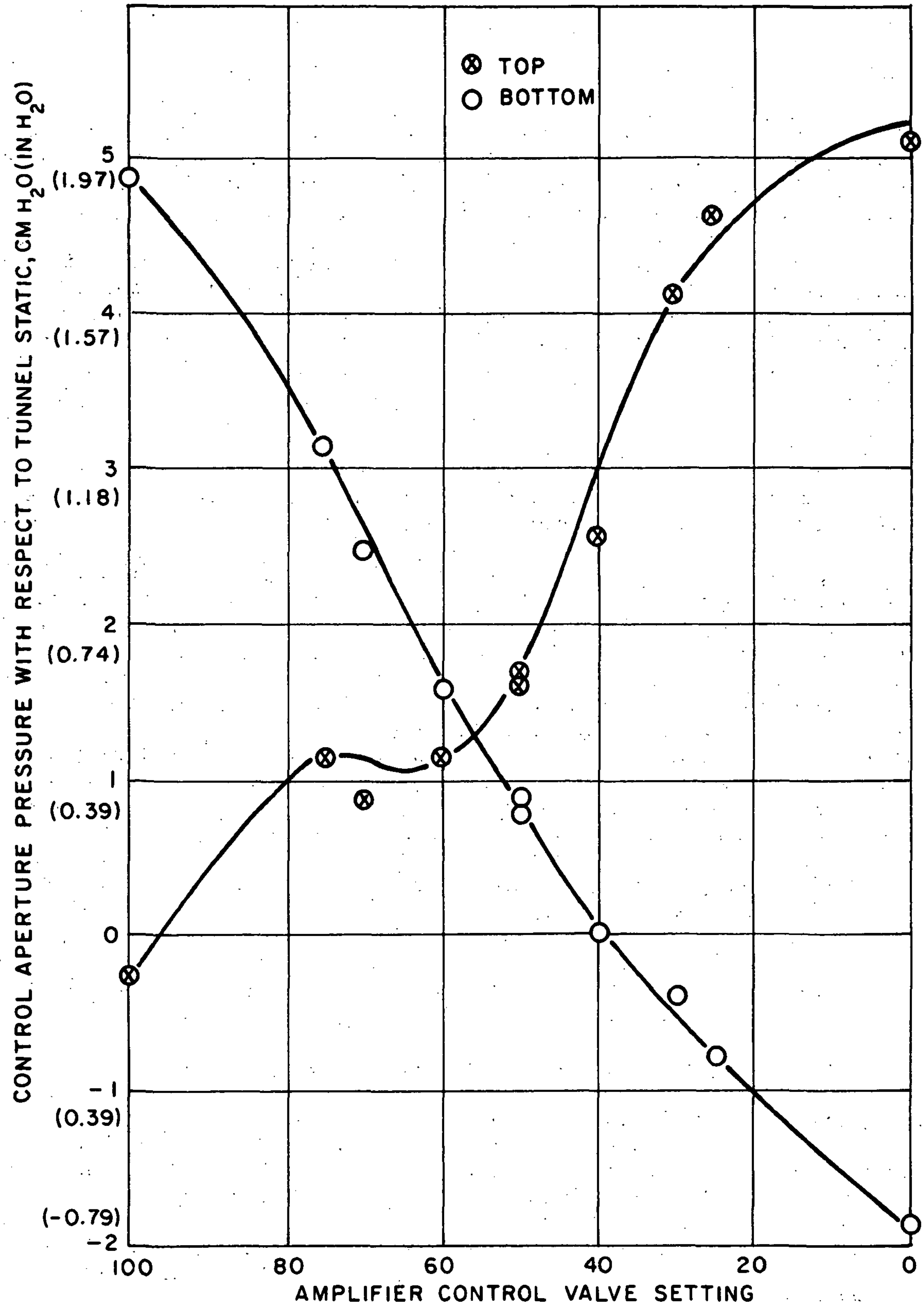


Figure 30. Amplifier Control Aperture Pressures vs. Control Valve Setting (Inboard Amplifier)

Figure 31 is a plot of the output flow, as measured with total pressure probes in the outlet slots of the inboard amplifier, versus control valve position. Again the control is proportional but some definite nonlinearities show up around the balanced condition.

Figure 32 is a combination of 30 and 31 relating amplifier differential output flow (slot total pressure) to amplifier differential control pressure. Here the amplifier exhibits proportional characteristics over most of the control range excepting in the vicinity of the balanced condition, where there is evidence of bistability.

Drag Characteristics

Drag characteristics of the airfoil with root scoop were measured and compared with the data previously measured with leading-edge scoops.

Figure 33 shows the effect on drag of the open area of the 245 cm^2 (38 in^2) root scoop. Note that the results show the combined effect of opening the scoop and flow out the top slots. The net effect is a 14% increase in drag.

Figure 34 compares the drag characteristics of the first wind tunnel model with leading edge scoop and the second model with a root scoop with nearly twice the frontal area. The lowest curve is the reference; leading edge scoops and slots sealed to make a clean airfoil. Opening the scoops and slots increases the drag approximately 8 newtons. With the root scoop and slots sealed the drag is increased approximately 45 newtons over the clean reference airfoil. This indicates that a penalty must be paid for a separate scoop but its magnitude cannot be defined because the root scoop has been shown to be oversize by a factor of two (Figure 23).

When the root scoop and slots are opened the drag increases by 9 newtons confirming the validity of the earlier test results.

Finally Figure 35 compares the effect on drag of the two means for force control, rudder and scoop-fed slots. The curves show that the drag change for full control is less than 0.7 newtons. With reference to Figure 21 we see that with zero rudder deflection, full amplifier control is equivalent to 0.9 degrees of rudder (26N/95N/3°). The drag factor is less than 0.8 newtons per equivalent rudder degree. The curves also show that 3 degrees of rudder control introduces 3.6 newtons of additional drag or 1.2 newtons per degree. These data indicate that force control with slots may introduce less drag than force control with a rudder.

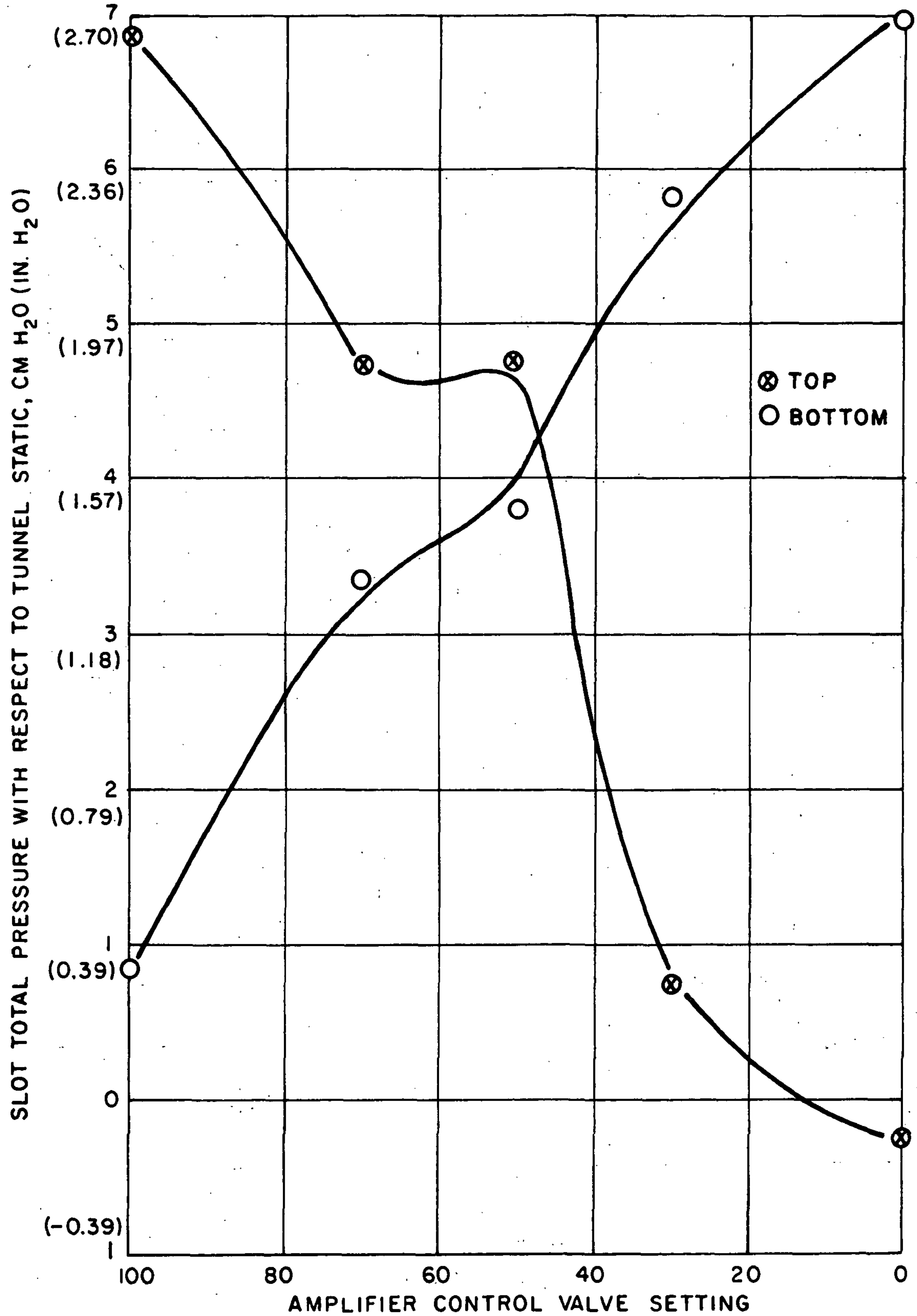


Figure 31. Amplifier Slot Total Pressure (Output Flow) vs. Control Valve Setting (Inboard Amplifier)

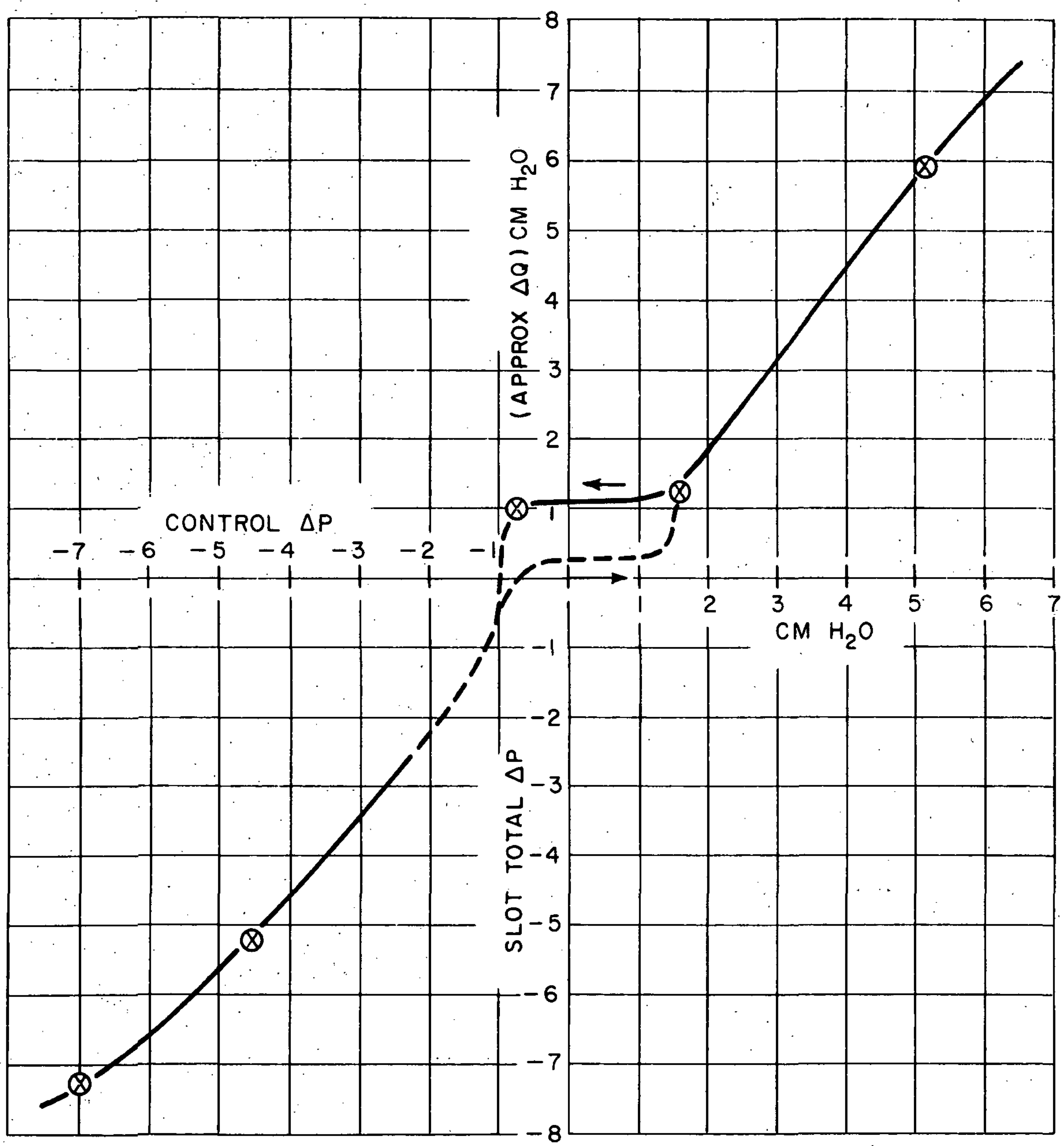


Figure 32. Gain Characteristic of the Fluidic Control Amplifier

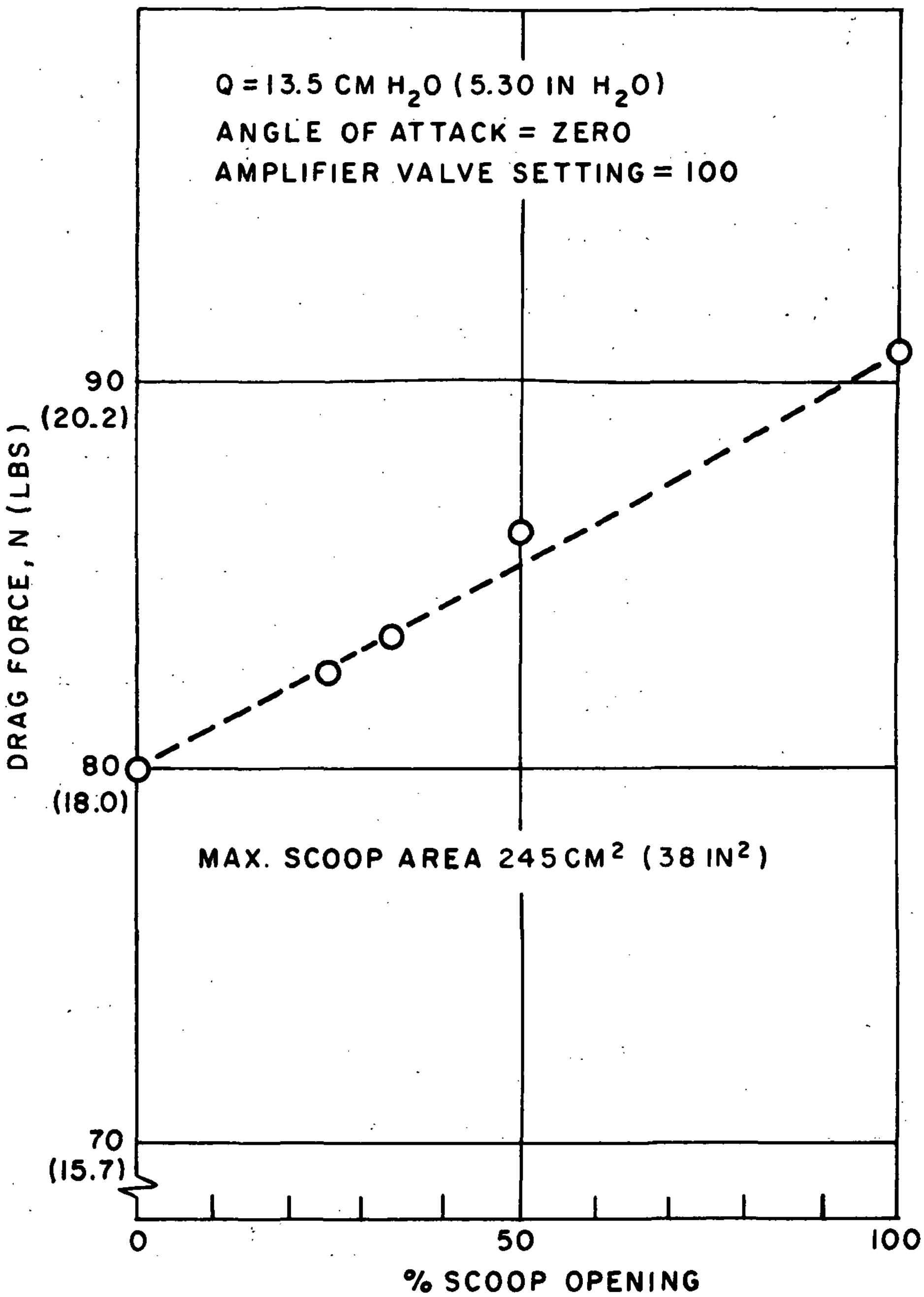


Figure 33. Drag vs Root Scoop Opening

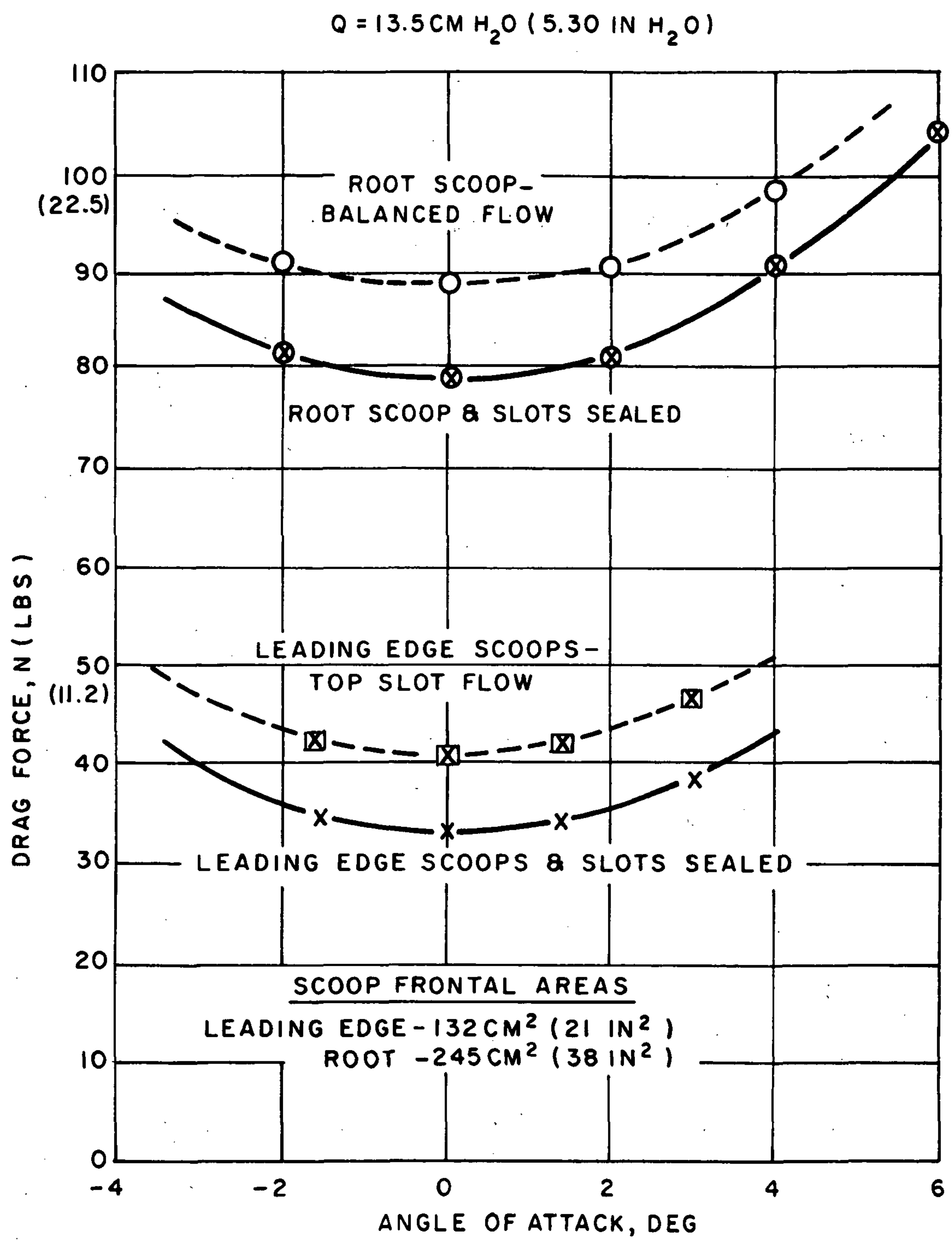


Figure 34. Drag Comparison-Leading Edge vs Root Scoop

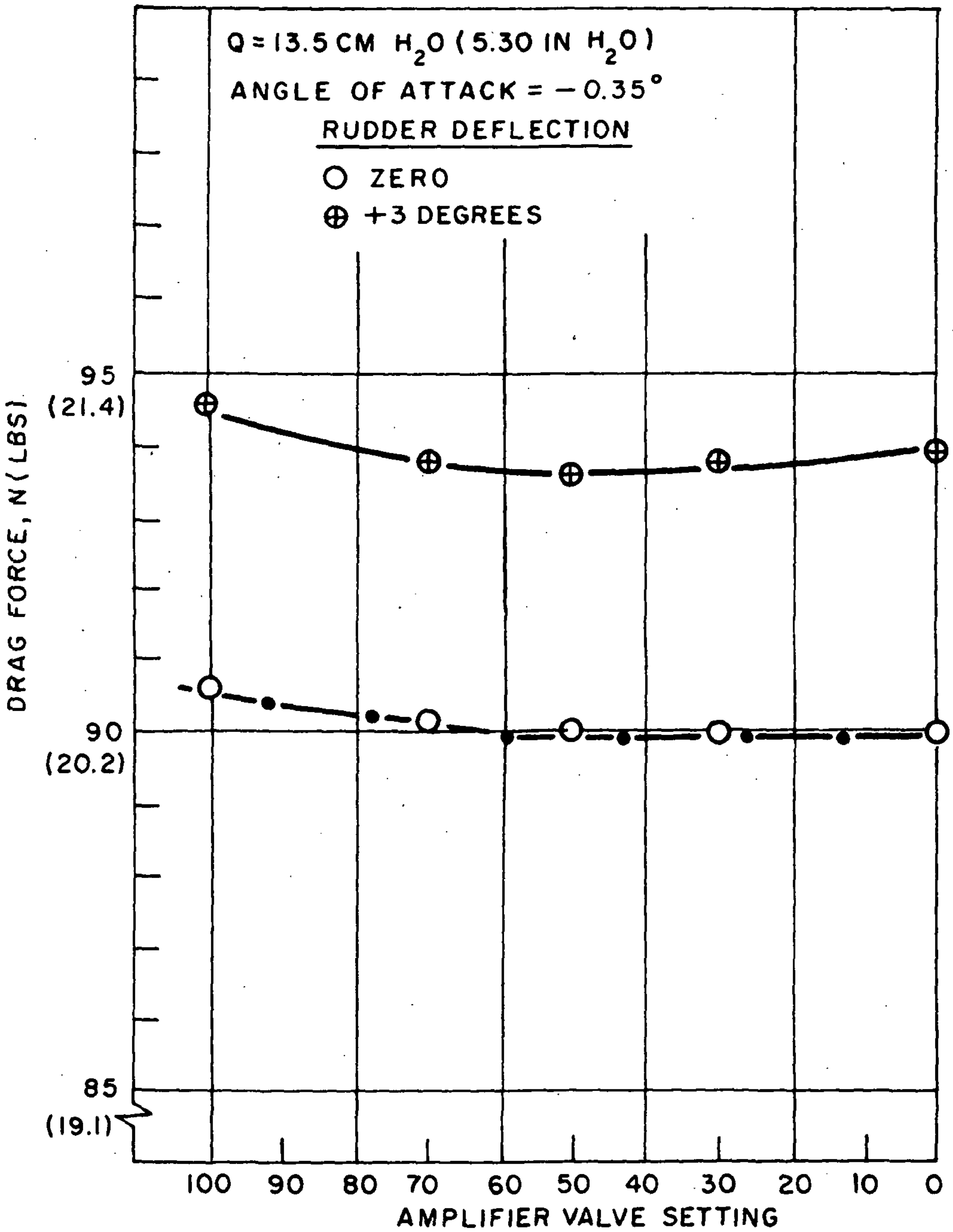


Figure 35. Drag vs Slot Control and Rudder Control

DISCUSSION AND CONCLUSIONS

With reference to the test results of the Phase I and the Phase II wind tunnel models we can discuss their meaning to the stated test objectives as follows:

(1) The feasibility of fluidic amplifier control of scoop-fed slots has been firmly established. The effect is smooth and proportional.

(2) Slot control couples with rudder control as a proportional algebraic addition over a wide range of angles of attack.

(3) The present slot dimensions (approximately 116 sq. cm.) provide aerodynamic control forces equivalent to approximately 1.47° of rudder deflection (from data with slots in one surface taped over).

(4) Considering effectiveness and scoop size, the optimum scoop frontal area is approximately equal to the area of the slots in one aerodynamic surface.

(5) As the angle of attack increases the effectiveness of slot lift control decreases. It appears to taper off toward zero at the stall conditon, which may be a desirable characteristic.

(6) Slot lift control reacts directly on the rudder, creating hinge moments directly proportional to change in lift and in a direction that would deflect the rudder to <u>aid</u> the slots.

(7) Drag tests show that a penalty must be paid for a separate scoop and indicate that force control with slots may introduce less drag than force control with a conventional rudder. More data should be collected to establish exact values.

(8) The configuration of the non-vented fluidic amplifier built into the Phase II wind tunnel model is basically sound. However, the dimensions have not yet been optimized. The ratio of the receivers to the power nozzle should be increased so the spreading jet will not spill over into both receivers at maximum deflection. The interaction chamber should also be modimodified to eliminate a tendency toward bistable operation near the balanced condition.

(9) To support further analytical work in system simulation and integration with existing fluidic controls, it is recommended that dynamic tests be run with the model in the wind tunnel.

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National Aeronautics and Space Administration
Wind Tunnel Tests of a Symmertrical
Airfold with scoop-fed slots. Charles A. Belsterling,
November 1974, 48 pp.

LIBRARY ABSTRACT CARD

The design and wind tunnel test of a model vertical tail fin is described in this report. The model is designed to provide the aerodynamic forces necessary for lateral stabilization without moving parts or a separate source of power. It employs scoop-fed slots on both surfaces of the symmetrical airfoil. They are to be controlled differentially by means of a fluidic amplifier to implement an automatic full-time lateral stabilization system.

The first phase of the work demonstrated the feasibility of no-moving-parts aircraft control. The second phase established that a practical fluidic amplifier can be built to control slot flows from fluidic signals. Recommendations are made to optimize the design of the fluidic amplifier and to characterize its dynamic response in support of further analytical studies.