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Technical Paper No. 40, Series B

A Dynamometer for the Two-Dimensional, Free-Jet Water Tunnel Test Section

by

E. SILBERMAN and R. H. DAUGHERTY

Prepared for
OFFICE OF NAVAL RESEARCH
Department of the Navy
Washington, D.C.
Contract Nonr 710(24), Task NR 062-052

June 1962
Minneapolis, Minnesota

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ABSTRACT

This paper describes a strain-gage type dynamometer designed for use in the two-dimensional test section of the free-jet water tunnel. This dynamometer replaces one originally installed in the tunnel and described in an earlier paper [1].[*]

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[*] Numbers in brackets refer to the list of references on page 10.

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A DYNAMOMETER FOR THE TWO-DIMENSIONAL, FREE-JET WATER TUNNEL TEST SECTION

I. INTRODUCTION

The free-jet water tunnel at the St. Anthony Falls Hydraulic Laboratory was described by Silberman and Ripken in Reference [1]. Included, was a description of a mechanical type dynamometer system designed for use in the two-dimensional test section of the tunnel. The system consisted of two identical dynamometers, one mounted in each tunnel wall, supporting a test body between them. Each dynamometer operated as a null balance instrument, its center being held in place by jack screws acting through hydraulic load cells, the load being measured by the pressure in the cells. Some features of the dynamometer were shown schematically in Fig. 19 of Reference [1].

After some intensive testing, it was found that the mechanical type dynamometer was unsatisfactory for the experiments being conducted in the tunnel. There were three main problems; these were: (1) There was binding in the formed rubber seal and in other clearance spaces between each dynamometer and the tunnel wall, and this resulted in poorly reproducible force readings with different tunnel pressures. Binding resulted from excessive deflection of the tunnel walls under operating pressure conditions. (2) Even under dead weight calibration in the dry tunnel, the load cells produced erratic readings. It is believed that the source of the trouble was in the flexible diaphragm in the cells or, possibly, occurred because air bubbles could not be completely eliminated from the oil in the cells. (3) The system, which had been designed for steady state testing, was not sufficiently responsive for the later unsteady test programs.

A new dynamometer system has now been placed in operation in the two-dimensional test section and has given satisfactory service for a period of one year. This new dynamometer is described in this report. The new dynamometer is a displacement type instrument, small displacements being measured by strain gages cemented to flexure members. There are actually two identical dynamometers, one for the front face and one for the rear face of the tunnel. One of these is shown installed in the front face of the tunnel in Fig. 1 and

b) Sudden changes in angle of attack of up to 10 deg from one accurately fixed value to another at a rate of 200 deg per sec.

c) Cyclic change of 10 deg total motion (5 deg maximum amplitude) at a rate of 5 or more cycles per second.

Test body twist must be less than 0.1 deg at any angle of attack setting, either while the body is fixed or moving.

(8) Because some of the hydrofoil models to be tested are very thin, the dynamometer system must be capable of supporting models at both ends.

(9) The inside surfaces of the dynamometer must be flush with the inside tunnel walls under all operating conditions.

(10) There must be no resonance of the dynamometer in any mode at frequencies less than 100 cps to allow for measurements with pulsating cavities.

(11) The dynamometer system must provide for obtaining cavity pressure measurements and for introducing air into cavities at or immediately downstream of the trailing edge of a test body without disturbing dynamometer readings.

Most of these specifications were realized and many were exceeded with the new dynamometer system. However, there were some disappointments. Moment measurements, as will be seen in connection with the discussion of Fig. 4, leave much to be desired. Also, requirement (5) for direct visibility of test body surfaces had to be relaxed. It is possible to see the test body surfaces by looking diagonally from one side or from the top or bottom of the dynamometer, but end views are cut off. All other specifications are considered to have been met satisfactorily.

III. DETAILED FEATURES

Considering the binding that occurred on the original dynamometer, it was at first thought that a submerged dynamometer without a seal fashioned after a model used earlier and described in Reference [2] would be required.

However, space limitations, the need for changing angle of attack during operation, and the availability of what promised to be an adequate seal led to the design of an external dynamometer system. Each dynamometer is encapsulated in a plastic container and may be removed from or installed in the tunnel as a unit in a few minutes. (The holes may be closed by transparent end plugs when one or both dynamometers are not in use. Both dynamometers are normally used together to facilitate changing and holding angle of attack of two-dimensional test bodies, but one may be used alone for half-span bodies.)

As indicated in Fig. 2, the space between the tunnel walls at the test station in the dry tunnel measures 5.08 in. Two-dimensional test bodies are manufactured with lengths of 5.02 in., allowing 0.06 in. clearance. About 0.03 to 0.045 in. of this clearance is actually used up when the tunnel is placed in operation because the tunnel walls are sucked in by the low operating pressure. The balance of the clearance assures free motion of the test body and the dynamometer spindles and allows for additional minor fluctuations of the walls produced by temperature changes. In order to alleviate axial forces on the dynamometers when the walls are sucked in, test bodies are fitted over pins extending from the dynamometer spindles as shown in Fig. 2. The pins fit snugly into holes in the test bodies to prevent play when changing angle of attack, but the holes are much longer than the pins to permit endwise motion. The pins are of high strength steel. Test bodies are interchanged by withdrawing one dynamometer unit a short distance. A special jack is provided for this purpose.

(Since there are two dynamometers, not only lift, drag and pitching moment, but also yawing and rolling moments, if any, can be measured. The yawing and rolling moments for the two-dimensional test bodies turned out to be zero, as expected from the velocity traverses of the jet. Thus, it is necessary to take readings from only one dynamometer in order to obtain two-dimensional lift, drag or pitching moment.)

Force is transmitted from a test body through the spindle and primary force plate of a dynamometer to the "drag" beams. There are four of these beams in each dynamometer, each one fixed to the secondary force plate and hinged to the primary plate. Thus the "drag" beams act as cantilevers in the "drag" direction with maximum flexural stress near the secondary force plate. Strain gages (Type SR 4, FAB-25-12) are cemented here (in pairs, one on each surface of each beam to eliminate temperature effects). There are eight strain gages - four pairs - measuring "drag" in each dynamometer. At the same time, the "drag" beams act as very deep fixed end beams in the "lift" direction and transmit the "lift" motion practically without distortion to the secondary force plate. The force is transmitted from the secondary force plate to the base plate by the "lift" beams which act as cantilevers in the "lift" direction but permit practically no motion in the "drag" direction. Again, there are eight strain gages - four pairs - measuring "lift" in each dynamometer. If there is no moment, one-eighth of the total "drag" and one-eighth of the total "lift" of a two-dimensional test body is carried by each beam. If there is moment, however, the load is distributed unequally between the beams and the differences are used for measuring moment. The beams and force plates of one dynamometer may be seen in the photographs of Fig. 3; the light colored areas on the beams have been prepared for receiving strain gages.

Fig. 2 shows a vertical section through the tunnel with the dynamometer oriented so that the "lift" beams read true lift and the "drag" beams true drag. Angle of attack is changed by rotating the plug, and with it the dynanometer and test body. Thus, at other angles of attack than the one shown the beams do not read true lift and drag. Rather, lift and drag are obtained by resolving the total force resulting from vector addition of the forces read from the "lift" and "drag" beams. No special treatment is required for moment.

To resist the total force and moment each "lift" beam is designed for a 15 lb, and each "drag" beam for a 2.5 lb, concentrated load at its end. The beams are fabricated from special heat treated and stress relieved flat steel. Cross sections are 1/8 in. deep by 3/8 in. wide for the "lift" beams and 1/16 in. deep by 1/2 in. wide for the "drag" beams; nominal lengths are 2 1/2 in. and 2 in., respectively. These beams may be interchanged with beams of other cross sections to measure heavier loads or to provide for greater sensitivity with lighter loads. The base plate is fabricated from cast iron while the force plates are of an aluminum alloy.

Referring to Fig. 2, the strain gage leads from the various beams are interconnected so that the tension and compression sides of D-1 form two adjacent arms of a bridge while the tension and compression sides of D-2 form the other two arms, the two "drags" being added. Similarily, D-3 and D-4 form another "drag" bridge while L-1 and L-2, and L-3 and L-4 form two "lift" bridges. An AC bridge system has been used to make possible the recording of oscillatory or transient forces. A CEC No. 1-118, 3KC carrier amplifier completes the bridge circuits. Recording is by a CEC Type 5-116, 14-channel recording oscillograph of which 6 channels are usually used, 4 for the four strain-gage bridges, one for angle of attack and one for cavity pressure. The strain-gage bridges may be reoriented by opening a dynamometer capsule and changing the connections on the terminal strip.

Typical static calibration curves for one of the dynamometers obtained using weights with the dynamometer in place in the dry tunnel are shown in Fig. 4. There is some hysteresis between loading and unloading; this may be attributable to binding in the hinged joints of the beams. As shown by the graphs, the hysteresis loop can be made to nearly disappear by recycling the loading and unloading or by working over a small load range. In steady flow problems, loading is programed so that loads always increase, thus avoiding the hysteresis loop. Under transient conditions, load changes are usually small enough that an average gage factor may be used. Typical average gage factors are written on the graphs, but actual conversion of recorded data is made directly from calibration charts obtained preceding and following each experiment. The load values given in Fig. 4 are total loads carried by both dynamometers while the scale readings are the separate readings for each bridge; the actual loads per bridge are only one quarter of those given as ordinates.

Because of the manner in which the strain gage bridges are formed, moment should be proportional to the differences in the "lift" bridge readings, and the moment calibration should be derivable from the "lift" calibration. The moment calibration curves in Fig. 4 show that moment sensitivity is much less than it should be based on the known lift calibration and that the calibration actually varies with load. Each calibration is repeatable for the same load. It is believed that the seal, to be described below, is resisting some of the moment and accounts for the observed deficiencies.

There are some interactions between "lift", "drag" and moment, but the only important one, aside from the effect of load on moment, is the influence of lift on drag. This is shown in Fig. 4. Experimental results are corrected directly from calibration curves like this. Neither lift nor drag is influenced by moment.

The seal shown in Fig. 2 and visible in the photograph of Fig. 3b is of the wrinkle diaphragm type fabricated from a polyvinyl chloride material

0.011-in. thick. The wrinkle permits free movement of the dynamometer spindle even when there is a pressure difference across the seal. Prior to selection of this seal, a number of seals, including this one, were tested in the tunnel for attenuation in lift and drag with up to the maximum possible pressure difference - one atmosphere - across the seals. Up to 100 cps, no undesirable resonance nor attenuation was detected. However, no tests were made for moment. (The same seals which underwent the tests have now been in use in the tunnel for nearly one year without signs of deterioration.) In use, the seals are not actually subjected to large pressure differences. The interior of the sealed dynamometer housing is connected by a direct passage (not shown in Fig. 2) to the wake area of the test bodies so that the dynamometer is maintained at wake pressure. A small quantity of water may accumulate in the bottom of the dynamometer housing behind the dam during operation because of this passage, but it never reaches the force beams or wiring. During shut down of the tunnel a drain cock in the bottom of the housing (not shown) is opened to the atmosphere to prevent inflow of water. After each run, nitrogen gas is blown through the dynamometers to dry them and the housings are kept slightly pressurized with nitrogen when the dynamometers are not in use. (The small tank visible on the left of the tunnel in Fig. 1 is used for storing nitrogen for these purposes.)

The seal clamp, shown in Fig. 2, serves several purposes in addition to holding the seal in place. The labyrinth in the clamp is intended to equalize the pressure around the spindle to prevent tare forces due to pressure differences. One of the clamps has four pressure taps drilled radially at 90 degree intervals into the groove of the labyrinth. These taps are individually connected to outside tubing connectors in the same manner as the cavity pressure measuring probe shown in Fig. 2 is connected to the outside. The taps have been used for measuring the differential pressures around the spindle under various operating conditions. The tare force produced by pressures has been found to be, at most, of the order of 10 per cent of the drag force on a 1/4-in. diameter, cavitating circular cylinder at 24 fps and decreased with increase of velocity and with increasing cylinder diameter. On a hydrofoil, maximum tare was in drag and was less than 5 per cent at zero lift and low velocity and decreased with increasing velocity and increasing angle of attack. Pressure drag on the spindle has been neglected in all subsequent measurements.

The seal clamp also serves as a mechanical stop, preventing overloading of the force beams. Maximum permissible deflection is 3/64 in. and the beams have been designed to just permit this deflection at design load.

As already indicated, angle of attack changes are produced by rotating both dynamometers simultaneously. No special bearings have been provided for this purpose. The dynamometer plugs fit very tightly into the holes in the tunnel walls and the load is carried by the "O" ring seal and by packing the clearance space between plug and wall with a special grease. Most of the effort required for turning the dynamometers goes into overcoming friction in this joint and only a small portion of the work is required because of the moment of inertia and added moment of inertia of the dynamometers and test body. The tight fit, "O" ring, and grease effectively seal this joint against leakage. (Both dynamometers, their seal clamps and spindles, together with the screws holding the seal clamps are so accurately aligned with the tunnel walls that no cavitation occurs at these joints even at the lowest operating pressures.)

The crank arm shown attached to the dynamometer in Fig. 1 is used for making cyclic angle of attack changes. Identical drive shafts on both dynamometers are driven from a single heavy cross arm at the right side of the tunnel and this, in turn, is driven by a crank arm connected to an eccentric flywheel driven by a variable speed hydraulic motor. Cyclic changes of 7 deg total motion (3.5 deg amplitude) at 5 cps on a hydrofoil of 2 1/2-in. chord have been obtained with this arrangement. Angle of attack is measured and recorded electrically by motion of a contact on the dynamometer plug; angle of attack may be read directly to the closest 10 min. from the scale visible at the left side of the dynamometer in Fig. 1 or Fig. 6. A typical record obtained during cyclic angle of attack change of a cavitating body is shown in Fig. 5a.

Changes of angle of attack other than cyclic are introduced through a bevel gear system driving a gear ring attached to the outside of each dynamometer plug. This system is shown in Fig. 6. Rapid linear changes are produced by hanging suitable weights on the drive pulley. Starting and stopping angle of attack may be set within 10 min. on the pulley; there is a quick release lever to start motion and a positive stop device to alleviate rebound at the end. Angle of attack for steady flow runs may be set by turning the pulley by hand and reading the scale. A typical record obtained during a rapid linear change is shown in Fig. 5b.

IV. PERSONNEL

The second author was responsible for the detailed design and for the selection of the method of operation of the dynamometer. The work was performed under the direction of the first author who set the specifications and prepared this report.

LIST OF REFERENCES

[1] Silberman, E. and Ripken, J. F. The St. Anthony Falls Hydraulic Laboratory Gravity-Flow Free-Jet Water Tunnel Tech. Paper No. 24, Series B, Aug. 1959, 45 pp.

[2] Silberman, E. "Experimental Studies of Supercavitating Flow about Simple Two-Dimensional Bodies in a Jet" Journal of Fluid Mechanics 5:pp 337-354,1959.

FIGURES

(1 through 6)

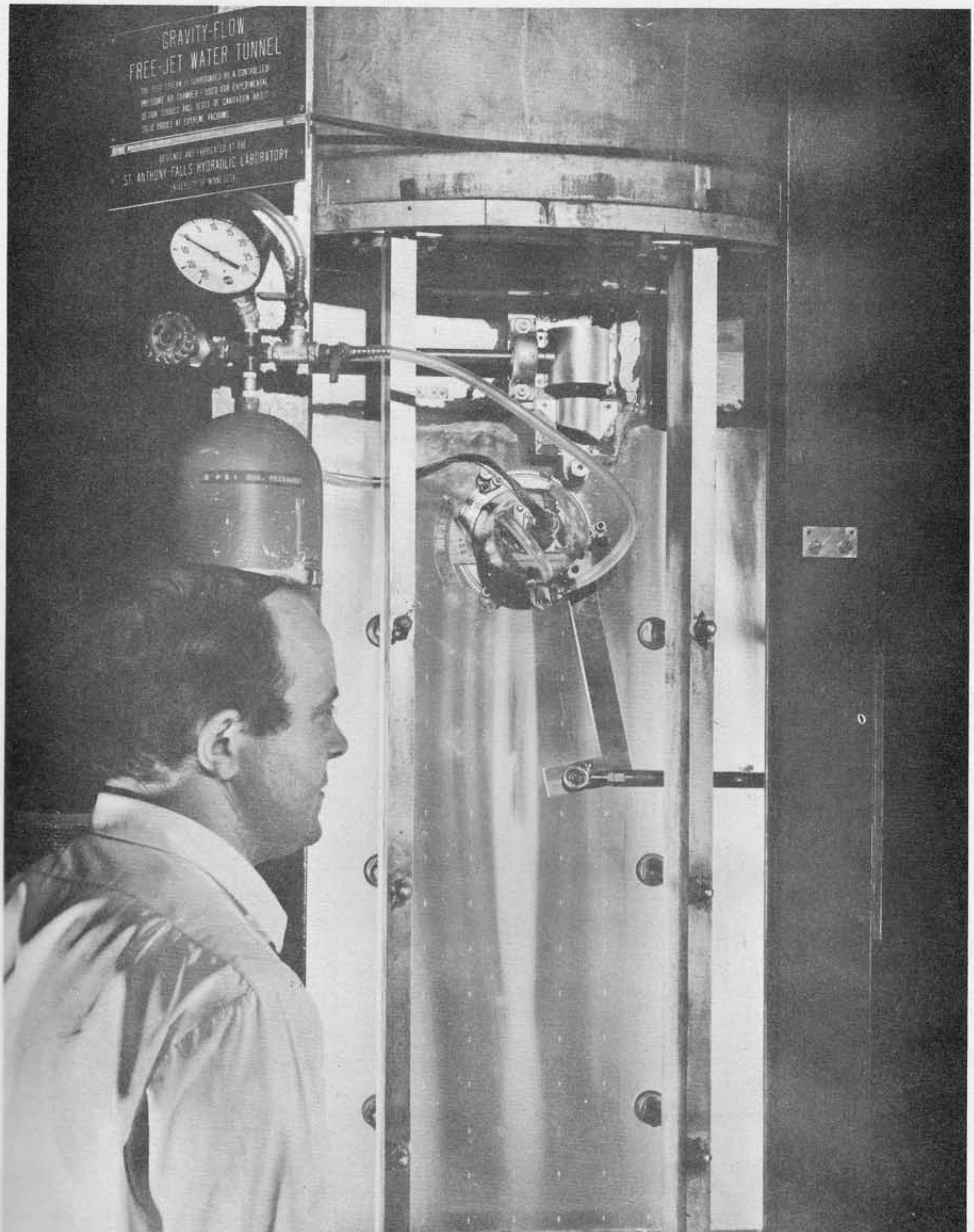


Fig. 1 - Strain Gage Dynamometer Installed in Two-Dimensional Test Section

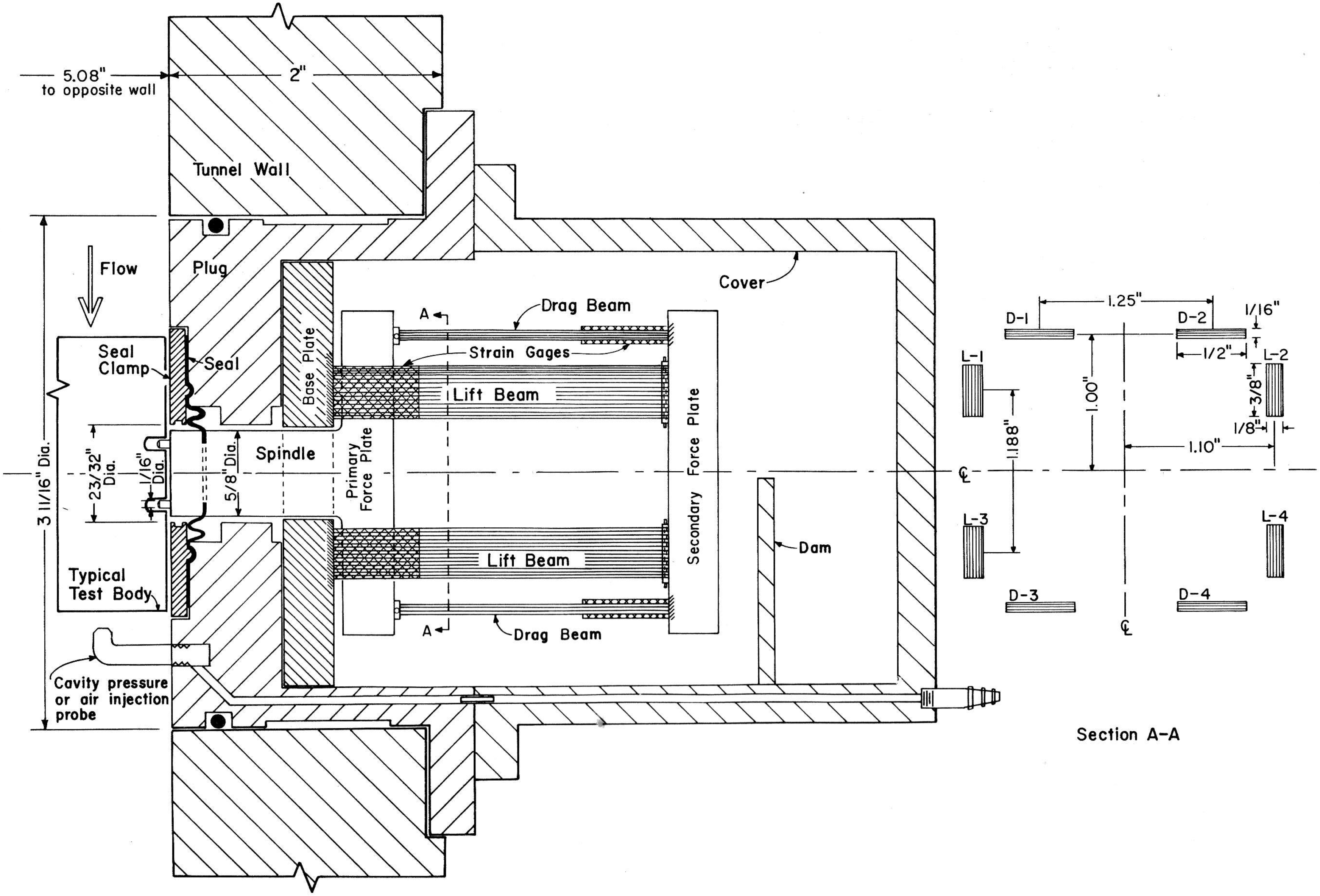


Fig. 2 - Arrangement of Strain Gage Dynamometer

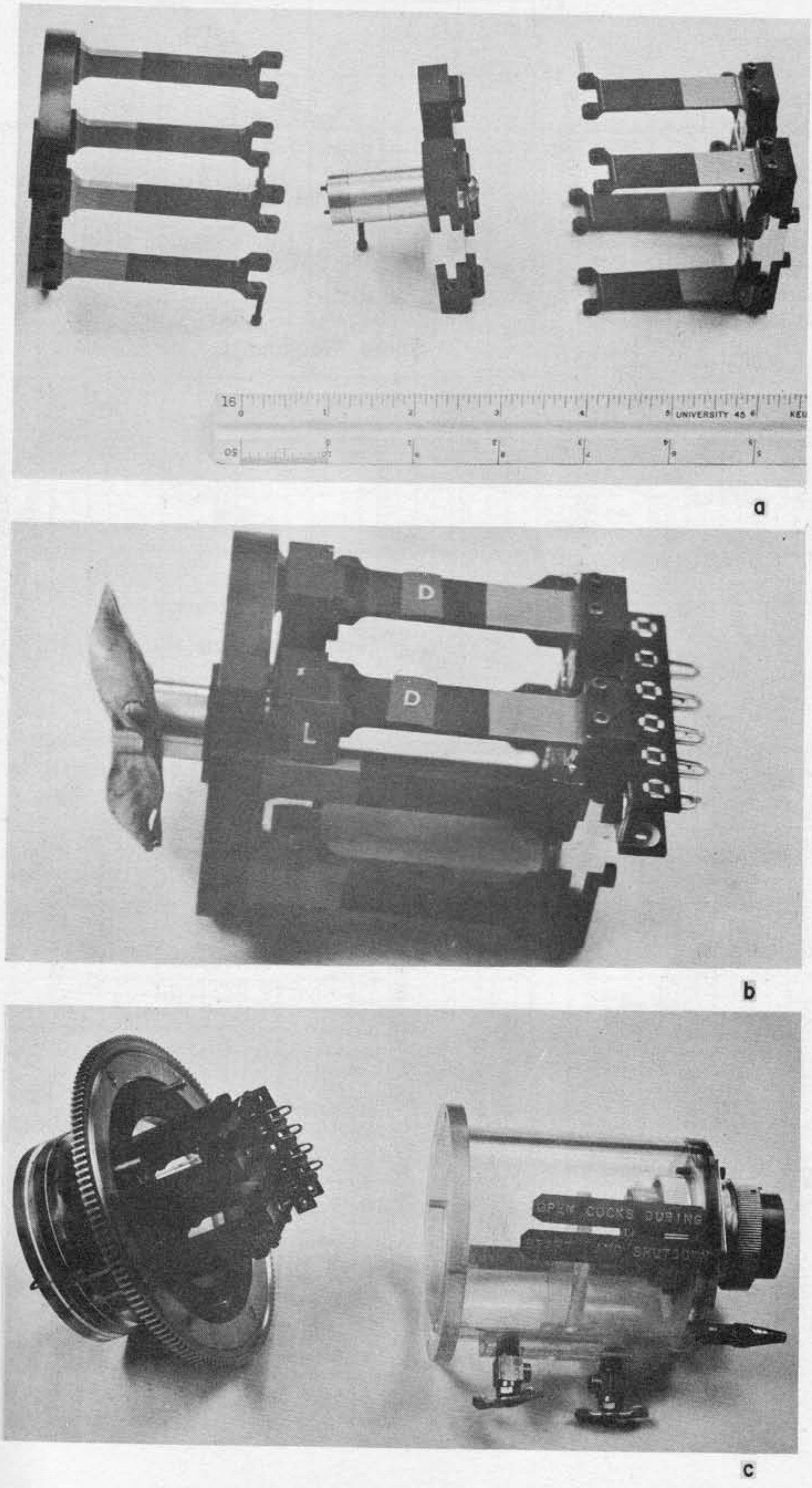


Fig. 3 - Assembly of Beams and Other Components

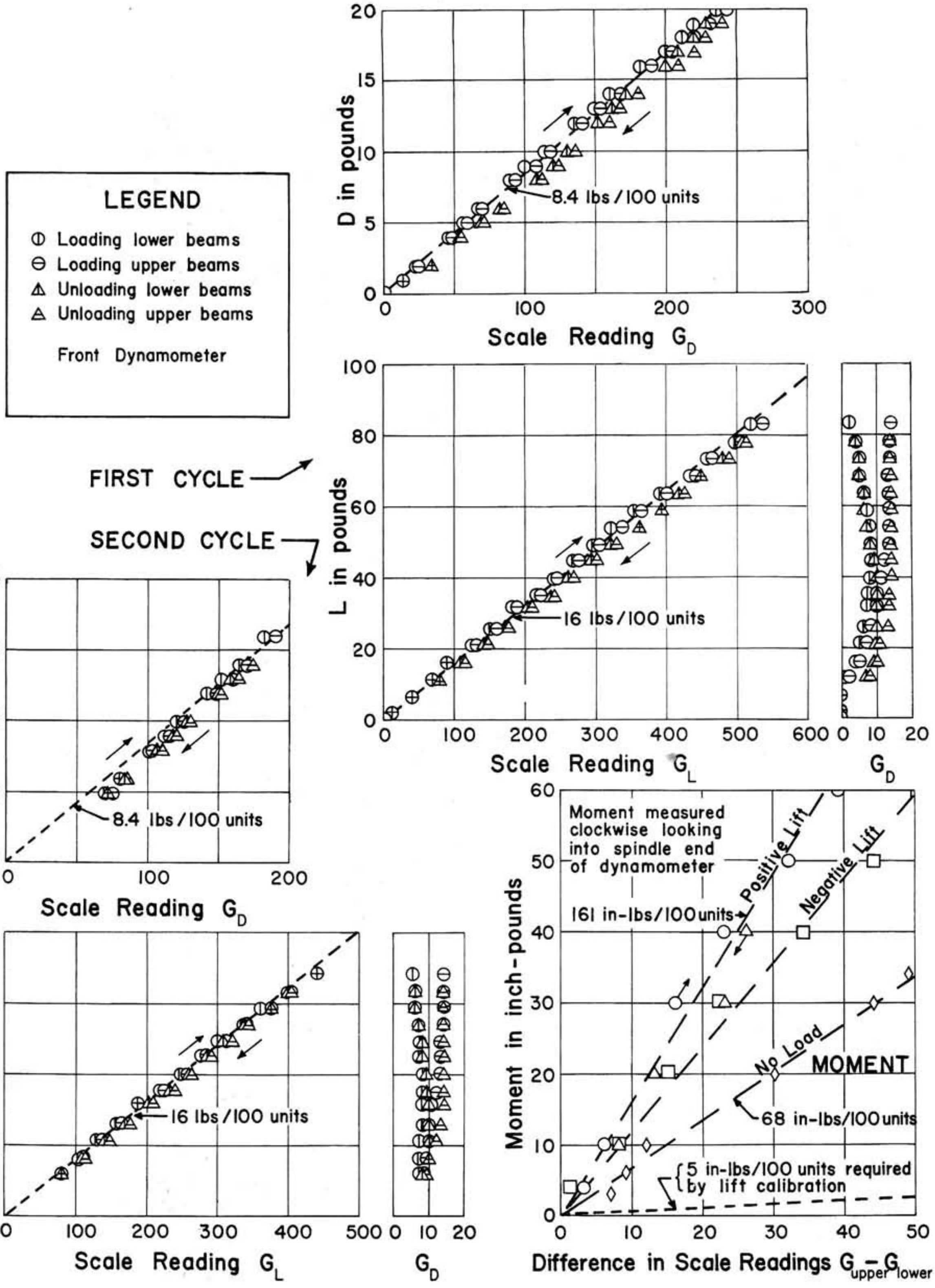
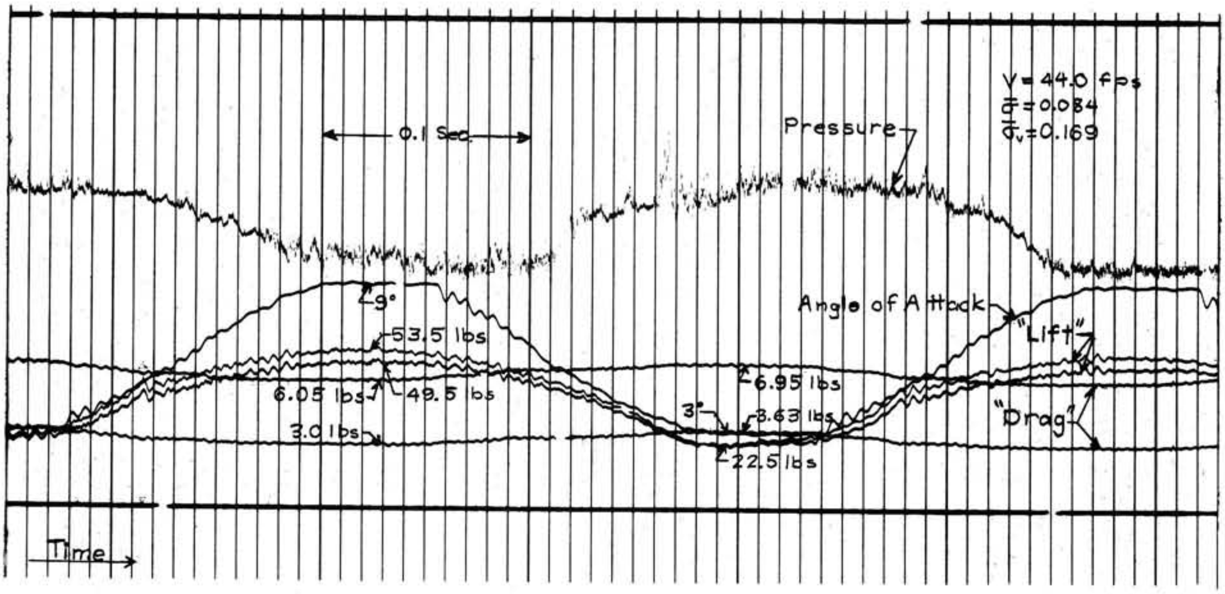
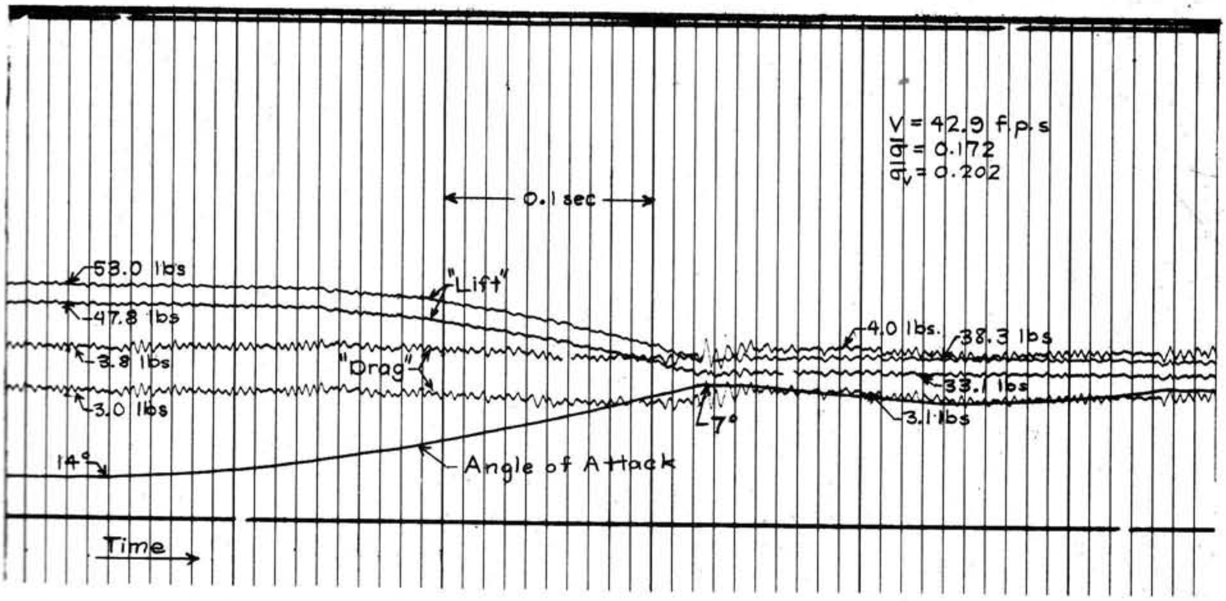


Fig. 4 - Typical Calibration Curves



(a) Oscillating foil



(b) Linear change in angle of attack

Fig. 5 - Oscillograph Records from 2-in. Flat Plate Hydrofoil

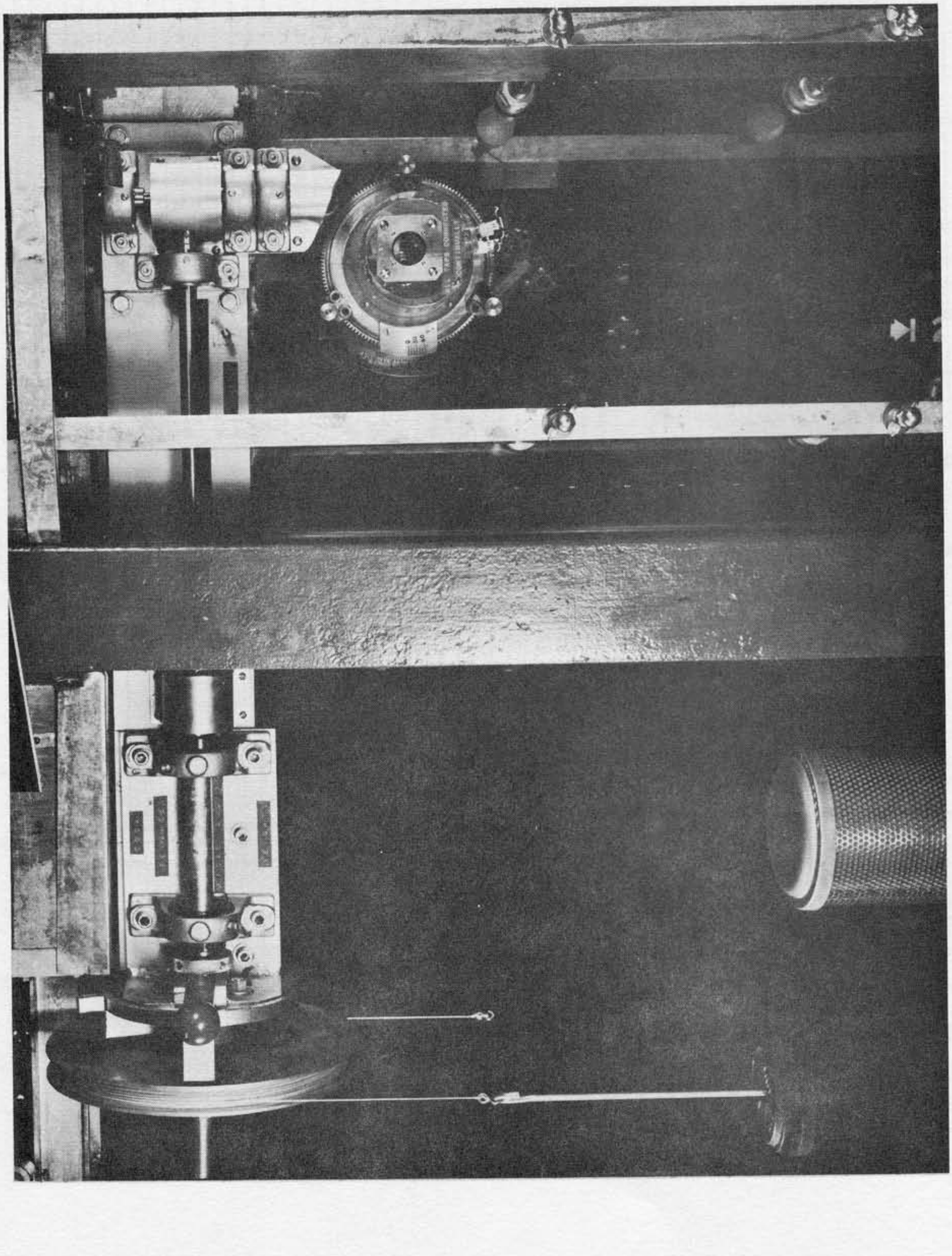


Fig. 6 – Weight Motor for Changing Angle of Attack

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