WIND TUNNEL BALANCE

By

WILLIAM D. LENG

Bachelor of Science

Lehigh University

Bethlehem, Pennsylvania

1953

Submitted to the faculty of the Graduate School of
the Oklahoma State University
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE
May, 1960

WIND TUNNEL BALANCE

Thesis Approved:

Ladislaus J. Fila

Thesis Adviser

J. H. Boggs

Robert MacVicar

Dean of the Graduate School

PREFACE

Progress in any field of engineering is dependent upon the application of well tested concepts and theories. In the field of aerodynamics, the primary testing device is the wind tunnel, an integral part of which must be an adequate balance system.

In preparing to write this thesis, I conducted a library study of the balance systems that have been used in other wind tunnels. The major problem I encountered in conducting this study was the fact that very little new work has been done in the field of subsonic aerodynamic testing since the advent of supersonic aerodynamics. As a result I was forced in some instances to work with literature and concepts up to 50 years old.

I wish to acknowledge my indebtedness to Professor L. J. Fila for his patient and considerate counsel and guidance throughout the preparation of this thesis. It was through his suggestion that I became interested in this subject.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I

THE PROBLEM

The wind tunnel under consideration in this thesis is located in the Mechanical Engineering Laboratory of the Oklahoma State University. The tunnel was built in 1939 by engineering students of that era.

A detailed description of the tunnel design need not be considered, as the primary concern here is the balance system. Briefly, the tunnel is of the open throat, return flow type. Its elliptical test section is 36 inches wide and 18 inches high. The distance, along the direction of flow, between the entrance and exit bellmouths is 27 inches. (King & Boggs, 1948).

The present balance system is a wire type balance with the supporting wires transmitting the loads to three overhead balance type scales. The measurements taken from these scales yield lift, drag and pitching moment information. Hence, the system allows three degrees of freedom. In addition, there is a rigid stinger adaptation which yields more reliable results where only drag information is required. This adaptation utilizes one of the overhead scales for its measurements. (King & Boggs, 1948).

While this balance system has proved satisfactory for instructional purposes, present thinking is that the usefulness of the tunnel is limited and that the stature of the College of Engineering can be enhanced by modernizing the balance.

The present wire balance has several disadvantages. Among these are:

1) Testing is restricted to three degrees of freedom. There is no provision to measure side force, rolling moment or yawing moment.

2) Model oscillations become severe. There is no means to damp oscillations of the three component balance. The oscillations become severe enough so that their effect on force measurement becomes questionable. The single degree adaptation for measuring drag only is equipped with a viscous dashpot which successfully damps out oscillations over a limited velocity range.

3) Excessive time is required to change models. Each time the model is changed, considerable rerigging is necessary.

4) Excessive manpower is required to operate the tunnel. Efficient operation requires approximately five men. In the training situation the manpower requirement is not objectionable. In the research situation however, this requirement can be a severe handicap.

5) Accuracy is questionable. Certain test data yield results which would be unacceptable in any other than the training situation.

Before a proposed balance system may be properly evaluated, there should be established a set of criteria against which the characteristics of the balance may be judged. The set may be conveniently broken into two parts. The first part includes the criteria which are used as a guide for selecting the basic type of balance. These criteria are selected on the basis of their application to the installation under consideration, and have already been used to eliminate some basic types from the ensuing discussion. The second part includes the criteria which apply to balance systems in general and which are used to determine how well the final design performs its intended function. Since the properties included in the second part of the set are closely related to the final design of the balance system, they will be discussed only in general terms in this design proposal. In some respects the second part overlaps the first.

The criteria which make up the first part of the set are:

1) The system must allow greater flexibility. A balance with six degrees of freedom shall be considered most desirable, and one with four degrees shall be minimum.

2) The system should allow operation of a complete test by one person. This will imply arrangement of all controls and all indications on one control panel.

3) The system should allow a variety in the type of test to be conducted, such as complete aircraft testing, component testing, boundary layer control testing, etc.

4) The sensing devices should be arranged so that simultaneous reading of all forces is possible.

5) Each degree of freedom should have a means of damping out undesirable oscillations.

6) Since the tunnel is used as an instructional device, the construction of the balance must be durable and the operation simple. There should also be an easy and quick means of changing the model.

The criteria which make up the second part of the set are primarily those recommended for this purpose by Pankhurst and Holder (1952).

1) Accuracy is the correct measurement of the applied load. This implies precision and requires knowledge of the geometry of the balance

and of the corrections that must be applied to compensate for distortion. Friction must be kept to a minimum in instances where it will interfere with measurements.

2) Sensitivity is the ability of the balance to sense and properly indicate small changes in relatively large loads. Sensitivity is closely related to accuracy.

3) Stability is the tendency of the balance to return to the undisturbed position following a displacement from a balanced condition.

4) Damping is the slowing or stopping of the oscillatory motion of the system, usually by dissipating the kinetic energy of motion into heat. Excessive damping causes the system to be sluggish, while insufficient damping causes difficulty in obtaining an exact balance.

Pavian (1940) includes variations of these criteria in a list of requirements which also contains some of the items in the first part of the present set.

Pankhurst and Holder (1952) also recommend the use of the period of oscillation as a criterion of quality, but specify that this characteristic is only of concern when the available operating time is short. Since the OSU wind tunnel is capable of continuous operation, the period need not be considered here.

The objective of this thesis is to offer, for future design consideration, a proposal of a balance system for the OSU wind tunnel. The problem then becomes one of studying the types of balance systems in general use and selecting the system that most adequately satisfies the established criteria.

CHAPTER II

BALANCE SYSTEMS

A search of the available literature indicates that there are three basic types of balance system worthy of consideration. The three types, each named according to its load carrying members, are: wire, platform and yoke. (Pope, 1947).

WIRE BALANCE

In a wire balance, the model is supported by wires which are connected to the scales (Fig. 1). The wires are generally directed upwards with the scales mounted overhead. Wires which sense forces in the horizontal plane, such as drag and side force, have their forces translated to a vertical direction through the use of a stay or a bracket mounted at 45 degrees to both the horizontal and the vertical directions. The model must be mounted in such a way that the lift forces will not slacken the wires. This is accomplished either by mounting the model in an inverted position, or by using a model heavy enough so that the weight is always greater than the lift.

The wire balance is by far the easiest to design and to build. Certain precautions must be taken in the design to insure that the sensing wires will remain parallel throughout the range of displacements over which the balance is used.

Damping the oscillations of a wire balance can be accomplished easily by attaching dashpots directly to the scales.

Changing the model in a wire balance generally is a time consuming operation. Most applications require at least a partial dismantling of the wire rigging at each model change.

A system that has been used in the Boeing Aeronautical Laboratory at the University of Washington eliminates the need for dismantling the wire balance at model change. (Farquharson, 1926). This system makes use of two skids mounted in and, at zero angle of attack, parallel to the wind stream. The skids are directly supported by the mounting wires and the model is secured to the skids. The procedure of changing models merely involves removing one model from the skids and securing another.

A serious disadvantage of the skid system is the tare drag and interference effect of the skids. At large angles of attack, either positive or negative, the tare drag in particular can become excessive.

The wire supports also introduce tare drag forces which can become excessive. Measuring the drag forces on the supporting wires is a difficult task and can not normally be accomplished with a consistent degree of accuracy.

Wires are more subject to unexpected breakage and joint separation than are other supporting shapes. Such breakage can result not only in loss of time, but also in damage to the model and to the testing equipment.

PLATFORM BALANCE

The platform balance consists of a platform or main frame which is mounted below the test section (Fig. 2). In the case of a closed throat tunnel section, the platform is mounted outside the tunnel walls.

The platform can be supported by three or four legs which are linked to the sensing devices.

The model is secured to the platform by a strut or a system of struts. Since the struts form an integral part of the balance system, there are no rerigging or alignment problems associated with changing models. One model is readily removed from the struts and another put in its place. On a platform balance, the model may be mounted in an upright position, since the weight of the model and platform combination can be made to exceed the maximum lift of the model.

An outstanding disadvantage of the platform balance is the fact that the resolving center is not located at the model but rather at the base of the strut. Moments cannot be read directly, but must be transferred from the resolving center to the model.

Rolling and yawing moments on the platform balance are sensed as small differences in rather large forces. This is inherently a poor situation and leads to large, frequently intolerable errors.

In order to reduce the errors in these moments, the asymmetric platform balance has been developed (Fig. 3). This balance is rigged so that three of the forces are read acting through the resolving center. In this case the moments are sensed as single forces rather than as the differences between forces. Much greater accuracy results when the subtraction process is eliminated.

YOKE BALANCE

The yoke balance is quite similar to the platform balance but is considerable larger since it must span the test section (Fig. 4).

The major advantage of the yoke balance over the platform balance is the fact that the model is mounted at the resolving center. Thus the moments need not be transferred but can be read directly. The large size of the yoke however, gives rise to long lever arms and in some instances, to large deflections.

Other characteristics of the yoke balance parallel those of the platform balance and need not be repeated. The yoke may also be designed asymmetrically in order to reduce the errors in reading moments (Fig. 5).

In comparing each of these types of balance with the established set of criteria (Chapter 1), it is seen that each type can be designed to provide six degrees of freedom, to allow centralized arrangement of the controls and indications, to permit simultaneous reading of all forces, and to allow damping in each degree of freedom.

However, the wire balance is at a disadvantage in the variety of tests that can be run. Testing of components such as vertical stabilizers or nacelles might require the use of additional wires or stingers which would increase the tare drag and interference of the system. Introduction of equipment for boundary layer control testing would also increase the tare drag and interference. Therefore, the wire balance is eliminated from further consideration.

The remaining balance types, the platform and the yoke, are equally satisfactory from the aspect of component and boundary layer control testing. Components can be easily mounted on the usual struts and the pressure or vacuum tubes necessary for boundary layer control testing can be introduced through these same struts with no increase in tare drag or interference. Strut arrangements will be considered in more detail in the next chapter.

In terms of simplicity of operation, the yoke balance is superior to the platform. This is so because the model on the yoke is located at the resolving center of the balance and there is no need to transfer moments. Therefore, the platform balance will be eliminated from further consideration.

A choice must now be made between the symmetric and the asymmertic design of the yoke balance. In the preceding discussion it was mentioned that with the symmetric design, moments are read as relatively small differences between large forces. This gives rise to mathematical errors which can be eliminated through the use of the asymmetric design.

Thus the asymmetric yoke is chosen as the basic type balance to be considered in the remainder of this thesis (Fig.5).

CHAPTER III

THE ASYMMETRIC YOKE BALANCE

It is now necessary to consider in detail some of the characteristics of the asymmetric yoke balance.

The basic purpose of the balance system is to resolve the total force and moment acting on the model into three force components and three moment components. The desired force components are those acting along the standard wind axes and the desired moment components are those acting about these same axes. (Perkins and Hage, 1949).

Ideally the three forces should each be measured by a single force reading directed along the appropriate axis and the three moments should each be measured by a single torque reading about the appropriate axis. This system would require that drag measuring equipment be placed in the wind stream, thus increasing the tare drag and interference of the balance. Also, the torque measuring equipment would ultimately produce directed force components which would effect the forces measured at the model.

Consequently, it is necessary to design the balance so that the aerodynamic forces are determined by summing certain measured forces and the aerodynamic moments are determined from the measured forces and the known geometry of the balance. Of the variety of possible arrangements for reading the forces and moments on the model, any one should be as satisfactory as any other for reading the forces. For reading the moments however, there may be some advantage in one arrangement over another. The choices available for the individual moments are:

Pitching moment - may be sensed by lift or drag forces (Fig. 6a & 6b).

Rolling moment - may be sensed by lift or side forces (Fig. 7a & 7b).

Yawing moment - may be sensed by drag or side forces (Fig. 8a & 8b).

Figures 6a and 8b indicate the use of stingers in sensing various forces. In order to reduce distortion under load to a minimum, these stingers would have to be relatively large and therefore relatively heavy. This added weight would disturb the balance of the yoke which, without the stingers, is symmetric with respect to a lateral plane through the center of gravity of the yoke. For this reason, the use of stingers should be avoided.

If the yoke is designed without stingers, the pitching moment is sensed as shown in Fig. 6b, and the yawing moment is sensed as shown in Fig. 8a. Both of these moments are sensed by drag forces.

Figures 7a and 7b illustrate the unbalanced nature of the asymmetric yoke balance. With the lift force measured by a single support as shown in Fig. 7b, the balance would tend to be unstable in a lateral plane. This situation can be avoided by measuring lift with two supports as shown in Fig. 7a. With this arrangement, the rolling moment is sensed by the lift forces, also as shown in Fig. 7a.

With the moments sensed in the manner described above, there are already sufficient readings available to provide complete lift and drag information. There remains the side force which can easily be sensed by one force measurement as shown in Fig. 7a and in Fig. 8a.

Figures 6b and 8a indicate that a minimum of two drag measurements are required. If only these two drag measurements are used, the possibility exists that there can develop an instability or lack of rigidity about an axis joining the points of application of the two lift measurements shown in Fig. 7a. This possibility can be eliminated by the use of a third drag measurement as shown in Fig. 5 and as recommended by Pope (1947). Accordingly, the forces represented by D_2 in Fig. 6b and in Fig. 8a represent the sum of two parallel forces.

With the yoke and its supports arranged as described above, the force and moment operating on the model are resolved into the six desired components. The measurement of these force components by adequate force measuring equipment will be discussed in the following chapter.

In the preceding chapter, brief mention was made of the struts by which the model is attached to the yoke. These struts should also be considered in more detail.

Since the struts provide the means of supporting the model, they must in some way be exposed to the wind stream and thus have a tare drag and interference effect. The tare drag may be reduced by the use of shields which are attached to the tunnel floor. Poorly designed shields can generate interference effects which are more undesirable than the tare drag effects which the shields relieve. Accordingly, the strut and shield combination must be carefully designed to allow a minimum of both tare drag and interference.

Successful strut systems have been designed using one or three struts. The single strut can attach to the model at one point directly below the center of gravity of the model, or it can branch into a fork with the two prongs of the fork attaching to the under side of the model along the lateral axis of the model. The single strut can also be provided with an adjustable prong which attaches to the aft portion of the model and which is used to control pitch. The entire strut can be rotated to provide yaw control. A simple but satisfactory single strut with a pitch control arrangement has been used at Virginia Polytechnic Institute and is well described by Seltzer (1947).

The three strut system uses two struts attached to the model along the lateral axis and the third attached to the aft portion of the model. The third strut is used to control pitch. The three strut system is capable of supporting larger and heavier models than the single strut, but will in general have a more pronounced tare drag and interference effect. The three strut systems can also be rotated to provide yaw control but, in general, requires more elaborate mechanism than the single strut.

For the small size models used in the OSU wind tunnel, a single strut should be adequate and is recommended in preference to a three strut system. The single strut should be provided with both pitch and yaw control.

CHAPTER IV

FORCE MEASUREMENT

In the preceding chapter, the means of resolving the force and moment operating on the model into useful force components were discussed. The discussion in the present chapter will concern the method by which the magnitudes of these force components will be measured.

Basically, there are three methods of measurement which should be considered. These are mechanical, electrical and pressure measurement.

MECHANICAL MEASUREMENT

In mechanical measurement, the force components are transmitted through linkages such as push rods, bell cranks or cables to weighing units. The weighing units might be balance beams or spring scales and would read the magnitudes of the forces directly.

A balance beam may be as simple or as elaborate as desired. A simple balance beam in common usage is the laboratory scale which must be balanced manually for each reading. A more elaborate balance is the automatic type beam which has a reversible electric motor to position the counter weight. The electric motor can be operated by an electric circuit which senses the deflection of the beam from a balanced position (Fig. 9). This makes balancing of the beam continuous and automatic for every reading.

Balance beams have one basic characteristic which makes them quite attractive for wind tunnel work - they are neutral reading. That is, at the time the force reading is taken from the balance, the beam, and hence the model in the tunnel, is returned to a previously determined neutral position, assuming elastic deformation and friction effects are negligible. On the other hand, they have a characteristic which can be a detriment. Since they depend upon the forces of gravity, all components from the balance must be resolved into a vertical plane. This requires the use of mechanical linkages which are subjected at every pivot point to friction losses. Adequate design can make these friction losses negligible.

Spring scales have been successfully used for force measurement in wind tunnels. (Pankhurst & Holder, 1952). Since spring scales depend upon elastic deformation for force measurement, some means must be provided for returning the model to a neutral position while a reading is taken. This is done by mounting the "free end" of the spring on an adjustable base (Fig. 10). This free end adjustment can be made automatic much the same as the balance beam is made automatic.

The characteristics of the spring scale give it advantages and disadvantages somewhat the reverse of those for the balance beam. Since the spring scale operates independently of gravity, it can be mounted in any position. There is no need to resolve forces into vertical components and one source of friction loss is eliminated. However, spring scales are not neutral reading. Corrections for this quality must be designed into the system, as previously discussed.

ELECTRICAL MEASUREMENT

Strain gages are in common use for measurement of deflections in structural members. If the deflected members are strained within their elastic ranges, the amount of strain and the known character of the material under strain measure the magnitude of the force causing the strain.

Three types of strain gage are readily available. They are resistive, capacitive and inductive. (Pankhurst & Holder, 1952).

Resistive strain gages measure the change in resistance of the strain gage which is caused by distortion of a resistor. Capacitive strain gages measure the change in capacitance of a capacitor caused by changing the separation between the plates. Inductive strain gages measure the change in inductance of an inductor caused by changing the position of a core in the center of the coil (Fig. 11).

The operation of strain gages demands distortion from a known position. This distortion can be made arbitrarily small so that it can be assumed to be negligible as far as the aerodynamic attitude of the model is concerned. The small amounts of distortion which are permitted mean that the changes in resistance, capacitance or inductance will also be small. Consequently some form of electrical amplification must be used. The amount of amplification used is determined from consideration of the permissible deflection, the change this deflection makes in the strain gage and the size of indication desired per unit distortion.

Using strain gages for force measurement permits the main frame of the balance to be attached directly to a fixed base. The strain gages are used to sense the deflection of the supporting members. With this arrangement friction losses from mechanical joints are completely eliminated.

PRESSURE MEASUREMENT

Through the use of either piston or bellows arrangements, the force components may be converted to fluid pressures which are easily measured with pressure gages. The fluid may be a gas such as compressed air, or a liquid such as light oil. The use of a gas would generally permit greater piston or diaphragm deflection than would the use of a liquid and would also require compressing equipment. Accordingly, gas will be eliminated from the remaining discussion. The discussion will also be limited to bellows or diaphragm type devices rather than to pistons.

The capsules which are used to convert the forces into pressures may be designed as sealed units or they may be designed to require a steady flow of fluid under constant pressure (Fig. 12). The former generate pressure within themselves as they are compressed. The latter depend upon a dynamic reaction between a diaphragm and a flowing fluid. The fluid flow is controlled by a variable orifice.

Each type of pressure system depends upon a small deflection for its operation. The deflections involve distortion of either a diaphragm or a bellows. The system may be designed so that the deflections and the losses associated with the distortions are negligibly small or so that they may be calibrated out of the final design. Since the fluid capsules may be used to connect the main frame of the balance directly to a fixed base, losses from friction in mechanical joints are eliminated.

The dynamic type capsules require a constant pressure fluid source. This means a hydraulic pump and reservoir system must be provided. Because of this feature, the sealed capsules seem more practical than the dynamic capsules.

In attempting to make a selection from the various force measuring systems discussed, consideration must be given to the time required to obtain a set of readings. With any of the electrical or pressure systems, a useful reading follows a force application almost immediately. With the mechanical systems, there will be a time delay between the force application and the balancing of the system. The time delay may be reduced by the use of automatic equipment but it will still be present. Accordingly, the mechanical system is eliminated from further discussion.

Before making a choice between the electrical and the pressure systems, consideration must be given to the state of the art of strain gage measurement. Strain gage measurement has been developed into perhaps the most versatile method of detecting distortion of structural members. Through proper selection of elasticity, resistance, capacitance or inductance, and amplification, the strain gage method can become the most accurate and most sensitive of the systems discussed here. At the same time it is simple to operate and demands very little in the way of maintenance.

The initial cost of the amplification equipment is perhaps its only forbidding quality. It is not recommended that such equipment be purchased especially for use with the OSU wind tunnel. However, at such time as amplification equipment might become available, it is recommended that the tunnel balance system be modified to permit the use of strain gage measurement.

The remaining method of measurement is the sealed hydraulic capsule. This unit is small and compact and once filled and sealed, requires very little attention. The deflection, accuracy and sensitivity of the capsules may be adjusted during the design phase by varying the cross sectional area of the diaphragm and by varying the total volume of the capsule and the pressure line connecting it to its gage. It has been previously mentioned that there are losses in the capsules resulting from the distortion of the diaphragm. The magnitude of these losses may be regulated by careful selection of the shape and material of the diaphragm.

CHAPTER V

SUMMARY

The objective of this thesis, as stated in Chapter I, is to offer for future design consideration, a proposal of a balance system for the OSU wind tunnel. In the preceding discussions, consideration has been given to types of balance systems, the means of resolving the aerodynamic force and moment into useful force components, strut arrangements for the yoke balance, and measurement devices. The recommendations of this thesis may be summarized as follows: The balance should be of the asymmetric yoke type with force and moments resolved as shown in Fig. 5. The model should be attached to the asymmetric yoke by a single strut which should incorporate mechanism for controlling pitch and yaw. The forces should be measured by sealed hydraulic capsules for the initial installation and, at such time as appropriate amplification equipment becomes available, the forces should be measured by electric strain gages.

Referring to the notation of Fig. 5, the mathematical operations necessary to convert the force readings into aerodynamic forces and moments are:

Lift $= L_1 + L_2$ | Pitching Moment $= (D_1 + D_2) \times h$

Drag $= D_1 + D_2 + D_3$ | Rolling Moment $= L_2 \times b$

Side Force $= S$ | Yawing Moment $= (D_2 + D_3) \times b$

The proposals above satisfy the set of criteria established in Chapter I as follows:

Part I

1) The proposals allow six degrees of freedom.

2) Both the pressure and the electrical measurement systems allow the indications to be conveniently displayed on a central control panel. This control panel should be mounted adjacent to the test section window so that the model and the indications can be observed simultaneously by a single observer.

3) The single strut of the asymmetric yoke can be designed for use with complete aircraft models or with component models such as nacelles or stabilizers. The single strut can also be designed to permit passage of hoses into the model for boundary layer control testing.

4) With hydraulic capsules or strain gages mounted along the force vectors shown in Fig. 5, readings of all forces may be taken simultaneously.

5) With either the pressure or the electrical measurement, simple dashpot damping can be provided for any degree of freedom that oscillates excessively.

6) The asymmetric yoke balance can be designed as a sturdy and durable device while still retaining its simplicity of operation. Since models attach directly to the top of the strut, the process of changing models is reduced to removing one model and securing another.

Part II

1.& 2) Accuracy and sensitivity are considered together here because they are closely inter-related. Attempts to adjust one will generally result in variations in the other as well. Among the factors which can be varied to control accuracy and sensitivity are the weight of the yoke, the physical size of the yoke, the relationship between the volume and cross sectional area of the individual pressure capsules, the fluid pressure within the capsules, and the amount of damping.

3) The stability of the final yoke design is dependent upon the weight distribution of the yoke, the aerodynamic force and moment on the model and the direction and points of application of the supporting forces. In the final design these items must be considered carefully so that any displacement from a balanced position is accompanied by a tendency to return to the equilibrium condition.

4) Damping the undersirable oscillations should be one of the last considerations in the design and construction of the balance. After the other properties of the balance have been adjusted as desired, a simple dashpot should be provided for each degree of freedom in which there is an excessive vibration.

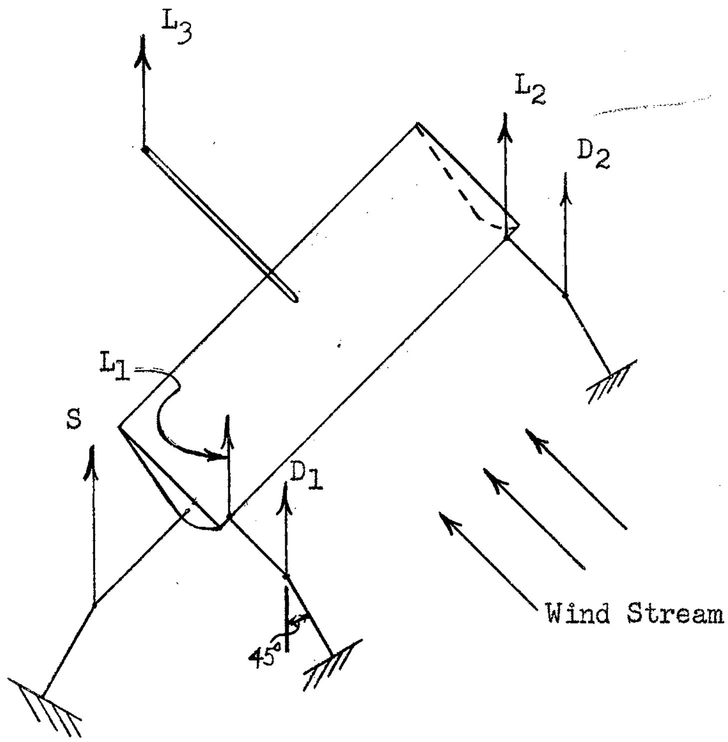


Fig. 1. Wire Balance

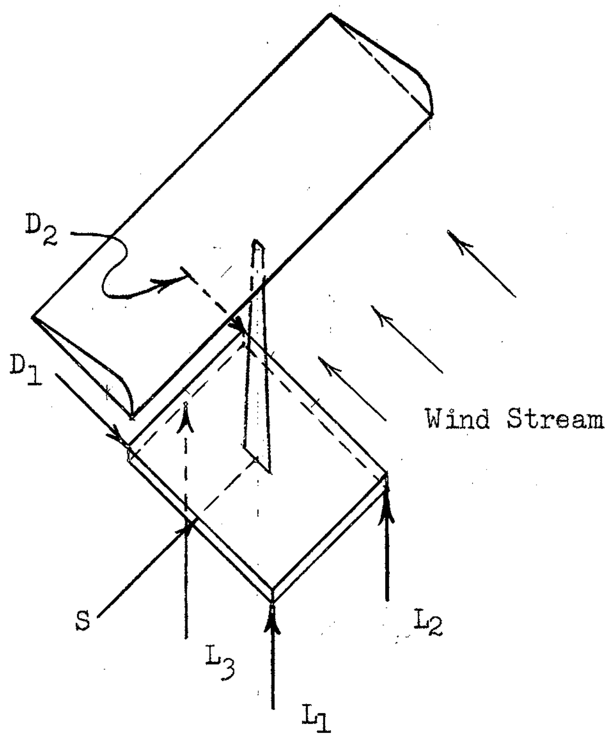


Fig. 2. Platform Balance

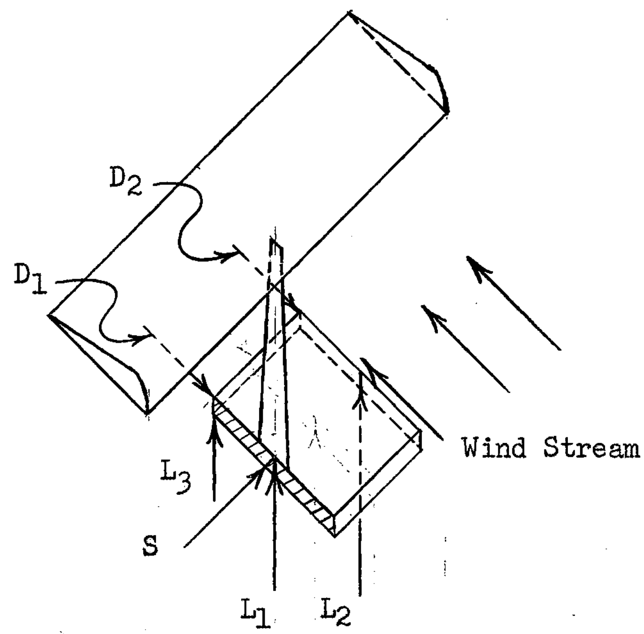


Fig. 3. Asymmetric Platform Balance

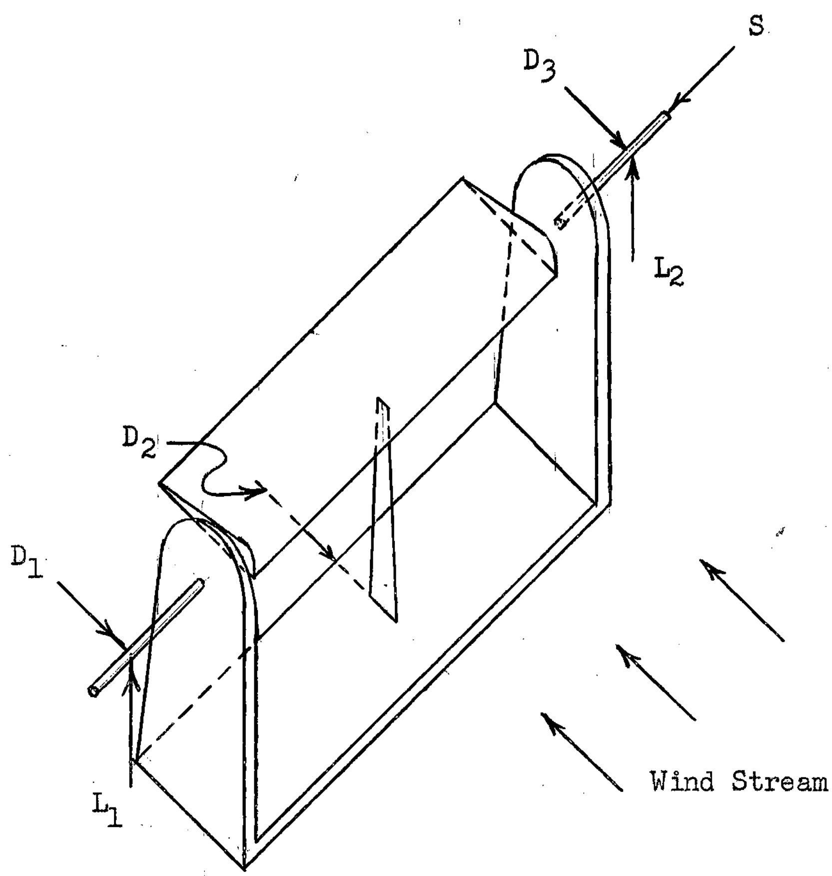


Fig. 4. Yoke Balance

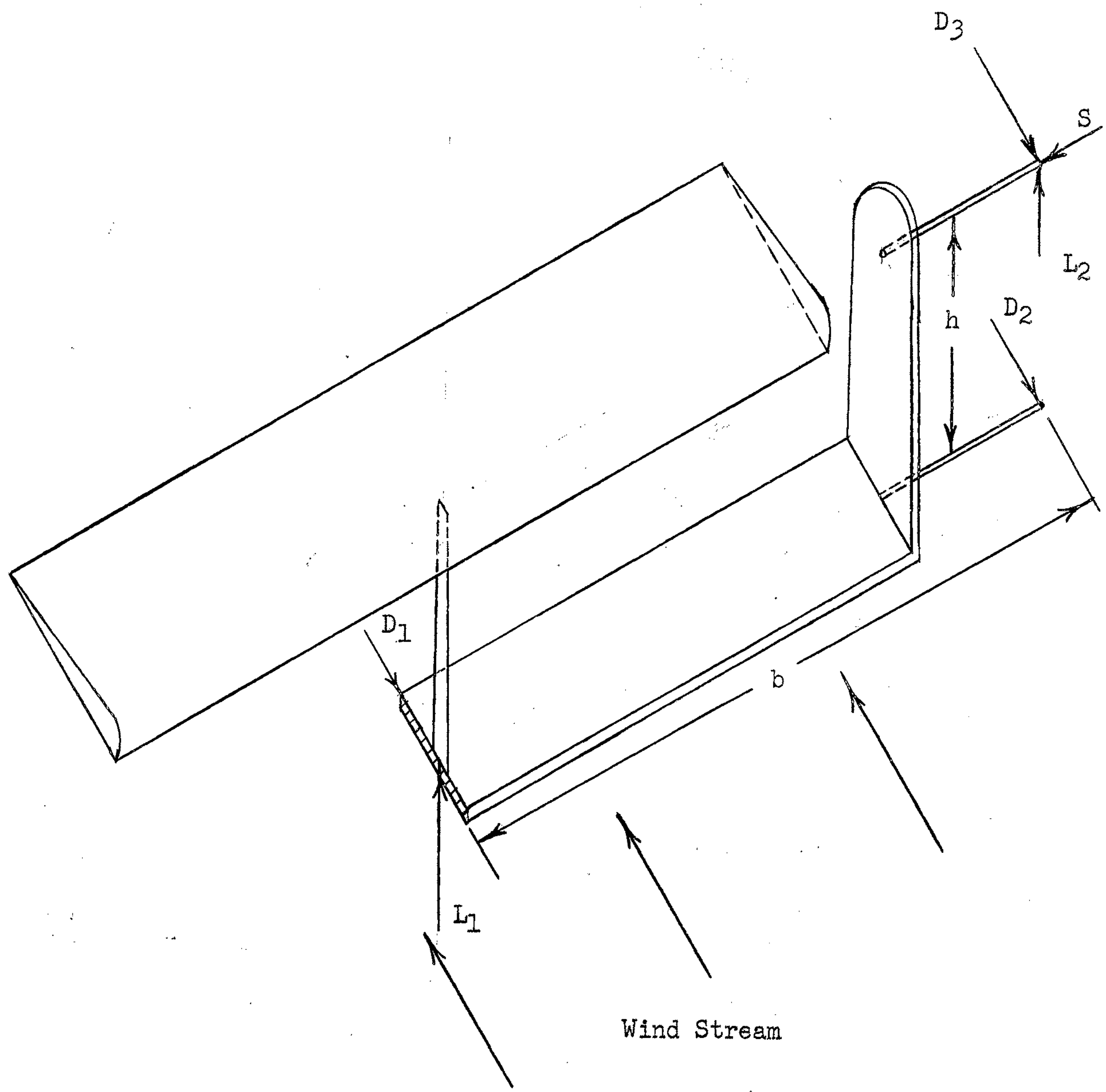
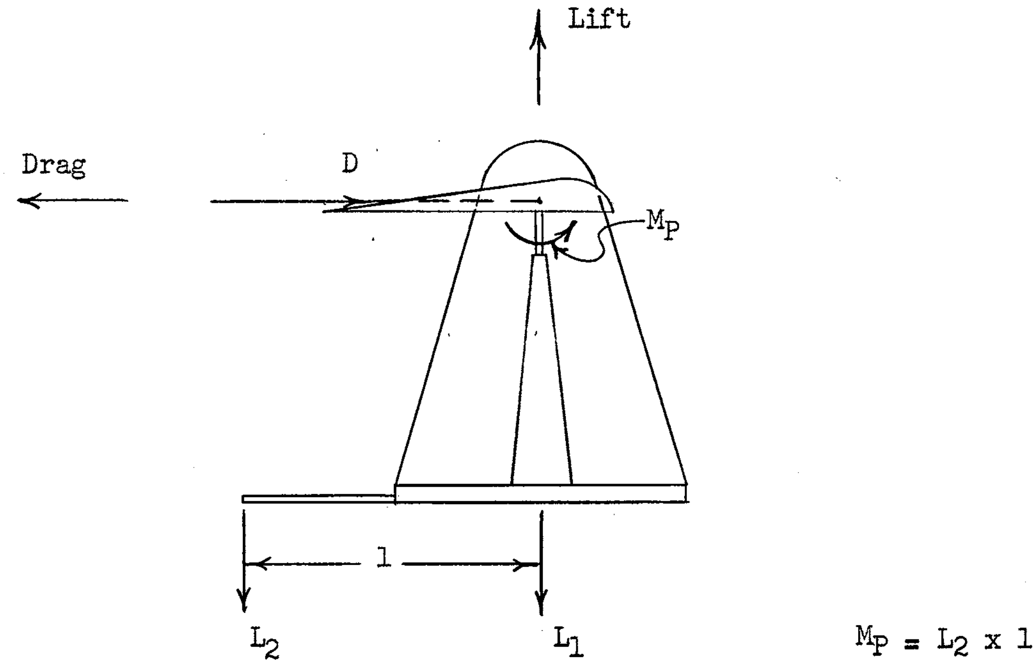
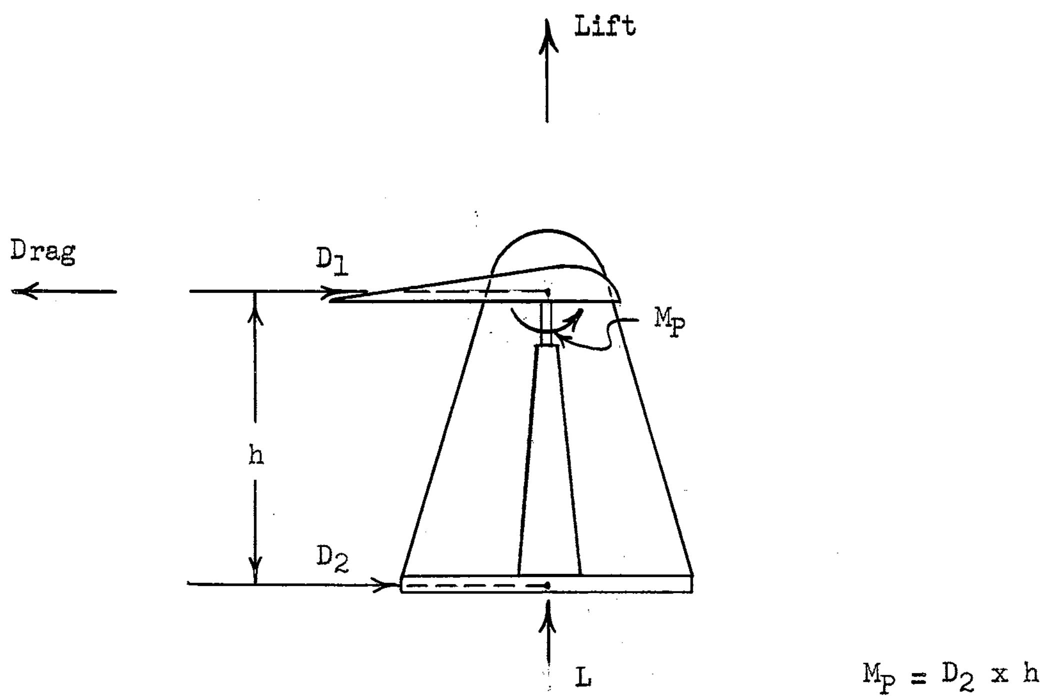


Fig. 5. Asymmetric Yoke Balance

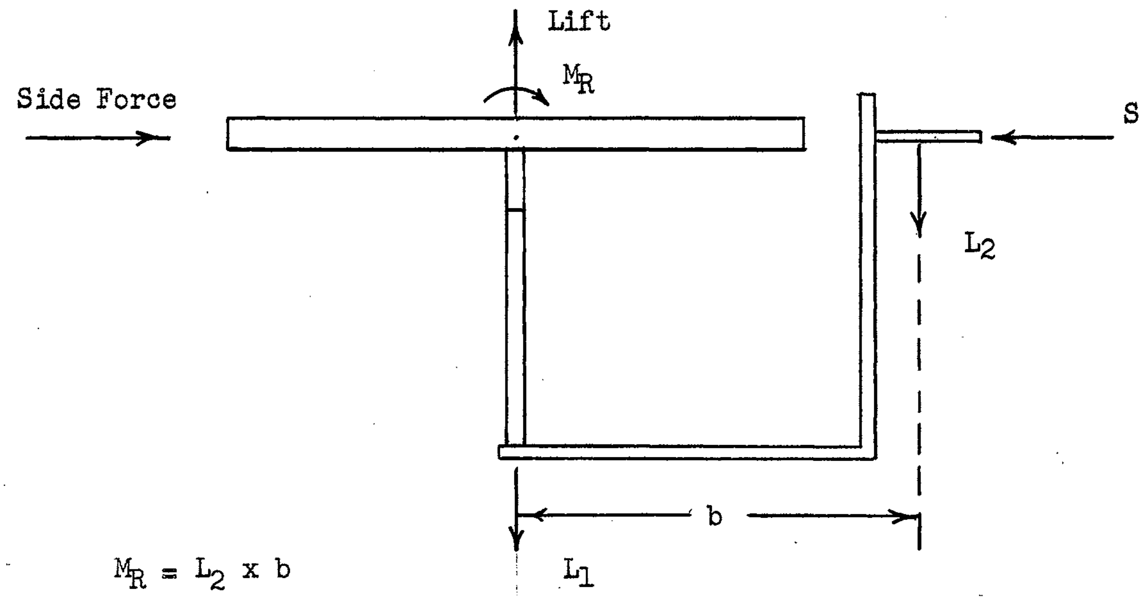


a) Sensed by Lift Forces

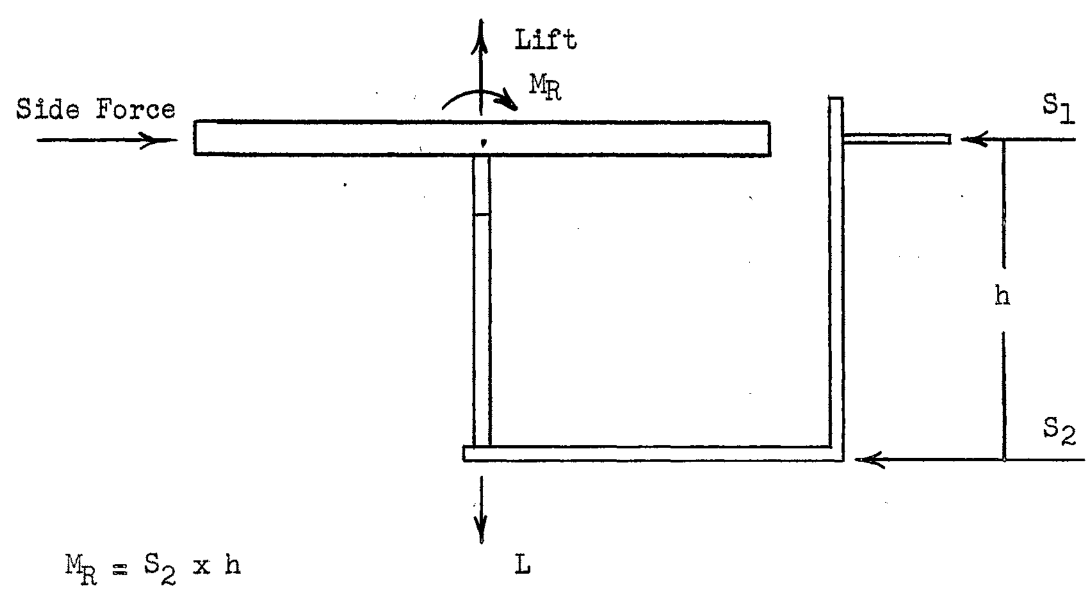


b) Sensed by Drag Forces

Fig. 6. Pitching Moment

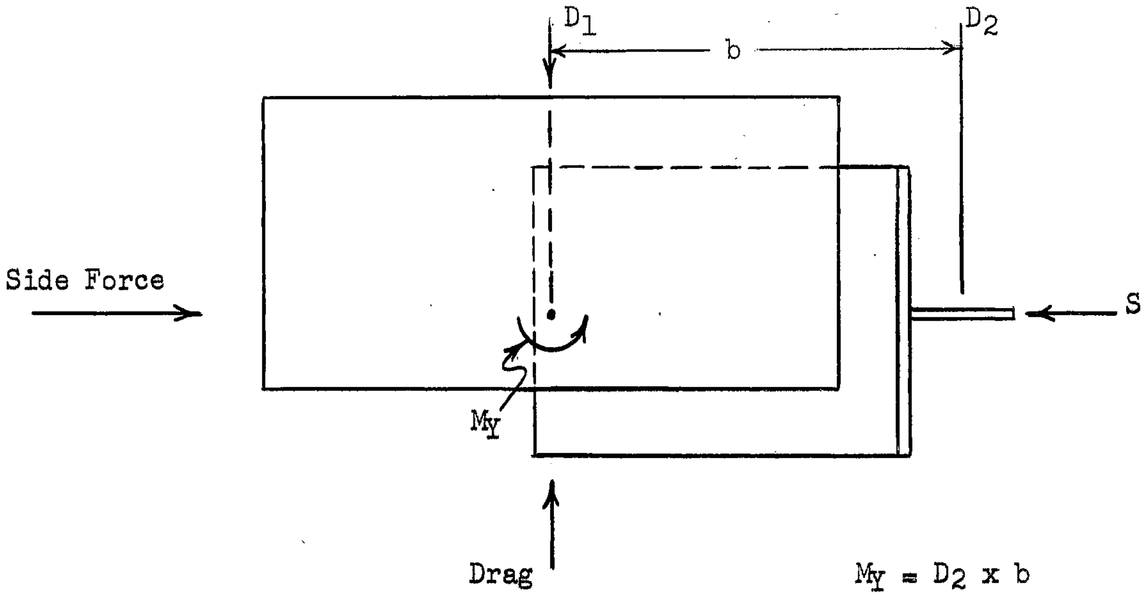


a) Sensed by Lift Forces

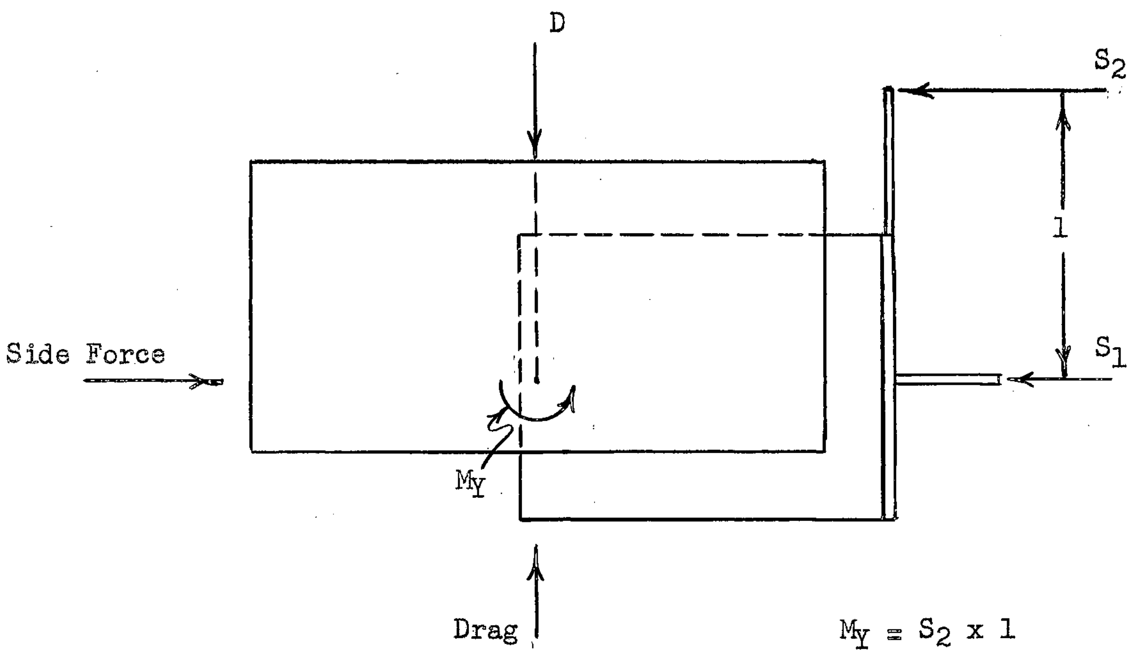


b) Sensed by Side Forces

Fig. 7. Rolling Moment



a) Sensed by Drag Forces



b) Sensed by Side Forces

Fig. 8. Yawing Moment

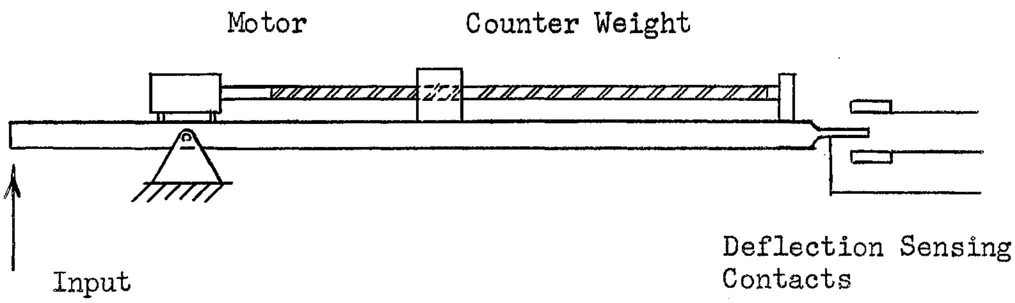


Fig. 9. Automatic Balance Beam

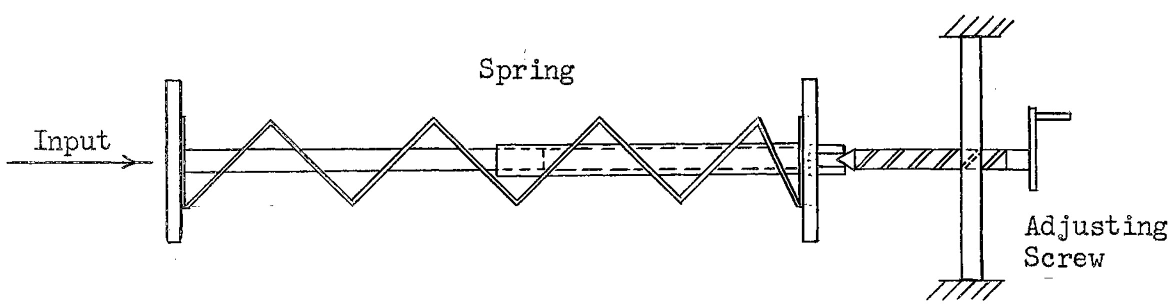
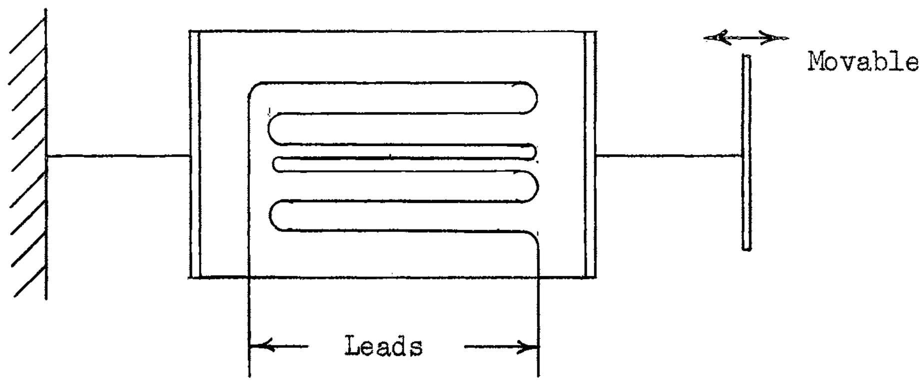
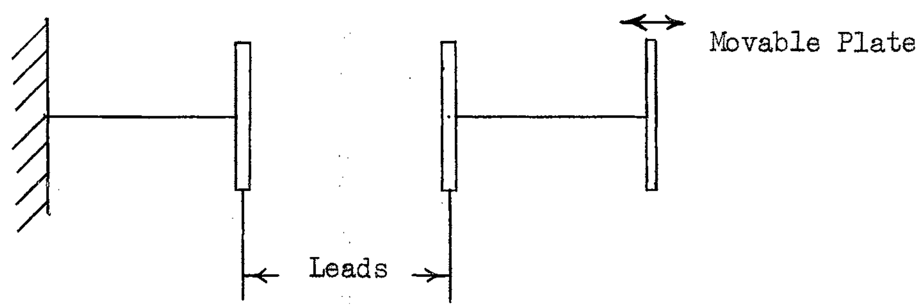


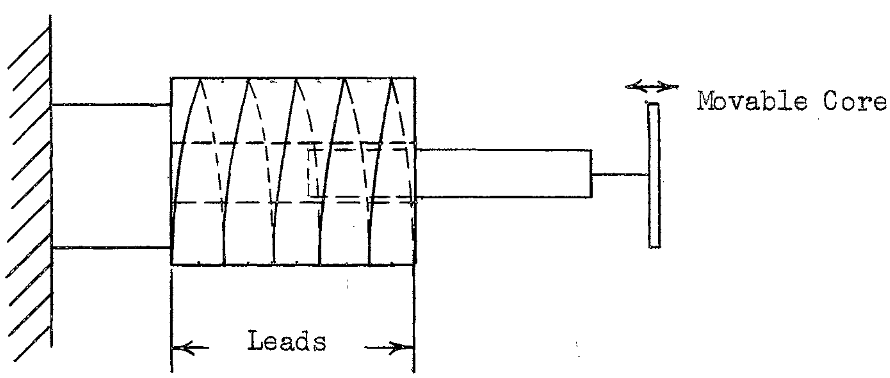
Fig. 10. Adjustable Spring Scale



a) Resistive Strain Gage

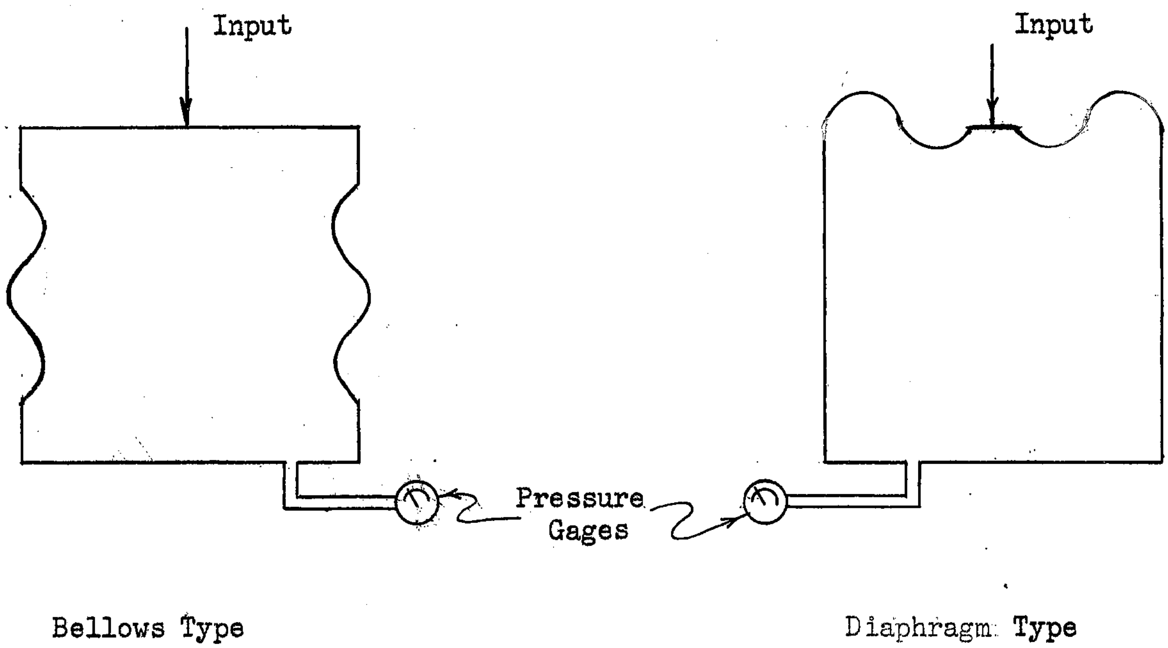


b) Capacitive Strain Gage

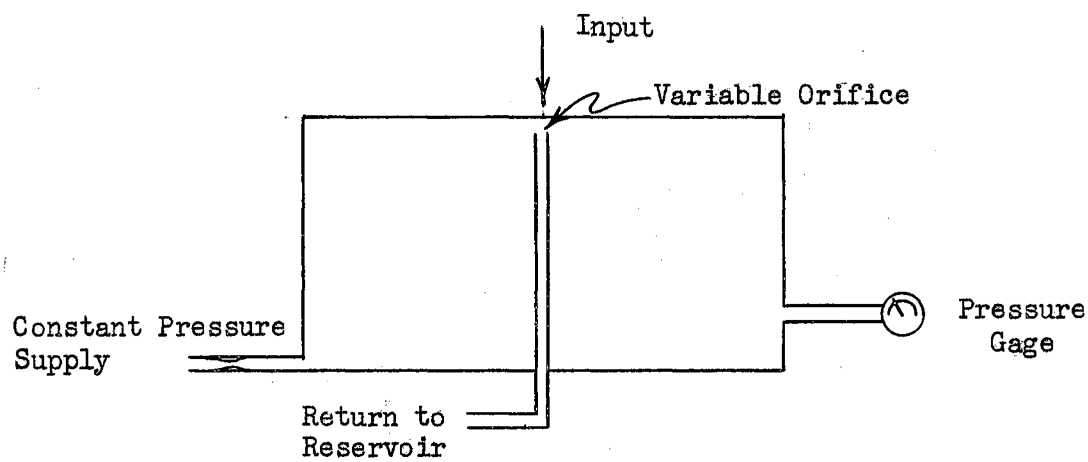


c) Inductive Strain Gage

Fig. 11. Strain Gages



a) Sealed Capsules



b) Dynamic Capsule

Fig. 12. Pressure Capsules

SELECTED BIBLIOGRAPHY

Farquharson, F. B. The Wind Balance in the Boeing Aerodynamical Laboratory at the University of Washington. Bulletin No. 38, University of Washington Engineering Experimental Station Series. Seattle, Washington: University of Washington, 1926.

King, W. B. and Boggs, J. H., Jr. Wind Tunnel Calibration. Stillwater, Oklahoma: Oklahoma State University, 1948.

Pankhurst, R. C. and Holder, D. W. Wind Tunnel Technique. London: Sir Isaac Pitman and Sons, Ltd., 1952.

Pavian, H. C. Experimental Aerodynamics. New York: Pitman Publishing Corporation, 1940

Perkins, C. D. and Hage, R. E. Airplane Stability and Control. New York: John Wiley and Sons, Inc., 1949.

Pope, Alan. Wind Tunnel Testing. New York: John Wiley and Sons, Inc., 1947

Seltzer, L. Z. The VPI Wind Tunnel Balance System. Bulletin No. 65, Virginia Polytechnic Institute Engineering Experimental Station Series. Blacksburg, Virginia: Virginia Polytechnic Institute, 1947.

VITA

William Dudley Leng

Candidate for the Degree of

Master of Science

Thesis: WIND TUNNEL BALANCE

Major Field: Mechanical Engineering (Aeronautical Option)

Biographical:

Personal Data: Born in New York, New York, April 6, 1932, the son of William R. and Anna F. Leng.

Education: Attended grade school in New York, New York; attended the Concordia Collegiate Institute, Bronxville, New York; was graduated from the Memorial High School, Pelham, New York in 1949; was awarded the Bachelor of Science degree by Lehigh University, Bethlehem, Pennsylvania in June, 1953 with a major in Mechanical Engineering; completed the requirements for the Master of Science degree in May, 1960.

Professional Experience: Joined the staff of the E. I. du Pont de Nemours Company at their Clinton, Iowa plant in June, 1953 and worked as an engineer in mechanical development; entered the United States Air Force in October, 1953, holds the aeronautical rating of Pilot and is presently on active duty as a Regular Air Force Officer serving in the rank of Captain.