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WIRE-STRAIN-GAGE HINGE-MOMENT INDICATORS FOR USE IN TESTS OF AIRPLANE MODELS

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SUMMARY

The design and construction of various forms of strain-gage spring units and hinge-moment assemblies are discussed with particular reference to wind-tunnel tests, although the indicators may be used equally well in flight tests. Strain-gage specifications are given, and the techniques of their application and use are described briefly. Testing, calibration, and operation of hinge-moment indicators are discussed and precautions necessary for successful operation are stressed. Difficulties that may be encountered are summarized along with the possible causes.

INTRODUCTION

Wire strain gages have been used as force-measuring instruments long enough that future projects can be greatly benefited by a summary of past experiences in flight and wind-tunnel tests of airplanes. Although many difficulties have been encountered, the compactness and simplicity of the mechanisms required have encouraged the full development of wire strain gages as force-measuring devices. In wind-tunnel models, particularly, these strain gages have satisfied the need for a remote-indicating hinge-moment instrument small enough to fit inside a wing or tail surface.

DESIGN

The sensitive element of this instrument consists essentially of a spring member so loaded that simple strains are produced on its surfaces by the force to be measured. Strain gages mounted on these surfaces produce on an electrical meter a reading that is proportional to the force applied. The spring member may be a simply loaded beam, a torque rod, or a member designed to take direct tension or compression loads. Figures 1 to 6 show several designs of hinge-moment assemblies that have been used successfully.

The simple cantilever beam is the most suitable for small models because it fits neatly within an airfoil shape and is the best form for obtaining high stresses with large surface areas when the loads applied are small. Surface areas required for gages are shown in table I. (See also references 1 and 2.)

The torque-rod spring is rarely used unless warranted by special design considerations. It is difficult to mount gages on the curved surface since the wires must be laid at an angle of 45° to the axis of the rod, the ratio of gage-mounting area to load is low, and deflection under load is generally excessive.

The tension or compression members are practicable only for high loads but have the advantage of very low deflection under load. This type of unit calls for a tension strip restraining the control surface in each direction unless the cross section is large enough to take compression without buckling.

SPRING MATERIALS

Material specifications for the spring members are much the same as for any other type of spring. A good-quality alloy steel, heat-treated to spring temper, is recommended for its strength, high proportional limit, and good temperature compensation with Advance or Copel wire gages. Phosphor bronze has little hysteresis and in beam form, as may be found by calculation, its lower modulus of elasticity provides greater stiffness with a given gage area, but temperature effects are apt to be worse than on steel. Dural has lightness and low modulus of elasticity but is not recommended because of its low proportional limit, which causes hysteresis, poor temperature compensation, and cementing difficulties.

DESIGN STRESSES

The best balance between safety factor, hysteresis errors, and electrical output is obtained with a strain of 0.001 inch per inch on the gages with the maximum load applied. The design stress therefore depends on the modulus of elasticity of the material used. For the most efficient use of space and material, the member should be of constant-stress design so that each gage is subjected to the maximum strain uniformly throughout its length. Greater output is thus provided from the gages than would be provided by a constant-section cantilever, for instance, unless the stress at the root of the beam is made considerably higher. Increasing the stress at the root of the beam reduces the safety factor and brings on hysteresis and cement slippage in the highly strained portion of the gages. Any good handbook provides data on constant-stress beams but, in cases in which a curved surface is indicated, a flat surface closely approximating the correct shape is quite suitable and much easier to machine.

It is very important that the beam be designed to cover only a limited range of load. If tests are to be made under low-load conditions requiring accuracy better than 1 percent of the maximum load, a low-range spring member interchangeable with the high-range spring should be constructed. This low-range spring should be designed to produce a strain of 0.001 inch per inch at 10 to 30 percent of the maximum load, depending on the range and accuracy desired.

If no control-position indicator is used, the beam must be stiff enough to keep the deflection of the control surface at a minimum. The allowable deflection from a known angle setting is specified by the wind-tunnel staff and depends on the size of the model and the nature of the tests. In general, the tolerance varies from $\frac{1^\circ}{10}$ to $\frac{1^\circ}{4}$. Since the gage surfaces cannot be decreased below the sizes shown in table I, there is a limit to how stiff a beam can be made by decreasing its length and width. In cases in which it seems impossible to meet these conditions, the wind-tunnel staff should be consulted about such alternatives as decreased sensitivity with lower design stress, calibration of deflection against strain-gage reading, or the design of a suitable remote-control and position-indicator system.

LOADING AND SUPPORT MECHANISMS

If properly connected, the gages on a cantilever beam measure only the stress induced by a bending moment on the beam. The manner of applying the force to the beam therefore is not important provided no moment is introduced by friction at the free end, provided the calibration is made in terms of the quantity desired, and provided no shift of fulcrum or loading point that is not accounted for during calibration occurs during the test. The pin and slot designs shown in figures 1 to 3 are suitable for small models. The slot or beam end must be rounded to prevent binding from misalinement, and the bearing surfaces must be well polished. Clearance between pin and slot should be 0.001 to 0.002 inch. If the applied load is 20 pounds or higher, these methods cannot be used because "brinelling" aggravates the friction effects. The load can be spread over a larger area by mounting a ball bearing on the pin with the outer race transmitting the load to the slot in the beam (fig. 4). If a linkage is used (figs. 5 and 6), a self-alining ball bearing in the end of the beam prevents frictional restraint and cramping. In special cases, it may be desirable to load the beam through a flexure pivot or emery knife edge (reference 3), which if properly designed will not reduce sensitivity and has the advantage of eliminating one source of friction.

Whatever type of spring member is used, the mechanism must be so designed that only the force desired is measured. The control surface must be mounted on frictionless bearings at the hinge line and restrained against rotation only by the spring member. Conversely, the spring member should be loaded only by the moment on the surface and not by warping, lift, or other forces. This requirement calls for rigid construction of the control surface and the supporting framework. The same careful consideration must be given to the measurement of any other type of force.

In spite of the very small movement permitted in hinge-moment measurements, friction in any part of the mechanism from the flap to the spring member can cause considerable error in the readings. Ball or roller bearings should be used as much as possible and, of course, the general practice of allowing no more than two bearings on a shaft must be followed implicitly. If plain bearings must be used, they should be short and beveled at the ends (fig. 2) so that misalinement or warping of the surface does not cause binding. Removal of all friction is impossible but vibration in the airplane or model during the running of the test is assumed to eliminate a slight amount of static friction. Tapping or vibrating the model during calibration simulates this condition. Friction caused by warping of the surface is harder to detect and remedy because it may occur only while the test is being made. One method of checking for this "tunnel-on" friction is to attach string or music wire to the flap and to take readings while the flap is pulled one way and then the other. A difference in readings indicates the presence of tunnel-on friction, which must be removed by stiffening the flap, installing self-alining bearings, or improving the method of loading the beam. If a control-position indicator is used, it should be so located that the friction in its movement does not affect the hinge-moment readings unless this friction is very small in proportion to the loads measured.

FLAP-ANGLE ADJUSTMENT

Several methods of changing flap angles are indicated in figures 1 to 6. The wind-tunnel staff should specify whether the angle is to be set by hand between runs or by remote control. Any form of clamp having sufficient holding force is suitable for manual setting. A well-designed friction clamp is satisfactory for small installations and is the simplest to build and use. Carefully designed screw adjustments are satisfactory for small angles. A worm and gear adjustment is an obvious solution but has not been used much because of its complication and expense.

The design of a remote-control system depends on the space available and the type of actuator used. In this case, the expense of the worm and gear may be justified. Any linkage system used should be kept within the fuselage or airfoil to prevent disturbances in the air stream. Remote control requires some type of position indicator, preferably electrical, that can be read to an accuracy of $\frac{1}{4}^{\circ}$ or better as specified by the wind-tunnel staff. It is best to register the position of the flap directly but, as mentioned before, the possibility of error due to friction in the position transmitter must be considered. An alternative is to register the position of some link between the actuator and the spring member but, unless deflection between the transmitter and the flap is within the limits of accuracy, an extended calibration of flap deflection against hinge moment is required to supplement the position-indicator readings.

SPARE SPRING MEMBERS

Since wire strain gages are composed of delicate wires cemented to a piece of metal and subjected to vibration, humidity, and pressure and temperature changes, some failures are inevitable. The cost and delay of holding up tests for a day or more while new gages are mounted and tested are often prohibitive. Spare gages on the spring member in use are not adequate, since they are subject to the same conditions that might cause the active gages to fail. Spring members must therefore be made in duplicate so that a spare, with gages on it, is always available in case of failure. Furthermore, design of the spring must provide for quick and easy replacement in order to effect any real saving in time.

GAGE SPECIFICATIONS

The gage sizes shown in table I are the standard products of Baldwin Southwark Division of The Baldwin Locomotive Works. (See also reference 1.) Others for special purposes can be made on request. Several users make their own. (See references 4 to 6.) The methods given in references 4 to 6 and other methods of manufacture have been used successfully at LMAL. For all methods used, the requirements are the same and are as follows:

(1) The wire used should be Advance, Copel, or other wire of reasonable gage factor and temperature stability. (See reference 7.)

(2) The wire should be small (0.0015 in. in diam. or smaller) so that its strength is low with respect to the adhesion of the cement on its surface.

(3) The strands of wire should be insulated from each other or wound so that there is no danger of short-circuiting during use.

(4) The wire should be well cemented to the insulating base.

(5) The insulating base should be as thin as possible so that the wire follows closely the strain of the spring member.

(6) The leads should be strongly soldered to the ends of the gage wire and well anchored on the base to prevent all movement of the joint.

(7) The cement must be an insulator when dry, must dry hard but not brittle, must have good adherence to metal, and should permeate the base material. A quick-drying cement is most convenient. Duco Household Cement, General Electric Glyptal cement, and radio service cement have given satisfactory service with proper use. Bakelite Cement BC-6035 is excellent, particularly for high temperatures, but requires baking for 1 hour at 175° F and 2 hours at 300° F for complete cure.

(8) Gages should be reasonably large, because difficulties tend to vary inversely with size.

MOUNTING THE GAGES

Before the gages are mounted (see reference 1), they must be trimmed to size; they should not be cut down on the lead ends, however, because at least 1/8 inch of the lead must be securely anchored to keep it from pulling loose. The surfaces of the spring member must be thoroughly cleaned - first, with medium-grade emery cloth; then, with alcohol or acetone; and, finally, with a dry lens tissue or lintless cloth. The cement is spread in a thick layer over the metal surface, the gage is immediately pressed firmly into place, and all air bubbles and excess cement are squeezed out. All air bubbles must be eliminated because erratic readings may result from poor adherence of the wire and the expansion and contraction of the bubbles under the varying pressures encountered in wind tunnels. (These pressures range from 4 atm to less than 1/2 atm.) Bubbles left by the drying of excess cement under the gage have the same effects as the air bubbles. The gage may be pressed by hand until the cement has dried enough to hold it or may be held by a clamp or weight with a flat plate on top of the gage to distribute the pressure. Air drying of the cements mentioned in the preceding paragraph takes 2 days for best results. Drying time can be shortened by baking in an oven or under incandescent or infrared lights. If an oven is used, the temperature should be raised slowly to 200° F and held for 2 hours. No. 400-5 clear Polymerin baking enamel, sold by Ault & Wiborg Corporation, is satisfactory for the Baldwin Southwark A-1 and A-5 gages and requires only 15 minutes baking at 300° F.

The leads from the gages should be soldered to terminals in some type of terminal block securely fastened, if at all possible, to the spring member itself. This not only makes the member a compact unit with no dangling wires but also enables the leads in the model to be soldered on with no fear of disturbing or pulling out the gage leads and, most important, keeps the gage wires from being strained by movements of the model leads during tests. As in other types of delicate electrical work, rosin-core solder should be used without soldering flux.

After the leads have been connected to the terminal block, the gages should be checked for grounds, short circuits, correct resistance, and proper connections. The spring member should then be heated slowly to 180° F and the gages and leads covered with melted ceresin wax, beeswax, or paraffin. This procedure is necessary to prevent moisture absorption by the cement and the resultant grounding of the gages. Humidity in wind tunnels is often 100 percent, and it is thought that the pressure changes in the tunnels contribute to moisture grounds because of the "breathing in" of water vapor by the cement as the external pressure increases. Moisture grounds, generally 50,000 ohms or more, may sometimes be remedied by baking at a temperature of 200° F until all moisture has been driven off.

ELECTRICAL CONNECTIONS

The type of connection between gages depends on the method of measuring the change in resistance. There are many methods and many instruments in use for this purpose, but a complete description of them is beyond the scope of this paper. Some form of Wheatstone bridge is usually necessary, however, because of the extremely small change in resistance, and practically all electrical equipment used for force measurements requires at least two gages connected to form two adjacent arms of the bridge. Essentially, one is the active gage and the other is a temperature-compensating gage mounted nearby on a piece of metal the same as that on which the active gage is mounted. When the spring member is a beam or torsion rod on which the two gages can be mounted to receive strains in opposite directions, both are active and the output is doubled. In either case, each pair of gages has three leads with one lead common to both gages (fig. 7). This arrangement is suitable for any direct-current circuit and is required for alternating-current circuits (reference 2). Commercial strain-indicating instruments such as those manufactured by Baldwin Southwark Division (references 1 and 8) are built for this type of connection.

With direct-current supply, location of four gages (all four arms of the bridge) in one place is desirable because (1) leads in the bridge circuit, which may cause false readings through temperature changes, bad connections, or broken strands, are eliminated, (2) better temperature compensation is provided, and (3) four active strain gages give twice as much output as two gages when subjected to the same strain. When four active gages are used, they are connected to form the complete Wheatstone bridge and the leads brought out from the four corners (fig. 8). More space is of course required for gages but this space is available on opposed tension strips and on beams designed for high loads.

The resistance changes measured in wire strain gages are so small that great sensitivity or amplification is required in the electrical system. Any increase in output from the strain gages, as previously mentioned, therefore is of great benefit because less sensitivity or amplification is required. With greater power output from the gages, a less sensitive meter that has quicker response to changing loads and is less affected by vibration can be used. Furthermore, electrical errors in the gages, such as thermal electromotive force and temperature drift, are reduced in proportion to the load measurements. An amplifier permits the use of a more rugged meter but tends to amplify the various errors present in the system.

TESTING AND CALIBRATION

A simple test of the strain-gage spring after completion provides a means of finding defects in the spring or gages before installation in the model - obviously a desirable precaution. The spring member is clamped to a bench top or another suitable fixture and some arrangement made for applying loads. The gages should be connected to indicate load just as they do in use. After a reasonable warm-up period of 5 to 10 minutes, the indicating meter should show no further drift with time. If the electrical circuit is assumed to be perfect, drift or erratic behavior of the meter indicates faulty gages or wet cement. If there is no drift, readings should then be taken as the maximum load is applied to the spring and removed. Failure of the meter to return to zero when the load is removed indicates hysteresis in the spring member. The remedy for this condition is the use of better spring material or better heat treatment. Movement of the meter past zero when the load is removed indicates slippage of the cement. This condition can sometimes be corrected by further drying or baking, but replacement of the gages with greater precaution is usually the only sure remedy.

Proper calibration of strain-gage spring members is essential to accuracy. The gages must be calibrated "on location" in the model; otherwise, accuracy is lost through change of wiring length and lever arm and errors due to friction cannot be detected readily. The spring is loaded through the control surface itself by hanging weights to produce an accurately determined moment about the hinge line. If negative moments are expected, the calibration can be made in the negative direction with the aid of pulleys or by hanging the weights on an arm attached to the surface and extended to the other side of the hinge line. Excessive deflection of the surface under load may lead to a slight error in the calibration. If the mechanism used is such as to cause a change of leverage at different flap-angle settings (fig. 6), check calibrations of one or two points up to maximum load should be made through the range of flap angle.

The readings in an electrical deflection system are directly proportional to the applied voltage, which must therefore be kept constant well within the limits of over-all error allowed. Voltage regulation is not important in a null system except that occasionally a change of heating effect due to power variation may cause zero shift. Under good conditions, the calibration is a straight line within 1 percent of the full range and should repeat itself within this same limit.

DIFFICULTIES AND CAUSES

Good design of the entire mechanical system connected with the strain-gage spring member is essential to accurate trouble-free operation. Minor difficulties in well-designed, well-made assemblies can be found and remedied, but it is almost impossible to get satisfactory results from an assembly that is inherently faulty. A study of the difficulties encountered in calibration and operation during 2 years use of strain gages at LMAL emphasizes the necessity for the precautions given previously. Difficulties associated with alternating-current equipment are beyond the scope of the present paper. The difficulties and possible causes are as follows:

Difficulty	Possible causes
(1) Curved-line calibration	Change of lever-arm length or shift of fulcrum because of excessive deflection of beam, linkage, control surface, or calibrating arm
	Binding or cramping of bearings due to deflection of structure under load
	Restraint of flexure pivot or emery knife edge
(2) Hysteresis loop in calibration curve	Friction in hinge bearings, loading point, linkage, or control-position indicator

Difficulty	Possible causes
	Brinelling or cramping at loading point
	Hysteresis in spring material
(3) Scatter of points	Friction
	Stickypivots in meter
(4) Change of calibration	Change of lever arm
	Change of voltage on strain gages
	Change of temperature
	Cement not fully dried
(5) Zero shift in direction of load	Hysteresis in spring material
	Residual friction
	Gage drift (electrical) caused by faulty gages, temperature change, pressure change, or moisture absorption
(6) Creep (meter reading increasing with time)	Creep in spring material
	Gage drift (electrical)
(7) Slip (meter reading decreasing with time) or zero shift opposite to load	Gage slipping on spring member
	Gage wires slipping in cement
	Gage drift (electrical)

Difficulty	Possible causes
(8) Erratic behavior of meter	Loose connection in circuit or at joint between gage wire and lead
	Weak or damp insulation
	Gages grounded because of moisture absorption

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TABLE I

SURFACE AREAS REQUIRED FOR BALDWIN SOUTHWARK

WIRE STRAIN GAGES

Type	Gage factor	Width (in.)	Length (in.)
A-1	2.0 to 2.1	1/2	$1\frac{3}{8}$
A-5	2.0 to 2.1	3/8	3/4
A-7	1.9 to 2.0	[a]3/16	9/16
A-8	1.7 to 1.8	[a]1/4	3/8
AB-1 (High-temperature gages)	2.0 to 2.1	1/2	$1\frac{3}{8}$

[a]More space required for mounting side by side.

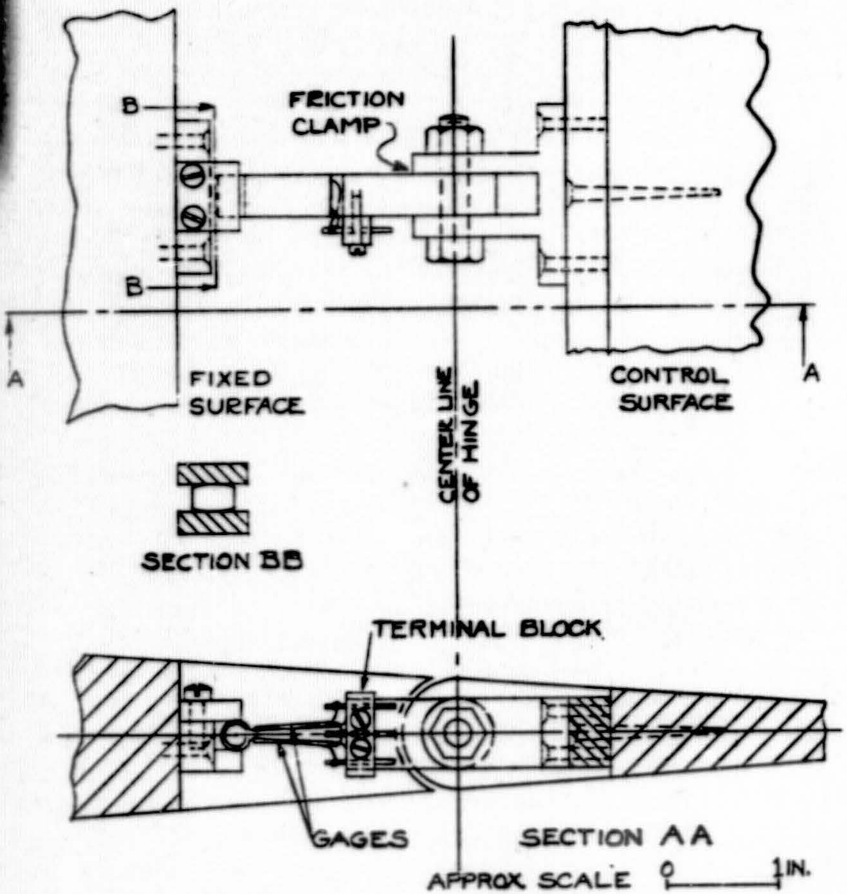

Figure 1.

FRICTION CLAMP FOR CHANGING FLAP ANGLE

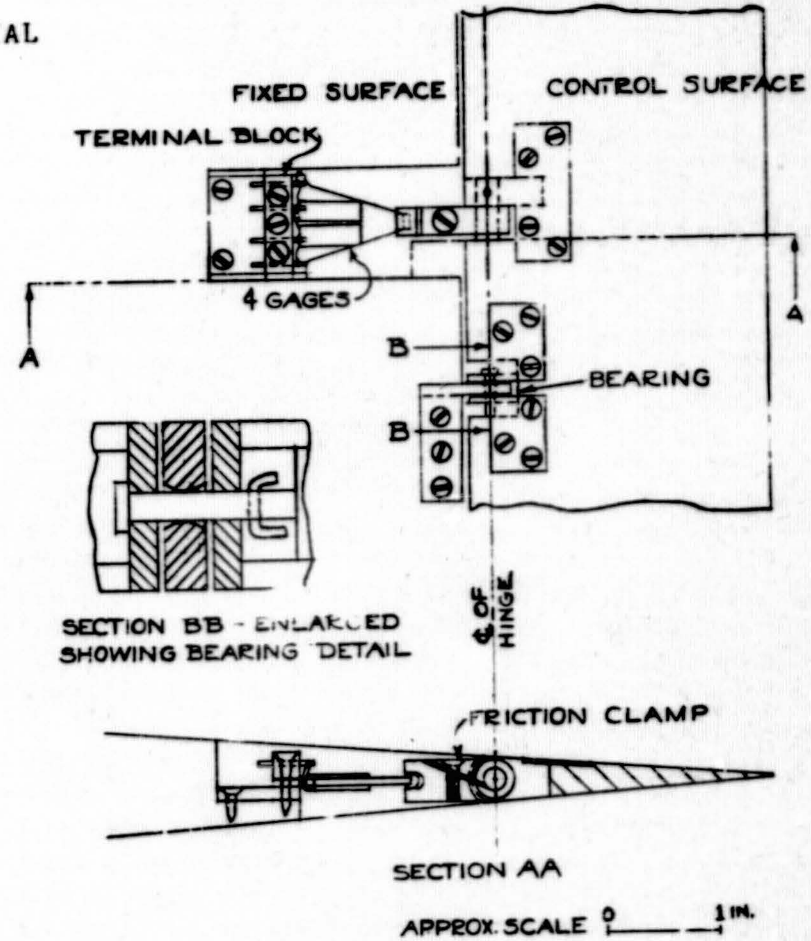

FIGURE 2.

FRICTION CLAMP FOR CHANGING FLAP ANGLE

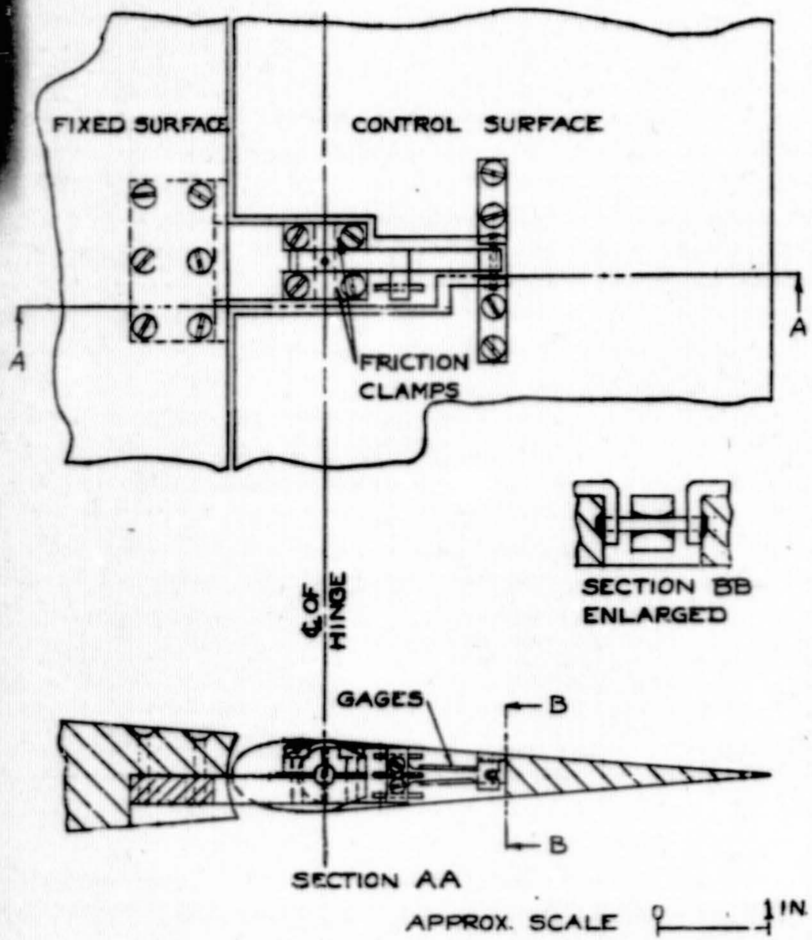

FIGURE 5.

FRICTION CLAMP FOR CHANGING FLAP ANGLE

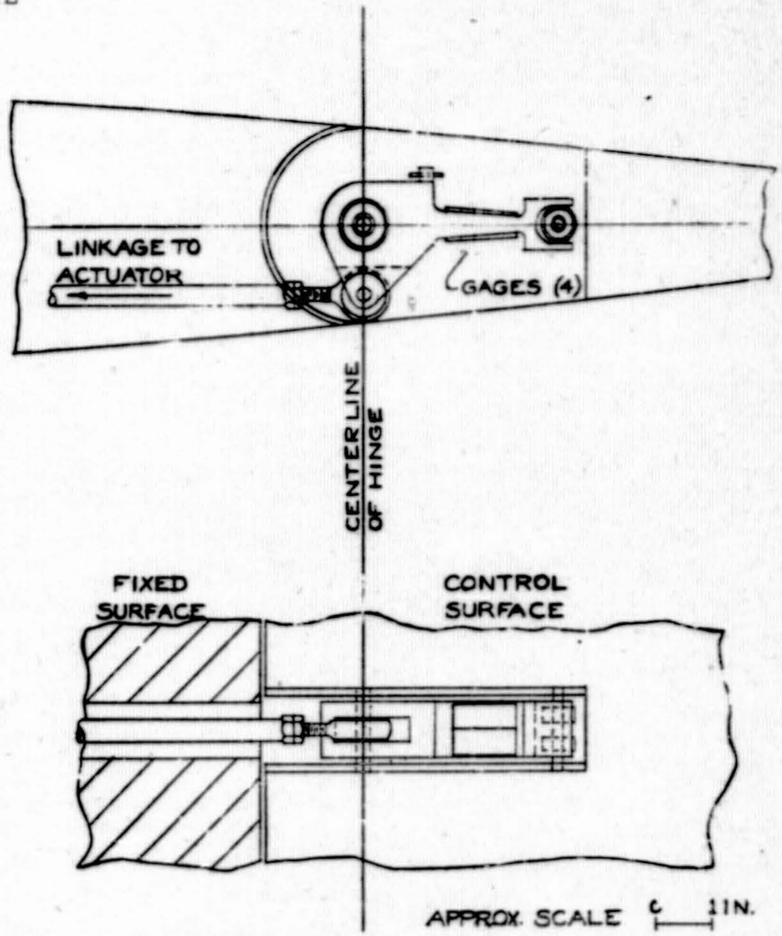

FIGURE 4
REMOTE CONTROL ACTUATOR
FOR CHANGING FLAP ANGLE

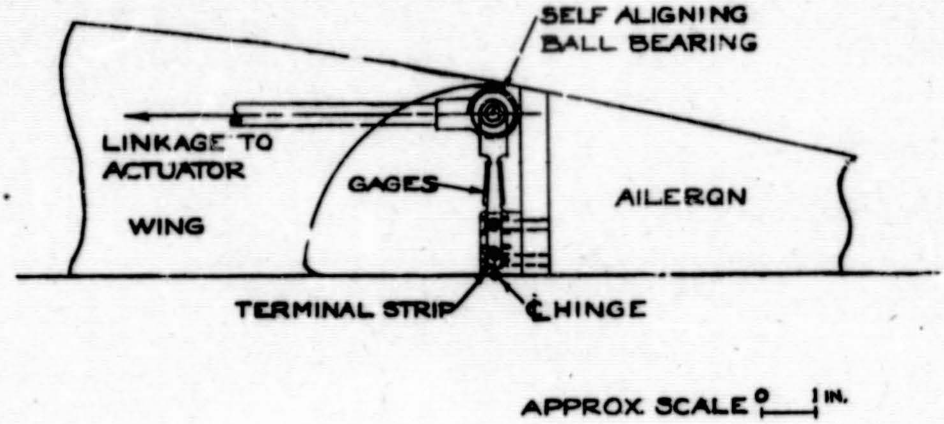

FIGURE 5.

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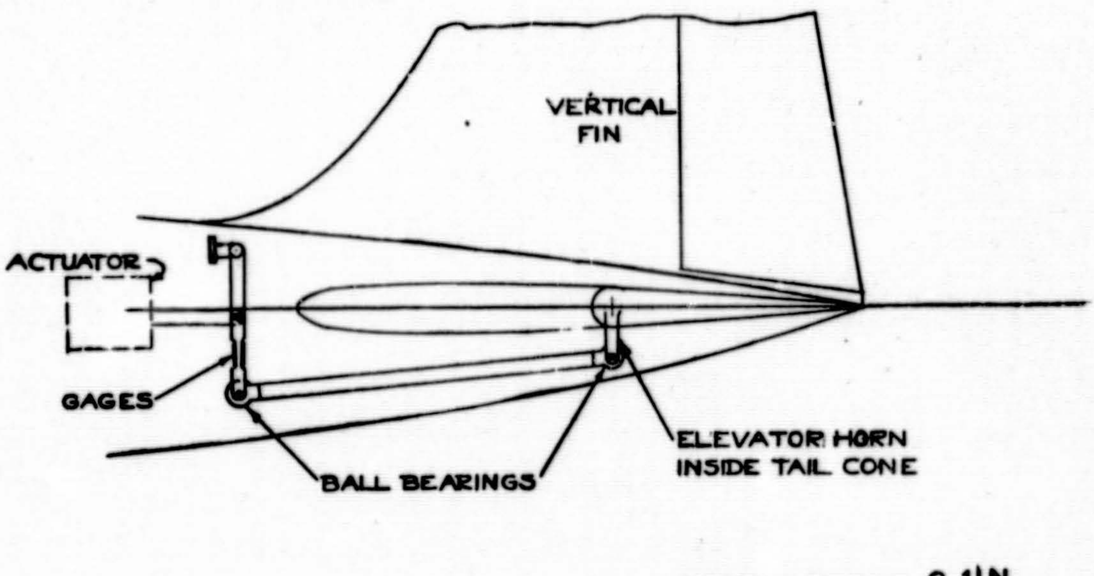

FIGURE 6.
REMOTE CONTROL ACTUATOR FOR
CHANGING FLAP ANGLE

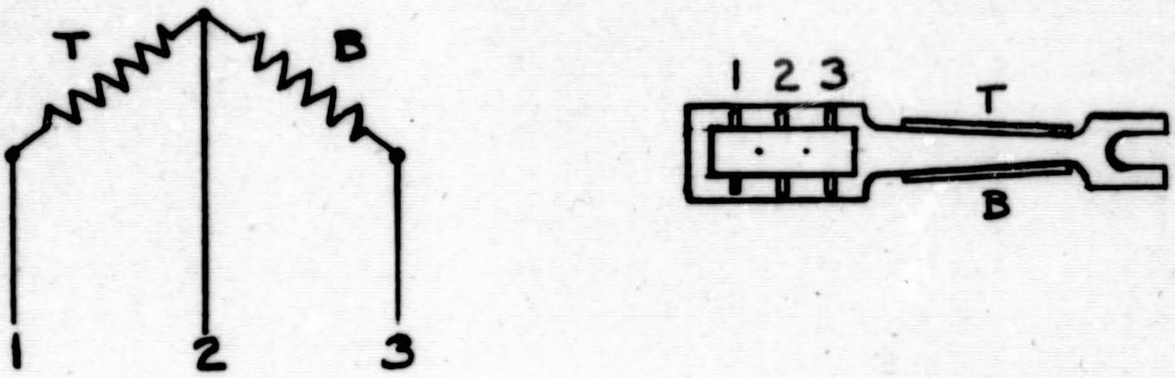

FIGURE 7.

TWO GAGES ON BEAM

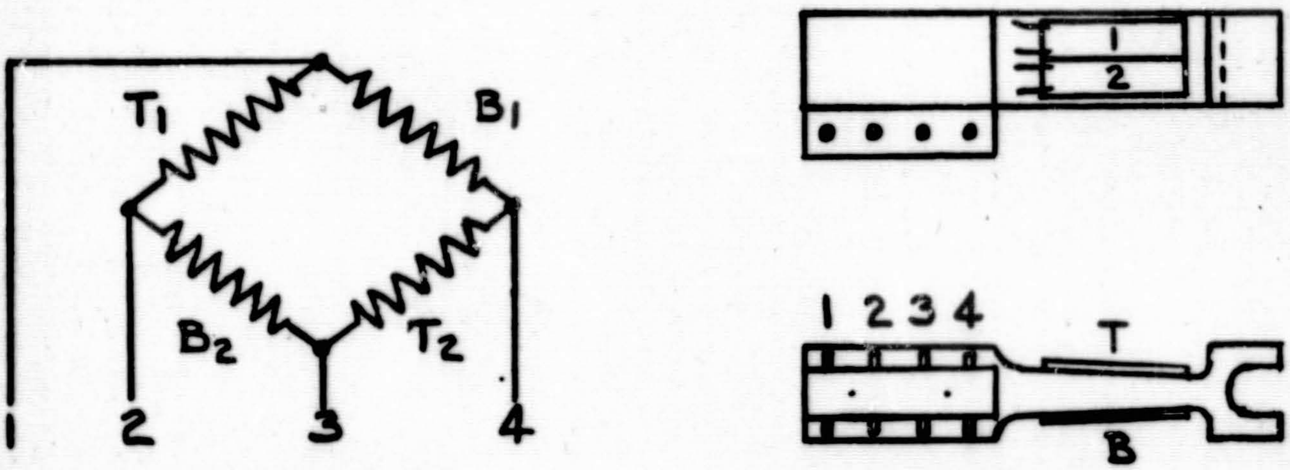

FIGURE 8.

FOUR GAGES ON BEAM