DESIGN OF A SIX COMPONENT
INTERNAL STRAIN GAGE BALANCE SYSTEM

Thesis by

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PART I

INTRODUCTION

A. Statement of the Thesis Problem

When the aerodynamic forces acting on a model are transmitted through struts, stings, etc. to the wind tunnel rigging for determination there are several corrections to be made to compensate for the various other forces which have unavoidably entered into the rigging. Among these are the tare corrections for the deflection of the model supports. These corrections were satisfactorily made in the case of slow speed aircraft in which the tare drag is small in comparison with the drag of the airplane. However, the performance of the new jet airplanes and missiles with extremely low drag and high speed, approaching the speed of sound and higher, cannot be satisfactorily evaluated using the same balance system. A balance system to give satisfactory data on the aerodynamic forces acting on these low drag high speed airplanes should measure only the forces acting on the model with a very high degree of accuracy. This can best be achieved through use of an internal balance system.

Among the many advantages which can be realized through use of a balance system which can be placed inside a model are: (a) The above mentioned corrections can be eliminated, (b) The balance system can be designed for the loads acting on the model alone, thereby increasing the sensitivity and accuracy, (c) The complexity of the wind tunnel rigging can be reduced and, (d) The electrical sensing of all the measured components simultaneously permits their direct automatic recording, thereby saving time and reducing personnel requirements.

It is the purpose of this thesis to describe a small internal balance system which has been designed to measure the six aerodynamic forces and moments which act on a model being tested and thereby realizing the above mentioned advantages.

B. Survey of the Field

Internal balance systems for measuring three or four of the aerodynamic forces and moments have been used for several years. These balances, in general, have been large in size thus restricting their use to large size models. Furthermore, galling of bearing surfaces and internal friction has in many cases reduced their load capacity and accuracy.

During the past year the author has been able to visit the following activities for the purpose of becoming acquainted with the details of the balance systems being used: (a) The Cooperative Wind Tunnel at Pasadena, California, (b) Ames Laboratory of NACA at Moffett Field, California, (c) North American Aviation Inc., at Inglewood, California. The Cooperative Wind Tunnel has three internal strain gage balance systems of the beam type. Two of these balances measure lift, drag and pitching moment while the third also measures rolling moment. These balances are large in size. A fourth balance system in use at the Cooperative Wind Tunnel, while not of the internal type, is of particular interest; This is the transonic bump balance to which the half model is secured for testing. This balance is also of the beam type and measures all six aerodynamic forces and moments.

Ames Laboratory 1 x 3 foot supersonic wind tunnel uses a four component beam type strain gage balance system in which all the beams are located in the sting and shielded from the airstream by a two inch diameter shield. The features of this balance are: (a) Use of ball bearings in races for transmitting the load to the beams, (b) Drag and rolling moment beams are readily interchangeable and, (c) The electrical system is set up to record all readings simultaneously by punching a single button.

North American Aviation, Inc. has developed a small six component internal strain gage balance system for use in their new supersonic wind tunnel. This gage is being used satisfactorily. It is fully described in ref. (a).

Due to the rapid lapse of time and after a conference with Mr. Bell and Mr. Gayman of the Cooperative Wind Tunnel it was decided that an internal strain gage balance system based on the North American design promised the quickest and most satisfactory solution of the design problem at hand. This met with the approval of Drs. Sechler and Klein.

PART II

DESCRIPTION

A. General

The subject Six Component Internal Strain Gage Balance has been designed for the following loads:

Lift	300 lbs.
Drag	75 lbs.
Side Force	150 lbs.
Pitching Moment	2000 in. lbs.
Rolling Moment	200 in. lbs.
Yawing Moment	1000 in. lbs.

The balance, except for the rolling moment section, is to be made of corrosion resistant steel heat treated to 150,000 psi. The rolling moment section is to be made of 75 ST Aluminum Alloy and anodized. A safety factor of five has been used based on ultimate strength of the material. A one and one-quarter inch tapered section is provided at the forward end of the balance for attachment of the model. The after end of the balance (the rolling moment section) is designed to fit into the Cooperative Wind Tunnel sting.

B. Lift and Pitching Moment and Side Force and Yawing Moment Beams

The two lift and pitching moment and side force and yawing moment beams are located one just aft the model attachment and the other just aft the drag section as shown in Part VI, Drawing No. 4-285-1. A three-quarter inch space is available for attachment of one-half inch type SR-4 strain gages.

Lift and pitching moment are determined by calculating the moment in the two beams from calibration curves. The moments are then plotted and the center of lift determined which would give moments observed at the stations of the lift and pitching moment beams. Then knowing the location of the aerodynamic center of the model, the lift and pitching moment of the model are readily resolved. Side force and yawing moments are determined in an analogous manner.

C. Drag Beams

The two drag beams are located in the center of the balance. Each is one-half inch long. They bend as a beam built in at both ends, ie. as a double cantilever beam. The drag force is determined by calculation of the strain in the drag beams, then, as before, determining the drag from calibration curves.

D. Rolling Moment Section

The rolling moment section screws onto the after end of the rear lift beam and is secured against backing off by two set screws. It is of 0.820 in. diameter circular section with a wall thickness of 0.0326 inches. It is shown in detail in Part VI, Drawing No. 1-285-2. When the rolling moment data are not desired the rolling moment section may be replaced by a steel section of greater stiffness. The rolling moment is figured by calculating the strain of the circular rolling moment section in torsion. Then from calibration curves the rolling moment is determined.

PART III

INSTRUMENTATION AND CALIBRATION

A. Positioning of the Strain Gages

Accurate positioning of the strain gages is essential if interactions are to be kept small. It is believed this can best be done through the use of cardboard templates. The position of the various strain gages is shown in Fig. 1.

B. Securing the Strain Gages in Position

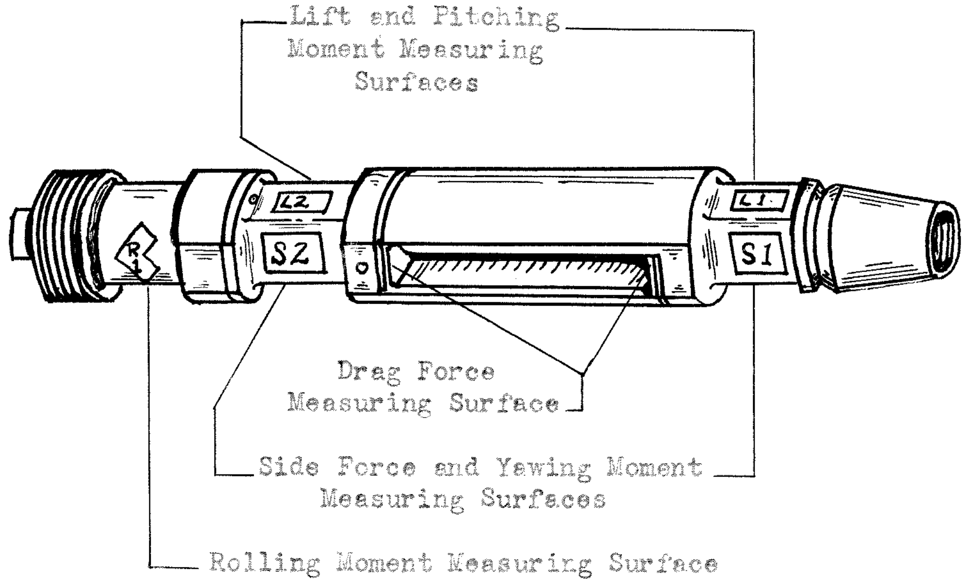
Accuracy requires that the strain gages be insensitive to temperature and humidity changes. Ames Laboratory recommends the use of bakelite cement to secure the strain gages in position on the beam. This type cement requires baking in an oven to set. After cementing the gages in position they should be wrapped with several layers of fine lisle cord which is then coated with several coats of Glyptol to make the installed gage water and vapor proof.

C. Electrical Connections

The following electrical details will simplify the electrical system, increase the sensitivity and reduce interactions: (a) Supply voltage to all gages from common leads, (b) Use two gages in each bridge as shown in Fig. 2, (c) The pair of gages in each bridge should be so arranged that maximum sensitivity of the strain to be measured is obtained and the other strain components (interactions) are balanced out. This arrangement has been made in Fig. 1. (Example; L1 and L1' are a pair of lift strain gages to be connected into same bridge circuit.)

D. Calibration Procedure

A simple and relatively inexpensive set up for calibrating this type of strain gage system is described in Ref. (a).



L1) On opposite sides ($\frac{1}{2}$ in. gage)
L1') Forward Lift Beam Surface

L2) On opposite sides ($\frac{1}{2}$ in. gage)
L2') Rear Lift Beam Surface

S1) On opposite sides ($\frac{1}{2}$ in. gage)
S1') Forward Side Force & Yawing Moment Surface

S2) On opposite sides ($\frac{1}{2}$ in. gage)
S2') Rear Side Force & Yawing Moment Surface

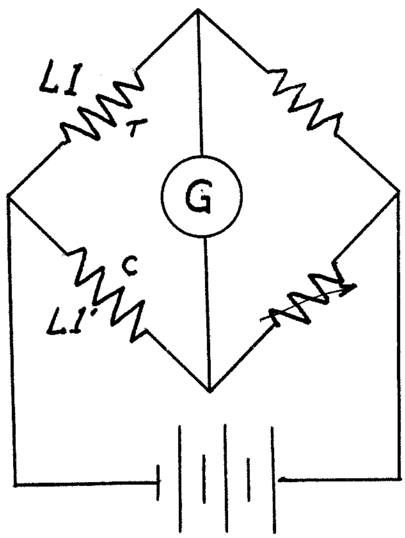
D1) On Drag Surface Forward ($\frac{1}{4}$ in. gage)
D1') One gage above the other

D2) On Rear Drag Surface ($\frac{1}{4}$ in. gages)
D2') One gage above the other

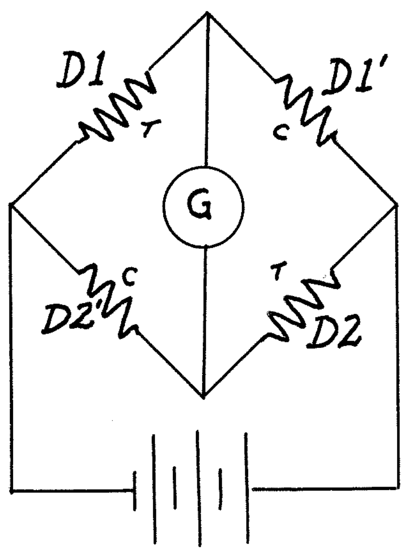
R1) 45° to Rolling Moment Surface
R1') $\frac{1}{2}$ in. gage 90° rossette)

R2) 45° to Rolling Moment Surface
R2') 180° from R1 & R1' ($\frac{1}{2}$ in. gage 90° rosette)

Fig. 1 Location of Strain Gages



(a) For two sensitive gages.



(b) For four sensitive gages. (D & R Gages)

Fig. 2. Bridge Connections

PART IV

CALCULATIONS

In the following calculations only the engineering formulae have been used. No attempt has been made to obtain an exact solution, in fact, it is the author's opinion that it would be impossible to obtain an exact solution because of the end effects on such short beams. The lack of exactness will be no handicap, however, since a safety factor of five on the ultimate strength of the material has been used and since the actual strain for a given loading will be obtained by calibration.

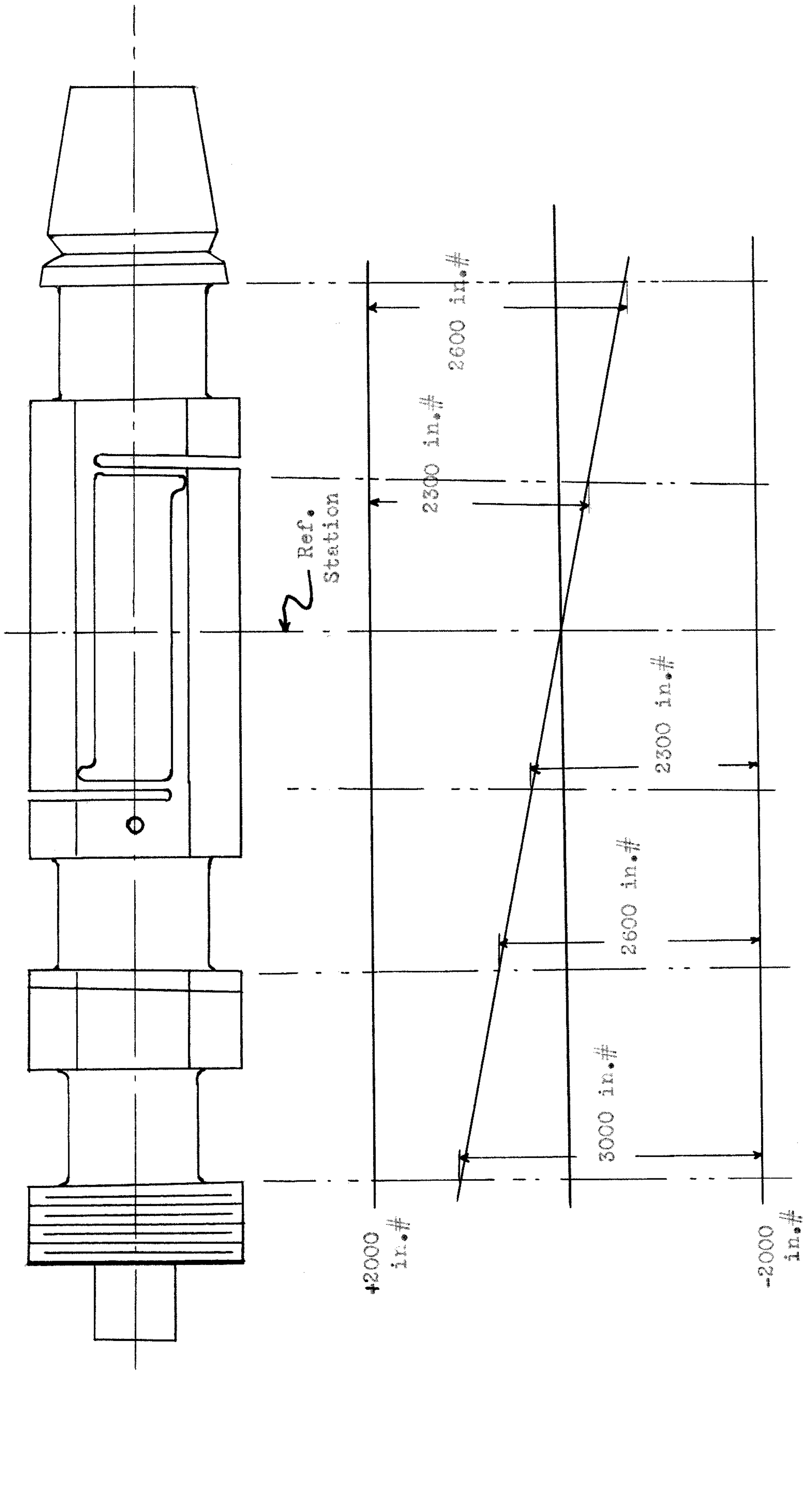


Fig. 3 Lift & P.M. B.M. Diagram

A. Lift and Pitching Moment Beams

Mmax. = 2600 in. lbs.

$$I = \frac{.6625(.925)^3}{12} - .7854(.28125)^4 = .0387 \text{ in}^4$$

$$\sigma = \frac{MC}{I} = \frac{2600 \times .4625}{.0387} = 31{,}000 \text{ p.s.i.}$$

B. Side Force and Yawing Moment Beams

Mmax. = 1300 in. lbs. (½ Lift & P.M. Loads)

$$I = \frac{.925(.6625)^3}{12} - .7854(.28125)^4 = .0175 \text{ in}^4$$

$$\sigma = \frac{MC}{I} = \frac{1300 \times .3625}{.0175} = 26{,}500 \text{ p.s.i.}$$

C. Rolling Moment Section

Mmax. (Bending) = 3000 in. lb.

$$I_x = \frac{\Pi}{4} \quad (.820)\ (.7874)^4 = .0612$$

$$\sigma = \frac{Mc}{I} = \frac{3000 \times .41}{.0747} = 20{,}100 \text{ p.s.i.}$$

R.M. = 200 in. lbs.

$$f_s = \frac{Mr}{I_p} = \frac{200 \times .41}{.1224} = 670 \text{ p.s.i.}$$

$$I_p = 2 \times I_x = .1224$$

D. Drag Beams

(a) Bending

Mmax. = 1150 in. lbs. ; $F = \frac{1150}{2} = 575$ lbs.

Mmax. in beam = 575 x .25 = 144 in. lbs.

$$\sigma = \frac{Mc}{I} = \frac{144 \times .57}{I} \qquad I = \frac{(1.14)^3 \times .050}{12}$$

$$\sigma = 13{,}300 \text{ p.s.i.} \qquad = .00618$$

(b) Tension - Compression

Mmax. = 2300 in. lbs.

$$F = \frac{2300}{2} = 1150 \text{ lbs.}$$

$$\sigma = \frac{P}{A} = \frac{1150}{1.14 \times .05} = 20,200 \text{ p.s.i.}$$

(c) Drag Load

Mmax. = 37.5 x .25 = 9.4 in. lbs.

$$\sigma = \frac{Mc}{I} = \frac{9.4 \times .019 \times 10^5}{1.188}$$

$$\sigma = 15,000 \text{ p.s.i.} \qquad I = \frac{1.14 \times (.05)^3}{12} = 1.188 \times 10^{-5}$$

PART V

DISCUSSION

It is realized that a precision instrument such as the Six Component Internal Strain Gage Balance described in this paper is not something that can be sketched up on a drawing board, built, instrumented and then put into service forevermore. It is rather, the evolution of an idea, based on sound fundamental principles, by the engineers and technicians directly concerned with the use of the instrument. It is believed that the subject balance is based on sound and workable principles and that in time such a system can and will be developed to a high degree of perfection and accuracy.

Corrosion resistant steel is specified for the body of the balance. More specifically an SAE 3330-40 or Stainless Steel "A" of Crucible Steel Company of America is intended. These steels have a proportional limit higher than any maximum calculated stress to be encountered in the balance. On the other hand the ordinary corrosion resistant 18-8 stainless steels have a proportional limit of only 28,000 psi, and would, therefore, not be satisfactory.

The measurement of the lift and pitching moment and side force and yawing moment are straightforward and no difficulty is anticipated in obtaining accurate readings of these components.

Several types of rolling moment measuring systems were considered which could have given greater sensitivity in roll. These other types would, however, have been much larger in size due to the magnitude of the lift and pitching moment loads which have to be carried through the rolling moment section. After a conference at CWT it was decided to go ahead with the type of rolling moment section shown. This lack of sensitivity is not a great handicap when using the balance system for testing projectile shaped missiles. Further, the rolling moment is considered less important than lift, drag and pitching moment.

A drag beam of the same type used in the North American balance was investigated but was discarded in favor of the type shown because the magnitude of the deflections of beams of sufficient size to carry the other loads in the system is too small to give any sensitivity in the North American type drag beam.

It is apparent from the calculations that maximum lift, pitching moment, side force and yawing moment must not be applied simultaneously. It is probable that this restriction will not affect the use of the balance but it should be recognized by anyone using the instrument that such a combination of loads will overstress the system beyond the designed safety factor of five. The stresses will, however, remain below the proportional limit of the material.

A. Evaluation of the Balance

This balance has the following advantages: (a) Small (Approx. 8" x 1 3/8" dia.), (b) Corrections to wind tunnel data reduced, (c) Wind tunnel rigging simplified, (d) Automatic recording of all forces and moments can be made simultaneously, and, (e) Balance is free from bearing friction, galling, etc.

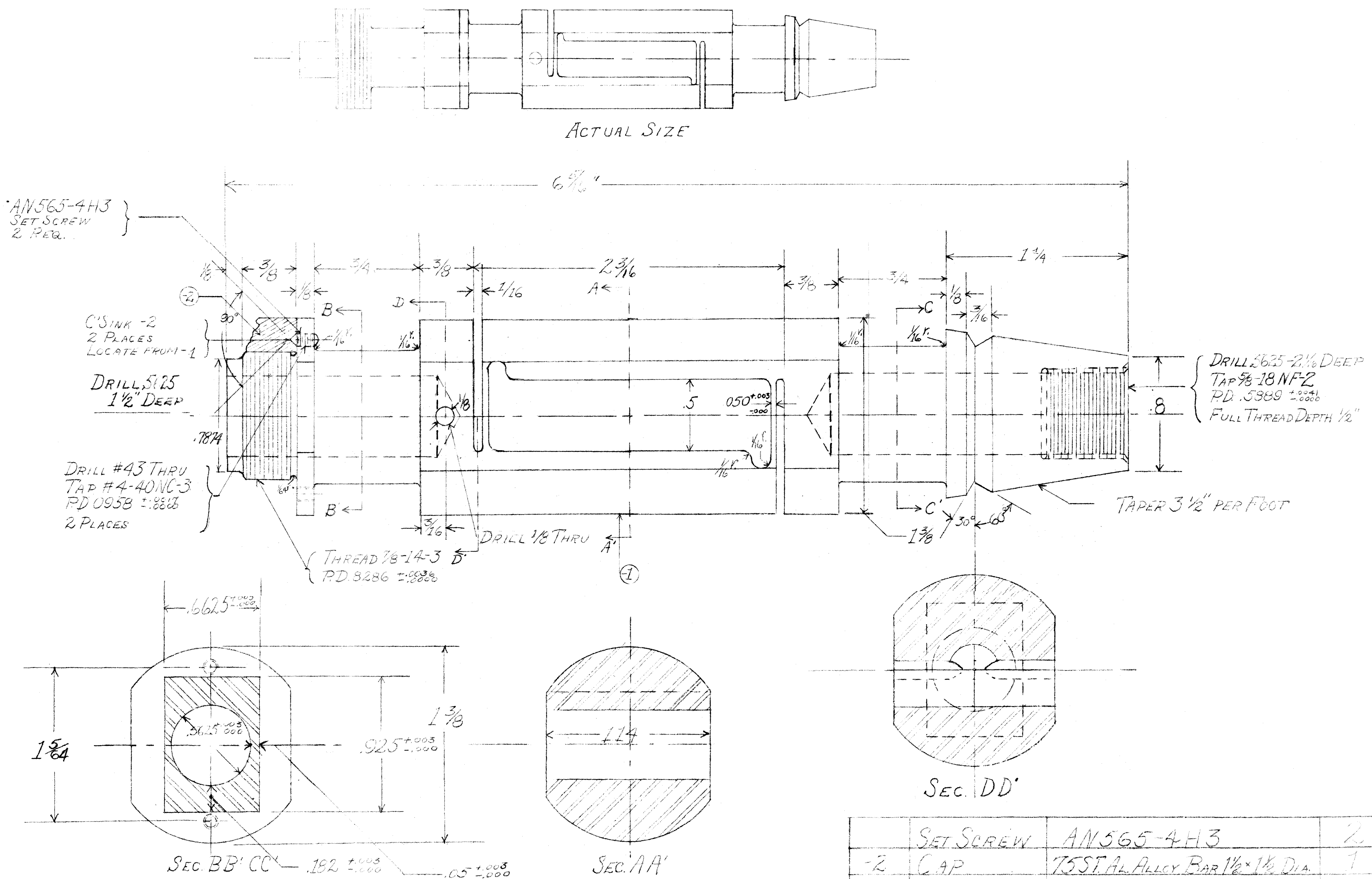
Certain disadvantages are also apparent. Among these are: (a) Interactions can creep in unless gages are positioned accurately and securely, (b) Single gage bridge sensitivity of rolling moment section is limited by the size of the section required to carry the other loads in the system, (c) Single gage bridge sensitivity of the drag beams is also limited by the size of the section required to carry the other loads in the system.

B. Development and Improvement

The sensitivity of the rolling moment and drag gages can be increased by using a double gage bridge circuit as indicated in Fig. 2b. A further increase in the sensitivity of the drag beams can be realized by relieving one end of each of the drag beams so that they will bend as a single cantilever instead of as a double cantilever. This will likely be accompanied by a reduction in maximum lift and pitching moment loads and should not be done until the results of calibration and/or use indicate the necessity or desirability of such a modification.

This balance system is readily adaptable to installation of inductance or capacative type electric pickups, when such improved pickups are developed. Furthermore, this type of balance system is not limited to wind tunnel use alone. It is equally adaptable for model testing while the model is installed on a sting mounted in an airplane which is in flight.

PART VI



	SET SCREW	AN565-4H3	2
-2	CAP	75ST. AL. ALLOY BAR 1 1/2 × 1 1/2 DIA.	1
-1	BODY	CORR. RES. ST. BAR 6 1/2 × 1 1/2 DIA.	1
PART NO.	DESCRIPTION	MATERIAL	NO. REQ.

MATERIAL	FINISH	HEAT TREAT	DRAFTSMAN	CHECKED	APPROVED	ENGINEER
-1		150,000				
-2		ANODIZE				

TOLERANCES ±.010 OR ... UNLESS OTHERWISE NOTED

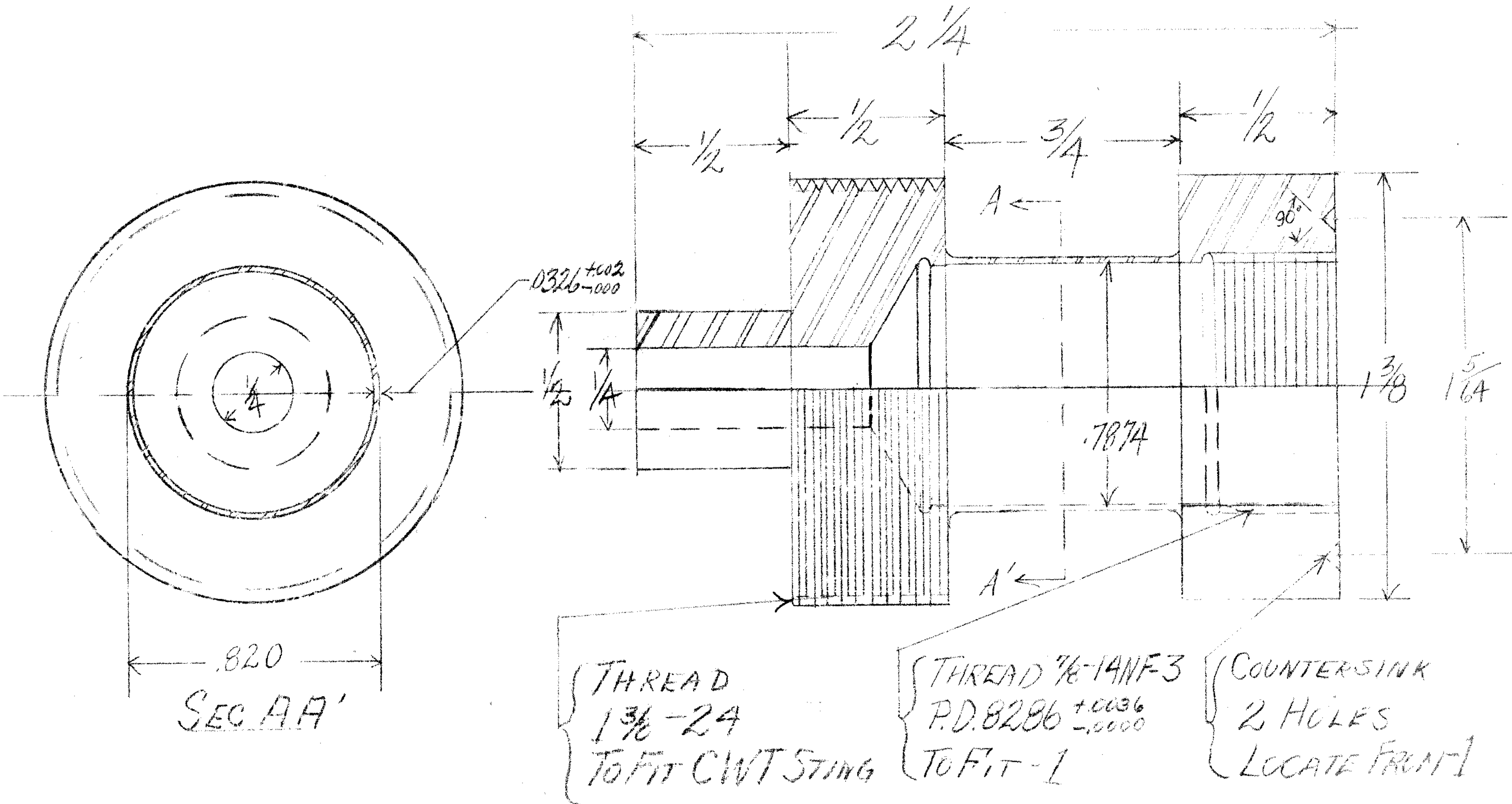
Scale: Twice

FIRST REVISION

GUGGENHEIM AERONAUTICAL LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

SIX COMPONENT INTERNAL STRAIN GAGE

4-285-1



NOTE: BREAK ALL SHARP EDGES

MATERIAL	FINISH	HEAT TREAT	DRAFTSMAN	CHECKED	APPROVED	ENGINEER	TOLERANCES ± .010 OR 1/64 UNLESS OTHERWISE NOTED
75ST AL ALLOY 1 1/2 × 1 1/2 Dia		ANODIZE	Dard	2-22-H Bowen			SCALE: TWICE SIZE SECOND REVISION
GUGGENHEIM AERONAUTICAL LABORATORY CALIFORNIA INSTITUTE OF TECHNOLOGY			NAME: CAP SIX COMPONENT INTERNAL STRAIN GAGE				DRAWING NO. 1-2852

PART VII

CONCLUSIONS

The Six Component Internal Strain Gage Balance system described in this paper is based on sound principles and can be developed to a high degree of accuracy and perfection.

This type gage has the following advantages: (a) Small size. (Approx. 8" x 1 3/8" dia. It can be made smaller for smaller loads), (b) Corrections to wind tunnel data are reduced, (c) Wind tunnel rigging simplified, (d) Automatic recording of all forces and moments can be made simultaneously, (e) Balance system is free from bearing friction, galling, etc.

The following disadvantages are also apparent: (a) Interactions will be present unless all gages are positioned accurately and securely. (b) Single gage bridge sensitivity of rolling moment section and drag beam is limited by the size of the section required to carry the other loads in the system, (c) Simultaneous application of maximum loads and moments will overstress the drag beams beyond their design safety factor. Stress will, however, remain within the elastic limit of the material.

The accuracy of this gage can be improved by using multiple strain gages in series or by the installation of more sensitive electrical pickups of inductive or capacitive type when they become available.

This type of balance system is satisfactory for model testing either in a wind tunnel or from an airplane in flight.

BIBLIOGRAPHY

(a) North American Aviation Inc. "A Six-Component Internal Strain Gage Balance System" by N. L. Miller, Report No. AL-646.