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The Investigation of Air Loads in Flight from Measurements of Strain in the Structure

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The Investigation of Air Loads in Flight from Measurements of Strain in the Structure

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Summary.—Strain measurements in flight involve considerably more work than on ground tests and should be restricted to problems which cannot be solved by ground tests.

Limited experience available suggests that for most flight work the overall bending and shear actions at each of about five sections of a major component are all that is required. These can be determined by suitable selection of positions of gauges, with no more than four to eight measuring stations at each section.

It is advisable to check any particular installation by ground tests using known loads.

1. *Introduction.*—The determination of strain of any part of an aircraft in flight is considerably more laborious than in static strength tests, as the fluctuating strain can only be separated from the steady strain by averaging numbers of readings. The distribution of strain can only be found by taking readings at all measuring positions at sensibly the same time; this requires very rapid switching even for comparatively few positions if only a single-channel oscillograph is available.

These increased difficulties in flight indicate that only those strain problems which cannot be done on the ground should be attempted in flight. In ground strength tests a known load distribution is applied to the structure, and by use of large numbers of strain measuring positions the strain distribution is deduced. In flight tests strain gauges should be fitted to determine the actual air load distribution applied to the aircraft; ground tests should be used for calibration wherever possible.

By careful selection of measuring positions and ground load calibrations it should be possible to determine the total air load distribution on a wing by taking from four to eight readings at each of five sections.

2. *Measurements Required at Each Section.*—2.1. *Ideal Case.*—The determination of the complete pressure distribution on a wing or fuselage in flight by means of strain gauges would require a prohibitive number of measurements, and attention should be confined to finding overall shears and bending moments at a number of sections.

The complete loading of a section is given by six parameters, *i.e.* three orthogonal end loads and three orthogonal couples.

For an aircraft wing or fuselage the total end load at right angles to a cross-section can be neglected. By taking a sufficient number of sections the bending moments need not be measured separately as they can be calculated from the shears.

The three measurements, lift shear, drag shear, and torque, at a number of sections are sufficient to determine all the loads which are applied to the specimen. As an overall check it is advisable to determine the bending moment also at one section.

* R.A.E. Report No. S.M.E. 3351 received 27th November, 1945.

It is shown in the Appendix that the shears, torque and lift bending moment at a section can be given as

$$\left.\begin{array}{lr} \text{Vertical shear*} & L = \Sigma h_{rl}\,.\,R_r \\ \text{Horizontal shear} & D = \Sigma h_{rd}\,.\,\mathrm{R}_r \\ \text{Torque} & T = \Sigma h_{rt}\,.\,R_r \\ \text{Lift bending moment} & M = \Sigma h_{rm}\,.\,Q_r \end{array}\right\} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad 2.1.1$$

where R_r is the shear strain and Q_r the direct strain at position r,

h_{rl}, h_{rd}, h_{rt}, h_{rm} are constant coefficients dependent on the geometry of the specimen.

Any one of the parameters, L, D, T, M, can be determined by one reading if the summations on the right-hand side of the equation 2.1.1 can be made automatically. The strain at each position is proportional to the fractional change in resistance of two strain gauges placed on opposite sides of the sheet at the position. It is possible to combine electrically a number of pairs of gauges so that the resultant change of resistance is proportional to $\Sigma h_r\,.\,R_r$ (Ref. 2). In this way each of the parameters, L, D, T, M can be found from one reading only.

The electrical circuit can be reduced to a number of gauges connected in series if all the constants in a particular summation are the same. For vertical shear, it is shown in the Appendix that

$$h_{rl} = G_r\,A_r \cos\theta_r$$

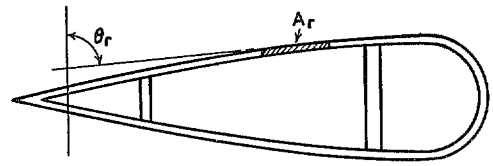

FIG 1.

The gauges at position r are placed on opposite sides of the material at the centre of area of A_r, and by suitable spacing of the positions $h_{rl}\,(= G_r\,A_r \cos\theta_r)$ can be made the same for all positions.

Ideally the three loads required at each section could be determined from three readings only, but the experimental difficulties would be very large due to the variation in spacing distance. By the addition of a few extra readings a more practical scheme can be achieved.

2.2. *Practical Case.*—The experimental work is simplified at the expense of a few extra readings by confining each summation of shear strain to sheets of the same thickness. Where the load is reacted entirely by a four-sided box as in most fuselages and in many two-spar wings, the total shear and torsion can be determined from the shear in each of the four sides of the box. In this way only one gauge is required at each position instead of three (two for the shear actions and one for the torsion). Also the number of gauges in each electrical circuit is greatly reduced due to gauges being connected in series only with gauges on the same side of the box instead of being connected to gauges on all four sides.

The more general case to be considered is that of a two-spar wing with the whole section reacting load as shown in Fig. 2. In most designs the skin will not change thickness other than at points A, B, C, D, E or F and usually will not change at A or D. Even if the sheets did not change sections at any of the points B, C, E, F, where three sheets meet, it would greatly complicate the installation if one circuit had gauges on two of the sheets.

It is advisable in the general case to find the shear loads on each of the eight panels, but in investigations where the drag loads are not important the readings on panels FA, AB and CD, DE can be combined to give two readings FAB, CDE and thus reduce the total number of readings to six.

3. *Determination of Loads from Strain Measurements.*—From the geometry of the whole specimen the gauge readings can be reduced immediately to shear per inch. The general section shown in Fig. 2 will be considered, as all other conventional wing sections and most fuselages are only particular cases of it.

Suppose that the gauge readings in any panel CD (say) give a shear/in. of R_{CD} in the direction CD.

* In order to keep the h's constant for all flying attitudes, vertical is taken as at right-angles to the horizontal datum fixed in the wing.

In the deduction of the overall shear and torsion it is convenient to consider first the proportion of torsion reacted by each of the three boxes ABF, BCEF, CDE as shown in Fig. 3.

Assume that the shear in the section is made up as follows:

S_1 = uniform shear/in. in section ABF in direction ABF
S_2 = uniform shear/in. in section BCEF in direction BCEF
S_3 = uniform shear/in. in section CDE in direction CDE
S_F = remaining shear/in. in front spar in direction CE
S_R = remaining shear/in. in rear spar in direction FB.

Also let

h_F, h_R = depths of front and rear spars respectively
A_1, A_2, A_3 = areas of boxes ABF, BCEF, CDE
d_F, d_R = distances of front and rear spars respectively aft of the axis about which the torsion is measured.

From an inspection of Fig. 3 the S's are given in terms of the R's as follows:

$$S_1 = \tfrac{1}{2}(R_{FA} + R_{AB}) \,, \qquad 3.0.1$$
$$S_2 = \tfrac{1}{2}(R_{BC} + R_{EF}) \,, \qquad 3.0.2$$
$$S_3 = \tfrac{1}{2}(R_{CD} + R_{DE}) \,, \qquad 3.0.3$$
$$S_R + S_2 - S_1 = R_{FB} \,, \qquad 3.0.4$$
$$S_F + S_2 - S_3 = R_{CE} \,. \qquad 3.0.5$$

The torque and shear loads on the section can be expressed in terms of the R's and S's. The torsion is the sum of the torsions round each box and the components from the webs.

Hence

The Torsion $\quad T = 2S_1A_1 + 2S_2A_2 + 2S_3A_3 - S_F h_F d_F + S_R h_R d_R \,, \qquad 3.0.7$

The Lift $\quad L$ = (vertical components of the R's)

$\qquad \simeq - h_F S_F + h_R S_R \,, \qquad 3.0.8$

The Drag $\quad D$ = (horizontal components of the R's) . $\qquad 3.0.9$

A correction will have to be made in the equations 3.0.7, 3.0.8 and 3.0.9 for the components due to the end load, in tapered specimens.

3.1. *Ground Calibration Tests.*—In addition to the effect of end load on the torsion and shear, certain small errors will be introduced by using equations 3.0.7, 3.0.8 and 3.0.9, due to the uncertainty of the exact dimensions of the flight aircraft and due to neglecting a small proportion of the shear particularly in equation 3.0.8. The method of making measurements described in section 3 was chosen so that the apparent change in one parameter was not appreciably affected by change of any other parameter.

The apparent proportion of load given by equations 3.0.7, 3.0.8., and 3.0.9 can be determined by the application of a known load. This can be done to some extent by comparison with extensive strain measurements made of similar specimens undergoing static tests, but it is much better to apply known loads to the flight aircraft on the ground and obtain a direct calibration.

4. *Conclusions.*—Due to the difficulties of measurement and analysis the number of strain measurements in flight should be kept to a minimum.

By connecting a number of strain gauges in series for each measuring point the total loads on a specimen can be determined by the use of from four to eight measuring stations at each section.

The number of measurements could be reduced to three per section by using more elaborate electrical circuits, but this extra complication is not worth while.

A considerable increase in the accuracy of the results can be achieved by calibration of the measurements against those obtained from the application of known loads to the specimen.

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2	E. H. Mansfield	Some Electrical Circuits for adding Strain Gauge Signals. R.A.E. Technical Note No. S.M.E. 388. A.R.C. 10,566. January, 1947. (Unpublished).

APPENDIX

Determination of Loads at a Section in Terms of the Strain at Selected Positions

If the direct and shear strain is known at all points of a section it is possible to determine rigorously the bending moment, shear and torque at the section. Even with a small number of positions, well selected, a good approximation to the loads can be made by considering the strain to be constant over a small area in the neighbourhood of each position.

Suppose that

R_r = shear strain at position r along and at right angles to the section.
Q_r = direct strain at position r at right angles to the section.
A_r = area associated with position r.
$(x_r\, y_r)$ = horizontal and vertical co-ordinates relative to any fixed origin.
θ_r = angle the tangent to the skin makes with the vertical.
p_r = perpendicular distance from the origin to the tangent.
G_r, E_r = shear and Young's moduli for the material.

The total loads at the section are determined as the sum of the loads on each element of area A_r.

The shear over area A_r $= G_rR_rA_r$;
the vertical component of shear $= G_rR_rA_r \cos\theta_r$;
the horizontal component of shear $= G_rR_rA_r \sin\theta_r$;
the torque component about the origin $= G_rR_rA_r\, p_r$.
The end load over area A_r $= E_rQ_rA_r$;
the lift bending moment component $= E_rQ_rA_r\, y_r$.

By summation of the above components

vertical shear L $= \Sigma h_{rl}\, R_r,$
horizontal shear D $= \Sigma h_{rd}\, R_r,$
torque T $= \Sigma h_{rt}\, R_r,$
lift bending moment M $= \Sigma h_{rm}\, Q_r,$

where $h_{rl} = G_rA_r \cos\theta_r\,,\quad h_{rd} = G_rA_r \sin\theta_r\,,\quad h_{rt} = G_rA_r\, p_r\,,\quad h_{rm} = E_rA_r\, y_r\,.$

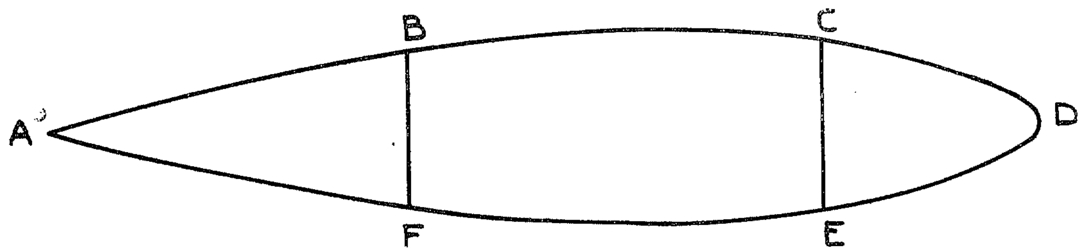

FIG. 2. Section of Two-spar Wing.

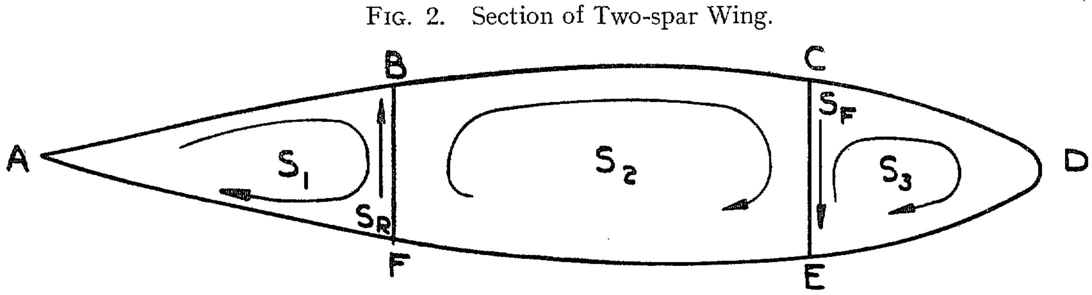

FIG. 3. Shear Loads on a Two-spar Starboard Wing.

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