R. & M. No. 2660
(11,725)
A.R.C. Technical Report

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

Flight Tests on Swinging during Take-off on a Single-engined Fighter-bomber (Typhoon Ib)

By

W. STEWART, B.Sc.

LONDON: HER MAJESTY'S STATIONERY OFFICE
1953

EIGHT SHILLINGS NET

Flight Tests on Swinging during Take-off on a Single-engined Fighter-bomber (Typhoon Ib)

By

W. Stewart, B.Sc.

Communicated by the Principal Director of Scientific Research (Air), Ministry of Supply

Reports and Memoranda No. 2660*

April, 1948

Summary.—Flight tests have been carried out on a *Typhoon* aircraft to compare the values of the aerodynamic side forces and yawing moments, during take-off, with the wind-tunnel measurements, and to compare various methods of estimating the rudder angles required to trim during a take-off run.

The side forces can be checked fairly simply by estimating the various component side forces acting at each instant during the run and comparing the summation with the resultant side force measured by an accelerometer. The aerodynamic side forces were evaluated from the wind-tunnel tests under the corresponding conditions and the side force from the undercarriage was estimated from the load on the wheels and the angle of crab of the wheels to their instantaneous direction of motion.

It is more difficult to compare the yawing moments operating as there is no direct method, at present, of measuring an angular acceleration. Angular accelerations are difficult to obtain by differentiation of the observed angular displacements of the aircraft, due to the rapid variations in angle produced by the pilot's over-corrections on the rudder. Nevertheless, it was possible in some of the runs to evolve the resultant yawing moment from double differentiation of the heading angles and where this could be done successfully, good agreement was obtained between this resultant moment and the summation of the estimated components. By integrating the summation of the estimated yawing moments along a take-off run, which should be approximately zero, a further check on the comparison of the flight and wind-tunnel yawing moments can be made.

The results show very good agreement with the wind-tunnel tests. As runs have been done under various cross-wind conditions on the aerodrome (*i.e.*, different angles of sideslip) the order of each of the aerodynamic components was verified.

A method of evaluating the rudder angles required to trim is suggested, by solving the side-force and yawing-moment equations simultaneously, using the wind-tunnel measurements for the aerodynamic components and introducing the side force from the undercarriage, in terms of the crab angle of the wheels. In the yawing-moment equation, the second-order differential inertia terms is neglected as the changes of angle in the theoretical calculations (representing a straight take-off run) are very small. The effect of the tail wheel has been disregarded as it is only in operation during the initial stages of the run.

Due to considerable over-correction by the pilot, it is desirable to design for a rudder range at least 20 per cent in excess of that required to trim.

1. *Introduction.*—There has been a marked tendency to swing during take-off on recent high-powered propeller-driven aircraft, particularly on Fleet Air Arm fighter types, where considerable flap angles are used. Some doubt has arisen on the validity of the rudder angle required to trim on these aircraft as deduced from the wind-tunnel tests.

Full-scale tests were initiated on a *Typhoon* to determine whether the values of the aerodynamic side-force and yawing-moment coefficients measured in the wind-tunnel tests were directly applicable to the full-scale aircraft and also to compare various methods of evaluating the rudder angles required to trim during take-off.

* R.A.E. Report Aero. 2261, received 21st August, 1948.

These tests were carried out during February to June, 1945. A considerable number of preliminary take-off runs were done to develop an instrumentation technique giving sufficient accuracy for the comparisons involved and to familiarise the pilot with the flight technique to be adopted. However, even with considerable experience and practice, it was not possible to obtain smooth application of the rudder and the records show considerable over-correction by the pilot. It should also be noted that this over-correction by the pilot on the rudder control is quite general and that as a result some considerable margin of control must be available in excess of that required to trim.

2. *Description of Aircraft and Instrumentation.*—The aircraft was a standard *Typhoon* Ib fighter-bomber, fitted with a Sabre IIA engine driving a De Havilland Hydromatic four-bladed propeller. A three-view general arrangement of the aircraft is given in Fig. 1 and a detail of the fin and rudder in Fig. 2. The main dimensions of the aircraft, the directional control and the propeller characteristics are given in Table 1.

The weight of the aircraft at take-off (including instrumentation, etc.) was 10,950 lb and the c.g. was 9·4 in. forward of datum, the limits being 10·5 and 7·0 in. forward of datum respectively.

An auto-observer was installed in the fuselage of the aircraft. Desynns fitted to the control surfaces were used to transmit the rudder and rudder tab angles and the angle of sideslip. The sideslip vane was fitted to a pole, replacing the port outboard cannon and extending 4 ft forward of the leading edge of the wing (*see* Fig. 1). A boost gauge was connected in parallel with the pilot's instrument and an electrical r.p.m. indicator operated from an engine-driven generator.

These instruments and a timing watch were photographed by a 24-volt, 16-mm G.42B camera gun operating at a film speed of about 12 frames per second.

A two-axis accelerometer and gyro unit was installed to indicate forward acceleration (springs arranged to give 0 to $0 \cdot 5g$), lateral acceleration (springs arranged to give $-0 \cdot 3$ to $+0 \cdot 3g$) and change of angle in the yawing plane, *i.e.*, the aircraft heading. It was not possible to put this unit at the aircraft c.g. In the preliminary tests it was situated in the fuselage immediately behind the pilot. In later tests it was in the wing in line with the c.g. laterally.

The inability to put this instrument at the c.g. introduces an error in the side-force readings due to rotation of the aircraft. With the second position tried, this error is very small. The correction for position is difficult to evaluate accurately as it depends on angular acceleration, etc. However, it is estimated that the side force can be measured to the nearest 50 lb.

To enable accurate measurements of the take-off path and heading of the aircraft to be made, a 35-mm Bell and Howell camera was installed in the tail wheel bay, photographing into a mirror giving a horizontal field of view, including the main undercarriage wheels and a white dotted line specially painted down the centre of the runway for these tests. Fig. 3 gives a photograph of the camera installation, and Fig. 4 is an enlargement of a typical frame taken by the camera during a take-off run. The camera was adapted for solenoid operation and the film speed was arranged at 12 frames per second. The position of the aircraft at any instant during the take-off run can be determined to an accuracy of one inch. The method of analysis of these measurements is given in Appendix I.

As the camera was located in the space occupied by the tail wheel when retracted, the latter was locked down by disconnecting the hydraulic lines. For ease of access to the camera, the fairings were not replaced. It is not considered that the aerodynamic effects of these modifications were significant.

Timing lamps on the undersurface of the fuselage in the field of view of the tail camera, in the auto-observer, and in the two-axis accelerometer unit were all operated from the same half-second timing clock. These lamps were also used to synchronise the three films.

The two cameras and the accelerometer film control were operated from one switch in the pilot's cockpit and a second switch controlled the gyro, desynns, timing lights and illumination lamps.

3. *Method of Test and Analysis.*—During a take-off run, the lateral force and resultant yawing moment operating on an aircraft may be separated into five components. The rotational flow in the propeller slipstream, considered with the rudder central, acting on the vertical surfaces gives a resultant side force and corresponding yawing moment about the centre of gravity. Displacement of the rudder from its central position produces a force at the fin and rudder which may be resolved into a side force through the centre of gravity and a yawing moment. Any angle of sideslip, *i.e.*, difference between the heading of the aircraft and the resultant direction of the airflow, gives a resultant side force and yawing moment about the centre of gravity. The undercarriage produces a side force, due to distortion of the tyres, which is proportional to the angle of crab of the wheels, defined as the angle between the heading of the wheels and the direction of motion of their points of contact, *i.e.*, the difference between the heading of the aircraft and its track relative to ground. The tail wheel, when in contact with the ground, produces a side force resisting any change of direction, due to the friction torque required to rotate it about its castoring axis.

The side force and yawing moment about the centre of gravity due to the propeller slipstream have been measured on a 1:5·5 scale model of the *Typhoon* in the wind tunnel[1], and are given as non-dimensional coefficients $(C_y J^2)$ and $(C_n J^2)$ against J, incidence (α) and rudder angle (ζ). The tests denoted by propeller C in Ref. 1, correspond with the flight conditions and the non-dimensional coefficient may be used direct for the flight tests.

In the flight tests, the measured values of J, incidence and rudder angle have been used to determine $C_y J^2$ and $C_n J^2$ from the respective wind-tunnel curves. These coefficients are then multiplied by the full-scale factors to give the estimated side force and yawing moment due to the rotation of the propeller slipstream and the displacement of the rudder.

In the wind-tunnel tests, the effect of sideslip angle was measured with the propeller slipstream operating and the rudder central. As the effect of the slipstream has already been obtained above with the rudder displacement, the side-force and yawing-moment coefficients were obtained by subtracting the value of the coefficients at zero sideslip from the values at the measured angle of sideslip for the appropriate value of J. This method is not strictly accurate as there may be some influence on rudder power due to sideslip but this effect should be very small in the present case.

The side force from the main undercarriage wheels is proportional to the load on the wheels and the angle of crab and is given by

$$Y_W = k(W - L)\theta$$

where k is a constant representing the distortion characteristics of the tyres. The distortion characteristics were obtained from the manufacturers and the value of k may be taken as 0·06 for the *Typhoon* wheels when θ is given in degrees.

The yawing moment produced by this force is obtained directly from the horizontal distance from the wheels to the centre of gravity and is a function of the incidence of the aircraft.

The effect of the tail wheel cannot be measured without the use of strain-gauges or some similar method. A castoring test gives a useful indication of the side force and yawing moment available at the tail wheel to prevent swinging. The flat plate supported on ball-bearings is placed under the tail wheel and measurements are made of the torque required to rotate the wheel about the castoring axis, thus measuring the sideforce which can be taken by the wheel before it will rotate and line itself up with the direction of motion. The result of this test is given in Fig. 6, and shows that in the static case on *Typhoon* PD615 the side force attainable before the tail wheel castors is of the order of 200 lb and the corresponding moment about the centre of gravity 4,000 lb ft. These will be reduced approximately in proportion to the load on the tail wheel.

The technique adopted during the take-off was to open up to full power as quickly as possible to give constant power conditions throughout the run and to raise the tail as early as possible to eliminate the effect of the tail wheel. Both of these objectives were achieved in about 2 sec from the initial movement of the aircraft.

In the wind-tunnel tests it was not possible to obtain aerodynamic data below $J = 0 \cdot 15$ due to the effect of the thrust of the propeller maintaining the airflow in the tunnel.

In view of the above limitations on the method of comparison, the analysis of the individual runs has been taken from the point at which the tail wheel left the ground.

4. *Results*.—4.1. *Analysis of Individual Take-off Runs*.—Figs. 7 to 12 give some of the measured quantities during six typical take-off runs. Two runs have been selected for each of the three flap positions 0 deg, 20 deg and 60 deg respectively. Rudder angle (the rudder tab was set for fully port trim throughout the tests), incidence, sideslip, boost and r.p.m. are given to the same time base.

The rudder angle curves show large over-corrective movements on the part of the pilot in his attempt to maintain a straight path along the runway, although a considerable number of practice runs had previously been made. This is probably due to the comparative ineffectiveness of the rudder at very low speeds and to the variation in undercarriage side force with rate of yaw of the aircraft.

Figs. 13 to 18 give the path, heading side-force and yawing-moment analyses corresponding to the measured quantities of Figs. 7 to 12 respectively.

In general, the take-off runs were within 6 ft of the datum line on the runway, as can be seen from the small path and heading angles occurring in the figures. With the flaps at 60 deg, it was more difficult to maintain a straight path as practically full rudder is required to trim. If the aircraft begins to swing, the undercarriage introduces forces tending to increase the swing and the rudder is unable to counteract this until a higher speed is reached. In Fig. 18 a small swing is illustrated but more serious swings than this were encountered and a divergence of as much as 14 deg off track has been measured.

The comparison of the summation of the estimated components of side force with the measured resultant gives very good agreement throughout the entire take-off runs and in each of the flap conditions considered. Only at one or two points in several of the runs, where very rapid changes of direction occur, does the discrepancy exceed the experimental limits of accuracy. This may be due to overshooting of the accelerometer or to the fact that in rapid changes of direction more load is distributed on the outer wheel resulting in the aircraft assuming a small angle of bank which is registered by the sideways accelerometer. This effect is particularly noticeable on several of the runs where one wheel leaves the ground before the other at the take-off point and the angle of bank is registered as a side force on the accelerometer.

As pointed out previously, no direct method of measuring the resultant moment on the aircraft could be devised. An attempt has been made to establish the resultant yawing moment from the moment of inertia and the angular acceleration, the latter being obtained from double differentiation of the aircraft heading. This is by no means accurate and only in some cases could successful yawing-moment curves be produced, as illustrated in Figs. 16, 17 and 18 respectively.

Any slight errors in the film reading of the heading angles lead to excessive oscillations in the production of an acceleration curve. By taking the change in angle over a period of time and plotting the angular velocities, it is then possible to fair off the angular velocity curve before differentiating to give angular acceleration. Where rapid changes of heading occur it is impossible to produce an angular acceleration curve.

However, where resultant yawing moment curves could be produced (Figs. 16, 17, 18) and considering the accuracy of this method, there is reasonably good agreement between the resultant yawing moment and the summation of the component moments.

Also, integrating the yawing moment summation curves along the take-off run and comparing this with the change of heading during the run, which is approximately zero, a further check is obtained of the order of the yawing moments.

4.2. *Effect of Undercarriage.*—This is the first occasion in which the effect of the undercarriage on the tendency to swing during take-off has been measured directly, and it is worth while dealing with this in detail.

For a given aircraft layout and power-plant–propeller combination, the resultant aerodynamic side force and yawing moment, at any given speed and incidence during the take-off run, is dependent only on the rudder displacement. To obtain a straight path, the aerodynamic side force must be balanced by an equal and opposite side force from the undercarriage wheels. This side force is produced by the undercarriage wheels taking up an angle of crab relative to the direction of motion of their points of contact with the ground, the side force being evolved as a resistance to the distortion of the tyres.

This side force, in turn, introduces a yawing moment due to the distance of the centre of gravity from the wheel base. At each instant during a take-off run, there is a unique rudder position and angle of crab, which satisfy the side-force and yawing-moment equations and provide a straight path.

The resultant aerodynamic force on the aircraft may act ahead of or aft of the centre of gravity. Thus, the moment introduced by the side force on the wheels may increase or decrease the swinging moment on the aircraft, depending on the direction of the aerodynamic side-force and yawing-moment relationship. On the *Typhoon* the undercarriage moment tends to reduce the swinging moment on the aircraft.

Another undercarriage effect is that obtained from the influence of the torque reaction. Using the data of Table 1, the torque reaction on the aircraft under take-off conditions is of the order of 10,000 lb/ft. This gives an effective increase in the reaction of one wheel and a corresponding reduction on the other. Thus the friction drag of one wheel increases and that of the other decreases so producing a yawing moment on the aircraft. Assuming the coefficient of rolling friction to be 0·03 the yawing moment applied to the aeroplane is about 300 lb/ft. As will be seen from Fig. 14, this is very small in relation to the overall yawing moments involved. Furthermore, the rotation of the slipstream causes an effective change in incidence on the section of the wing within the slipstream and produces a rolling moment tending to counter the torque reaction and hence reducing the value of the yawing moment given above. In addition, as the speed increases the ailerons can easily outweigh the torque reaction. The effect of the torque reaction on the tendency for the aircraft to swing is therefore negligible.

5. *Evaluation of Rudder Angles Required to Trim*.—5.1. *Equations of Motion*.—The equations of motion of an aircraft in the yawing plane during a take-off run (using the notation given in the list of symbols) are given by

$$Y_a + Y_\zeta + Y_\beta + Y_W + Y_T = \frac{W}{g}\ddot{y} \quad \ldots \quad (1)$$

$$N_a + N_\zeta + N_\beta + N_W + N_T = \frac{I}{g}\ddot{\theta} \quad \ldots \quad (2)$$

where the axes are taken along and perpendicular to the instantaneous direction of motion of the aircraft.

The side force and yawing moment due to the rotation of the slipstream may be regarded as constant for any given set of conditions (J, C_p, α). Displacement of the rudder from its central position introduces a side force and yawing moment proportional to the rudder angle (ζ). In zero cross-wind conditions the angle of crab taken up by the wheels, introduces an aerodynamic sideslip angle of equal value. Thus, indicating the variables on which the independent terms depend, the equations may be written

$$Y_a + Y_\zeta(\zeta) + Y_\beta(\theta) + Y_W(\theta) + Y_T = \frac{W}{g}\ddot{y} \quad \ldots \quad (1A)$$

and

$$N_a + N_\zeta(\zeta) + N_\beta(\theta) + N_W(\theta) + N_T = \frac{I}{g}\ddot{\theta}\,. \quad \ldots \quad (2A)$$

The essential aspect of the take-off is to maintain a straight path throughout the run, *i.e.*, $\ddot{y}$ must be zero at any instant during the take-off run.

Omitting the terms introduced by the tail wheel, since they affect only the initial stages of the run, the equations become

$$Y_a + Y_\zeta(\zeta) + Y_\beta(\theta) + Y_W(\theta) = 0 \quad \ldots \quad (3)$$

and

$$N_a + N_\zeta(\zeta) + N_\beta(\theta) + N_W(\theta) = \frac{I}{g}\ddot{\theta}\,. \quad \ldots \quad (4)$$

At each instant during the take-off run, having fixed the velocity, incidence, etc., and using the wind-tunnel curves for side force and yawing moment due to slipstream, rudder and sideslip, we have two simultaneous equations containing only the two variables ζ and θ (in zero wind conditions the angle of crab of the wheels and the angle of sideslip of the aircraft are equal).

Unfortunately, the moment equation is a second-order differential equation and, since a number of points along the take-off run are required, considerable work would be entailed in evaluating the rudder angles required to trim.

5.2. *Approximations*.—As will be seen in the calculations, the changes in heading to maintain equilibrium are very small and thus the angular accelerations to produce these may be neglected as a first approximation. We have now two simple simultaneous equations in ζ and θ to solve.

$$Y_a + Y_\zeta(\zeta) + Y_\beta(\theta) + Y_W(\theta) = 0 \quad \ldots \quad (5)$$

and

$$N_a + N_\zeta(\zeta) + N_\beta(\theta) + N_W(\theta) = 0\,. \quad \ldots \quad (6)$$

It is also worth considering the effect of introducing further simplifications and in particular, the simplified method adopted in the wind tunnels.

The next simplification is due to the effects of the wheels dominating the effects of sideslip, except during the last fraction of the run. Thus, the equations

$$Y_a + Y_\zeta(\zeta) + Y_W(\theta) = 0 \quad \ldots \quad (7)$$

and

$$N_a + N_\zeta(\zeta) + N_W(\theta) = 0 \quad \ldots \quad (8)$$

give a good approximation except near the take-off point.

Since
$$N_W = Y_W(d)$$
$$= -(Y_a + Y_\zeta)d$$

equation (8) may be rewritten

$$N_a + N_\zeta(\zeta) - d(Y_a + Y_\zeta)(\theta) = 0 \quad \ldots \quad (9)$$

which is the equation for the moments of the slipstream and rudder taken about the centre of the wheel base. Thus, the solution of equations (7) and (8) is equivalent to considering the wheel base as an instantaneous centre of rotation.

The last simplification is to neglect the side forces and the effect of the undercarriage entirely and to consider only the moments produced by the slipstream and the rudder.

Thus,
$$N_a + N_\zeta(\zeta) = 0\,. \quad \ldots \quad (10)$$

In practice, the present method adopted in the wind tunnels is to obtain the rudder angles to trim from the solutions of equation (10), *i.e.*, moments about the centre of gravity, and also from equation (9), *i.e.*, moments about the wheel base. It is then assumed that at the beginning of the take-off run the aircraft rotates about its wheel base and at the take-off about its centre of gravity. Thus, a curve is interpolated between the solutions from equations (9) and (10) beginning on equation (9) at the start of the run and diverging towards equation (10) at the take-off. This gives fairly good results when the side forces are small, but as the side forces increase the gap between the two curves increases and the interpolation becomes more inaccurate. Also, it does not allow for the fact that at take-off, the aircraft must possess an angle of sideslip to prevent it drifting sideways.

5.3. *Comparison of Solutions.*—The rudder angles to trim obtained by the various methods of solution detailed above are given in Figs. 20, 22 and 24 for the 0 deg, 20 deg and 60 deg flap settings respectively and are compared with the average rudder angles obtained during the take-off runs (Figs. 19, 21, 23).

At any given J, the rudder angle to trim is a function of incidence. The rudder angles for a number of runs at given flap setting and the corresponding incidence curves have been superimposed, and the average rudder angle to trim curve at the corresponding average incidence obtained. This average incidence curve was used in the evaluation of the solutions.

It will be seen that the measured rudder angles correspond very closely with the most exact solution, except at low values of J, where the effect of the tail wheel reduces the rudder angle required considerably. This applies to each of the flap positions considered. The effect of omitting the sideslip terms is not noticeable at the beginning of the run but increases as the value of J increases. Taking moments due to slipstream and rudder only, gives a considerable divergence particularly at the lower speeds.

In the case of the *Typhoon*, the present wind-tunnel method of interpolating between the two latter curves would give reasonably good agreement with the more accurate method. However, this method of interpolating is by no means accurate and may not be satisfactory in the case of other types of aircraft, particularly where large aerodynamic side forces are involved. It also breaks down at take-off where the aircraft may take up an angle of sideslip, to prevent it drifting from its intended track.

The above method of estimating the rudder angles to trim during a take-off run gives the condition in which the rudder position at any instant would prevent any divergence from a straight path. In practice, it is impossible for a pilot to follow such a curve of a rudder displacement and attempts to maintain a straight path lead to considerable over-correction, particularly at the lower speeds. This point must be borne in mind when any requirement for rudder angles to trim is considered. For an aircraft in which there is just sufficient rudder control according to the rudder angle required to trim, the application of the over-correction means that for certain periods the rudder will come up against the stops and there will be a tendency to swing. It must also be remembered that if a slight swing develops, a rudder angle range must be available in excess of the position to trim to correct it. This was shown on the *Typhoon* where, in the flaps 60 deg case, almost full rudder is required to trim during a period of the run. If the pilot anticipates this correctly, a straight take-off can be carried out but if the aircraft has a slight swing as it reaches this period, there is insufficient rudder control and the swing develops rapidly and is only corrected when sufficient rudder power becomes available at higher speed.

6. *Conclusions.*—6.1. *Comparison of Wind-Tunnel and Flight Tests.*—The flight tests were carried out under various wind conditions and hence in various sideslip conditions, and for three positions of the flap 0 deg, 20 deg and 60 deg respectively. In all the conditions considered, the side-force and yawing-moment coefficients measured in the wind tunnel give very good agreement with the flight-test measurements.

6.2. *Rudder Angles to Trim.*—An accurate method of determining the rudder angles required to trim during the take-off run has been developed. The wind-tunnel tests are used to evaluate the side force and yawing moment due to the rotation of the slipstream, rudder displacement and angle of sideslip in terms of the two variables, rudder angle and sideslip angle. The effect of the undercarriage is introduced in terms of the angle of crab, which is numerically equal to the sideslip angle for conditions of no cross-wind. The side-force and yawing-moment equations to give a straight take-off path can then be solved simultaneously, to give the rudder angle to trim.

It is necessary to assume an incidence variation during the take-off run. In the tests, the measured values were used but, in the general case, a suitable arbitrary variation must be devised.

6.3. *Rudder Range Required.*—Considerable over-correction on the rudder control occurs during take-off runs and an allowance must be made for this in excess of the rudder angle required to trim when considering the available rudder range. From consideration of Figs. 19, 21 and 23, especially in the latter where the pilots could not prevent swinging in several cases with full rudder applied, it would appear that a rudder range at least 20 per cent greater than that required to trim, will be necessary to provide the pilot with adequate control.

6.4. *Design Considerations.*—In view of the large allowance necessary to allow for over-correction by the pilot, it hardly seems justified in general to consider very accurate estimation of the rudder range. The method of taking moments about the wheels at the beginning of the run and about the centre of gravity at take-off seems to give sufficient accuracy for design purposes, provided that—as mentioned above—an extra 20 per cent is provided over and above the static trim value for rudder angle in order to allow for pilots over-correction.

REFERENCE

No.	*Author*	*Title*
1	J. Seddon	Wind Tunnel Measurements of Yawing Moment and Side Force on Model of Single-engined Fighter (Typhoon) for Analysis of Swinging during Take-off. R.A.E. Report Aero. 2193. April, 1947.

APPENDIX I

Camera Installation for Giving Take-off Path

An accurate method of determining the path and heading of the aircraft during the take-off run was required. This was achieved by installing a 35-mm Bell and Howell camera in the tail wheel bay of the aircraft, photographing into a mirror. The field of view was arranged to include the main undercarriage wheels and the datum line on the runway.

This datum line for the lateral measurements is a white line consisting of one yard dashes at one yard intervals. Each fifth dash was crossed, giving larger increments for use at the higher velocities.

A photograph of the camera installation is given in Fig. 3. In Fig. 4, an enlargement is given of a typical frame obtained by the camera during one of the actual take-off runs.

Forward Velocity.—Observation of the datum line dashes intersecting the undercarriage track gives an accurate distance-time history of the take-off run. The forward velocity is thus obtained direct and can be checked against the forward acceleration given by the two-axes accelerometer unit.

Lateral Velocity.—The intersection of the datum line with the undercarriage track gives the instantaneous position of the aircraft. Knowing the distance between the undercarriage wheels and measuring the apparent distance on the film, the distance to this intersection is scaled direct. The instantaneous position of the aircraft can be obtained to an accuracy of one inch. The lateral distance against time gives the lateral velocity.

Angle of Path.—The angle of the path of the aircraft to the datum line is obtained by combining the forward and sideways velocities.

Heading.—The longitudinal axis of the aircraft is contained in a vertical plane represented on the film by a vertical line through the centre of the undercarriage track. The offset of the intersection of the datum line with the horizon from this vertical line is a measure of the heading angle of the aircraft to datum. The angular scale is obtained from the apparent length of the undercarriage track and the known angle subtended by it at the camera.

Angle of Crab.—The angle of crab of the wheels is the difference between the instantaneous angle of the path of the aircraft and the heading.

Incidence.—The incidence of the aircraft is given by the position of the horizon relative to a fixed point on the aircraft. The angular scale is obtained from a vertical geometric distance on the aircraft and the angle that it subtends at the camera. This does not correspond exactly with the angular scale in the horizontal plane due to the introduction of the mirror.

Y_a	Resultant side force on the aircraft surfaces due to the propeller slipstream (rudder central)
N_a	Corresponding yawing moment due to slipstream
Y_ζ	Side force produced by displacement of the rudder from its central position
N_ζ	Yawing moment due to rudder
Y_β	Side force due to aerodynamic sideslip of the aircraft
N_β	Yawing moment due to sideslip
Y_W	Side force produced by the main undercarriage wheels
N_W	Yawing moment produced by the undercarriage wheels
Y_T	Side force produced by the tail wheel
N_T	Yawing moment produced by the tail wheel
Y_R	Resultant side force acting on the aircraft
N_R	Resultant yawing moment acting on the aircraft

TABLE

Aircraft Particulars

Wing area	279 sq ft
Span	41 ft 7 in.
Aspect ratio	6·2
Dihedral	Inner —1° 11′ Outer +5° 30′
Weight at take-off	10,950 lb
Flap type	Split
Flap area (total)	31·4 sq ft
Max. flap angle	80 deg

Directional Control

Fin and rudder area	23·7 sq ft
Rudder area	12·3 sq ft
Rudder angles	Port 23·5 deg Starboard 23·5 deg
Trimming tab area	1·13 sq ft
Trimming tab angle	8·5 deg starboard for take-off

Engine and Propeller Characteristics

Engine	Sabre IIA
Take-off power	1950 h.p.
Gear ratio	0·274
Propeller type	D.H. Hydromatic Mark 1/3/446/1
Diameter	14 ft
Number of blades	4
Solidity	0·12
Thickness/chord	6·7 per cent

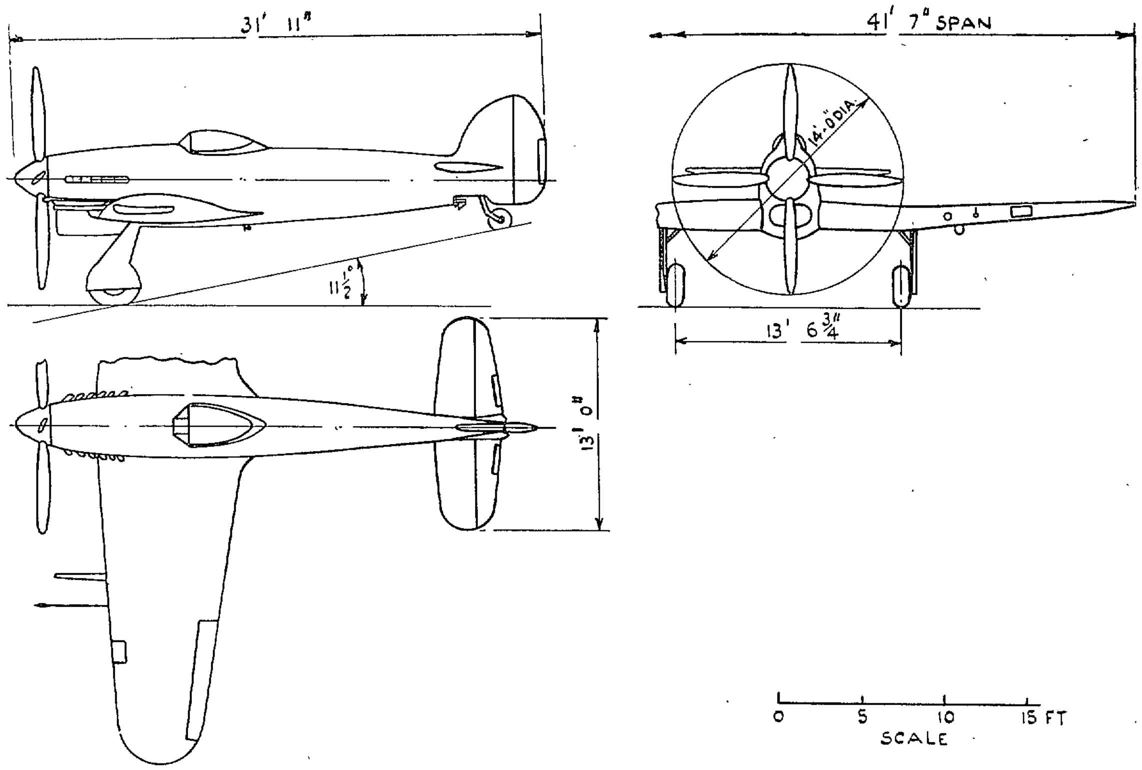

FIG. 1. *Typhoon* IB. PD. 615.

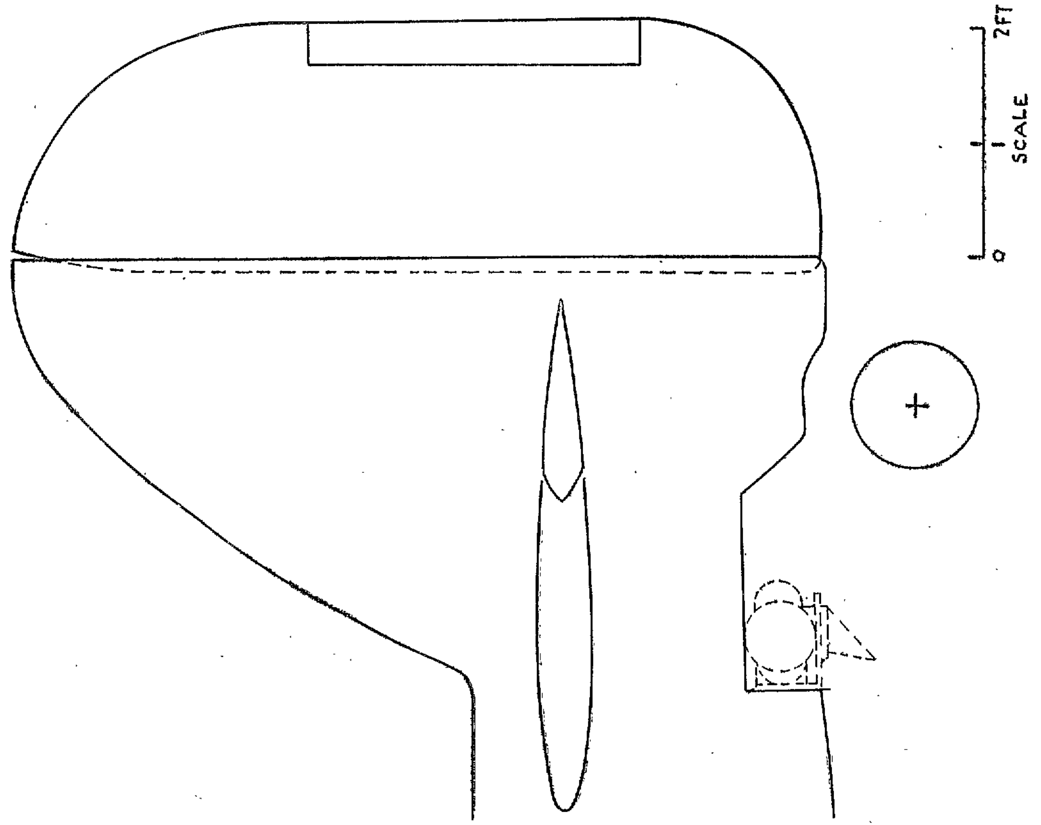

FIG. 2. Fin and rudder arrangement.

FIG. 3. Camera installation in tail-wheel bay.

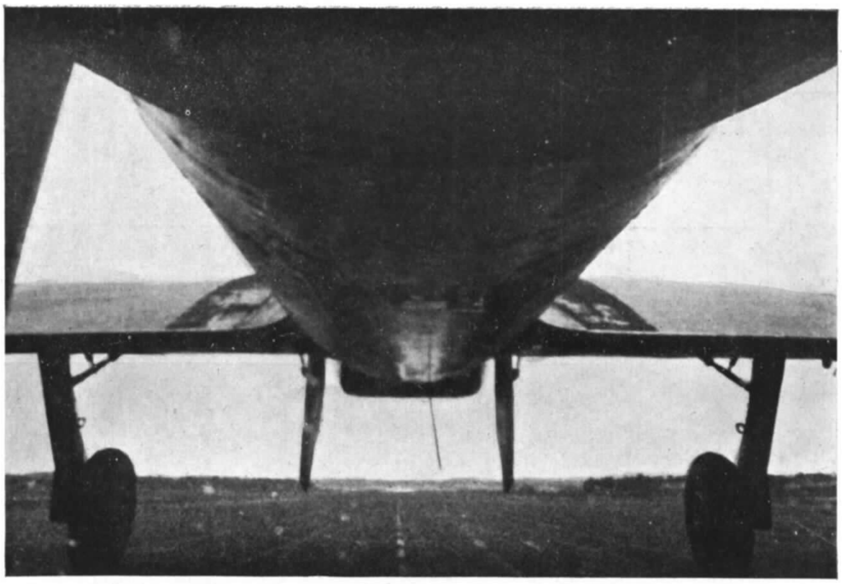

FIG. 4. View from tail camera.

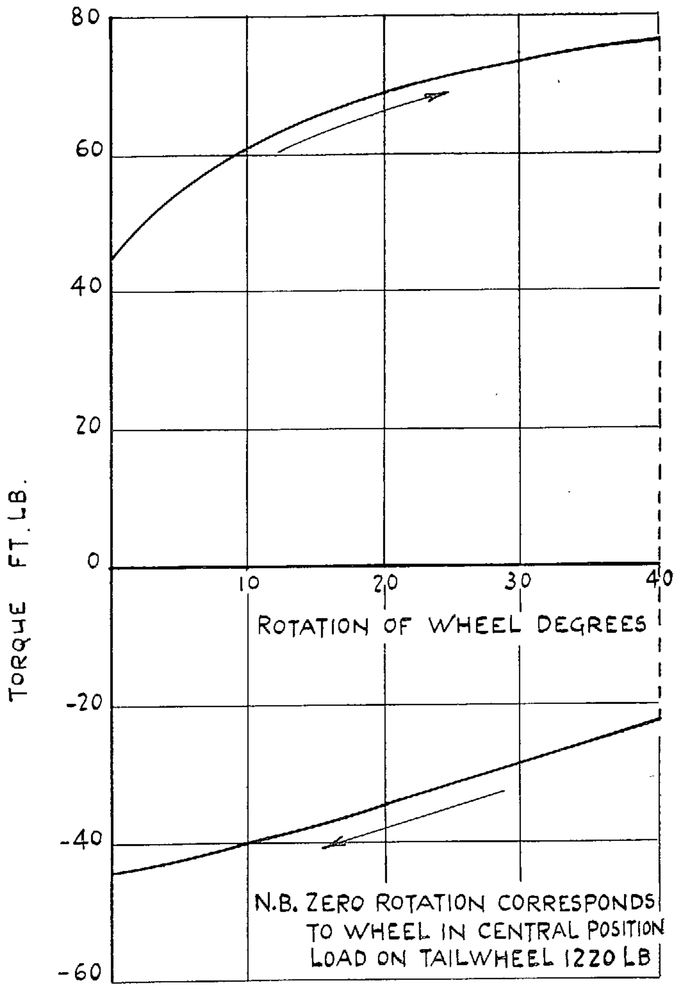

FIG. 6. Castoring test on tail-wheel.

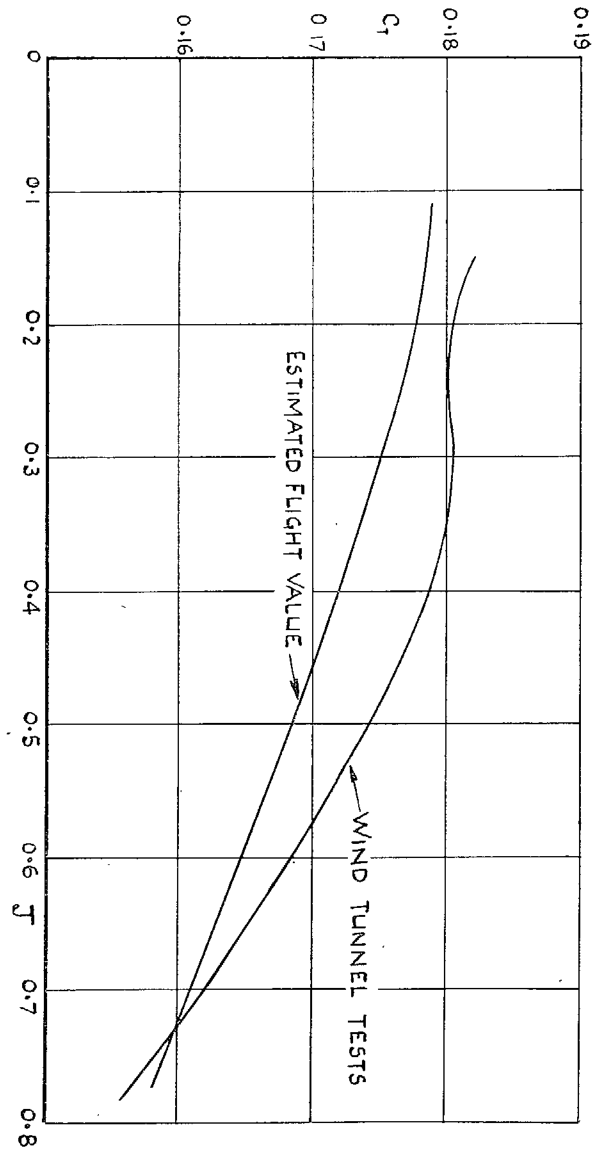

FIG. 5. Flight and wind-tunnel thrust coefficients.

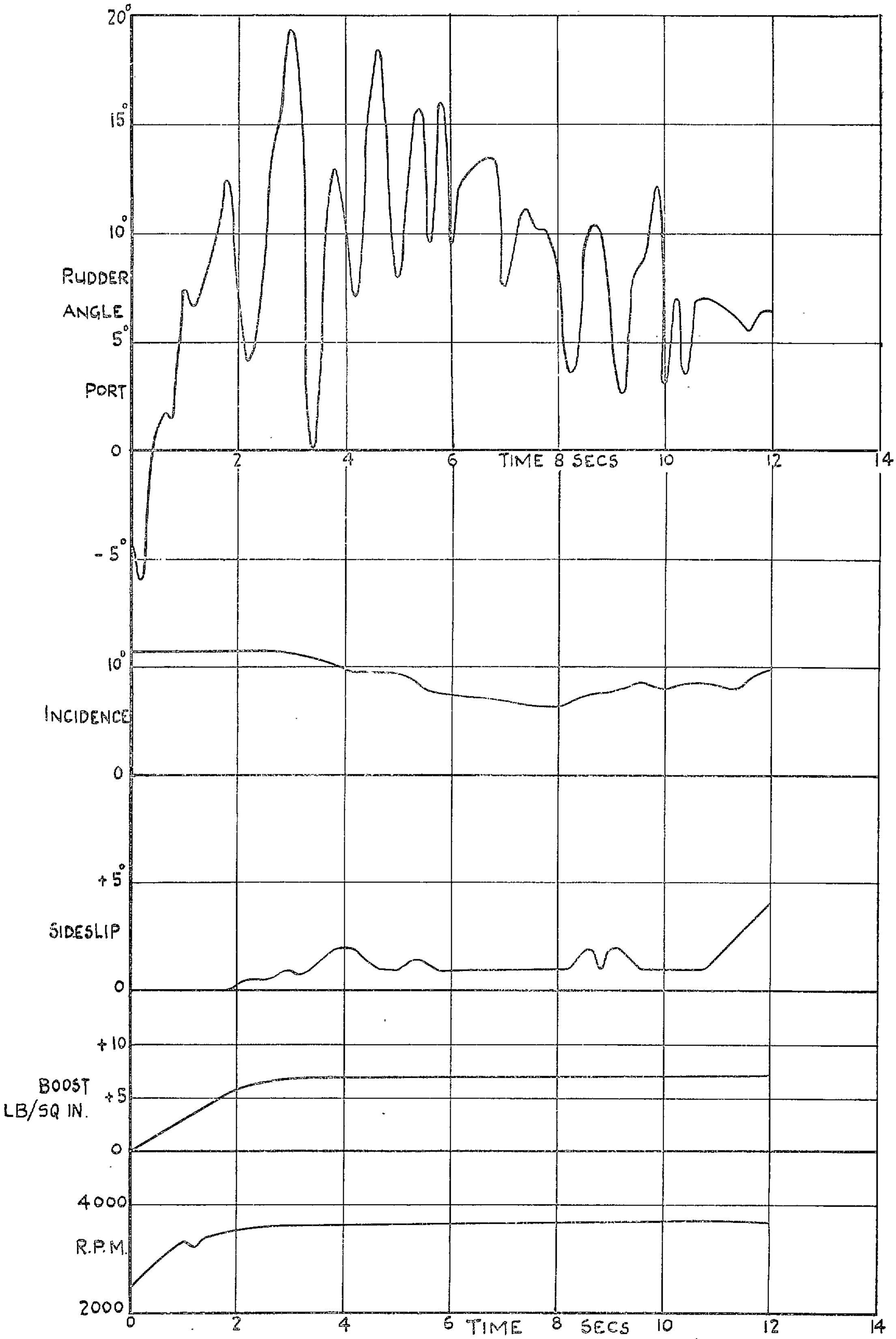

FIG. 7. Measured quantities during take-off. Flaps 0 deg.

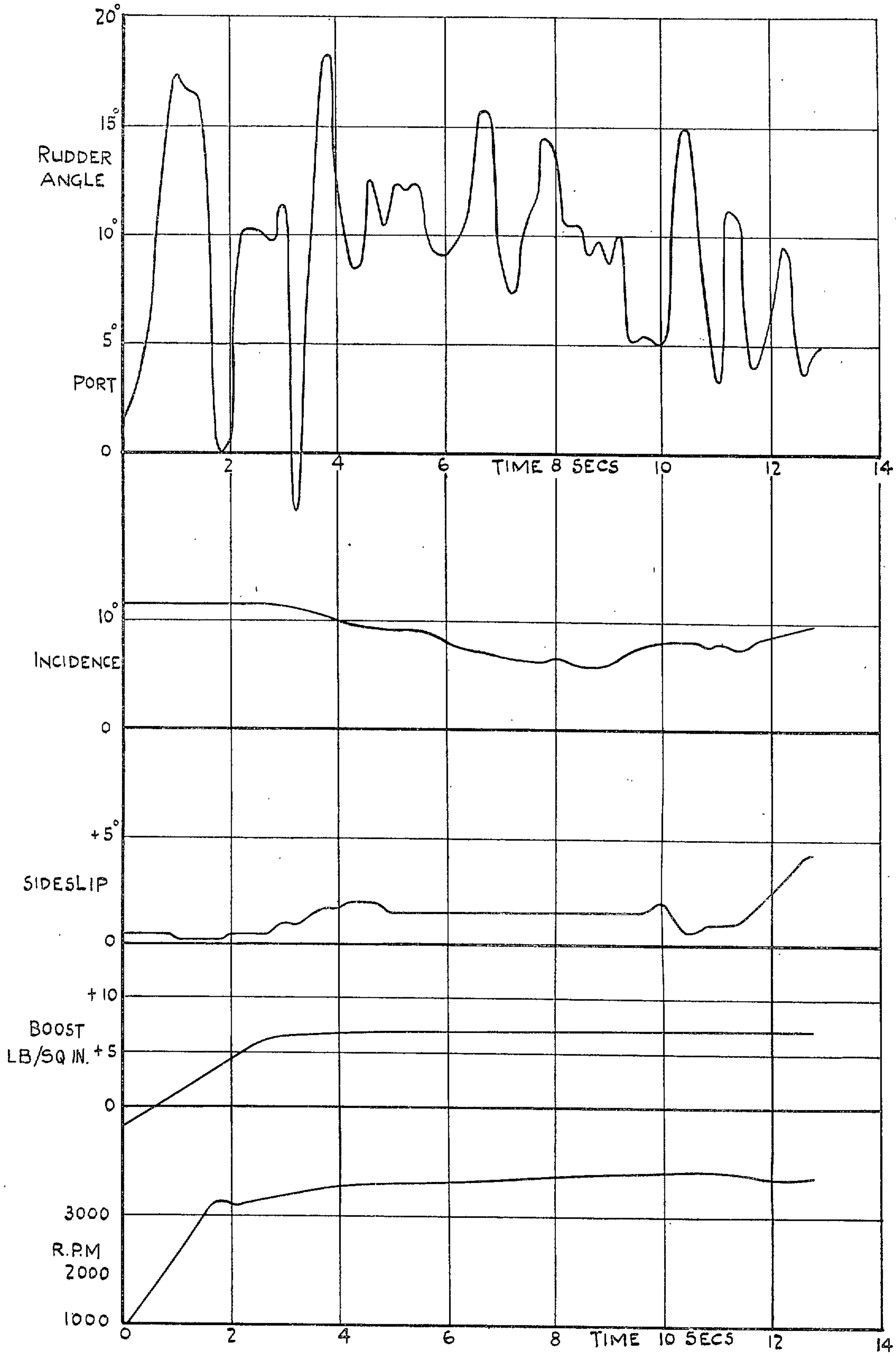

FIG. 8. Measured quantities during take-off. Flaps 0 deg.

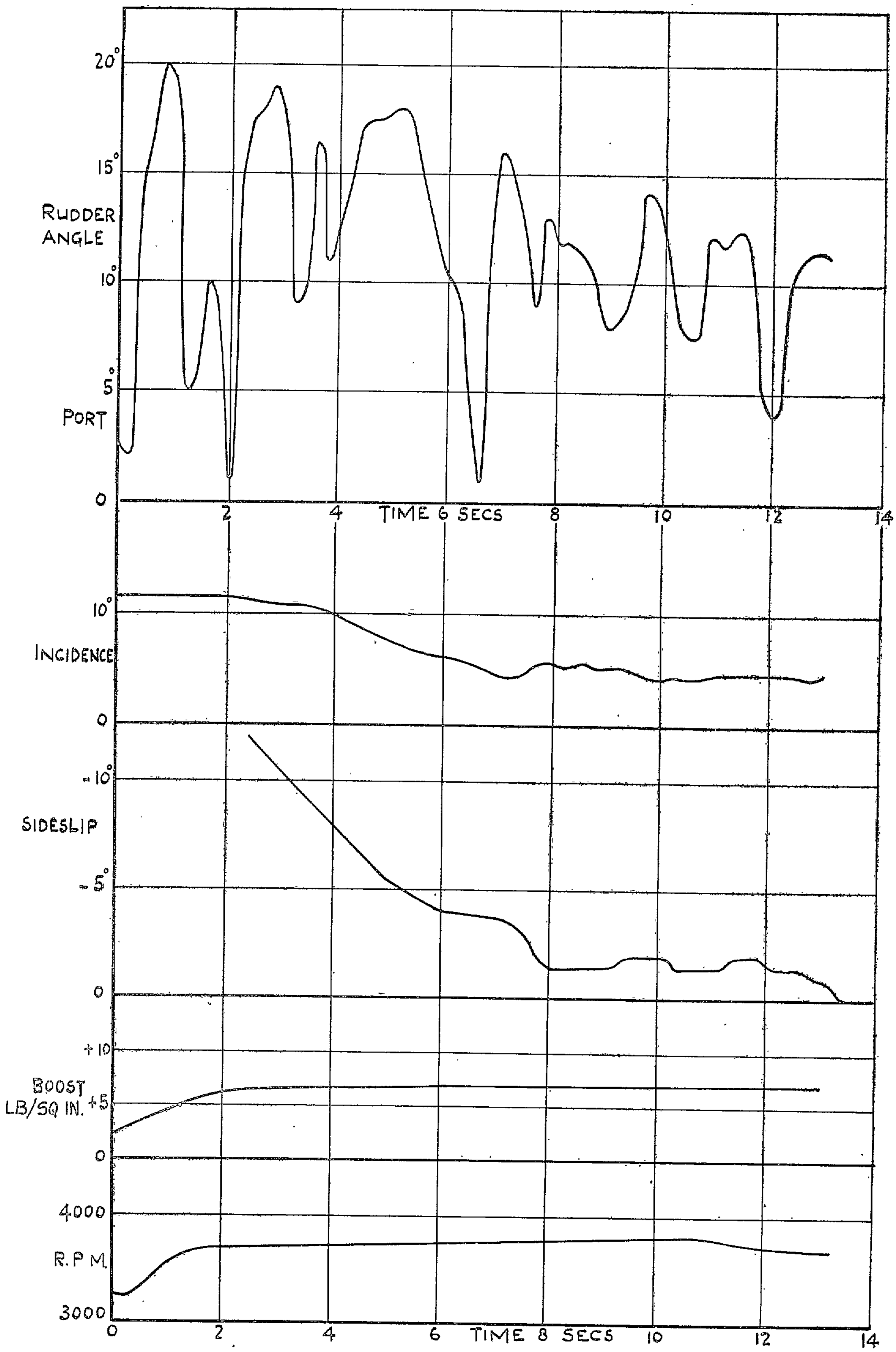

FIG. 9. Measured quantities during take-off. Flaps 20 deg.

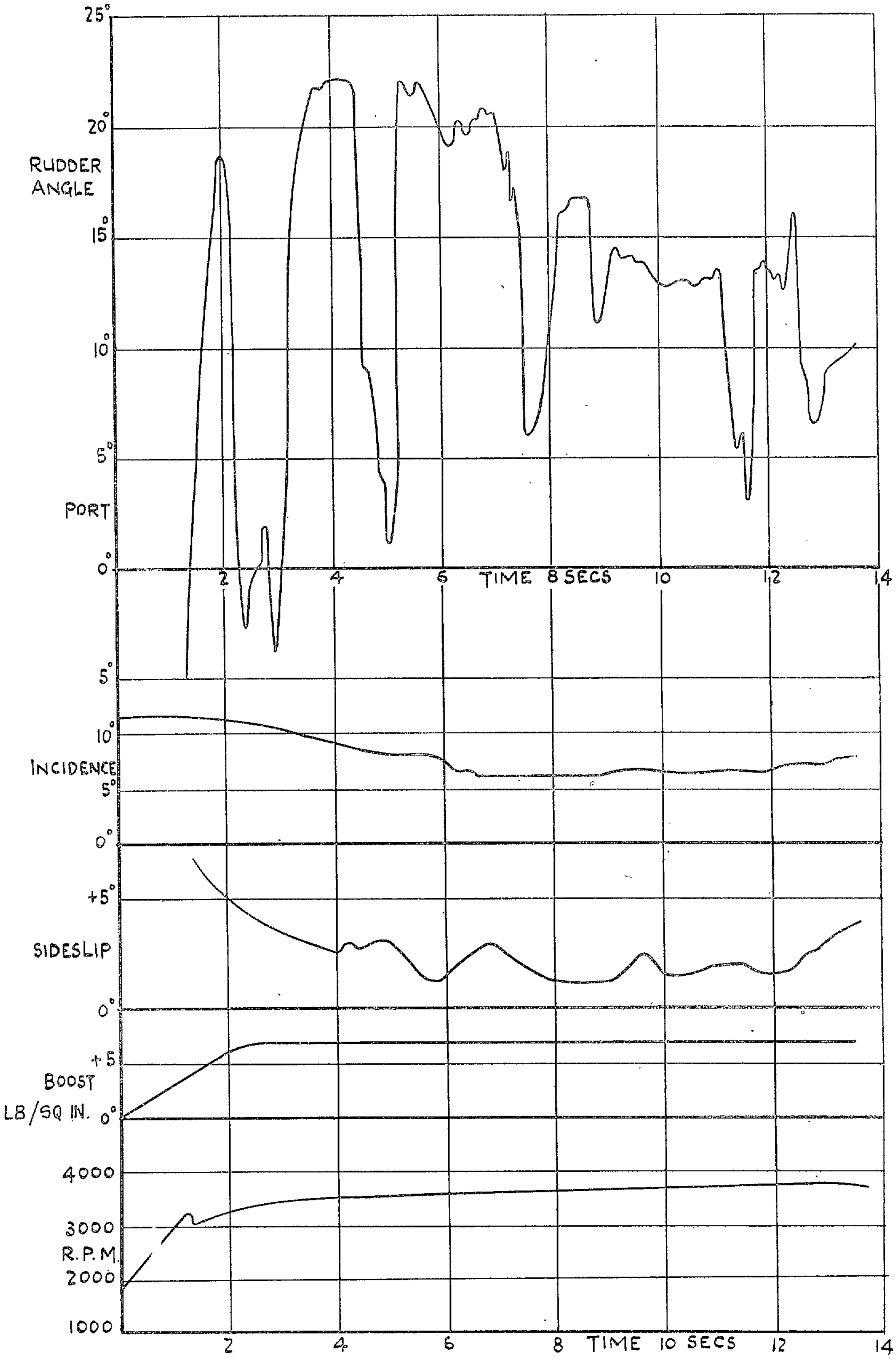

FIG. 10. Measured quantities during take-off. Flaps 20 deg.

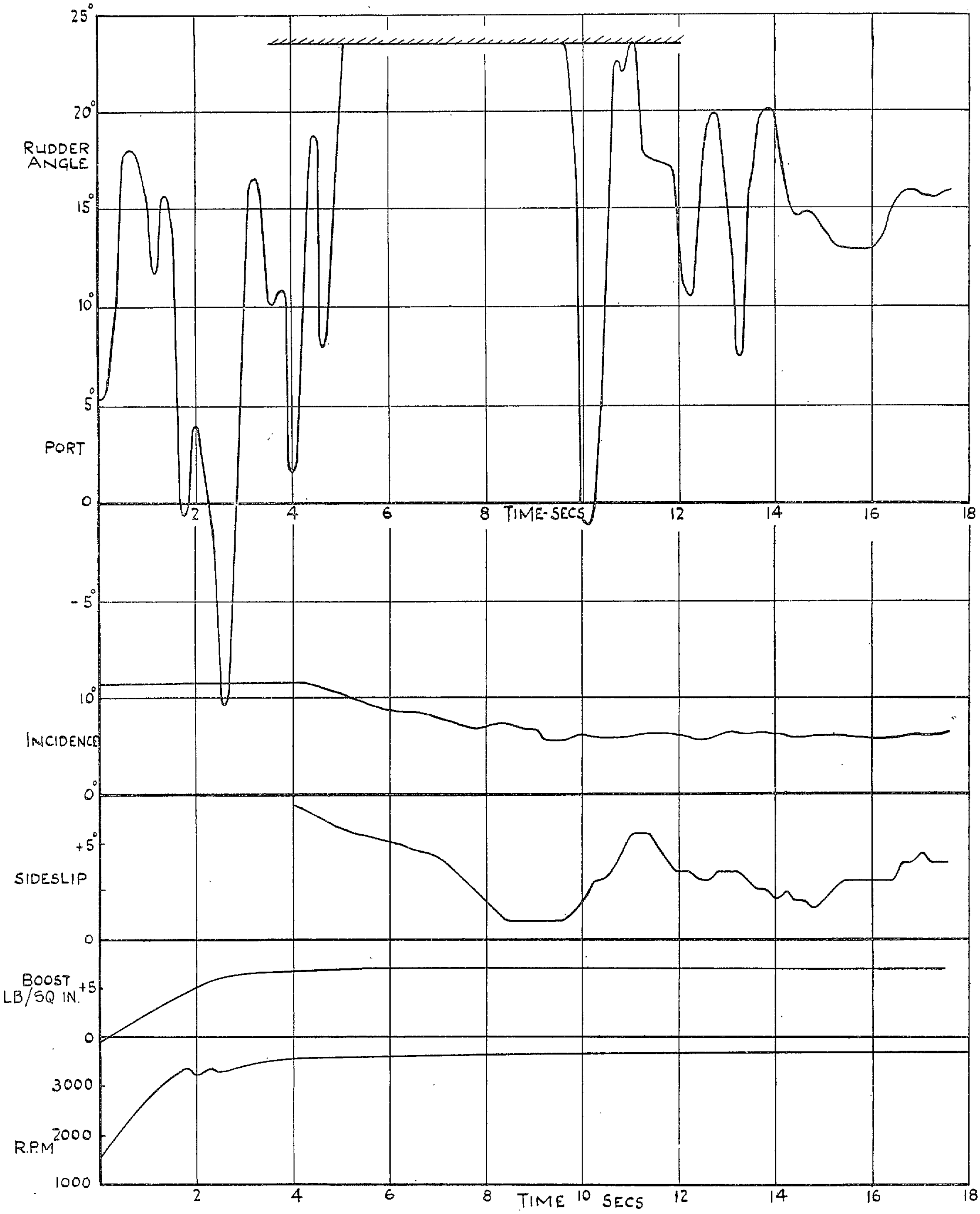

FIG. 11. Measured quantities during take-off. Flaps 60 deg.

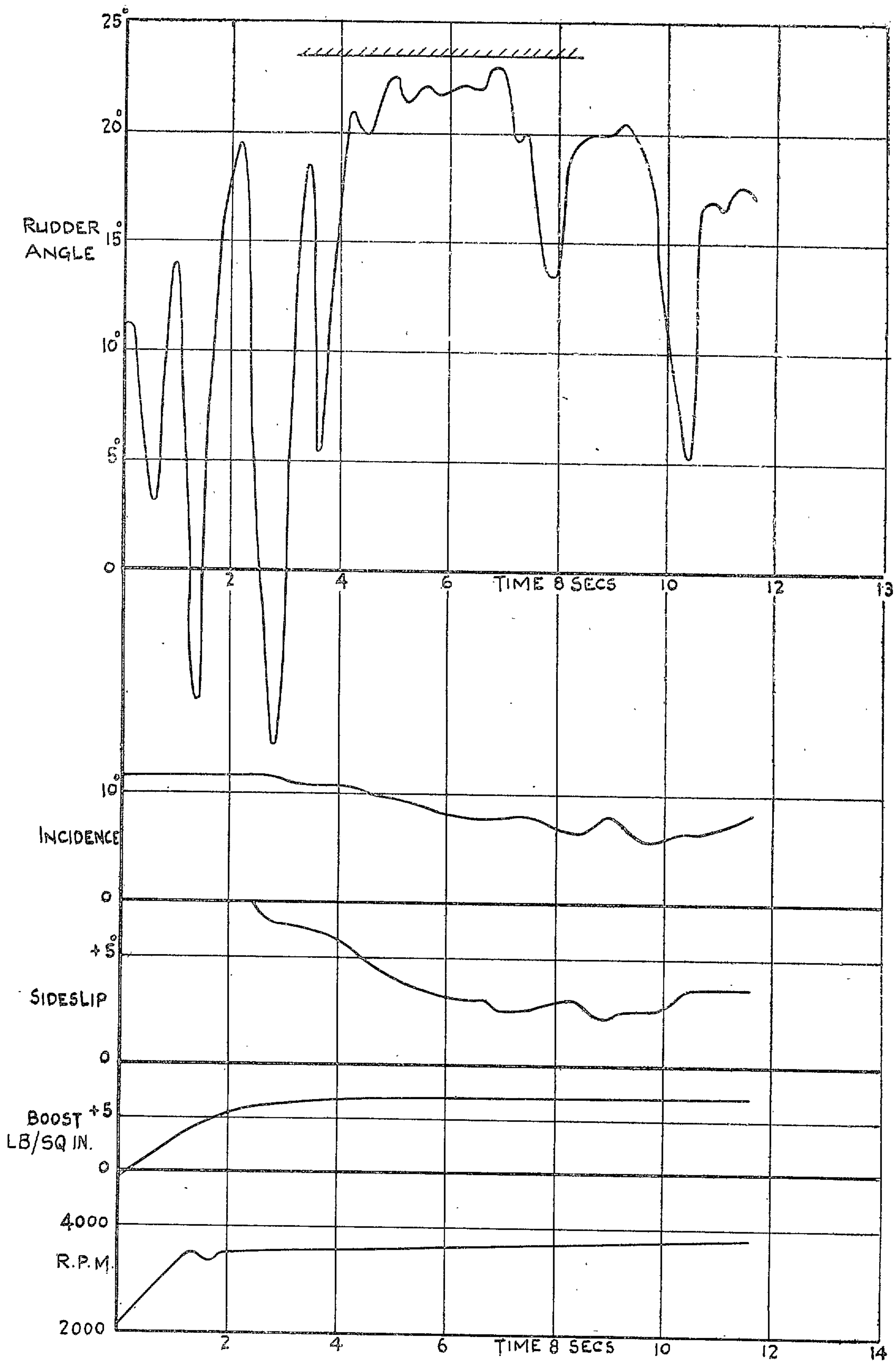

FIG. 12. Measured quantities during take-off. Flaps 60 deg.

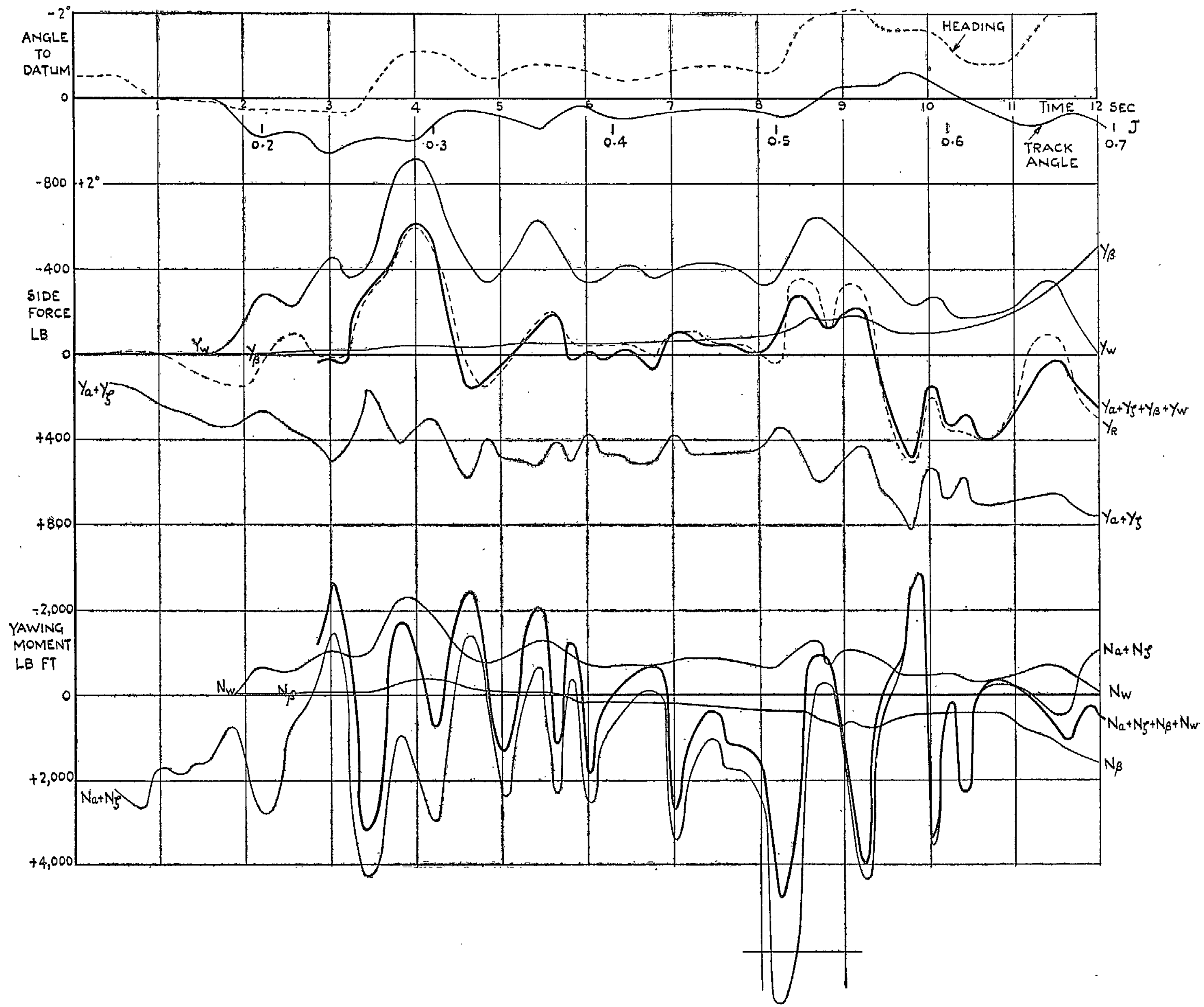

FIG. 13. Side-force and yawing-moment analyses. Flaps 0 deg.

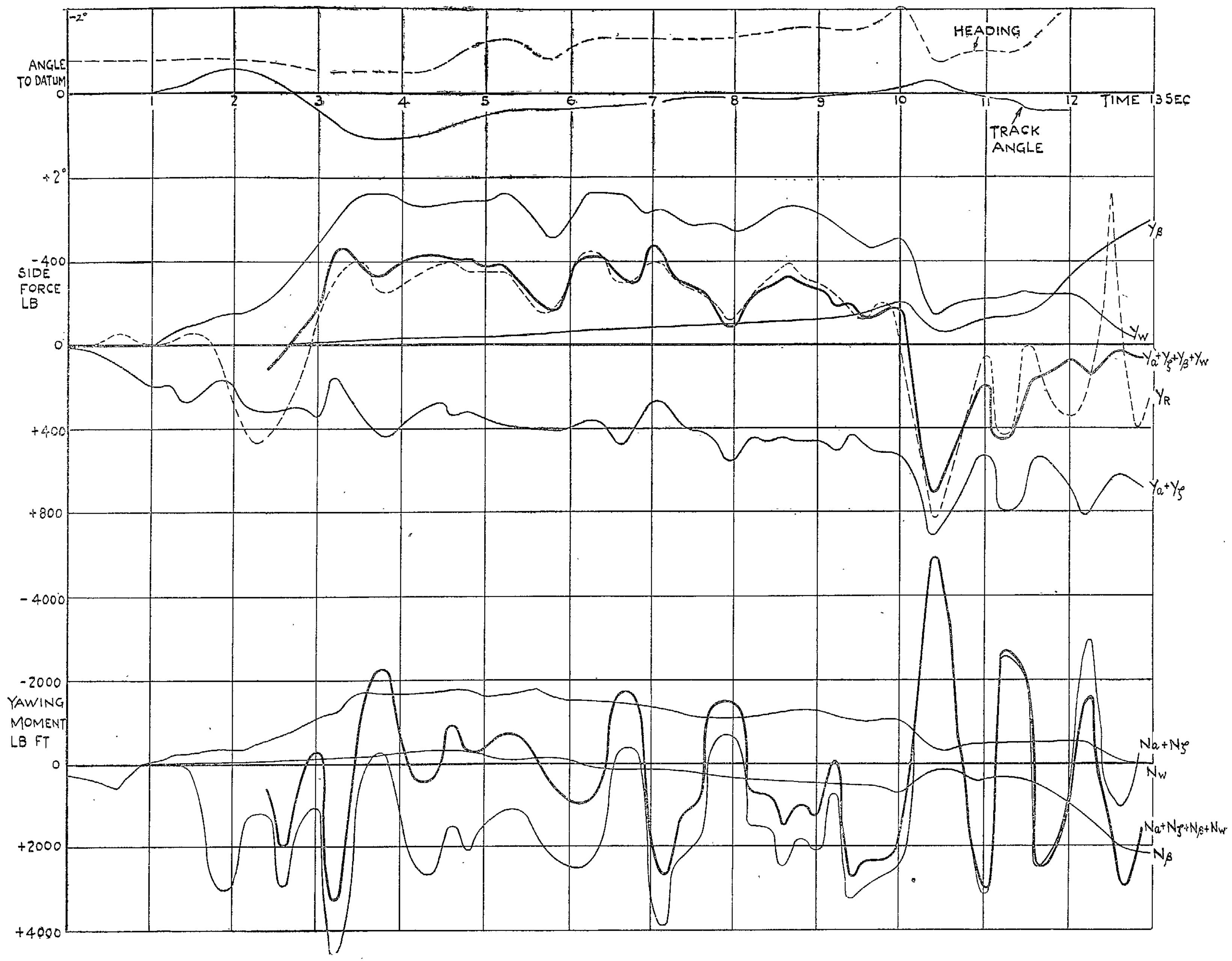

FIG. 14. Side-force and yawing-moment analyses. Flaps 0 deg.

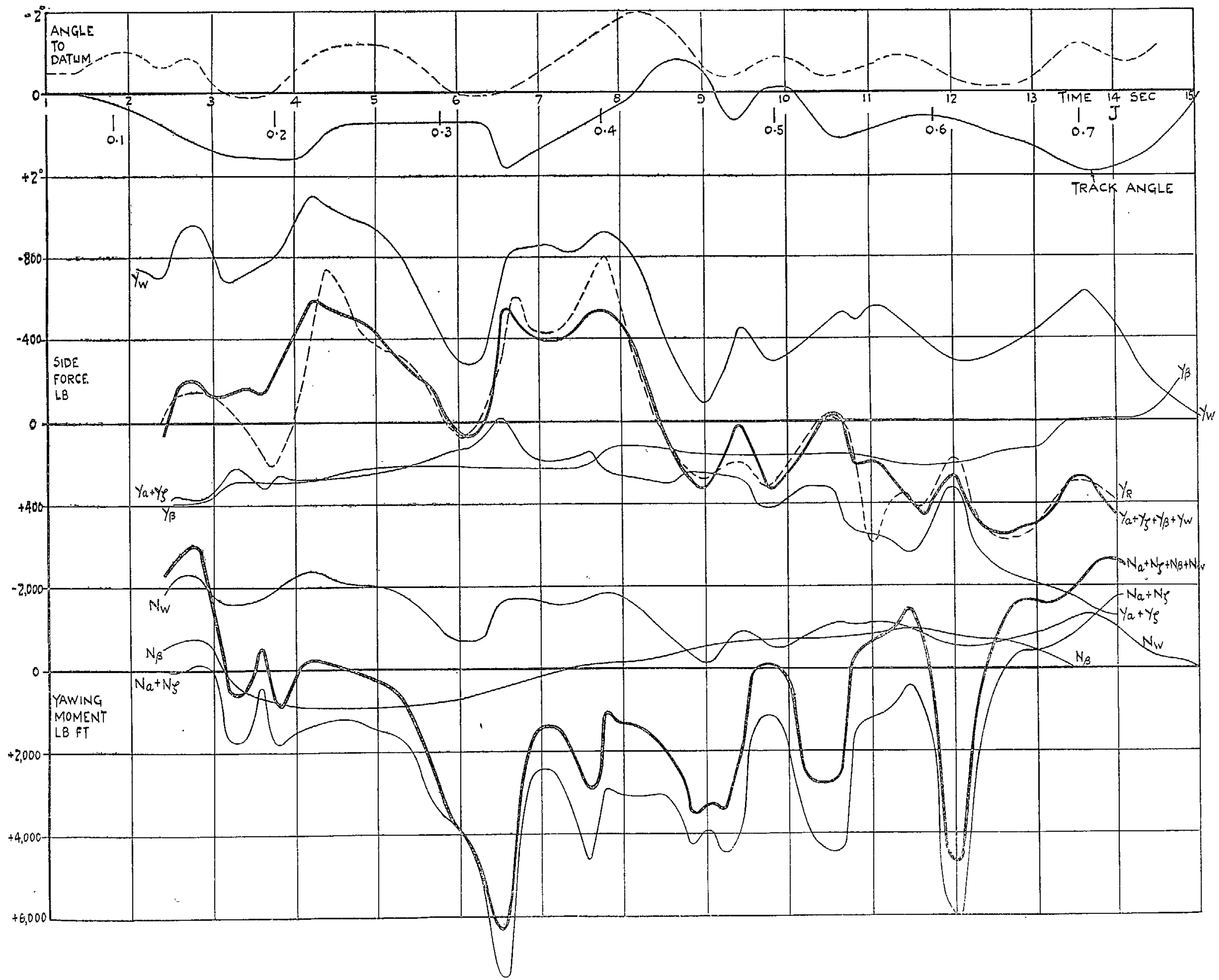

FIG. 15. Side-force and yawing-moment analyses. Flaps 20 deg.

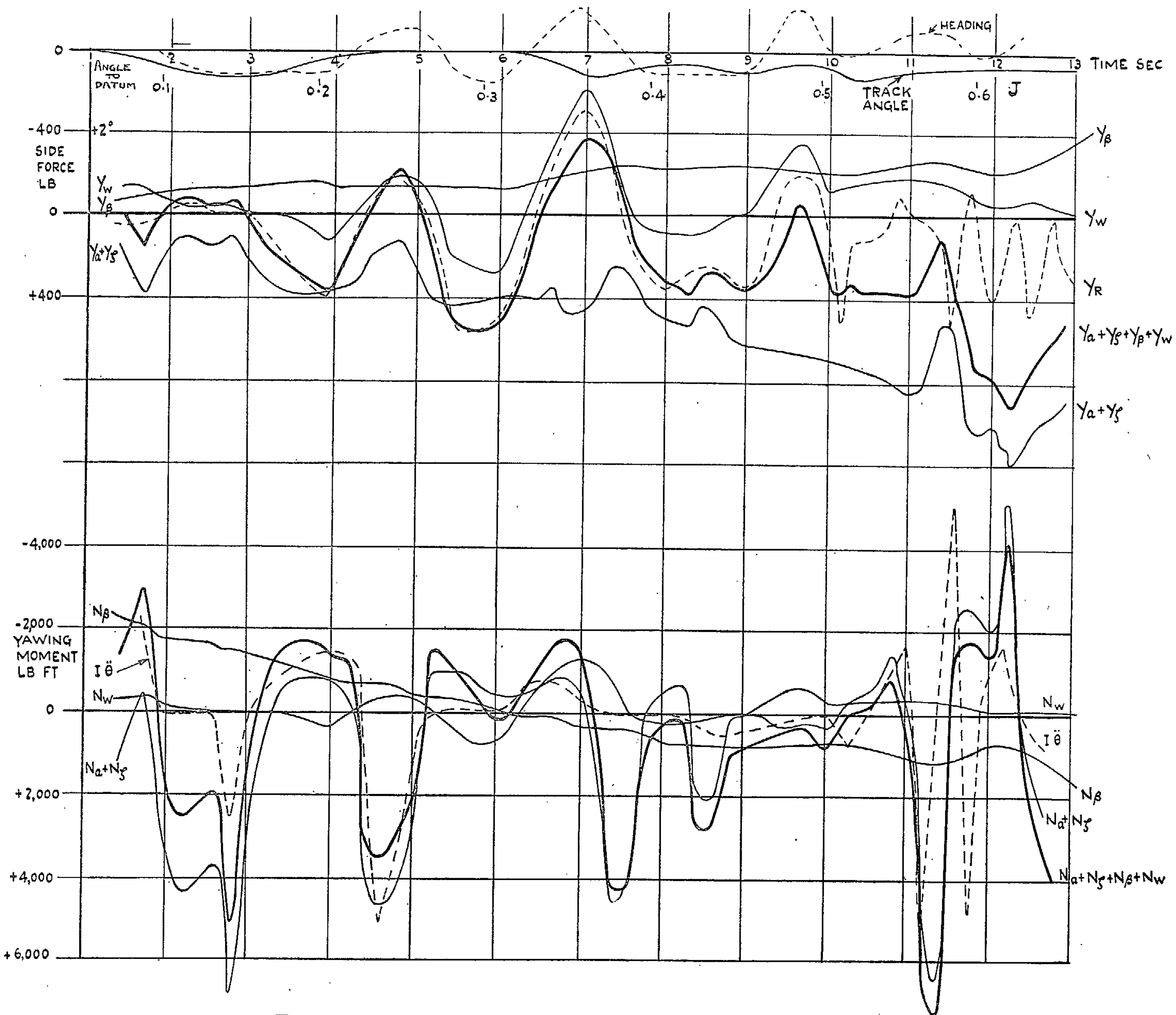

FIG. 16. Side-force and yawing-moment analyses. Flaps 20 deg.

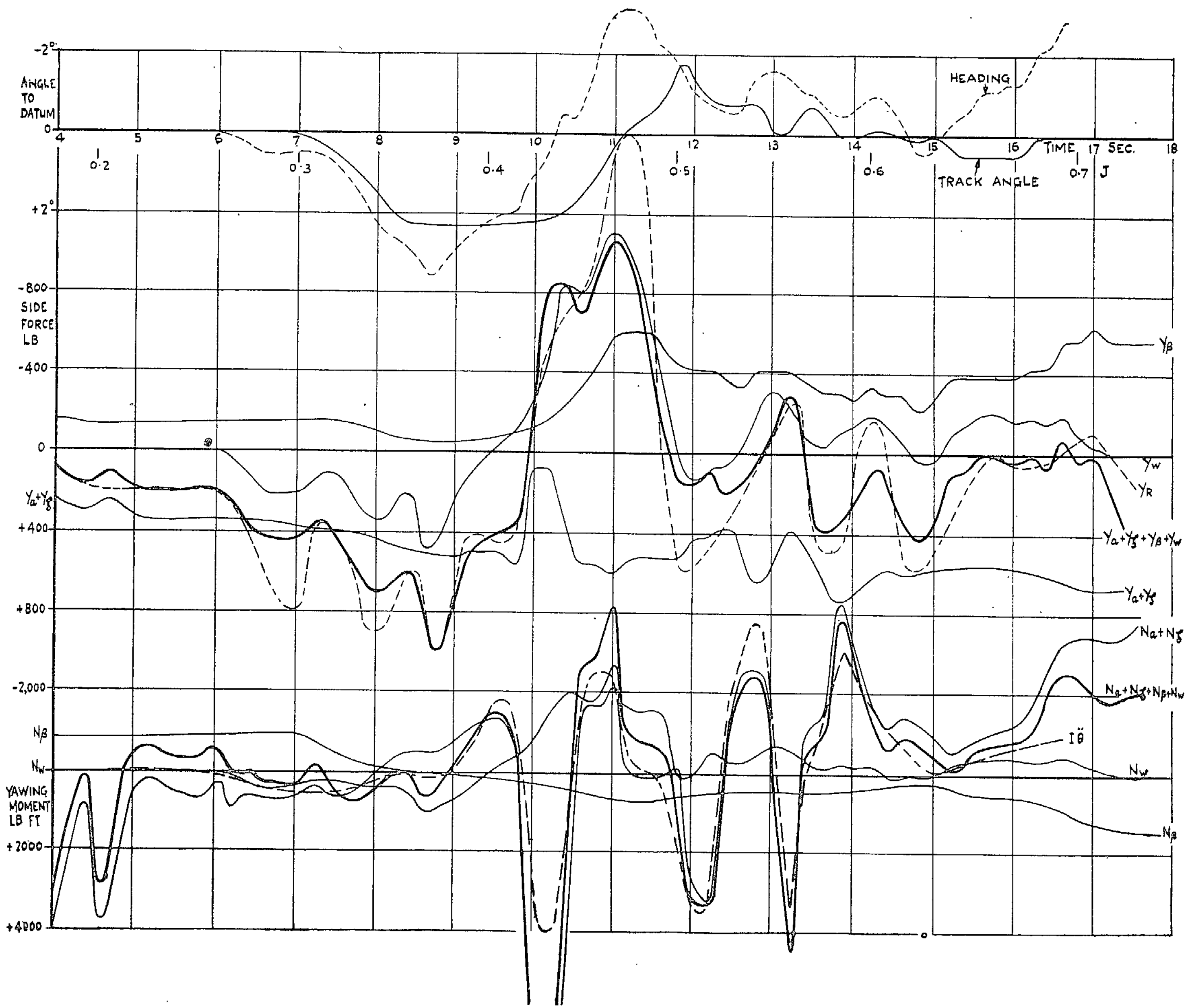

FIG. 17. Side-force and yawing-moment analyses. Flaps 60 deg.

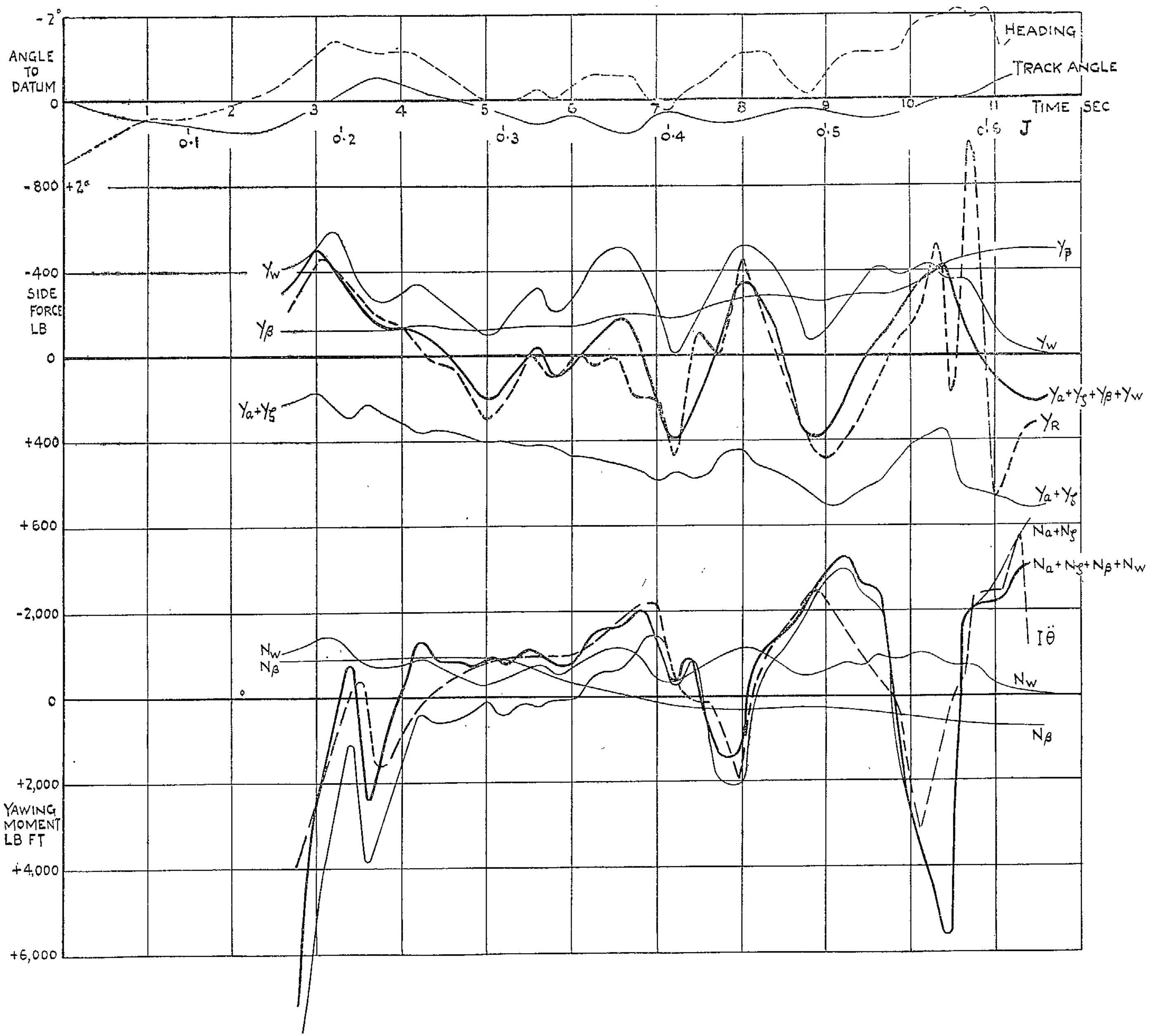

FIG. 18. Side-force and yawing-moment analyses. Flaps 60 deg.

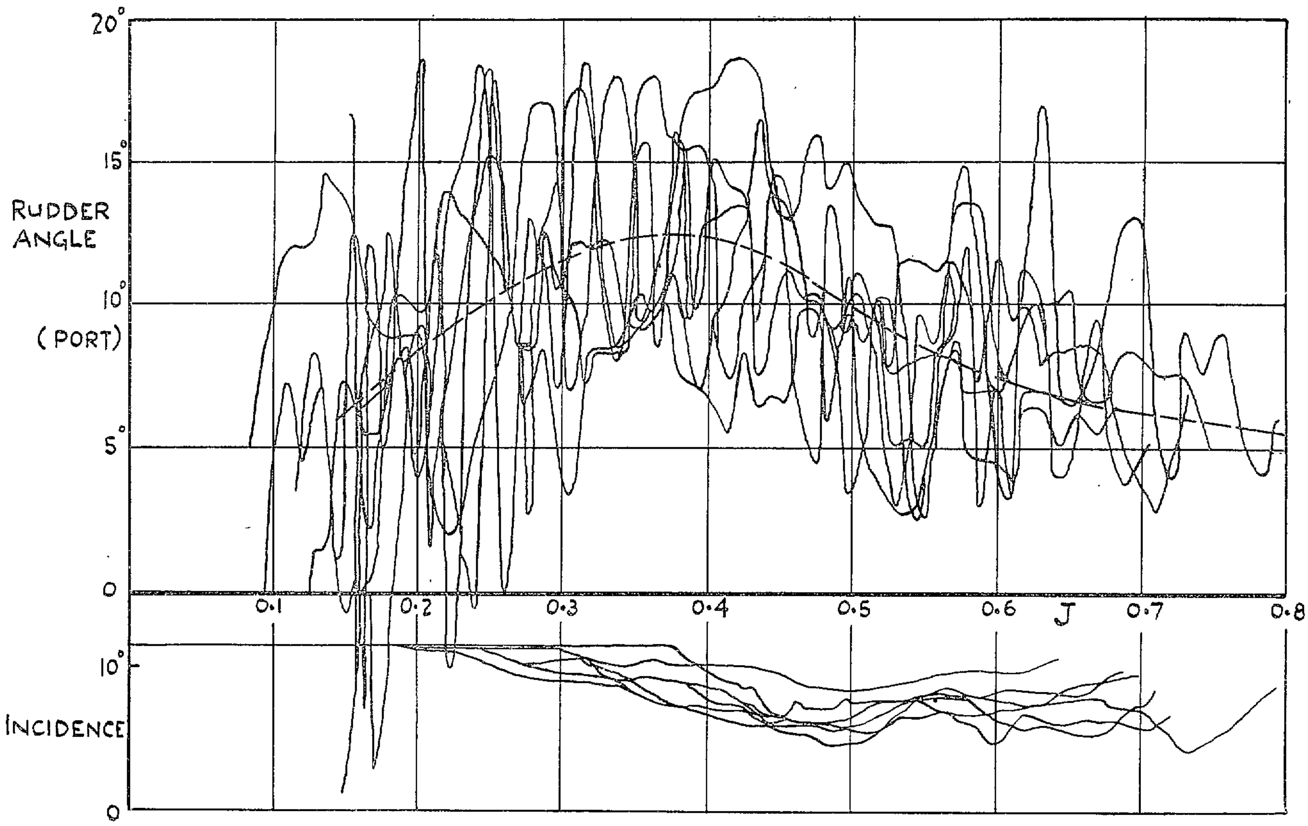

FIG. 19. Rudder angle *vs.* *J*. Flaps 0 deg.

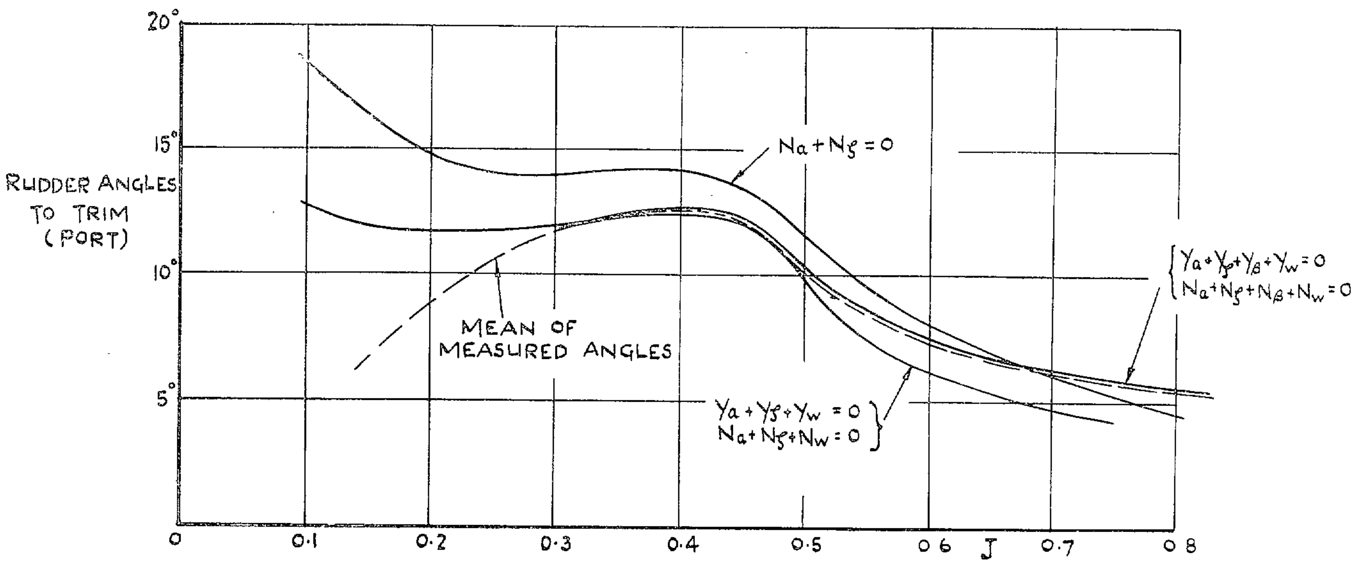

FIG. 20. Estimations of rudder angles to trim. Flaps 0 deg.

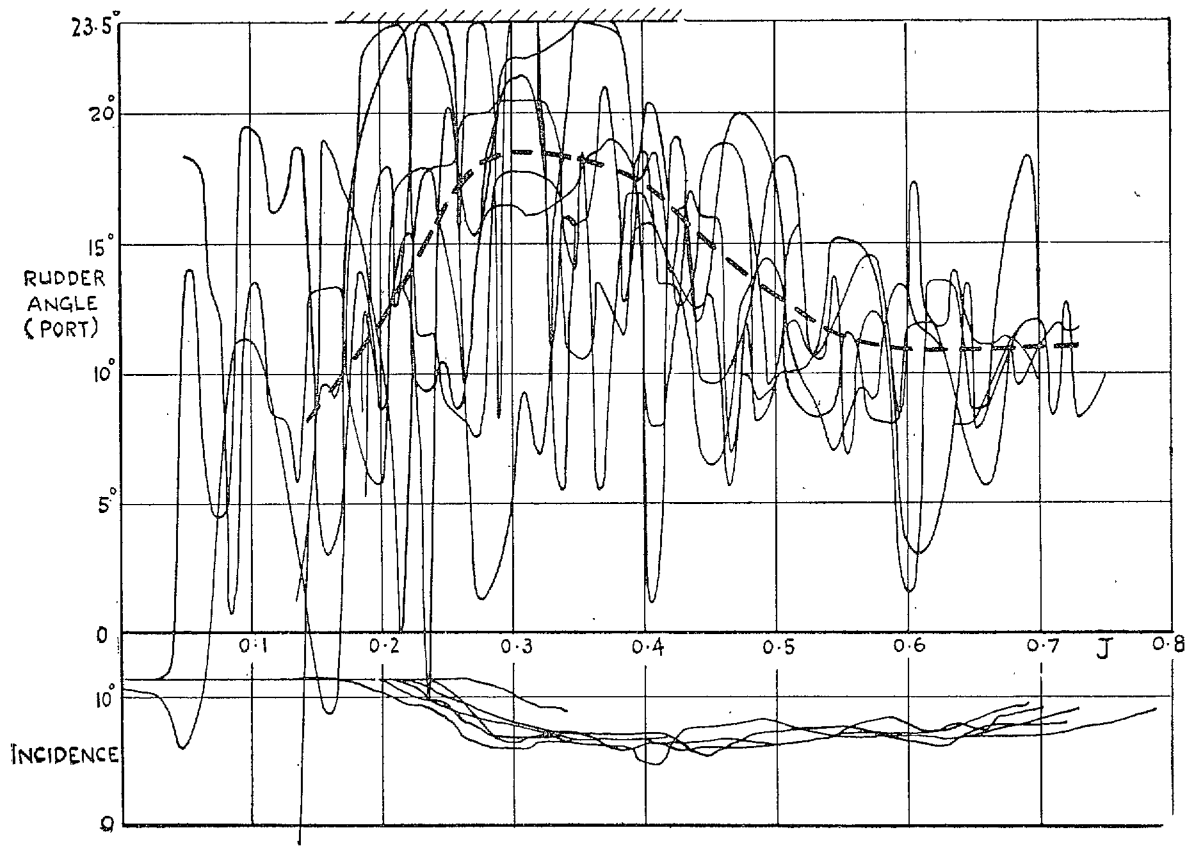

FIG. 21. Rudder angle *vs.* *J*. Flaps 20 deg.

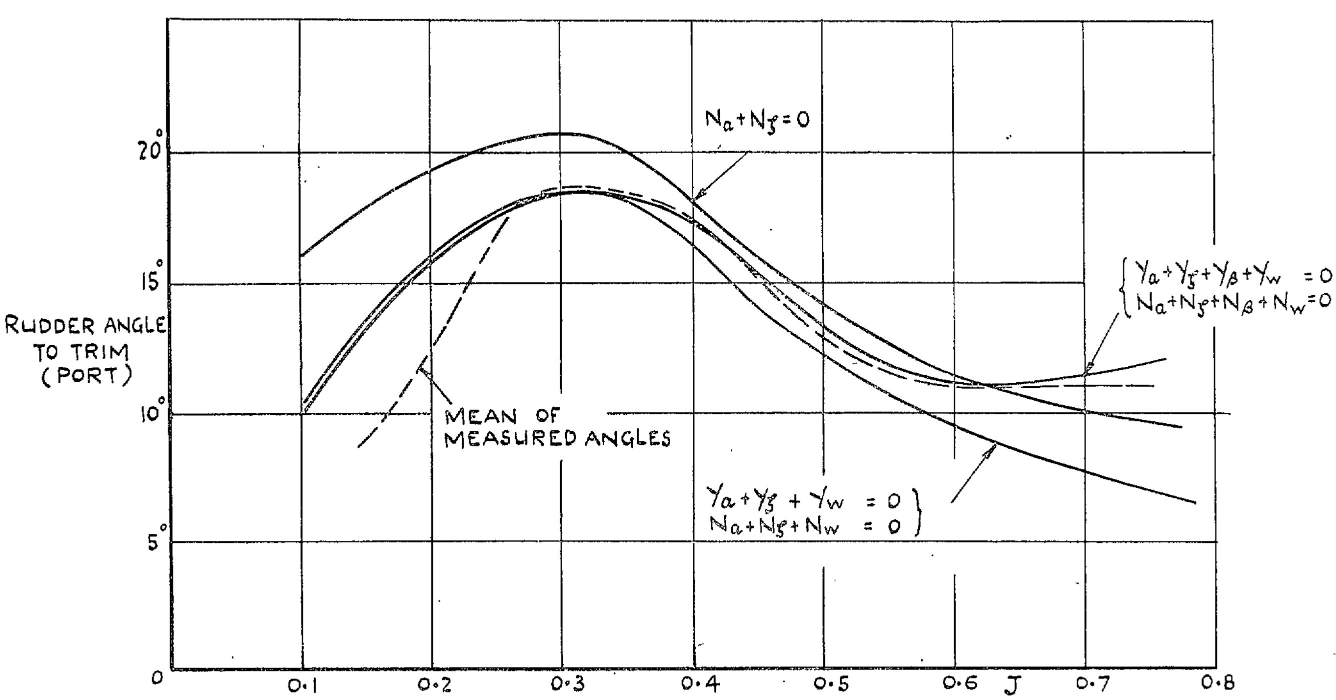

FIG. 22. Estimations of rudder angles to trim. Flaps 20 deg.

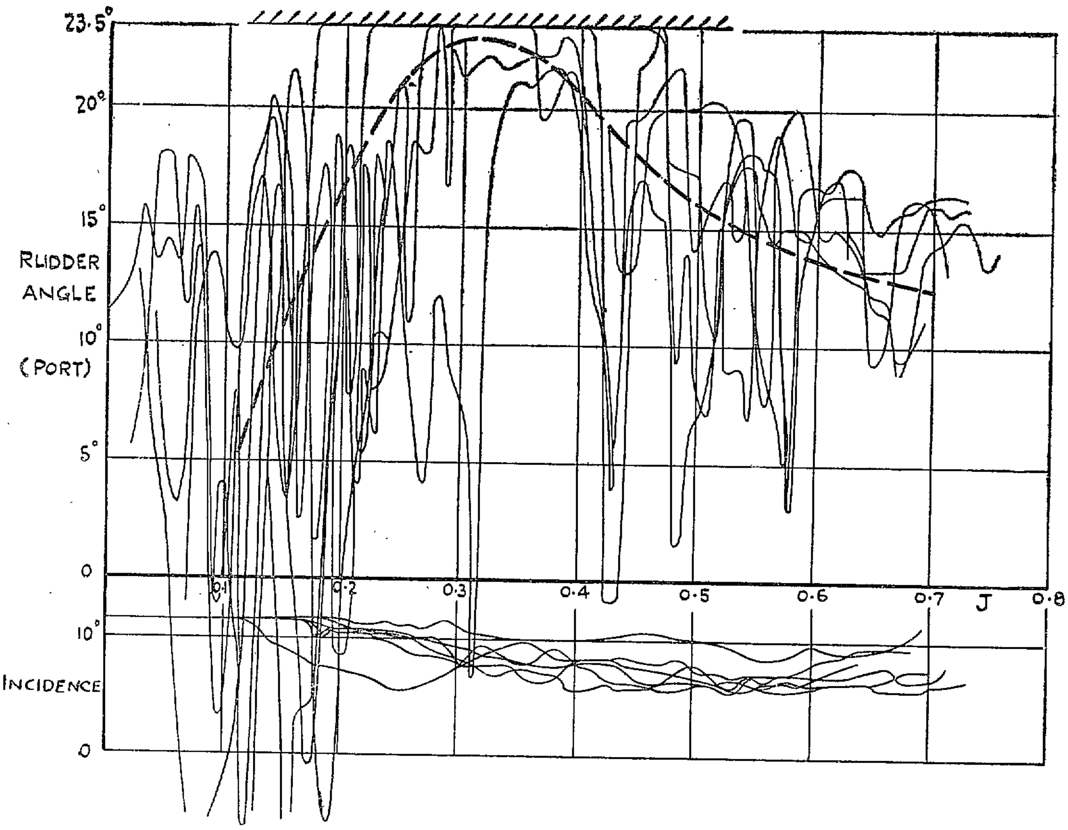

FIG. 23. Rudder angle *vs. J*. Flaps 60 deg.

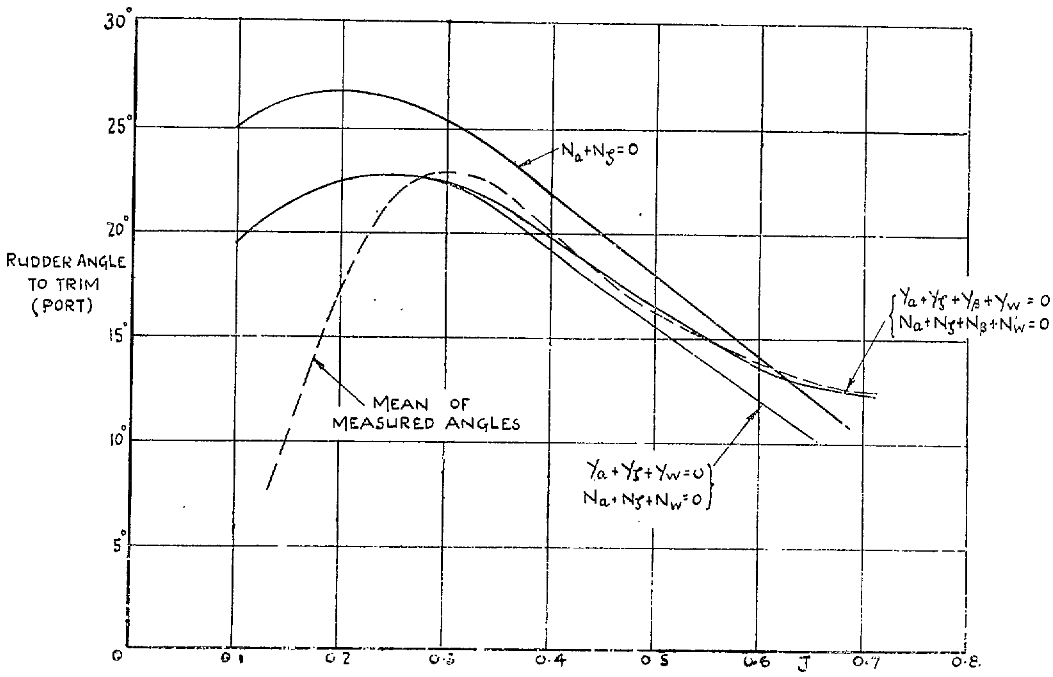

FIG. 24. Estimations of rudder angles to trim. Flaps 60 deg.

(1876) Wt. 13/806 K.9 12/53 H.P.Co. 34-261

PRINTED IN GREAT BRITAIN

Publications of the Aeronautical Research Council

ANNUAL TECHNICAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL (BOUND VOLUMES)—

1936 Vol. I. Aerodynamics General, Performance, Airscrews, Flutter and Spinning. 40*s.* (40*s.* 9*d.*)
Vol. II. Stability and Control, Structures, Seaplanes, Engines, etc. 50*s.* (50*s.* 10*d.*)

1937 Vol. I. Aerodynamics General, Performance, Airscrews, Flutter and Spinning. 40*s.* (40*s.* 10*d.*)
Vol. II. Stability and Control, Structures, Seaplanes, Engines, etc. 60*s.* (61*s.*)

1938 Vol. I. Aerodynamics General, Performance, Airscrews. 50*s.* (51*s.*)
Vol. II. Stability and Control, Flutter, Structures, Seaplanes, Wind Tunnels, Materials. 30*s.* (30*s.* 9*d.*)

1939 Vol. I. Aerodynamics General, Performance, Airscrews, Engines. 50*s.* (50*s.* 11*d.*)
Vol. II. Stability and Control, Flutter and Vibration, Instruments, Structures, Seaplanes, etc. 63*s.* (64*s.* 2*d.*)

* 1940 Aero and Hydrodynamics, Aerofoils, Airscrews, Engines, Flutter, Icing, Stability and Control, Structures, and a miscellaneous section. 50*s.* (51*s.*)

* 1941 Aero and Hydrodynamics, Aerofoils, Airscrews, Engines, Flutter, Stability and Control, Structures. 63*s.* (64*s.* 2*d.*)

* 1942 Vol. I. Aero and Hydrodynamics, Aerofoils, Airscrews, Engines. 75*s.* (76*s.* 3*d.*)
Vol. II. Noise, Parachutes, Stability and Control, Structures, Vibration, Wind Tunnels. 47*s.* 6*d.* (48*s.* 5*d.*)

* 1943 Vol. I. (*In the press*).
Vol. II. (*In the press*).

* *Certain other reports proper to these volumes will subsequently be included in a separate volume.*

ANNUAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL—

1933–34	1*s.* 6*d.* (1*s.* 8*d.*)	1937	2*s.* (2*s.* 2*d.*)
1934–35	1*s.* 6*d.* (1*s.* 8*d.*)	1938	1*s.* 6*d.* (1*s.* 8*d.*)
April, 1935 to Dec. 31, 1936.	4*s.* (4*s.* 4*d.*)	1939–48	3*s.* (3*s.* 2*d.*)

INDEX TO ALL REPORTS AND MEMORANDA PUBLISHED IN THE ANNUAL TECHNICAL REPORTS, AND SEPARATELY—

April, 1950 . . . . . . R. & M. No. 2600. 2*s.* 6*d.* (2*s.* 7½*d.*)

AUTHOR INDEX TO ALL REPORTS AND MEMORANDA OF THE AERONAUTICAL RESEARCH COUNCIL—

1909–1949 . . . . . . R. & M. No. 2570. 15*s.* (15*s.* 3*d.*)

INDEXES TO THE TECHNICAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL—

December 1, 1936 — June 30, 1939.	R. & M. No. 1850.	1*s.* 3*d.* (1*s.* 4½*d.*)
July 1, 1939 — June 30, 1945.	R. & M. No. 1950.	1*s.* (1*s.* 1½*d.*)
July 1, 1945 — June 30, 1946.	R. & M. No. 2050.	1*s.* (1*s.* 1½*d.*)
July 1, 1946 — December 31, 1946.	R. & M. No. 2150.	1*s.* 3*d.* (1*s.* 4½*d.*)
January 1, 1947 — June 30, 1947.	R. & M. No. 2250.	1*s.* 3*d.* (1*s.* 4½*d.*)
July, 1951.	R. & M. No. 2350.	1*s.* 9*d.* (1*s.* 10½*d.*)

Prices in brackets include postage.

Obtainable from

HER MAJESTY'S STATIONERY OFFICE

York House, Kingsway, London, W.C.2; 423 Oxford Street, London, W.1. (Post Orders; P.O. Box 569, London, S.E.1); 13a Castle Street, Edinburgh 2; 39 King Street, Manchester 2; 2 Edmund Street, Birmingham 3; 1 St. Andrew's Crescent, Cardiff; Tower Lane, Bristol 1; 80 Chichester Street, Belfast OR THROUGH ANY BOOKSELLER.

S.O. Code No. 23-2660

R. & M. No. 2660