R. & M. No. 3508

MINISTRY OF TECHNOLOGY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

Take-off Tests on a Transport Aircraft Including the use of a 'SCAT' Take-off Director

By C. O. O'Leary, J. N. Cannell and R. L. Maltby

LONDON: HER MAJESTY'S STATIONERY OFFICE
1968
PRICE £1 6*s*. 6*d*. NET

Take-off Tests on a Transport Aircraft Including the use of a 'SCAT' Take-off Director

By C. O. O'Leary, J. N. Cannell and R. L. Maltby

Reports and Memoranda No. 3508*
April, 1966

Summary.

A large number of take-off tests have been made on a Comet aircraft with the object of
(a) acquiring comprehensive data on undirected take-offs;
(b) testing a SCAT take-off director.

SCAT is explained in detail and the aircraft installation and test method described. Tests to determine ground effect on lift and on the SCAT Lift Transducer are also described. Undirected and directed take-offs are compared using statistical techniques and the performance of the director under abnormal conditions is discussed.

The tests have confirmed that the variability of undirected take-offs is such that an improved pilot aid is needed. The comparison between undirected and SCAT directed take-offs indicates that, although this director did not significantly improve variability, pilot's work load was considerably reduced, especially under abnormal flight conditions.

A simple technique has been developed for filming the pilot's eye movements to analyse his scan of the instrument panel and some results are discussed.

LIST OF CONTENTS

1. Introduction

2. Description of Aircraft and Installation
    2.1. The test aircraft
    2.2. The SCAT system
        2.2.1. Principles of operation
        2.2.2. The limitations of the transducers
    2.3. Installation and calibration of the SCAT system in Comet XP 915

3. Flight Calibration of the Aircraft in Free Air and in Ground Effect

4. Description of Take-off Tests

5. Analysis of Results

---

*Replaces R.A.E. Tech. Report No. 66 117—A.R.C. 28 283.

LIST OF CONTENTS—*continued*

6. Discussion
  - 6.1. Variability of undirected take-offs
  - 6.2. SCAT directed take-offs
    - 6.2.1. Director following
    - 6.2.2. Summation of component signals
    - 6.2.3. Lift transducer performance
    - 6.2.4. Use of SCAT during configuration changes, turns, engine cuts and 'abuse' cases
    - 6.2.5. Effect of a pitch-rate term in SCAT
    - 6.2.6. Statistical comparison of undirected and SCAT directed take-offs
    - 6.3. Pilot opinions of the F.4B as a take-off director display instrument
  - 6.4. Pilot scan during take-off

7. Conclusions
  - 7.1. Undirected take-offs
  - 7.2. Directed take-offs

Acknowledgements

List of Symbols

References

Appendix A Methods of determining wing lift coefficient for checking the accuracy of the lift transducer

Appendix B Analysis of ground effect tests

Tables 1 to 4

Illustrations—Figs. 1 to 43

Detachable Abstract Cards

LIST OF TABLES

Table 1 Recorded quantities and instrumentation

Table 2 Statistical comparison of undirected and directed take-offs

Table 3 Effect of accurate director following on C_{LW} distributions at 20 ft and 50 ft

Table 4 Aerodynamic particulars of Comet 3B relevant to tests

1. *Introduction.*

Since the introduction of large jet aircraft into the civil transport field, there has been concern about the overall safety of the take-off manoeuvre; indeed, nearly a quarter of the fatalities in jet airliner accidents in the four years from 1959 occurred during or immediately after take-off[1]. Two main areas of difficulty in the take-off of these aircraft can be distinguished; first the problem of bringing the aircraft safely to rest after a take-off has had to be abandoned, and secondly, the problem of setting up a safe climb path once the aircraft has been committed to flight.

For the consideration of these problems, it is convenient to divide the manoeuvre into the following four phases:

Ground run
Rotation
Flare-up
Climb-out

The handling problems in the ground run are mainly concerned with the difficulty of assessing the latest point at which the take-off can be safely abandoned in emergency conditions. For instance, if there is a significant loss of thrust, the pilot must weigh the risk of committing the aircraft to flight in an underpowered condition against the risks of abandoning the take-off and not having sufficient length of runway available for braking. He must therefore have the earliest possible warning of the emergency condition and its extent and be able to relate his speed at the time to the amount of runway already used and the expected braking performance. A significant number of accidents have occurred from this kind of situation and considerable effort has been put into devising means of providing pilots with the information required to deal with it.

Improvements have been made in flight deck management and instruments have been proposed which would monitor the progress of the aircraft and continuously predict its possible stopping point. No completely satisfactory solution has yet been found for the design of such a Take-off Monitor and it seems likely that a more limited form of Take-off Progress Indicator may be more practicable.

The handling problems in the remaining three phases of take-off which are the subject of this Report, are rather more complex and are concerned with avoiding the possibility of loss of control in emergency situations and with maintaining sufficient performance in order to clear obstacles.

In the rotation phase the pilot must raise the nose of the aircraft so that it reaches the attitude necessary to unstick at the required speed. If this manoeuvre is completed too early, the extra induced drag will reduce the acceleration and an unnecessary length of runway will be consumed or the aircraft will lift off too far below the minimum flight safety speed. If it is initiated too late, unstick will be delayed to higher speed and, again, too much runway will be used. The optimum speeds for initiation of rotation for different weights are normally laid down in the aircraft flight manuals, but errors in excess of ±20 knots have been recorded on scheduled flights. There are, of course, a number of possible reasons for these errors, but some proportion at least must be due to the difficulty of providing the pilot with a precise indication of the instant at which rotation speed is reached while he is looking ahead. This is usually done by the co-pilot calling out the speeds from his own instrument and some precision is inevitably lost in the process. A direct positive indication to the pilot could well reduce these errors to a more acceptable level.

The rate of rotation is largely determined by the nature of the initial elevator input and must be neither too small to achieve the desired unstick speed nor so large as to lead to over-rotation. Since the pilot has no guidance for this beyond his experience and because variation in weight and c.g. position have a marked effect on the response in pitch, it is hardly surprising that large variations in the rate of rotation can occur. In fact, measurements under operational conditions show that errors in unstick speed of 10 or 20 knots are quite common.

During the flare-up the incidence reaches its peak value and the margin from the stall is reduced to a minimum. Although the stall warning indicator will show when a dangerous condition is being approached, it is possible that the rate of rotation could be too rapid for the pilot to be able to take corrective action in time, particularly if some emergency such as engine failure should occur at about the same time. The pilot is normally guided in this manoeuvre by the A.S.I. and by his assessment of pitch attitude from either external reference or from the artificial horizon, but these clues may be inadequate to monitor the manoeuvre with the required precision. The circumstances of the accident to a Comet at Ankara in 1961[2] illustrate this point.

After unstick, the pilot must allow the aircraft to accelerate smoothly to the selected climb speed whilst the undercarriage and flaps are retracted and the thrust is adjusted to suit noise abatement procedures. If there has been an engine failure, it is likely that there will be only just enough power to achieve the required climb gradient. The aircraft must therefore be held at a low speed in order that climb performance should not be sacrificed for acceleration. Existing instruments appear to provide insufficient information to allow pilots to maintain this lower speed with reasonable accuracy, especially when engine failure also causes lateral handling difficulties.

All these considerations suggest the need for an instrument which will measure the performance of the aircraft and present the pilot with an indication of the correct action to take at any stage in the manoeuvre. Such a Take-off Director should provide warning of the approach of rotation speed, direct a smooth rotation, flare-up and climb-out, so that the correct unstick and climb-out speeds are attained. It should provide automatic compensations for changes in the aircraft's configuration and thrust conditions and should always indicate a safe recovery action from unusual situations.

Pilots are known to find director displays compulsive to their attention, and consequently, they find it difficult to absorb information from other instruments and from the external view. Some earlier exploratory tests[3] on a simple take-off director showed that pilots felt that, if the director information were to be superimposed upon the artificial horizon, the compulsive nature of the director display would be less serious. It is vital that the take-off director system should have a very high degree of reliability because, even if a fault is detected, it is unlikely that successful reversion to conventional instrument flight would be possible within the time scale of a critical situation.

This Report describes a series of tests made to investigate the take-off of a typical jet airliner under various controlled conditions including simulated engine failure and pilot error. The tests included an assessment of a take-off director system known as "SCAT", which is in limited use in airlines in the United States. The director equipment, apart from the pilot's display, was provided on loan by the Safe Flight Instrument Corporation, who also provided technical support.

The tests were made on a Comet 3B aircraft at the Royal Aircraft Establishment, Bedford, during 1963. A total of 422 directed and undirected take-offs were made by 23 pilots, including 7 from airlines.

2. *Description of Aircraft and Installation.*

2.1. *The Test Aircraft.*

The tests were conducted with a De Havilland Comet Mk. 3B aircraft, serial XP 915 – formerly G-ANLO (Fig. 1). This aircraft, the only one of its mark, was originally used as a prototype for the Mk. 4 series. It has the fuselage length and engines of the Comet 4, with the reduced span of the Comet 4B. On arrival at R.A.E. Bedford, a large nose probe carrying sideslip and incidence vanes was fitted.

Since previous experiments[3] had indicated that the take-off director display should be combined with the attitude indication, the starboard instrument panel was rebuilt to accept a Kelvin Hughes F.4B Director Horizon. This instrument consists of a 'ring and spot' director, superimposed on a roller blind artificial horizon. The fixed spot of the director represents the aircraft and the moving ring represents the target. The displacement of the ring from the spot indicates the direction the nose of the aircraft must be moved to null the flight path error (Figs. 2 and 3.). The roller blind in this case was driven by signals from a Ferranti F.S.16 vertical gyro. This latter also supplied bank angle information, which together with heading error, was summed as in the standard Zero Reader installation and presented on the lateral motion of the target ring. The pitch director signal was displayed by the vertical movement of the director ring. This signal was supplied by the SCAT Computer (Fig. 4), which also fed the SCAT Indicator Pointer mounted immediately above (*See* Fig. 2 and Section 2.2.). Fig. 5 shows the system diagrammatically. It should be noted that the instrument arrangement of the starboard panel was largely dictated by the physical size of the director-horizon instrument which, unfortunately, could not be mounted either centrally or high enough to be incorporated in a standard airline type layout. The compass and pressure instruments were, apart from their location, standard Comet instruments.

For comparative undirected take-offs the pilot had to use the horizon of the F.4B without deriving assistance from the take-off director. Provision was made for the flight observer to switch out the pitch director signal when it was not required, at the same time illuminating an amber warning light on the starboard panel.

The aircraft was equipped with a stall warning system which was quite independent of SCAT and was particularly relevant to the present tests. It is shown diagrammatically in Fig. 6. The system consists of two separate detector units, either of which will operate both the stick shaker and the warning lamp. Each detector unit contains two capsules, one of which is connected to a static vent under the leading edge of the port wing (at approximately 10 per cent chord) and the other to the appropriate aircraft pitot pressure source. The detector unit case is connected to the normal aircraft A.S.I. static pressure source. When the ratio of the pressure differences across the two capsules reaches a given figure, an electrical contact is made which operates the stick shaker and warning lamps. In effect, the switch is closed at a value of C_p, $\left(\frac{p-p_a}{H-p_a}\right)$ appropriate to the desired stall margin. The static vent is positioned near the leading edge so as to give large changes of pressure with incidence change.

The aircraft was used for a variety of tasks by two departments of R.A.E. Bedford and, as a result, carried comprehensive test instrumentation. Table 1 lists the relevant quantities measured for the present tests, together with the sensors and recording elements used. Broadly, the test instrumentation gave continuous trace records of the aircraft's longitudinal motion and of all the principal signals used in the director. In addition, a kine theodolite installation was used to measure the take-off path. A common time base fed all recorders and a signal received from the kinetheolodite installation enabled the correlation of individual kinetheolodite frames with the trace records. Undercarriage operated event markers gave an accurate indication of the moment of lift-off. An event mark indicated when the pitch director signal had been removed for the undirected take-offs. Both accelerometers used and both pendulums, were mounted close to the aircraft centre of gravity. The airspeed capsule used for recording was fed from the standard starboard pitot static system supplying the pressure instruments of the starboard panel.

A 16 mm GSAP cine-camera was installed to record the pilot's scan. The camera was mounted transversely above the centre instrument panel and viewed the subject through a 45 deg mirror (Fig. 2). An event mark indicated the period during which this camera was used.

2.2. *The SCAT System.*

2.2.1. *Principles of operation.* The SCAT system has been developed as a pilot aid for use during both the take-off and the approach phases of flight. It has evolved over a period of years from a relatively simple stall warning system produced in large numbers by the Safe Flight Corporation. This stall warning system is based on the principle that the position of the leading edge stagnation point is directly related to the section lift coefficient. The position of the stagnation point is sensed by measuring the force on a small spring loaded tab which protrudes into the airstream from the underside of the wing close to the leading edge (Fig. 7). A warning of the approach to a stall can be given when the force on the tab passes through a preset value.

In the SCAT director system, the tab (or 'lift transducer') is arranged to give a calibrated signal over the whole incidence range so that the lift coefficient is measured continuously. This signal is combined with signals representing the aircraft's performance derived from pitch attitude gyro and pendulum transducers in such a way that the resultant signal is nulled when the aircraft is following the desired flight path. The total signal is displayed to the pilot on the vertical motion of the director target of a director-horizon instrument and also on a special 'slow-fast indicator' which is intended to be mounted above the airspeed indicator.

In order that the director should demand an optimum flight path in all conditions, the law is derived from the summation of specially shaped functions of the signals from the three inputs:

$$D_z = f(\tau) + g(\Gamma) + h(\theta)$$

where D_z is the director signal

τ is the tab signal

Γ is the pendulum angle

θ is the pitch attitude

During the later stages of the test flying, the pitch attitude term was augmented by a pitch rate term so that:

$$D_z = f(\tau) + g(\Gamma) + h(\theta) + j(q)$$

where q is the pitch rate and the functions of τ, Γ and θ are unchanged.

The pitch rate term was derived by differentiating the unshaped pitch attitude signal using a capacitive resistive network. The pitch rate output was filtered to remove higher frequency noise. Various gains for the pitch rate term were tried.

The following description of the system is concerned only with the operation in the take-off mode, but similar principles apply to the approach and overshoot modes as well. Three simplifying assumptions about the significance of the component signals are made in order to clarify the description, but these are discussed again in more detail in para. 2.2.2.

(1) The measured force on the tab can be related to the mean wing lift coefficient if the tab is placed in a suitable spanwise position.

(2) The difference between the signals from the pendulum and the pitch attitude gyro gives an approximate measure of the horizontal acceleration.

(3) The pendulum angle gives an approximate measure of the thrust margin $\left(\frac{T-D}{n_f W}\right)$ in the conditions encountered during take-off.

Thus the law contains elements capable of controlling the lift coefficient (and therefore the speed) to suit the thrust margin and weight. It also contains an acceleration term capable of providing anticipatory information to assist the maintenance of a constant airspeed as well as information which can be used for stall protection.

In Fig. 8, the director law is illustrated in terms of the currents (in microamps) produced by the three transducers, suitably modified by the shaping circuits in the computer. That is:

$$I_{D_z} = I_\tau + I_\Gamma + I_\theta$$

where a positive value of I_{D_z} represents a nose-up demand. For convenience, the inertial terms I_Γ and I_θ are plotted separately from the tab characteristic, I_τ.

It will be seen that, for the lower angles, I_Γ and I_θ vary linearly with angle and are equal but of opposite sign. At higher angles, I_Γ decreases in slope and reaches a limiting value, while I_θ increases in slope. I_τ decreases linearly with C_L until it becomes zero at the C_L corresponding to the minimum flight safety speed (V_2). At higher values of C_L, it becomes negative and the slope increases rapidly as the stall is approached.

The operation of the law will be explained by first considering some simple flight situations and then by following through the complete take-off procedure:

(a) Steady climb with one engine failed.

In this condition speed is assumed constant and therefore $\Gamma = \theta$. If the engine failure has caused the value of $\Gamma \doteqdot \frac{T-D}{n_f W}$ to become sufficiently low, the signal I_Γ (and therefore I_θ) will lie on the linear part of the curve. Thus, as can be seen from Fig. 8, the value of $I_\Gamma + I_\theta$ will be zero. In order that the director law should be satisfied and the indicator nulled, the value of I_τ must also be zero. This is arranged to occur when the lift coefficient corresponds to V_2 and so this speed will be demanded however low the thrust margin becomes.

(b) Steady climb at normal thrust.

As in the previous example, the speed is constant and $\Gamma = \theta$, but, in this case, the thrust margin is sufficiently large for I_Γ and I_θ to lie on the non-linear parts of the curves in Fig. 8. Here the value of $I_\Gamma + I_\theta$ will be negative and an equal positive value of I_τ will be required to null the director resulting in a higher speed. In this way, the excess thrust over that required to maintain the specified climb gradient is used for acceleration and uncomfortably large pitch attitudes are avoided.

(c) Phugoid oscillation.

In a phugoid oscillation, potential and kinetic energy are exchanged while the lift coefficient and thrust remain constant and pitch attitude, speed and climb gradient vary. Thus, for instance, if pitch attitude is increasing and speed is decreasing, I_θ becomes more negative and I_Γ and I_τ remain constant. The director therefore produces a negative signal and a nose-down demand to counteract the motion*.

(d) Aircraft decelerating towards a stall.

As the aircraft decelerates, the value of $I_\Gamma + I_\theta$ will become negative and a nose-down signal is generated. If the lift coefficient becomes significantly greater than that corresponding to V_2, an increasingly strong signal is provided by the rapid increase in the slope of the tab signal I_τ. The combination of these two signals gives an unmistakable indication to the pilot that a stall is being approached with sufficient phase advance for a controlled recovery.

With these illustrative examples in mind, it is now possible to follow the progress of a directed take-off (Fig. 9).

(i) Ground roll (Fig. 9a).

During this phase the wing incidence will be quite low and thus the leading edge stagnation point will be well forward of the lift sensor tab. In these conditions the force on the tab will be roughly proportional to the free stream dynamic pressure, giving an increasing nose-up demand with increasing airspeed. Thus, when the brakes are released, there will first be a nose-up demand arising from the acceleration followed by an increasing demand arising from the response of the tab to the increasing speed. However at this stage, the pilot does not attempt to follow the director but he satisfies himself that the signal indicates that the equipment is working normally.

(ii) Rotation (Fig. 9b).

When the aircraft reaches the scheduled rotation speed, the pilot responds to the nose-up demand and attempts to null the director. Pitch attitude, incidence and pendulum angle all increase so that the nose-up demand is rapidly decreased and, when unstick is reached, the director becomes almost nulled. The scaling of the director instrument is intended to be arranged so that, during this phase, the director ring moves down the instrument at the same rate as the artificial horizon bar. This correspondence assured the pilot that the whole system is operating correctly**.

(iii) Flare-up (Fig. 9c).

During the flare-up, the pitch attitude must be increased without increasing the lift coefficient beyond a safe level so that a satisfactory angle of climb is established. With the SCAT director, the increasing pitch attitude produces an increasingly nose-down demand which, when satisfied, is balanced by the tab responding to a decrease in lift coefficient. When the balance is reached, the aircraft is directed to the appropriate lift coefficient for the climb-out, as described in (a) and (b) above.

---

*It may be noted here that the signal from the lift transducer is modified to some extent by changes in airspeed at a given lift coefficient. This effect is in the sense which tends to damp the phugoid.

**It was not possible to incorporate this feature in the tests described here.

In practice, there is normally a slight overshoot in the pilot's attempt to null the director, but the steepening of the output from the pitch attitude and tab sensors are designed to prevent dangerous situations developing.

The pendulum signal I_{Γ} is usually on the upper limit and the variations in accelerations do not affect the balance between the other two components. If, however, an engine failure occurs, the pendulum signal is not limited and the initial demand will not only be less strong but it will be further weakened by the effect of the vertical acceleration on the pendulum. Thus, in these circumstances, the director will demand a less rapid manoeuvre.

(iv) Climb-out (Fig. 9d).

Once the climb-out conditions have been established, the director holds the aircraft at the scheduled climb-out speed and provides information to the pilot to damp the phugoid (*see* (d) above). If, however, an engine fails during the steady climb, the immediate reduction of pendulum angle will take the pendulum signal off the limit and give a nose-down demand. As described above, the pitch attitude will reduce and the steep characteristic of the signal I_{θ} will cause the aircraft to settle at a higher lift coefficient which is equal to or slightly less than that which corresponds to the minimum safety speed V_2. Thus, an engine failure during a steady climb will result in a reduction in the climb-out speed. Although this is contrary to normal flying practice, it is justified in this case, because the situation is being properly assessed by the director and an optimum flight path is demanded.

2.2.2. *The limitations of the transducers.*

(a) *The lift transducer.*

The lift transducer is intended to measure the wing lift coefficient by sensing the position of the leading edge stagnation point at a selected spanwise station. The relationship between the position of a section stagnation point and the mean wing C_L will depend firstly on the choice of spanwise station and secondly on the changes in spanwise loading imposed by changes in flap configuration and the effects of ground proximity.

In the SCAT system, the spanwise section is chosen either by calculation or from wind tunnel tests, so that the desired characteristics are obtained on the clean wing in free air. Changes in flap configuration are allowed for by providing a compensating signal from a transducer measuring the flap position. Final adjustments are made by rotating the tab in the plane of the wing when the system is being calibrated in flight.

The effect of ground proximity is more difficult to assess and will depend to a great extent on the planform of the wing. However, it is clear that the position of the stagnation point is likely to be related more to lift coefficient than to incidence. Furthermore, since there is some evidence that stalling is related more to lift coefficient than to incidence, it is likely that the lift transducer will act as a satisfactory stall warning sensor in these conditions.

The question of how well the measured force on the tab can indicate the position of the stagnation point raises further difficulties. Clearly the situation is satisfactory when the force on the tab is zero for, here, the stagnation point must lie on the tab. At other conditions, however, the force on the tab depends on the local velocity at that point and this will depend both on the position of the stagnation point (i.e. the lift coefficient) and also the free stream velocity. Thus, the lift transducer signal will be uniquely related to lift coefficient only at the calibrated weight. Normal accelerations or changes in weight will destroy the relationship and introduce errors.

To minimise these difficulties, the tab is so situated that zero force occurs at some critical speed such as V_2 at a mean take-off weight. At speeds in this neighbourhood the errors will be small and at higher speeds the errors are, in any case, less significant. In some circumstances the errors due to accelerations can be used beneficially to provide anticipatory information for speed control (*see* Section 2.2.1.).

The operation of the lift transducer is discussed in more detail in relation to its performance in Section 6.2.3.

(b) *The pendulum.*

The pendulum is a simple, critically damped transducer which measures the angle in the pitching plane between the fuselage datum and the apparent vertical, the true vertical being modified by the longitudinal and normal accelerations. It will be seen from Fig. 10a that the horizontal acceleration can be obtained by subtracting the pitch attitude from the pendulum angle and applying a correction for the vertical acceleration thus:

$$l_e = n_e \tan(\Gamma - \theta)$$

where n_e = the vertical acceleration and
l_e = the horizontal acceleration.

For most of the take-off, n_e is nearly 1 and $(\Gamma - \theta)$ is less than 10 deg, thus the horizontal acceleration is given approximately by:

$$l_e \simeq (\Gamma - \theta) .$$

Fig. 10b shows that when n_e exceeds 1, an apparent decrease in $(\Gamma - \theta)$ is immediately indicated and this gives a measure of anticipation to the sensing of the consequent decrease in l_e.

(c) *The pitch attitude gyro.*

The chief difficulty in measuring the horizontal acceleration is in the maintenance of the verticality of the pitch attitude gyro under the significant accelerations experienced in the take-off manoeuvre. Conventional gyros would miserect by a considerable amount during this period. This problem is dealt with in the SCAT system as follows:

(i) *Before commencement of ground roll.* The vertical gyro is erected in roll in the conventional manner, using a mercury level switch to control the erection motor. The pitch erection motor is controlled by the pendulum and the pitch attitude signal, so that θ becomes equal to Γ.

(ii) *During ground roll.* The pitch erection motor supplies are cut off by the throttle switch when take-off thrust is selected. The vertical gyro then behaves as a free gyro. If the take-off is delayed after the selection of take-off power, the erection supplies are arranged to re-connect after a period of 90 seconds.

(iii) *Airborne.* The erection motor supplies are reconnected by the operation of the oleo switch. The pitch erection motor is now controlled by the summation of three quantities; pendulum angle, pitch attitude and an approximate flight path acceleration term derived from the differentiation of the tab signal (τ). Thus, the erection motor drives so that $(\Gamma - \theta) - \dot{\tau} \rightarrow 0$ (Fig. 11). This term is very much smoothed by the long time constant of the erection motor, the erection rate being of the order of 4 deg per minute.

2.3. *Installation and Calibration of the SCAT System in Comet XP 915.*

The SCAT system fitted to Comet XP 915 was adapted in certain minor respects to suit the aeroplane and the test programme:

(i) The SCAT output was presented to the second pilot only; the captain, who acted as safety pilot for the experiments, retained the standard Comet instrument presentation.

(ii) It was considered simpler and more convenient to use the trace recorder ON-OFF switch in place of the throttle switch to prime the SCAT system for take-off.

(iii) The computer switching logic was modified to hold the system in the take-off mode to enable repeated take-offs from both standing starts and roller landings to be performed. Normally the system automatically switches to the landing mode four minutes after unstick.

As mentioned in Section 2.2., the lift transducer system needs to be calibrated for each aircraft type in all flap configurations. The calibration was carried out in conjunction with the Safe Flight Instrument Corporation who provided the necessary special measuring equipment. Values from a digital presentation of the tab signal were noted over a range of aircraft configurations and speeds while the aircraft was flown in trimmed flight in smooth air conditions. The configurations of most interest here were those applicable to take-off, although, of course, flap settings other than the recommended 20 deg had to be investigated and set up to cater for possible incorrect selection of flap. The cases with 20 deg flap were:

(a) Undercarriage up, full take-off power (7500 r.p.m.) – various airspeeds between 1·15 V_s and 1·60 V_s;

(b) Undercarriage up, 6650 r.p.m. – stall and various airspeeds between 1·05 V_s and 1·60 V_s.

6650 r.p.m. was chosen as the thrust which gave level flight at V_2. The results of this calibration are shown in Fig. 12a. It can be seen that the effect of power is negligible. The kink in the calibration illustrates a difficulty with the use of this type of tab. Unhampered by structural considerations and given time to investigate other positions, a linear calibration could probably have been achieved. However, as the crank did not occur at too critical an incidence, this position was accepted. It can also be seen that in fact $I_\tau = 0$ occurs at a slightly higher airspeed than the recommended V_2. It is of course quite acceptable to err slightly in this direction. In retrospect, it is now felt that the point at which the shaping circuit causes the tab signal to steepen, (Fig. 12b) might have been set at a slightly higher airspeed than that selected.

During the early flying of the system difficulties were experienced with the inertial signals due to voltage and frequency variations in the aircraft supply. This trouble was largely cured by feeding the SCAT system from an Elliott single phase transistorised 115V, 400 c/s inverter. A further improvement was made later by the Safe Flight Instrument Corporation who regulated the d.c. voltage feeding the pitch attitude and pendulum angle potentiometers. Even so, it was noticed during exceptionally cold weather that the transistors of the pitch and pendulum shaping circuits were temperature sensitive, thereby giving characteristics which varied with temperature. It is understood that these shaping circuits are eliminated in more recent models of the SCAT system, in favour of a mechanical pendulum stop.

3. *Flight Calibrations of the Aircraft in Free Air and in Ground Effect.*

Since it is essential that an adequate stall margin be maintained during take-off, it was necessary to establish a sound basis for the accurate measurement of lift coefficient. Flight tests were carried out in free air and in ground effect with the object of determining

(i) position error of the incidence vane in free air;

(ii) variation of wing lift coefficient* with incidence in free air;

(iii) the variation of lift transducer load with wing lift coefficient in free air;

(iv) ground effect on wing lift coefficient, leading-edge tab and incidence vane.

Items (i), (ii) and (iii) were determined from several trimmed level flight runs in the take-off configuration for the speed range 100 kt to 140 kt. Incidence vane indication was compared with pitch attitude to give the position error correction for the vane shown in Fig. 13. C_{LW} was calculated using the method given in Appendix A. Figs. 14 and 15 show, respectively, the variation of C_{LW} with incidence and the calibration of the lift transducer load against C_{LW}.

Since the aircraft was equipped with an automatic landing system, it was possible to utilise the flare height control to act as a precision height lock for ground effect runs. Normally the flare height control is used to obtain an optimum touch-down but if the control is set so that the aircraft completes the flare at a given height above the ground (indicated by a radio altimeter), this height will remain substantially constant as the aircraft continues down the runway. Several low level runs were made along the runway in the take-off configuration, at a nominal speed of 120 knots. By varying the flare height setting for each run, it was possible to measure ground effect between 3 ft and 20 ft (height of main wheels). To obtain results for greater heights up to 80 ft it was necessary to analyse data during flares. Due to the dynamic state of the aircraft in this manoeuvre the corresponding results were less reliable. In addition to the airborne recorders, kinetheodolites were used to track the aircraft relative to the ground. There was some variation of speed and incidence during the runs, so that the ground effect results shown in Figs. 16 and 17 are subject to an incidence variation of the order of ±1·3 deg.

---

*It was necessary to separate wing lift from total lift in order to assess the performance of the leading-edge tab which is designed to measure C_{LW}.

During the runs wind speed varied from 6 knots to 11 knots; not ideal conditions for ground effect tests for which a flat calm is desirable.

A detailed account of the ground effect analysis is given in Appendix B. A comparison with theoretical results according to the method given in the R.Ae.S. Data Sheet on ground effect[4] is shown in Fig. 18. The data are presented in terms of the parameter $K_2 = -\dfrac{\Delta\alpha}{(C_{LW}/\pi A)}$, where $\Delta\alpha$ is the change in effective incidence due to ground effect when C_{LW} is kept constant. A result from wind tunnel tests on a Comet 3 model[5] is also shown in Fig. 18. Part of the discrepancy between the tunnel and flight results may arise from the differences between the Comet 3 and the Comet 3B (wing area, span, flaps, wing tanks, etc.).

4. *Description of Take-off Tests.*

During the period from November 1962 to May 1963, 85 undirected and 337 directed take-offs were carried out by 23 pilots. Of the 85 undirected take-offs, 68 were fully recorded and available for analysis. 244 directed take-offs were recorded and analysed with the director functioning correctly; the others were carried out mostly during the setting-up process.

Although most of the tests were conducted with 4 Aero Flight test pilots, others were invited to take part to assess the director when used by pilots of different background and also to gain experience of the variability to be expected in undirected take-offs by a variety of pilots. The distribution of analysed undirected and directed take-offs between the groups of pilots is as follows:

4 Aero Flight test pilots – 35 undirected, 153 directed;
4 other R.A.E. or A. & A.E.E. test pilots – 10 undirected, 24 directed;
5 firms' test pilots – 3 undirected, 21 directed;
2 Air Registration Board pilots – 1 undirected, 14 directed;
7 airline pilots – 19 undirected, 32 directed.

All the airline pilots had considerable experience on the Comet; other pilots had varying amounts of experience on this aircraft.

For most flights, it was necessary to operate the aircraft at weights no greater than the maximum landing weight; take-off power was downrated in order to give more representative thrust/weight ratios. Normal operating A.U.W. during the tests varied between 105 000 lb and 90 000 lb, whereas the maximum is 145 000 lb. The power setting of 7500 r.p.m. used in the tests gave 82 per cent of the maximum thrust available for take-off. These weights and power setting corresponded to thrust/weight ratios between 0·31 and 0·36, compared with 0·26 for a Comet 4 at maximum A.U.W. and take-off power. When a full fuel load was carried on a small number of flights, the thrust/weight ratio was reduced to 0·26. The aircraft was normally flown with a mid c.g. position varying between 0·27 $\bar{c}$ and 0·24 $\bar{c}$ during the course of a flight.

The take-off procedure, as recommended in the Flight Manual, is outlined in the following paragraph. For undirected take-offs, pilots were briefed to follow this procedure where it was possible to do so within the limits of the tests. Departures from the Manual procedure will be given in a subsequent paragraph.

The wing flaps must be at the 20 deg position and for the mid c.g. position used, it is recommended that elevator trim is set to neutral. The take-off may be commenced from a standing start, or from a rolling start, when the runway is entered (from perimeter or taxying track) at not less than flight idling power and the power is increased immediately the aircraft and nose wheels are lined up with the runway. Nosewheel steering should be used until the rudder becomes effective. Except on very rough or slush covered runways, the nosewheel should not be raised from the runway until a speed approximately 10 knots below the scheduled unstick speed (reproduced in Fig. 19). Rotation is initiated by a firm rearward movement of the control column, which should be continued smoothly so that the aeroplane leaves the ground at the scheduled unstick speed. After unstick, the pull force should be maintained as firmly as necessary to achieve a smooth transition to the initial climb-away attitude. With all engines operating at take-off power, the aeroplane should be allowed to accelerate gently to reach a speed of 170 knots at a height of approximately 900 feet. In the case of a continued take-off after engine failure, the climb-out should be carried out at a speed as close as practicable to the scheduled free air take-off safety speed (Fig. 19). If an engine fails during the initial climb, the speed should be maintained at that obtaining at the moment engine failure is recognised (if it is above safety speed).

Owing to the need for consistency and high utilisation of the aircraft during the tests, some aspects of the normal take-off procedure were sacrificed. Since the ground run distance was not of interest, the majority of take-offs were carried out using a 'roller' technique. After touch-down, following a take-off and circuit, the aircraft was held in a high nose-up attitude for as long as possible to achieve maximum retardation. When the speed had decreased below 60 knots, the nosewheel was lowered onto the runway, flaps were raised to 20 deg and the throttles opened for a subsequent take-off.

Except on a limited number of take-offs, aircraft configuration was not changed during the flare-up and climb-out, so that the climb-out was established at 140 knots. This was a non standard technique adopted for convenience in the present tests. When the undercarriage and flaps were raised, the pilots were briefed to use the Manual speed. Apart from these procedural details, no specific instruction were given to pilots regarding technique for undirected take-offs, each pilot using his own particular experience and interpretation of the Flight Manual.

When using the director, pilots were briefed to carry out the ground run and initiate rotation as when undirected and then to capture and hold the director centred for the remainder of the take-off. Since lateral guidance was also provided on the director horizon, it was possible to carry out the later stages of a directed take-off without looking outside or referring to other instruments, but no specific instructions were given to the pilot in this respect. The climb-out was normally terminated by 2000 ft when the speed had stabilised on a steady flight path.

Besides a series of 'standard' take-offs, some tests were made to investigate the effect of using the director during configuration changes, turns during the climb-out, engine failure and for 'abuse' cases.

(i) Configuration changes. The undercarriage was retracted soon after unstick and the flaps at approximately 700 ft.

(ii) Turns. Heading changes of up to 90 deg were set on the director during the climb-out and the pilot attempted to null the demand using maximum directed bank angles of up to 30 deg, depending on the change of heading set.

(iii) Engine failure was simulated at the different stages of take-off from V_R to the climb-out, the pilot attempting to follow the director demand when the safety pilot had cut an engine and made him aware of it. The effect of a double engine failure was also investigated.

(iv) 'Abuse' cases. These were simulated by deliberate early and late rotation, and by deliberate gross errors in the initial climb-out. The pilot was then instructed to recover by following the director demand.

The effect of introducing a pitch rate term in the director signal was also investigated on a small number of take-offs. Pilots were briefed to vary the rate of rotation to determine whether the phase advance supplied by pitch rate would enable the director to be nulled more quickly.

A subsidiary part of the tests was concerned with filming pilots scan during take-off. Cine films of the pilot's face were taken for some 40 take-offs by several different pilots.

The tests were carried out in a wide range of weather conditions within the limitations of the aircraft. Undirected take-offs were interspersed at random with directed take-offs. Pilots invited to take part in the tests usually made one or two undirected take-offs before using the director so that they could

(a) familiarise themselves with the aircraft's characteristics;

(b) provide data for statistical comparison.

But it was not generally possible to prevent a technique learned with the director from influencing undirected take-offs carried out by the 4 Aero Flight pilots.

5. *Analysis of Results.*

After the extraction of data from the airborne records, the bulk of the analysis was concerned with the calculation and statistical treatment of quantities which determine the consistency of the different phases of take-off. The following quantities were determined for each take-off (estimated accuracy in brackets):

errors in rotation speed (±2 kt);
errors in unstick speed (±2 kt);
maximum elevator used during rotation (±0·2 deg);
maximum pitch rate during rotation (±0·2 deg/sec);
maximum incidence (±0·3 deg);
wing lift coefficient at 20 ft and 50 ft a.g.l. (±0·02);
airborne distance to 35 ft a.g.l.;
maximum deviations from a mean climb-out speed (±1 knot).

Error in rotation speed was taken to be the difference between the scheduled rotation speed and the speed at which the pilot applied elevator in order to rotate the aircraft prior to unstick. In most cases, initiation of rotation was precisely identified, but since some airline pilots applied up-elevator to raise the nosewheel before the recognised rotation speed, initiation of rotation was difficult to identify for these cases and resulted in some rather doubtful measurements. Errors in unstick speed were obtained using a recorder event mark actuated by undercarriage oleo switches. Since the pitch rate gyro installed in the aircraft was found to be unreliable, pitch rate was determined from the slope of the pitch attitude trace. Incidence was read from the nose probe incidence vane trace and corrected for position error and pitch-rate effects. In order to assess stall margins during the flare-up, values of wing lift coefficient were determined for two particular instances, namely, when the aircraft had reached heights of 20 ft and 50 ft. The reason for choosing these particular heights is explained in Section 6.2.6. Airborne distance to 35 ft above ground level was calculated by graphical integration of airspeed between unstick and 35 ft. To reduce the results to a common datum weight, a linear correction for weight differences was applied. For each take-off, maximum deviations from a mean climb-out speed were measured from the airspeed trace after a mean line had been drawn. Although this was perhaps not the ideal method of analysing speed holding, it was the only practicable technique in the circumstances.

Histograms of the various quantities measured are shown in Fig. 20 to 28. On each figure, except Fig. 20, variations between undirected and directed take-offs are illustrated for each of three groups of pilots in addition to an overall comparison. Since the same procedure was used to initiate rotation for both undirected and directed take-offs (the director did not provide a rotation demand), the results of rotation speed measurements from all take-offs have been combined in Fig. 20.

A quantitative comparison of means and variances is given in Table 2. Normality of distribution is also indicated. Standard statistical tests[6] have been used to determine normality and to compare means (the 't' test) and variances (the 'F' test) of distributions. It should be explained that the 't' and 'F' tests strictly apply only to normal distributions and the results of these tests for non-normal distributions are questionable. The Wilcoxon test for the comparison of means is unaffected by normality and has been used for the non-normal distributions. All results are significant to a 95 per cent confidence level.

6. *Discussion.*

6.1. *Variability of Undirected Take-offs.*

Although an attempt is made to compare the characteristics of take-offs by the three categories of pilots, the small sample size for two of the categories must be borne in mind.

For the purpose of discussion, the following three phases are considered separately:

(i) rotation;
(ii) flare-up;
(iii) climb-out.

The ground roll is not within the scope of this Report and will not be considered.

(i) *Rotation.* The variability of quantities determining the rotation phase are shown in Figs. 20 to 23 (undirected). The large variation of rotation speed errors is comparable with those emerging from operational measurements, although the method of identifying rotation was slightly different. In the case of operational measurements, change of position error on pressure height was used, so that rotation speed was defined by the initiation of the aircraft response and not the initial elevator input. In the tests described here, only pilot response errors were measured. Due to the technique used by some pilots of lifting the nosewheel during the ground run, it was not always possible to identify accurately when the pilot made the elevator movement which was intended to rotate the aircraft. Consequently, the histograms of rotation speed errors, shown in Fig. 20, include some rather doubtful instances of gross early rotation. Ignoring these, the overall mean rotation speed appears to be approximately 4 knots late and somewhat less for airline pilots.

Comparing the means for different groups of pilots in Figs. 21, 22 and 23, it is evident that there is a definite relation between maximum elevator used, maximum pitch rate and unstick speed. With pilots less familiar with the aircraft, there is a larger difference between rotation and unstick speeds due to the cautious use of elevator and a consequent lower pitch rate. In fact, the margin of 10 knots between V_R and V_U, suggested in the Operating Manual, was generally considered to be too small by the pilots. Aero Flight pilots tended to rotate at a high rate in an attempt to achieve the scheduled unstick speed, though they also carried out gentle rotations early in the test series and on the first take-off after a long lay-off period. This resulted in the wide range of maximum pitch rates shown in Fig. 22. It also became apparent that pilots could not identify unstick speed accurately; they often reported that unstick had occurred at the scheduled speed when, in fact, the records showed that it had occurred at higher speeds.

(ii) *Flare-up*. The most critical phase of take-off is the transition to a steady climb after the aircraft has left the runway. Quantities of most significance in this phase are stall margin and airborne distance to reach a 35 ft screen height.

Owing to ground effect, the maximum wing lift coefficient reached could not readily be calculated, but the distribution of peak incidence (Fig. 24) should give some indication of the performance of pilots in maintaining a consistent stall margin. In the majority of cases, peak incidence occurred before a height of 20 ft was reached, especially for take-offs by Aero Flight pilots. Some other pilots preferred to gain speed and delay the flare-up. In these cases, peak values of incidence did not occur until the IAS was greater than V_2 and they were generally lower than those which occurred soon after unstick. Differences in piloting technique are illustrated in Fig. 29, where the time histories of typical take-offs by an Aero Flight and an airline pilot are compared; weights and weather conditions were comparable. Histograms of wing lift coefficient at 20 ft and 50 ft shown in Figs. 25 and 26 also indicate differences between pilots; Aero Flight pilots decreased the lift coefficient by a mean of 0·08 in climbing from 20 ft to 50 ft, whereas for airline and 'other' pilots, the decrease is 0·06 and 0·03 respectively. The small number of results for these histograms was due to the fact that they could only be obtained when a radio altimeter was available.

In order to appreciate the significance of the results as regards consistency of stall margin, it is necessary to understand the stalling behaviour of swept wings in ground effect. When an aeroplane is in ground effect, the pressure distribution on the wings is changed and, for a given incidence, the lift coefficient will be higher than the free air value. How the stall is affected is not certain and will probably be particular to the aircraft type, but it is considered more likely that the stalling lift coefficient as opposed to the stalling incidence will remain constant. If this is so, then it follows that the aeroplane will stall at a lower incidence in ground effect. If this assumption is made, then it is possible to use the peak incidence distribution to make a crude estimate of the probability of a stall (found to be at $C_{LW} = 1{\cdot}6$ approximately in free air). Owing to the skewed nature of the distribution, it was necessary to 'normalise' it by considering the portion to the left of the mode* as a mirror image of that to the right. This is permissible since only the probability of exceeding a high incidence is of interest. Using either the free-air lift curve or the lift curve applicable to ground level, the probability of a stall was found to be less than 1 in 10^{15}**. Therefore it can be said that under the conditions of the test the probability of a stall through over rotation in ground effect was negligible, but it is unlikely that a similar probability would obtain under operational conditions, where, although the mean value of maximum incidence reached might not be as high, the variance would almost certainly be greater. Differences in aircraft and instruments and a wider spectrum of weather conditions would tend to increase stalling risks.

---

*i.e. the most frequently occurring value.

**95 per cent confidence level.

Piloting technique has a marked effect on airborne distance to 35 ft, as shown in Fig. 27. The technique used by Aero Flight pilots, i.e. increasing the incidence to a maximum immediately after unstick, produces the shortest distance to 35 ft, although it must be remembered that the same technique was used by Aero Flight pilots for directed take-offs as well, so it is likely that the steep climb-out adopted by this group of pilots was, to some extent, due to rather intense practice.

In general, the histograms for Aero Flight pilots indicate that optimum performance can consistently be achieved in the flare-up without the risk of over rotation and consequent stall. The chance of a stall is shown to be slight by the skewed nature of the maximum incidence histogram, indicating awareness of the existence of a 'never exceed' incidence. Also the wing lift-coefficient distributions have a low standard deviation. The technique of reaching a maximum incidence early in the flare-up also has the advantage that, even if a stall were to occur, the consequences are less likely to be disastrous, since the aircraft will be very near the ground. If the initial build-up of incidence is prolonged, climb performance is sacrificed and there is the possibility of a stall through the pilot pulling excessive 'g' later in the flare-up when he decides to steepen the flight path. It is considered that a take-off director which gave continuous direction through the rotation and flare-up would provide the necessary aid in maintaining a consistent optimum performance.

(iii) *Climb-out.* When the climb-out speed has been attained, the pilots normal task is simply to hold the aircraft on course at a steady speed. Due to the phugoid oscillation this is not always easy, as is evident in Fig. 28, where deviations of up to 11 knots from the mean speed are shown. Oscillations of this magnitude would be especially undesirable during a three-engine climb-out when the mean speed could well be as low as V_2.

A director which provided effective phugoid damping would be a desirable aid for this phase of the take-off.

6.2. *SCAT Directed Take-offs.*

In this section the functioning of various aspects of SCAT will be considered with reference to flight records and pilot reports. The overall effectiveness of the system will be discussed in the light of a statistical comparison of undirected and SCAT directed take-offs.

6.2.1. *Director following.* The pilots' assessment of the SCAT system was unfortunately coloured by the fact that they disliked the director display instrument used in the present tests*. The pilots' reactions to the tests can best be represented by the following synopsis of pilots' comments**.

Since it was intended to utilise the director as early as possible in the take-off, the aim was to make a 'comfortably fast' rotation to null the director as early as possible after V_R. This was usually achieved within 2 sec of unstick, although not very precisely. It must be remembered that at rotation the pilot was only presented with a target on the director and unless the initial elevator input was of the appopriate magnitude and rate of application, some oscillation was likely to occur before the director was nulled. At low aircraft weights and consequently increased acceleration, rotation was inclined to be 'a rather disconcerting and untidy manoeuvre'. If rotation was begun early and was less hurried, transfer to the director was easier and 'a generally smoother and more flyable take-off pattern resulted'. Pilots felt that, with some familiarisation, a rotation could be made using the director as the only reference but, owing to deficiencies in the F.4B lateral guidance, crosswinds would still be difficult to cope with. After an initial learning period, the flare-up could be flown without any tendency to overshoot the required attitude. Speed built up smoothly and progressively. Early on in the tests there was some difficulty in following the director through the large trim changes which are characteristic of a Comet during take-off and, although it was possible to complete the take-off without re-trimming, most pilots found that following the director during the remainder of the take-off was eased by re-trimming. Even when the pilots considered that the director scaling had been optimised, the effects of turbulence were thought to be too severe because there was an excessive amount of 'random jitter' which made it difficult to detect genuine com-

---

**See* Section 6.3.

**Actual phrases used by pilots are in inverted commas.

mands. Some form of filtering was called for to suppress gust effects. Even if it was possible for the pilot himself to do the filtering in the climb-out, every movement had to be followed during the rotation and flare-up. Generally speaking, the director was liked most during the climb-out where speed was held steady with about half as much effort as on an undirected take-off. On a few occasions when speed wander did occur with the director nulled, it was attributed to 'stiction' in the director instrument drive mechanism.

Flight records show that director following accuracy is dependent on a number of factors. The best following accuracy was achieved by a pilot with considerable director experience on a calm day when the aircraft was heavily loaded to give a low thrust/weight ratio. With low acceleration, the pilot's task is eased due to the slower time scale, and in these conditions he is capable of keeping the director spot on the target to within ±0·025 in. (±10 microamps) throughout the flare-up and climb-out, as opposed to an accuracy of ±0·05 in. (±20 microamps) in less favourable conditions. Pilots who were continually using the director were able to null soon after unstick, whereas those without previous experience found it difficult to follow the director accurately until well into the flare-up. Perhaps due to the pitching characteristics of the aircraft as it climbs out of ground effect and the desire to null the director demand quickly, there was a marked tendency for pilots to overshoot the demanded attitude after rotation. These overshoots quite often caused unusually high values of incidence to occur. During the climb-out, the pilots were generally more successful in following the director and the phugoid appeared to be well damped.

6.2.2. *Summation of component signals.* The behaviour of the SCAT component signals during a typical flare-up is illustrated in Fig. 30. The effect of the shaping circuits on pendulum angle and pitch attitude signals is clearly seen: there is little change in nose-up demand with pendulum angle, whereas large pitch attitudes give rise to a strong nose-down demand. Lift transducer signal is fairly linear with deflection since it has not been deflected into the range where the strongly biased nose-down demand signal takes effect. The maximum discrepancy between the component sum and the computer output is seen to be of the order of 10 μA, approximately 0·8 deg. Analysis of a number of runs showed that the discrepancy never exceeded this level, at least not in the working range of ± 100 μA.

6.2.3. *Lift transducer.* Although the lift transducer is a device which nominally measured wing lift coefficient, it is also sensitive to speed change at a given incidence. Hence a change in aircraft weight alters the relation between C_{LW} and the transducer signal. As the stagnation point moves away from the transducer position, speed sensitivity is increased. Using Bernoulli's equation, it can be shown that, for a change in airspeed ΔV at a constant incidence, the resulting change in the lift transducer load is proportional to

$$(1-C_p)\left(\frac{V+\Delta V}{V}\right)^2$$

where C_p is the pressure coefficient at the tranducer position. This effect is illustrated in Fig. 15, where the characteristic has been calculated from theoretical estimations of pressure coefficient distribution near the leading edge. It is not surprising that this characteristic does not agree with experiment since the pressure distribution was only available for one spanwise position which was some distance from the tab position, and furthermore, no allowance was made for the effect on the pressure distribution of the presence of the transducer itself. However, the weight change effect will be very much as shown. Sensitivity to weight change is seen to be least in the region where the stangation point coincides with the transducer position. The transducer must be located at the approximate position of the stagnation point at flare-up lift coefficients if the director is to be unaffected by weight changes during this critical phase. Since the runs were carried out at near constant weight, it is not possible to detect effects due to weight change at the highest lift coefficients where the theoretical characteristic indicates increased weight sensitivity. During the take-off tests there were weight changes of ±15 per cent from the mean weight. This could have had a significant effect on the stall protection provided by the lift transducer signal.

Since stall protection is an essential feature of a take-off director system, particular attention was paid to the consistency of the lift transducer in this respect. Unfortunately, the assessment of consistency was hampered by the difficulty of accurately measuring wing lift coefficient near the ground in the rather unsteady conditions which exist during the take-off. A discussion of the problems and the method of calculation used is given in Appendix A.

On six directed take-offs during the test series the Comet stall warning device* operated momentarily shortly after unstick. The stall warnings occurred on each of two take-offs on three separate flights and in every case a normal directed take-off was being attempted by an Aero Flight pilot in turbulent weather conditions with moderate to strong crosswinds. Although the aircraft was in no immediate danger and the safety pilot did not find it necessary to take over control, these occurrences were disturbing and warranted special attention. It was not possible to identify on the records exactly when stall warning occurred, but peak incidence was thought to be a fair indication. Director indication, aircraft height and C_{LW} pertaining to these instants are shown in Fig. 31. The lift transducer C_{LW} obtained from the calibration in Fig. 15 is also shown for comparison.

It is apparent from the heights and the director indications, that with the possible exception of occurrence No. 4, the operation of stall warning was partly or wholly due to over-rotation of the aircraft. In all cases but one, the director was giving a nose-down demand, so that on these occasions the SCAT indication was in the right sense. On occurrence No. 4 the director was nulled, but since C_{LW} as indicated by both the lift transducer and incidence vane was less than the assumed stall warning value, it is probable that the stall warning device triggered prematurely. This device operates at a certain value of pressure coefficient C_p, measured at a point near the wing leading edge, and it is possible that crosswinds and gusts cause premature operation.

If one assumes, as was argued earlier, that the stall near the ground occurs at about the same lift coefficient as in free air (rather than at the same incidence), the occurrences of lift coefficient at the stall warning levels following rapid rotation suggests that in these cases inadequate safety margins were maintained. Consequently it would seem advisable to strengthen the stall protection given by the shaping of the lift transducer signal over that chosen in the present tests.

The lift transducer measures C_{LW} by sensing local dynamic pressure near the stagnation point. Although C_{LW} and stagnation point position are uniquely related in free air, the same relation cannot be assumed in ground effect, since the wing-section lift characteristics are then altered in a way which is not equivalent to incidence change. Tests have shown that below the stall, the lift transducer does measure C_{LW} in ground effect reasonably well (Fig. 17), but there still remains the question of whether it can be used to predict the stall in ground effect.

6.2.4. *Use of SCAT during configuration changes, turns, engine cuts and 'abuse' cases.* Pilots generally felt that SCAT was particularly useful when they were required to deal with changes in flight conditions.

During configuration changes, SCAT programmed a climb/acceleration profile which was smooth and easy to follow; records show that speed and height increased progressively with no tendency for a phugoid oscillation to occur. The transitions from take-off to cruise configuration were thought to be more smoothly accomplished than without SCAT.

Turns were also easy to follow and the speed remained steady throughout. Pilots were of the opinion that the director did all it was supposed to.

When an engine was cut during rotation or flare-up, SCAT programmed a shallower climb-out than with all engines and the speed stabilised at about 10 knots below the normal climb-out speed. When an engine was cut during the climb-out, a gentle push-over was demanded and there was a gradual speed reduction of 5 to 10 knots. The director was easy to follow throughout the transition. Even pilots without previous experience of SCAT performed much better transitions following an engine failure using SCAT than without. Time histories of an undirected and a directed take-off with a simulated engine failure during the flare-up are compared in Fig. 32. Both take-offs were carried out by an airline pilot on the

---

*The Comet stall warning device is independent of SCAT. It was described earlier in Section 2.1.

same flight, the undirected before the directed. Although the pilot was unfamiliar with SCAT and some over-controlling is apparent, it is clear that a more precise climb-out resulted with the use of SCAT than without.

The recovery action programmed after abuse of the director was also very much liked by the pilots. From an 'under-rotated, over-speed condition' reversion to SCAT resulted in a quick and very comfortable return to the correction condition. Records show that there was no appreciable overshoot and oscillation about the demanded attitude. Transfer to the director after loss of speed was also very straightforward; airspeed was smoothly and progressively returned to the 140 knot climb-out speed.

A genuine case of inattention occurred during a three-engine climb-out when the pilot, who was unfamiliar with the procedure, was confused about whether or not the undercarriage was to be retracted. Time histories of this take-off (Fig. 33) show that the consequent attitude and speed errors were effectively corrected when the director demand was recaptured.

6.2.5. *Effect of a pitch rate term in SCAT.* The addition of a pitch rate term in the director signal proved to be of some use in the rotation phase but was of doubtful benefit in the climb-out, especially in turbulence. Pilots found it easier to centre the director during rapid rotations since they received an earlier indication of when to check the initial pull on the control column: overshoot was prevented surprisingly easily and quickly by a forward check and the director was nulled just before the aircraft unstuck. However, it should be remembered that SCAT does not programme rotation itself, and pilots felt that direction through the rotation phase was desirable. In the climb-out speed holding was improved, since the phase advance of the system was increased by the pitch rate term, but in turbulence the increased liveliness of the signal was disliked by the pilots.

Take-offs were shallower with pitch rate in than without, since its addition subtracted from the director pitch-up demand. For a sample of 31 take-offs with pitch rate in there was a reduction in peak incidence and an increase in airborne distance to 35 ft. The mean value of peak incidence was 8·5 deg, compared with 9·3 deg without pitch rate; the mean value of airborne distance to 35 ft rose from 1052 ft to 1118 ft.

6.2.6. *Statistfcal comparison of undirected and SCAT directed take-offs.* In order to assess the overall effect of the director, it was considered necessary to carry out a statistical comparison of results from undirected and directed take-offs, although in most cases, it was found that there was no clear-cut difference. As in Section 6.1, it is convenient to consider the three phases of take-off separately.

(i) *The rotation.* Although continuous direction was not provided during this phase of the take-off, some effects of SCAT were apparent. The speed at which rotation was initiated was of course not affected, since the same technique was used for both directed and undirected take-offs. As shown in Figs. 21, 22 and Table 2, the maximum elevator angle and maximum pitch rate were generally higher when the director was used, but the variance was not affected. There was no significant change in unstick speed error.

The tendency of pilots to rotate more rapidly on directed take-offs was partly due to their desire to null the director as early as possible and also to their confidence that SCAT would prevent them over-rotating. Figs. 21 and 22 show this tendency to be more noticeable for airline and 'other' pilots who normally executed a gentle rotation and could comfortable increase the rate of pitch when they used the director. It is possible that if the Aero Flight pilots had not developed the habit of using high pitch rates when using the director, their undirected rotations would also have been less rapid. Apparently, even with higher pitch rates, it was not possible to reduce the unstick speed errors significantly; an indication that the 10 knot difference between V_R and V_U was too small.

(ii) *The flare-up.* The extent to which SCAT aided the pilot during this phase was largely dependent on the pitch rate developed during the rotation and also on the pilot's familiarity with the aircraft's pitching characteristics in ground effect. If the aircraft was rotated slowly, it had climbed to 100 ft or more before the director was nulled. On the other hand, if the aircraft was rotated sharply and not checked at the appropriate time, severe overshoot occurred, followed invariably by a pitching oscillation. The pilot was then not able to follow the director accurately until well into the climb. Only when pilots were accustomed to the aircraft's pitching characteristics while climbing out of ground effect could the director be effectively used for the flare-up. Even so, it is shown in Fig. 24 that Aero Flight pilots limited peak incidence more effectively when they were not using the director. With other pilots no difference can be detected. Although these peaks in incidence occurred when the aircraft was in a transient condition only a few feet off the ground and it can be argued that this is not critical, there is no doubt that a more definite incidence limitation should have been maintained throughout since SCAT is intended to control attitude after rotation. As shown in Table 2, the overall mean peak incidence was significantly higher when the director was used. This is dependent simply on how SCAT has been set up; it is the 'long tail' of the histogram towards high incidences which is undesirable, although on the basis of this data the probability of exceeding the assumed stalling incidence in ground effect would still be less than 1 in 10^{15}.

Wing lift coefficients at 20 ft and 50 ft, shown in Figs. 25 and 26, are thought to give a better indication of the consistency of control achieved during the flare-up when the demands are properly within the pilot's capacity. As explained earlier, maximum incidence is not thought to be a reliable indication of stall proximity in ground effect. Since it was not possible to identify when maximum C_{LW} occurred on the records without calculating a time history of C_{LW} for each take-off, a histogram of maximum C_{LW} was not easily obtainable. Furthermore, since maximum C_{LW} was generally found to occur immediately after unstick, the consequences of a stall at this stage of the take-off would not necessarily be lethal. At 20 ft, a stall would almost certainly be lethal. By 50 ft, the pilot would generally have the director demand well under control.

The only significant differences in the corresponding directed and undirected distributions is that at 20 ft higher mean C_{LW}'s occur in the directed take-offs. It is disappointing that at this stage C_{LW} has not been more narrowly confined by the director. The pilots felt that their director following might have been improved by use of a more sophisticated director display instrument*.

To show whether the large scatter in C_{LW} was due to deficiencies in the director or to inaccurate following by the pilot, values of C_{LW} were correlated with the indication of the director at the same instant. The data was separated into 3 groups, each containing all the occasions in which the director demand was within a certain band. They are presented in separate histograms. Those recorded for the smaller director demand ($+20\ \mu A$ to $-20\ \mu A$) can then be interpreted to represent conditions in which the director was most accurately followed.

Fig. 34 shows the results for C_{LW} at 50 ft. Data for 20 ft have been similarly analysed and statistical results are shown together with those for 50 ft in Table 3. Surprisingly, there were more occasions when the director was nulled at 20 ft than at 50 ft. It so happened that on many take-offs, the director ring was passing back through the null position after the first overshoot just as the aircraft reached a height of 20 ft. The results also show that when the director was accurately followed there was large reduction in the variability, especially at 50 ft.

Besides maintaining an adequate margin from the stall during the flare-up, a take-off director is also required to limit the variability of distance to reach a given height. With SCAT, only the airborne distance was considered to be significant. The results of a statistical comparison (Table 2 and Fig. 27) of results from undirected and directed take-offs show that there is no significant difference between the two cases, but there is perhaps some indication that consistency was improved when the director was used.

(iii) *The climb-out.* This was the most successfully directed phase of the take-off. Time histories of an undirected and a directed take-off by one particular airline pilot with no previous experience of SCAT are compared in Fig. 35. The difference shown is fairly typical of take-offs by pilots other than those from Aero Flight and it is true to say that with airline and 'other' pilots especially, take-offs tended to be more stable when the director was used.

Maximum deviations from the mean climb-out speed for each flight are compared in Fig. 28. The mean of the maximum deviation was not significantly lower for the directed take-offs, but the differences in standard deviation show that there was less chance of undesirably large speed variations occurring during directed climb-outs. As stated in Section 6.1, accurate speed holding becomes critical during, for instance, a three-engine climb-out at V_2.

Pilots' comments and the flight records indicate that when the director was used, the phugoid oscilla-

---

**See* Section 6.3.

tion was more easily and effectively damped. Although some pilots found it possible to hold the speed slightly more accurately using the ASI, considerably more effort was required.

6.3. *Pilot Opinions of the F.4b as a Take-off Director Display Instrument.*

The F.4b director horizon display as originally used (Fig. 3a) was considered to be inadequate for take-off director application. The main criticisms were:

(i) Due to the lack of aircraft reference axes on the instrument face the director pitch demand tended to be misinterpreted when the aircraft was banked, especially when there were azimuth demands as well (Fig. 36).

(ii) When yaw occurs after unstick (in crosswind) the lateral director demands a correction, but since it is not expedient to roll at this stage, pitch guidance suffers since the pilot has to fly with the director ring displaced to one side of the spot.

(iii) The pilot's eyes focus on the director spot and it is difficult for him to absorb attitude information.

As an interim modification to the instrument face, small 'wings' were added to the central spot and although these were found to assist director following, perception of attitude was still difficult.

The majority of the tests were carried out with the instrument face modified as shown in Fig. 3b and this display was considered to be much more useable. Besides assisting the pitch task, the 'inverted omega' and the lines on the white sector made the pilot aware of bank angle, especially during a turn, when he was concentrating hard on the director. Even so, azimuth director demands shortly after unstick were thought to be a nuisance and since the pitch task was far more important at this stage, a large decrease in azimuth sensitivity or, better still, separate pitch and roll bars were thought to be desirable. One pilot even felt he would prefer to use the compass to monitor azimuth rather than follow the F.4B azimuth demands.

Initially, when following the director with the desired accuracy, pilots found that it was not easy to carry out their normal scan pattern, though the rather unconventional instrument layout (Fig. 2) and the fact that the director instrument was sitting proud of the panel, was certainly not conductive to a good scan pattern. With practice, some pilots found that they were able to scan normally, using the director as an additional aid. Even so, if it is at all likely that future take-off director instruments will monopolise the pilot's attention, the reliability requirement of such instruments and their signal sources will have to be carefully considered. It has been suggested that if a take-off director is to be compatible in integrity with automatic landing equipment, a triplex system is required for the pitch signalling lines and a duplicate monitored technique used for the display.

6.4. *Pilot Scan During Take-off.*

The study of pilot's scan during the flying of particular manoeuvres has been the subject of many experiments in the past. The majority of techniques used to determine the pilot's line of sight have the disadvantage that they involve the use of elaborate equipment and/or interfere with the pilot. It has become apparent that the simplest technique which does not affect the pilot is to use a cine camera to film the pilot's face during the manoeuvre. The tests described here were carried out with the object of determining the practicability of this technique for providing information on pilot scan during take-off. A sample of film taken during the tests is shown in Fig. 37.

Before analysis of the films could proceed it was necessary to carry out a calibration of the pilot's line of sight for each instrument. The camera was run while a 'pilot' looked at each instrument in turn, and by studying this film carefully frame by frame, it was possible for the analyser to become proficient in identifying which instrument any particular pilot was looking at. Using a hand film analyser or a projector at one or two frames a second, the number of frames was counted for which a pilot was flying visually, on instruments or blinking. From the known camera speed, a time history of pilot scan and percentage time spent on each instrument was obtained. Since a camera on/off event was recorded on the airborne data recorders, the time history could be related to any particular feature of the take-off, e.g. rotation.

It is not proposed to present a complete analysis of the films taken here, but the time histories of undirected take-offs shown in Fig. 38 do give some indication of the differences to be expected in the scan pattern of different pilots. Initiation of rotation has been used as the time datum for each take-off. The following points appear to be significant:

(i) There is a large variation in the amount of time spent flying visually and on instruments, although in the example given for pilot C, an important factor was poor visibility during the take-off.

(ii) As might be expected, the ASI was used as the master instrument, but whereas pilots A and C used it for roughly threequarters of the time, pilot B flew visually for nearly half the time.

(iii) It is noticeable that the artificial horizon was not used by any of the pilots during rotation. Provided visibility is good, a Comet pilot is not obliged to fly on instruments during rotation, since the horizon is not cut off until the attitude increases beyond 8 deg after unstick. In any case, the artificial horizon is not thought to be sufficiently accurate for use during rapid changes in attitude.

(iv) In the flare-up and climb-out, pilots A and B maintained lateral control visually or by using the artificial horizon, but surprisingly, pilot C made more use of the compass. He confirmed that he preferred to keep the wings level by referring to the compass rather than the artificial horizon.

Films were also taken during directed take-offs. These showed that pilots concentrated almost exclusively on the director instrument during the flare-up and climb-out. One time history is illustrated in Fig. 39. Although pilots were not briefed to maintain a normal scan pattern, they did remark that the director instrument exerted a very powerful draw on their attention and scanning could only be carried out at the expense of director following accuracy. It is possible that, with a more conventional instrument panel layout and an improved director, instrument scanning would be more feasible.

7. *Conclusions.*

7.1. *Undirected Take-offs.*

The variability of rotation and unstick speeds in this series of tests compare quite well with those which are emerging from operational measurements on Comet aircraft in service. Since the pilots engaged in these experiments were operating in tests conditions to standard briefings, it is probable that none of the resulting variability was a reflection of deliberate modifications to the piloting technique. It therefore seems likely that the variability in service, which is not very different from that experienced in the present tests, has less deliberate content than is sometimes believed. The fact that the unstick speed is nearly always several knots higher than scheduled suggests that the rotation procedure laid down in the Flight Manual is unrealistic because it demands very high rates of rotation. Delaying the unstick speed by making less rapid rotations is likely to cause increases in the airborne distance to 35 ft and probably accounts for the large variability of this quantity measured in these tests.

These results, as well as the large variabilities measured on the other quantities, suggest that the take-off manoeuvre is difficult to control with precision with the instruments currently used and that an extra aid to the pilot might usefully improve his performance, particularly in emergency conditions.

7.2. *Directed Take-offs.*

On the whole, the SCAT director operated much as the manufacturer had claimed. The lift transducer provided a reasonably accurate measure of wing lift coefficient, even in ground effect, although there is no evidence on how well it would indicate the approach to a stall in ground effect. The exact positioning of the lift transducer on the leading edge appeared to be critical and it is possible that its performance could have been improved if more time had been available for adjustment during the early stages of the trials. In a commercial installation its position would be optimised in wind tunnel tests, leaving less adjustment to be dealt with in the flight trials.

The performance of the attitude gyro and pitch pendulum appeared satisfactory. The computer provided accurate summations of the individual signals, but the shaping circuits were found to be sensitive to temperature changes. In other respects the reliability of the equipment during the course of the trials was satisfactory.

The SCAT director law in the form tested provided the pilot with a clear safe demand for a high performance manoeuvre during the latter stages of flare-up and in the climb-out in all the conditions tested, including simulated engine failure and pilot error. It provided no warning nor demand for the initiation of rotation and an insufficient indication of correct rotation rate. Although it always indicated clearly when the correct attitude had been reached, over-rapid rotations almost always led to an overshoot in attitude. When a pitch rate term was added to the director law in some tests, pilots were able to 'capture' the director much more easily after rapid rotations. It should be noted, however, that the F.4B director horizon instrument which was used in these tests to display the SCAT signal, was not satisfactory for this purpose and was also badly sited on the instrument panel. A more suitable display instrument might have improved pilot's performance in this phase.

Useful improvements were made only in the variability of airborne distance to 35 ft and in speed holding during climb by using the SCAT director, but it had little effect on the other quantities measured. This latter result probably arises from a number of causes quite apart from the efficiency of the SCAT director. In the first place the undirected take-offs were possibly unrepresentatively consistent because they were made under test conditions, largely by experienced test pilots accustomed to very accurate flying. Secondly, the undirected take-offs were dispersed through the whole series of tests so that there was inevitably some feed-back of learning from the directed take-offs. Shortcomings in the display instrument, too, degraded the performance in the directed take-offs to some extent. But perhaps the most telling reason is that the director would be expected to show its best in extreme or emergency situations and these are difficult to simulate properly in test conditions. Nearly all the pilots agreed that the director was particularly helpful after engine failure; they felt they were relieved of some of the strain caused by the difficulty in flying the aeroplane, leaving them, to some extent, free to cope with the other aspects of the emergency.

Acknowledgements.

The authors wish to acknowledge the help given by the Safe Flight Instrument Corporation who provided the SCAT system and gave technical support throughout the trials.

The authors also wish to acknowledge the assistance given by the pilots from airlines, firms and other organisations who took part in the trials.

LIST OF SYMBOLS

A	Aspect ratio	
b	Wing span	ft
C_L	Aircraft lift coefficient	
C_{LT}	Tailplane lift coefficient	
C_{LW}	Wing lift coefficient	
C_p	Pressure coefficient	
d	Distance between aircraft c.g. and incidence vane	ft
D_y	Azimuth director indication	
D_z	Pitch director indication	
g	Acceleration due to gravity	$32{\cdot}2\, f/s^2$
l_f	Measured accleration along flight path	g
'	Horizontal acceleration	$\underline{g}$

LIST OF SYMBOLS (Contd.)

n_f	Measured acceleration normal to flight path	g
n_e	Vertical acceleration	$\underline{g}$
h	Altitude (mean quarter-chord point)	ft
h_R	Radio altitude (wheel height)	ft
I_{D_z}	Pitch director signal	μA
I_Γ	Computer output current due to pendulum angle	μA
I_θ	Computer output current due to pitch attitude	μA
I_τ	Computer output current due to tab deflection	μA
l_d	Longitudinal accelerometer indication	g
n_d	Normal accelerometer indication	g
q	Rate of pitch	deg/sec
R	Resultant acceleration	g
S_W	Wing area	ft^2
S_T	Tailplane area	ft^2
T	Net thrust	lb
V	Equivalent airspeed	kt
V_R	Rotation speed	kt
V_S	Stalling speed	kt
V_U	Unstick speed	kt
V_2	Take-off safety speed	kt
W	Aircraft all-up weight	lb
$\dot{x}$	Horizontal ground velocity along runway	ft/s
$\dot{z}$	Vertical ground velocity	ft/s
α	Wing incidence	deg
α_T	Tailplane incidence	deg
α_V	Vane indicated incidence	deg
γ	Flight-path angle	deg
Γ	Pendulum angle	deg
$\Delta\alpha$	Increment in incidence at a given C_{LW} due to ground effect	rad
$\Delta\alpha_V$	Increment in incidence vane indication due to ground effect	deg
ε	Downwash angle	deg
η	Elevator angle	deg
η_T	Tailplane setting relative to wing	deg

LIST OF SYMBOLS—*continued*

θ	Pitch attitude	deg
ρ_0	Air density at 15 deg C, 1013·2	slug/ft^3
τ	Lift-transducer deflecting force	tip grams
$\dot{\tau}$	Rate of change of lift-transducer force	tip grams/s
ϕ	Bank angle	deg
ψ	Heading	deg
ψ_D	Heading demand	deg

LIST OF REFERENCES

No.	*Author(s)*	*Title, etc.*
1	A. E. Smith	Now 5,000,000 jet hours. Flight International, *Vol. 83*, No. 2829, 781–783. 1963.
2	—	Civil Aircraft Accident. Report of the Turkish Investigating Commission on the accident to Comet 4B G-ARJM at Esenboga Airport, Ankara on 21st December 1961. C.A.P. 188, H.M. Stationery Office. 1962.
3	Compiled by A. C. Browning and H. W. Chinn	Preliminary flight tests on take-off directors. Symposium on aircraft take-off and landing problems (R.A.E. 17th and 18th December 1962). R.A.E. Rep. D.D.1. July 1963. A.R.C. 25 770.
4	Royal Aeronautical Society ..	Ground effect on lift and drag. R.Ae.S. Data Sheet, Aircraft 01.01.01. March 1958.
5	D. A. Kirby and A. P. Cox	Low speed wind tunnel tests on a 1/18th scale model of the de Havilland Comet. R.A.E. Tech Note Aero 2277. November 1953.
6	K. A. Brownlee	Statistical theory and methodology in science and engineering. New York, J. Wiley. 1960.

APPENDIX A

Methods of Determining Wing Lift Coefficient for Checking the Accuracy of the Lift Transducer.

A.1. *Determination of C_{LW} vs. α from trimmed, level-flight runs in free air.*

The wing lift coefficient of the aircraft was calculated by subtracting the tailplane contribution from the total lift corrected for thrust component. Lift due to the fuselage was considered to be included in the wing lift.

Assuming steady, level flight,

$$C_L = \frac{W - T\sin\alpha}{\frac{1}{2}\rho_0 V^2 S_W}. \tag{A.1}$$

Position error corrections to IAS were not available for this aircraft but from Comet 4 data it was expected that they would be small for the flight range considered.

Wing lift coefficient is given by

$$C_{LW} = C_L - C_{LT}\frac{S_T}{S_W}$$

where

$$C_{LT} = \frac{\partial C_{LT}}{\partial \alpha_T}\alpha_T + \frac{\partial C_{LT}}{\partial \eta}\eta$$

and

$$\alpha_T = \alpha + \eta_T - \varepsilon \tag{A.2}$$

therefore

$$C_{LW} \doteq \frac{W - T\sin\alpha}{\frac{1}{2}\rho_0 V^2 S_W} - \frac{S_T}{S_W}\left\{\frac{\partial C_{LT}}{\partial \alpha_T}\left[\alpha + \eta_T - \left(\varepsilon_{\alpha=0} + \frac{\partial \varepsilon}{\partial \alpha}\alpha\right)\right] + \frac{\partial C_{LT}}{\partial \eta}\eta\right\}. \tag{A.3}$$

Substituting from Table 4,

$$C_{LW} = \frac{0{\cdot}316\,(W - T\sin\alpha)}{V^2} - (0{\cdot}00744\,\alpha + 0{\cdot}00813\eta - 0{\cdot}0538). \tag{A.4}$$

After the incidence vane indication had been corrected for position error, C_{LW} was calculated for each run and the wing lift calibration constructed (Fig. 14).

A.2. *Determination of C_{LW} during take-off.*

Two methods were available; the direct method using weight, normal acceleration and airspeed and the indirect method using incidence and the lift curve. Both methods involved corrections for ground effect. In the direct method, ground effect on IAS was a serious difficulty. An accurate flight calibration of IAS with height a.g.l. was found to be impracticable owing to the requirement for zero wind and turbulence. The indirect method required a correction for ground effect on C_{LW} which was in fact carried out with a fair degree of accuracy (Fig. 16). This latter method was therefore preferred and the following procedure used to calculate C_{LW} during all stages of the take-off:

(i) α, V and q were obtained from the recorders, q being calculated from the slope of the θ trace;

(ii) the q correction to α_V was calculated using the relation

$$\Delta\alpha_q = -\frac{qd}{V}$$

where d is the distance between the vane and the aircraft c.g.

(iii) α was read off from Fig. 13.

(iv) By assuming a linear relation between incidence and increment of C_{LW} due to ground effect, it was possible to use the ground effect curve at one incidence (Fig. 16) and the free air C_{LW}/α relation (Fig. 14) to determine C_{LW} at any incidence and height a.g.l. The relation is illustrated in Fig. 40. At a height h and incidence α_1,

$$C_{LW1} = (5{\cdot}5+\alpha_1)\left[\frac{0{\cdot}915+(\Delta C_{LW})_{9^\circ}}{14{\cdot}5}\right]$$

where $(\Delta C_{LW})_{9^\circ}$ is read off from Fig. 16.

A.3. *Checking the accuracy of the lift transducer.*

The lift transducer load was plotted against C_{LW} at one second intervals after unstick for several take-offs and the resulting scatter envelope is shown in Fig. 41. The corresponding results for trimmed, level flight runs at 10 000 ft are also shown. The increased scatter of points occurring during take-off is perhaps not surprising since, in addition to weight differences, dynamic conditions are bound to cause deviations from the steady state behaviour of both the lift transducer and the incidence vane. It is not an easy matter to decide what proportion of the scatter is due to inconsistency in the lift transducer and what proportion is due to inaccuracy in determining C_{LW}. For the trimmed level flight runs, C_{LW} was determined to an estimated accuracy of 3 per cent, i.e. approximately $\pm 0{\cdot}03$. Since the overall scatter for these runs is of the order of $\pm 0{\cdot}06$, it can only be assumed that in steady state conditions the lift transducer measured C_{LW} to, at best, 3 per cent accuracy.

The apparent divergence of the trimmed, level flight and take-off envelopes at the lower values of C_{LW} is not readily explained. Although the level flight runs were carried out at 10 000 ft, Mach number effects on the lift transducer are considered to be negligible, since airspeeds were lower than 150 knots. A possible explanation could be the effect on indicated incidence of changes in engine intake airflow. At lower incidences, increased power on take-off might have influenced the airflow direction at the incidence vane position, causing the indicated incidence to differ from that measured during trimmed, level flight, when considerably less power was used. When C_{LW} was calculated using the direct method for one take-off, making the appropriate correction for engine thrust and tail plane lift, there was better agreement between the two envelopes at the lower values of C_{LW}.

APPENDIX B

Analysis of Ground Effect Tests.

Owing to the rather unsteady conditions during the ground effect runs, it was necessary to give careful consideration to the calculation of incidence and wing lift coefficient.

B.1. *Calculation of incidence.*

From Fig. 42, the accelerations along and normal to the instrument datum are given by

$$l_d = l_f \cos(\alpha - 2) + n_f \sin(\alpha - 2) \tag{B.1}$$

and

$$n_d = -l_f \sin(\alpha - 2) + n_f \cos(\alpha - 2) \tag{B.2}$$

also

$$\frac{l_d}{n_d} = \tan \Gamma \tag{B.3}$$

where l_f and n_f are accelerations along and normal to the flight path respectively.

For small γ,

$$l_f \simeq \frac{\ddot{x}}{g},$$

$$n_f \simeq -\left(\frac{\ddot{z}}{g} + 1\right)$$

and $\tan \gamma \simeq \sin \gamma \simeq \frac{\dot{z}}{\dot{x}}$

where x and z are horizontal and vertical earth axes.

Since accelerations were small, it was possible to extract $\ddot{x}$ and $\ddot{z}$ as well as $\dot{x}$ and from kinetheodolite data. Hence, knowing the longitudinal and normal accelerometer readings l_d and n_d, either equation (B.1) or (B.2) could be solved for α by an iterative process. In practice it was found that (B.1) was more suitable, but since the longitudinal accelerometer was found to be unreliable, it was necessary to use the pendulum angle Γ, the normal accelerometer reading n_d and the relation (B.3) to determine l_d. Substitution in (B.1) gives

$$n_d \tan \Gamma = \frac{\ddot{x}}{g} \cos(\alpha - 2) - \left(\frac{\ddot{z}}{g} + 1\right) \sin(\alpha - 2)\,. \tag{B.4}$$

B.2. *Calculation of C_{LW}.*

From Fig. 42 the acceleration normal to the flight path is given by

$$n_f = R \cos[\Gamma - (\alpha - 2)] = \frac{n_d}{\cos \Gamma} \cos[\Gamma - (\alpha - 2)] \tag{B.5}$$

therefore

$$C_L = \frac{0{\cdot}316 \left\{\frac{W\, n_d \cos[\Gamma - (\alpha - 2)]}{\cos \Gamma} - T \sin \alpha\right\}}{V^2} \tag{B.6}$$

and

$$C_{LW} = \frac{0{\cdot}316\left\{\dfrac{W\, n_a \cos\left[\Gamma-(\alpha-2)\right]}{\cos\Gamma} - T\sin\alpha\right\}}{V^2} - (0{\cdot}00744\alpha + 0{\cdot}00813\eta - 0{\cdot}0538). \qquad \text{(B.7)}$$

Ground effect on tailplane and elevator lift was assumed to be a second order effect and was neglected.

B.3. *Calculation of ground effect.*

On each of the four ground effect runs the records were analysed at 2 second intervals to give a total of 55 points covering a range of heights from 3 to 80 feet.

(a) *Ground effect on lift.* Using the methods given in Sections 1 and 2, α and C_{LW} were calculated for each data point. By referring to Fig. 13 for the free air C_{LW} at the calculated values of α, the lift increment due to ground effect was given by

$$\Delta C_{LW} = (C_{LW})_{\text{near ground}} - (C_{LW})_{\text{free air}}\,.$$

(b) *Ground effect on the lift transducer.* The lift transducer deflecting force in ground effect was related to C_{LW} by the calibration given in Fig. 15. ΔC_{LW} as indicated by the transducer was calculated by subtraction as in (a).

(c) *Ground effect on the incidence vane.* This was given by:

$$\Delta\alpha_V = \alpha - \alpha_V\,.$$

A comparison of Fig. 13 and Fig. 43, which give position errors in free air and ground effect respectively, shows that the general level of scatter does not permit any error in the indicated incidence to be ascribed to ground effect.

TABLE 1

Recorded Quantities and Instrumentation.

Quantity	Sensor	Pick off	Intermediate circuitry	Recording element
Recorder 1: Type IT3–14–61 90 mm 12 channel recorder				
Pitch attitude	H.G.U. Type B	D.C. potentiometer	Series resistor	IT–23–59 galvanometer
Pitch rate	Test equip. 10 deg/sec	2 kc A.C. pick off	Full wave demodulator/filter	IT–23–59 galvanometer
Elevator	De Havilland	A.C. pick off	Full wave demodulator/filter	IT–23–59 galvanometer
Nose incidence	Aero F. vane	A.C. pick off	Full wave demodulator/filter	IT–21–59 galvanometer
Normal acceleration	Aero F. 0–2g	A.C. pick off	Half wave demodulator/filter	IT–23–59 galvanometer
Longitudinal accel.	Aero F. ±1g	A.C. pick off	Half wave demodulator/filter	IT–23–59 galvanometer
Scan camera event	—	—	—	IT–1–20–59 galvanometer
Time base	1 sec clockwork timer	—	—	IT–1–20–59 galvanometer
Recorder 2: Type SFIM A22 3H 60 mm 6 channel recorder				
Leading edge tab	SCAT lift sensor	A.C. pick off	SCAT computer demodulator	E 311 galvanometer
SCAT pitch attitude	SCAT vertical gyro	D.C. potentiometer	Series resistor	E 311 galvanometer
SCAT pendulum	SCAT pendulum	D.C. potentiometer	Series resistor	E 311 galvanometer
SCAT director signal	SCAT computer	D.C. output	Series resistor	E 611 galvanometer
Pendulum level	Direct recording	—	—	J 33 pendulum
Pitch director cut event	Director cut relay	—	—	E 02 event
Time base	1 sec clockwork timer	—	—	E 02 event
Recorder 3: Type ACB A13 90 mm recorder				
Airspeed	Direct recording	—	—	H 111 capsule
Radio altitude	Mk. 7 radio altimeter	—	Series resistor	E 601 galvanometer
Kinetheodolite tones	VHF receiver	—	Demodulator/filter	E 601 galvanometer
Port oleo extended	Limit switch	—	—	E 07 event
Port Bogie trailing	Limit switch	—	—	E 07 event
Stbd. oleo extended	Limit switch	—	—	E 07 event
Stbd. Bogie trailing	Limit switch	—	—	E 07 event
Nose oleo extended	Limit switch	—	—	E 07 event
Time base	1 sec clockwork timer	—	—	E 07 event

TABLE 2

Statistical Comparison of Undirected and Directed Take-offs.

U = undirected; D = directed

Quantity	Number of occasions		Mean		Standard deviation or or (variance)$^{\frac{1}{2}}$		Is the distribution normal?		If the difference in means significant?	Is the difference in standard deviation significant?
	U	D	U	D	U	D	U	D		
Error in unstick speed kt	58	158	6·1 late	5·4 late	3·1	2·9	Yes	Yes	No	No
Maximum up-elevator used deg	65	172	9·8	10·5	1·1	1·3	Yes	No	Yes	No
Maximum pitch rate deg/sec	58	166	3·5	4·0	0·89	0·85	Yes	No	Yes	No
Maximum incidence	57	161	8·8	9·3	0·71	0·77	No	No	Yes	No
Wing lift coefficient at: 20 ft	40	127	0·96	0·98	0·056	0·054	Yes	Yes	Yes	No
50 ft	40	127	0·89	0·89	0·055	0·056	Yes	Yes	No	No
Airborne distance to 35 ft ft	45	125	1097	1052	153	127	Yes	Yes	No	No
Maximum deviation from mean climb-out speed	45	105	3·5	4·0	2·8	1·9	No	No	No	Yes

TABLE 3

Effect of Accurate Director Following on C_{LW} Distribution at 20 ft and 50 ft.

C_{LW}	Overall results			Director accurately followed		
	Number	Mean	S.D.	Number	Mean	S.D.
At 20 ft	120	0·982	0·054	69	0·992	0·048
At 50 ft	120	0·892	0·057	44	0·863	0·040

TABLE 4

Aerodynamic Particulars of Comet 3B Relevant to Tests.

Wing data

Gross area, Sw	2059 ft^2
Span, b	107 ft 9·7 in
Aspect ratio, A	5·64
Aerodynamic mean chord	19 ft 1·8 in
Chord at root	29 ft 11·7 in
Chord at tip	8 ft 3·0 in
Thickness/chord ratio	11 per cent average
Sweepback (at 25 per cent chord)	20 deg
Leading edge tab position (tab set parallel to wing leading edge)	2·4 per cent chord at 52 per cent semi-span from a/c

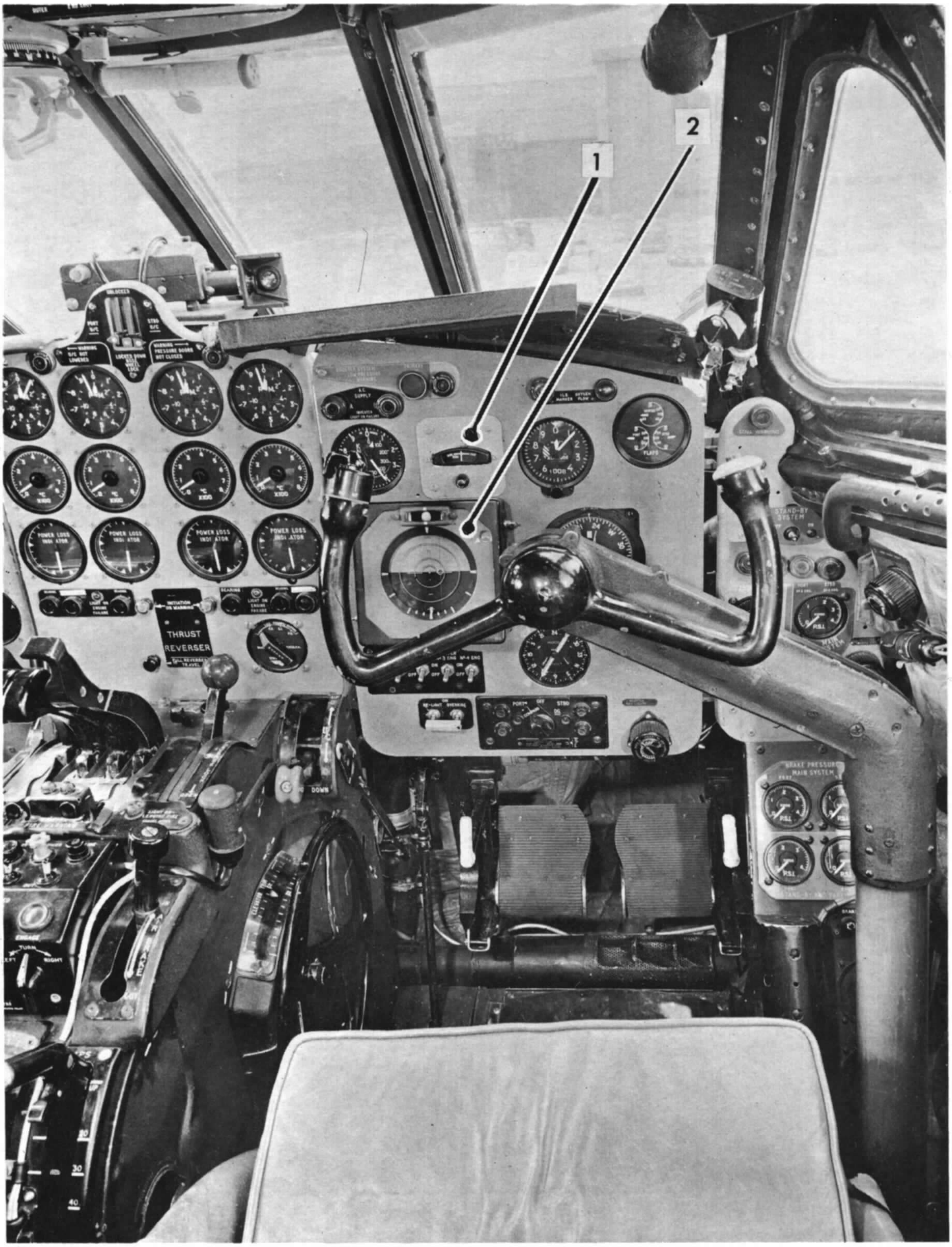
Tailplane data.

Gross area, S_T	426 ft^2
Setting relative to wing, η_T	$-1{\cdot}5$ deg
Rate of change of lift with incidence, $\partial C_{LT}/\partial\alpha_T$	0·0611 per deg
Lift at zero incidence, $C_{LT(\alpha=0)}$	0
Rate of change of lift with elevator deflection, $\partial C_{LT}/\partial\eta$	0·0393 per deg
Lift with zero elevator deflection	0

Downwash data.

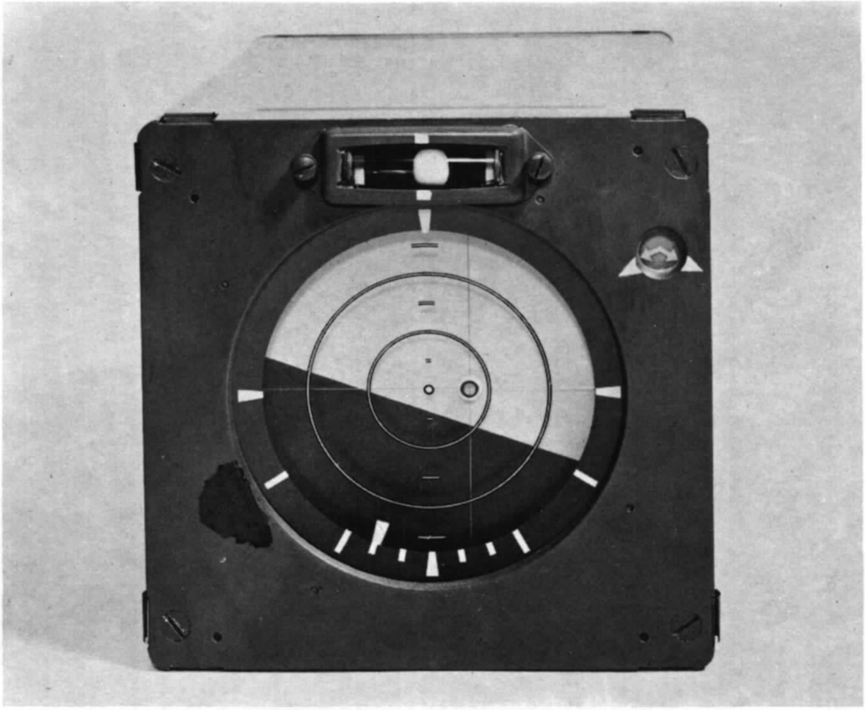
Rate of change of angle with incidence, $\dfrac{\partial\varepsilon}{\partial\alpha}$	0·41 per deg
Angle at zero incidence, $\varepsilon_{(\alpha=0)}$	2·75 deg

FIG. 1. Comet 3B XP915.



1. SCAT slow-fast indicator 2. F.4B director-horizon.

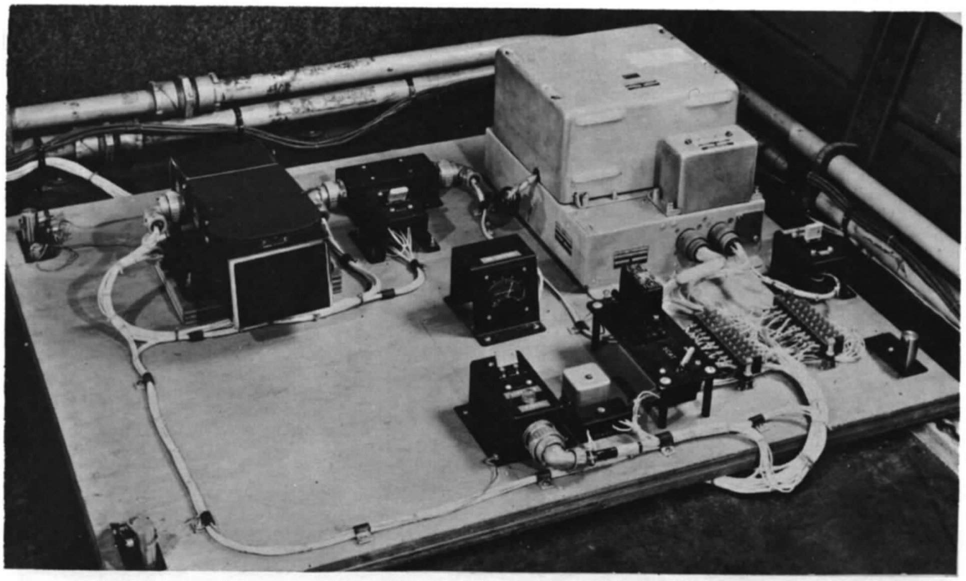
FIG. 2. Comet XP915 starboard instrument panel.



a. Original display.

b. Modified display.

FIG. 3. F.4B director horizon.



a. Computer mounted on instrumentation ‘breadboard’.

FIG. 4a. SCAT computer.

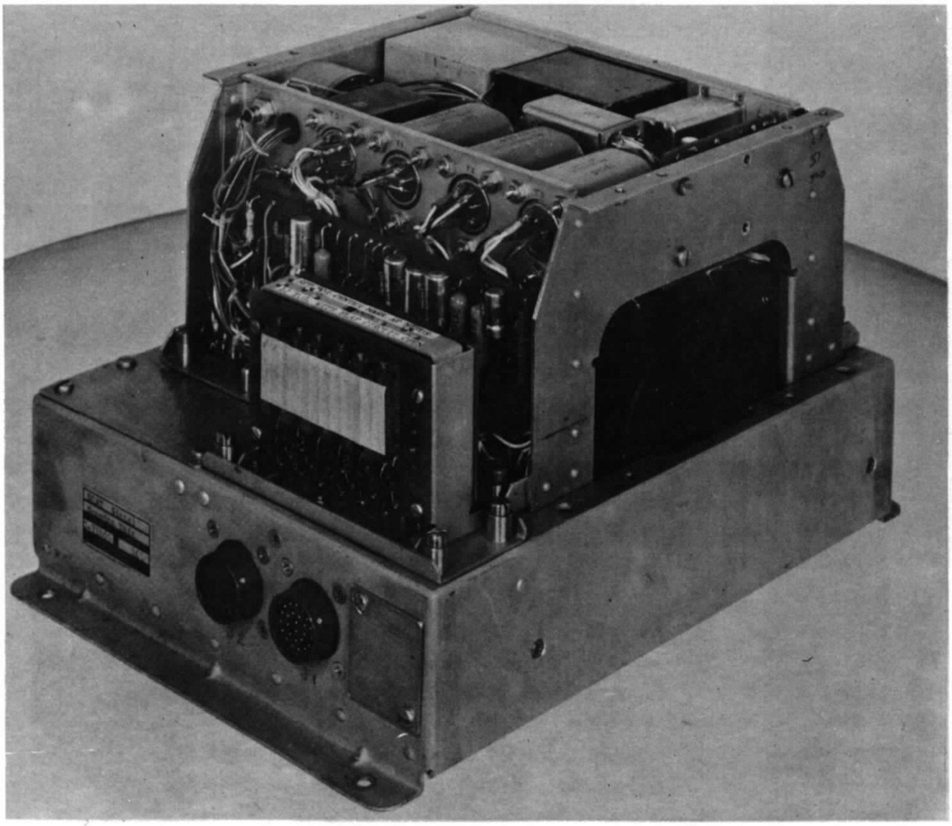


FIG. 4b. Computer with covers removed.

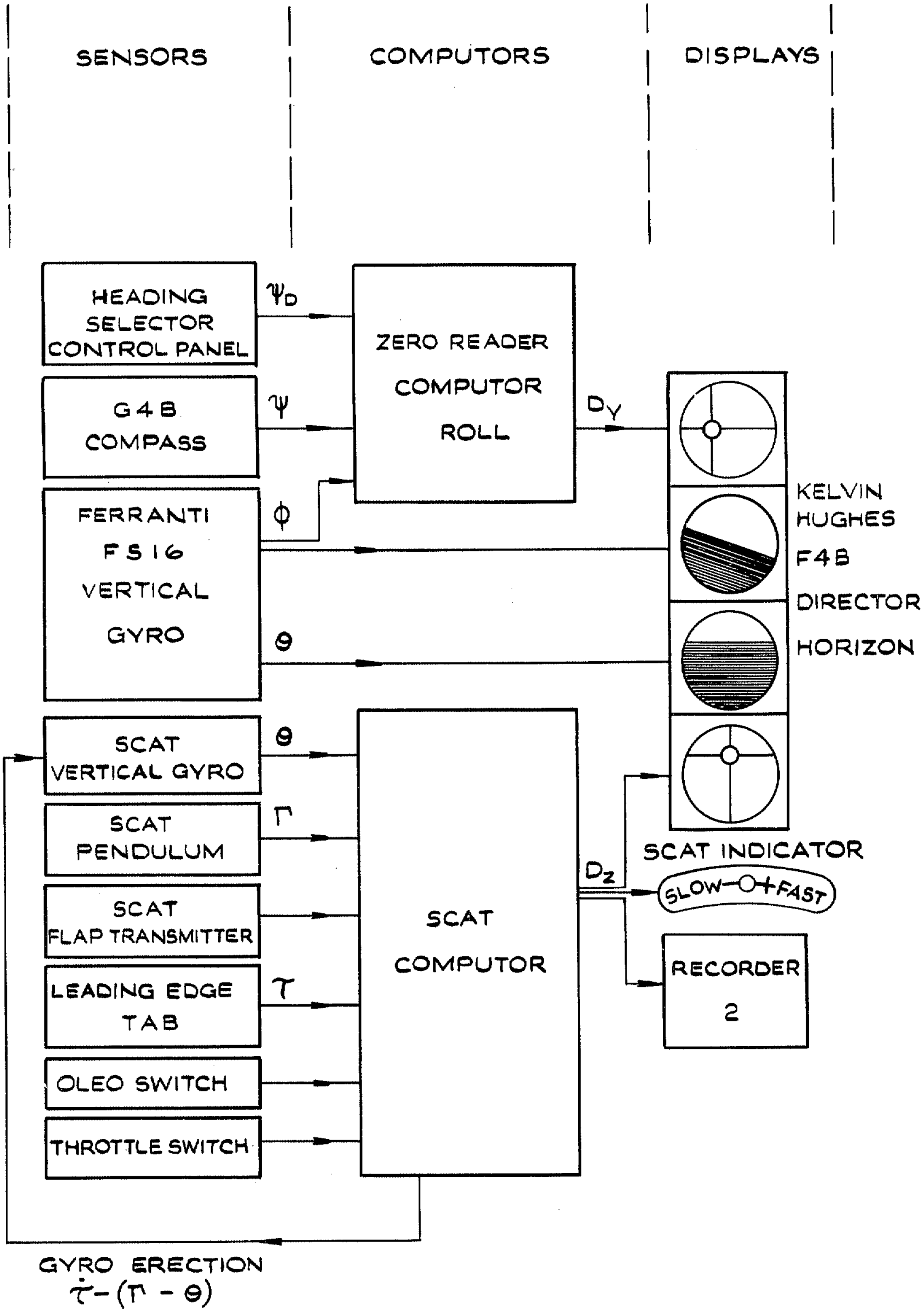


FIG. 5. The SCAT system and lateral director.

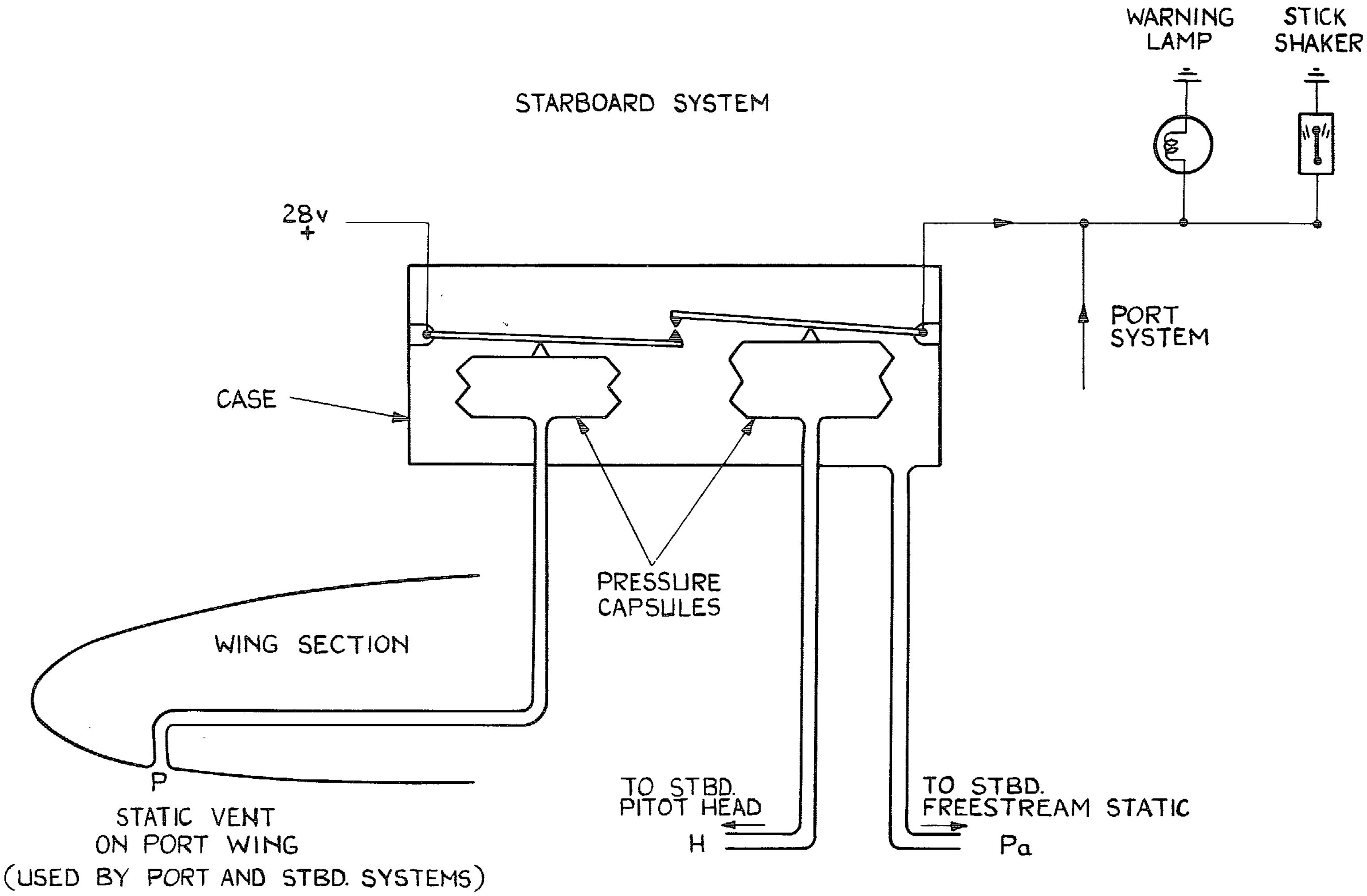
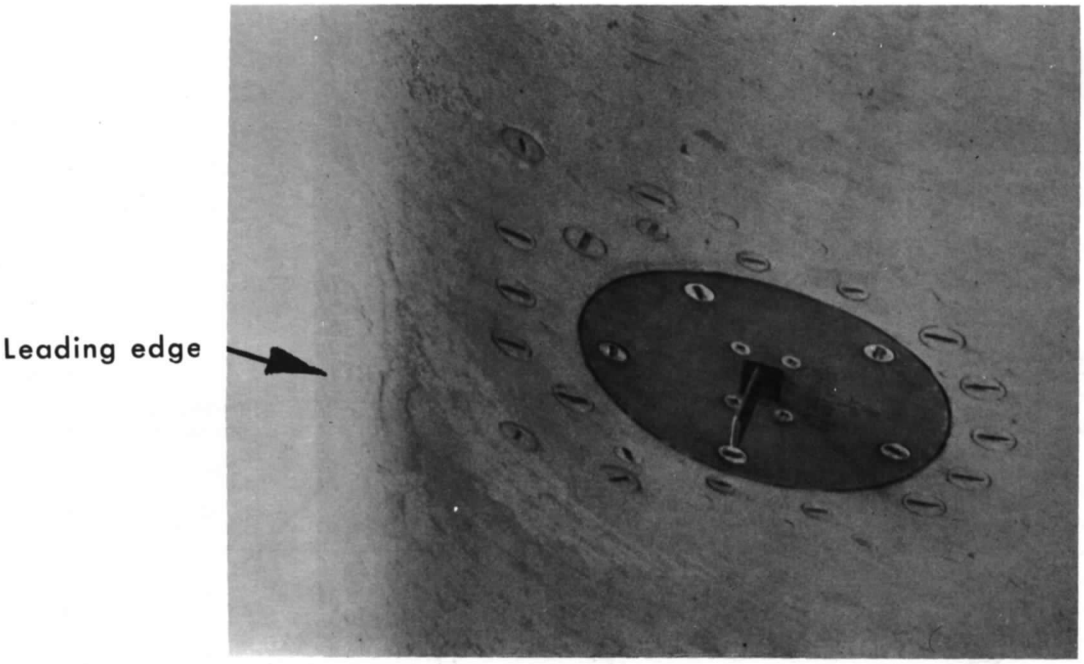
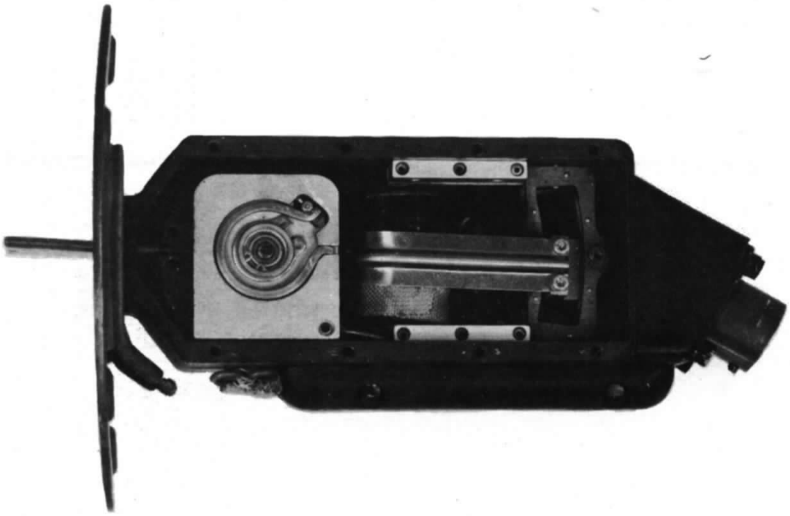


FIG. 6. Comet stall warning system.



a. The sensor mounted below wing leading edge.



b. The transducer.

FIG. 7. The SCAT lift transducer.

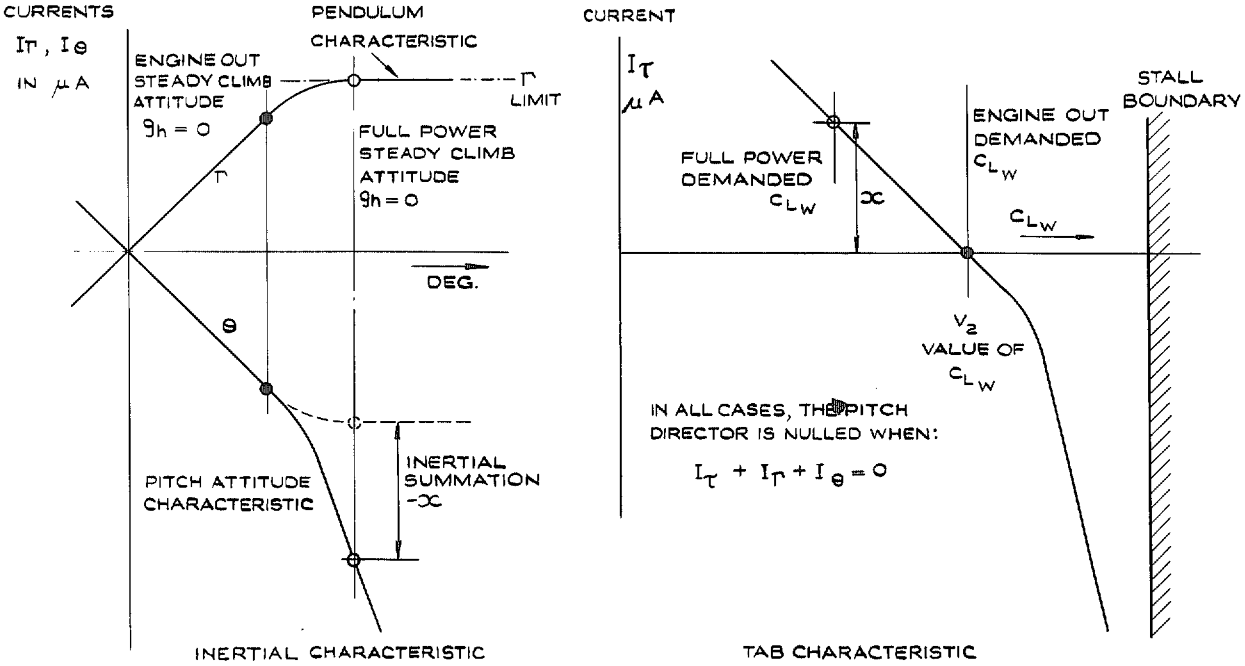


FIG. 8. SCAT system operation—static cases.

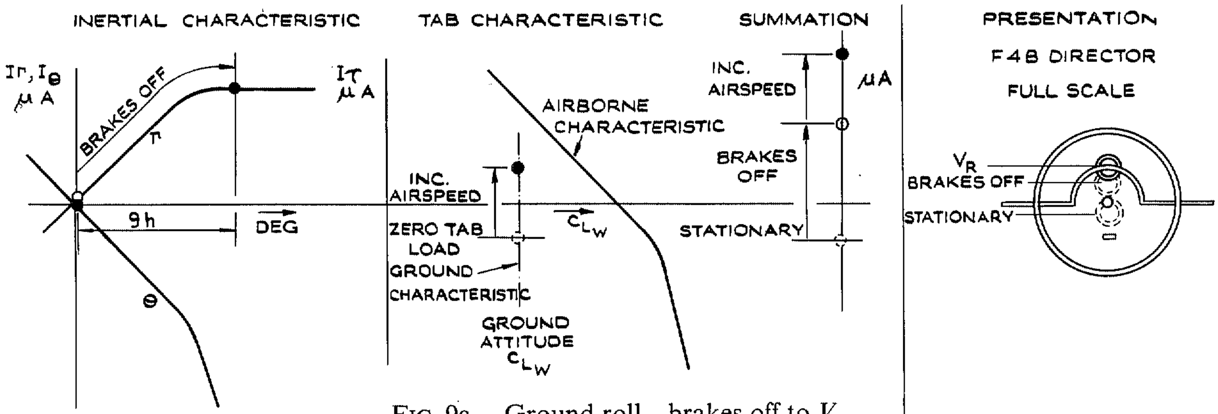


FIG. 9a. Ground roll—brakes off to V_R.

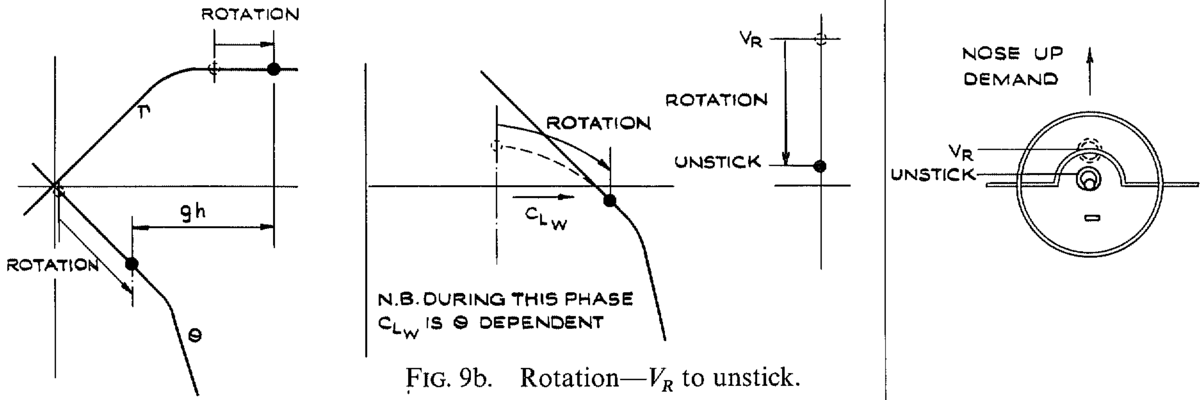


FIG. 9b. Rotation—V_R to unstick.

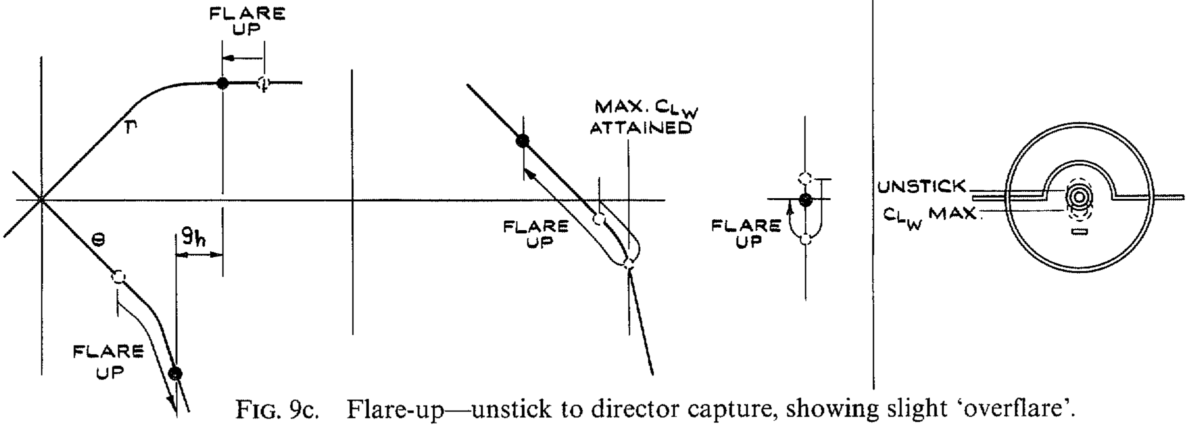


FIG. 9c. Flare-up—unstick to director capture, showing slight 'overflare'.

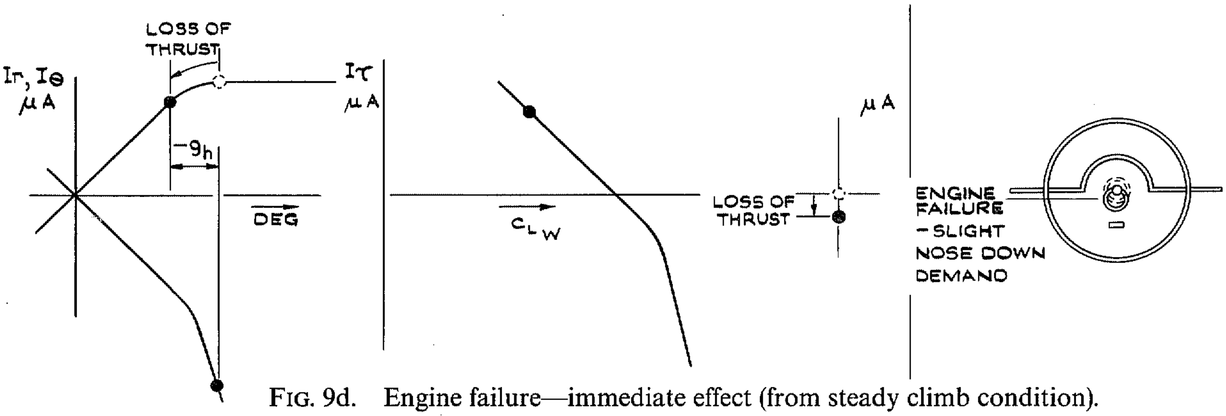


FIG. 9d. Engine failure—immediate effect (from steady climb condition).

FIG. 9. SCAT system operation—dynamic cases.

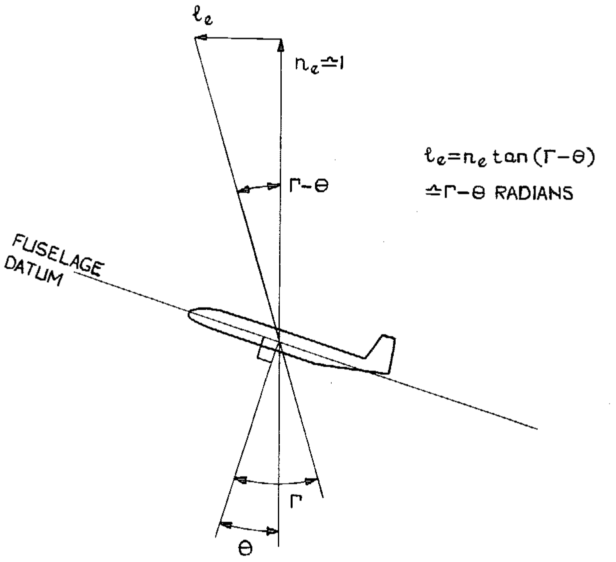


FIG. 10a. Derivation of horizontal acceleration l_e.

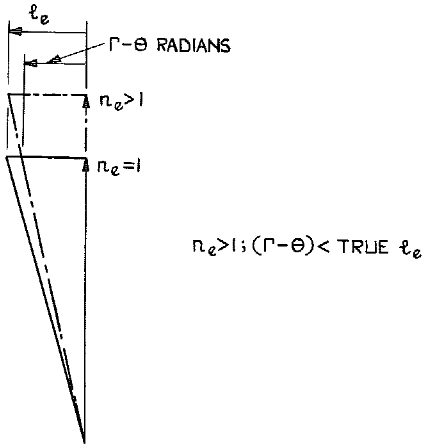


FIG. 10b. Apparent reduction in l_e with increased n_e.

FIG. 10. Operation of inertial term in SCAT.

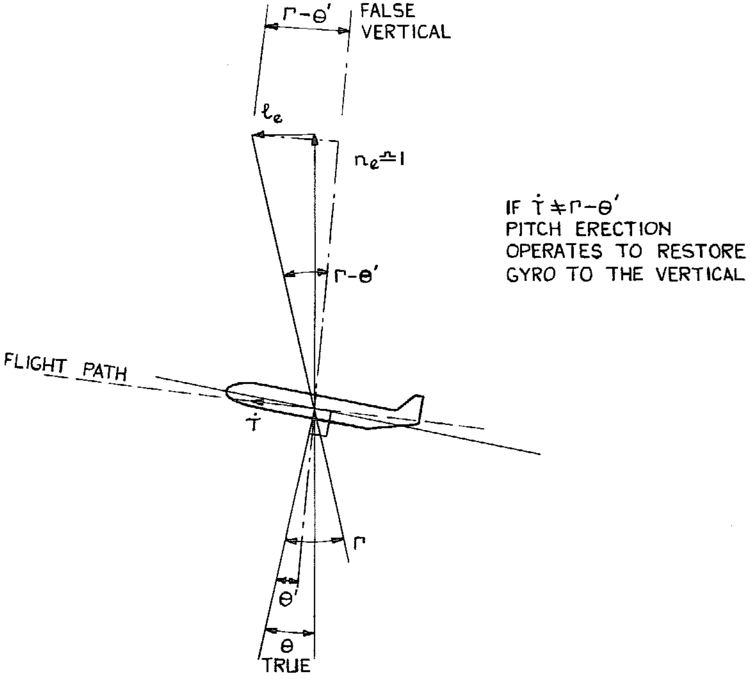


FIG. 11. Airborne operation of pitch erection.

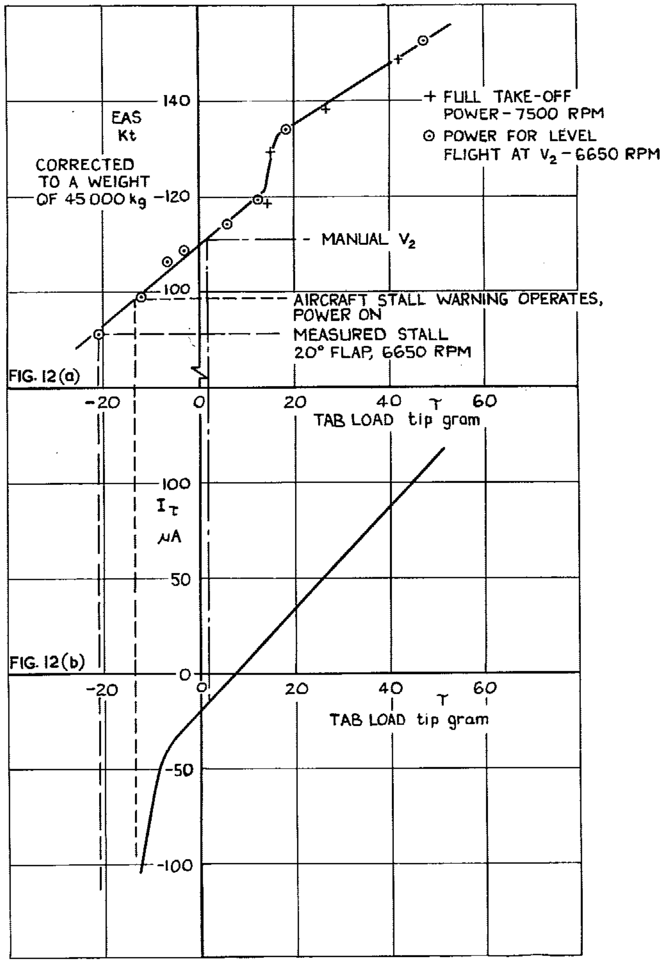


FIG. 12. Measured tab characteristics—Comet 3B, take-off flap (20 deg).

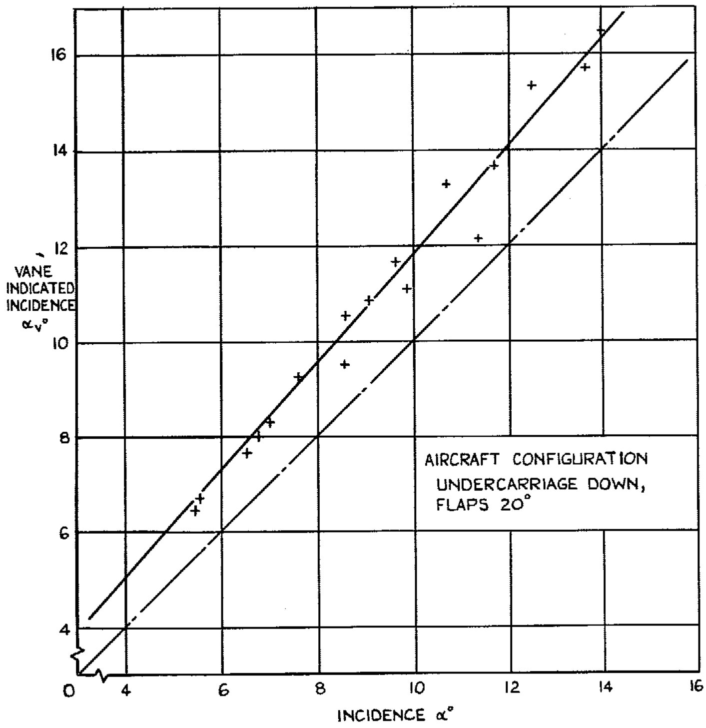


FIG. 13. Position error of incidence vane in free air.

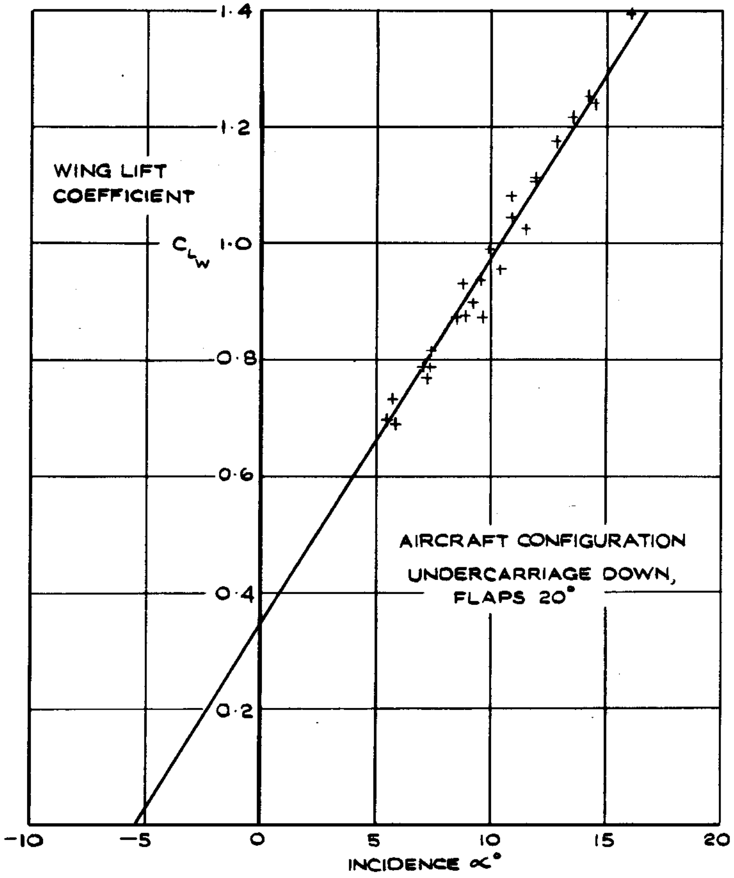


FIG. 14. Variation of wing lift coefficient with incidence. Comet 3B.

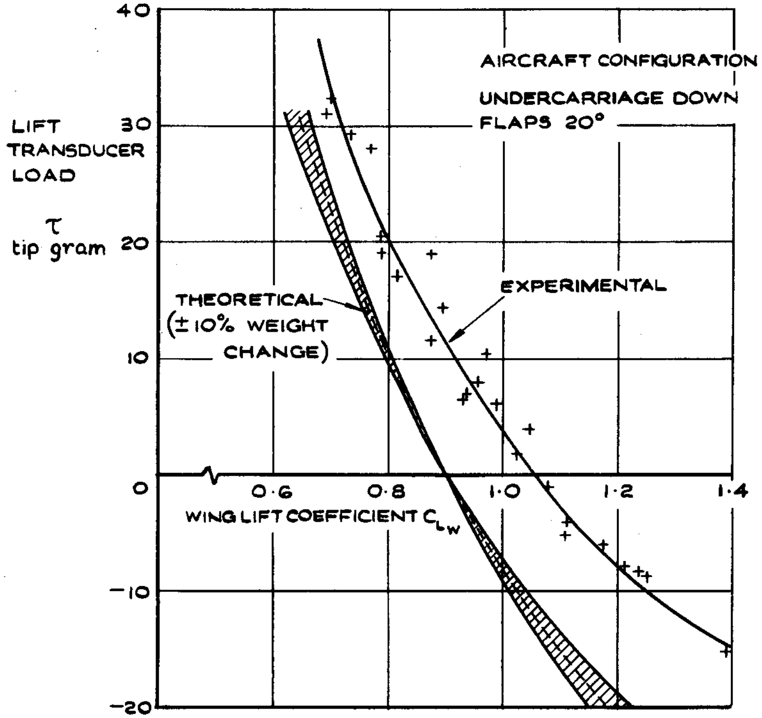


FIG. 15. Variation of lift transducer load with C_{Lw}.

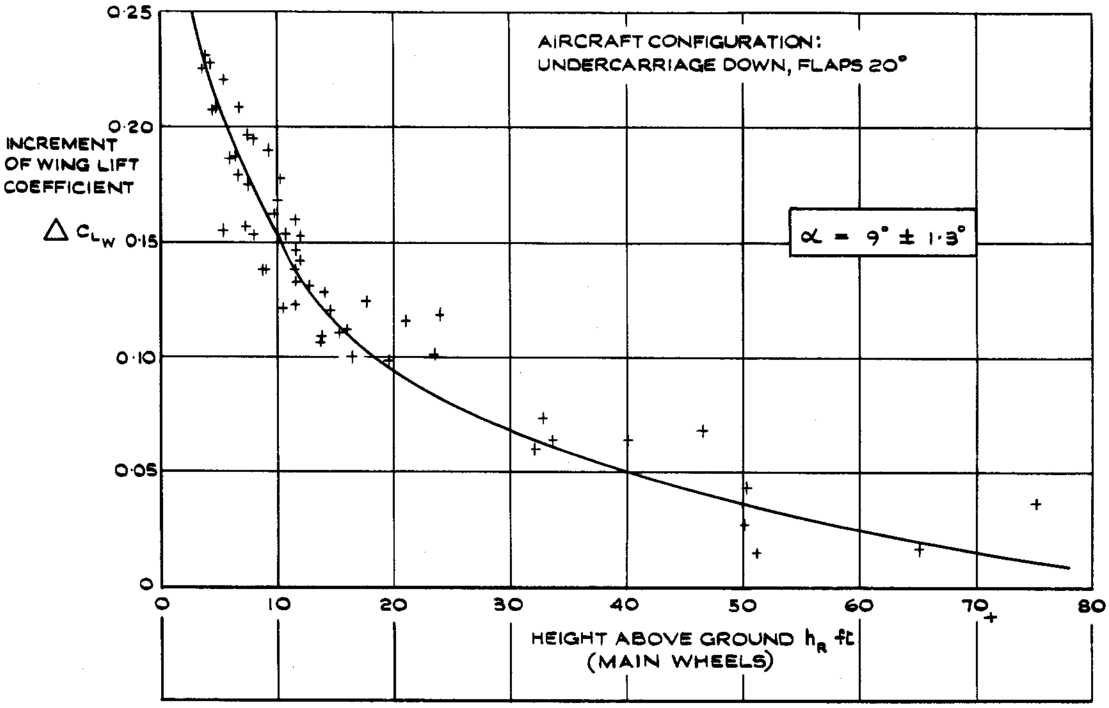


FIG. 16. Ground effect on lift.

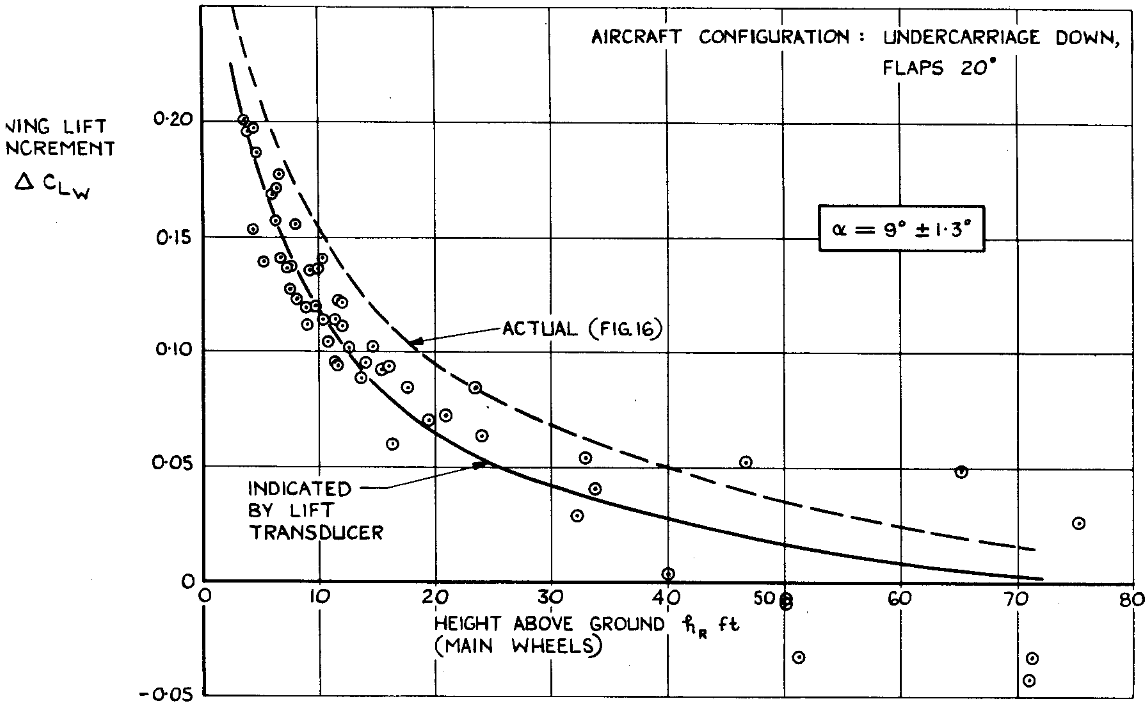


FIG. 17. Ground effect on lift as measured by the lift transducer.

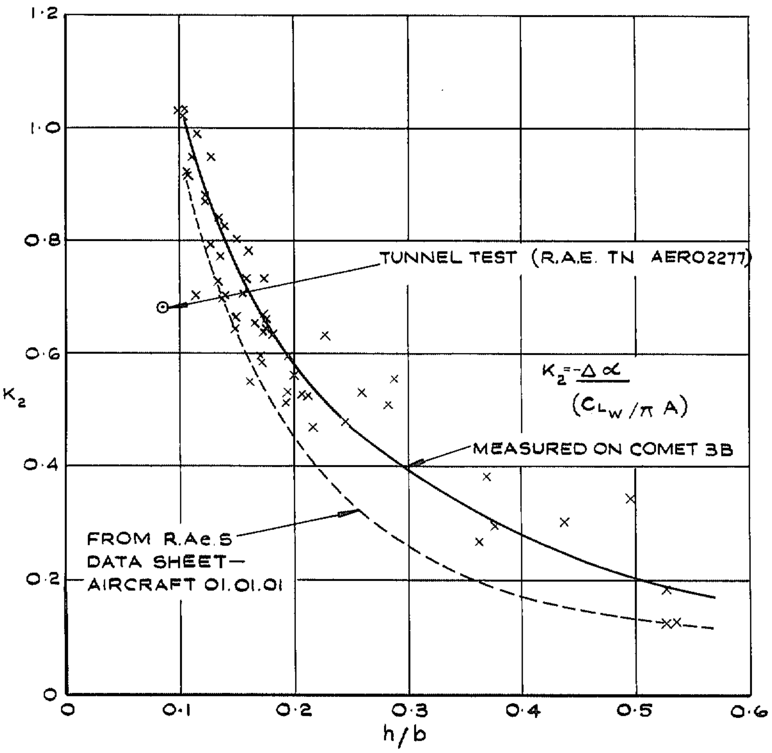


FIG. 18. Comparison of measured and predicted ground effect on lift for Comet 3B.

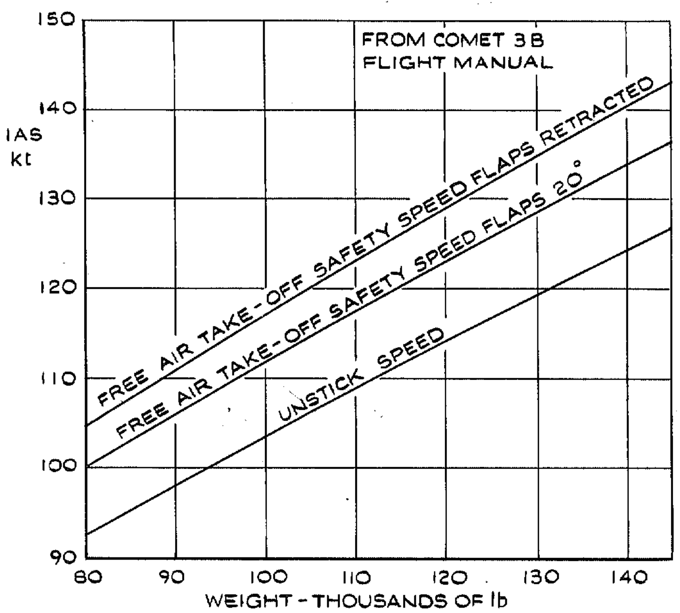


FIG. 19. Take-off safety and unstick speeds for Comet 3B.

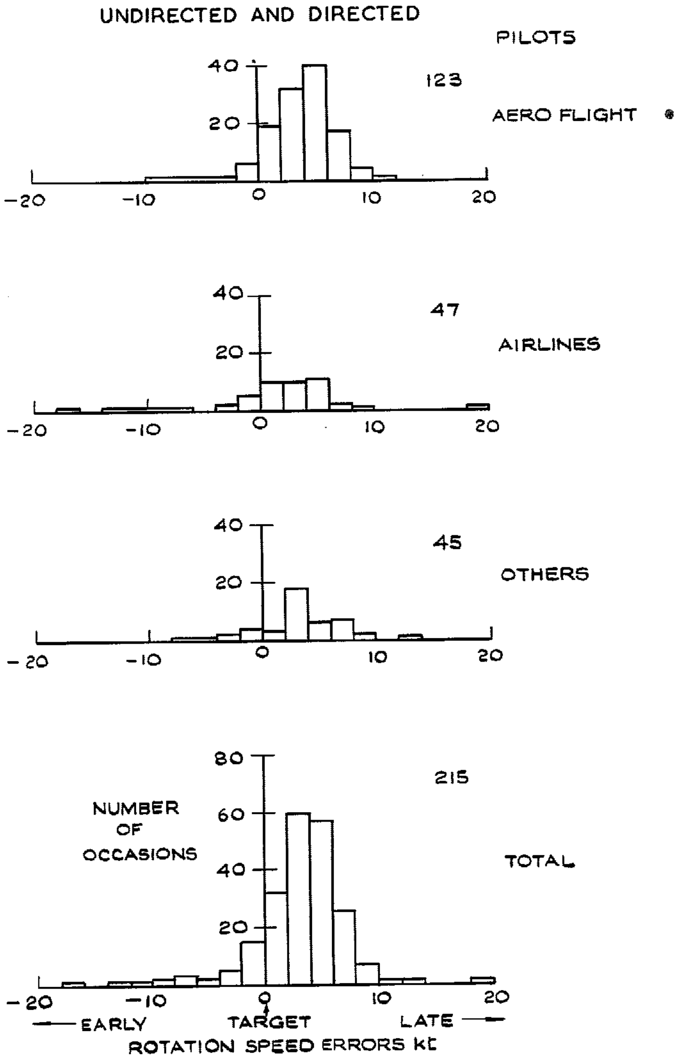


FIG. 20. Histograms of errors in rotation speed.

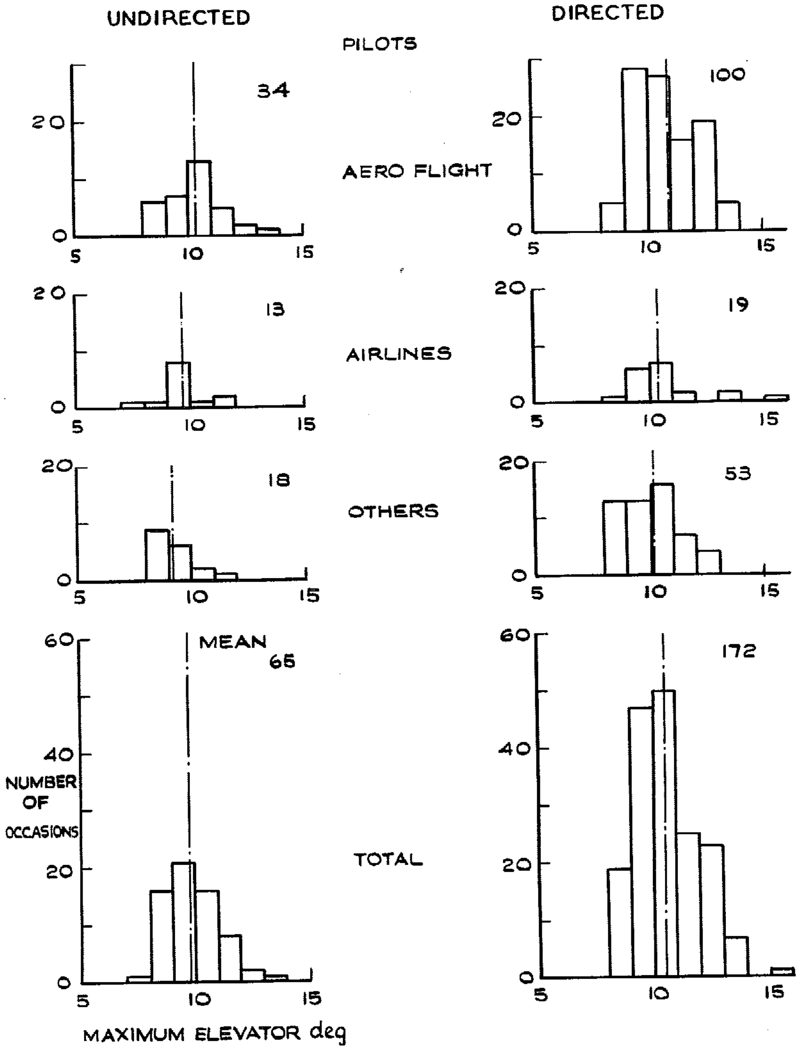


FIG. 21. Histograms of maximum elevator used.

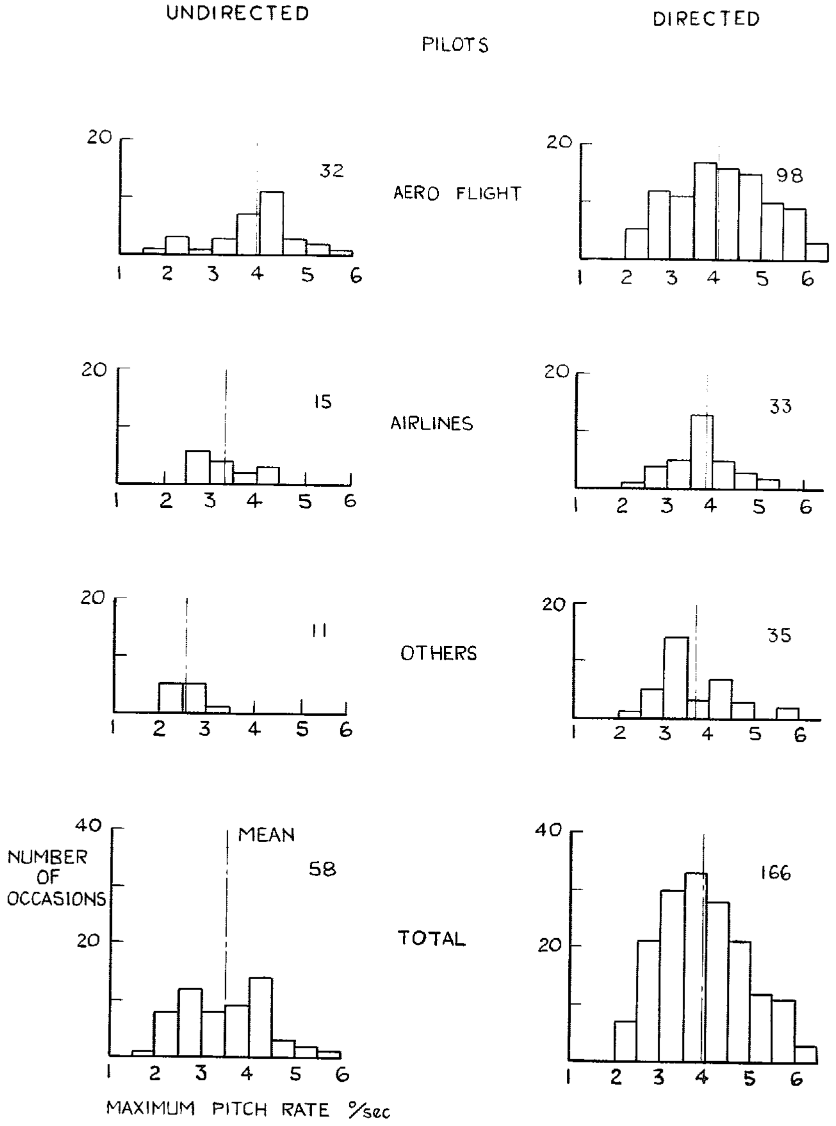


FIG. 22. Histograms of maximum pitch rate during rotation.

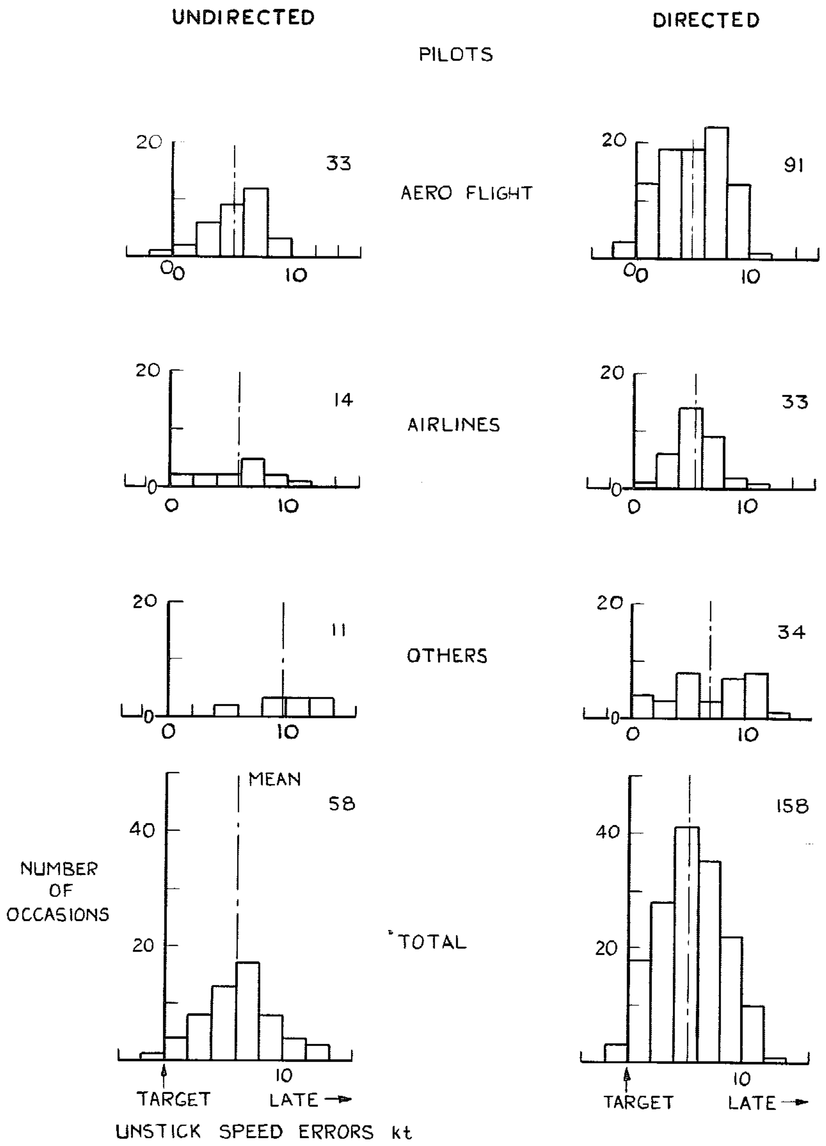


FIG. 23. Histograms of errors in unstick speed.

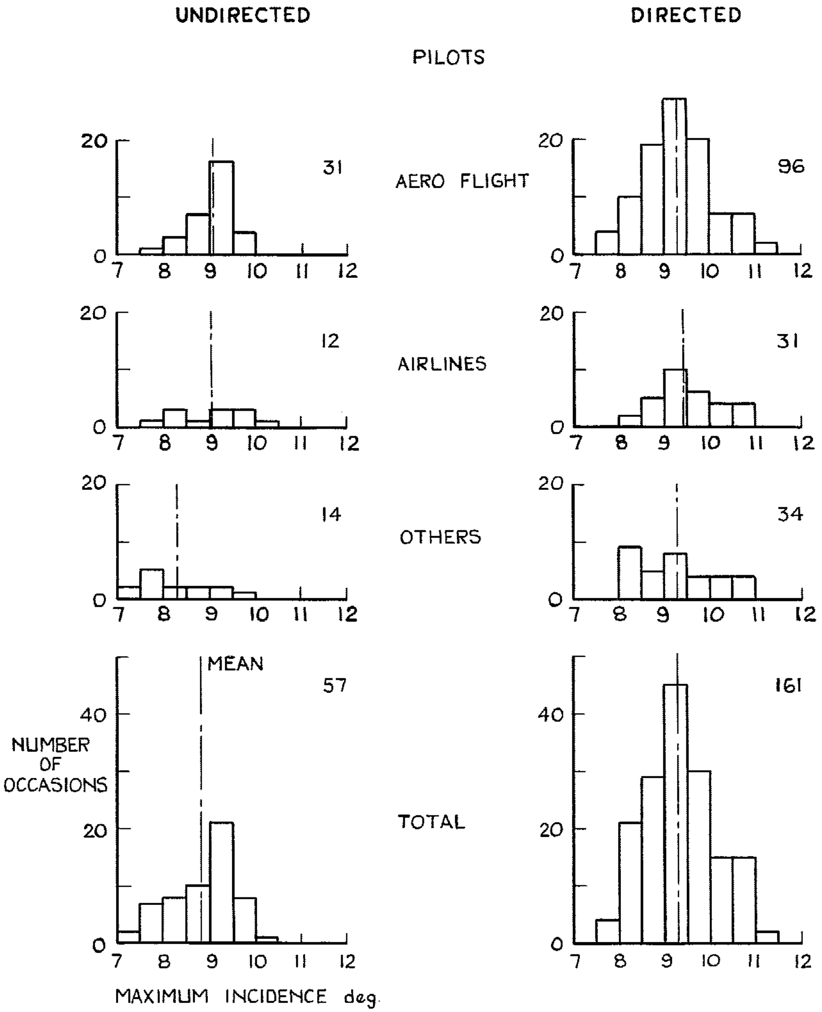


FIG. 24. Histograms of peak incidence in the flare-up.

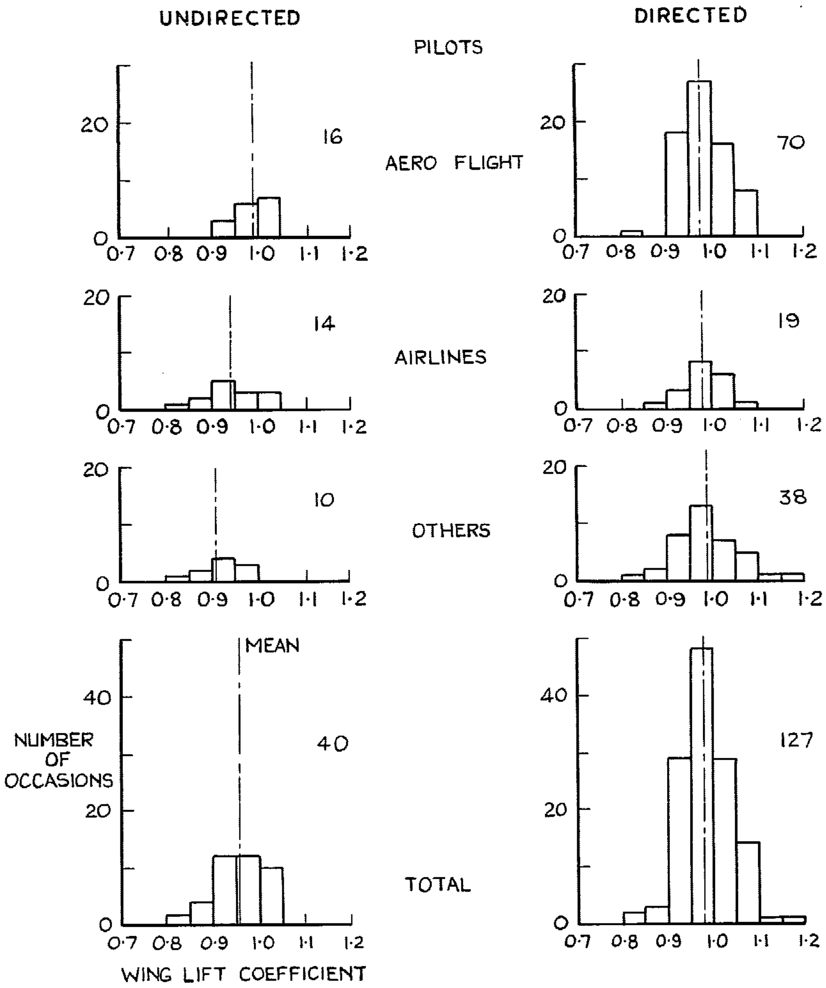


FIG. 25. Histograms of wing lift coefficient at 20 ft A.G.L.

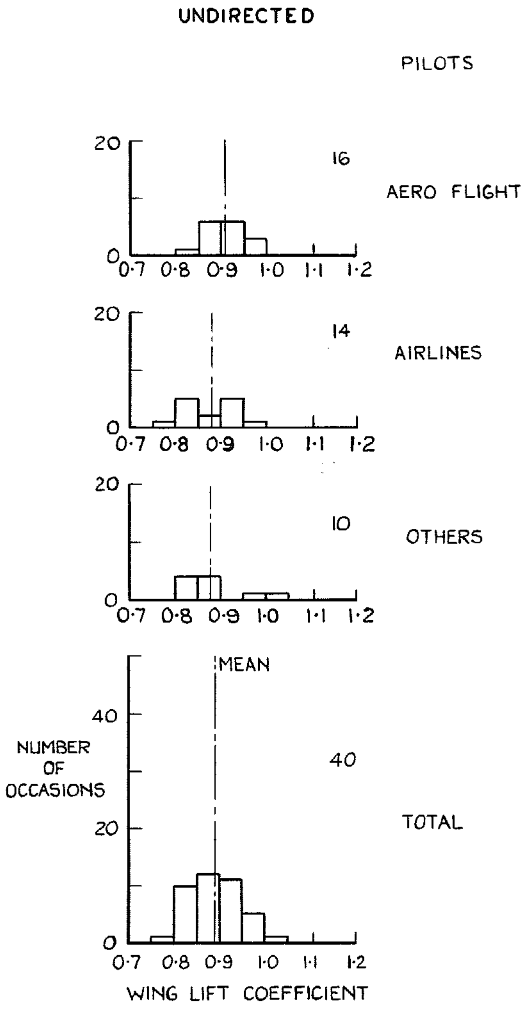


FIG. 26. Histograms of wing lift coefficient at 50 ft A.G.L.

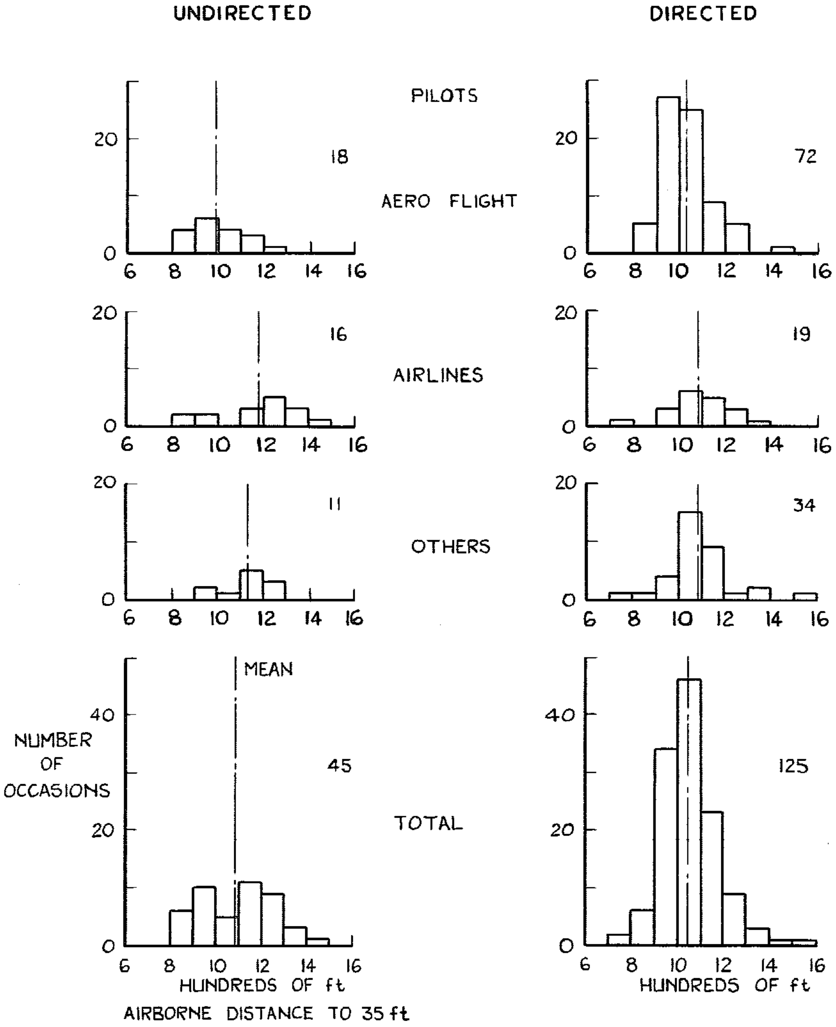


FIG. 27. Histograms of airborne distance to 35 ft screen height.

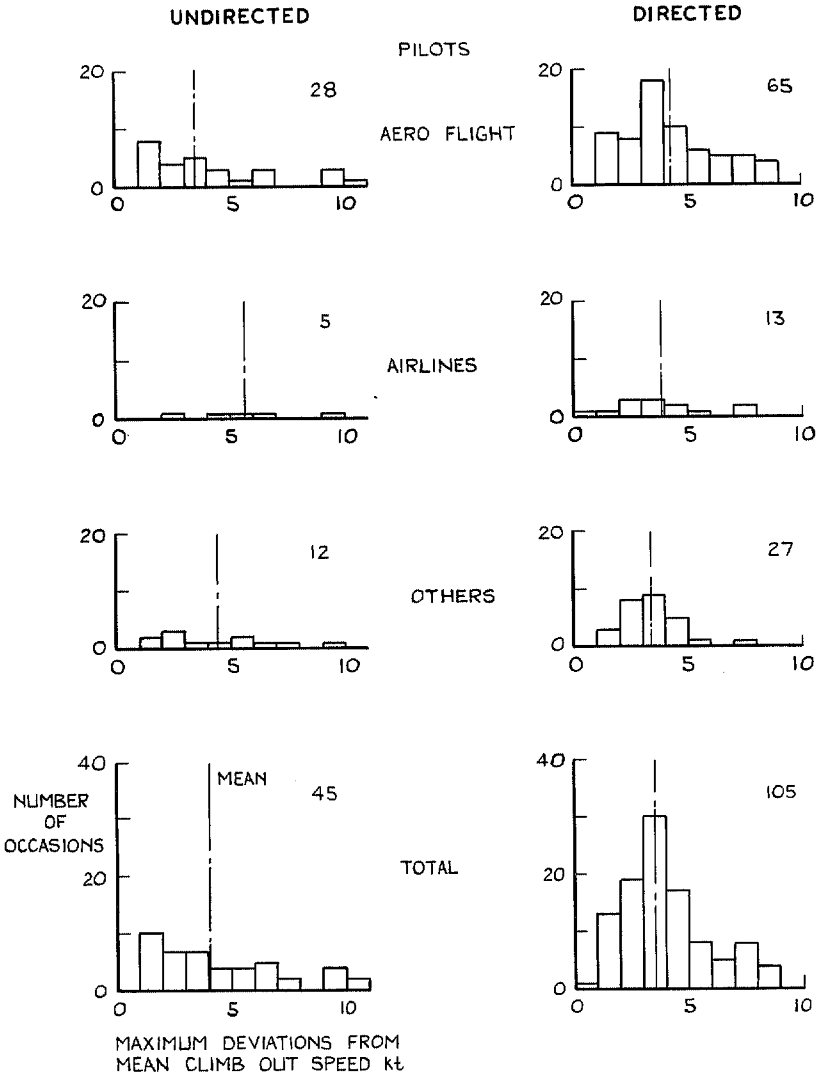


FIG. 28. Histograms of maximum deviations from mean climb-out speed.

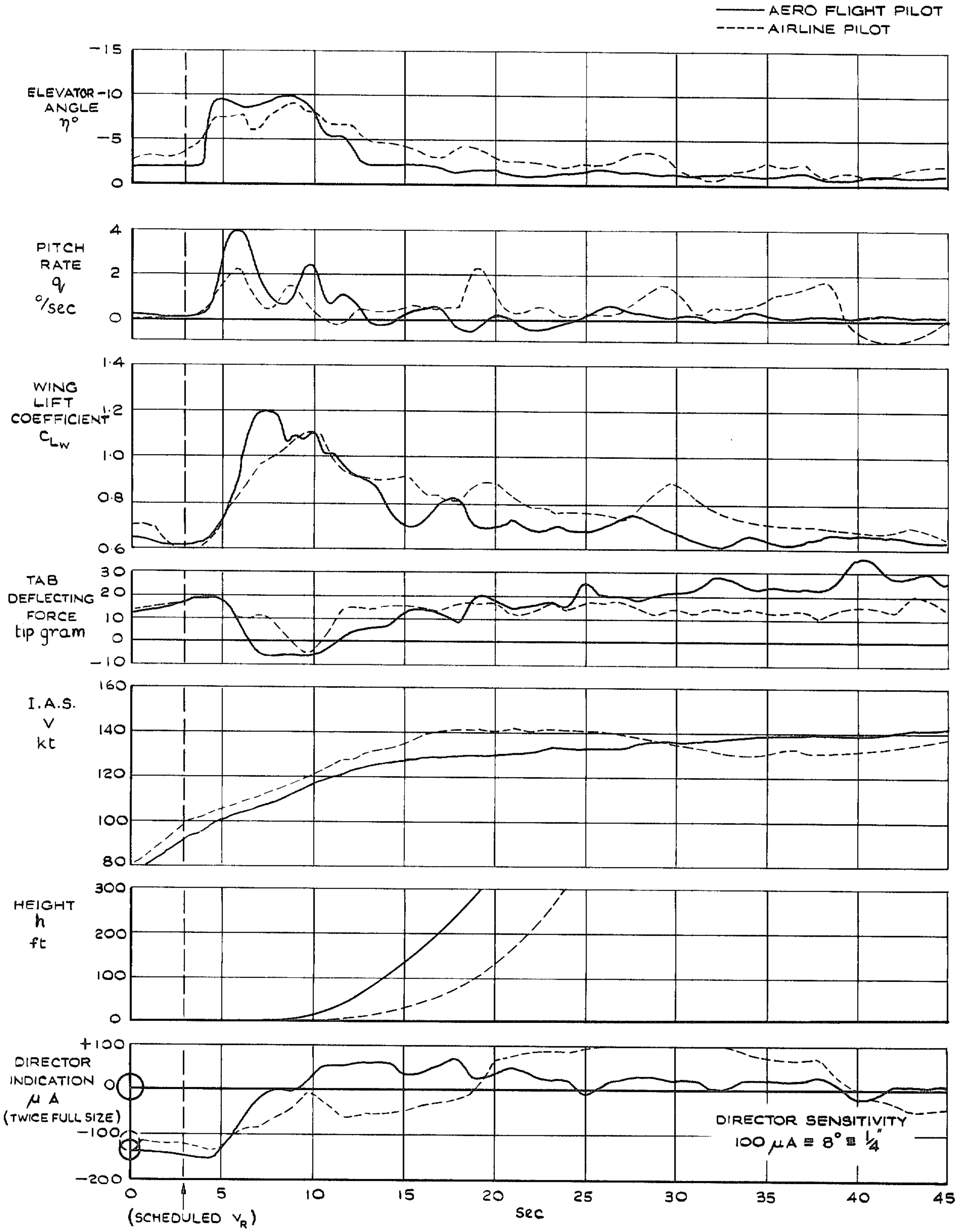


FIG. 29. Typical time histories of undirected take-offs showing differences in technique used by two pilots.

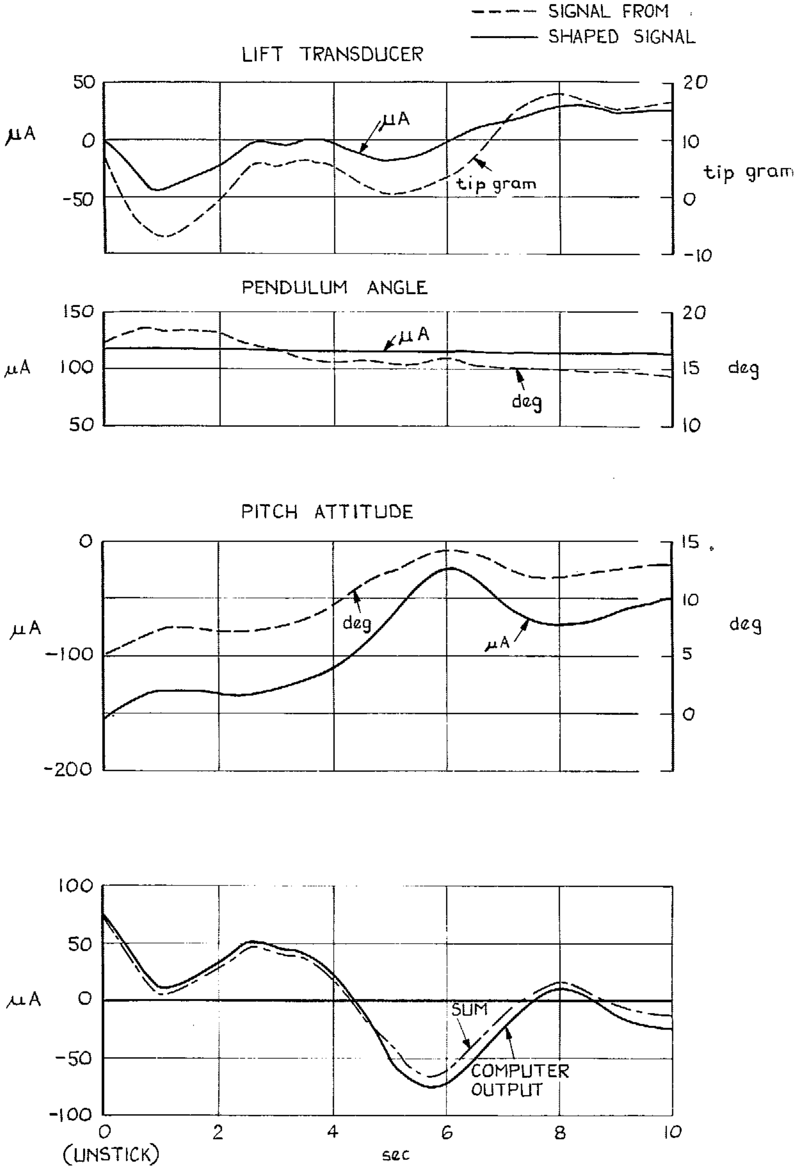


FIG. 30. Behaviour of SCAT component signals during a typical take-off.

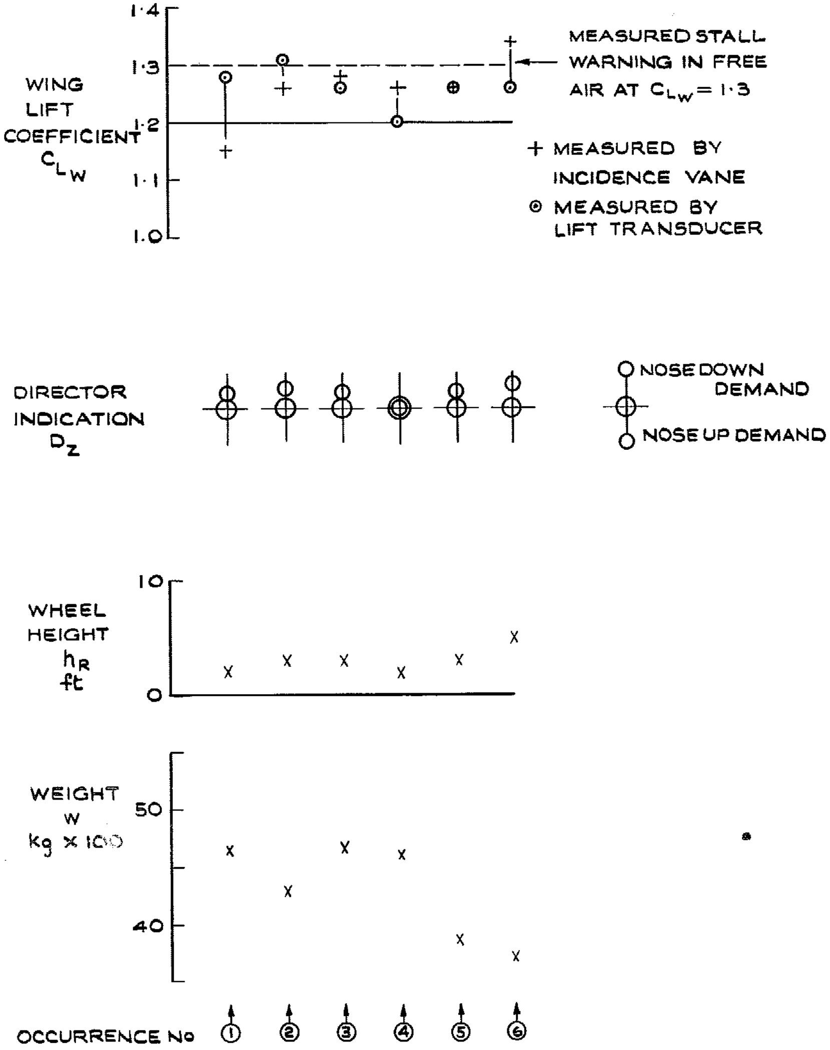


FIG. 31. Stall warning occurrences during take-off.

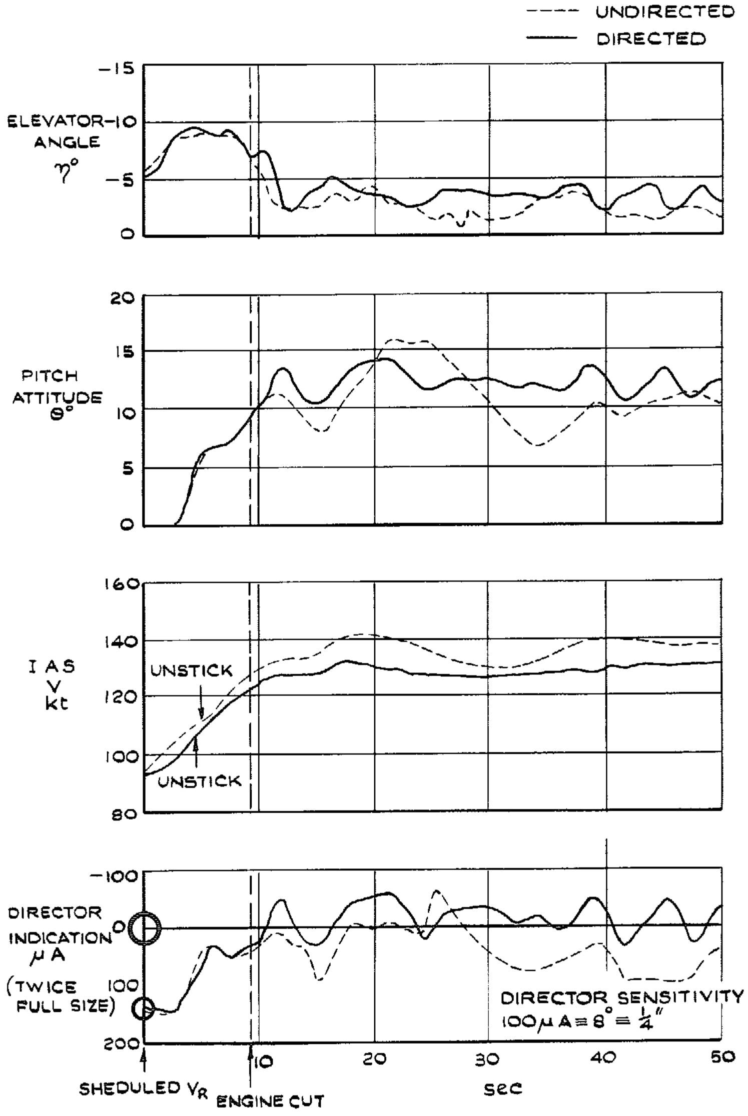


FIG. 32. Comparison of time histories of an undirected and a directed take-off with a simulated engine failure during the flare up.

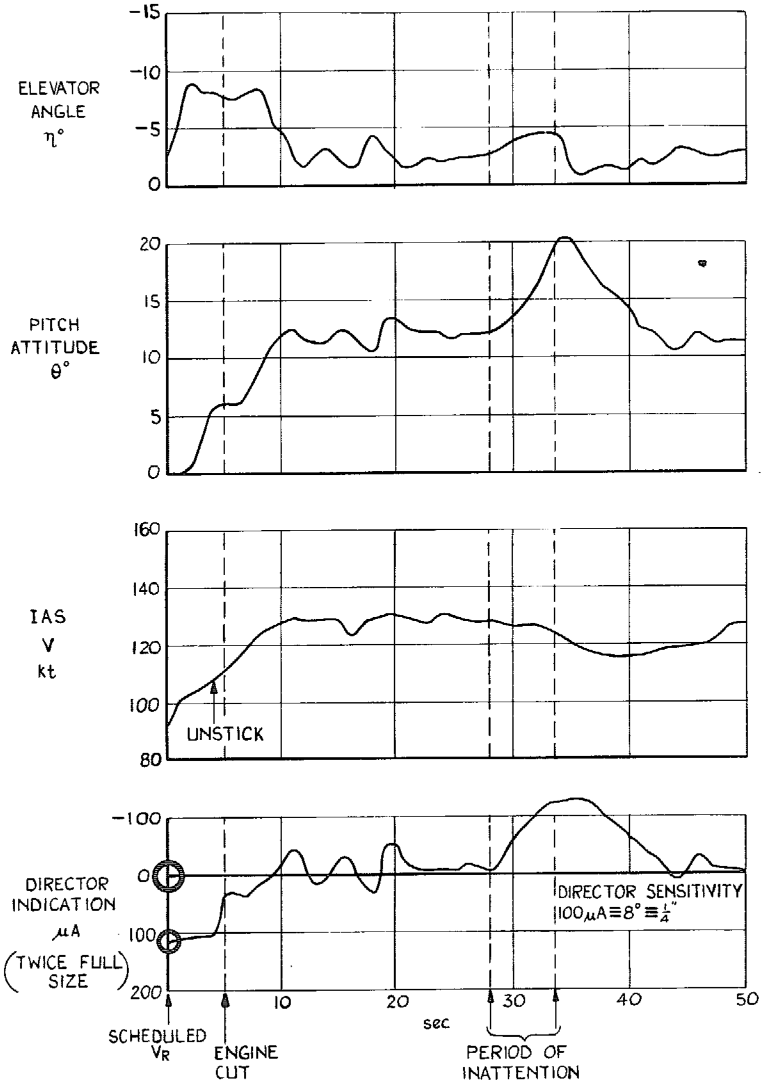


FIG. 33. Time history of a directed take-off showing recovery after a period of pilot inattention.

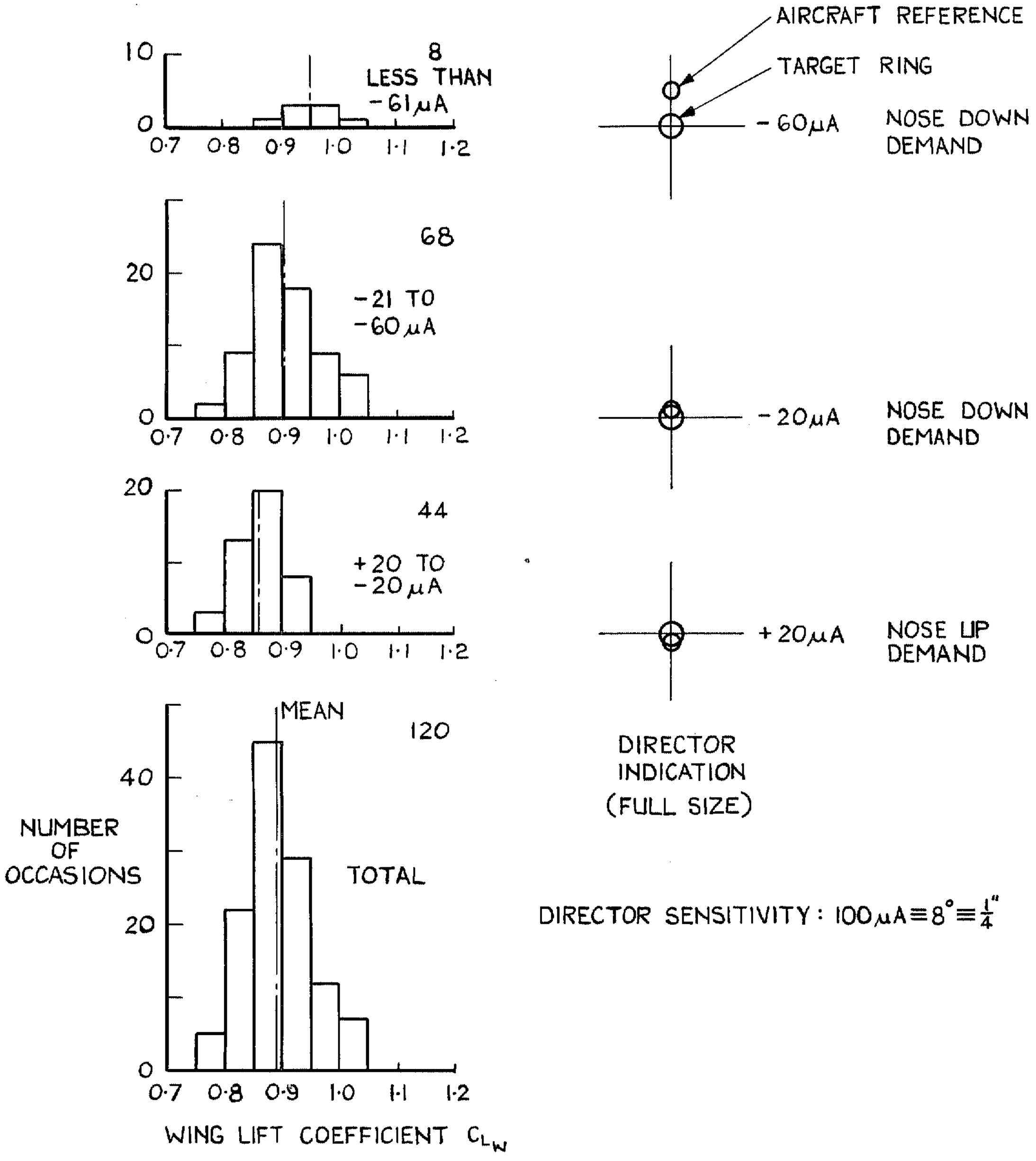


FIG. 34. Histograms showing the effect of director following accuracy on C_{L_W} at 50 ft.

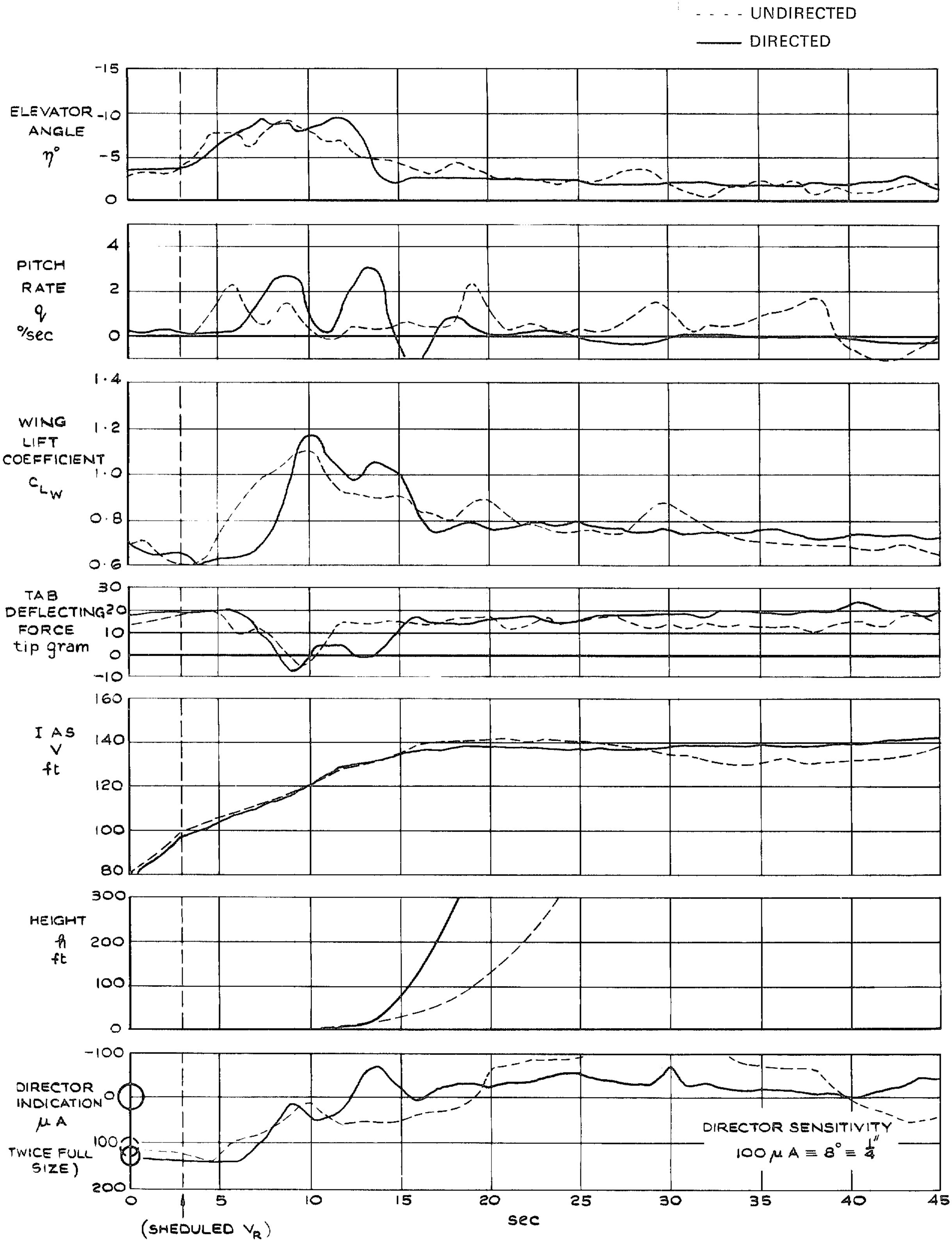


FIG. 35. Comparison of time histories of an undirected and a directed take-off by an airline pilot.

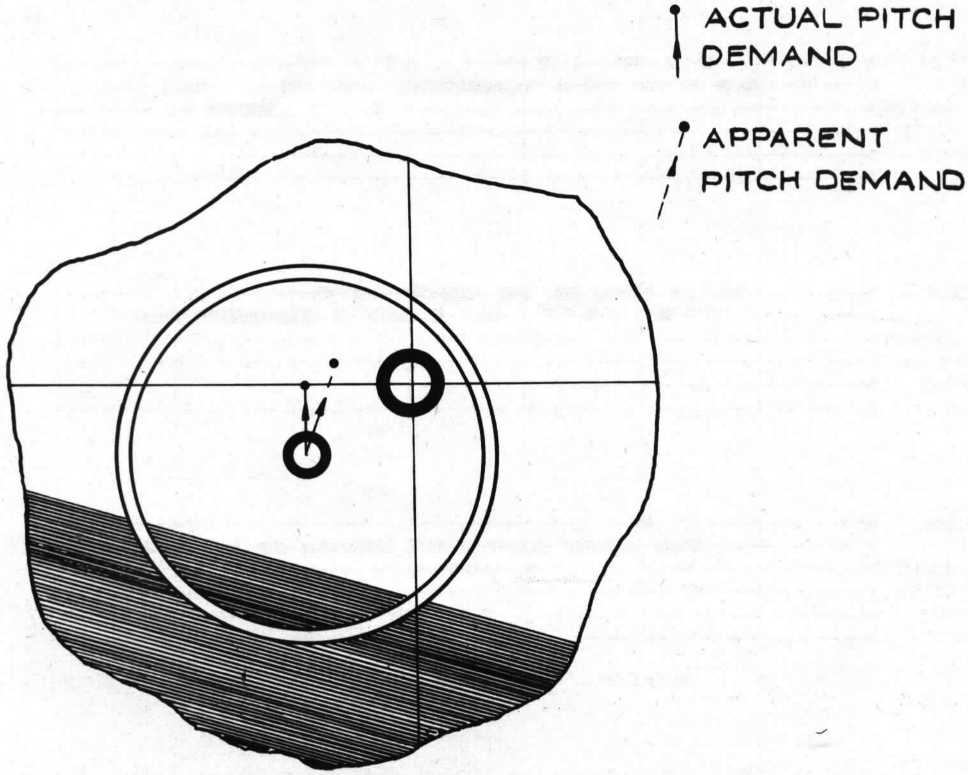


FIG. 36. Misinterpretation of F.4B director demand.

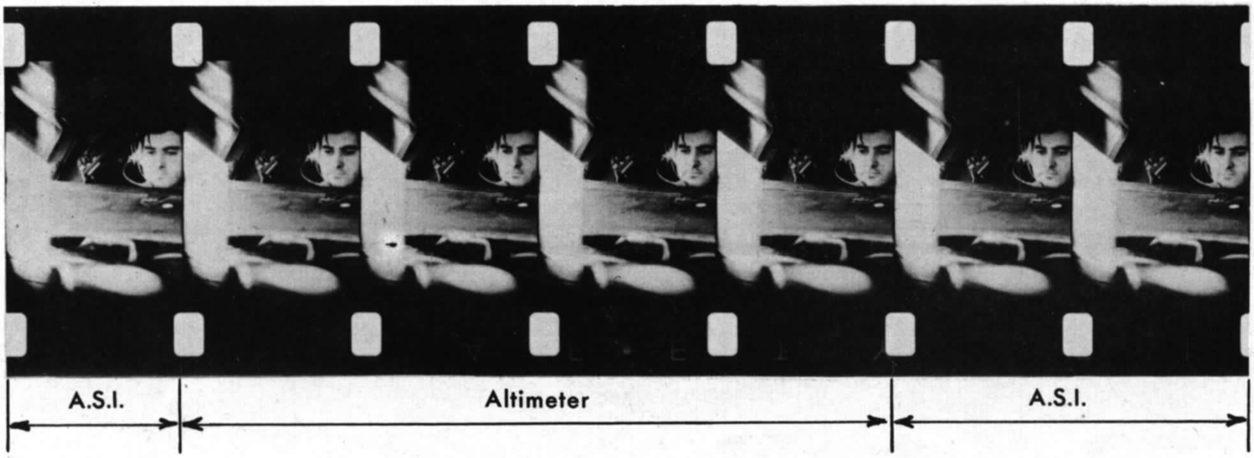


FIG. 37. A typical section of pilot-scan film (4 times full size).

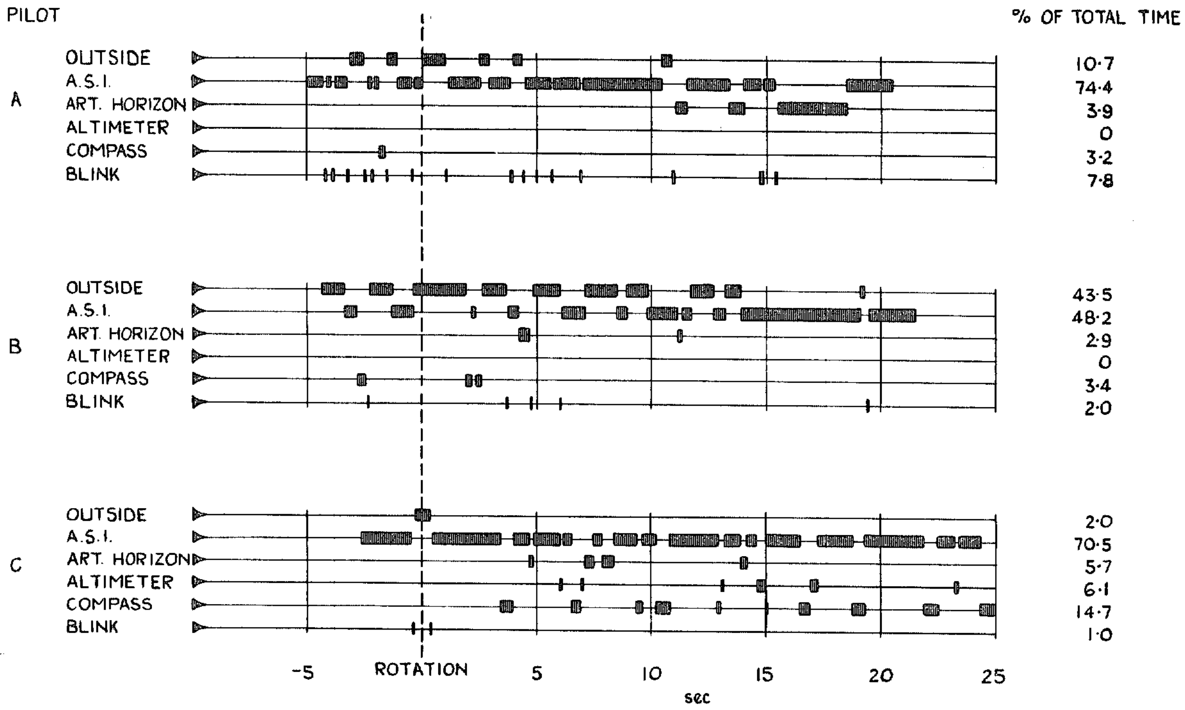


FIG. 38. Time histories of scan of 3 pilots during undirected take-offs.

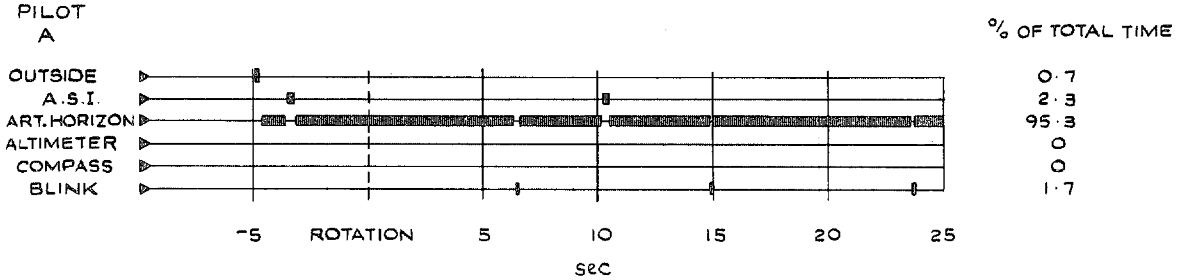


FIG. 39. Time history of a pilot's scan during a directed take-off.

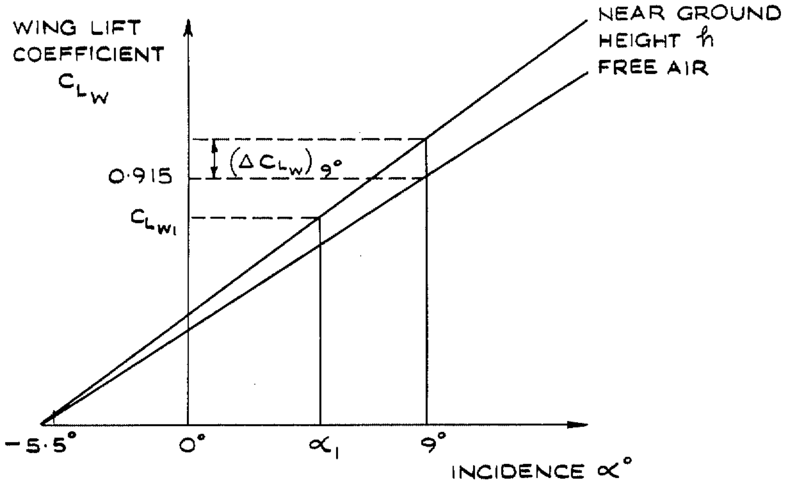


FIG. 40. Method of determining wing lift coefficient in ground effect.

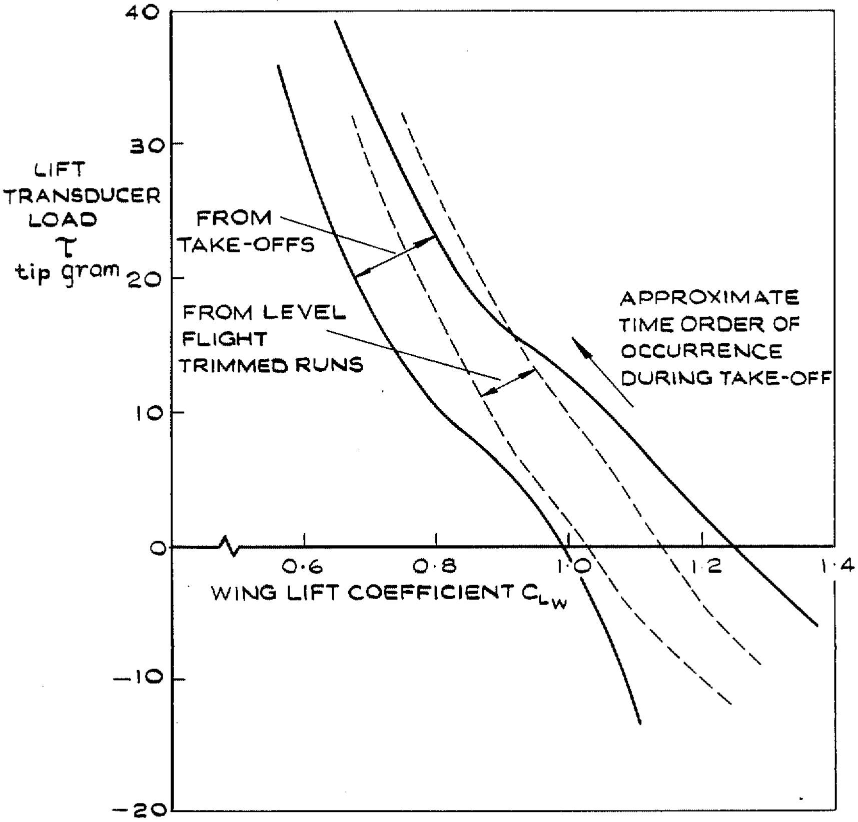


FIG. 41. Scatter in the measurement of lift transducer-load variation with wing lift coefficient.

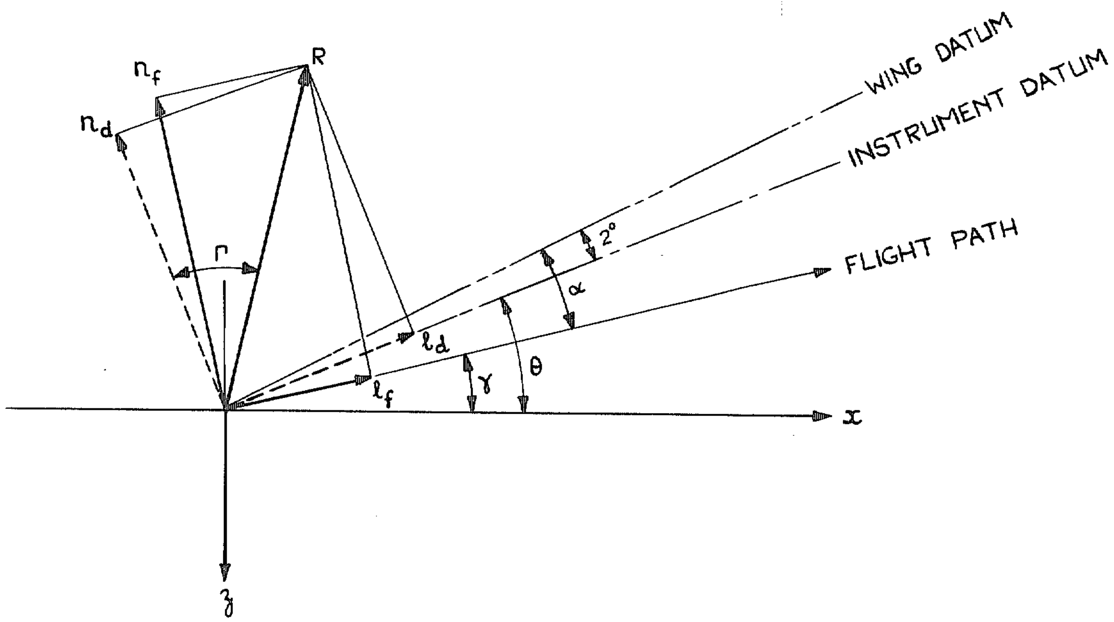


FIG. 42. Acceleration diagram.

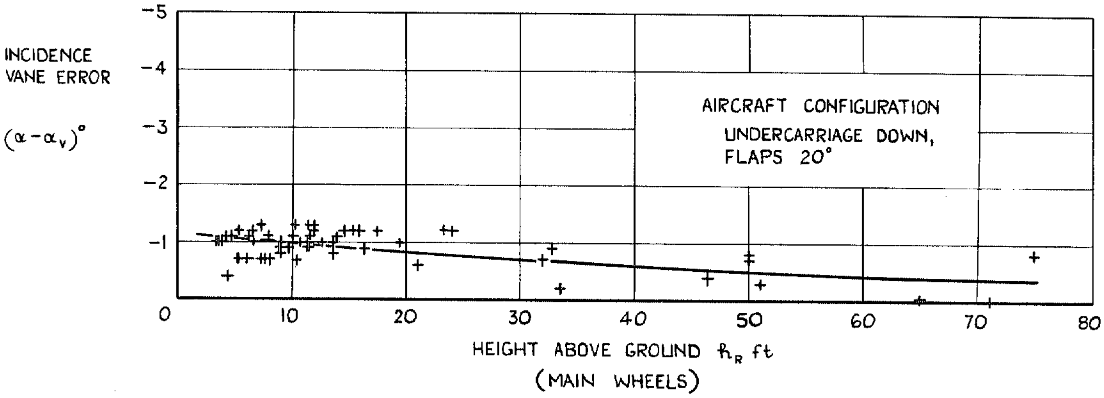


FIG. 43. Position error of incidence vane in ground effect.

Printed in Wales for Her Majesty's Stationery Office by Allens Printers (Wales) Limited.

Dd. 129527. K.5.

R. & M. No. 3508

Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
49 High Holborn, London w.c.1
423 Oxford Street, London w.1
13A Castle Street, Edinburgh 2
109 St. Mary Street, Cardiff CF1 1JW
Brazennose Street, Manchester 2
50 Fairfax Street, Bristol 1
258–259 Broad Street, Birmingham 1
7–11 Linenhall Street, Belfast BT2 8AY
or through any bookseller

R. & M. No. 3508

S.O. Code No. 23–3508