R. & M. No. 3611



MINISTRY OF TECHNOLOGY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

# Flight Measurements of Ground Effect on the Lift and Pitching Moment of a Large Transport Aircraft (Comet 3B) and Comparison with Wind Tunnel and Other Data

by C. O. O'Leary

Aerodynamics Dept., R.A.E., Bedford



LONDON: HER MAJESTY'S STATIONERY OFFICE

1969

PRICE 8s 6d [42½p] NET

# Flight Measurements of Ground Effect on the Lift and Pitching Moment of a Large Transport Aircraft (Comet 3B) and Comparison with Wind Tunnel and Other Data

by C. O. O'Leary

Aerodynamics Dept., R.A.E., Bedford

*Reports and Memoranda No.* 3611*

*June*, 1968

*Summary.*

Ground effect on lift and pitching moment has been measured on a Comet 3B in flight at one particular value of incidence for the whole range of heights where ground effect is significant. The flight results are in reasonably good agreement with wind-tunnel results and semi-empirical prediction data.

LIST OF CONTENTS



*Replaces RAE Technical Report 68 158—A.R.C. 30 616.

---

1. *Introduction.*

The effect of ground proximity on the lift, drag and pitching moment of an aeroplane can significantly influence its take-off and landing characteristics and it is important that methods of predicting ground effect during the design stage should be reliable. Ground effect can be measured in wind tunnels and for simple wing configurations at least, theoretical methods are available to permit predictions. However, in the absence of corresponding full-scale flight results, the validity and accuracy of these methods are impossible to establish and have indeed often been questioned. Flight tests to measure ground effect are difficult to conduct as they demand precise stabilised flying close to the ground and also require very stable weather conditions. Consequently, few flight measurements of ground effect have been made for comparison with theoretical and wind-tunnel results. One fairly comprehensive comparison of flight, tunnel and theoretical results for a small slender-wing aircraft is reported in Ref. 1 and the technique used in the flight measurements is similar to that used in the present tests. Some tests have been made[2] in which the ground effect on lift, drag and pitching moment was extracted from measurements of constant incidence approaches onto the runway, but these introduce dynamic considerations and require perhaps an even higher degree of piloting precision than the more conventional technique of constant height runs along the runway.

During the flight testing of an experimental take-off director[3] on a Comet 3B aircraft (Fig. 1), measurements were made of the effectiveness of a 'lift sensor' device in and out of ground effect, and from these tests results were obtained for ground effect on the lift and pitching moment of the aircraft at various heights above ground. These results are presented and compared with wind-tunnel measurements[4,5,6] and the lift results are also compared with semi-empirically derived prediction data[7].

2. *Test Method.*

The Comet 3B aircraft was equipped with an automatic landing system which considerably aided the accurate conduct of the experiment since 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 radio altimeter height above the ground this height will then 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 kt which was held constant by autothrottle for most of each run. Since all runs were made at this one speed results were obtained for only one value of incidence $\alpha = 9°$. By selecting a different flare height for each run it was possible to measure ground effect on lift and pitching moment over the height range from 3 ft to 20 ft (height of main wheels). To obtain results for greater heights up to 80 ft it was necessary to analyse data during flares, but owing to the non-steady flight conditions obtaining, results for these heights are less reliable. Incidence variation during the runs was unavoidable but was limited to $\pm 1{\cdot}3$ deg; during the later stages of all runs there was a gradual decrease in airspeed of about 5 kt. Weather conditions were not ideal for ground-effect tests with wind speed varying between 6 kt and 11 kt but the results were corrected for wind speed and gradient.

Quantities recorded on the aircraft recorders are listed in Table 1. Kinetheodolites were also used to record aircraft flight path and velocity.

Owing to the difficulty of measuring thrust it was not possible to obtain results for ground effect on drag.

## 3. *Method of Analysis.*

### 3.1. *Ground Effect on Lift.*

The analysis of lift data has previously been reported in Ref. 3 where lift was expressed in terms of wing lift coefficient $C_{Lw}$. This required the correction of the measured total $C_L$ for the tailplane contribution and as this has to be estimated, especially in ground effect, the result may have been less accurate than the basic flight data. It should be noted that the increment in $C_L$ due to ground effect, $\Delta C_L$ is obtained as the difference between measured $C_L$'s in tests in and out of ground effect and therefore derived from a difference between relatively large quantities. Small errors in the derivation of lift coefficient can therefore have serious consequences on the final result for the ground-effect increment. In order to avoid this difficulty and to be strictly comparable with-tunnel data the results are presented here in terms of trimmed lift coefficient, i.e. the total $C_L$ measured directly in the tests.

The relation between $C_{L(\mathrm{trim})}$ and $\alpha$ out of ground effect was determined from tests at altitude when several level flight, trimmed runs were recorded covering a speed range from 100 kt to 160 kt. For these tests, where the aircraft could be very accurately stabilised in smooth air, the determination of incidence and lift is straight forward. But for the ground-effect runs it was necessary to examine carefully the aircraft kinematics.

3.1.1. *Derivation of incidence and lift.* Incidence was derived from the pendulum angle, $\Gamma$, the normal accelerometer reading, $n_d$ and the horizontal and vertical components of acceleration of the aircraft obtained from kinetheodolite records. An incidence vane mounted on the aircraft nose probe could not be used since it was not certain that its position error would be unaffected by ground proximity.

From Fig. 2a the longitudinal acceleration along the instrument datum is given by

$$l_d = n_d \tan \Gamma^\circ = \frac{\ddot{x}}{g} \cos(\alpha^\circ - 2 + \gamma^\circ) + \left(\frac{\ddot{z}}{g} + 1\right) \sin(\alpha^\circ - 2 + \gamma^\circ) \tag{1}$$

where $\ddot{z}$ is positive in the negative direction of $z$. Since the angle $\alpha^\circ - 2 + \gamma^\circ$ is small,

$$\cos(\alpha^\circ - 2 + \gamma^\circ) \simeq 1 \tag{2}$$

and

$$\sin(\alpha^\circ - 2 + \gamma^\circ) \simeq \frac{\alpha^\circ - 2 + \gamma^\circ}{57 \cdot 3}. \tag{3}$$

Hence, solving (1) for $\alpha$, gives

$$\alpha = \frac{\left(n_d \tan \Gamma^\circ - \frac{\ddot{x}}{g}\right) 57 \cdot 3}{\frac{\ddot{z}}{g} + 1} + 2 - \gamma^\circ. \tag{4}$$

Since there were no rapid changes in speed it was possible to extract $\ddot{x}$ and $\ddot{z}$ from kinetheodolite records and the flight path angle, $\gamma$ was also calculated from these using the relation

$$\gamma = \frac{\dot{z}}{\dot{x}}. \tag{5}$$

Incidence was calculated from (4) and a time history for one run is shown in Fig. 3 together with other relevant parameters. A comparison with incidence indicated by the vane showed that the free air position error of the vane was reduced from $+1{\cdot}5$ to $+1$ deg for heights up to 20 ft.

For small flight path angles the trimmed lift coefficient is expressed as

$$C_{L(\mathrm{trim})} = \frac{n_f W - T \sin \alpha^{\circ}}{\frac{1}{2} \rho_0 V^2 S_w} \tag{6}$$

where $W$ and $T$ are the weight and thrust respectively and the thrust line is parallel to the wing datum.

From Fig. 2b,

$$n_f = R \cos[\Gamma - (\alpha - 2)] = \frac{n_d}{\cos \Gamma} \cos[\Gamma - (\alpha - 2)]\,. \tag{7}$$

Hence by substitution in (6)

$$C_{L(\mathrm{trim})} = \frac{0{\cdot}316 \left\{ \dfrac{W n_d \cos[\Gamma - (\alpha - 2)]}{\cos \Gamma} - T \sin \alpha \right\}}{V^2}\,. \tag{8}$$

3.1.2. *Ground effect increment.* The records from four runs were analysed every two seconds and $C_{L(\mathrm{trim})}$ calculated for each data point. Since the incidence was not held exactly at 9° during the runs, each value of $C_{L(\mathrm{trim})}$ was corrected to $\alpha = 9°$ using an estimated lift slope appropriate to the particular height above ground. By deducting from the corrected $C_{L(\mathrm{trim})}$ the corresponding free air $C_{L(\mathrm{trim})}$ appropriate to 9°, the lift increment due to ground effect is then given by

$$\Delta C_{L(\mathrm{trim})} = [C_{L(\mathrm{trim})}]_{\text{near ground}} - [C_{L(\mathrm{trim})}]_{\text{free air}} \tag{9}$$

and the results are shown in Fig. 4.

In order to make a comparison with the semi-empirical data of Ref. 7 the results were also expressed in terms of a parameter $K_2 = -\dfrac{\Delta\alpha}{(C_L/\pi A)}$, where $\Delta\alpha$ is the increment in incidence, at a given lift coefficient due to ground effect, and is given by

$$\Delta\alpha = \alpha_{\text{near ground}} - \alpha_{\text{free air}}\,, \tag{10}$$

for a given value of $C_L$.

$C_L$ is the measured lift coefficient in ground effect and $A$ is the aspect ratio. $K_2$ was calculated for each flight data point and plotted against height of the mean quarter-chord point in Fig. 5 where a comparison is made with the theoretical $K_2$ characteristic.

3.2. *Ground Effect on Pitching Moment.*

The ground effect on pitching moment was obtained by simply measuring the difference in elevator angle to trim at a given $C_{L(\mathrm{trim})}$ in and out of ground effect and expressing this difference in terms of a change in pitching moment:

$$\Delta C_m = \frac{\partial C_m}{\partial \eta} \Delta\eta$$

where $\dfrac{\partial C_m}{\partial \eta} = 0{\cdot}0219$ is the elevator power which was measured in flight at altitude at two cg positions.

The assumption is made that ground effect on elevator power is negligible. The results are shown in Fig. 6.

### 4. *Comparison of Flight Results with Prediction Data and Tunnel Results.*

#### 4.1. *Lift.*

Fig. 5 shows that the flight measurements of the parameter $K_2$ agree quite closely with the predicted $K_2$ characteristic given in Ref. 7. At the same time, it must be noted that $K_2$ is a parameter which is concerned with wing lift increments only and since the flight measurements include the tail lift contribution, the results are not strictly comparable. However, since an accuracy of only $\pm 30$ per cent of the indicated increment is claimed for the prediction data the comparison is encouraging.

Unfortunately the various tunnel results available for comparison with the flight results were obtained on models of different marks of Comet aircraft which are shown in Fig. 7 together with relevant particulars. The Comet 3 and 4 models which were used in the tests of Refs. 4 and 5 respectively, differed from each other in respect of flap deflection, split flap area and tail setting angle. The Comet 3B aircraft used for the flight tests had a smaller wing span and area than the aircraft represented by the models, no wing tanks, smaller split flap area, undercarriage down and yet another tail setting angle.

The tunnel results shown in Fig. 4 are seen to be within the scatter of the flight results but the result for the Comet 3 model is on the edge of the envelope. It is possible that differences between the Comet 3 model and the 3B aircraft might account for some discrepancy in the results although corrections were made to the tunnel result for the differences in flap deflection angle and tail plane setting angle. The larger split flap area and absense of undercarriage on the Comet 3 model were not corrected for. No corrections were made in the case of the Comet 4 model.

A manufacturers flight test result[5], is also represented in Fig. 4 and is seen to be in good agreement with the R.A.E. flight results.

#### 4.2. *Pitching Moment.*

Two tunnel results are compared with the flight results in Fig. 6. The Comet 3 model result was again corrected for flap deflection and tail setting differences. Agreement with flight results is reasonable although both tunnel measurements are on the edge of the flight results scatter envelope. Possible causes for this discrepancy could be that there is some ground effect on elevator power or that the differences between the models and the aircraft have more effect on the pitching-moment increment than on the lift increment because of small differences in centre of pressure position. Flight measurements show that the undercarriage produces only a small nose down trim change and would be unlikely to cause the discrepancy.

### 5. *Conclusions.*

The increments in lift and pitching moment due to ground effect measured in the flight tests have been compared with tunnel measurements, which are within the scatter limits of the flight data. This agreement must be considered very satisfactory, especially since the increments are relatively small and the wind-tunnel models tested differed in detail from the aircraft used in the flight tests. A semi-empirical method for predicting ground effect on lift also gives results which are within the scatter of the flight measurements.

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $A$ | Aspect ratio | |
| $b$ | Wing span | ft |
| $C_{L(\mathrm{trim})}$ | Trimmed lift coefficient | |
| $g$ | Acceleration due to gravity | 32·2 ft/sec$^2$ |
| $h$ | Height above ground of mean quarter chord point | ft |
| $h_R$ | Height above ground of main wheels | ft |
| $K_2$ | Ground effect on lift parameter | |
| $l_d$ | Longitudinal accelerometer indication | g |
| $n_d$ | Normal accelerometer indication | g |
| $n_f$ | Acceleration normal to flight path | g |
| $R$ | Resultant acceleration | g |
| $S_w$ | Wing area | ft$^2$ |
| $T$ | Net thrust | lb |
| $V$ | Equivalent air speed | kt |
| $W$ | Aircraft all up weight | lb |
| $x$ | Horizontal earth axis | |
| $z$ | Vertical earth axis | |
| $\alpha$ | Wing incidence | deg |
| $\Gamma$ | Pendulum angle | deg |
| $\Delta C_{L(\mathrm{trim})}$ | Increment in trimmed lift coefficient due to ground effect | |
| $\Delta C_m$ | Increment in pitching-moment coefficient due to ground effect | |
| $\Delta\alpha$ | Increment in incidence, at a given $C_L$, due to ground effect | deg |
| $\Delta\eta$ | Increment in elevator angle to trim due to ground effect | deg |
| $\partial C_m/\partial\eta$ | Pitching moment due to elevator deflection | deg$^{-1}$ |
| $\rho_0$ | Air density at 15°C, 1013·2 mb | slug/ft$^3$ |

## REFERENCES


| No. | Author(s) | Title, etc. |
|---|---|---|
| 1 | L. S. Rolls and D. G. Koenig | Flight measured ground effect on a low aspect ratio ogee wing including a comparison with wind tunnel results. NASA TN D–3431, (A.R.C. 28469) June 1966. |
| 2 | W. Schweikhard | A method of in-flight measurement of ground effect on fixed wing aircraft. *Journal of Aircraft*, Vol. 4, No. 2, March-April, 1967. |
| 3 | C. O. O'Leary, J. N. Cannell and R. L. Maltby | Take-off tests on a transport aircraft including the use of a 'SCAT' take-off director. A.R.C., R. & M. 3508 (1966). |
| 4 | D. A. Kirby and A. P. Cox | Low speed wind tunnel tests on a 1/18 scale model of the de Havilland Comet 3. R.A.E. Technical Note Aero 2277 (1953). |
| 5 | — | Correlation of wind tunnel and flight results for the Comet 4. (Free air and in ground effect.) de Havilland Aircraft Co. Ltd., Wind Tunnel Report No. 47, April 1959. |
| 6 | — | The effect of ground proximity on the DH 106 Comet—comparison of wind tunnel and flight tests on Comet 1, 3 and 4. de Havilland Aircraft Co. Ltd., Wind Tunnel Note No. 32, April 1957. |
| 7 | — | Ground effect on lift and drag. R.Ae.S. Data Sheet, Aircraft 01.01.01, March 1958. |


TABLE 1

*Recorded Quantities.*

| Quantity | Sensor |
|---|---|
| Airspeed | Aircraft pitot static system and H 111 capsule |
| Height | Mk. 7 radio altimeter |
| Elevator angle | de Havilland |
| Normal acceleration | Aero Flight 0–2g |
| Incidence | Aero Flight vane |
| Pendulum angle | J 33 pendulum level |
| Kinetheodolite synchronisation tones | VHF receiver |
| Time base | 1 sec clockwork timer |

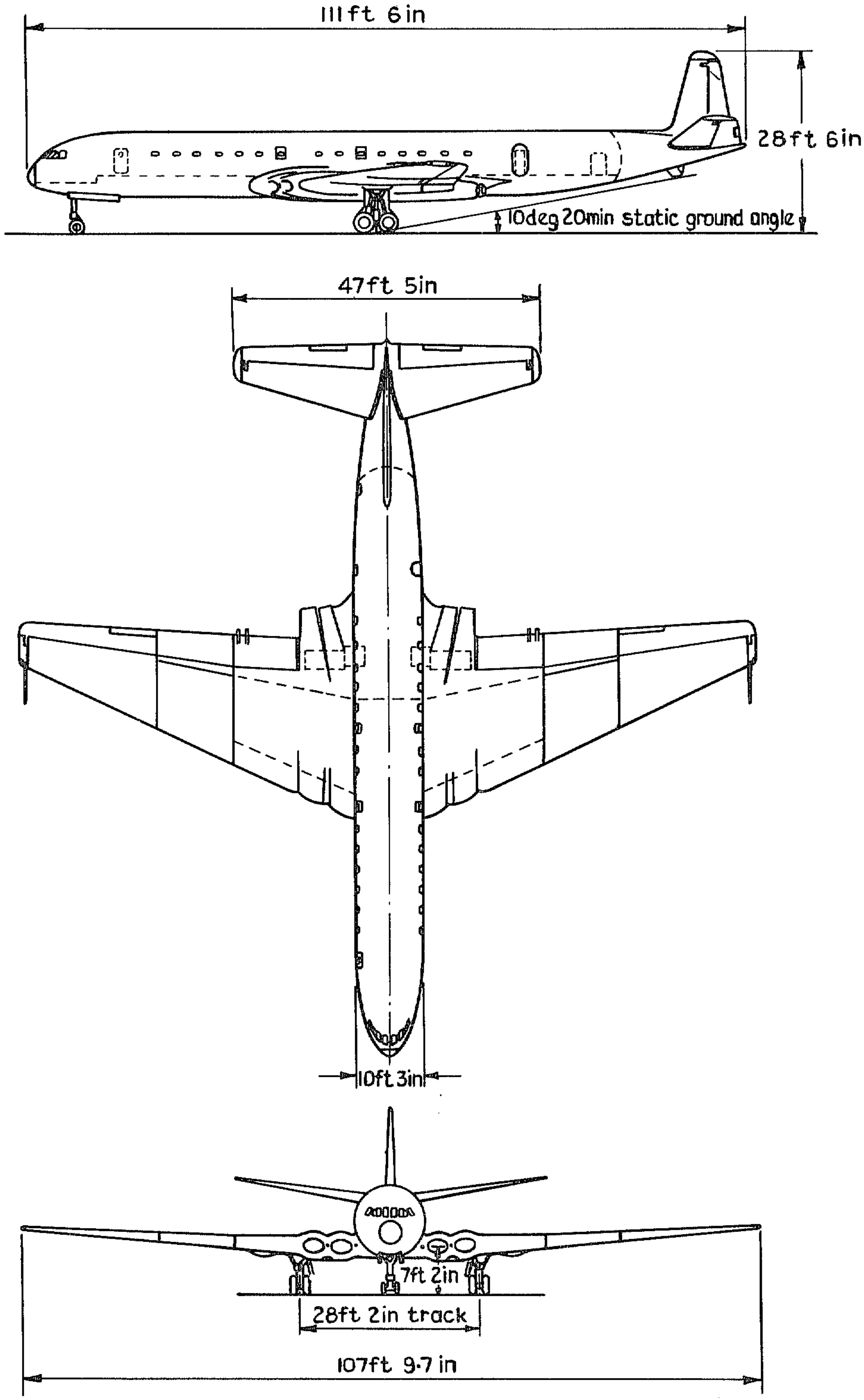
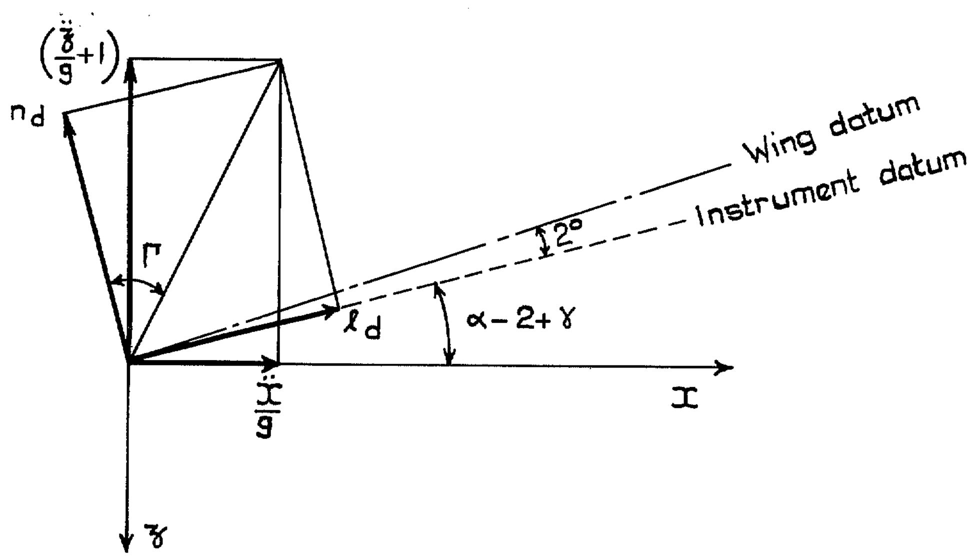
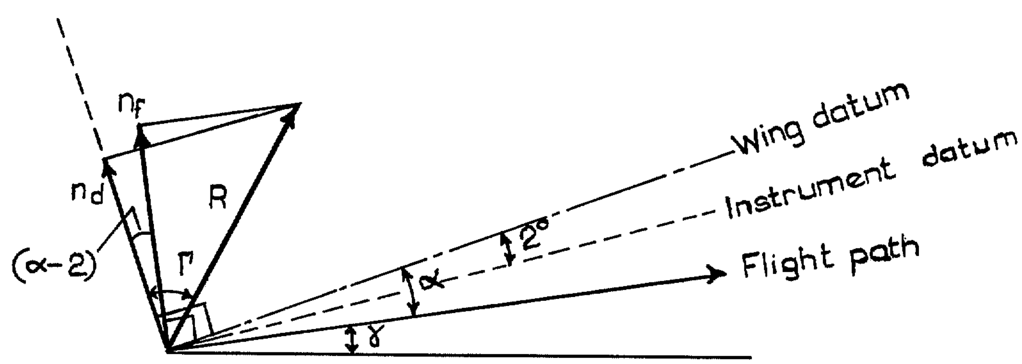



FIG. 1. Comet 3B.




**(a) Relation between earth axes acceleration and aircraft accelerometer readings**




**(b) Derivation of acceleration normal to flight path**

FIG. 2a & b. Acceleration diagrams.

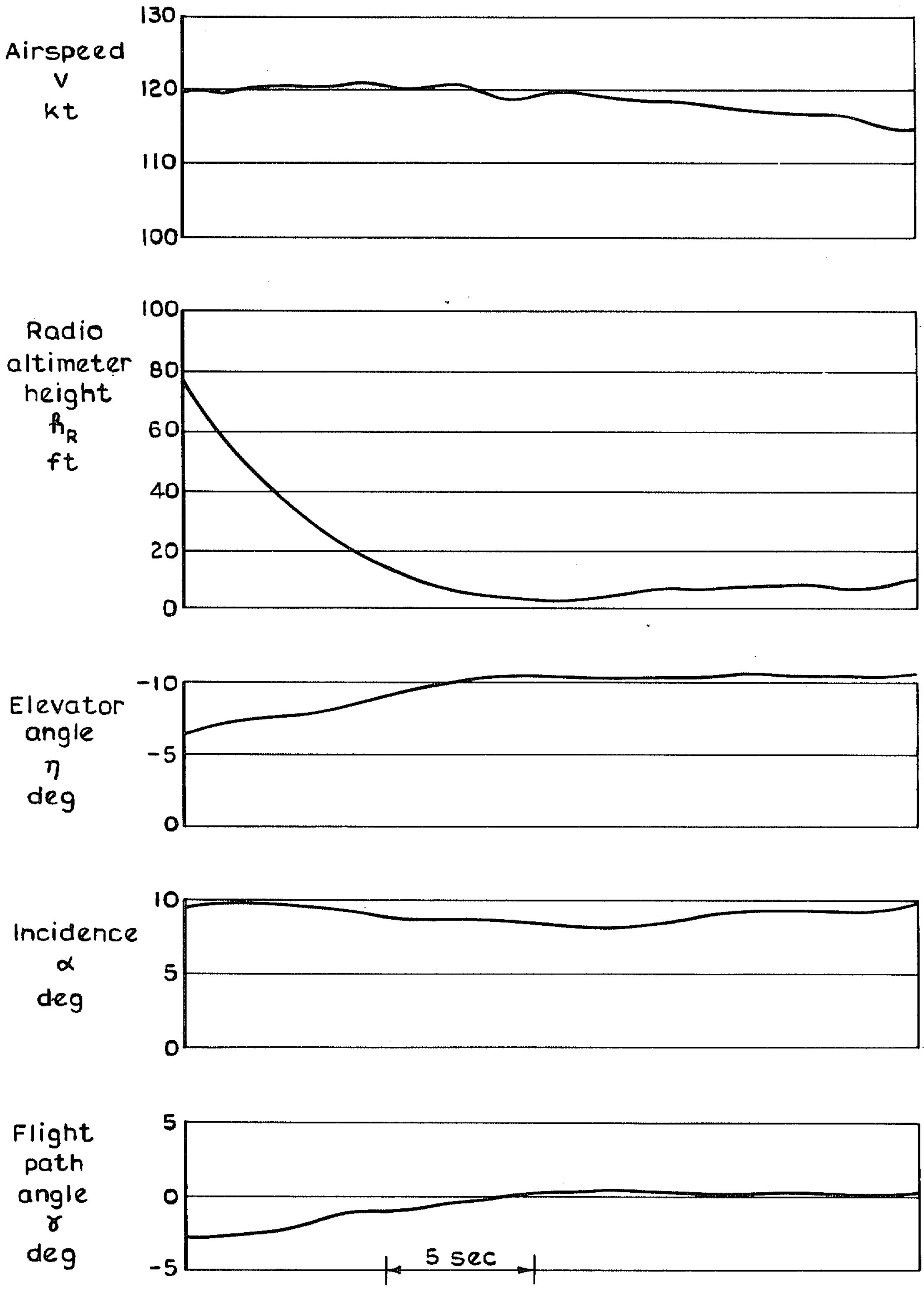



FIG. 3. Time history of typical ground effect run.

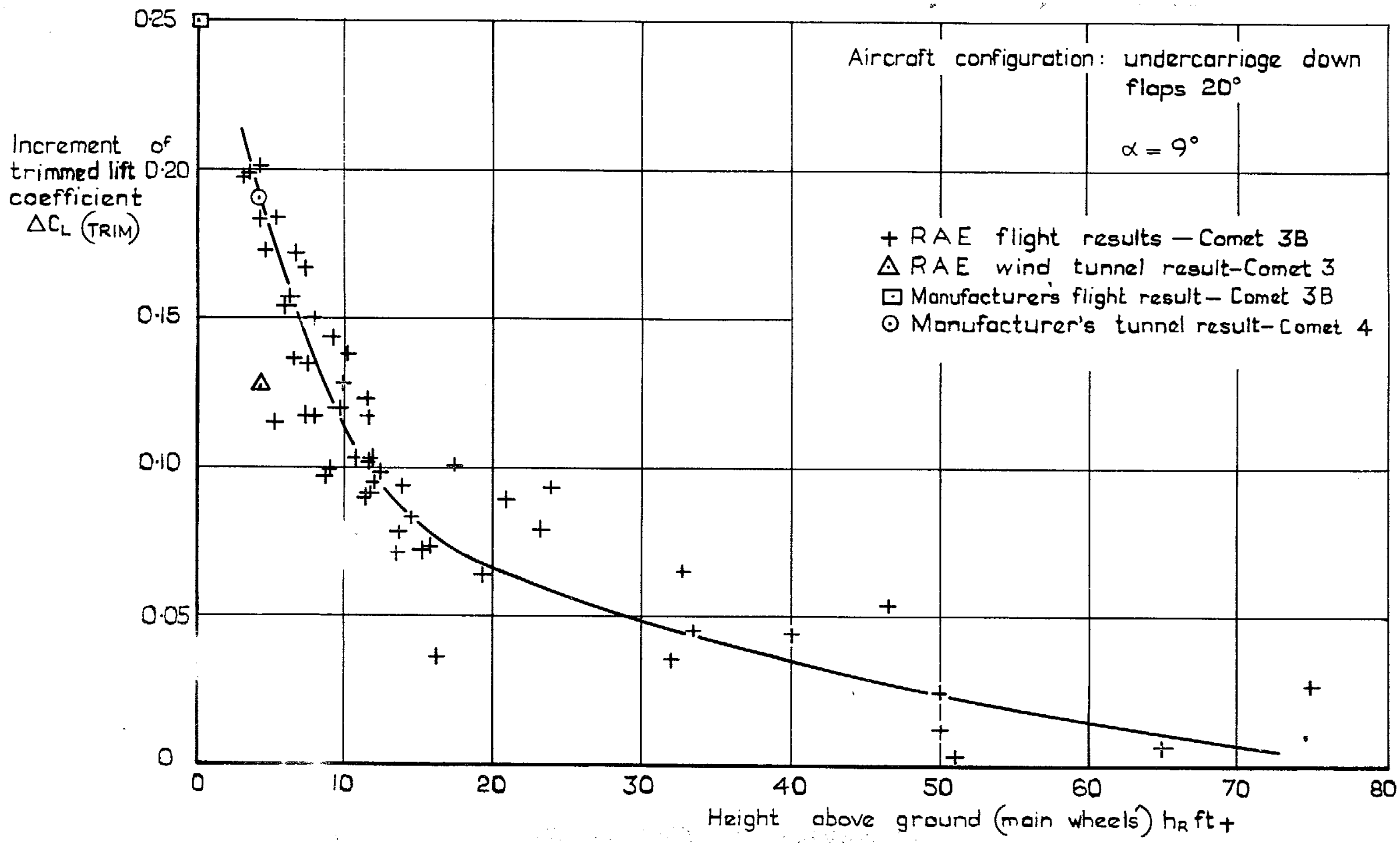



FIG. 4. Comparison of flight and tunnel measured ground effect on trimmed lift.

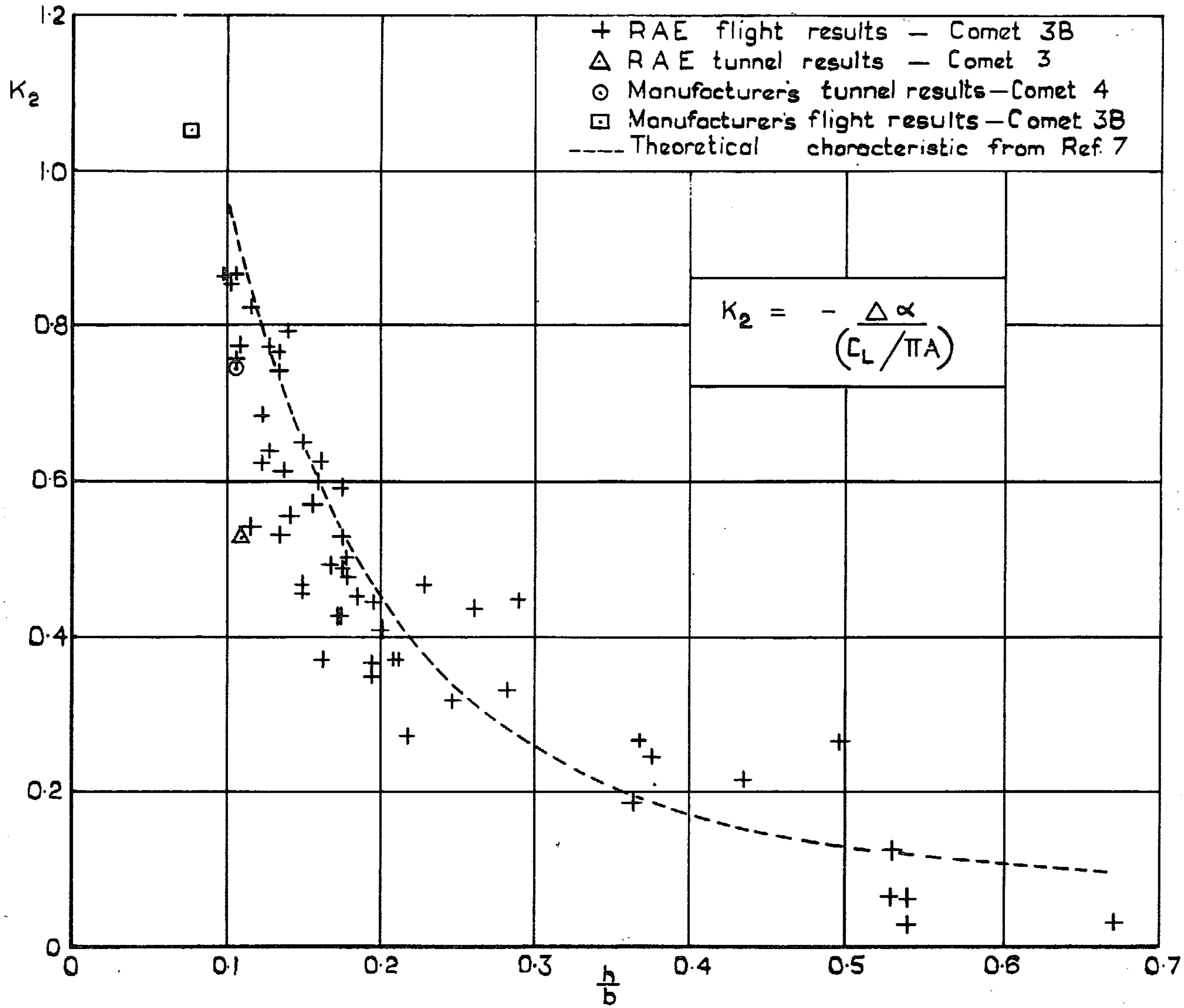



FIG. 5. Comparison of flight and tunnel measurements of ground effect on lift with semi-empirical prediction data.

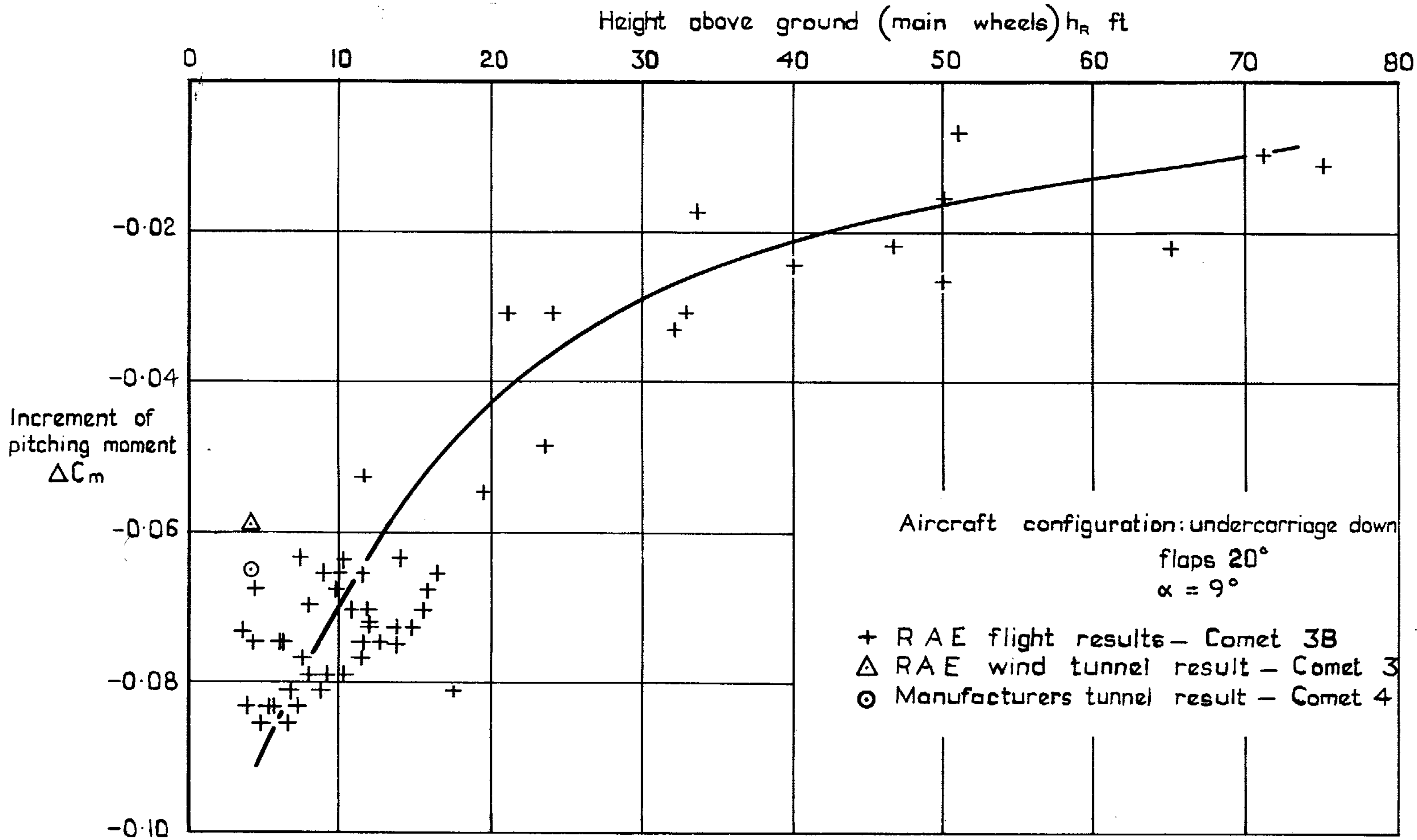



FIG. 6. Comparison of flight and tunnel measured ground effect on pitching moment.

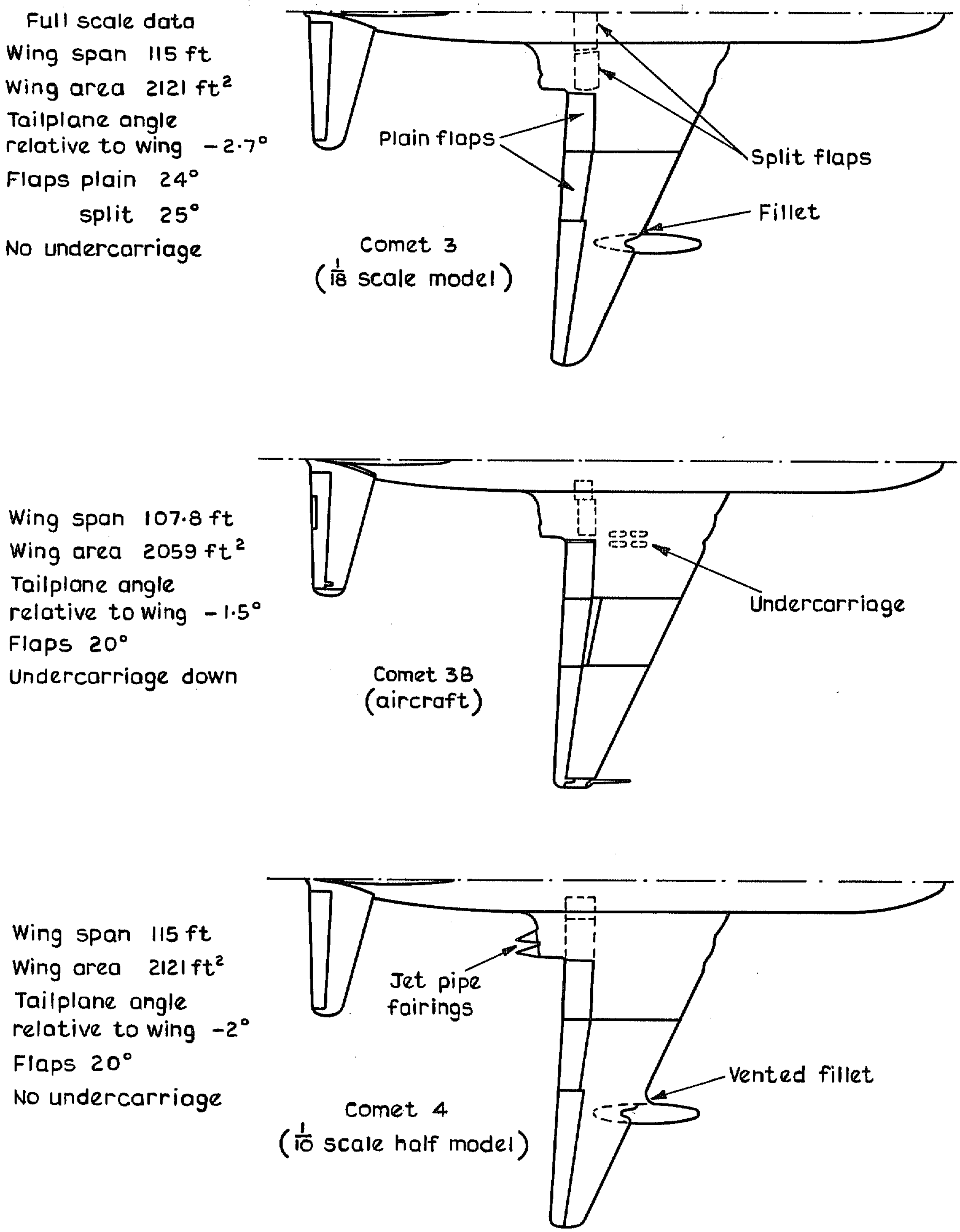



FIG. 7. Comparison of geometry of Comets 3, 3B and 4.



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

Dd. 146916 K.5.

Published by
Her Majesty's Stationery Office

To be purchased from
49 High Holborn, London WC1
13a Castle Street, Edinburgh EH2 3AR
109 St. Mary Street, Cardiff CF1 1JW
Brazennose Street, Manchester M60 8AS
50 Fairfax Street, Bristol BS1 3DE
258 Broad Street, Birmingham 1
7 Linenhall Street, Belfast BT2 8AY
or through any bookseller

R. & M. No. 361
SBN 11 470243 8