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COMMUNICATED BY THE DEPUTY CONTROLLER AIRCRAFT (RESEARCH AND DEVELOPMENT), MINISTRY OF AVIATION

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Summary. Flight tests to determine the dynamic lateral-stability characteristics of the Boulton-Paul IIIA aircraft, have been made at aspect ratios 3·8, 3·0 and 2·3.

They showed that the changes in damping, period and phase angle were not large when the aspect ratio was varied, but the roll to yaw ratio increased considerably as aspect ratio was reduced.

The comparison between the characteristics measured in flight, and those estimated, is generally fair. Agreement is closest over the range of lift coefficient 0·25 to 0·45.

1. *Introduction.* There is a shortage of flight measurements of dynamic lateral stability, and the Boulton-Paul IIIA, a 45-deg delta, provided an opportunity to study some of the problems. This research aircraft was of particular interest for this purpose since its aspect ratio could be varied, thus enabling the effect of changes in this important parameter to be studied in flight.

Calculations have been made using, where available, stability derivatives based on wind-tunnel results (Ref. 1), or otherwise estimated values (Refs. 2, 3 and 4). The time-vector method described in Ref. 5 was used; it proved very convenient for the study of the significance of some of the more important derivatives.

2. *Aircraft and Instrumentation.* The Boulton-Paul Delta is a variable aspect ratio (*i.e.*, 3·8, 3·0 and 2·3) research aircraft, designed for flight at high subsonic Mach numbers. An unusual feature of the aeroplane is the system of controls, which comprise fully-powered, irreversible elevons with plain spring feel, and a variable gearing between control column and surfaces. Trim changes are made by shortening or lengthening the control runs, and automatic trimming in flight is accomplished by a load sensing device, which maintains control-surface hinge movements at zero, ensuring only a small stick force for the pilot in the event of reversion to manual control. The rudder is entirely manually operated, but incorporates a spring to increase foot loads. Both elevons and rudder have manual aerodynamic trimming tabs for emergency or manual flying.

A general arrangement drawing of the aircraft is shown in Fig. 1 and some aerodynamic data are given in Table 1. The test instrumentation included a photo-panel and a continuous trace recorder.

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Airspeed and altitude indicators were photographed by an F-73 camera, taking pictures every $2\frac{1}{2}$ seconds. Rates of roll and yaw, together with sideslip and rudder angles, were measured using a Hussenot A.22 continuous trace recorder. The roll gyro had a natural frequency of 8 cycles/second, and a damping factor of about $0 \cdot 7$ of critical, whilst the yaw gyro's natural frequency was also 8 cycles/second, with a damping factor of $0 \cdot 65$. These gyros were carefully aligned along the appropriate aircraft axes. Rudder angle was measured accurately over the range $\pm$ 4 deg in order to detect small rudder movements during the oscillation. Once the oscillation was started, the pilot held the rudder in the neutral position by tensioning a chain clamped at one end to the rudder bar, and at the other to a strong point on the cockpit floor. Thus the pilot was able to hold the rudder bar still during the oscillation.

3. *Method of Test.* The aircraft was trimmed at the required condition in level flight, the automatic trim tabs were switched off, and with hands off the control column, the rudder was sharply deflected and then returned to neutral, and held neutral by tensioning the rudder chain. Residual rudder motion was expected to be small (*see* Section 4.5). At higher speeds, where only small angles of sideslip were allowable from structural considerations, rudder was applied slowly until a safe sideslip angle was attained, and then returned smartly to neutral, and held still. The resulting oscillations were thus obtained with controls fixed.

Recording was started before the rudder was deflected and was continued until the oscillation was no longer perceptible to the pilot.

Tests were carried out over the speed range 125 knots to 500 knots (or $M = 0 \cdot 90$ whichever was lower) at altitudes of 5,000 ft and 35,000 ft.

4. *Results.* Two typical time histories of the oscillation, at aspect ratio $3 \cdot 0$, are shown in Figs. 2*a* and 2*b*. They were taken at an altitude of 5,000 ft and the lift coefficients were $0 \cdot 1$ and $0 \cdot 6$ respectively. Rates of roll and yaw, sideslip and rudder angle, are shown.

4.1. *Period of the Oscillation.* The period of the oscillation is plotted against C_L in Fig. 3 for the three aspect ratios, at both 5,000 ft and 35,000 ft. There is only a small variation in period with aspect ratio, and it is generally about 1 second at $C_L = 0 \cdot 05$, increasing to about $2\frac{1}{2}$ seconds at $C_L = 0 \cdot 6$. The effect of altitude is very small.

4.2. *Damping of the Oscillation.* In Fig. 4 the logarithmic decrement, δ, of the oscillation is plotted against C_L for the three aspect ratios, at the two altitudes.

The logarithmic decrement was evaluated from the various traces after the rudder had stopped moving. A smooth envelope was drawn through the amplitude peaks of the roll, yaw and sideslip traces, and the logarithmic decrement deduced. The rate gyros did not give accurate readings at low amplitudes, and hence only the larger amplitudes were used in the calculation of δ. A mean of the dampings obtained from the rate of roll, rate of yaw and sideslip traces, has been used throughout the Report.

The results at the three aspect ratios show similar trends with respect to both lift coefficient and altitude. Within the range of flight conditions explored, there are variations in logarithmic decrement between $0 \cdot 4$ and $0 \cdot 8$. In the lower C_L range, the damping of the oscillation is slightly higher at 5,000 ft, than at 35,000 ft, but at high C_L, the difference in damping at the two altitudes is negligible. The loss in damping at high speeds should be noted.

4.3. *Phase Angle.* The phase angles of rate of roll behind rate of yaw were corrected to wind axes and the results are presented in Fig. 5. Here also a definite trend with altitude and aspect ratio is apparent. The phase lag is largest (175 deg) at aspect ratio 2·3 at 35,000 ft. For all the plan-forms, the higher altitude generally gives a larger lag, which in general tends to increase with C_L.

4.4. *Roll to Yaw Ratio.* Roll to yaw (Dutch Roll) ratio for the various flight conditions are shown in Fig. 6. This ratio was obtained from the envelopes of the rates of roll and yaw records, and have been corrected to wind axes for comparison with calculated values. The ratio is, in general, larger at the higher altitudes and higher lift coefficients. The highest value is shown at aspect ratio 2·50 at 35,000 ft.

Only a few points were obtained at high altitude with the aspect radio 2.3 configuration and so the curve is poorly defined.

4.5. *Rudder Motion.* As explained earlier (Section 3), the rudder pedal was held as still as possible by pilot pressure against the cockpit chain, throughout the oscillations. The time histories of Fig. 2 are typical, and show that rudder movement was small, and quickly became negligible. The oscillation was not analysed until the record indicated that rudder motion had ceased.

5. *Estimated Stability.* 5.1. *Estimation of the Stability Derivatives.* The derivatives n_r, n_v, l_v and y_v at aspect ratio 3·0 were obtained from wind-tunnel tests on a model of the aeroplane (Refs. 1 and 6). The derivatives corresponding to aspect ratios 3·8 and 2·3 were estimated on the basis of these results. The values of l_p were estimated using Ref. 2. The variations of n_p and l_v with lift coefficient were deduced from Refs. 3 and 4.

The derivatives thus obtained are plotted against lift coefficient in Figs. 7, 8 and 9. Inertia coefficients were taken from Messrs. Boulton and Paul estimates, corrected to a mean flight condition at each aspect ratio.

5.2. *Stability Calculations using Vector Calculators.* Theoretical estimates of the damping, period, roll to yaw ratio and phasing were obtained by the semi-graphical method of vector analysis (Ref. 5), using slide rule calculators developed by W. J. G. Pinsker. The method is an iterative one, involving the initial assumption of the frequency of the oscillation. The damping, Dutch roll ratio, phase lag and finally the frequency were calculated, the latter quantity being compared with the assumed value. The iteration process was repeated until the difference between consecutive iterations was 2 to 3 per cent; thus any discrepancy between flight and estimated characteristics can be attributed primarily to the use of inaccurate stability derivatives.

Two typical vector diagrams, not strictly to scale but presented to give the relative order of importance of the principal terms, are shown in Figs. 10 and 11. For example, at the conditions assumed the yawing-moments diagram indicates that at $C_L = 0 \cdot 1$, the contributions of $E\ddot{\phi}$ (the product of inertia terms) and $N_p\dot{\phi}$ (the yawing due to rate of roll term) have a very small effect on the damping angle ϵ_D which is directly proportional to the damping ($\delta = 2\pi \tan \epsilon_D$). But, at $C_L = 0 \cdot 6$, the picture is changed substantially. The product of inertia and N_p terms are increased, and modify ϵ_D considerably. Terms which have components in phase with n_r will increase or decrease ϵ_D in direct proportion to their size. These diagrams give an indication of the difficulty of using approximate formulae to predict the motion from known stability derivatives, since simplifications, adequate at low incidence, may be unjustified at higher incidences.

6. *Comparison of Measured and Calculated Motions.* The calculated periodic times, dampings, phase lags and Dutch roll ratios are compared with flight results in Figs. 12, 13, 14 and 15.

6.1. *Period of the Oscillation.* The comparison of flight and estimated periodic times (Fig. 12), is good at all aspect ratios. The calculations show negligible change in period with altitude, and the small differences shown by the flight tests are not readily explainable.

6.2. *Damping of the Oscillation.* The damping of the oscillations, as obtained from theory and flight are compared in Fig. 13. Agreement is poor at the extremes of the speed range covered. At low lift coefficient, the difference is probably due to Mach number effects on the values of the derivatives, which have not been included in the estimates. At high lift coefficients the difference is partly due to uncertainties in the derivative n_p and the cross inertia term i_E.

For all aspect ratios, there is a significant difference between the estimated and measured effects of altitude on the damping, the measured effect of altitude being small, becoming negligible at the higher lift coefficients. As approximate theory indicates that the logarithmic decrement of the oscillation should be proportional to the square root of air density for a given indicated airspeed, and assuming negligible Mach number effects, this difference is difficult to understand.

6.3. *Phase Angle.* The phase lags between rates of yaw and roll are presented in Fig. 14. Agreement is quite good over most of the range of lift coefficient, but becomes poor at the higher speeds, where Mach number effects are appreciable, particularly so at aspect ratio 3·8.

6.4. *Dutch Roll Ratio.* The comparison given in Fig. 15 shows only fair agreement for all three aspect ratios. Once again, agreement is closest over the centre range of lift coefficients. The poor agreement at the higher speeds is probably due to Mach number effects.

The explanation of discrepancies in the roll to yaw ratios are most likely due to inaccuracies in the assumed values of l_v, since this derivative has a most powerful influence on this ratio. (*See* Section 7.)

7. *Effect of Changing some Derivatives.* The inertia coefficients used in the calculation were mean flight values taken from the manufacturers estimated figures, and so they constitute a basic possible error in the computation.

The effect on the calculated motion of variations in the derivatives was investigated by altering some of the more important ones, namely, l_p, l_v, n_v and n_r. Derivatives l_r, y_v and n_p ,were in general, of secondary importance in determining the oscillation, except at the higher lift coefficients, and they were not altered. It is important to remember in the following discussion that the comments apply only to the Boulton-Paul Delta over the ranges specified, and are not generally applicable.

l_p

The effect of a considerable change in this derivative was small for all three aspect ratios in the range $C_L = 0{\cdot}1$ to $0{\cdot}6$. A typical example (for A.R. 2·3 at $C_L = 0{\cdot}6$) in which l_p was increased by 50 per cent, gave a p/r change equal to 3 per cent, and a phase angle reduction of 7 deg; the alterations in period and damping were almost imperceptible.

l_v

This derivative proved to be of great importance in determining Dutch roll ratio. p/r varied almost directly in proportion to l_v at all C_L's and aspect ratios. The alteration in phase lag, period and damping was less pronounced. These latter quantities were found to be more sensitive to alterations in l_v at the higher lift coefficients, than at low incidence.

n_v

As would be expected the derivative n_v proved to be of great importance in determining all the derived quantities. For all aspect ratios at small angles of attack, the periodic time was proportional to $1/\sqrt{n_v}$, other derivatives playing a small part in determining the period. Increases in n_v reduced the Dutch roll ratio and the damping, for all three plan-forms, whatever the lift coefficient. The effect of change in n_v on the phase angle was small. For example a reduction of 40 per cent in n_v at $C_L = 0 \cdot 10$ (aspect ratio $2 \cdot 3$), increased the Dutch roll ratio by 60 per cent, increased damping by 25 per cent, but phase angle changed by only 5 deg.

n_r

The damping of the oscillation was found to be almost directly proportional to n_r. Changes in n_r had little influence on the other quantities.

8. *Some Aircraft Handling Aspects.* Broadly speaking, the aircraft Dutch roll characteristics were similar for all three aspect ratios, but the pilots noticed the small differences in the amplitude of roll during the oscillations. The overall characteristics were considered acceptable.

There was very little spiral instability at any aspect ratio, and the speed remained substantially constant throughout an oscillation.

9. *Conclusions.* Flight tests have been made on the Boulton-Paul Delta aircraft at three aspect ratios ($3 \cdot 8$, $3 \cdot 0$ and $2 \cdot 3$), to investigate its dynamic lateral-stability characteristics. The aircraft was flown at two altitudes, 5,000 ft and 35,000 ft. These characteristics have been compared with those predicted from calculations using stability derivatives obtained from wind tunnel tests and estimates.

The work done shows that:

(i) The aircraft exhibited similar oscillatory characteristics at all three aspect ratios.

(ii) The variation in aspect ratio did not cause marked changes in the damping of the oscillation; the logarithmic decrement was between $0 \cdot 5$ and $0 \cdot 8$ for most of the altitude and speed range covered in these tests. The effect of altitude on damping was surprisingly small but there was a marked reduction in damping at low lift coefficients presumably due to Mach number effects.

(iii) The periodic time of the motion changed little with altitude or aspect ratio for a given indicated airspeed.

(iv) Roll to yaw ratio increased as aspect ratio was reduced, and it has been shown that this is primarily due to changes in l_v and n_v. There was always a pronounced altitude variation —higher ratios at the higher altitudes. The ratio was never more than about $2\frac{1}{2}$, which is quite low for modern aircraft.

(v) Phase lag of roll behind yaw became longer as aspect ratio was reduced, and attained a maximum of 175 deg at aspect ratio $2 \cdot 3$ (35,000 ft).

(vi) The calculated period and damping of the oscillation, and the roll to yaw ratio and phase lag all agreed reasonably well with the measured values except for over-estimating the effect of altitude on the damping. The agreement was best in the lift-coefficient range from $0 \cdot 25$ to $0 \cdot 45$.

(vii) The relative importance of the major stability derivatives has been studied. The work showed that l_p is unimportant, that l_v is significant always—in particular in determining Dutch roll ratio, that n_v is important always and that n_r affects the damping of the oscillation only.

LIST OF SYMBOLS

A		Aircraft moment of inertia in roll
C		Aircraft moment of inertia in yaw
E		Product of inertia about rolling and yawing axes
L		Rolling moment
N		Yawing moment
S		Wing area
V		Airspeed
W		Mean aircraft weight
Y		Side force
b		Aircraft wing span
i_A	=	$A \Big/ \frac{w}{g}\left(\frac{b}{2}\right)^2$
i_C	=	$C \Big/ \frac{w}{g}\left(\frac{b}{2}\right)^2$
i_E	=	$E \Big/ \frac{w}{g}\left(\frac{b}{2}\right)^2$
l		Non-dimensional rolling-moment derivative (with appropriate suffix)
n		Non-dimensional yawing-moment derivative (with appropriate suffix)
y		Non-dimensional side-force derivative (with appropriate suffix)
p		Rate of roll
r		Rate of yaw
α		Incidence of the principal axis of inertia
β		Angle of sideslip
δ		Logarithmic decrement
σ		Relative density of air
ξ		Aileron angle
ζ		Rudder angle
ϕ		Angle of bank
ψ		Angle of yaw
ϵ_ψ		Phase angle between sideslip and yaw
ϵ_D		Phase angle between sideslip and $\ddot{\psi}$ (second derivative of ψ)

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2	A. Goodman and G. H. Adair ..	Estimation of the damping in roll of wings through the normal flight range of lift coefficient. N.A.C.A. Tech. Note 1924. July, 1949.
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5	K. H. Doetsch	The time vector method for stability investigations. A.R.C. R. & M. 2945. August, 1953.
6	Boulton-Paul Aircraft Ltd. ..	Measurement of the rotary derivatives in pitch and yaw of a model of the E27/46. Tech. Report No. 77.

TABLE 1

Aerodynamic data

Engine, Rolls-Royce Nene II

		Aspect ratio 3·8	*Aspect ratio* 3·0	*Aspect ratio* 2·3
Weight (mean)	lb	9,750	10,000	10,400
Ballast	lb	Nil	250	660
Inertia in roll	lb/in.^{2}	20×10^6	$19 \cdot 6 \times 10^6$	$18 \cdot 6 \times 10^6$
Inertia in pitch	lb/in.^{2}	$34 \cdot 1 \times 10^6$	$37 \cdot 8 \times 10^6$	$43 \cdot 8 \times 10^6$
Inertia in yaw	lb/in.^{2}	$48 \cdot 4 \times 10^6$	$51 \cdot 6 \times 10^6$	$56 \cdot 3 \times 10^6$
Wing area	sq ft	294	290	274
Span	ft	33·5	29·5	25
Leading-edge sweep	deg	45	45	45
Taper ratio		0·026	0·147	0·274
Dihedral	deg	0	0	0

Wing

Section 10 per cent thick, Squires high-speed section 'C'.

Elevons

Area aft of hinge line	29·3 sq ft
Spanwise limits (from aircraft centre-line)	2·9 ft to 12·5 ft
Proportion of wing chord	15 per cent
Angular movement	
As ailerons	$\pm 13\frac{1}{2}$ deg
As elevators	$\pm 13\frac{1}{2}$ deg

Fin

Gross area (including fin and rudder above aircraft centre-line)	48·3 sq ft
Nett area (including rudder)	34·5 sq ft
Aspect ratio	2·0
Sweepback on leading edge	45 deg
Thickness/chord ratio	10 per cent

Rudder

Area aft of hinge line	6·7 sq ft
Spanwise limits (from aircraft centre-line)	1·7 to 8·4 ft
Angular range	$\pm$ 15 deg

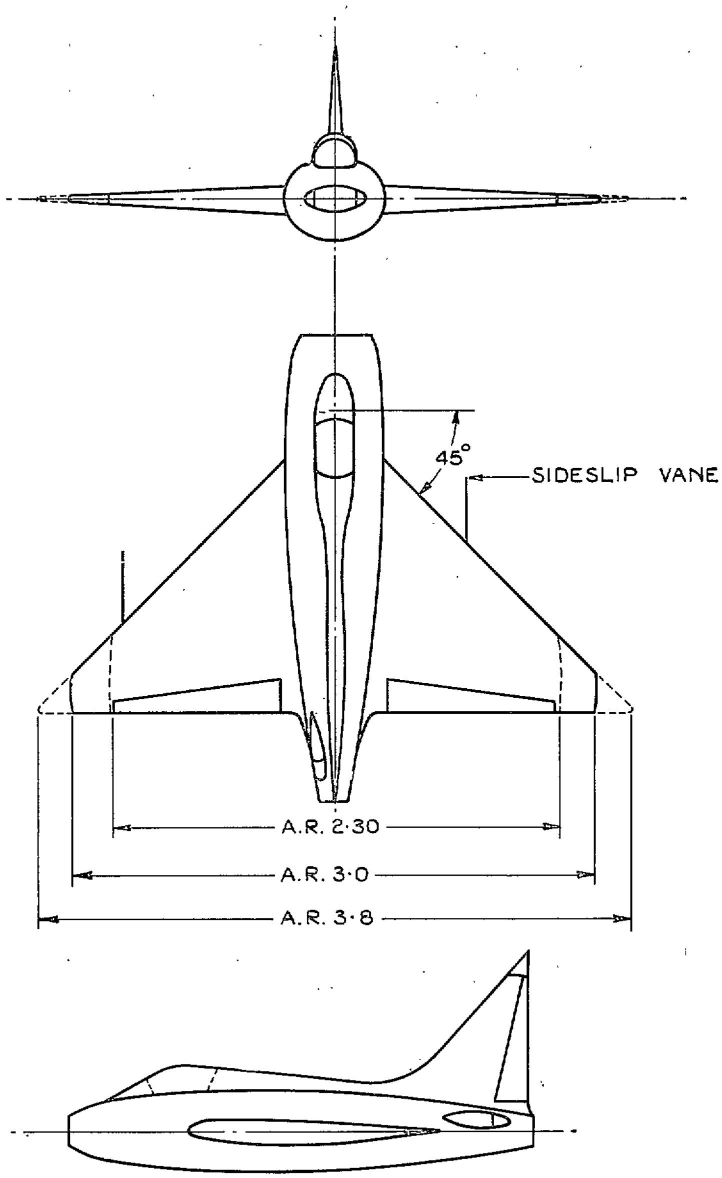

FIG. 1. General arrangement of Boulton-Paul Delta.

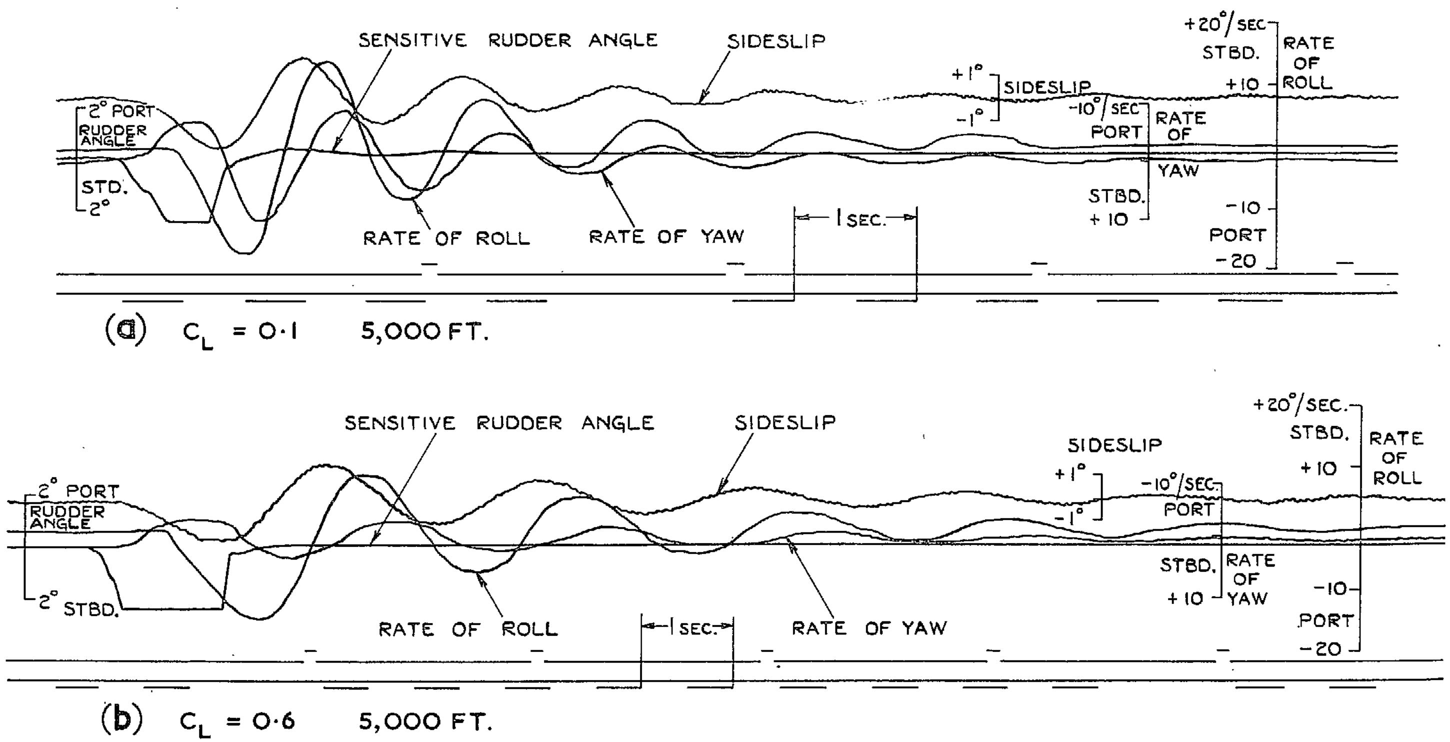

FIG. 2. Boulton-Paul Delta. A.R. 3·0. Typical Time Histories of the oscillation.

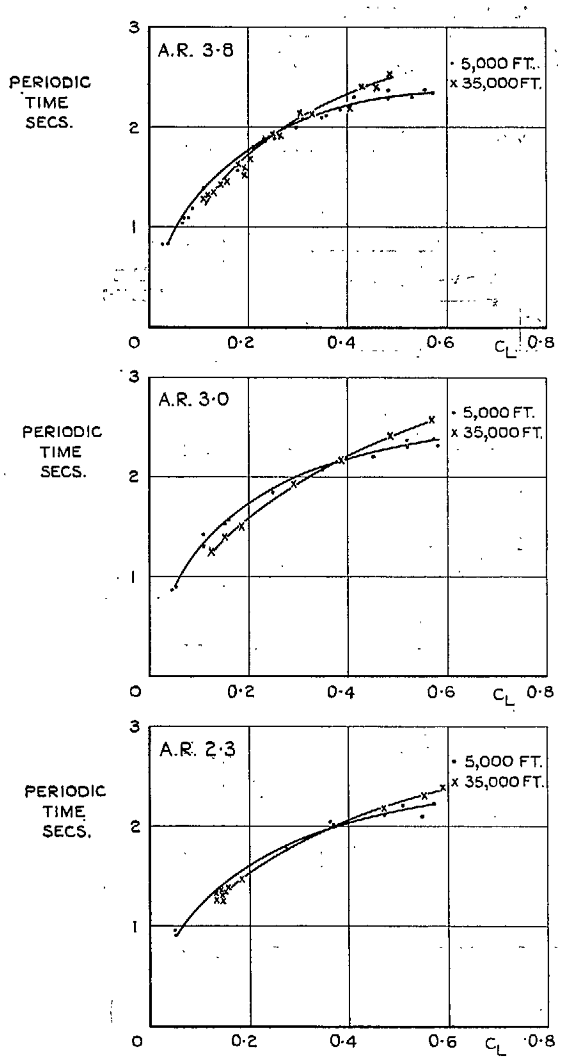

FIG. 3. Boulton-Paul Delta. Period of the oscillation. Rudder Fixed. Three aspect ratios.

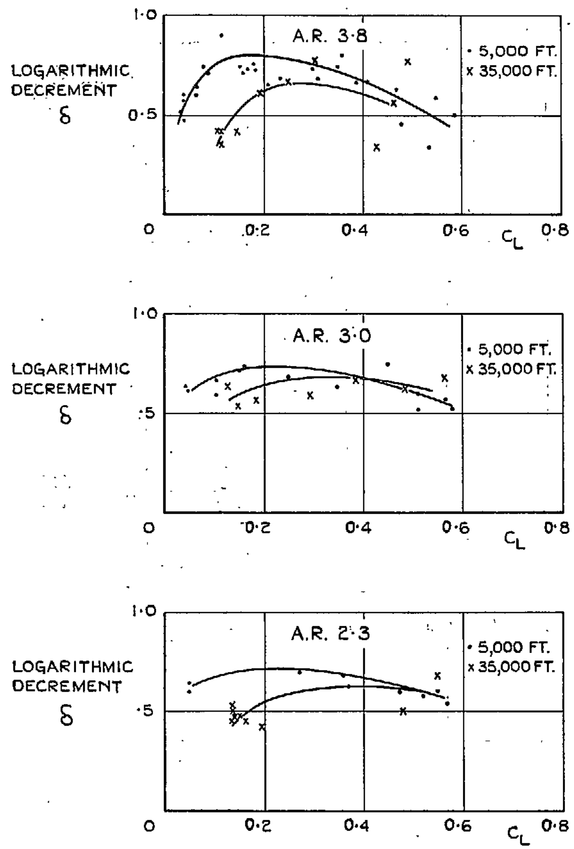

FIG. 4. Boulton-Paul Delta. Damping of the oscillation. Rudder Fixed. Three aspect ratios.

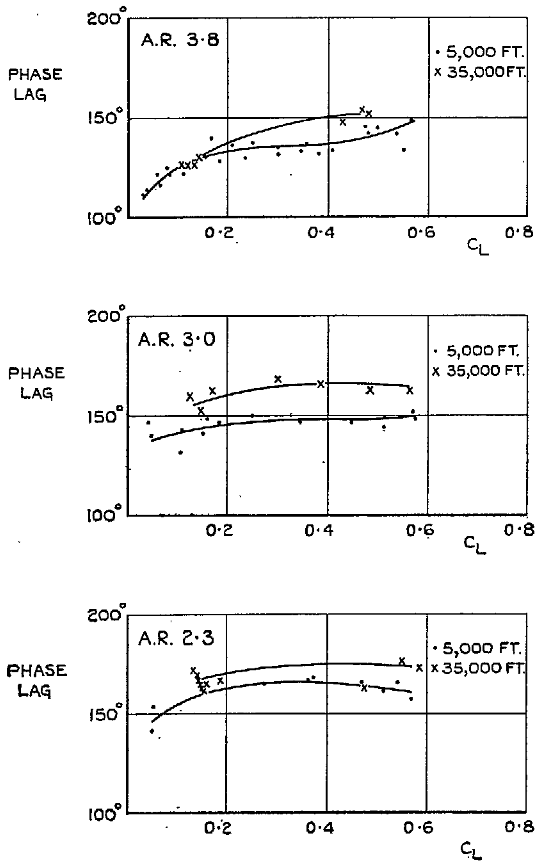

FIG. 5. Boulton-Paul Delta. Phase lag of rate of roll behind rate of yaw. Three aspect ratios.

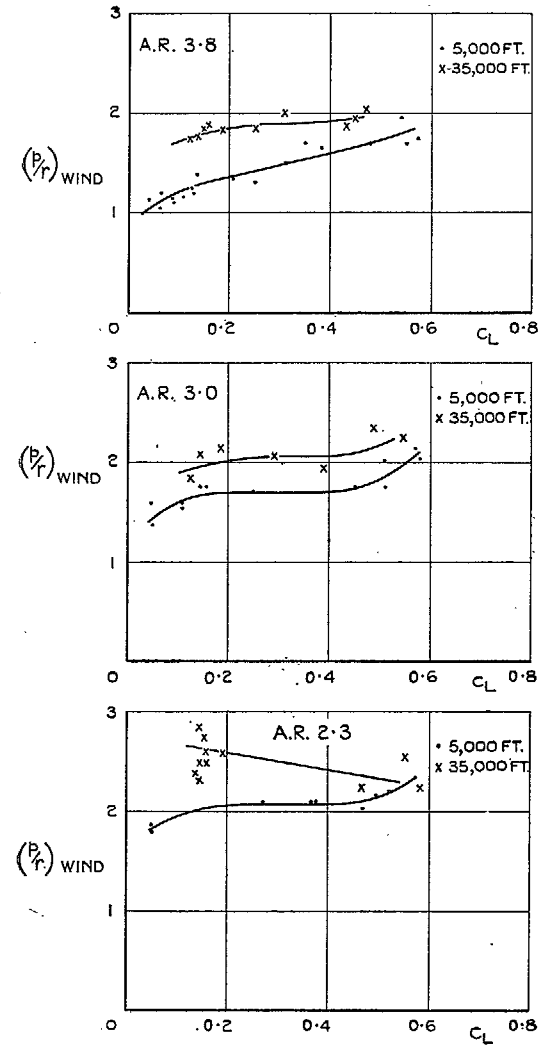

FIG. 6. Boulton-Paul Delta. Roll to yaw ratio. Rudder fixed. Three aspect ratios.

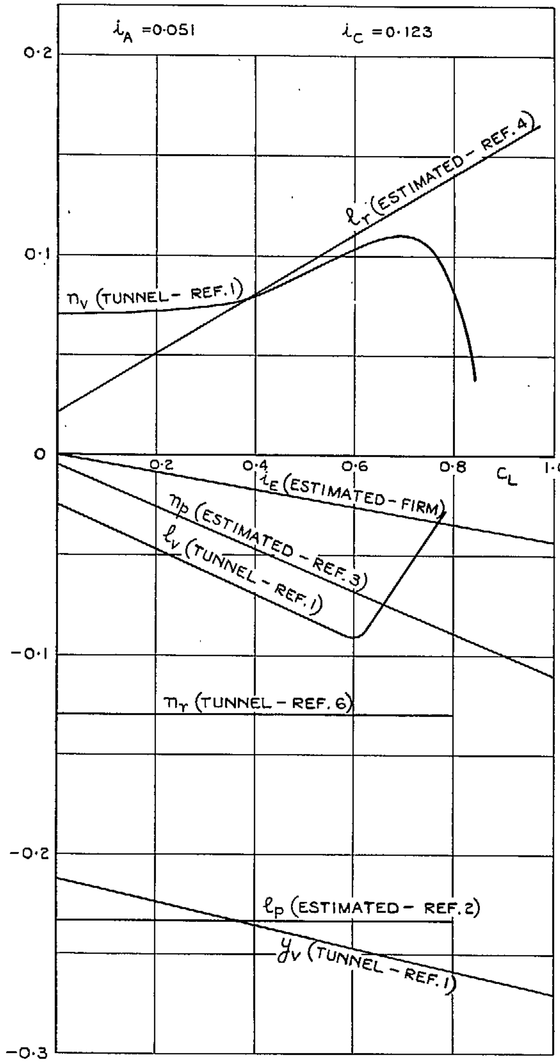

FIG. 7. Boulton-Paul Delta. A.R. 3·80. Aerodynamic derivatives.

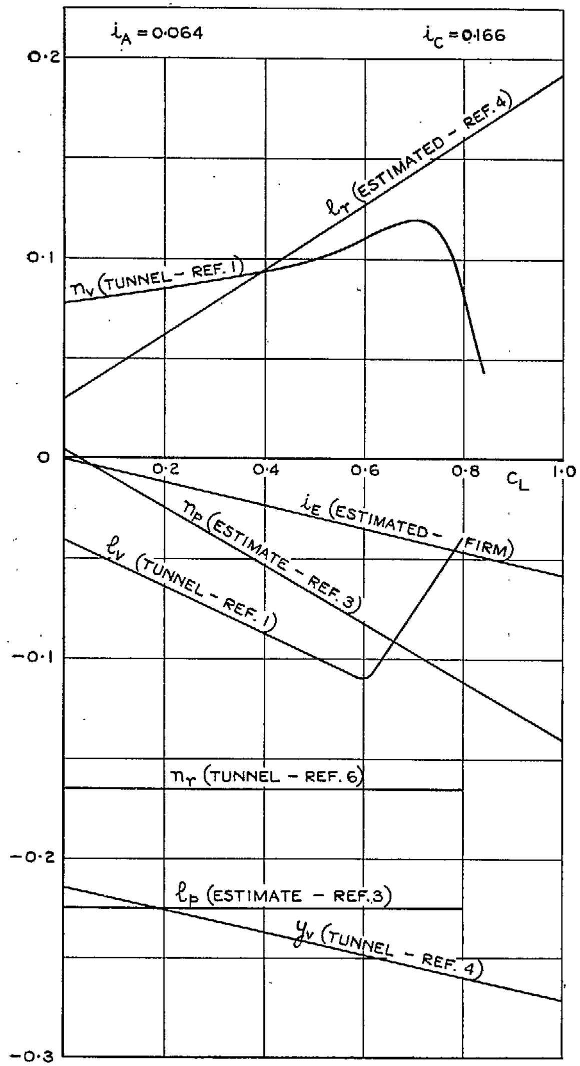

FIG. 8. Boulton-Paul Delta. A.R. 3·0. Aerodynamic derivatives.

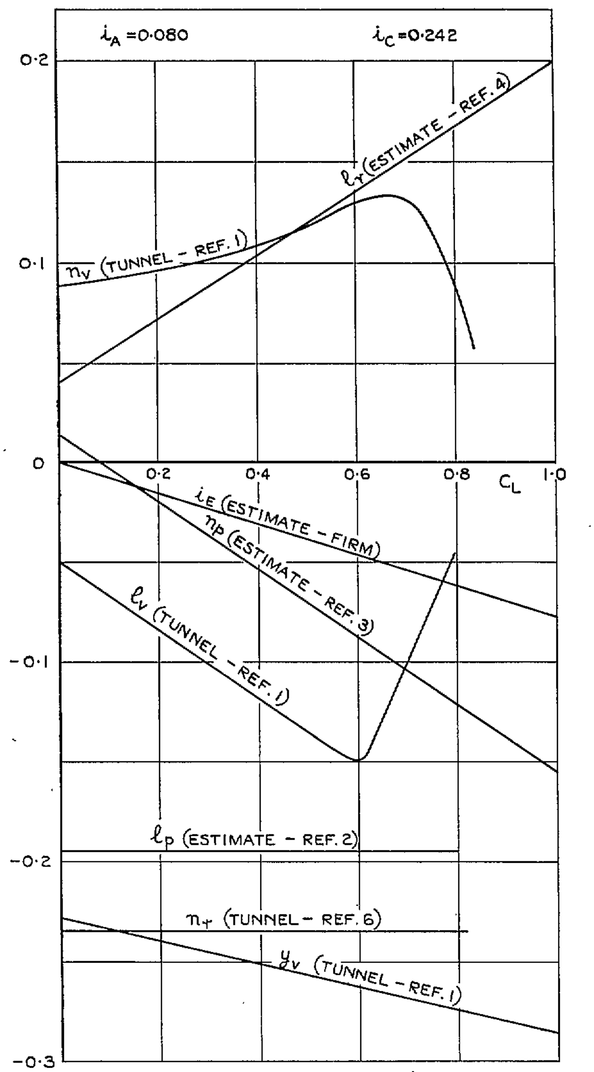

FIG. 9. Boulton-Paul Delta. A.R. 2·30. Aerodynamic derivatives.

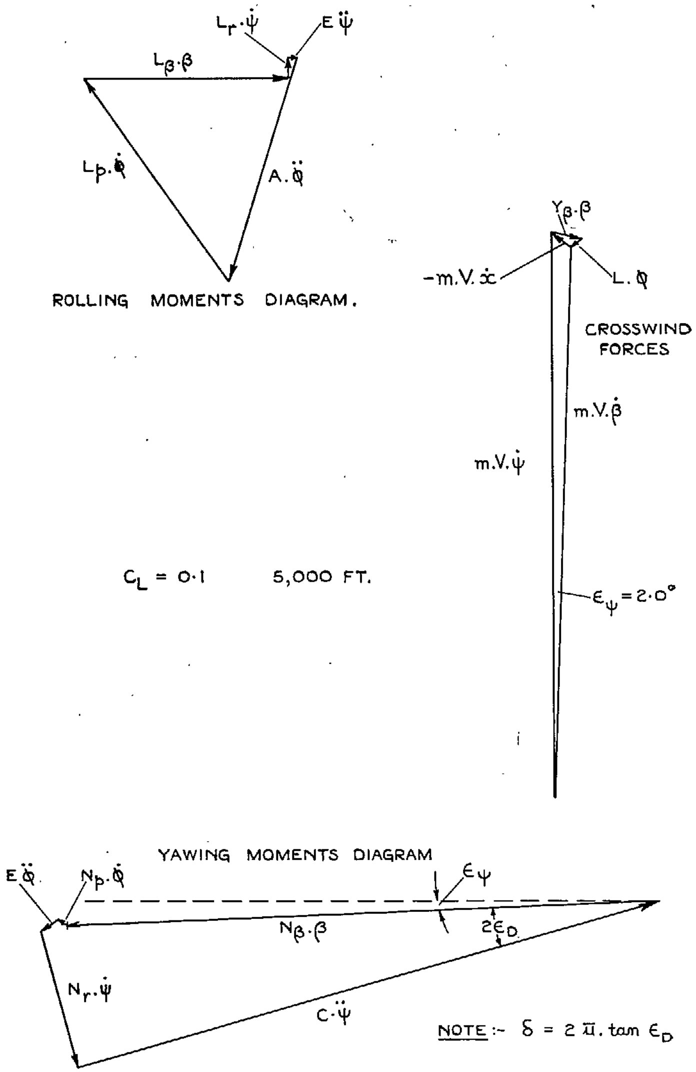

FIG. 10. Boulton-Paul Delta. A.R. 3·0. Vector diagrams of the oscillation.

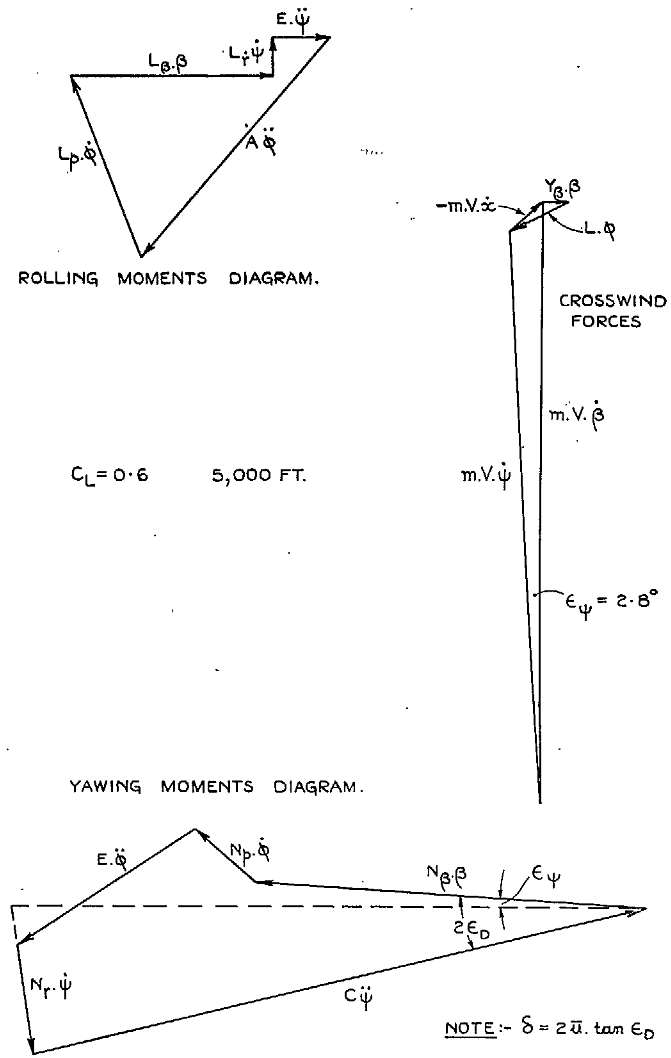

FIG. 11. Bouton-Paul Delta. A.R. 3·0. Vector diagrams of the oscillation.

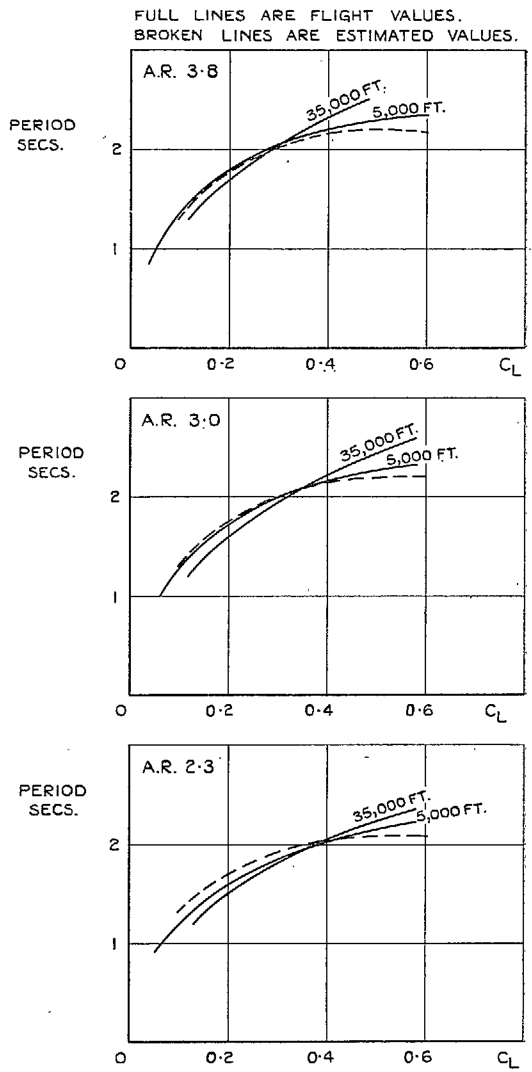

FIG. 12. Boulton-Paul Delta. Period of the oscillation. Comparison between flight and estimate. Three aspect ratios.

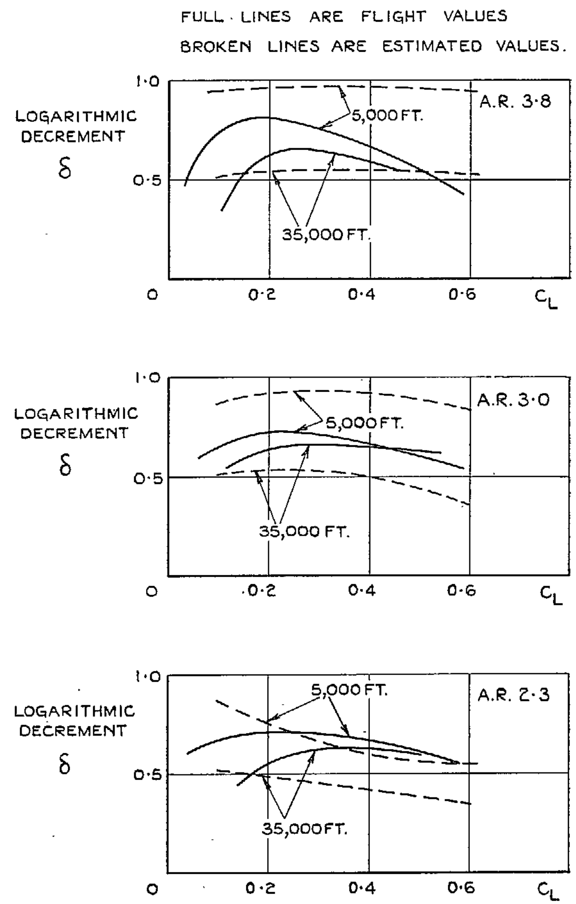

FIG. 13. Boulton-Paul Delta. Damping of the oscillation. Comparison between flight and estimate. Three aspect ratios.

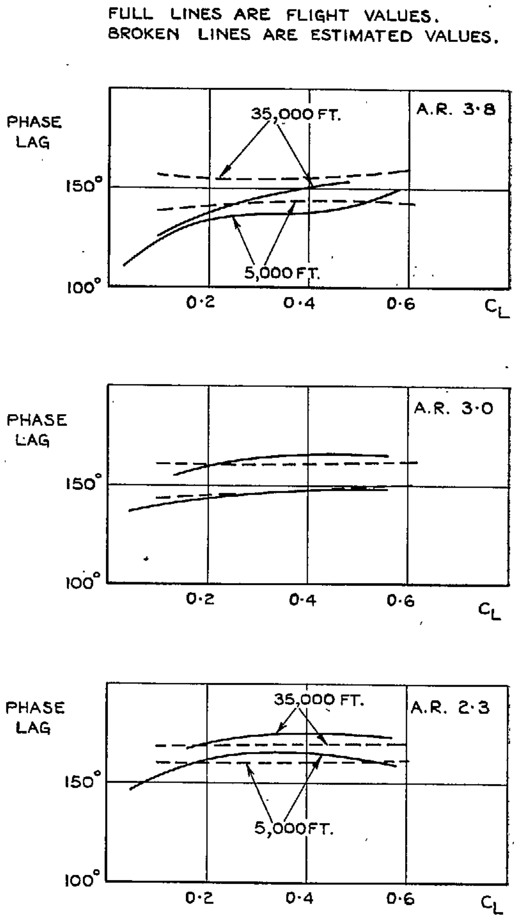

FIG. 14. Boulton-Paul Delta. Phase lags. Comparison between flight and estimate. Three aspect ratios.

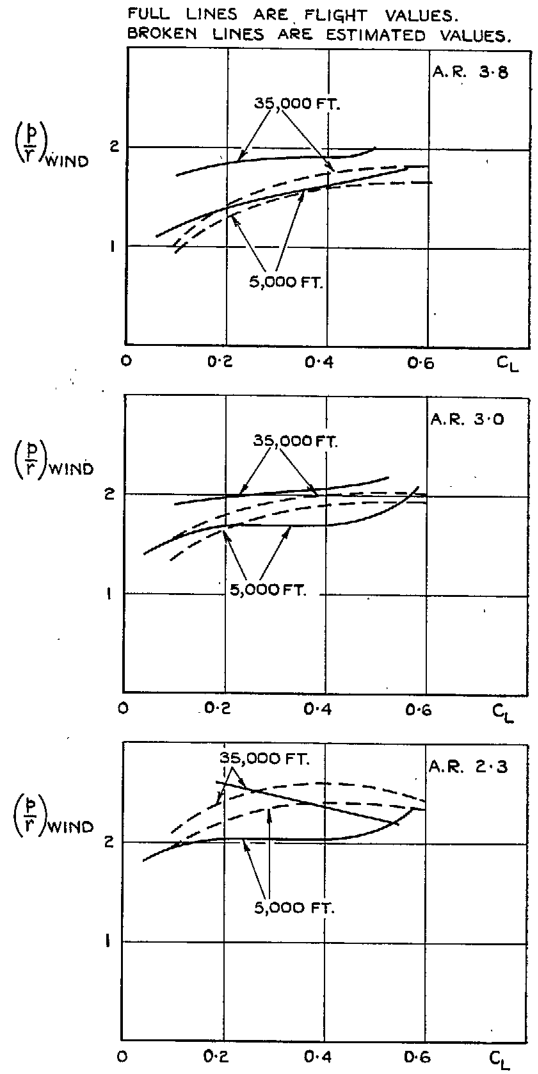

FIG. 15. Boulton-Paul Delta. Dutch roll ratios. Comparison between flight and estimate. Three aspect ratios.

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