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An Improved Technique of Stability Testing in Free Flight at Transonic Speeds, Applied to a Non-Lifting Slender Wing

by

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AN IMPROVED TECHNIQUE OF STABILITY TESTING IN FREE FLIGHT AT TRANSONIC SPEEDS, APPLIED TO A NON-LIFTING SLENDER WING

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SUMMARY

It has been found possible to fly slender wing models at zero lift on such a trajectory that the terminal velocity is close to Mach 1. This makes it possible to measure the stability at slowly-varying transonic speeds and to obtain much more reliable results than have been available hitherto. This Report describes the method and presents interim results.

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* Replaces RAE Technical Report 69239 - ARC 32058.

CONTENTS

1 INTRODUCTION

The *slender wing configuration Orion has been used for a number of years* for general aerodynamic studies directed towards the design of supersonic transport aircraft. It has a shape that is typical of the range of configuration studies for an SST but at the same time is simple enough both to manufacture and to be amenable to theoretical treatment. For this reason no fuselage is represented but the wing is deeper than is usual in order to make space for instrumentation.

The general aim of the free flight programme has been to measure the stability derivatives over a range of transonic and supersonic speeds both at zero incident and over a range of lifting conditions. Some wind tunnel work has also been done and a great deal of data has been accumulated on the Orion shape at both subsonic and supersonic speeds. This work has been further stimulated by the adoption of the Orion configuration as a standard AGARD shape[1]. However at speeds close to M = 1, reliable measurements have been difficult to obtain both in free flight and wind tunnels.

The standard free-flight technique is to disturb the model at short intervals as the Mach number decreases. The oscillations in pitch, roll and yaw arising from each disturbance are analysed to determine the aerodynamic derivatives at the average Mach number of several cycles of oscillation. This is satisfactory provided the derivatives change little with Mach number so that they are sensibly constant during an oscillation; but near M = 1 it was suspected that rapid changes occurred in the magnitude of the derivatives, so that either analysis is impossible or the results unreliable. There is no difficulty in achieving a constant Mach number in a wind tunnel but work at the N.P.L.[2] and Bristol[3] has shown that interference effects dependent on the number of slots in the working section can greatly influence the measurements.

The measurement of rotary and acceleration derivatives in wind tunnels is difficult, in any case, although Thompson and Fail have overcome most of the problems in their oscillatory rig[4]. In the course of development of the rig, measurements were made of the longitudinal derivatives of an Orion model over a wide range of speeds. Results tended to confirm the free flight results then available except for a large increase of pitch damping at precisely M = 1. Although the accuracy of the measurements was uncertain and for this reason they have not been published, the damping increase was repeatable and seemed genuine, but the doubts about the effect of wind tunnel interference remained.

The free flight technique has the important advantage that there are no such tunnel constraints, so that the problem is to devise a technique for achieving only a slow rate of change of Mach number through the transonic regime. Various schemes were proposed, some of which would have required considerable development involving the fitting of a motor to the model controlled by an integrating accelerometer, measuring velocity. The scheme finally adopted is very simple, and was suggested by the observation that most free flight models tended to fly on a ballistic trajectory and reach a terminal velocity late in flight, in common with most bodies in free fall. Computer studies showed that it would be just possible to make Mach 1 the terminal velocity of Orion, using the current size of models and available types of rocket boost, by carefully selecting the weights of model and boost. The only departure from previously established technique was that measurement would have to be made towards the end of flight rather than from the beginning, so that tracking and telemetry reception would be required at unusually long ranges.

Orion 19 was flown in September 1968 mainly for the purpose of proving the validity of the constant speed technique and to discover any tracking or telemetry problems. The minimum speed reached of M = 0.98 was very close to that predicted and this success justified the flight of Orion 20 in January 1969 to measure stability in the transonic region. Six disturbances were given to the model between Mach numbers of 1.075 and 0.995 and were intended to excite mainly longitudinal oscillations. Further firings are planned to fill in some of the measurement gaps, so this paper is only an interim report. It describes the scope and limitations of the transonic technique, and presents a set of measured derivatives for the first two firings, Orion 19 and 20, although no transonic measurements were made with Orion 19.

2 FREE FLIGHT TECHNIQUE

The established practice is to launch the models pick-a-back fashion from solid-fuel rocket motors. With a launch quadrant elevation, Q.E. of about 30 degrees, the model reaches an altitude of about 10000 ft before descending. The basic idea for achieving a constant forward speed, is to balance the drag deceleration by the component of the acceleration due to gravity. For constant velocity the drag will increase as density increases, but if the model is following a ballistic zero lift trajectory the component of gravity will also increase as the flight path steepens. On a typical computed Orion trajectory it was found that if the gravity/drag balance is achieved when the flight path angle is 10 degrees it can be maintained for as much as 20 seconds until the flight angle is more than 50 degrees. The conditions is inherently stable because a decrease in velocity decreases the drag unless the drag coefficient increases. Mach 1 is therefore a particularly stable speed for zero life models because the drag coefficient decreases sharply as speed becomes subsonic.

This natural property of trajectories can only be useful in practice if the variation of Mach number with time is reasonably predictable. It is therefore obvious that the Cd-Mach number curve of the model must be known and the performance of the motor predictable. The technique would also seem, at first sight, to be limited to zero lift models but in practice if the model is made to roll slowly during flight an approximate zero-lift trajectory is obtained. Given these conditions the Mach number time history will be controlled by the following three parameters.

(a) The launch angle or Q.E.

(b) The velocity at model separation (controlled by all-up weight of boost and model at launch).

(c) The drag weight ratio of the model.

The influence of these parameters on the minimum Mach number is shown in carpet form in Fig.2, with the time at which Mach 1 is reached in Fig.3. The configuration is an Orion of area 12.813 sq ft and weight of 280 lb on a solid fuel boost. Changes in model mass are plotted in drag factors so that a k of 0.8 means the model weight has increased to 350 lb. The carpets for launch Q.E. of 35 degrees and 32.5 degrees have been superimposed, and it will be seen that the influence of Q.E. on the minimum Mach number and on the time of reaching Mach 1 is small. This is very fortunate because tip-off at launch makes it difficult to guarantee the launch Q.E. to better than 2 degrees. The total time of flight for this configuration varies between 50 and 60 seconds so that the period of transonic flight can be estimated with the help of Fig.4.

Choosing a design Mach number of 0.99, a practical all up weight of boost with model would be 1200 lb and the model weight 295 lb. From Fig.4, Mach 1 would be reached at 36 seconds so that about 20 seconds of flight at a speed between Mach 0.99 and 1.00 would be available. Errors in the prediction would be caused by errors in (i) atmospheric density of up to ±2%, (ii) model drag due to small trim angles causing drag due to lift of another +2%, and (iii) model weight, for which a tolerance tighter than ±1% would be unreasonable.

Thus an error of 5% in k must be expected or of ±0.01 in minimum Mach number and 5 seconds in reaching Mach 1. This was considered to be quite an acceptable order of error.

It is worth considering at this point the limitations of the terminal velocity technique for achieving a constant speed. The carpet of Fig.2 has been plotted in a more general form in Fig.4 using drag factor and separation velocity as parameters. The variation of drag weight ratio (SC_D/m) on which the graph is based is plotted in Fig.5. During the terminal velocity period, the average value $\frac{1}{2}\rho V^2$ is roughly 1000 lb/sq ft and the average component of gravity along the flight path is 16 ft/sec^2. Consequently for constant velocity, SC_D/m must be approximately 0.016 and it would have to be this value for any sort of model. A similar shape of drag curve is also desirable although the dashed curve in Fig.5b of an Orion (weighing 560 lb flying at an incidence of 5° transonically) would be permissible. In practice to achieve an SC_D/m of 0.016 is not easy. The present Orion has every vacant space filled with lead to reach 300 lb; more than 350 would be impossible. Consequently, flying Orion at a high steady transonic speed at a moderate trim angle presents many problems. These are discussed more fully in the Appendix. The application of this terminal velocity technique are certainly limited, and it is fortuitous that it was possible to make it work for Orion at zero lift with so little alteration to an established technique.

3 PERFORMANCE ACHIEVED

As a result of the computer study, nominal weights were chosen of 300 lb for the model and 1200 lb for all up weight at launch of model plus boost. A tolerance of 0 to +6 lb was put on the model weight and ±10 lb on boost weight. The Q.E. of the launcher was set at 32.5 degrees. The actual model weight of 304.5 lb for Orion 19 was within specification, the 308 lb of Orion 20 was allowed partly because of lack of time and partly because Orion 19 had reached Mach 0.98 which was slightly less than expected. On the other hand the Orion 19 boost weight of 1225 lb was rather high while Orion 20 at 1198 lb was well within specification.

A comparison of the observed trajectories with the prediction based on the nominal weight is shown in Fig.6 as Mach number variation with time. The agreement with Orion 19 is remarkably good, presumably the possible sources of error have cancelled out. Orion 20 did not agree so well with the prediction, probably because of the extra weight and perhaps an error in the initial Q.E. The deduced values for SC_D against Mach number are shown in Fig.7 and compared with the curve used in the prediction. The agreement is very good, particularly for Orion 20. The difference for Orion 19 may be due to accelerometer zero errors leading to errors in the correction for lift, or alternatively the air density may be incorrect. The latter is plotted in Fig.8 and for Orion 19 the measured values show a peculiar kink at about 7000 ft. The predicted curve of SC_D is based on results from previous Orion models, and shows good agreement with SC_D of Orion 19 and 20 deduced by the improved method of analysis.

Both models rolled slowly during flight and the angle as a function of time is plotted in Fig.9 for Orion 20. Roll angle is computed using both optical methods and roll telemetry, which indicates the plane of polarization of the telemetry signal. The accuracy of the method is poor and the shape of the curves in Fig.9 suggests that the correction for aspect is in error.

The difference in the height–time curves of the two rounds is shown in Fig.10, the cause is differences of tip off at launch. In spite of this difference in the trajectories the minimum Mach number is very close to that expected, confirming the computer prediction that errors in launch Q.E. were of small importance. The Reynolds number for Orion 20 is plotted in Fig.11.

4 STABILITY MEASUREMENTS

4.1 Design of the models

The method of construction is described fully in Refs.5 and 6 with the important details given in Fig.1 and listed in Table 1. Basically the wing is constructed as a sandwich having a 1/4 inch thick alloy centre plate forming the planform with hollow glass-fibre mouldings glued above and below to give the profile shape. A number of stiffening ribs are also incorporated and glued to the centre plate. Access to the instrumentation is via a detachable hatch on the top of the wing. To achieve the desired 300 lb almost the whole of the space forward of the cg and some behind was filled with lead.

The moments of inertia were measured by a bifilar suspension method. This proved an adequate method for the moments of inertia about the three axes but failed to give consistent results for the dynamic out of balance or position of the principal axes. The reasons for the inconsistencies are now understood and it is hoped to have no further troubles in future. For these models the very small dynamic out of balance is taken to be zero.

4.2 Method of disturbance

The method adopted for disturbing the models in flight was to fire pulse rockets, or 'bonkers', by a clockwork sequence switch at predetermined times. The position of the 12 bonkers is shown in Fig.12. They are wired to fire in pairs, and by firing a pair on one side of the fin only, the interference effect produces a strong lateral as well as a longitudinal disturbance, exciting both the dutch-roll and short perod pitching modes. When a pair of bonkers is fired simultaneously on both sides of the fin, the lateral disturbance is present but much less in magnitude. Eight of the bonkers can fire upwards next to the fin so a maximum of 4 lateral disturbances can be produced. On Orion 20 the bonkers were fired at 2-second intervals from 33 seconds from launch, the first 4 were primarily longitudinal, the last 2 were primarily lateral.

4.3 Instrumentation

The models were equipped[6] with the R.A.E. 465MH subminiature telemetry system, the aerials being mounted on the trailing edge of the fin. All measurements were made by accelerometers. Three linear accelerometers were placed as near as possible to the cg to measure $\dot{x}$, y and $\ddot{z}$. Two others were placed as far aft of cg as possible to measure the acceleration in the y and z directions, most of this being from the angular accelerations $\dot{q}$ and $\dot{r}$. Accelerometer coordinates are listed in Table 2. Roll angular acceleration was measured directly by an angular accelerometer.

For tracking purposes the models were fitted with a Doppler transponder with aerials in the trailing edge of the wings and in addition two 50-second duration flares were fitted to help the optical tracking.

A close-up of Orion 20 with its hatch removed is shown in Fig.13, and most of the instrumentation, except for some of the accelerometers, can be seen. The telemetered data was of exceptionally high quality and free of noise; a part of the telemetry record for Orion 20 is reproduced in Fig.14, and shows all six disturbances. Before analysis each telemetry channel is digitised, partially smoothed and calibrated before appearing as a deck of punched cards. The data in this form can be printed and plotted or read into a computer for further analysis.

5 ANALYSIS OF RESULTS

5.1 Method

A new method of analysis was used, entirely different from the vector diagram and frequency and damping analysis used hitherto. It is a development of a technique used for the analysis of data from re-entry vehicles[7] and is based on the fitting of a mathematical model of the output of accelerometers to the actual observations by a least squares method on a computer. The mathematical model involves the numerical integrations of the full three-dimensional equations of motion, rather than the use of an analytical solution. This enables cross coupling and non-linear terms in derivatives to be included in the model, so that in principle almost any response can be analysed. The least squares technique is a variety known as the method of differential corrections in which an initial guess at the parameters of the model is progressively improved until a best fit to data is obtained. The parameters in this case are the initial velocities and angular velocities, and the aerodynamic derivatives in the equations of motion*:

$$\dot{w} = z_w w \,.\, \rho VS/m + qV - pv + g\cos\theta\cos\phi \qquad (1)$$

$$\dot{q} = m_w w \,.\, \rho VS\bar{c}/I_y + (m_q + m_{\dot{w}})q \,.\, \rho VS\bar{c}^2/I_y + m_t \rho V^2 Ss/I_y + b_y pr \qquad (2)$$

$$\dot{v} = y_v v \,.\, \rho VS/m + pw - rV + g\cos\theta\sin\phi \qquad (3)$$

$$\dot{p} = \ell_v v \,.\, \rho VSs/I_x + \ell_p p \,.\, \rho VSs^2/I_x + \ell_{vw} vw \,.\, \rho Ss/I_x + \ell r_r \,.\, \rho VSs^2/I_x + \ell_t \rho V^2 Ss/I_x + b_x q_r \qquad (4)$$

$$\dot{r} = n_v v \,.\, \rho VSs/I_z + n_p p \,.\, \rho VSs^2/I_z + n_{vw} vw \,.\, \rho Ss/I_z + (n_r - n_{\dot{v}})r \,.\, \rho VSs^2/I_z + n_t \rho V^2 Ss/I_z + b_z pq \qquad (5)$$

$$\dot{V} = -\ 0.5\, \rho V^2 SC_D/m - g\sin\theta \qquad (6)$$

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* Equations (1)-(5) are in terms of body axes (oxyz) where o is at the cg, equations (6)-(9) are in flight path axes.

$$\dot{\theta} = - g \cos \theta / V \quad (7)$$

$$\dot{\phi} = p \quad (8)$$

$$\dot{\bar{z}} = V \sin \theta \quad (9)$$

where $\bar{z}$ is altitude, $V^2 = U^2 + v^2 + w^2$, $g = g_o R_o^2/(R_o + \bar{z})^2$ and $b_x = (I_y - I_z)/I_x$ etc., ℓ_t, m_t and n_t are moment coefficients associated with trim.

The computed values of velocity and angular velocity are used to calculate the accelerometer readings by use of the following equations which give the acceleration in the directions ox,oy and oz at position (x,y,z).

$$a_x = - \tfrac{1}{2}\rho V^2 S C_x/m - (q^2 + r^2)\, x + (pq - \dot{r})\, y + (pr + \dot{q})\, z \quad (10)$$

$$a_y = y_v v \rho V S/m + (pq + \dot{r})\, x - (p^2 + r^2)\, y + qr - \dot{p})\, z \quad (11)$$

$$a_z = z_w w \rho V S/m + (pr - \dot{q})\, x + (qr + \dot{p})\, y - (p^2 + q^2)\, z. \quad (12)$$

There are certain properties of free flight aircraft motion which make it possible to split the analysis into; first, analysis of the trajectory, and analysis of the coupled longitudinal and lateral motion.

(a) The trajectory is principally affected by drag, made up of the zero lift drag and the drag due to lift. Equation (6) can be rewritten as:

$$\dot{V} = a_x - a_z^2/z_w \rho V S - g \sin \theta \quad (13)$$

with all oscillatory terms ignored because they would have zero net effect. Provided the aircraft is rolling the $\dot{\theta}$ equation is also unaffected by aerodynamic forces and the trajectory may be regarded as zero-lift in this sense. These approximations were justified by results in the case of Orion 19 and 20. Excellent fits to the observed trajectory were obtained by using these equations to calculate the position x,y in ground axes and adjusting the initial values V_o, θ_o, x_o and $\bar{z}_o$. It is necessary to know the value of z_w approximately for this analysis, particularly if a_z is appreciable; there was no problem here for Orion 19 and 20.

(b) The coupled longitudinal and lateral motion is modelled mathematically by equations (1) to (5) for short period oscillations of small amplitude. The trajectory parameters are already known and enable V, ρ, θ and ϕ to be calculated directly from equations (6) - (9) or from tables of values.

The unknown parameters to be determined from the response analysis are the conditions at the start of a response, w_o, v_o, q_o, r_o and p_o, the aerodynamic derivatives z_w, m_w, $(m_q - m_{\dot{w}})$, y_v, ℓ_v, ℓ_p, ℓ_{vw}, n_v and $(n_r - n_{\dot{v}})$, plus instrument zero errors and trim adjustments. Constant values are assumed for all other parameters including the derivatives ℓ_r and n_p, which do not have a distinct effect.

Iterative curve fitting methods aimed at finding such a large number of unknown parameters are very prone to solution divergence problems and the minimising of the risk of divergence greatly influences the design of the computer program. Early versions of the response analysis programs attempted to reduce the chance of divergence by analysing the longitudinal response separately from the lateral response so that fewer parameters were derived at a time. Although it was found possible to include some allowance for cross coupling effects, it was never entirely satisfactory and much time was still wasted by divergence. In the latest response analysis programs, as described in Reference 8, the divergence problem has been almost eliminated and it has become possible to analyse fully 3 dimensional coupled motions.

Apart from the need to spend a little time in choosing very approximate values for the parameters, the latest system is fully automatic. The program starts by fitting a relatively crude mathematical model to the data, using so few parameters that convergence is virtually certain. The model is then automatically elaborated until the complete sophisticated version has been matched to all the data. All this is achieved in a single computer run of about 1 minute duration. Normally this completes analysis but a second computer run is sometimes necessary to improve the fit to the data.

5.2 Discussion of results

It should be remembered that this technique for measuring aerodynamic derivatives uses the effect these have on the motion of the vehicle. Clearly the accuracy of determination varies inversely as the sensitivity of the motion, but by the same token, so does the importance. Transonic stability results were obtained only with Orion 20, and most of these were mainly for longitudinal oscillations, although some of the lateral oscillations, arising from crosscoupling, were analysed. As these were often of small amplitude the errors in the lateral results were large, so that a full discussion of the results will be more appropriate in a later report when better lateral data have been obtained. For comparison purposes the wind tunnel measurements of longitudinal derivatives by Thompson and Fail have been included but it must be emphasised that these are of uncertain accuracy because the rig was in its early stages of development. A survey of theoretical predictions was published in Ref.5 and, where possible, these have also been compared with results but with only a minimum of comment.

5.2.1 Longitudinal motion

Some examples of the fitted curve to data from the aft accelerometer measuring a_z, is shown in Fig.15. The fits are very satisfactory. The scatter at the start of OSC.2 (i.e. the response to the second disturbance) is probably because the 'bonker' is still affecting the motion; the relatively poorer fit to OSC.5 is because of the marked change in trim during the oscillation. The fitted curves to the cg accelerometer are not shown but were of similar quality.

The results of the analysis of all disturbances (including separation from the boost of both Orion 19 and 20 are given in Figs.16 to 18. The two separation disturbances at Mach 2 are distinguished by the model number 19 and 20, the transonic disturbances of Orion 20 have the oscillation number (1 to 6) written by the plotted point. A vertical bar indicates the order of error in measurement where this is greater than the size of the point. Triangular points are used for the unpublished wind tunnel (shown W/T) results of Thompson and Fail and dashed lines are theoretical predictions extracted from Ref.3.

The results from the analysis of the separation disturbances have been given mainly to show that the method of analysis does give valid results. It will be seen that at the separation Mach number of 2.0, the results agree well with theory for all three derivatives and it is shown in Ref.5 that experiment checks with theory at Mach 2 on previous Orions. Therefore, there can be little doubt that the analysis of the transonic disturbances is giving correct results. It will be noticed that at transonic speeds the agreement between theoretical and free flight results is very good for z_w and $(m_q + m_{\dot{w}})$ but that m_w differs by about 30%. This theoretical discrepancy has been noted before[5], and no explanation can yet be offered except to observe that theoretical methods for estimating m_w are suspect. It is clear that further measurement, i.e. down to Mach 0.98, are necessary in order to define completely the behaviour of the derivatives through the transonic regime.

Wind tunnel measurements were made in two tunnels viz. the A.R.A. transonic tunnel and the 8 × 8 ft at Bedford, over the Mach number range 0.5 to 1.3. Measurements were not possible in the latter between Mach 0.9 and 1.3, so only the A.R.A. measurements by Thompson and Fail are plotted in Figs.16 to 18. It will be noted that the wind tunnel results are about 15% lower than free flight for z_w and $(m_q + m_{\dot{w}})$ and 30% lower for m_w. Before drawing any conclusions it should be mentioned that difficulties were experienced in calibrating the oscillatory rig, particularly in the A.R.A. tunnel, and that between Mach 0.5 to 0.9 and at 1.3 there was a discrepancy of the same order between the results from the two tunnels. It is therefore possible that the discrepancy is due to the rig which was in its early stages of development, and for which reason Thompson and Fail have deferred publication of the results until they have had an opportunity to retest.

The discrepancy might also be explained by wind tunnel interfernce. N.P.L. work[9,10,11] has shown interference in perforated tunnels can be comparable to that in slotted tunnels especially for model/tunnel area ratios of the order applicable to the A.R.A tests (0.1). Errors of the order of 30% in m_w with smaller errors in damping are also quite possible, because interference effects on both stiffness and damping cannot usually be minimised at the same time. It was mentioned in the introduction that the original reason for making the free flight transonic tests was that it was believed that interference might be responsible for the peak in damping at Mach 1. In fact, both free flight and theory suggest that the damping peak is genuine.

5.2.2 Lateral motion

The principal lateral oscillations for Orion 20 were OSC.5 and OSC.6 and the best fit to the roll angular acceleration for these cases is shown in Fig.19. The distortion due to the pitching motion is very marked, but, even so, the fit to the data is remarkably good although it is obvious that a linear ℓ_{vw} is inadequate and probably varies with w. Results for roll derivatives for all oscillations analysed are plotted in Figs.20 to 22. The dotted lines represent theoretical predictions from Ref.5 and agreement is good for OSC.5 and 6 in particular which were the only ones to give oscillation of reasonable amplitude. The agreement for ℓ_v in Fig.20 for all disturbances is surprisingly good although this would be the least affected by poor data. The damping in roll derivative ℓ_p is particularly sensitive to poor data and it is noticeable that agreement is best for OSC.3 and 6. Quite good results were obtained for the rolling moments due to combined sideslip and incidence ℓ_{vw}, the best agreement with theory being achieved with OSC.2, OSC.3, OSC. and OSC.6. Some examples of the best fit to the lateral accelerometer a_y in the aft position are shown in Fig.23 with the corresponding derivatives in Figs.24-26. Of these, n_v plotted in Fig.25 is probably the most reliable as it is dependent on frequency. Certainly the results are very consistent with each other, but the sharp transonic change is not predicted by theory. The derivatives y_v and $(n_r - n_{\dot{v}})$ are interdependent; y_v can only be determined from the cg acceleration a_y which was usually too small in amplitude to be accurately measured, so that too much notice should not be taken of departures from theory. The results are reasonably satisfactory however.

The rolling moment due to rate of yaw, ℓ_r, and the yawing moment due to rate of roll n_p have a small effect on the motion that is indistinguishable from that of ℓ_p and n_r and hence cannot be measured. The theoretical values assumed for analysis purposes are given in Figs.27 and 28. For sake of completeness the crosscoupling derivative n_{vw}, the yawing moment due to combined sideslip and incidence, determined by analysis is plotted in Fig.29.

6 CONCLUSIONS

The simple 'terminal velocity' technique for flying slender wing models at almost constant transonic speeds has been successfully demonstrated. For the first time, this has enabled precise measurement of aerodynamic derivatives to be made at Mach 1 without the possibility of interference from wind tunnel-constraints. At the moment the only wind tunnel results available for comparison are not considered very reliable because they were made with an oscillatory rig in its early stages of development. So although some wind tunnel measurements of longitudinal derivatives agree quite well with those from free-flight, this may be fortuitous and no firm conclusions can be reached until further wind tunnel measurements are made and extended to include lateral stability derivatives.

These free flight experiments were chiefly concerned with the measurement of longitudinal derivatives, and good agreement with theory was obtained for z_w and $(m_q + m_{\dot{w}})$; the poor theoretical prediction for m_w has been noted previously[5]. Most of the lateral measurements were made using low amplitude disturbances arising from crosscoupling, and accuracy is often poor. Indeed most of the lateral responses could not have been analysed without the aid of a new semiautomatic method which has made it possible to extract much more from the data than was possible by old graphical methods. The most accurate results were obtained from the last disturbance and here agreement with theoretical values is particularly good.

The terminal velocity technique has been shown to be remarkably successful for flying low drag models, such as slender wings at zero lift, at constant transonic speeds. Unfortunately practical problems make it difficult to apply the technique to models with fairly high drag or those flying at more than a few degrees of incidence. Although these problems are not insurmountable they will limit the application of the technique. However, we now have a precision technique for checking transonic wind tunnel results at zero incidence in free flight. Where agreement is good, at least wind tunnel results for models at incidence can be accepted with more confidence.

Appendix

SOME NOTES ON STABILITY MEASUREMENTS USING LIFTING, FREE FLIGHT MODELS (ORION) AT TRANSONIC SPEEDS

The extension of the terminal velocity technique to lifting models poses several considerable problems:

(a) Drag variation at transonic speeds

It is usual to use fixed elevators on free flight models designed to fly at incidence. Port and starboard settings are made slightly different so that the model rolls continuously and maintains an effective 'zero-lift' flight path. Because of the consequent trim change at M = 1, the subsonic incidence and the resulting induced drag are much higher than the supersonic values, as shown in Fig.30. This is opposite to what happens at zero incidence where the decrease in C_D helps to stabilize the terminal velocity at Mach 1. Therefore a constant terminal at Mach 1 is not possible for models producing more than some critical value of lift. Nevertheless, provided the change in C_D is not too great, a slowly changing speed can be obtained whereby the Mach number change is not greater than 0.01 per second so that reasonably accurate response analysis is possible. Calculations indicate that the speed change on the Orion configuration is tolerable only up to an incidence of about 7 degrees, even if the appropriate model weight and trajectory can be achieved. Fig.31 gives typical speed variations for fixed elevator models designed to give subsonic incidences of 0, 5 and 10 degrees respectively.

(b) Model weight increases

At the terminal velocity the drag must approximately balance the weight. For an incidence of 5 degrees the transonic C_D is 1.5 times the zero lift value. Therefore to fly Orion at lift on the same trajectory would require an impossible increase in weight of the present size of model from 300 to 450 lb. Since weight varies as the cube of the scale and drag only as the square of scale, the desired drag/weight ratio can be achieved by increasing the size. If the model density is constant this would mean increasing the size by 50% and the weight to 1000 lb. Such a model would pose constructional and handling problems. Probably, the maximum convenient size would be an 8 ft model, or a 1.2 increase in size, with a scaled weight of 520 lb; if a further 130 lb could be added then a total of 650 lb would be achieved, which is equivalent to 450 lb model of the present size. This is thought to be the maximum size of model for all practical purposes which means that 5 to 6 degrees is the maximum incidence of the Orion 19 type of drag-stabilized, low altitude trajectory. Higher incidence could be achieved by flying higher in less dense air, but even then it would be difficult to stabilize speed sufficiently for incidences greater than 7 degrees.

(c) Availability of boost motors

Flying the present size and weight of models at higher altitudes to reduce drag and/or heavier models on the present trajectory boty require bigger boost motors and the ideal size is not available. The Rook is much too big for the heavier models on a low trajectory; an all up weight of 6000 lb would be required to obtain the separation velocity of 2000 ft which means carrying over a ton of ballast. It is also rather large for high altitude tests, but for these the AUW of 4000 lb is more reasonable. The problem here is the high separation Mach number of 3. It is proposed to try it out in a later vehicle.

The present boost is too small for the heavier models, but the utilization of two in parallel is a possibility and has been used in the past. The only alternative has an impracticably small fineness ratio and would need considerable extra structure. However, the maximum AUW of 2200 lb with a 650 lb model would only allow 450 lb for this structure and ballast; this is considered too little. The problem might be alleviated by boosting. Clearly some development firings would be necessary.

(d) Pulse rockets

At present on the 300 lb models, the model is disturbed by a pair of *Imp IV 'bonker' rockets, the largest available. The disturbance produced is* only just big enough; bigger models would obviously require larger disturbances. Other than developing more powerful pulse rockets, the only solution would be to fire more at a time. The bigger models may give the necessary space, if 6 disturbances per flight are to be maintained.

(e) Instrumentation

Analysis of the motion of lifting models is more difficult than that of zero lift models, because certain terms in the equations of motion become significant. Most of these arise from constant rates p, q, r inherent in the barrel roll motion. It would therefore be advantageous to carry rate gyros in addition to accelerometers. Problems in the analysis of Orion 18 were largely due to lack of angular velocity information. Roll altitude from a magnetometer would also be very useful. The advantage of making larger models is that more space for instrumentation would be available.

A disadvantage of larger models is that the accelerations tend to be less for a given disturbance, making it necessary either to fit more sensitive instruments or induce greater amplitude motions. There would be problems in both these approaches. More sensitive accelerometers are not available of the present type, and we have seen that bigger bonkers are not available.

Flying models of the present size at higher altitudes clearly has certain disadvantages. It would not be possible to fit extra instruments like rate gyros. Also accelerations would tend to be lower in the less dense air, and damping is reduced, making it more difficult to measure.

Conclusion

It is concluded that some development of both models and boost assemblies is inevitable if aerodynamic derivatives at near constant transonic speeds in high lifting attitudes are to be measured. To use the present 300 lb models would require launches at high velocity on a Rook boost so that they could operate in less dense air. This means a loss of Reynolds number, difficulties in accommodating the extra instrumentation, and the possibility of flutter due to high launch speeds. To make the present models strong enough to launch on the Rook requires a redesign so the opportunity should be taken to increase the size at the same time. This would enable weight/size ratios to be improved, there would be more room for instrumentation and for the necessary extra bonkers, and launchings could be at Mach 2 which would improve Reynolds number matching.

It is emphasized that the foregoing has been concerned only with models with fixed elevators. More elegant and predictable experiments would be possible with elevators controlled so that the models fly with a constant lift acceleration. Apart from the design and construction of the control system, the problem would be to reach the desired 'g' supersonically. However, it may be possible to design an acceptable compromise.

Table 1

MODEL DATA

Geometry			
Wing:	Planform area		12.813 ft^2
	Aspect ratio		0.865
	Planform parameter, P		0.578
	Span		40 in
	Span/length ratio		0.5
	Geometric mean chord, $\bar{c}$		3.843 ft
	Volume		1.926 ft^3
	Thickness/chord ratio on centre line		0.065
	Newby area distribution		4 s t x (1-x)
	Zero camber and twist		
Fin:	Area (gross)		1.281 ft^2
	Aspect ratio		0.695
	Geometric mean chord $\bar{c}_F$		1.379 ft
Centre of gravity			0.50 C_D
Weight and inertias		Orion 19	Orion 20
Weight		304.5 lb	307.5 lb
Inertia in roll, I_x		2.104 slug ft^2	2.044 slug ft^2
Inertia in pitch, I_y		20.720 slug ft^2	20.228 slug ft^2
Inertia in yaw, I_z		21.917 slug ft^2	21.269 slug ft^2

Table 2

ACCELEROMETER COORDINATES (RELATIVE TO cg)

	Orion 19			Orion 20		
	x, ft	y, ft	z, ft	x, ft	y, ft	z, ft
Nose normal	0.767	0.000	- 0.078	0.708	0.000	- 0.078
cg normal	0.000	0.000	- 0.092	0.010	0.000	- 0.092
Aft normal	- 2.108	- 0.075	- 0.092	- 2.098	- 0.075	- 0.092
cg lateral	0.117	0.000	- 0.078	0.115	0.000	- 0.078
Aft lateral	- 2.560	0.192	- 0.041	- 2.594	0.188	- 0.041

SYMBOLS

a_x, a_y, a_z	components of acceleration at (x,y,z) in body axes
b	span
C_D	drag coefficient
C_x	axial force coefficient
C_o	root chord
$\bar{c}$	geometric mean chord
$\bar{c}_F$	" " " of fin
g	acceleration due to gravity
I_x, I_y, I_z	moments of inertia in roll pitch and yaw respectively
k	drag factor
L_p, L_r, L_v	rolling moment derivatives e.g. $L_p = \partial L/\partial p$
L_t	rolling moment associated with trim
ℓ_p	$L_p/\rho V S s^2$
ℓ_r	$L_r/\rho V S s^2$
ℓ_t	$L_t/\rho V^2 S s$
ℓ_v	$L_v/\rho V S s$
M	Mach number
$M_q, M_w, M_{\dot{w}}$	pitching moment derivatives, e.g. $M_q = \partial M/\partial q$
M_t	pitching moment associated with trim
m	mass of model
m_q	$M_q/\rho V S \bar{c}^2$
m_t	$M_t/\rho V^2 S s$
m_w	$M_w/\rho V S \bar{c}$
$m_{\dot{w}}$	$M_{\dot{w}}/\rho S c^2$
$N_p, N_r, N_v, N_{\dot{r}}$	yawing moment derivatives e.g. $N_p = \partial N/\partial p$
N_t	yawing moment associated with trim
n_p	$N_p/\rho V S s^2$
n_r	$N_r/\rho V S s^2$
n_t	$N_t/\rho V^2 S s$
n_v	$N_v/\rho V S s$
$n_{\dot{v}}$	$N_{\dot{v}}/\rho S s^2$
P	planform parameter, $S/b\ c_o$
p,q,r	angular velocity resolutes in roll, pitch and yaw
R_e	Reynolds number
R_o	radius of Earth
S	wing area

SYMBOLS (Contd.)

s		semispan
V		velocity along flight path
v,w		lateral and normal perturbation velocity
x,y,z		coordinates relative to cg
Y_v		side force derivative due to sideslip, $Y_v = \partial Y/\partial v$
y_r	=	$Y_v/\rho\ S\ V$
Z_w		normal force derivative due to normal velocity, $Z_w = \partial Z/\partial w$
z_w	=	$Z_w/\rho\ S\ V$
$\bar{z}$	=	altitude
θ		flight path elevation
ρ		air density
ϕ		roll angle

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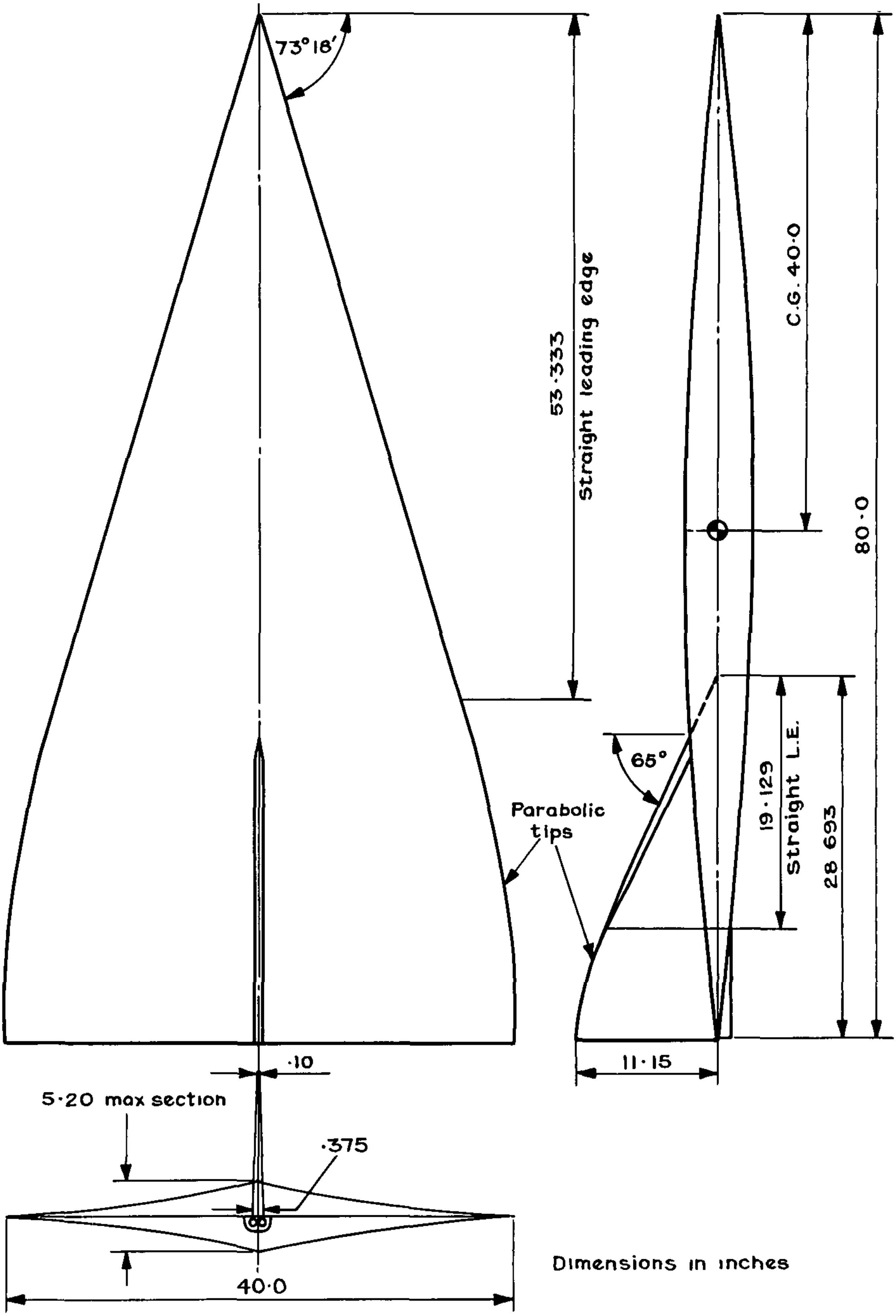


Fig. 1 Model geometry

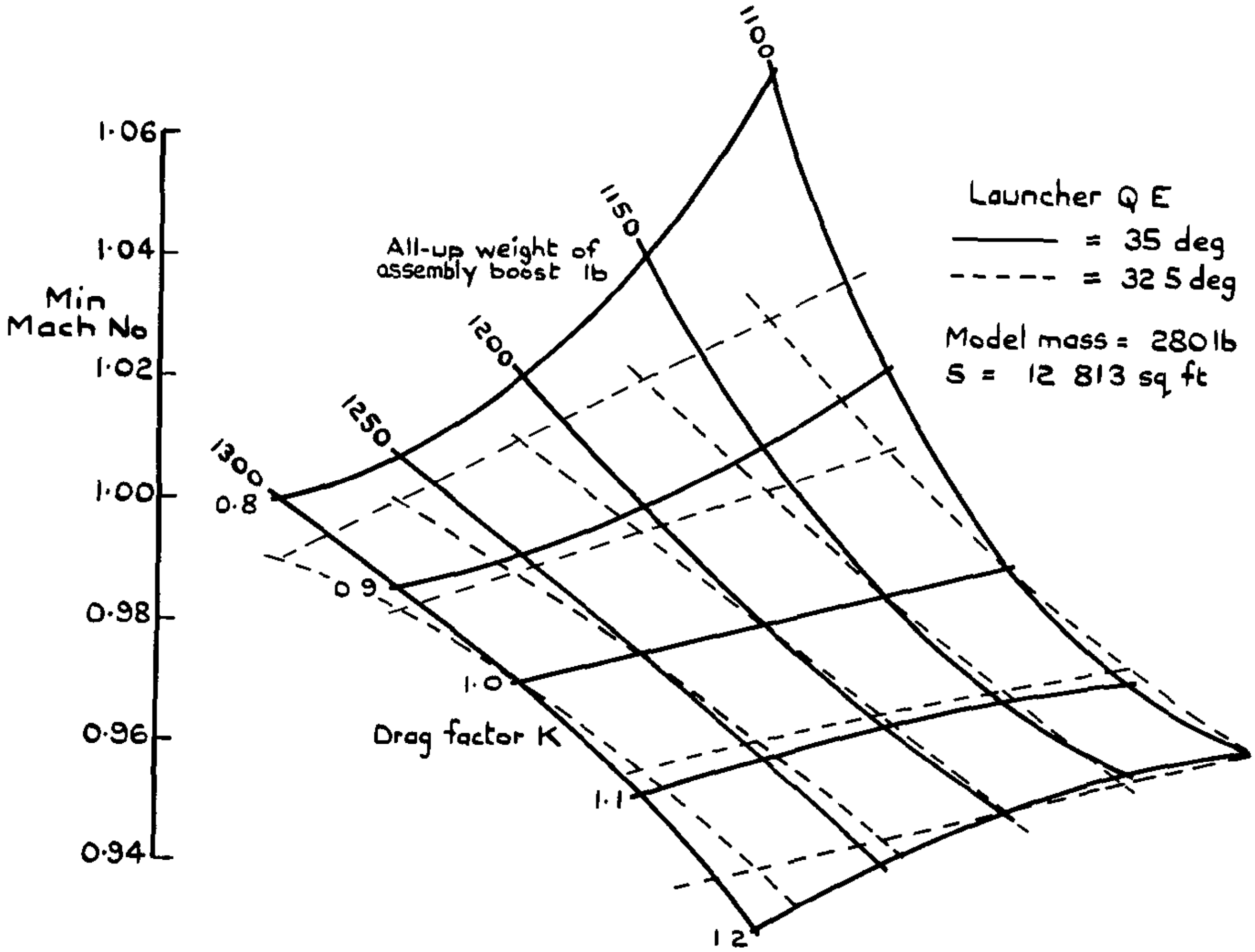


Fig. 2 Variation of minimum Mach No of Orion model carried by solid fuel boost with all-up weight and model drag factor

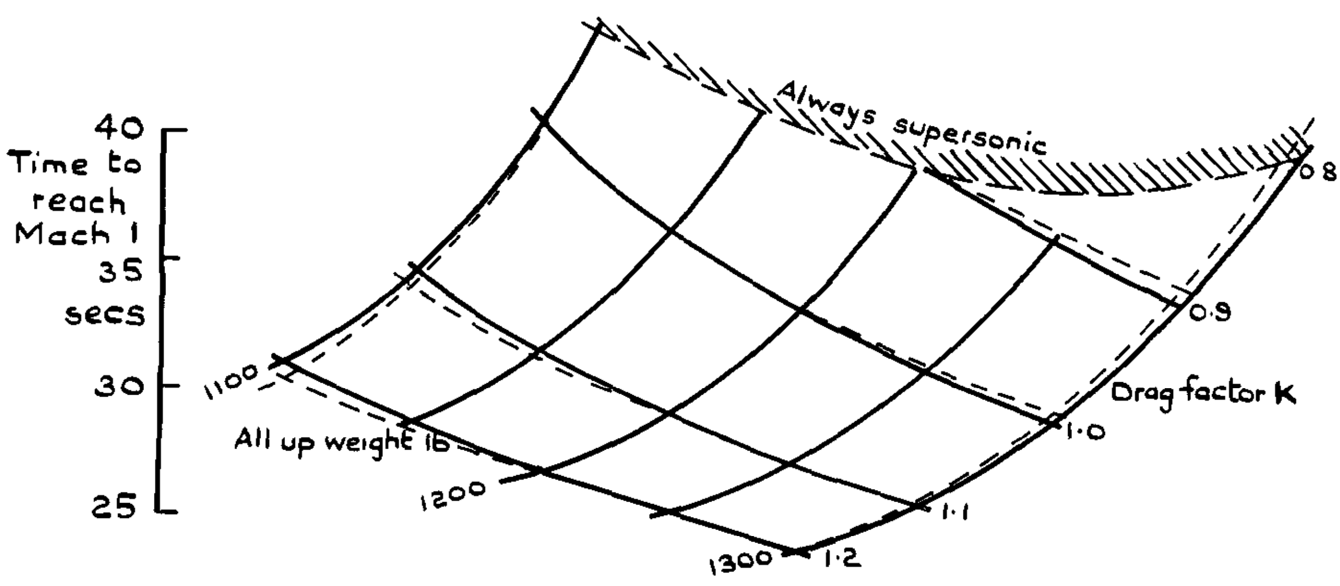


Fig. 3 Time to reach Mach No 1 as a function of model drag factor and all-up weight of Orion on solid fuel boost

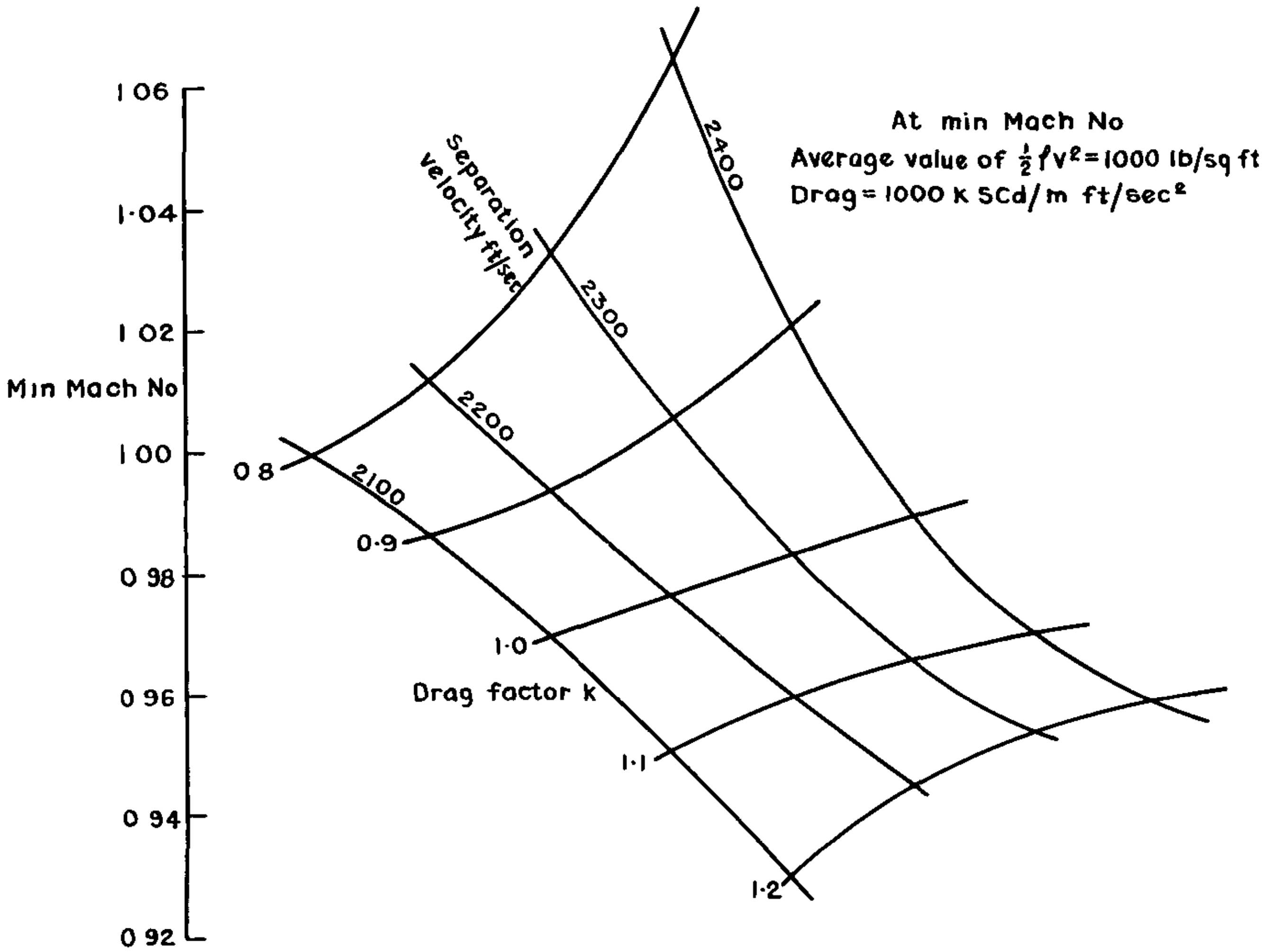


Fig. 4 Variation of minimum Mach No with Model separation velocity and drag factor for separation Q.E. of 29 deg approx

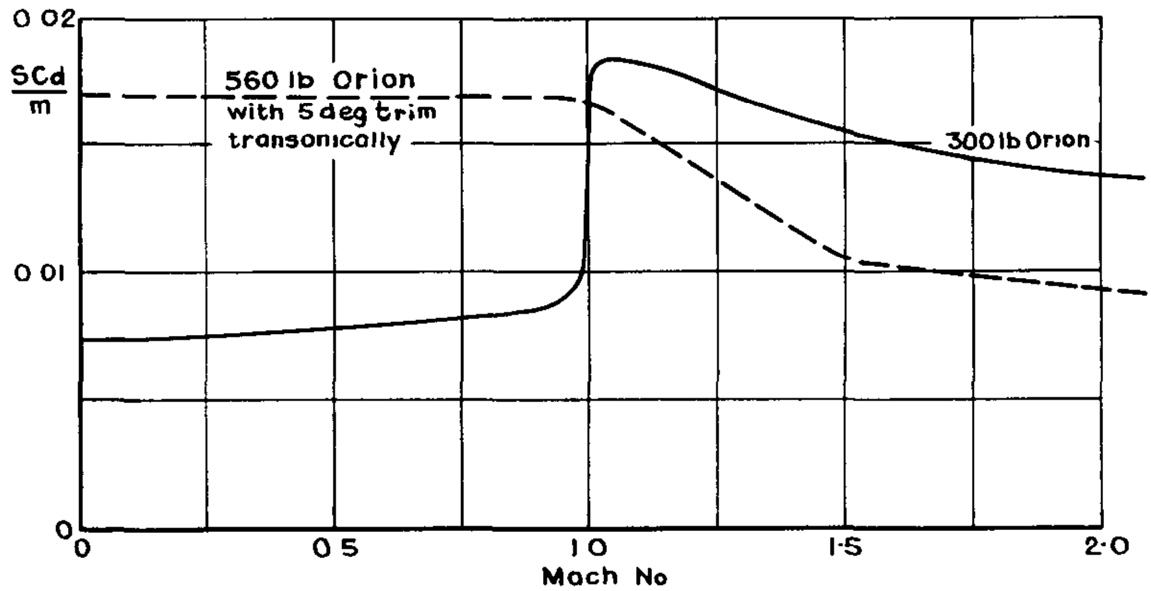


Fig. 5 Variation of SCd/m with Mach No assumed in calculations of min Mach No

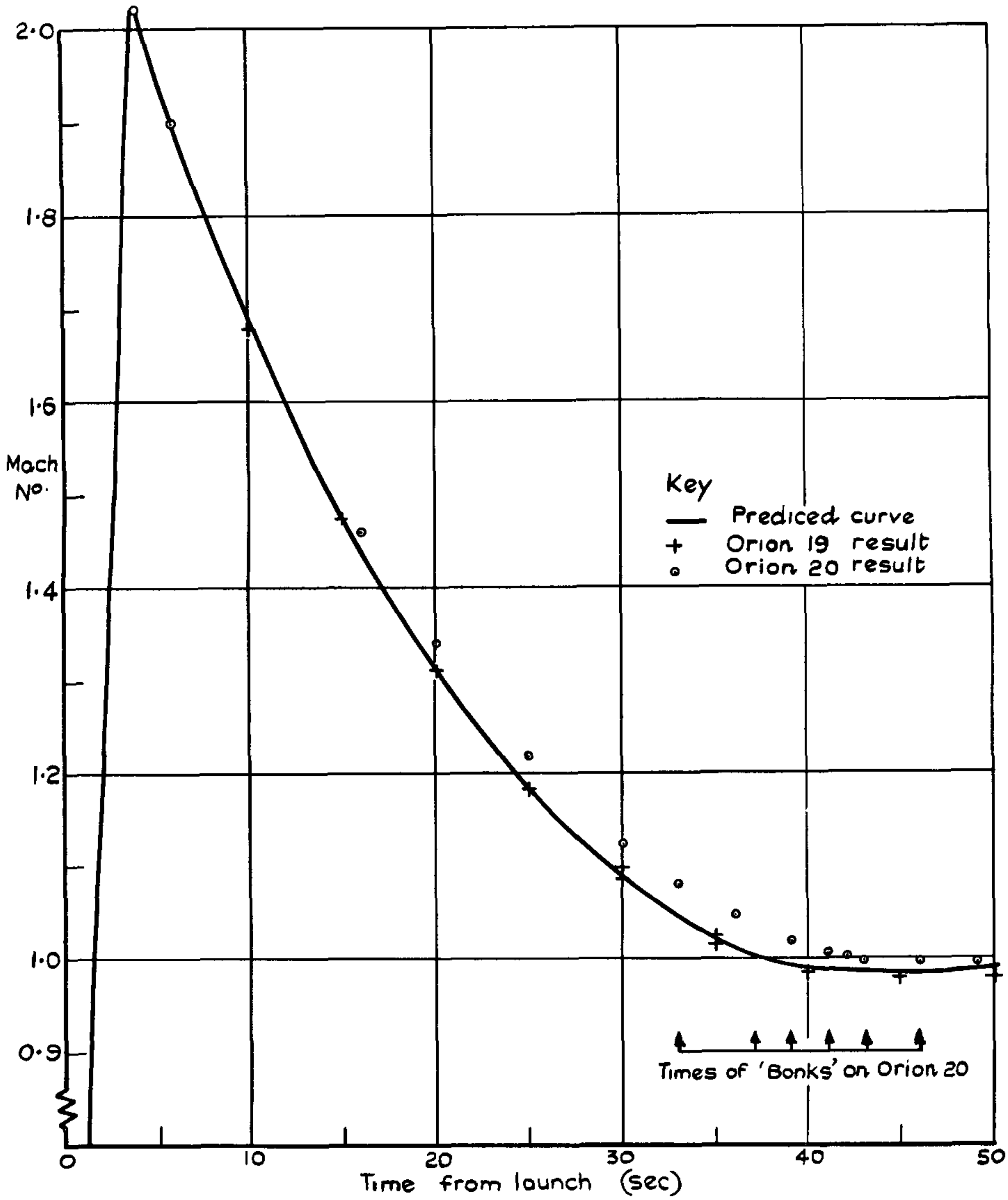


Fig. 6 Comparison of the predicted variation of Mach Nº. with time, with the actual results from Orions 19 and 20.

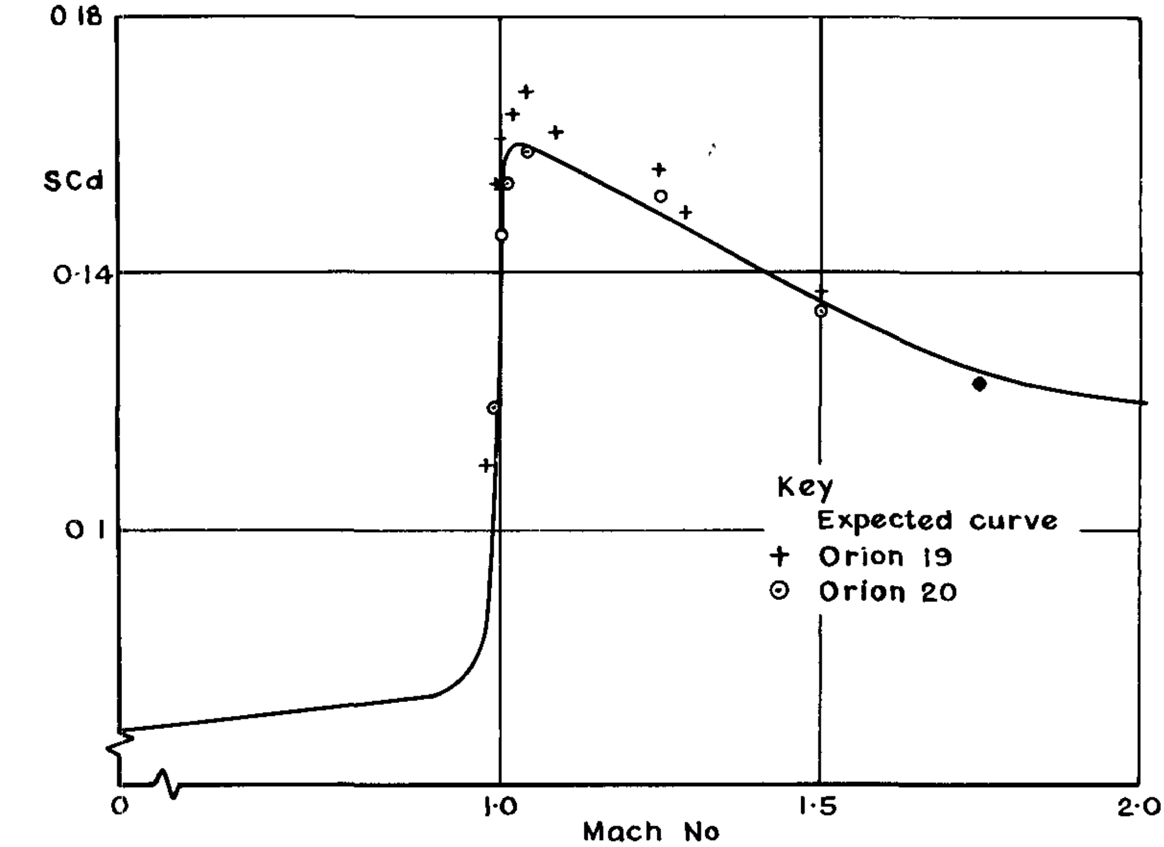


Fig. 7 Measured drag coefficient compared with value used in trajectory prediction

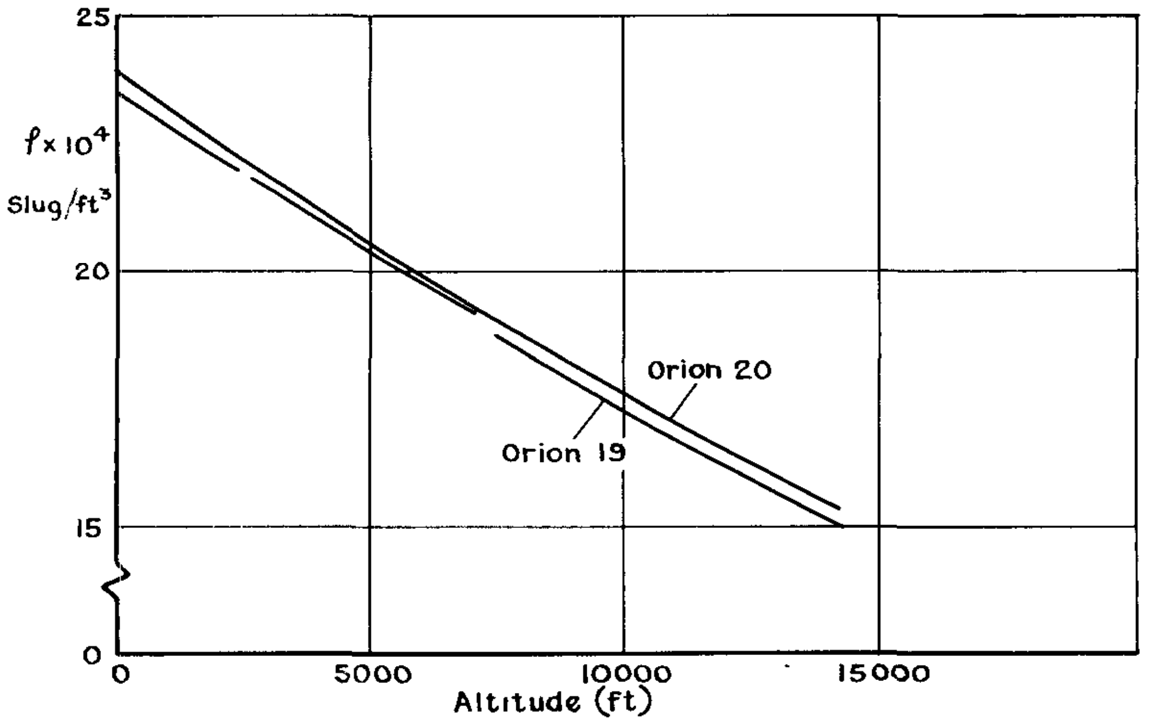


Fig. 8 Measured air density compared with standard atmosphere

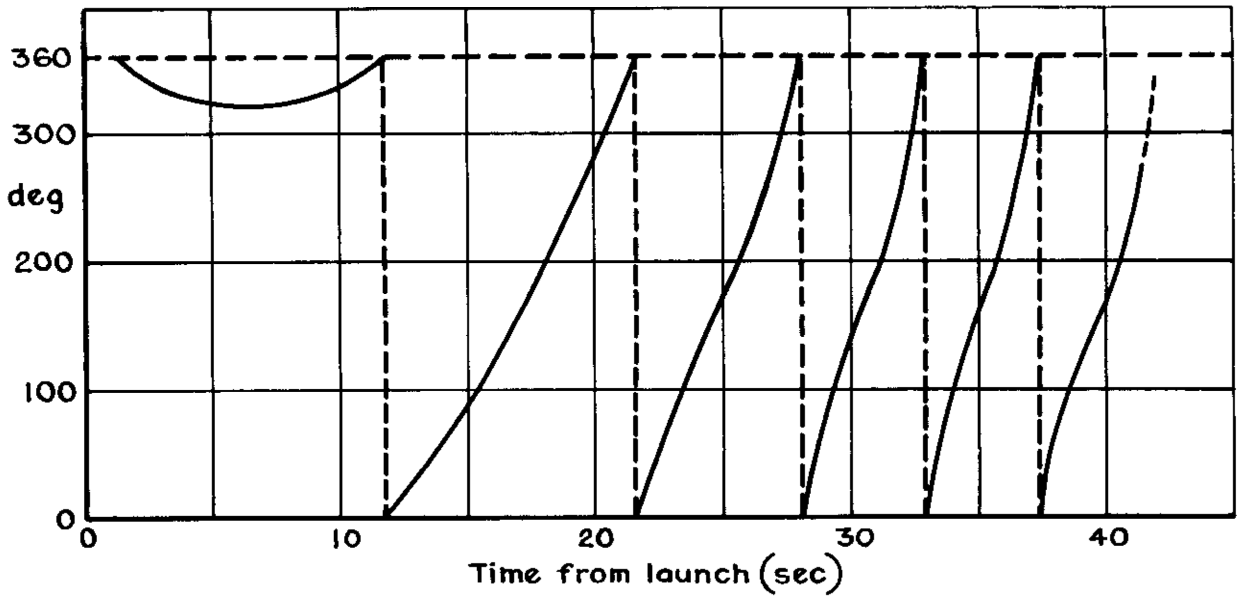


Fig. 9 Roll angle of Orion 20 as function of time

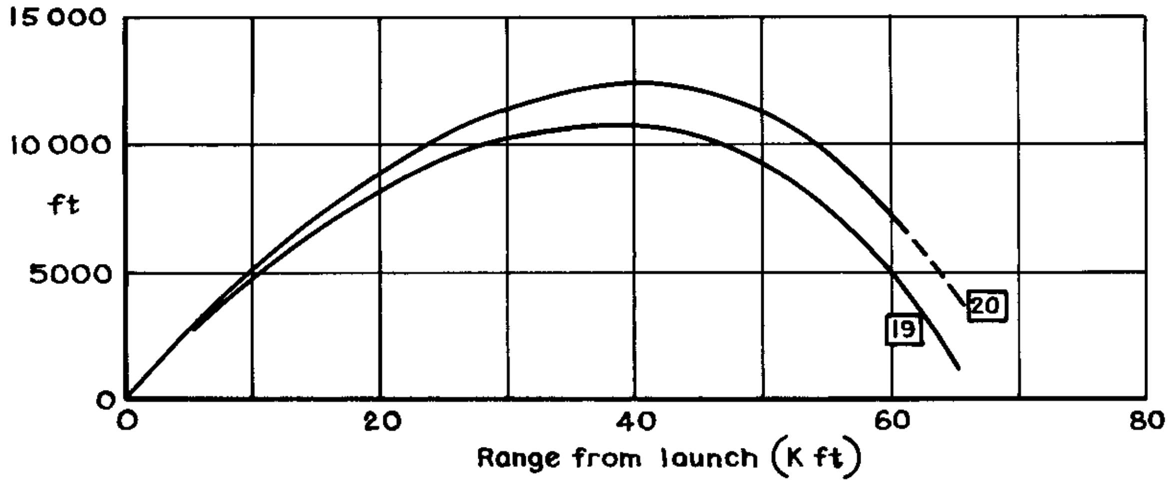


Fig. 10 Trajectory of Orion 19 and 20

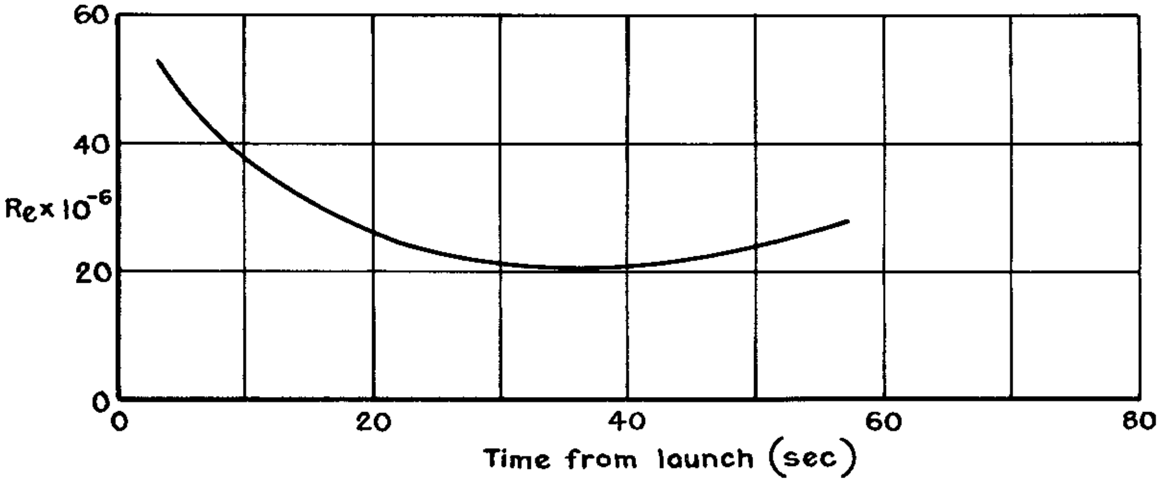


Fig. 11 Reynolds number (based on $\bar{C}$) for Orion 20

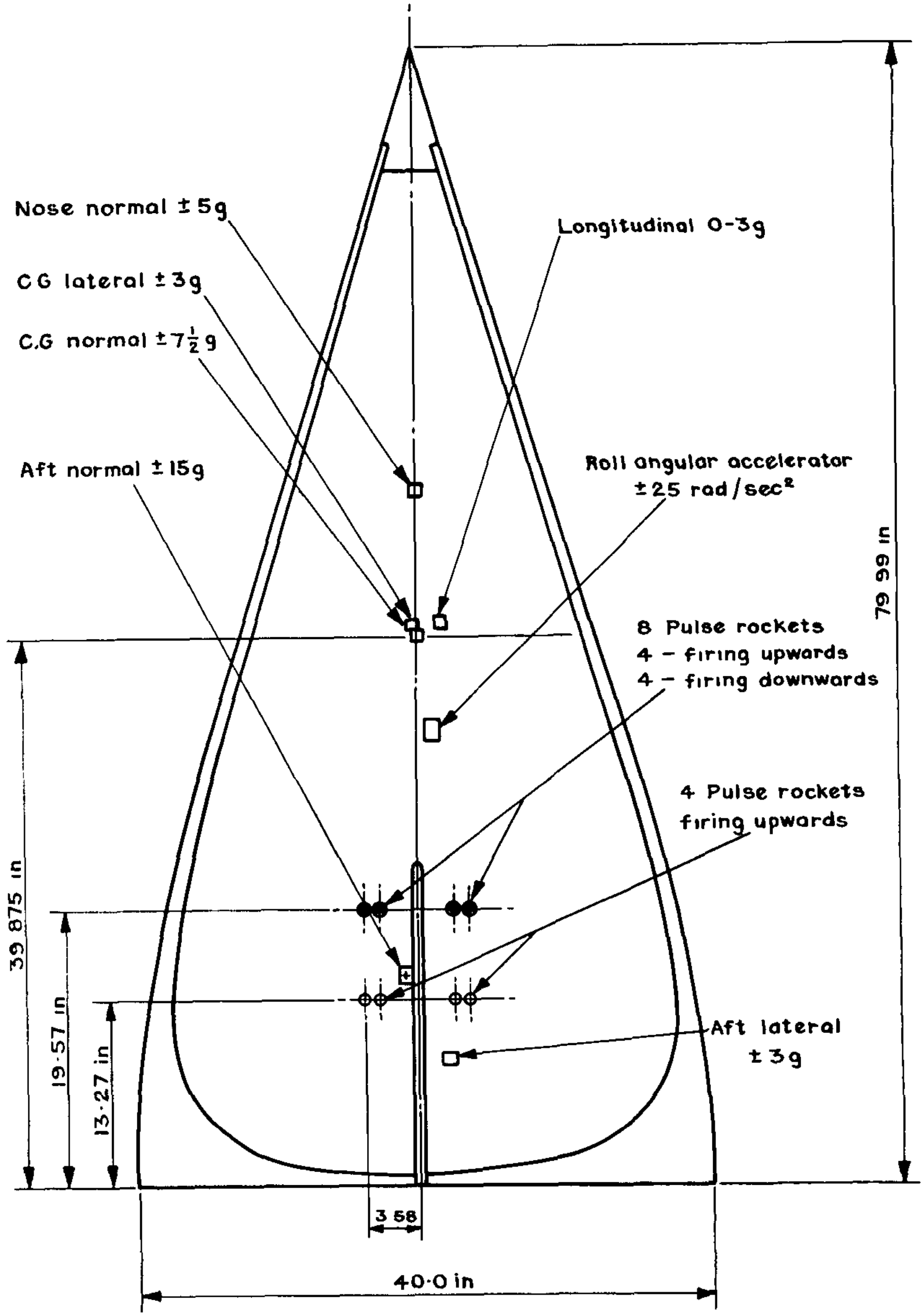


Fig. 12 Positions of accelerometers and pulse rockets

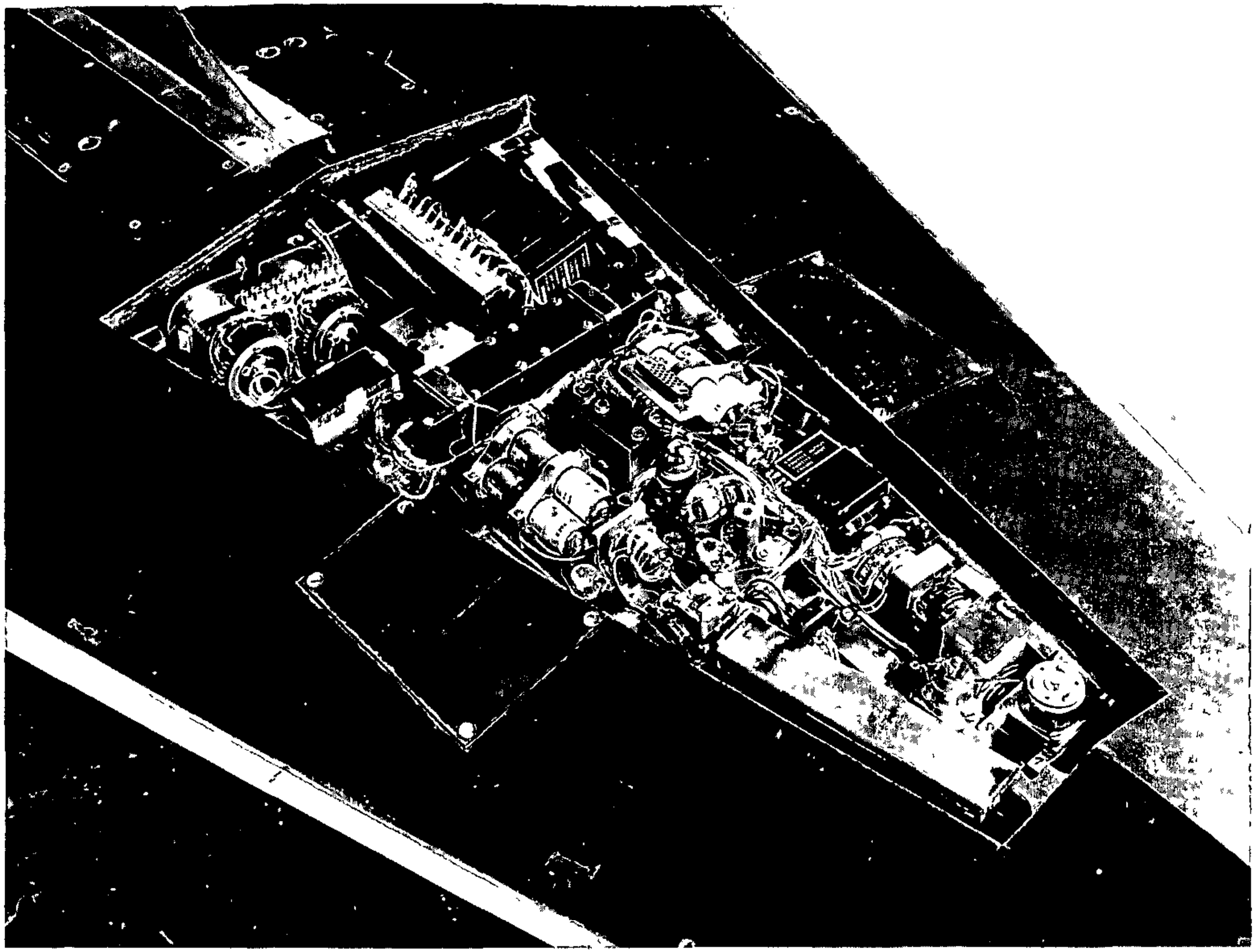


Fig.13. Close-up of instrumentation of Orion 20

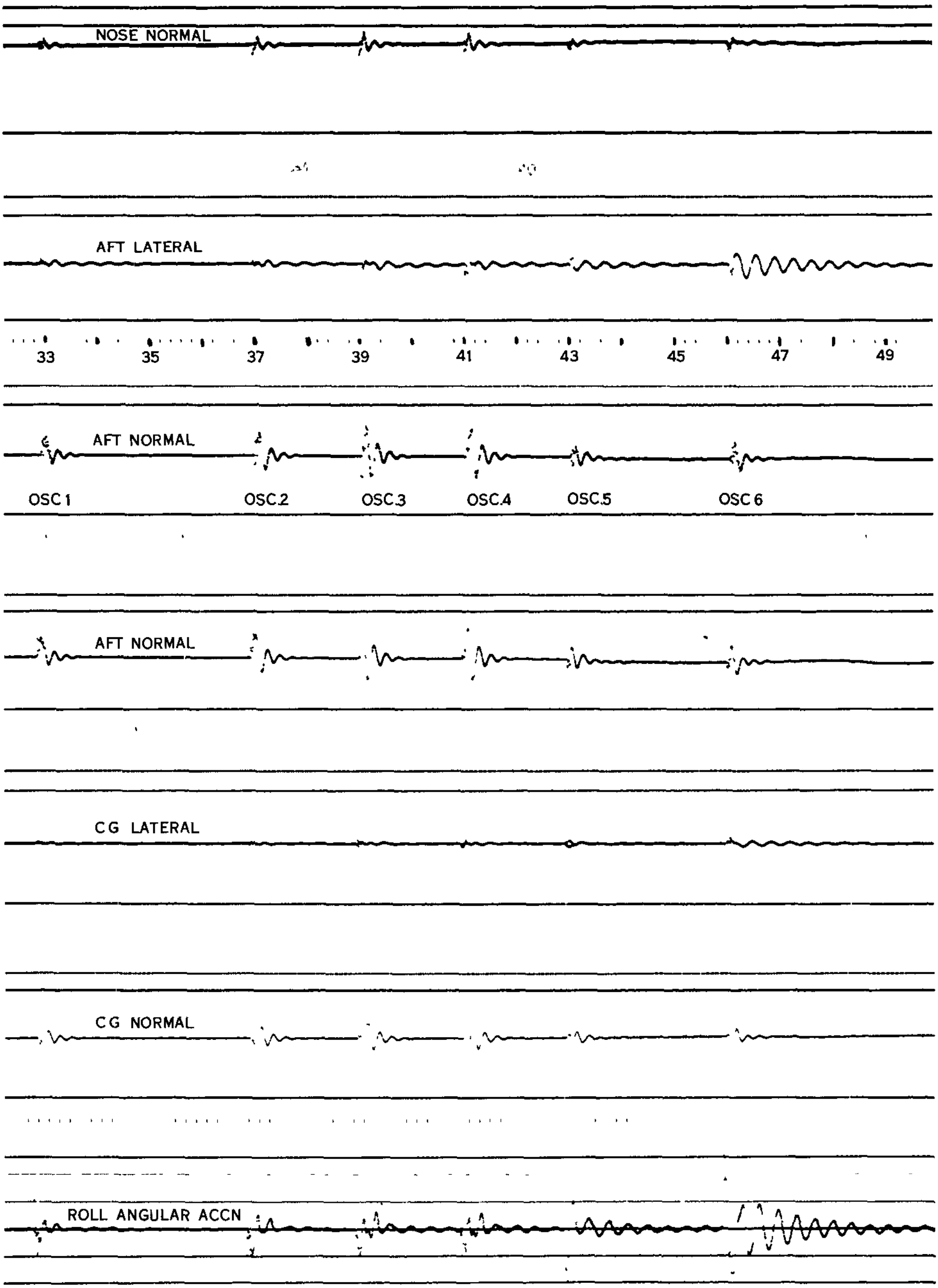


Fig.14. Telemetry record of part of Orion 20 flight

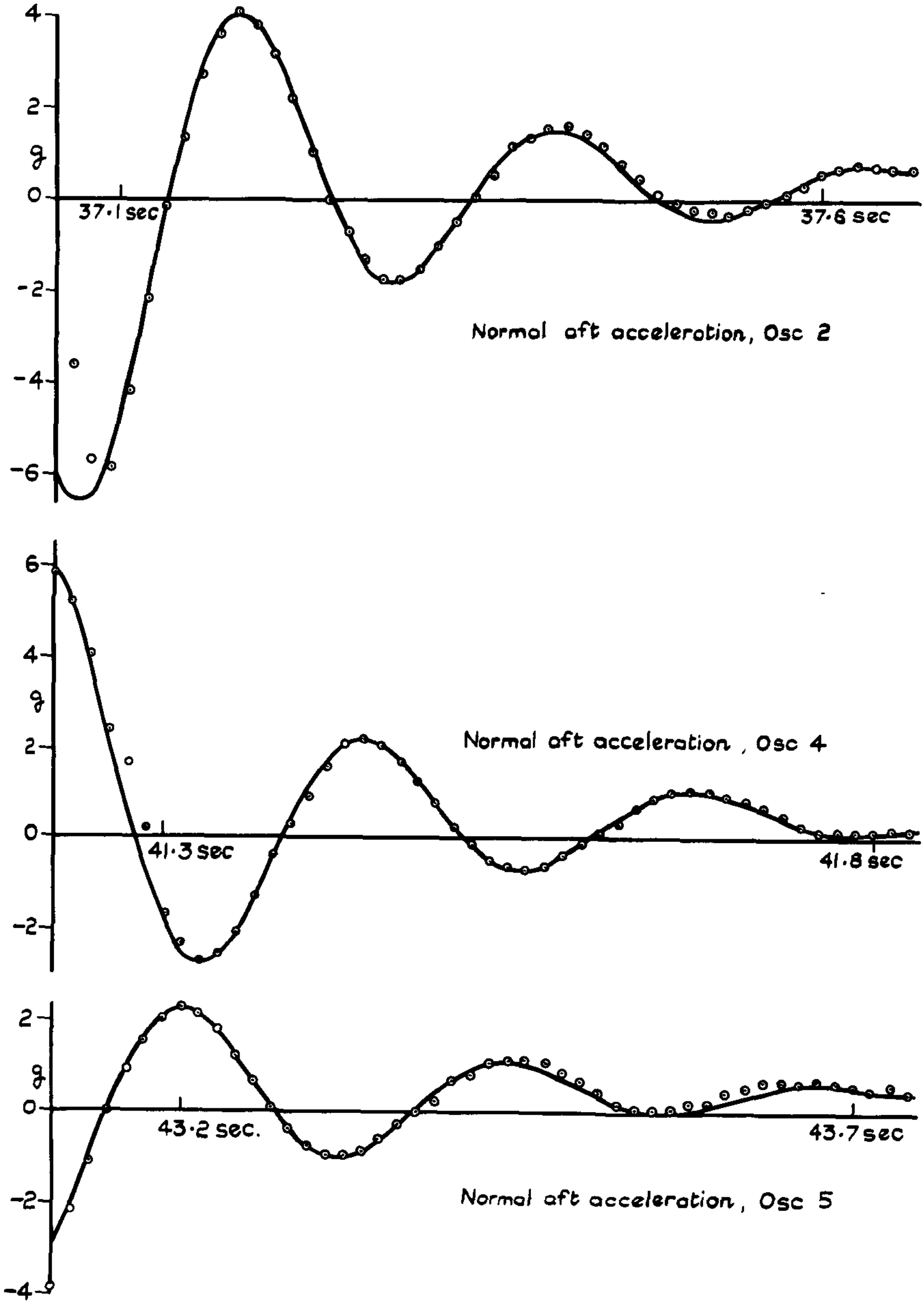


Fig.15 Some examples of best fit to normal aft acceleration on Orion 20

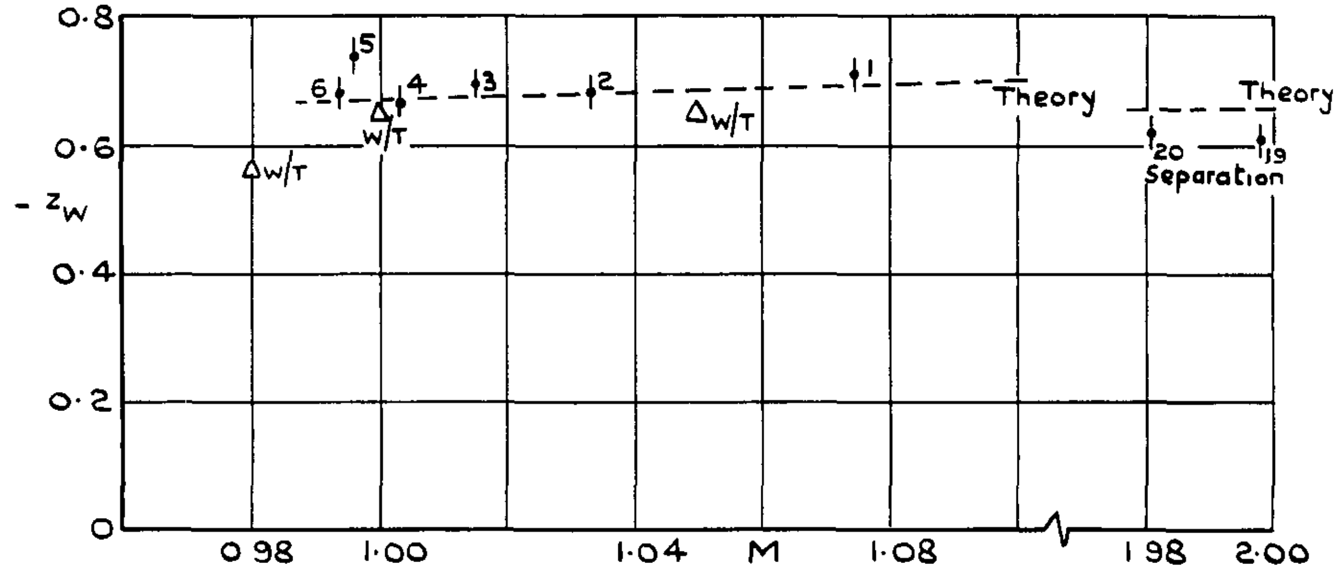


Fig.16 Normal force due to incidence z_w

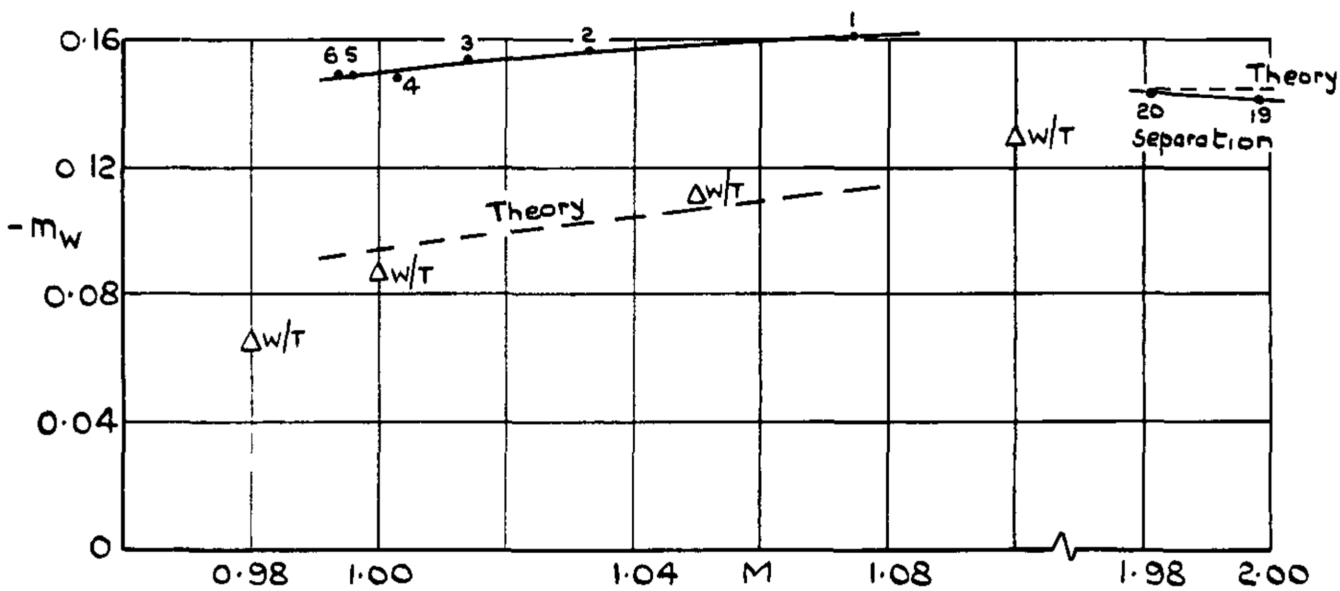


Fig. 17 Pitching moment due to incidence m_w

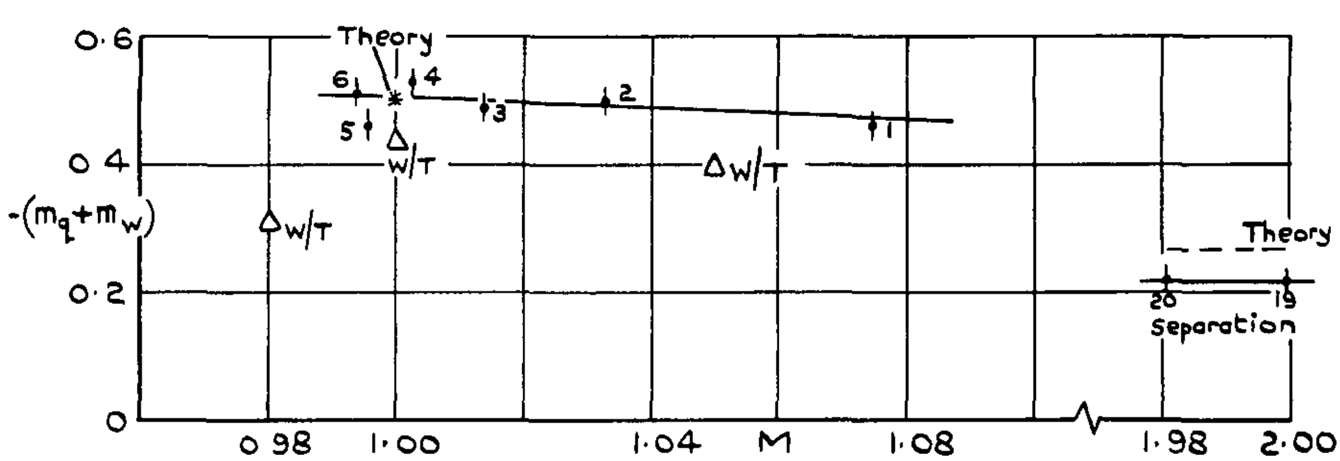
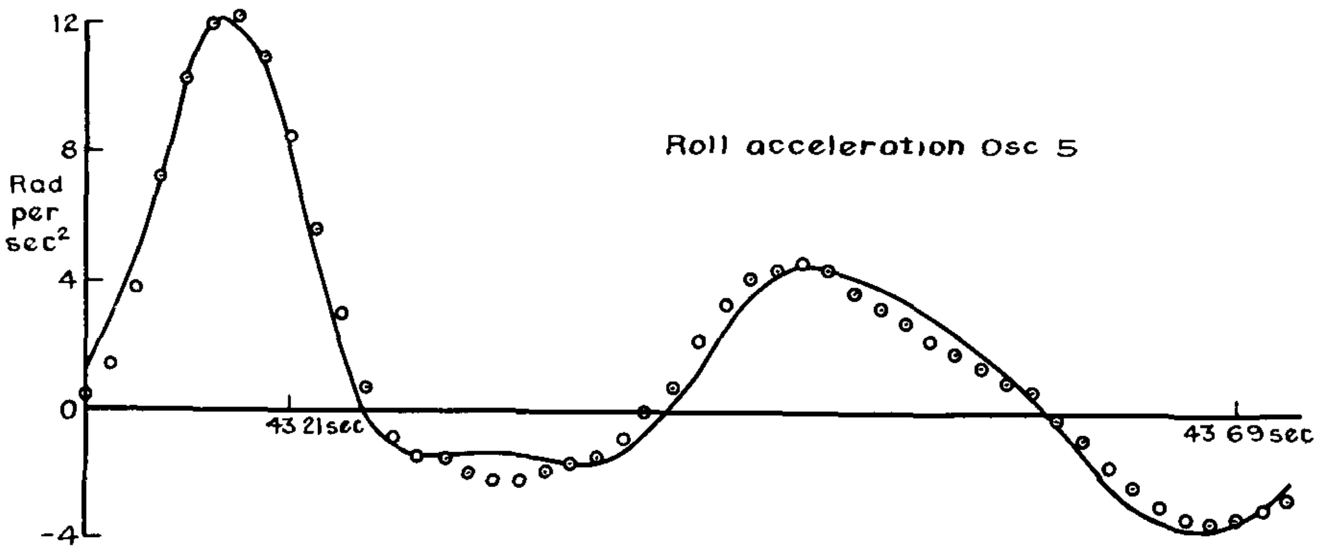


Fig. 18 Damping-in-pitching derivative m_q+m_w



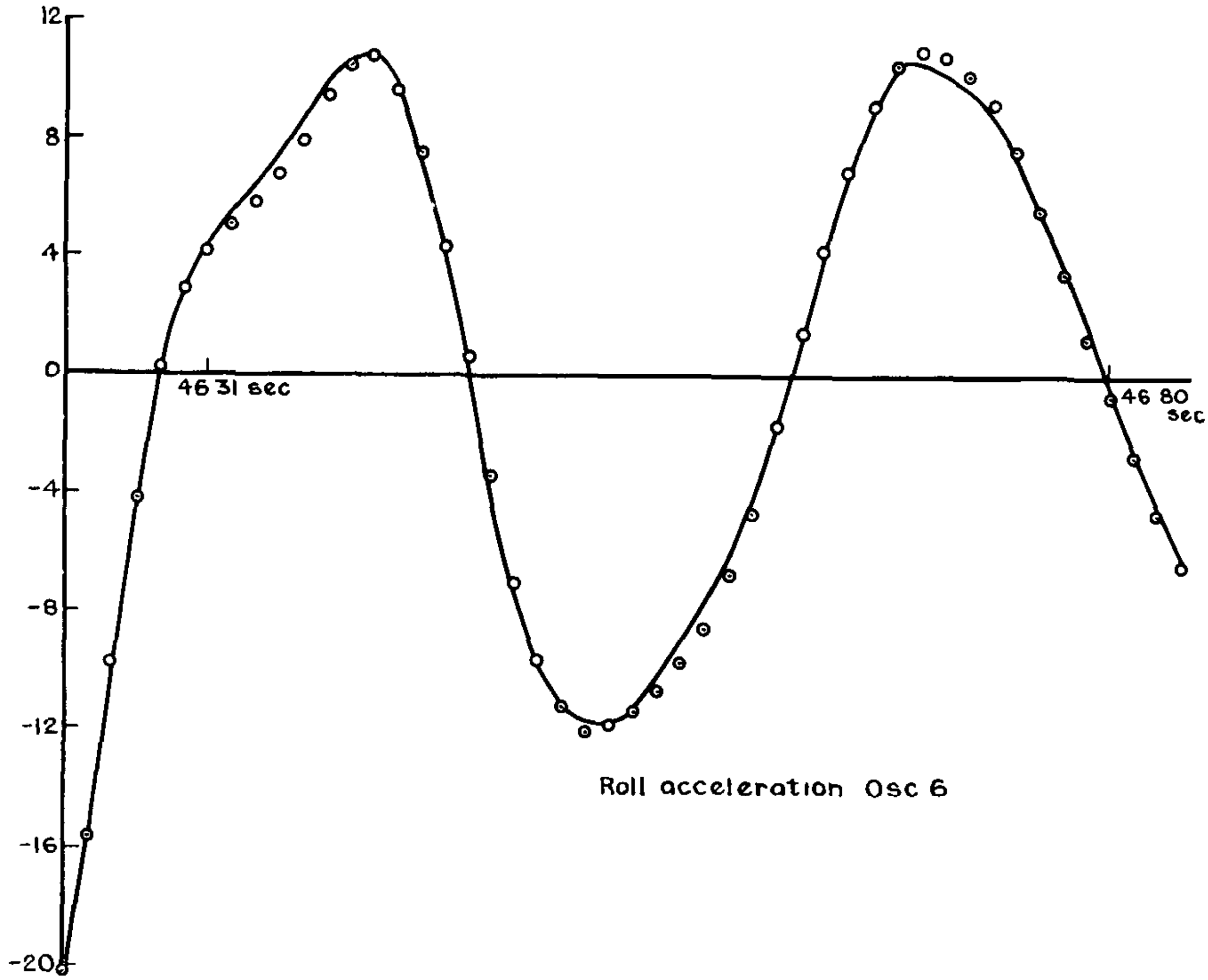


Fig.19 Some examples of best fit to roll acceleration on Orion 20

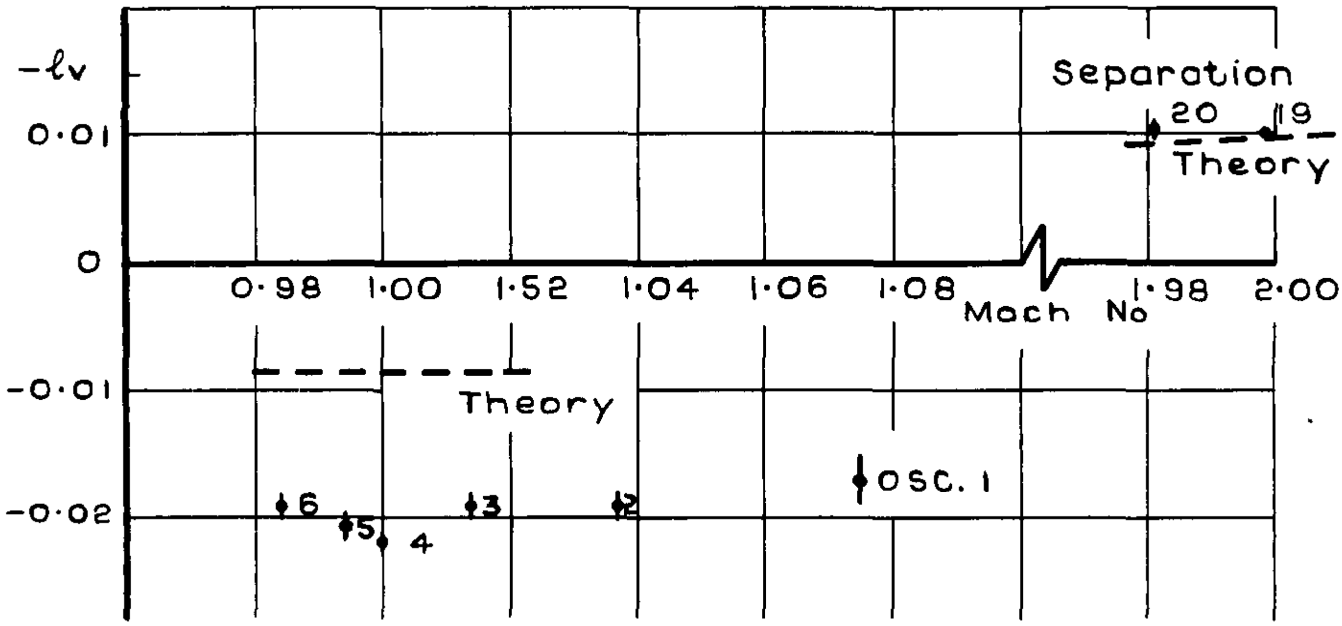


Fig 20 Rolling moment due to slideslip, ℓ_v

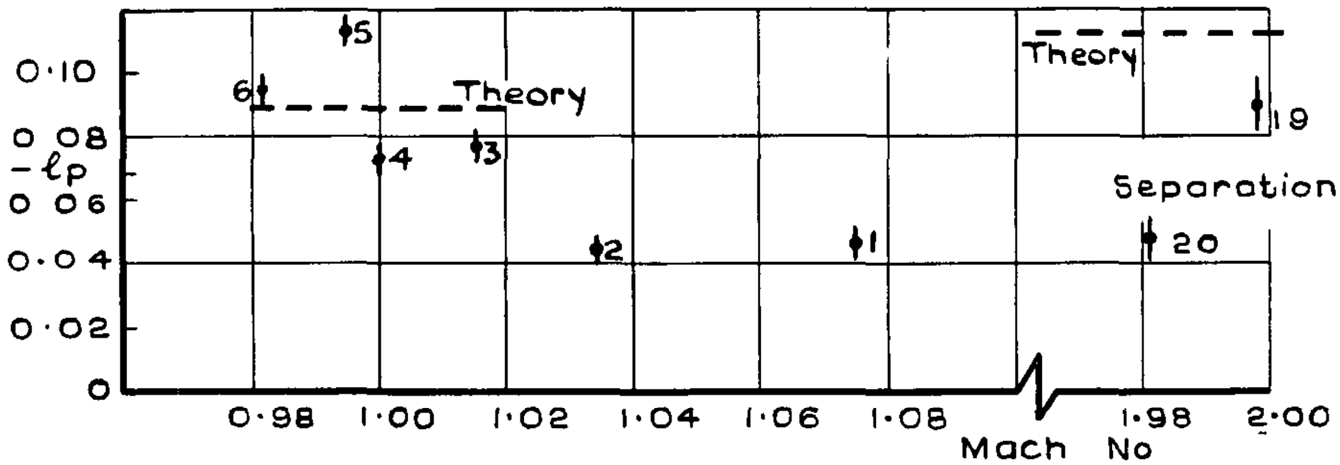


Fig. 21 Damping in roll derivative, ℓ_p

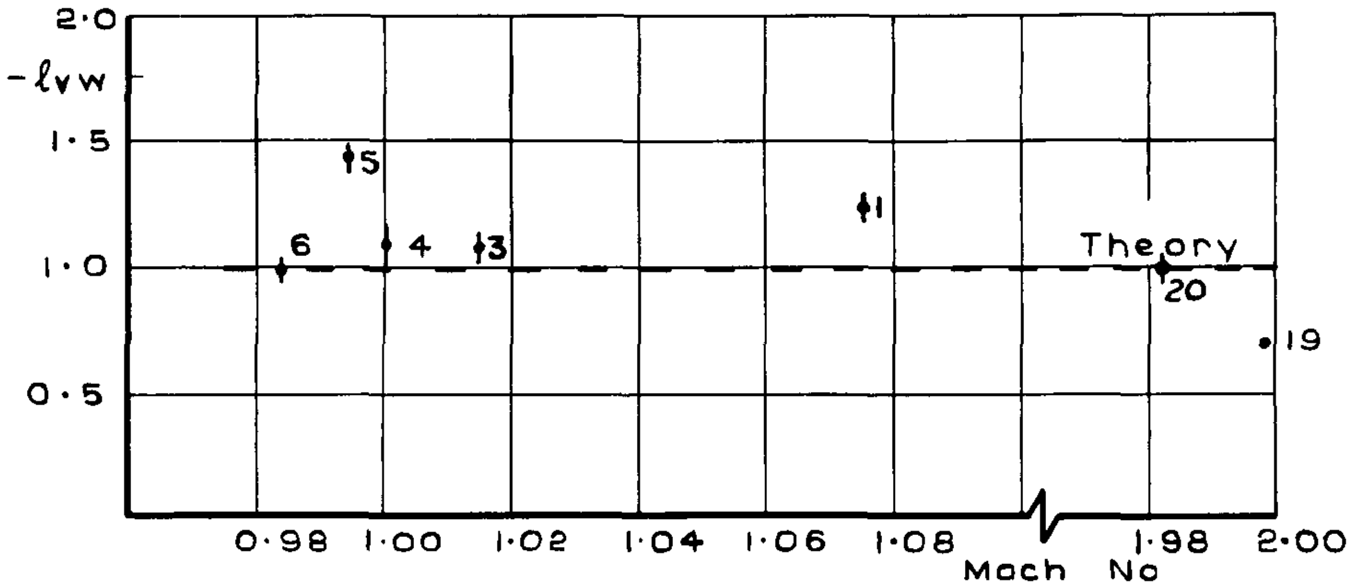


Fig. 22 Rolling moment to combined sideslip and incidence, ℓ_{vw}

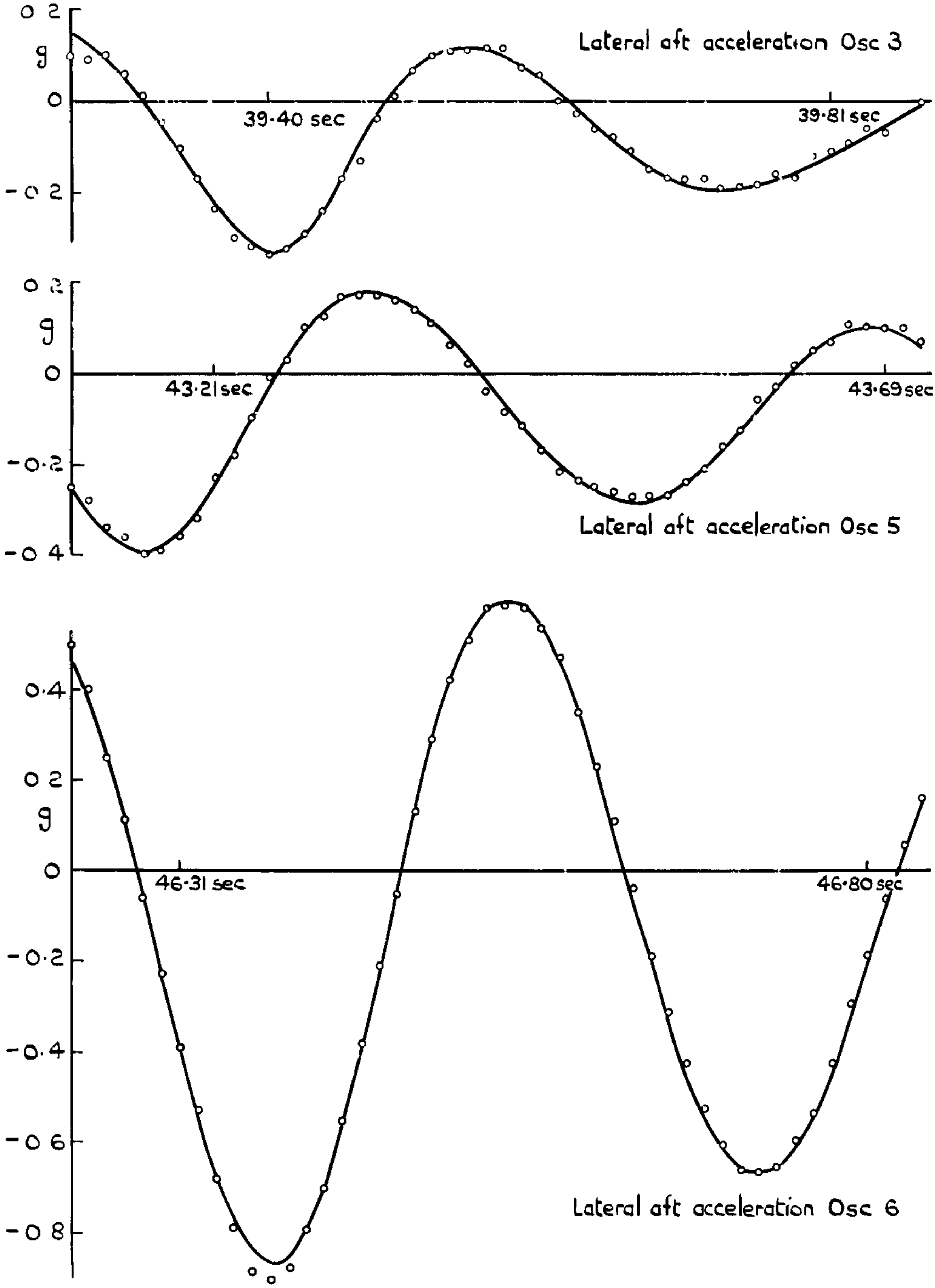


Fig. 23 Some examples of best fit to lateral acceleration on Orion 20

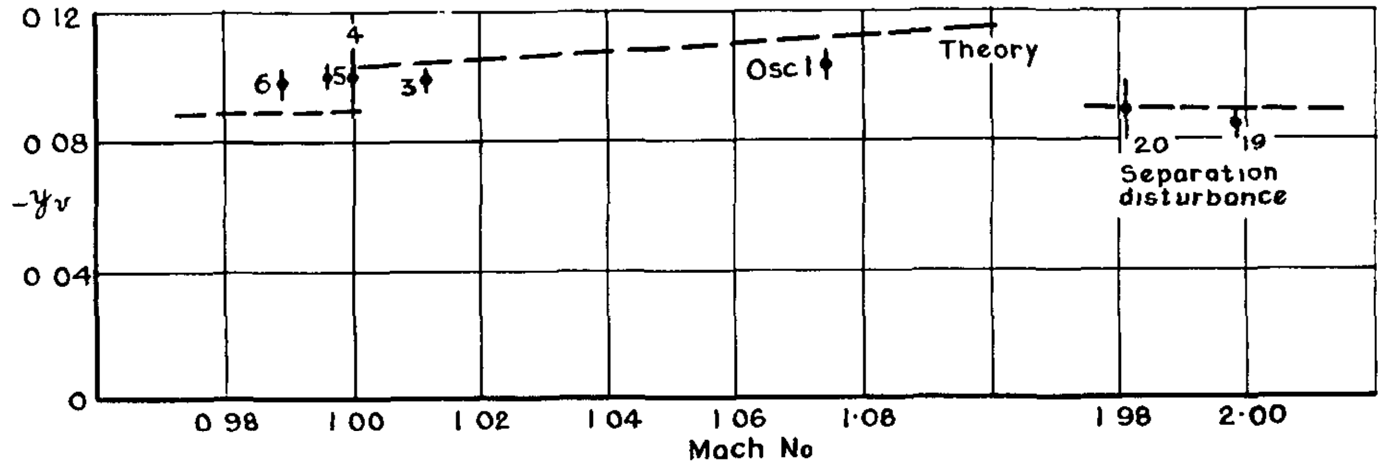


Fig. 24 Sideforce due to sideslip, y_v

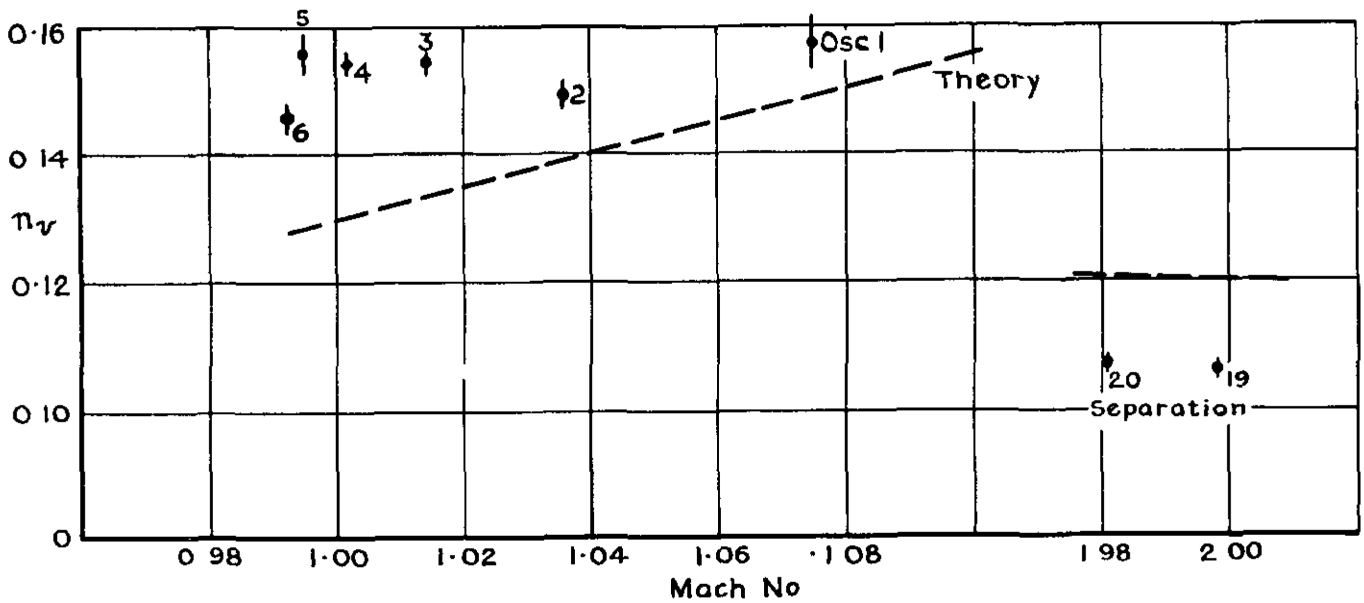


Fig 25 Yawing moment due to sideslip, n_v

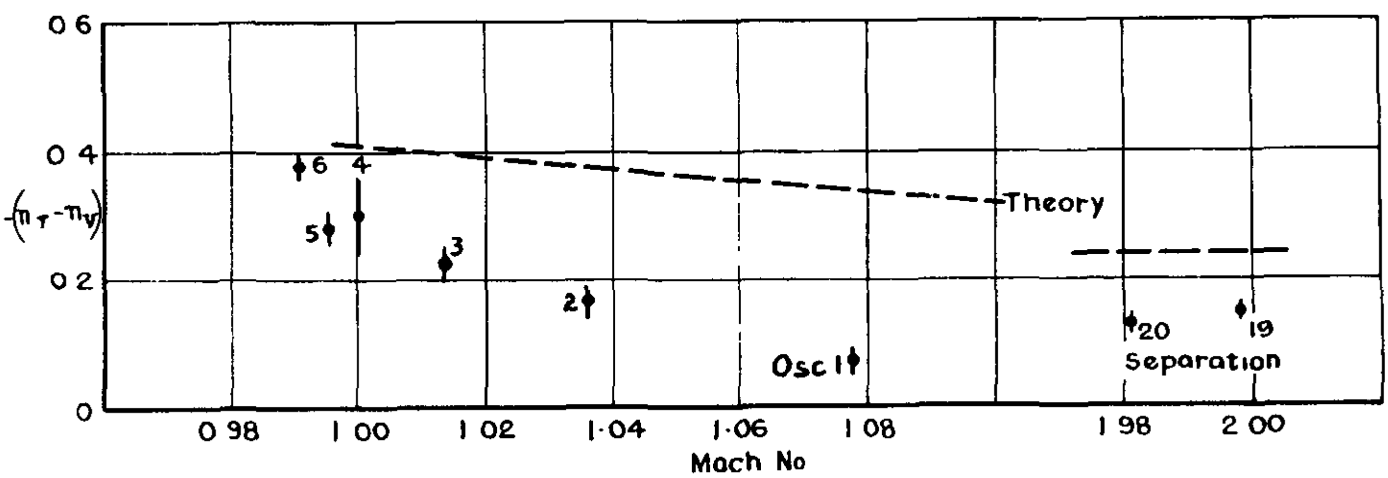


Fig. 26 Damping-in-yaw derivative, $n_r - n_v$

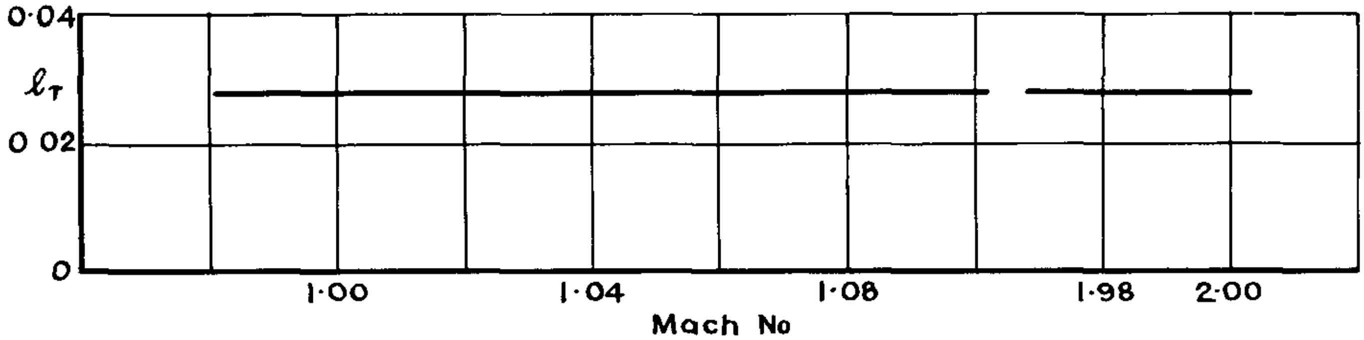


Fig.27 Theoretical estimate of rolling moment due to rate of yaw, ℓ_r assumed for analysis

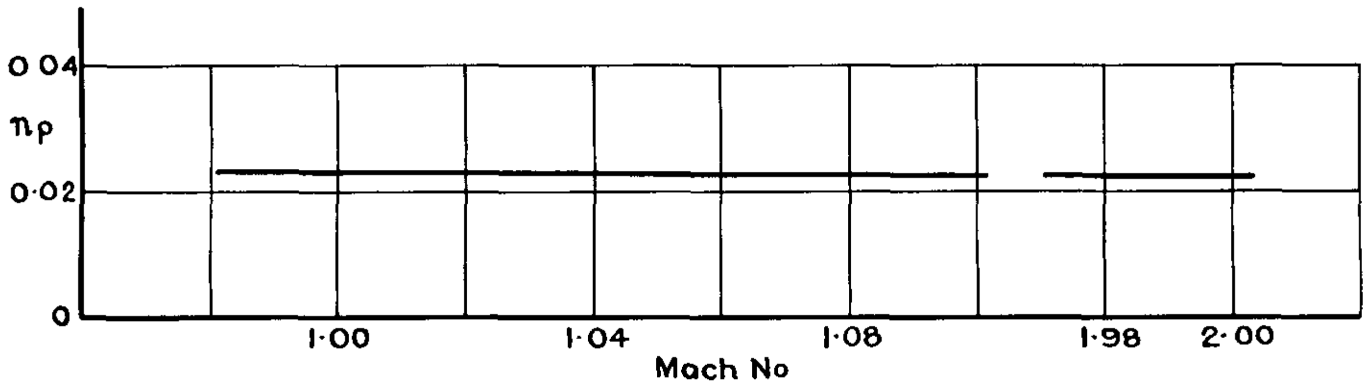


Fig.28 Theoretical yawing moment due to rate of roll, n_p assumed for analysis

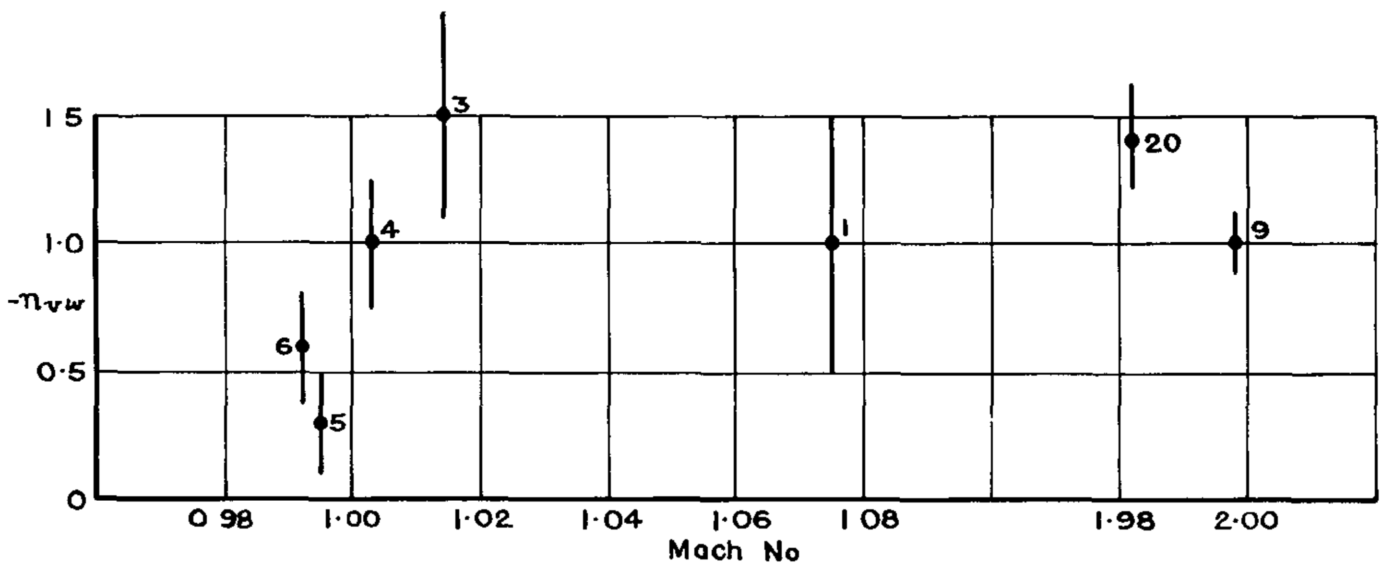


Fig.29 Yawing moment due to combined sideslip and incidence, n_{vw}

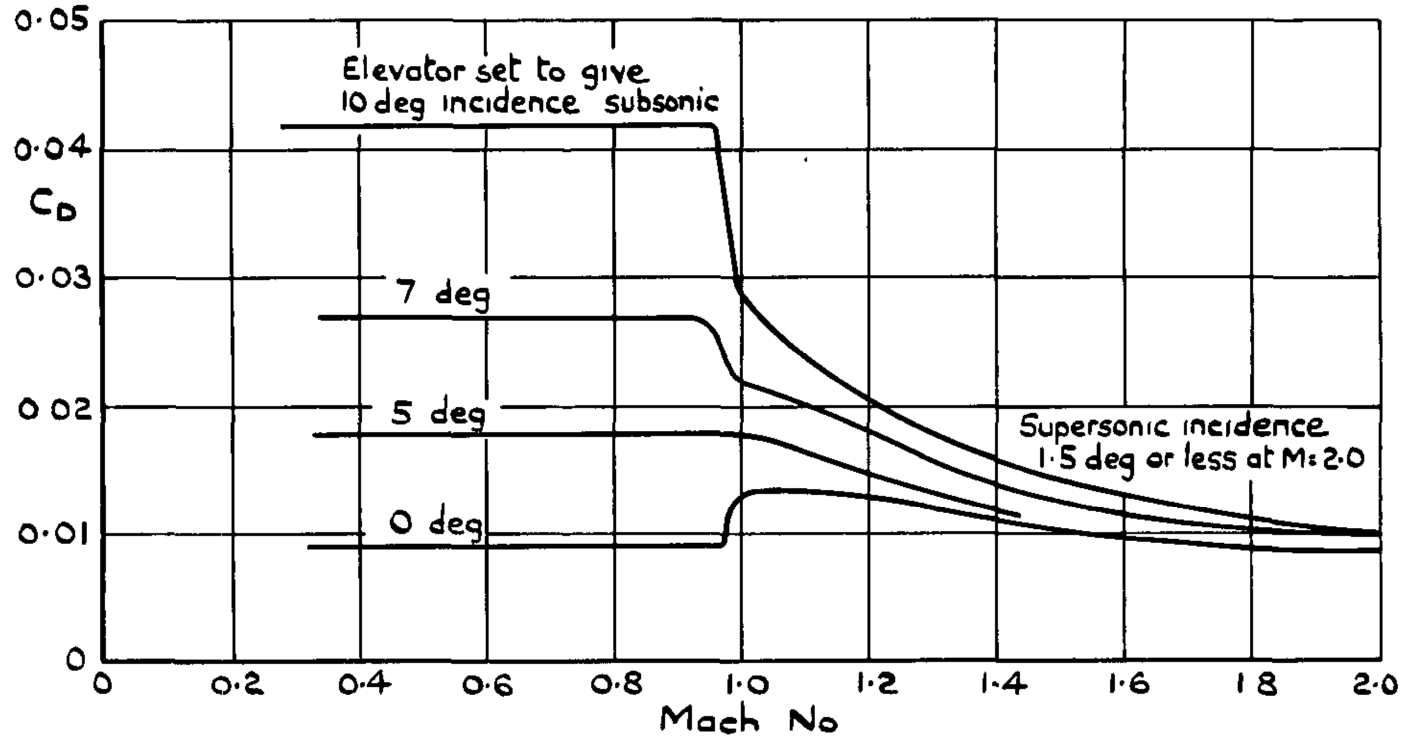


Fig.30 Variation of C_D with Mach No for Orion models with different elevator settings (cg at 1/2 chord)

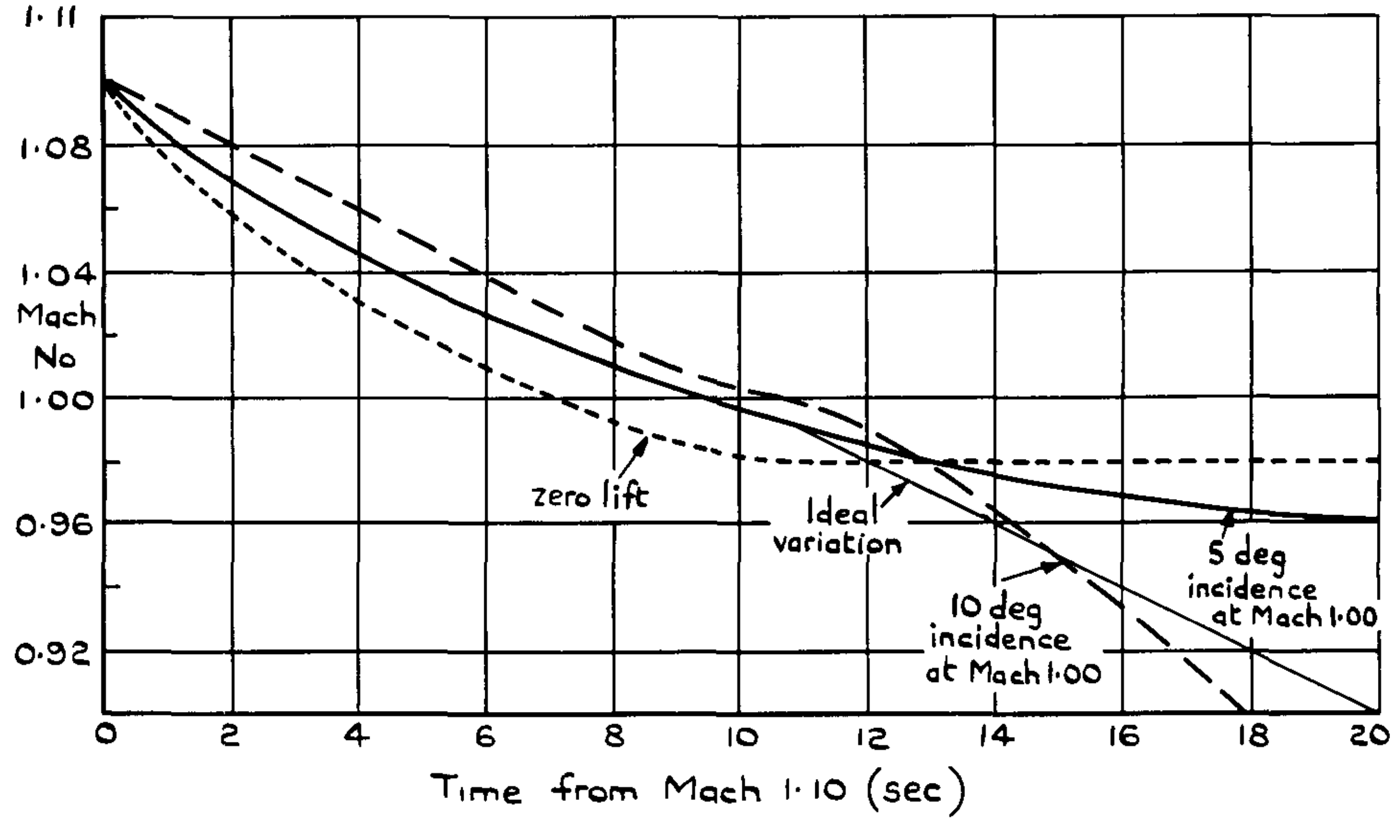


Fig.31 Transonic variation of Mach No with time for Orion at various incidences (Traj and weight adjusted for Mach 1 terminal V)

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