C.P. No. 1151

C.P. No. 1151

MINISTRY OF AVIATION SUPPLY

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

Scale Effects on Oscillatory Control-Surface Derivatives

By

A. W. Moore

Aerodynamics Division NPL

LONDON: HER MAJESTY'S STATIONERY OFFICE

1971

PRICE 60p net

C.P. No. 1151*

July, 1969

Scale Effects on Oscillatory Control-Surface Derivatives

- By -
A. W. Moore
Aerodynamics Division NPL

SUMMARY

The limited evidence available concerning scale effects on control-surface derivatives suggests a general tendency for in-phase hinge-moment derivatives to increase when Reynolds number increases but to decrease sharply when boundary-layer transition is artificially fixed. Damping (in-quadrature) derivatives in two-dimensional tests seem to follow a similar pattern, but with three-dimensional models, neither an increase in Reynolds number nor fixing boundary-layer transition appears to have any significant effect. It is therefore tentatively concluded that provided boundary-layer separation is not a feature of the flow, wind-tunnel tests should be done without fixing boundary-layer transition. However, it is emphasized that this conclusion is based on results from a limited number of papers and further measurements should be made, in which Reynolds number is systematically varied over a wide range with and without a means for fixing boundary-layer transition.

List of Contents

1./

---

* Replaces NPL Aero Report 1283 - A.R.C.31 368

1. Introduction

There is a need for wind-tunnel measurement of aerodynamic forces due to oscillating controls because at present theoretical treatment of the problem has limited practical application, particularly for high subsonic speeds. Furthermore the behaviour of an oscillating control is conditioned by the nature of the boundary layer on the aerofoil, so greater reliance must be placed on the results of wind-tunnel measurements in order that empirical methods may be formulated for modifying potential theory to allow for viscous effects. The final requirement is information appropriate to flight conditions. Most wind-tunnel tests are made at considerably lower Reynolds numbers than those of full scale so the question arises as to how well the wind tunnel measurements represent forces appertaining to free flight.

In steady flow it has long been recognised that wind-tunnel tests of models at low Reynolds numbers may not produce results consistent with full-scale flight; for most flight conditions of importance the boundary layer on the components of an aeroplane will be principally turbulent, whereas a laminar boundary layer is often obtained on the greater part of scaled-down replicas. Indeed, it has become the practice to add roughness on the forward part of small wind-tunnel models to ensure that the boundary layer is turbulent, thereby avoiding possibilities of laminar separations. This device is not entirely satisfactory, as noted by Loving[1] for instance, because the boundary layer so obtained may be much thicker relative to model chord than is the natural turbulent boundary layer in flight. Consequently for a wing at transonic speeds with a local supersonic region of flow terminated by a shock, the position of the shock wave may be forward of the position appropriate to flight. On the other hand, if natural transition occurs on a model the turbulent boundary layer may be too thin relative to model chord in which case the shock wave could be aft of its position appropriate to flight. With subcritical flow also, an unrepresentative pressure distribution may be obtained in a wind-tunnel due to incorrect boundary-layer simulation.

The present review is an attempt to assess experimental measurements of oscillatory control-surface derivatives in which Reynolds number and/or position of boundary-layer transition are varied. The evidence is so sparse that no firm conclusion can be reached concerning the influence of scale effects on the wind-tunnel tests. Nevertheless, some trends seem to be present and these indicate that results of certain two-dimensional tests might be more affected than three-dimensional measurements: two-dimensional measurements are therefore considered first in Section 3. From the available three-dimensional results discussed in Section 4, it appears that the in-quadrature hinge-moment derivatives are not particularly sensitive to changes in the boundary layer on the wing.

2. General Notes

Following an extensive literature search, it is apparent that there is little experimental information concerning oscillatory control-surface derivatives, and that only a few of these published measurements include changes in Reynolds number alone or changes in boundary-layer condition. Furthermore, the author has found only a handful of papers which consider derivatives other than oscillatory control or tab moments. Typical of these are papers by Guyett and Curran[2] and Molyneux and Ruddlesdon[3] where wing forces are measured directly, and papers by Bergh[4] and Hertrich[5] where oscillatory pressures are integrated to

obtain/

obtain the aerodynamic forces due to control deflection. With steady flow the situation is improved and the results discussed in Sections 3 and 4 include some steady measurements of scale effect on the rates of change of various forces with control deflection: any such effect should also be applicable to in-phase components of corresponding oscillatory forces unless the frequency parameter is large. Table 1 contains a summary of direct experimental evidence, i.e., experiments which show the effects of a change in Reynolds number and/or the effects of fixing boundary-layer transition. For two-dimensional flow it seems that the magnitude of hinge-moment derivatives tends to increase with Reynolds number but to decrease when boundary-layer transition is artificially fixed. In three-dimensional tests the in-phase derivatives appear to behave in a similar way but the in-quadrature derivatives do not change in value. Other papers not referred to in Table 1 cover a wide range of parameters such as model planform, model and control-surface section, hinge-line position etc., but independent tests on compatible models have been made in only two cases[33,34]. In Ref.33, the hinge moments due to a full-span flap on a half-delta wing are measured in a wind-tunnel giving a Reynolds number (based on root chord) of about 3×10^6, whilst in Ref.34 the results are given of a flight test on a similar half-model giving a Reynolds number of about 10×10^6. Unfortunately, the flight test used a decaying oscillation technique with only a few cycles suitable for analysis at a given flight condition. The reliability of the measurements is therefore questionable.

Table 1 includes the values of Reynolds number based on wing chord for the models tested. It can be seen that increases achieved in the experiments are sometimes quite small compared with typical full scale values. In particular for the two-dimensional tests the maximum increase in Reynolds number[8] is from the range 1.2×10^6 to 3.7×10^6 to the range 3.0×10^6 to 9.2×10^6, but this caused seriously large changes in measured hinge moments. Since a full-scale Reynolds number might exceed 15×10^6, the implication is that two-dimensional tests may not give representative values of aerodynamic forces due to an oscillatory control. This is discussed further in Section 3. The results for three-dimensional flow cover a satisfactory range of Reynolds number and the trends of scale effects on aerodynamic forces should be realistic although there are only two cases[28,36] where oscillatory derivatives are measured both at a low Reynolds number and at a value appropriate to full-scale conditions.

3. Two-Dimensional Tests

The experiments reported in Refs.6, 7 and 8 contain many similar features. Wight[6,7] measured oscillatory control derivatives for a wing-flap-tab system in which a symmetric 15% thick aerofoil with a 20% flap and 4.2% tab was tested at low speeds ($V \leq 200$ ft/sec, 61 m/sec) in a 9 ft × 7 ft (2.75 m × 2.14 m) tunnel at frequencies in the range $0.22 < \nu < 3.14$. Andreopoulos et al[8] likewise measured control derivatives for a wing-flap-tab system in which a symmetric 10% thick aerofoil with a 40% flap and 10% tab was tested at speeds up to 240 ft/sec (73 m/sec) in a 12 ft × 8.5 ft (3.66 m × 2.59 m) tunnel at frequencies in the range $0.5 < \nu < 4$. In both cases the total chord of the model was 30 in (76 cm). If any scale effects are present their influence on the values of the measured derivatives ought to have similar trends in the two cases. The results in Ref.8 show the changes in derivatives due to an increase in Reynolds number obtained by raising the tunnel stagnation pressure from 1 atmosphere to 2.5 atmospheres: transition of the boundary layer from laminar to turbulent was "natural" since there was no roughness band on the model. Wight's results[6,7] were obtained at a constant stagnation pressure but it is argued that, in the absence of compressibility effects at the low speeds used, changes caused by an increase in tunnel speed with constant frequency parameter are effectively those due to an increase in Reynolds number; the values of Reynolds number lay in the range $1 \times 10^6 < Re < 3 \times 10^6$. An investigation was also made of the effect of fixing transition to turbulence at various chordwise positions on the model.

Measured/

Measured derivatives from Ref.8 are illustrated in Fig.1 where hinge moment due to flap oscillation is plotted against frequency parameter. It should be noted that the large scatter in the results is partly due to magnified reading errors arising from the calculation of stiffness and damping from values of parameters proportional to ν^2 times stiffness and ν times damping which were plotted against an inverted frequency parameter. The information given in Ref.8 is not sufficient to enable the reader to differentiate between the separate effects of Reynolds number and frequency, so a direct comparison cannot be made with the results of Ref.7 because Wight shows clearly that the reduced velocity is not a universal parameter, i.e., for a given value of ν different values of the derivative can be obtained as speed and frequency are appropriately varied. Hence, the results in Ref.8 are examined for an indication of changes associated with the increase in stagnation pressure at a given value of the reduced frequency. The tests were apparently done at speeds in the range 80 ft/sec (24 m/sec) $< V <$ 240 ft/sec (73 m/sec) so the Reynolds number with atmospheric stagnation pressure varies from about 1.2×10^6 to 3.7×10^6, and with a stagnation pressure of 2.5 atmospheres the range becomes approximately $3.0 \times 10^6 < Re < 9.7 \times 10^6$. Fig.1 shows a consistent increase in value of the damping derivative with Reynolds number increase and a similar pattern can be seen for the cross-derivative tab damping due to flap oscillation in Fig.2. However, for the stiffness (in-phase) derivatives in Figs. 1 and 2, it is difficult to see any reliable trend although the values of $-h_\beta$ with $\nu < 1.2$ increase consistently with increased Reynolds number. Measurements of the flap torque due to tab oscillation and tab torque due to tab oscillation were not noticeably affected by changes in Reynolds number.

It is seen in Fig.3 that the value of hinge-moment damping measured by Wight[6, 7] also increases with Reynolds number provided transition is fixed although changes in the stiffness derivative h_β are small. Of the remaining derivatives considered (t_γ, $t_{\dot\gamma}$, h_γ, $h_{\dot\gamma}$, t_β, $t_{\dot\beta}$) only $h_{\dot\gamma}$ increases with Reynolds number, the others are practically unchanged. However, when Reynolds number is kept constant serious changes may occur on fixing transition as can be seen in Figs.4 and 5. Natural transition occurred at 0.68 c moving forward to 0.65 c at the highest speed and tests were made with transition fixed first at 0.4 c and then at 0.1 c. With the exception of the cross-derivative t_β, the in-phase derivatives sharply decrease at all speeds as transition is moved forward; the damping derivatives likewise decrease (with the exception of $t_{\dot\beta}$) at the lowest speed but the effect is reduced as Reynolds number increases. Indeed, as shown in Fig.5, if the frequency is sufficiently low at the higher speeds, then the damping can increase with forward movement of transition.

The trends from these results appear to indicate that tests at low speeds should not be made with transition artificially fixed on a model unless the frequency of oscillation is low. Damping derivatives measured with small Reynolds number will probably be low in value, but, at most frequencies, fixing transition to simulate a full-scale turbulent boundary layer decreases the damping still further. For the stiffness derivatives, fixing transition seriously decreases their values at all frequencies of oscillation whereas with natural transition there are usually only small increases over the range of Reynolds number achieved in Refs.6, 7 and 8. Bryant and Batson[9] report some steady-flow measurements on a wing-flap model having the same section and dimensions as the model used by Wight. The Reynolds number was 1×10^6 and it is again shown that the value of dC_H/d_β (equivalent to $2h_\beta$) sharply decreases as the position of

boundary-layer/

boundary-layer transition is moved forward; they also measured the lift associated with flap deflection and found that dC_L/d_β likewise decreases when transition is fixed on the model. Steady-flow tests at the high Reynolds number 14×10^6 for a 12% thick low-drag aerofoil with a 24% flap are discussed in Ref.10. Natural transition occurred at mid-chord and fixing transition with a roughness band at the leading edge reduced dC_H/d_β by 4% and dC_L/d_β by 2%. These changes are somewhat less than those at low Reynolds number but are in the same direction.

Since the low-speed tests discussed so far do not include any results measured with high angles of incidence, it is probable that there are no cases involving boundary-layer separation. It follows that the main influence of the boundary layer manifests itself as an effective thickening of the aerofoil, so it is important in small-scale tests to obtain a representative boundary-layer thickness. This would explain why the results indicate that transition should not be artificially fixed because this would almost certainly give a turbulent boundary layer which is thicker relative to model chord than would be obtained on a full scale. However, when tests are made at high subsonic speeds with a region of supercritical flow on the model terminated by a shock, it may be essential to ensure that the boundary layer is turbulent because of the substantial differences which may arise between laminar and turbulent shock-wave boundary-layer interaction. This could be particularly true for investigations of control-surface buzz because the behaviour of an oscillating flap is often closely associated with the motion of the shock wave on the aerofoil[11]. Several investigations have been made of scale effects on steady-flow measurements, but no criteria that can reliably be applied to oscillatory tests have been suggested for the simulation of full-scale conditions. Harrin[12] reports large differences between pressure distributions for laminar and turbulent boundary layers ahead of a shock at a Reynolds number of 3×10^6, whilst in a corresponding flight test giving a Reynolds number of about 20×10^6 there was little change in pressure distribution when boundary-layer transition was fixed near the leading edge. Furthermore he notes that the distribution at the low Reynolds number with a turbulent boundary layer was very similar to that in the full-scale test. Conversely, as noted earlier, Loving[1] reports a comparison between tests at low Reynolds number and a flight test which showed that the best agreement was obtained with no transition on the model. He suggests that when transition was fixed in the tunnel test the resulting turbulent boundary layer was too thick relative to model chord. Haines et al[13] also note this source of error in fixing transition at low Reynolds number but suggest that the boundary layer will not be too thick provided the Reynolds number is greater than about 1.8×10^6. In a recent paper, Pearcey et al[14] show that this criterion remains valid only when adverse pressure gradients downstream of the shock are not strong enough to influence the overall flow pattern. In such cases, the pattern of development depends primarily on changes in the immediate vicinity of the shock, and more on those in the external flow adjacent to the separating boundary layer than on those in the boundary layer itself. The whole shock-induced phenomenon is then relatively insensitive to scale effects and to differences in boundary-layer thickness or profile provided that the boundary layer is turbulent at the separation point. But when rear separation is already present or incipient when the shock and the separation at the foot of the shock appear, this modulates the rate and magnitude of the development, and in many cases dominates it. Small changes in the disturbance at the foot of the shock, resulting from differences in the thickness or profile of the boundary layer approaching the shock, assume greater significance than they otherwise would.

It/

It is suggested that the measurements by Loving[1] involved a flow of the latter type, but no recommendation is made as to what minimum value of Reynolds number should be used to eliminate such effects. Blackwell[15] describes an approach in which these scale effects are avoided by properly locating the point of boundary layer transition on a model. The required location is predicted by theoretically simulating the boundary-layer characteristics at the aerofoil trailing edge using a theoretical model of a subcritical part-laminar part-turbulent boundary layer. But the point is made in Ref.14 that as attention moves from cruise lift coefficients with shock waves that are well aft on the chord to higher lift coefficients and lower Mach numbers for which shocks approach the leading edge, so the range of difference in transition position that is available for compensating the effects of Reynolds number becomes smaller and smaller.

Despite the uncertainties in the specification of the position at which transition should be fixed on some small-scale models, these results with steady flow suggest that most wind-tunnel tests at high subsonic speeds should be made with a turbulent boundary layer. Nakamura and Woodgate[16] fixed transition at the leading edge of their model in a recent investigation of control-surface buzz. They used a 10% thick symmetric aerofoil with a 25% flap and the Reynolds number of the tests was varied progressively from 1.6×10^6 to 3.2×10^6 by increasing tunnel stagnation pressure. As seen in Fig.6 there are substantial changes in the value of the damping derivative (note that damping is negative) and for values of the frequency parameter less than about 0.36, there are also substantial increases in hinge-moment stiffness when Reynolds number is increased. The latter result is similar in trend to the low-speed results discussed earlier when, as in Fig.1 for instance, it was only for the lower frequencies that hinge moment noticeably varied with Reynolds number. Loiseau[17] reports that in some measurements of hinge-moment damping on a 6% thick two-dimensional aerofoil with a 30% flap, instability was obtained at about $M = 0.92$. However, when boundary-layer transition was fixed on the model the instability disappeared: the Reynolds number at this speed was about 3.8×10^6. A similar trend has been found by Wight[18] for a 10% thick RAE 102 section with a 25% flap. The Reynolds number of the tests was about 4.5×10^6 and it is clear in Fig.7 that the tendency for instability is much reduced when transition is fixed near the leading edge: it can also be seen that the positive damping at the lower speeds is considerably reduced. It is known that this is an example in which the character of the shock boundary-layer interaction is changed on fixing transition from a laminar to a turbulent separation. Assuming that the RAE 102 aerofoil tested at zero incidence is not subject to the rear separation of the highly loaded sections mentioned in Ref.14, then the results in Fig.7 with transition fixed are likely to be more representative of full scale than the results with laminar boundary-layer separation which gave much the larger negative damping. When a thinner (4%) aerofoil having a 25% flap with a thick trailing edge was tested, the results reproduced in Fig.8 show that damping was not consistently changed on fixing transition except at Mach numbers less than about $M = 0.85$ when, as opposed to the trend in Fig.7, transition increased the damping: the stiffness derivative was reduced at all speeds.

It is clear that there can be significant scale effects present in two-dimensional tests at high subsonic speeds, but there is insufficient evidence in Refs.16-18 to show whether or not conditions with transition fixed are more representative of full scale. Intuitively, it seems likely that in the cases discussed, a turbulent boundary layer is essential. Even with transition fixed, Ref.16 shows that the results may still vary with Reynolds number.

4./

4. Three-Dimensional Tests

Table 1 shows that relevant three-dimensional experiments cover a wide range of Reynolds numbers and most of the results follow similar trends. In general the damping derivative is not sensitive either to a change in Reynolds number or to changes in the boundary layer caused by artificially fixing boundary-layer transition. But when transition is fixed the stiffness derivative $-h_\beta$ decreases in value, and there is a tendency for its value to increase when Reynolds number increases. Of the two papers[19, 20] which do not conform to the general pattern, that by Loiseau[19] does not represent a full-scale three-dimensional flow because tests are made on a two-dimensional 6% thick airfoil having a 30% flap with span equal to one sixth of tunnel span. As might be expected, the behaviour of the damping derivative, shown in Fig.9, is similar to the trends of the two-dimensional tests discussed in Section 3; the main effect of fixing transition is a small decrease in the value of the damping derivative at low speeds, and a marked reduction in the tendency for instability around $M = 0.95$. The stiffness derivative in Fig.10a is consistently reduced in magnitude at subsonic speeds, and for transonic speeds in Fig.10b this leads to a serious increase in the speed range for divergence. There is no obvious reason why the trends in Ref.20 should differ from the other available results. A 5% thick swept fin with full-span 25% rudder was tested at Reynolds numbers which ranged from 1.4×10^6 to 5.0×10^6 as tunnel stagnation pressure was changed from 0.25 atmospheres to 0.70 atmospheres with tunnel speeds $0.6 \leq M \leq 1.2$. As seen in Figs.11a and 11b both stiffness and damping derivatives noticeably decrease in value when Reynolds number is increased although the Mach number for instability in Fig.11b is prectically unchanged.

Consider now the more general changes in hinge moments due to fixing the position of boundary-layer transition. With the aforementioned exceptions the evidence outlined in Table 1 indicates a decrease in the stiffness derivative $-h_\beta$ with negligible effects on damping. Guyett and Curran[3] describe some oscillatory force measurements on a modified cropped-delta wing having a horn-balanced control surface with constant chord 27% of mean wing chord. Transition was fixed with wires at distance 25% of local chord from the wing leading edge and the test Reynolds number varied between 0.35×10^6 and 1.4×10^6. It can be seen in Fig.12 that transition has no significant effect on hinge-moment damping but, particularly at the higher frequencies and amplitude of oscillation, the value of derivative $-h_\beta$ is decreased. One might note that h_β is positive for this wing which has a large horn balance with area ahead of the hinge line approximately equal to 35% of the control surface area aft of the hinge line. A loss of load downstream of the hinge increases the positive hinge-moment stiffness which is in the same sense as a decrease of negative hinge-moment stiffness. Measurements were also made of wing oscillatory lift and pitching moments due to control deflection. The derivatives ℓ_β and m_β showed little dependence on frequency but consistently increased in magnitude by up to 5% when transition was fixed. Changes in the corresponding damping derivatives $\ell_{\dot\beta}$, $m_{\dot\beta}$ were dependent on the amplitude of oscillation, and transition increased damping when $\beta \approx 8°$ but decreased damping when $\beta \approx 4°$.

The lack of a change in damping is particularly interesting in the work of Lambourne et al[21] because their tests were made at quite low Reynolds numbers. As mentioned in Section 2, fixing transition with a Reynolds number $< 10^6$ probably gives a turbulent boundary layer which is much thicker relative to chord

length/

length than is a true full-scale turbulent boundary layer. Lambourne measured the aerodynamic hinge moments of a 42% horn-balanced elevator on an unswept tailplane; the area of the horn-balance ahead of the hinge line in this case was only 3.8% of the area behind the hinge line. The Reynolds number varied from 0.085×10^6 to 0.254×10^6 as speed increased from 20 ft/sec (61 cm/sec) to 60 ft/sec (183 cm/sec) and results were obtained with and without a transition wire at approximately mid-chord. On fixing transition, hinge stiffness decreased from a mean value $h_\beta = -0.59$ to $h_\beta = -0.53$ but damping was not noticeably changed. Moseley and Gainer[22] made an extensive investigation of a series of swept and unswept wings having ratios of wing thickness to chord from 0.04 to 0.10 and having constant 30% chord flap-type control surfaces. Oscillatory hinge moments were measured through a speed range $0.60 \leqslant M \leqslant 1.02$, giving Reynolds numbers from about 1.10×10^6 to 1.35×10^6, for oscillation amplitudes up to 12°. Although the majority of the tests were done with a carborundum roughness band added at the leading edge, some measurements were made with natural transition. It is shown in Fig.11 of Ref.22 that the stiffness derivatives are consistently reduced in magnitude when transition is fixed, but whilst there are a few instances of substantial changes in damping, there is no overall trend in the results and it is concluded that in general the effect of boundary-layer transition on damping is negligible. Reese[23] likewise finds that fixing transition at the leading edge of an aspect ratio 2 triangular wing has a negligible effect on hinge-moment damping as can be seen in Fig.13. The wing had a control surface with constant chord about one fifth of wing mean chord and tests were made at oscillation amplitudes up to 5° over Mach number ranges 0.6 to 0.9 and 1.3 to 1.9 with Reynolds number fixed at 1.86×10^6. There is a large scatter in the results both with and without transition fixed, but no evidence of a boundary-layer effect.

Finally, the effect of transition as measured in two related steady-flow tests is briefly considered. The model is an unswept wing having a 25% control surface and was tested by Johnson[24] at speeds in the range $0.65 \leqslant M \leqslant 1.10$ with $0.5 \times 10^6 \leqslant Re \leqslant 0.9 \times 10^6$. When a roughness band was added near the leading edge dC_h/d_β, dC_L/d_β and dC_m/d_β were reduced at all speeds. In rocket model tests of a similar wing English[25] measured the rate of roll due to a fixed control deflection of 5° over a speed range $0.7 \leqslant M \leqslant 1.5$ with Reynolds number varying from about 2.0×10^6 to 5.8×10^6. The rolling effectiveness of the control was reduced when transition was fixed near the leading edge, and it was lower for a wing with a roughness strip formed by a series of ridges than for the wing with solid projections of half the height of the ridges.

The experiments described in Refs.21 and 26 were done with tunnel speeds $V \leqslant 60$ ft/sec (152 cm/sec) such that for a given frequency parameter, changes due to an increase in tunnel speed are effectively those due to an increase in Reynolds number. Lambourne[21] notes little change in hinge-moment stiffness with frequency parameter, but when Reynolds number is increased from 0.13×10^6 to 0.25×10^6 the stiffness increases by nearly 10%; there is no measureable change in the damping derivative. Scruton et al[26] tested an unswept large-aspect-ratio wing having an outboard aileron with chord approximately 23% of local chord. In this case, an increase in Reynolds from 0.4×10^6 to 0.6×10^6 again caused an increase in stiffness (this time by 15%) with negligible changes in damping. Measurements were also made of lift derivatives ℓ_β and $\ell_{\dot\beta}$ which behaved in a similar way to the hinge-moment derivatives. The trend in the variation of stiffness with Reynolds number is confirmed in some steady-flow measurements at high subsonic speeds[27]. An aspect-ratio-2 triangular wing having a flap with constant chord approximately equal to 15% wing mean chord was tested over a speed range $0.5 \leqslant M \leqslant 1.2$ using three different methods; a wing-flow method with $1.0 \times 10^6 < Re < 1.7 \times 10^6$; a model test in a large tunnel with Reynolds number fixed at 5.3×10^6; a rocket-model test with $10 \times 10^6 < Re < 20 \times 10^6$. The value of dC_h/d_β measured by the first method was much less than the value obtained in the large tunnel, a typical increase in dC_h/d_β being from -0.12×10^{-3} to -0.19×10^{-3} corresponding to a Reynolds number increase from 1.3×10^6 to 5.3×10^6. However, neglecting an unusual trough in the values of dC_h/d_β around $M = 0.85$ in the rocket-model tests, there is no further appreciable increase when Reynolds number is increased into the range 10×10^6 to 20×10^6.

An extensive study of oscillatory pressures on swept and unswept wings, each with a 30% constant-chord flap, has been made by Hertrich[5]. The pressure distributions are analysed to give direct and cross derivatives for the wing-flap combinations and included are some comparisons between results where Reynolds number varied in the range $0.55 \times 10^6 \leq Re \leq 1.4 \times 10^6$ and results where Reynolds number was fixed at 1.6×10^6. None of the damping derivatives showed any effect of this small increase, but neither did the majority of the stiffness derivatives. Only in the case of the in-phase component of flap lift due to flap oscillation was there any indication of a consistent change - this derivative showed a tendency to increase with the small increase in Reynolds number.

Some tests at representatively large Reynolds numbers from 10.4×10^6 to 14.8×10^6 were made by Wyss et al[28] who tested a mid-span 30% flap on an unswept wing of aspect ratio 3 at speeds $0.60 \leq M \leq 1.12$. They report that when Reynolds number was reduced by a factor of three, only small changes resulted in the trends and magnitudes of the data presented.

5. Indirect Evidence

In Sections 3 and 4, results are discussed of tests in which Reynolds number is varied or in which the effect of artificially fixing transition is noted. In view of the sensitivity of control-surface derivatives to variations in other parameters such as frequency parameter, Mach number, trailing-edge thickness, wing section etc., it is difficult to compare tests on different models for the purpose of evaluating scale effects. Nevertheless, in order to extend the limited evidence considered in the previous sections, some attempts are now made to compare relevant results for models having similar features.

5.1 Two-dimensional results

Fig.14, taken from Ref.29, shows a comparison between hinge moments measured on two-dimensional aerofoils each having a 25% flap. Transition was fixed near the leading edge of the models described in Refs.29, 30 and 31 and the Reynolds numbers did not exceed 4×10^6; the larger aerofoil in Ref.32 gave a Reynolds number greater than 10×10^6 and transition was 'natural'. Each model had a different thickness to chord ratio, but if the effect of increasing thickness is the same as that found in the three-dimensional tests described in Ref.22 then as thickness increases, the values of the hinge-moment stiffness derivatives should gradually decrease in magnitude. It can be seen in Fig.14 that the thickest wing gives the largest values of stiffness derivative $-h_\beta$ so it is likely that the values for the other models have been significantly reduced due to fixing transition. The very low values for the NLR wing with a circular biconvex section may further have been influenced by the severe flow separation at the rear of the aeroflow reported by the authors. Since an increase in thickness from 4% to 10% is shown in Ref.22 to have only small effects on damping at subsonic speeds (and $\nu \approx 0.5$),

the/

the changes in thickness indicated in Fig.14 do not account for the substantial differences between values obtained with transition fixed and the value measured in Ref.32. It follows from these two-dimensional tests that artificially fixing transition on small models at low Reynolds numbers does not satisfactorily reproduce results at large Reynolds number.

5.2 Three-dimensional results

The independent investigations described in Refs.33 and 34 provide the most useful comparison. In each case the model was a half-wing of cropped-delta planform with an aspect ratio of 2 made so that the fixed part was a triangular wing having approximately 60° sweepback with a rectangular full span flap attached at its trailing edge. The half-wing used by Bratt et al[33] had a 6% symmetrical section with the flap chord equal to 25% wing mean chord. Oscillatory hinge moments were measured in a small high-speed tunnel at speeds in the range $0.4 \leq M \leq 1.1$ giving Reynolds numbers from 1.01×10^6 to 2.59×10^6, and the frequency parameter based on wing mean chord varied from about 0.15 to 0.58 at $M = 0.4$ and 0.07 to 0.23 at $M = 1.1$. Martz[34] made rocket-model tests on a 5% symmetrical wing with flap chord equal to 23% wing mean chord. The Mach number varied from 0.4 to 0.9 giving Reynolds numbers in the range $3.5 < Re \times 10^{-6} < 19$ and frequency parameters in the range $0.3 < \nu < 0.7$. The measured damping derivatives do not agree at all well in trend or magnitude as may be seen in Fig.15 which also includes some wind-tunnel measurements from Ref.35; the model tested in this case is again a 5% triangular wing having an aspect ratio of 2, but the control has only a 13% chord and its outboard edge is swept to form a continuation of the wing leading edge. The Reynolds number was fixed at 3.1×10^6 and the frequency parameter had a quite high value between approximately 2.1 and 2.9. There was little change from earlier results with a much lower frequency ($\nu \approx 0.5$) and it is clear that the trend with Mach number has the same form as that from Bratt's experiments. It is unrealistic to attribute such marked differences in the trend of the rocket-test results to Reynolds number effects alone, and as the wind-tunnel measurements were made under carefully controlled conditions the discrepancies are probably due to the influence of other factors on the decaying oscillation technique used in the free-flight tests. Martz notes that his experimental trends seem wrong in comparison with two-dimensional theory, and suggests that his measured damping derivatives may have been affected by flow disturbances at the inboard ends of the controls caused by part of his plucking mechanism. It might also be noted that at each Mach number only a few cycles were available for determining the rate of decay of the motion, and errors in damping are quoted to be as much as ±30% at subsonic speeds. However, the stiffness derivatives are determined by measurement of frequency of oscillation and the errors are estimated to be less that ±10%. Fig.16 shows that the stiffness derivatives from Refs.33 and 34 are in excellent agreement which implies that there are no significant Reynolds number effects present.

In Ref.36 Martin et al present some hinge-moment derivatives for a triangular wing which is identical to the wing described in Ref.35 except that the control surface has a bigger chord. Measurements made in a tunnel at a Reynolds number of 2.4×10^6 are compared with free-flight tests at Reynolds numbers in the range $3.5 < Re \times 10^{-6} < 18$ on a similar wing with the control surface having a thickened trailing edge. With reference to Fig.15, it can be seen that thickening the trailing edge of the rocket model used by Martz did not appreciably affect the damping derivatives and the same result was found in wind-tunnel tests of an unswept wing at subsonic speeds[36]. Assuming that thickening the trailing edge of the triangular wing has a negligible effect on the results discussed by Martin et al, then since the damping derivatives

reproduced/

reproduced in Fig.17 are seen to be in reasonable agreement it follows that the Reynolds number effects on the results are not large. However, stiffness derivatives are apparently quite sensitive to changes in trailing-edge thickness and the good agreement on measured hinge-moment stiffness in Fig.17 does not necessarily indicate an absence of Reynolds number effects.

6. Concluding Remarks

There are very few papers which report measurements of oscillatory control-surface derivatives other than hinge or tab moments. Furthermore, only a minority of the published measurements of control forces include results which show the effect of variations in Reynolds number or the effect of artificially fixing boundary-layer transition. These are discussed in the present report and some general trends seem to be present. In the two-dimensional tests it appears that an increase in Reynolds number tends to increase the magnitude of derivatives h_β, $h_{\dot\beta}$, whilst artificially fixing transition decreases the hinge moments. This indicates that boundary-layer thickness is probably the dominant parameter because one might then expect that if the boundary layer is too thick (transition fixed) the control effectiveness is reduced whereas if the boundary layer is thinned (increase in Reynolds number) then control effectiveness is increased. If, however, boundary-layer separation is a feature of the flow then it is probably essential to obtain a turbulent boundary layer in order to avoid laminar separation. With no separation, the conclusion from the two-dimensional results is that when measurements are made at low Reynolds numbers transition should not be fixed in an attempt to simulate large-scale conditions; the hinge-moments with no transition will probably be rather low in value but on fixing transition, they are decreased further.

With three-dimesional tests the general effect on damping due to a change in Reynolds number or due to fixing transition appears to be small. For hinge stiffness, changes due to an increase in Reynolds number are often small but show a tendency to increase the value of $-h_\beta$ whereas its value decreases when transition is fixed. It is again probable that when boundary-layer separation occurs to the rear of the wing, results with boundary-layer transition fixed at low Reynolds numbers will be more representative of full-scale values. With this proviso, the results discussed indicate that in order to obtain representative values of hinge-moment stiffness, tests at low Reynolds numbers are best done without a transition band on the model. With or without transition fixed, damping derivatives measured in a wind-tunnel appear to be representative of full scale values.

It must be emphasized that these are tentative conclusions based on limited evidence. There is a need (notably to confirm the two-dimensional results) for careful measurement of control derivatives on a given model both at a large Reynolds number, i.e., $Re > 10 \times 10^6$, and at low Reynolds numbers with all other parameters constant. In particular, tests should be made with and without boundary-layer transition fixed for a low Reynolds number and a high Reynolds number at the same Mach number and frequency parameter. Tests should also be made under conditions where boundary-layer separation occurs to the rear of the model. The trends of scale effects on oscillatory derivatives must be established conclusively by such tests before a reliable empirical method can be deduced for modifying theory to allow for viscous effects as, for instance, has been done for two-dimensional flaps in steady incompressible flow[37].

List/

List of Symbols

C_h	Steady hinge-moment coefficient
C_L	Steady lift coefficient
C_m	Steady pitching-moment coefficient
c	Mean wing chord
E	Ratio of flap mean chord to mean wing chord
M	Mach number
Re	Reynolds number based on mean wing chord
s	Span of half-wing
V	Velocity
β	Amplitude of flap oscillation
γ	Amplitude of tab oscillation
ν	Frequency parameter $= \omega c/V$
ρ	Fluid density
ω	Frequency of oscillation, radians/sec

Derivatives

H — Flap hinge moment

$$= \rho V^2 c^2 s \left[(h_\beta + i\nu h_{\dot\beta})\beta + (h_\gamma + i\nu h_{\dot\gamma})\gamma \right]$$

T — Tab hinge moment

$$= \rho V^2 c^2 s \left[(t_\beta + i\nu t_{\dot\beta})\beta + (t_\gamma + i\nu t_{\dot\gamma})\gamma \right]$$

L — Lift

$$= \rho V^2 c s \left[(\ell_\beta + i\nu \ell_{\dot\beta})\beta + (\ell_\gamma + i\nu \ell_{\dot\gamma}\ \gamma \right]$$

Subscript

f — Denotes derivative made non-dimensional with respect to control surface chord instead of wing mean chord

---

References/

References

No.	Author(s)	Title, etc.
1	D. L. Loving	Wind-tunnel-flight correlation of shock-induced separated flow. NASA TN D-3580. September, 1966.
2	P. R. Guyett and J. K. Curran	Aerodynamic derivative measurements on a wing with a horn-balanced control surface. ARC R & M.3307. 1961.
3	W. G. Molyneux and F. Ruddlesdon	Derivative measurements and flutter tests on a rectangular wing with a full-span control surface, oscillating in modes of wing roll and aileron rotation. ARC R & M.3010. 1955.
4	H. Bergh	Experimental determination of the aerodynamic forces on an oscillating wing with an aerodynamically balanced flap in incompressible two-dimensional flow. NLR Amsterdam Report NLL-TM F.205. 1957.
5	H. Hertrich	Zur experimentellen Prüfung instationärer dreidimensionaler Tragflächentheorien bei inkompressibler Strömung. Max-Planck-Institut, Göttingen Report Nr.40. 1967.
6	K. C. Wight	Measurements of two-dimensional derivatives on a wing-aileron-tab system with a 1541 section aerofoil. Part 1 - Direct aileron derivatives. ARC R & M 2934. 1952.
7	K. C. Wight	Measurements of two-dimensional derivatives on a wing-aileron-tab system with a 1541 section aerofoil. Part II - Direct tab and cross aileron-tab derivatives. ARC R & M 3029. 1955.
8	T. C. Andreopoulos, H. A. Cheilek and A. F. Donovan	Measurements of the aerodynamic hinge moments of an oscillating flap and tab. USAF Technical Report No.5784. April, 1949.
9	L. W. Bryant and A. S. Batson	Experiments on the effect of transition on control characteristics, with a note on the use of transition wires. ARC R & M.2164. November, 1944.

10/

No.	Author(s)	Title, etc.
10	S. F. Racisz and J. F. Cahill	Wind-tunnel investigation of effects of forward movements of transition on section characteristics of a low-drag airfoil with a 0.24 - chord sealed plain aileron NACA Technical Note 1582. May, 1948.
11	N. C. Lambourne	Flutter in one degree of freedom. AGARD Manual on aero-elasticity Vol.5, Chapter 5. October, 1968.
12	E. N. Harrin	A flight investigation of the effect of shape and thickness of the boundary layer on the pressure distribution in the presence of shock. NACA Technical note 2765. September, 1952.
13	A. B. Haines, D. W. Holder and H. H. Pearcey	Scale effects at high subsonic and transonic speeds, and methods for fixing boundary-layer transition in model experiments. ARC R & M 3012. 1954.
14	H. H. Pearcey, J. Osborne and A. B. Haines	The interaction between local effects at the shock and rear separation - a source of significant scale effects in wind-tunnel tests on aerofoils and wings. AGARD Conference proceedings No.35. Paper 11. September, 1968.
15	J. A. Blackwell	Effects of Reynolds number and boundary-layer transition location on shock-induced separation. AGARD Conference proceedings No.35. Paper 21. September, 1968.
16	Y. Nakamura and L. Woodgate	Effects of Reynolds number and frequency parameter on control-surface buzz at high subsonic speeds. NPL Aero Report 1312, 1970.
17	H. Loiseau	Étude expérimentale des flottements a un degré de liberté en écoulement transsonique. ONERA Note Technique NO.95. 1966.
18	K. C. Wight	Private communication.
19	H. Loiseau	Mesure de coefficients aerodynamiques instationnaires de gouvernes en transsonique. La Recherche Aérospatiale No.97 November/December, 1963.
20	R. W. Herr, F. W. Gibson and R. S. Osborne	Some effects of flow spoilers and of aerodynamic balance on the oscillating hinge moments for a swept fin-rudder combination in a transonic wind tunnel. NACA RM L58 C28 TIL.5999. May, 1958.

No.	Author(s)	Title, etc.
21	N. C. Lambourne, A. Chinneck and D. B. Betts	Measurements of the aerodynamic derivatives for a horn-balanced elevator. ARC R & M 2653. 1949.
22	W. C. Moseley and T. G. Gainer	Effect of wing thickness and sweep on the oscillating hinge-moment and flutter characteristics of a flap-type control at transonic speeds. NASA TM X-123. October, 1959.
23	D. E. Reese	An experimental investigation at subsonic and supersonic speeds of the torsional damping characteristics of a constant-chord control surface of an aspect ratio 2 triangular wing. NACA RM A53D27 TIB 3782. July, 1953.
24	H. I. Johnson	Measurements of aerodynamic characteristics at transonic speeds of an unswept and untapered NACA 65-009 airfoil model of aspect ratio 3 with $\frac{1}{4}$-chord plain flap by the NACA wing-flow method. NACA RM L53D21 TIB 3761. June, 1953.
25	R. D. English	Some effects of leading-edge roughness on the aileron effectiveness and drag of a thin rectangular wing employing a full-span plain aileron at Mach numbers from 0.6 to 1.5. NACA RM L53I25 TIB 3956. November, 1953.
26	C. Scruton, W. G. Raymer and Miss D. V. Dunsdon	Experimental determination of the aerodynamic derivatives for flexural-aileron flutter of BAC wing type 167. ARC R & M 2373. 1945.
27	G. A. Rathert L. S. Rolls and C. M. Hanson	The transonic characteristics of a low-aspect-ratio triangular wing with a constant chord flap as determined by wing-flow tests, including correlation with large-scale tests. NACA RM A50E10 TIB 2682. July, 1950.
28	J. A. Wyss, R. E. Dannenberg, R. M. Sorenson and B. J. Gambucci	Effects of boundary-layer suction and spoilers on transonic flutter derivatives for a midspan control surface on an unswept wing. NASA TM X-160. February, 1960.
29	H. Tijdeman and H. Bergh	Analysis of pressure distributions measured on a wing with oscillating control surface in two-dimensional high subsonic and transonic flow. National Aerospace Laboratory Report NLR-TR F.253. March, 1967.

No.	Author(s)	Title, etc.
30	H. Bergh, P. G. Cazemier and C. M. Siebert	Preliminary results for the instationary aerodynamic derivatives of a wing with oscillating flap in high subsonic and transonic flow (in Dutch). NLR Internal Report FF.6. 1960.
31	Y. Nakamura and Y. Tanabe	Some experiments on control surface buzz. NAL (Japan) Technical Report TR-72T. 1964.
32	J. A. Wyss and R. M. Sorenson	An investigation of the control-surface flutter derivatives of an NACA 65_1-213 airfoil in the Ames 16-foot high-speed wind tunnel. NACA RM A51J10 TIB 2952. December, 1951.
33	J. B. Bratt, C. J. W. Miles and R. F. Johnson	Measurements of the direct hinge-moment derivatives at subsonic and transonic speeds for a cropped delta wing with oscillating flap. ARC R & M 3163. 1957.
34	C. W. Martz	Experimental hinge moments on freely oscillating flap-type control surfaces. NACA RM L56G20 TIL 5294. October, 1956.
35	D. E. Reese and W. C. A. Carlson	An experimental investigation of the hinge-moment characteristics of a constant-chord control surface oscillating at high frequency. NACA RM A55J24 TIL 4908. December, 1955.
36	D. J. Martin, R. F. Thompson and C. W. Martz	Exploratory investigation of the moments on oscillating control surfaces at transonic speeds. NACA RM L55E31b TIB 4778. August, 1955.
37	H. C. Garner	Charts for low-speed characteristics of two-dimensional trailing-edge flaps. ARC R & M 3174. 1957.

Additional Bibliography

Some reports included in the bibliography contain relevant investigations of steady control forces, but this survey does not cover extensively work concerned with non-oscillatory flows. Futhermore, papers dealing only with theoretical considerations have been omitted.

No.	Author(s)	Title, etc.
38	E. E. Angle and R. R. Lundstrom	Flight and wind-tunnel investigation to determine the aileron-vibration characteristics of $\frac{1}{4}$-scale wing panels of the Douglas D-558-2 Research airplane. NACA RM L8H09 TIB 3305. November, 1948.

No.	Author(s)	Title, etc.
39	W. E. A. Acum	The comparison of theory and experiment for oscillating wings. AGARD Manual on Aeroelasticity Vol.II, Part II, Chapter 10. May, 1962.
40	B. Beals and W. P. Targoff	Control surface oscillatory coefficients measured on low aspect ratio wings. WADC Tech. Report 53-64. April, 1953.
41	H. Bergh	Experimental determination of the aerodynamic forces on an oscillating wing with control surface in incompressible two-dimensional flow. NLL TM F175. 1955.
42	H. Bergh	Experimental determination of the aerodynamic forces on an oscillating wing with an aerodynamically balanced flap in incompressible two-dimensional flow. NLL TM F205. August, 1957.
43	A. L. Braslow	Two-dimensional wind-tunnel investigation of low-drag vertical-tail, horizontal-tail, and wing sections equipped with sealed internally balanced control surfaces. NACA TN 1048. April, 1946.
44	H. H. Brown G. A. Rathert and L. A. Clousing	Flight-test measurements of aileron control surface behaviour at supercritical Mach numbers. NACA RM A7A15 TIB 1367. April, 1947.
45	L. W. Bryant and H. C. Garner	Control testing in wind tunnels. ARC R & M.2881. January, 1951.
46	L. W. Bryant, A. S. Halliday and A. S. Batson	Two-dimensional control characteristics. ARC R & M 2730. April, 1950.
47	S. A. Clevenson	Some wind-tunnel experiments on single-degree-of-freedom flutter of ailerons in the high subsonic speed range. NACA Technical Note 3687. June, 1956.
48	H. L. Crane	An investigation of aileron oscillations at transonic speeds on NACA 23012 and NACA 65-212 airfoils by the wing-flow method. NACA RM L8K29. TIB 2041. December, 1948.
49	J. Dorr	Determination of critical speed for a plane model with two degrees of freedom by calculation and wind-tunnel testing. ONERA TN 3. 1951

No.	Author(s)	Title, etc.
50	H. Drescher	Experimental determination of unsteady lift. 2.1 General considerations. 2.2 Experimental methods. 2.3 Results of measurement available so far. 2.4 Conclusions. A.R.C.11 843. 1948.
51	H. Drescher	An experimental investigation of aerodynamic forces on an airfoil with oscillating rudder. Osterreich Ingenieur-Archiv Vol.4. Parts 3 and 4. English Electric Company Translation. 1950.
52	A. L. Erickson and R. C. Robinson	Some preliminary results in the determination of aerodynamic derivatives of control surfaces in the transonic speed range by means of flush-type electrical pressure cells. NACA RM A8H03 TIB 2016. October, 1948.
53	A. L. Erickson and J. D. Stephenson	A suggested method of analysing for transonic flutter of control surfaces based on available experimental evidence. NACA RM A7F30 TIB 1505. December, 1947.
54	M. Fink and B. W. Cocke	A low-speed investigation of the aerodynamic, control, and hinge-moment characteristics of two types of controls and balancing tabs on a large-scale thin delta-wing - fuselage model. NACA RM L54B03 TIB 4165. March, 1954.
55	J. E. Fischler	Supercritical flow effects on some unsteady aerodynamic coefficients used for flutter analysis. Jnl. Aircraft Vol.5, No.6, pp 555-563. November-December, 1968.
56	C. E. Grigsby	An investigation of the effects of jet exhaust and Reynolds number upon the flow over the vertical stabilizer and rudder of the Douglas D-558-II research airplane at Mach numbers of 1·62, 1·93 and 2·41. NACA RM L54E03 TIB 4259. June, 1954.
57	H. Hall	Information on oscillatory aerodynamic derivative measurements. ARC R & M 3232. 1959.
58	H. Hall	A comparison of the measured and predicted flutter characteristics of a wing-aileron-tab model. ARC C.P.715. August, 1963.
59	H. Hall and J. A. Rein	Wind tunnel tests on the flutter of a swept and unswept wing with ailerons. ARC C.P.478. October, 1959.

No.	Author(s)	Title, etc.
60	Y. Hara and T. Ogawa	Some experiments of the unsteady vibrations in the transonic region. Journal of Mechanical Lab. of Japan. Vol.8, No.2. 1962.
61	A. B. Henning	Results of a rocket-model investigation of control-surface buzz and flutter on a 4-percent-thick unswept wing and on 6-, 9-, and 12-percent-thick swept wings at transonic speeds. NACA RM L53I29 TIB 3984. November, 1953.
62	F. N. Kirk	Wind tunnel tests on tunnel corrections to hinge moments of control surfaces. RAE TN Aero 1277. September, 1943.
63	G. Kurylowich	Investigation of the oscillatory derivatives of an airfoil with flaps oscillating at negative angles of attack. Toronto University Institute of Aerophysics Report TN.55. 1961.
64	N. C. Lambourne	Effect of boundary layer thickness on flutter of control surfaces. A brief survey of relevant reports. AGARD Report 183. March-April, 1958.
65	N. C. Lambourne	Some instabilities arising from the interactions between shock waves and boundary layers. ARC C.P.473. February, 1958.
66	N. C. Lambourne	Control-surface buzz. ARC R & M 3364. 1962.
67	B. Laschka	Die Druck-, Auftriebs- und Momentenverteilungen an einem harmonisch schwingenden pfeilflugel kleiner streckung im niedrigen Uterschallbereich. Vergleich zwischen theorie und Messung. Proc. ICAS 4th Congress (ed. R. R. Dexter) pp 295-315. August, 1964.
68	L. L. Levy and E. D. Knechtel	Experimental study of the effect of sweepback on transonic aileron flutter. NACA RM A51E04 TIB 2841. 1951.
69	H. Loiseau	Essais de flottement en air libre sur maquettes larguees. La Recherche Aeronantique No.70 pp 47-55. May-June, 1959.
70	D. J. Martin R. F. Thompson and C. W. Martz	NACA Conference on aircraft loads, flutter and structures: a compilation of papers presented. NASA-TM-X-57821.

71/

No.	Author(s)	Title, etc.
71	C. W. Martz	Experimental hinge moments on two freely oscillating trailing-edge controls hinged at 55% control chord. NACA RM L57J25 TIL 5789. December, 1957.
72	W. C. Moseley and T. G. Gainer	Some effects of control profile and control trailing-edge angle on the oscillating hinge-moment and flutter characteristics of flap-type controls at transonic speeds. NASA TM X-170. January, 1960.
73	W. C. Moseley and G. W. Price	Effects of control profile on the oscillating hinge-moment and flutter characteristics of a flap-type control at transonic speeds. NACA RM L57E27 TIL 5644. August, 1957.
74	W. C. Moseley and R. F. Thompson	Effect of control trailing-edge thickness or aspect ratio on the oscillating hinge-moment and flutter characteristics of a flap-type control at transonic speeds. NACA RM L58B25 TIL 5958. April, 1958.
75	Y. Nakamura	Some contributions on a control-surface buzz at high subsonic speeds. Journal Aircraft Vol.5, No.2. March-April, 1968.
76	Y. Nakamura and Y. Tanabe	Some experimental contributions on single degree-of-freedom flutter in two-dimensional low supersonic flow. Journal Aircraft Vol.3, No.5. September-October, 1966.
77	K. J. Orlik-Rückemann	Some data on elevator damping and stiffness derivatives on a delta wing aircraft model at supersonic speeds. NRC Canada Aero Report LR-250. June, 1959.
78	A. Perone and A. L. Erickson	Wind-tunnel investigation of transonic aileron flutter of a semispan wing model with an NACA 23013 section. NACA RM A8D27 TIB 1867. July, 1948.
79	W. H. Phillips and J. J. Adams	Low-speed tests of a model simulating the phenomenon of control-surface buzz. NACA RM L50F19 TIB 2453. August, 1950
80	J. H. Polve	The state of ignorance of flutter-flight testing. AIAA Paper No.66-883. AIAA TIS 3/02. December, 1966.
81	A. G. Rainey	Interpretation and applicability of results of wind-tunnel flutter and control surface buzz investigations. AGARD Report 219. October, 1958.

No.	Author(s)	Title, etc.
82	D. E. Reese	An experimental investigation of the unsteady lift induced on a wing in the downwash field of an oscillating canard control surface. A.R.C.18 511. June, 1956.
83	A. A. Regier	Flutter of control surface and tabs. AGARD Manual on Aeroelasticity Vol.5, Part 5. February, 1960.
84	R. M. Reynolds and D. W. Smith	Aerodynamic study of a wing-fuselage combination employing a wing swept back 63°. Subsonic Mach and Reynolds number effects on the characteristics of the wing and on the effectiveness of an elevon. NACA RM A8D20 TIB 1942. October, 1948.
85	H. Saito	On the aileron buzz in transonic flow. Aero Research Institute Tokyo University Rep.346 pp 109-147. July, 1959.
86	C. Scruton	Experiments on tail flutter. ARC R & M 2323. June, 1948.
87	C. Sinnott	Hinge-moment derivatives for an oscillating control. ARC R & M 2923. September, 1953.
88	R. I. Taylor	Experimental determination of the aileron aerodynamic damping derivative. A.R.C.16 920. July, 1954.
89	H. H. B. M. Thomas	Estimation of stability derivatives (State of the Art). ARC C.P.664. 1961.
90	R. F. Thompson	Investigation of a 42·7° sweptback wing model to determine the effects of trailing edge thickness on the aileron hinge-moment and flutter characteristics at transonic speeds. NACA RM L50J06 TIB 2702. December, 1950.
91	R. F. Thompson and W. C. Moseley	Oscillating hinge moments and flutter characteristics of a flap-type control surface on a 4-percent-thick unswept wing with low aspect ratio at transonic speeds. NACA RM L55K17 TIL 4995. February, 1956.
92	R. F. Thompson and S. A. Clevenson	Aerodynamics of oscillating control surfaces at transonic speeds. NACA RM L57D22b TIL 5575. June, 1957.
93	W. J. Tuovila and R. W. Hess	Aerodynamic damping at Mach numbers of 1·3 and 1·6 of a control surface on a two-dimensional wing by the free-oscillation method. NASA TN D-116. February, 1960.

94/

No.	Author(s)	Title, etc.
94	H. Voigt, F. Walter and W. Heger	Flutter experiments on the influence of aerodynamic balance achieved by means of a geared tab. RAE Library Translation No.318. February, 1950.
95	H. Wittmeyer	The design of aircraft wings for safety against flutter. Part 2. The flutter coefficient $gf\ell$ of a wing of trapezium planform, mounted at its root, and an aileron. RAL Library Translation No.161. July, 1947.
96	D. Woodcock	Research on aerodynamic derivatives in the United Kingdom. A.R.C.22 909. RAE Int.Memo No.Structures 504. May, 1961.
97	J. A. Wyss, R. M. Sorenson and B. J. Gambucci	Effects of modifications to a control surface on a 6-percent-thick unswept wing on the transonic control-surface flutter derivatives. NACA RM A58B04 TIL 6038. May, 1958.
98	J. A. Wyss, R. M. Sorenson and B. J. Gambucci	Measurements of transonic flutter derivatives for a midspan control surface on a modified delta wing. NASA TM X-157. January, 1960.

Table 1/

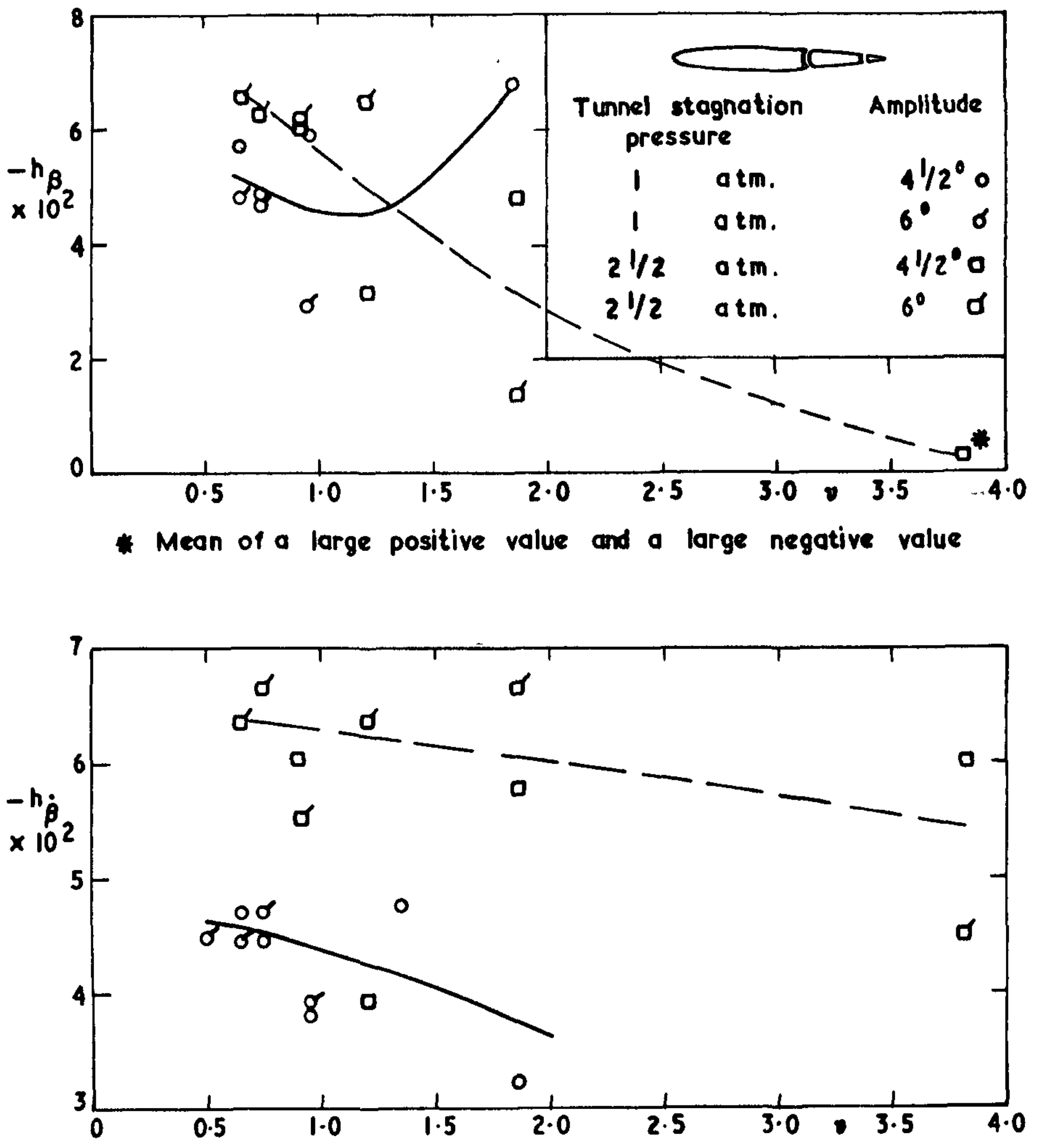
Table 1

Effect of increase in Re				Effect of fixing transition			
Ref.	Derivative		Range of Re × 10^{-6}	Ref.	Derivative		Range of Re × 10^{-6}
	$-h_\beta$	$\lvert h_{\dot\beta} \rvert$			$-h_\beta$	$\lvert h_{\dot\beta} \rvert$	
(a) Two-Dimensional Tests							
6,7	Negligible	Increase	1 to 3	6,7	Decrease	Decrease	1 to 3
8	Increase (ν<1)	Increase	1.2 to 3.7 and 3.0 to 9.2	9	Decrease	-	1
				10	Decrease	-	14
16	Increase	Increase	1.6 to 3.2	18	Decrease	Decrease	4 to 6
(b) Three-Dimensional Tests							
5	Negligible	Negligible	0.55 to 1.60	2	Decrease*	Negligible	0.35 to 1.40
20	Decrease	Decrease	1.4 to 5.0	19	Decrease	Decrease	4
21	Increase	Negligible	0.09 to 0.25	21	Decrease	Negligible	0.09 to 0.25
26	Increase	Negligible	0.4 to 0.6	22	Decrease	Negligible	1.10 to 1.35
27	Increase	-	1.0 to 20	23	-	Negligible	1.86
28	Negligible	Negligible	10.4 to 14.8 and approx. 4	24	Decrease	-	0.5 to 0.9
				26	Decrease	-	2.0 to 5.8
36	Negligible	Negligible	3.5 to 18 and 2.4				

* Stiffness derivative is positive in this case.

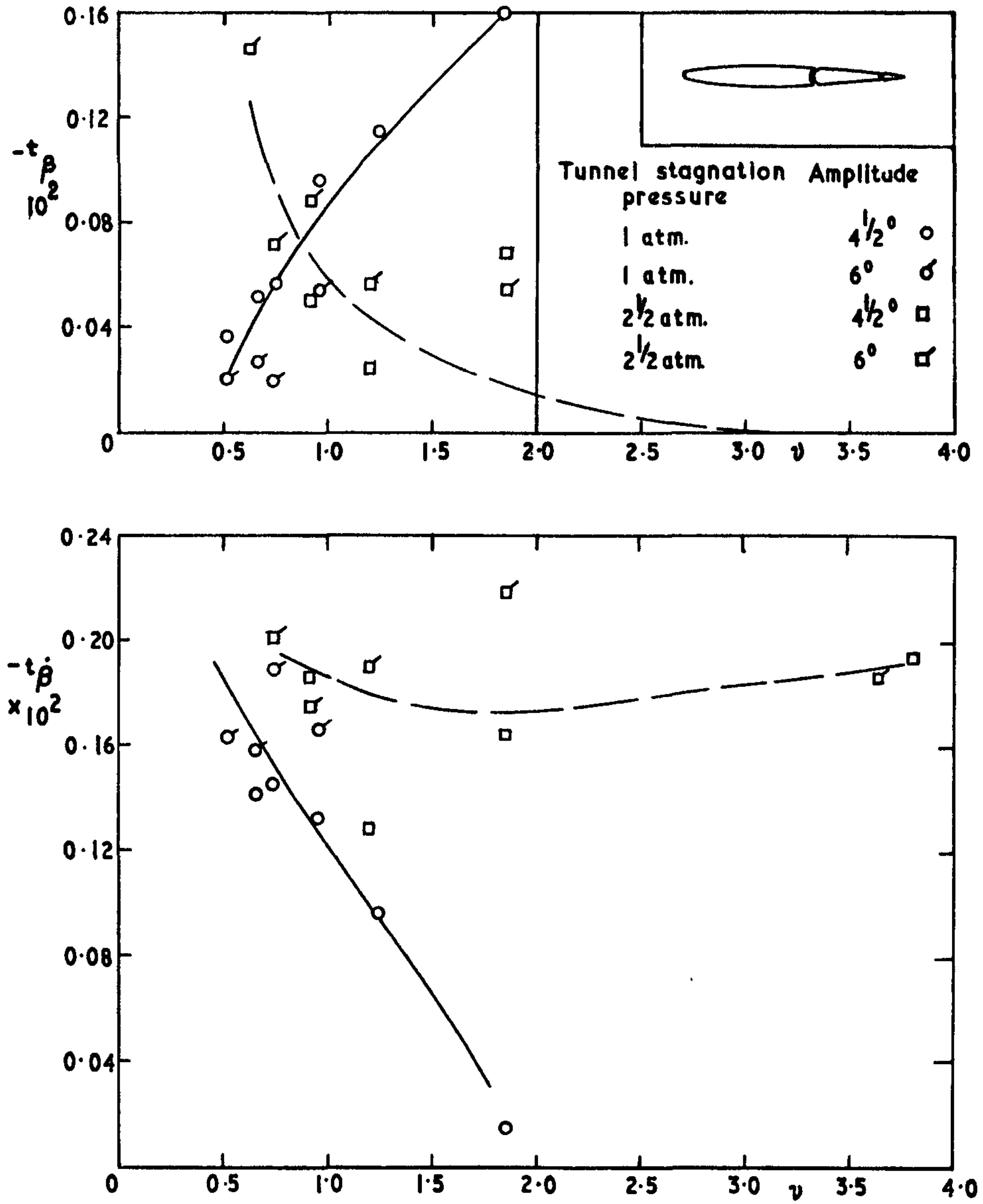
JED

FIG. 1



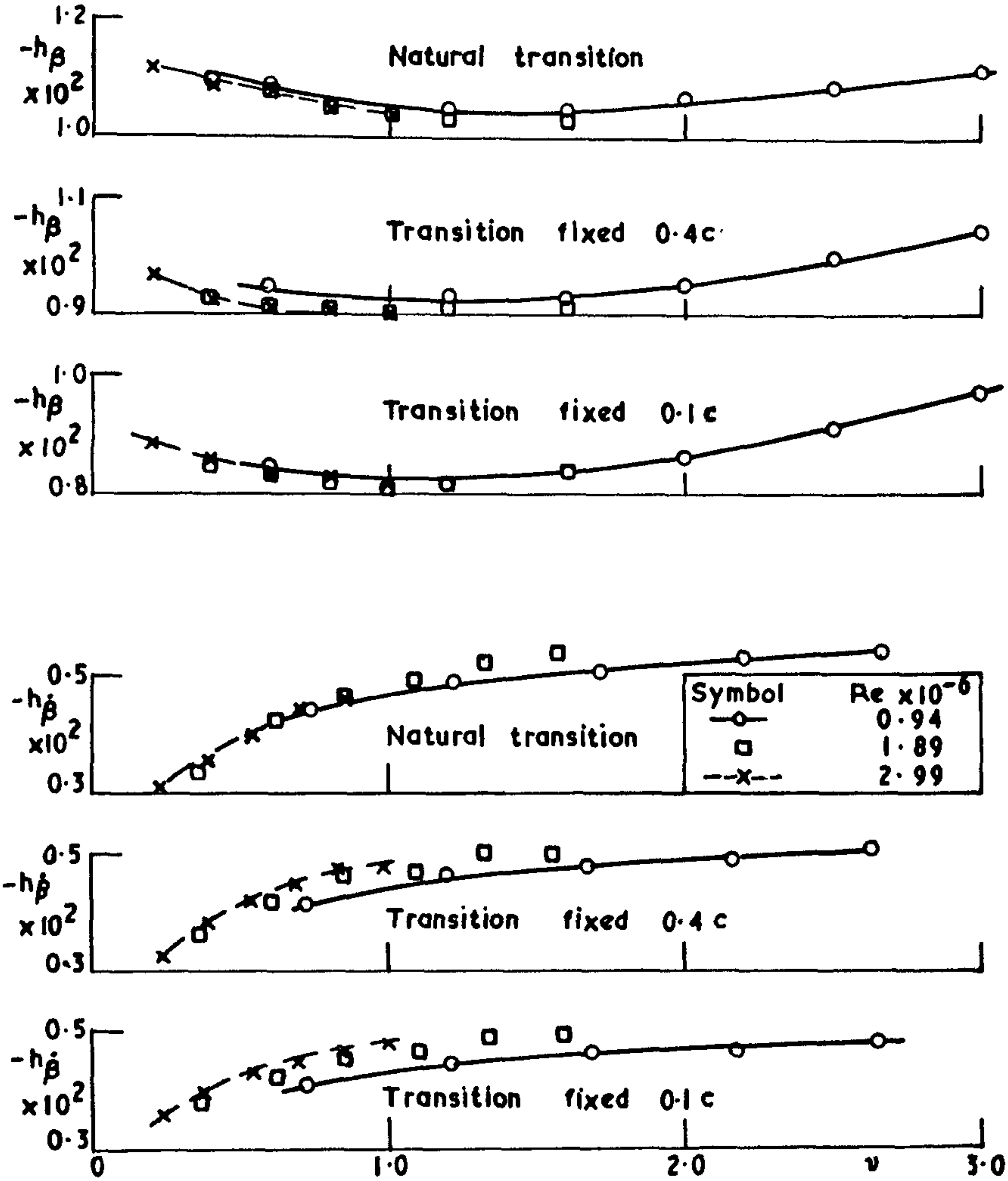
Hinge-moment derivatives due to flap oscillation on a two-dimensional wing at low speeds, E = 0·4: Ref. 8.

FIG. 2



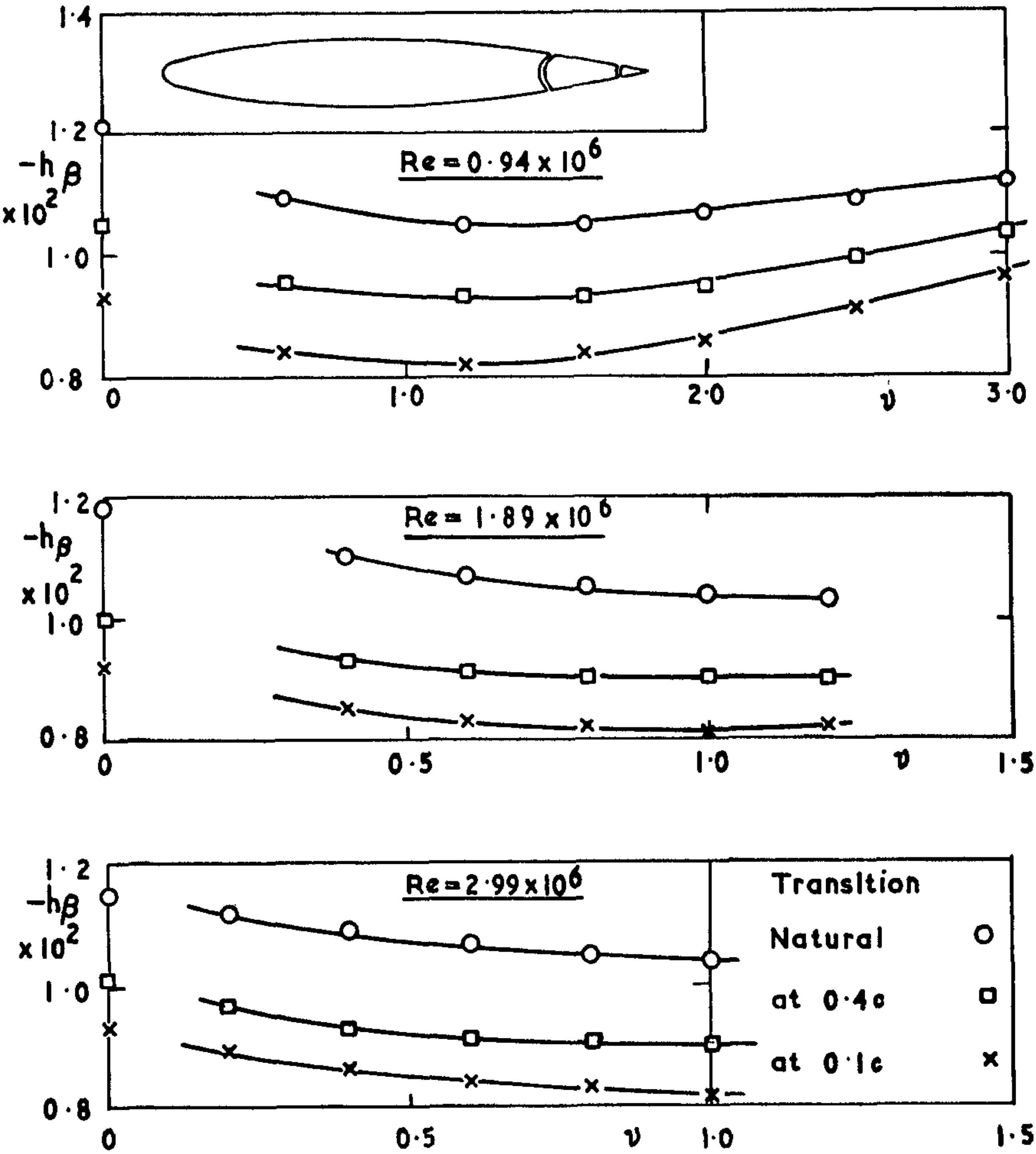
Cross derivatives of tab moment due to flap oscillation on a two-dimensional wing at low speeds, E = 0·4: Ref. 8.

FIG. 3



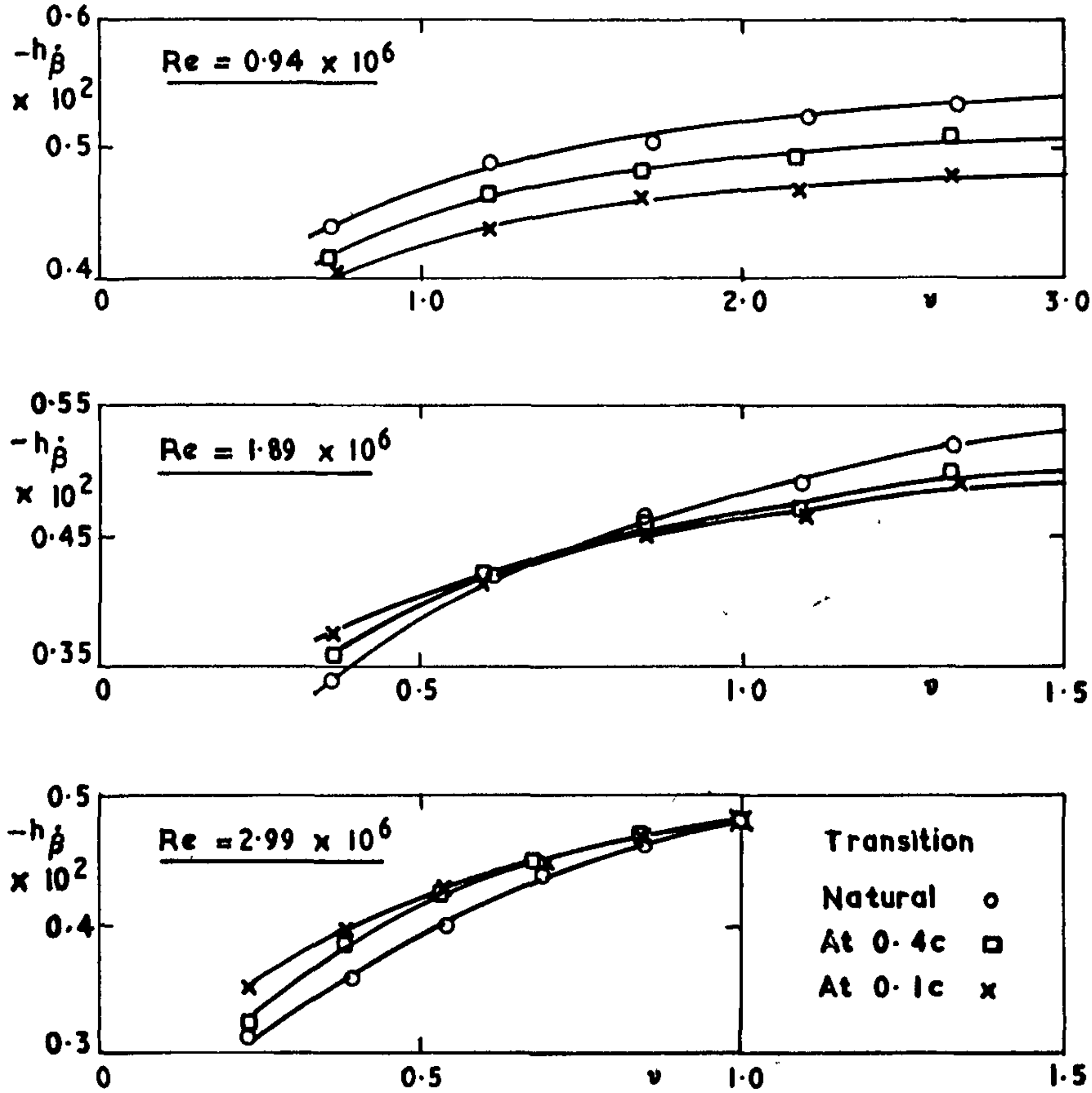
Hinge-moment derivatives due to flap oscillation on a two-dimensional wing at low speeds, E = 0·2 : Ref. 6.

FIG. 4



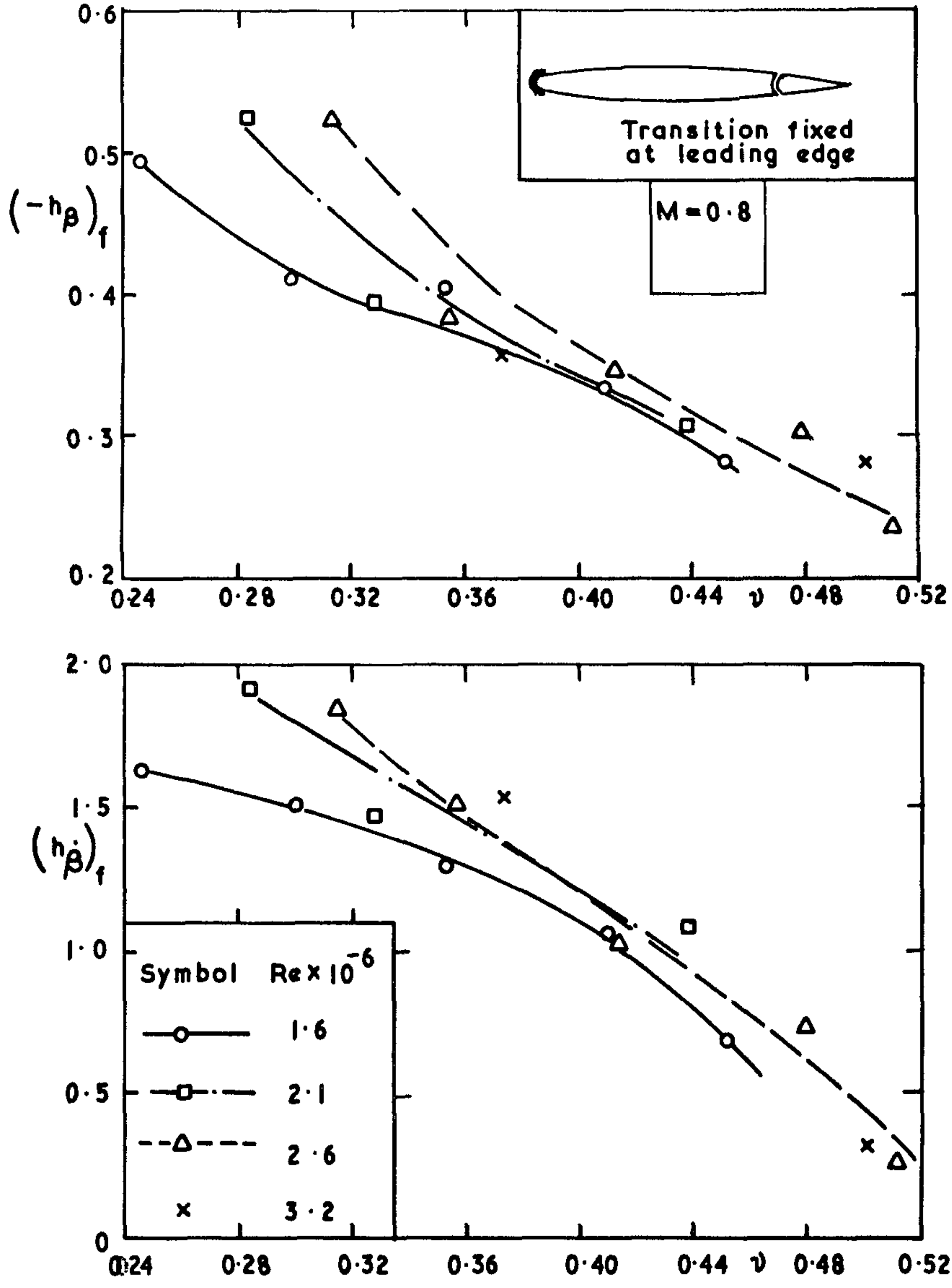
Effect on hinge-moment stiffness of fixing boundary-layer transition in a two-dimensional wing at low speeds, E = 0·2: Ref. 6.

FIG. 5



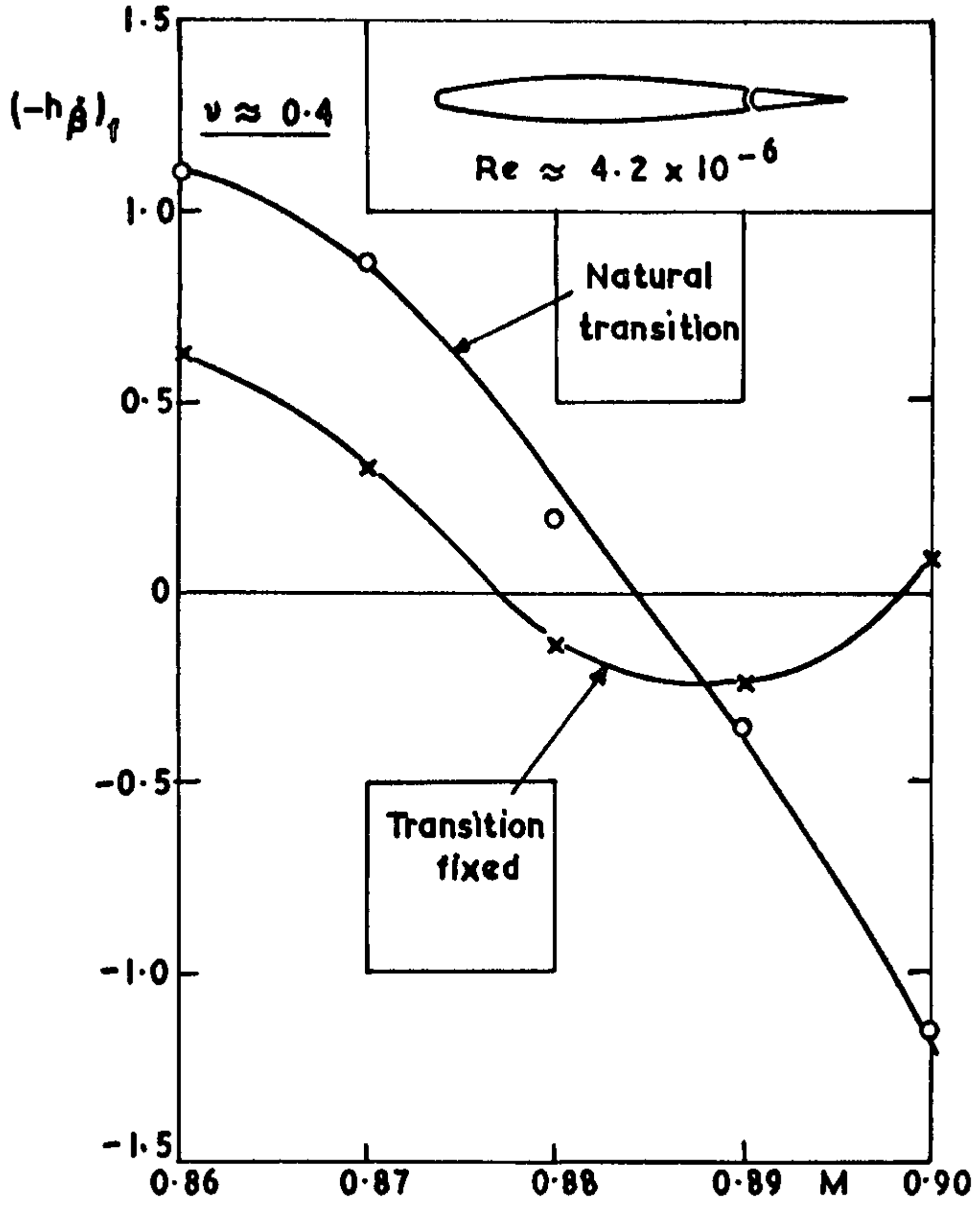
Effect on hinge-moment damping of fixing boundary-layer transition on a two-dimensional wing at low speeds, E = 0·2 : Ref. 6.

FIG. 6



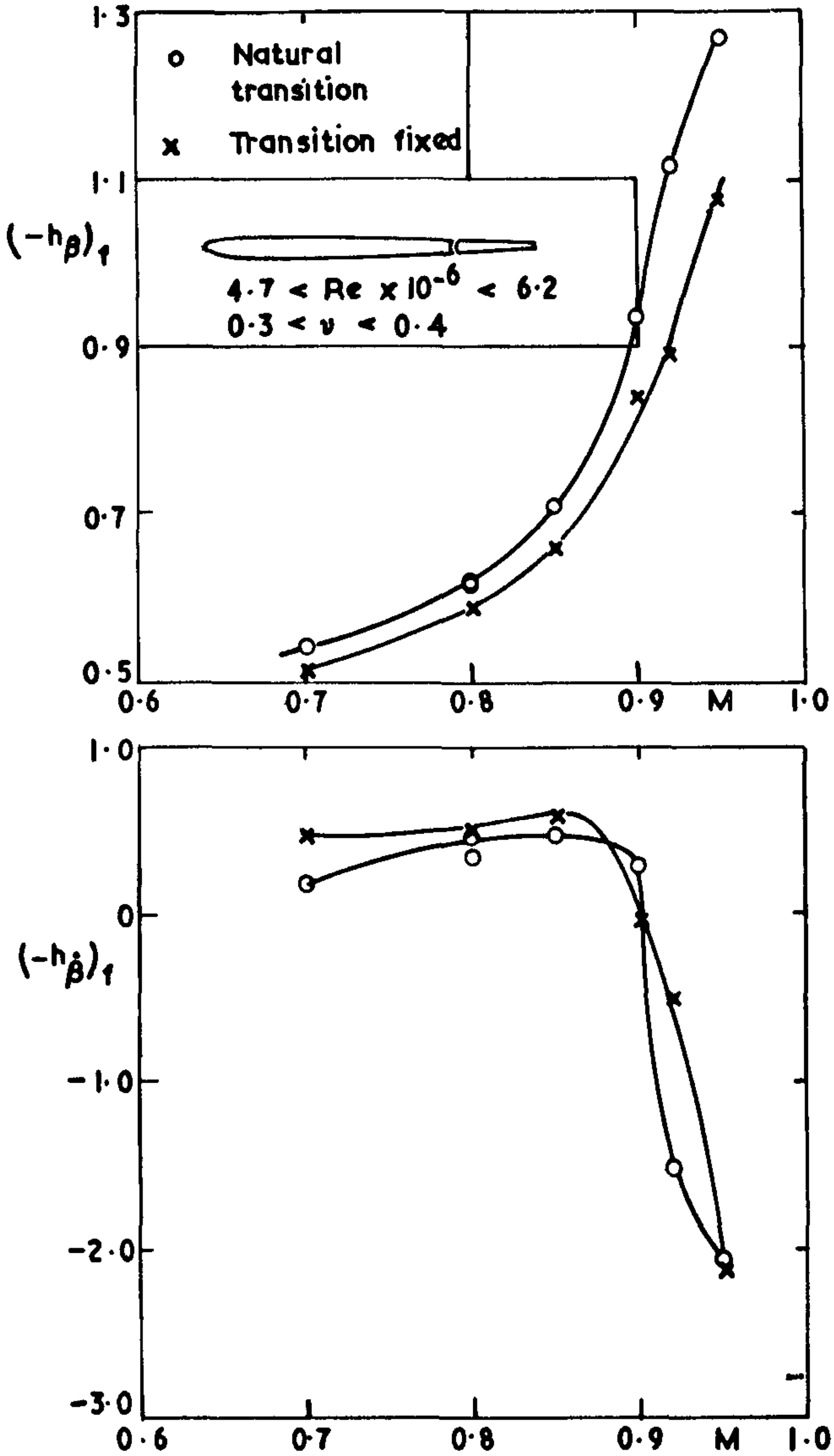
Effect of Reynolds number on the hinge-moment derivatives for a two-dimensional wing, E = 0·25; Ref. 16.

FIG. 7



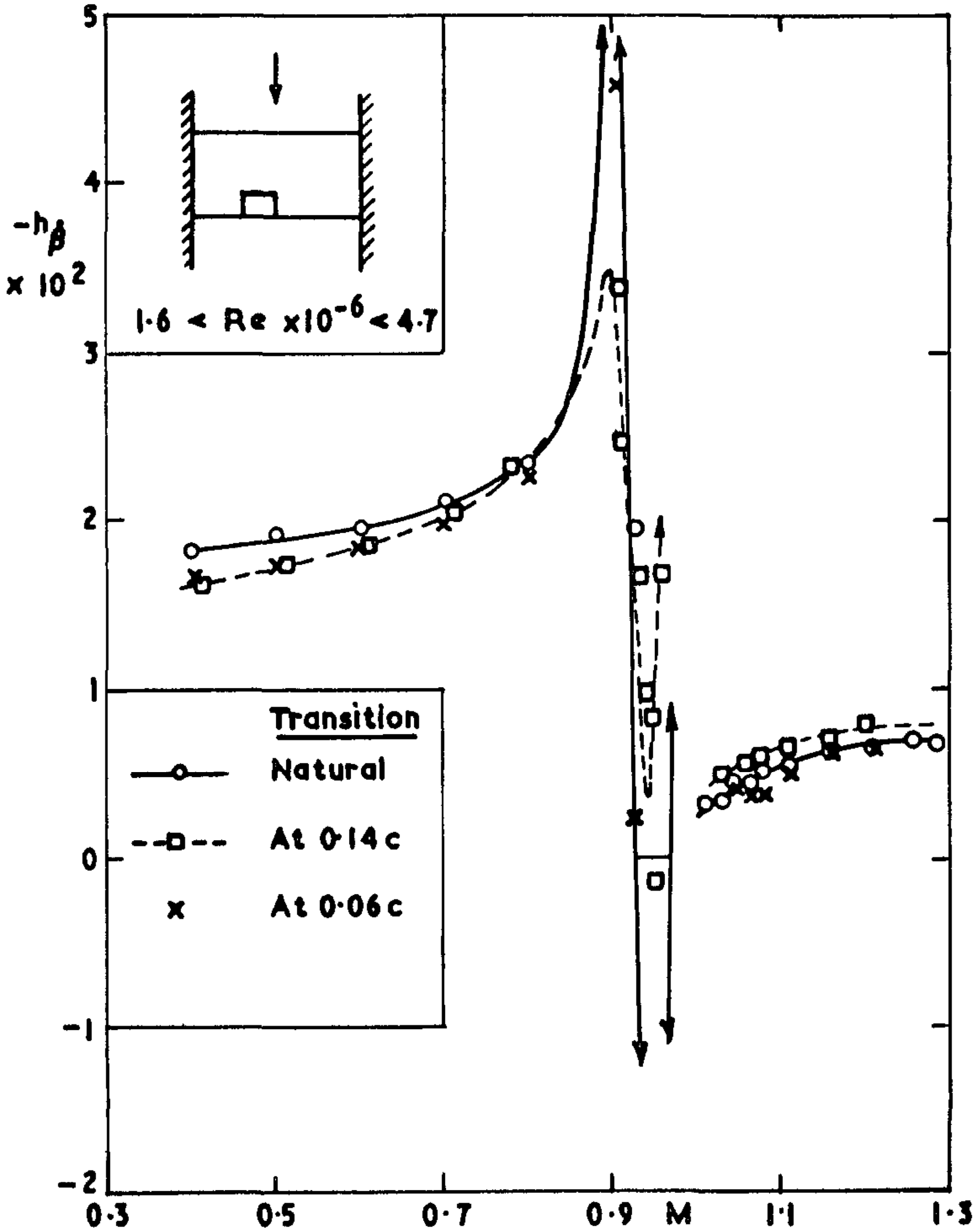
Effect on hinge-moment damping of fixing transition on a two-dimensional wing at high subsonic speeds, E = 0·25: Ref.18.

FIG. 8



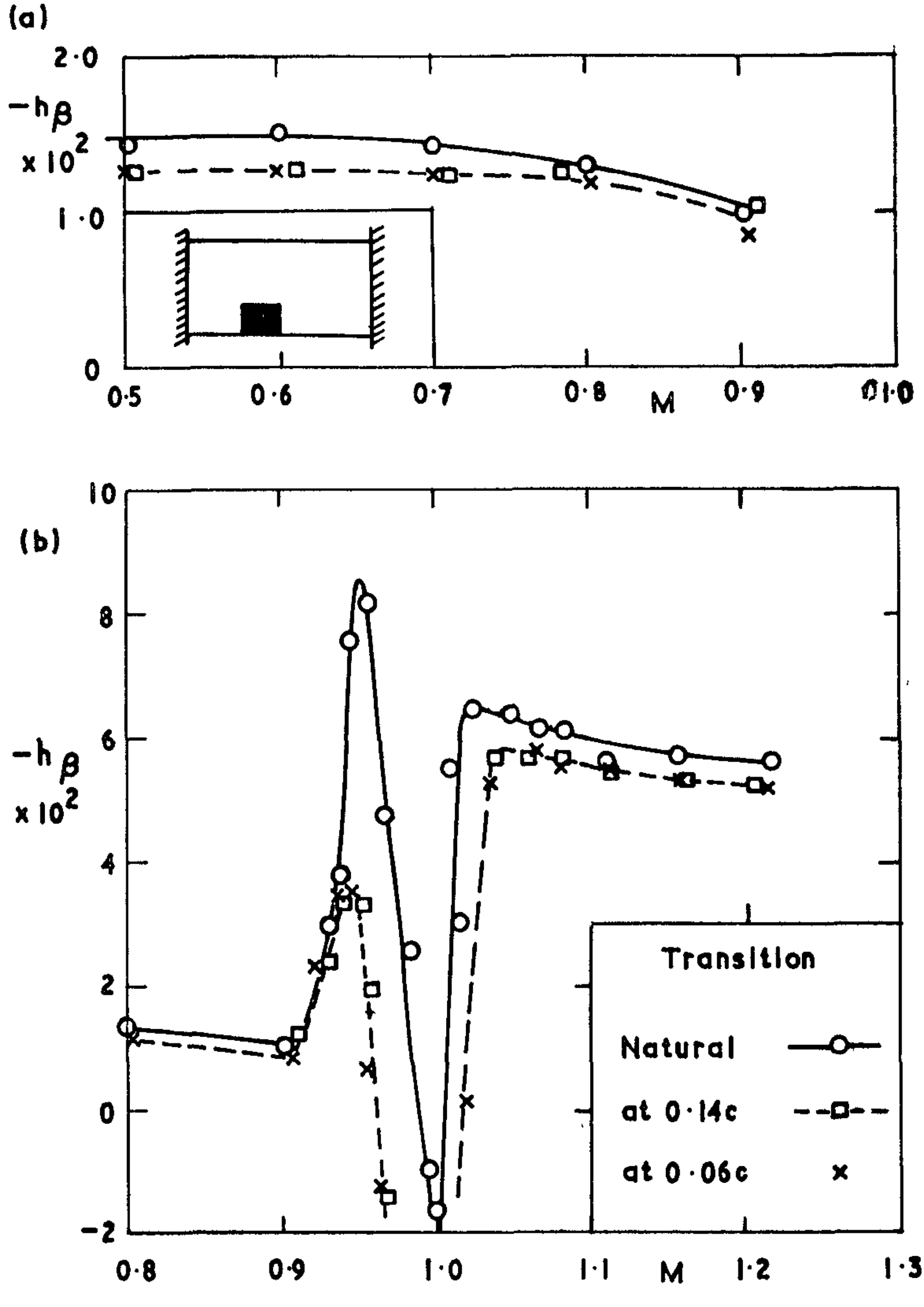
Effect on hinge moments of fixing transition on a two-dimensional aerofoil with blunt trailing edge, E = 0·25: Ref. 18.

FIG. 9



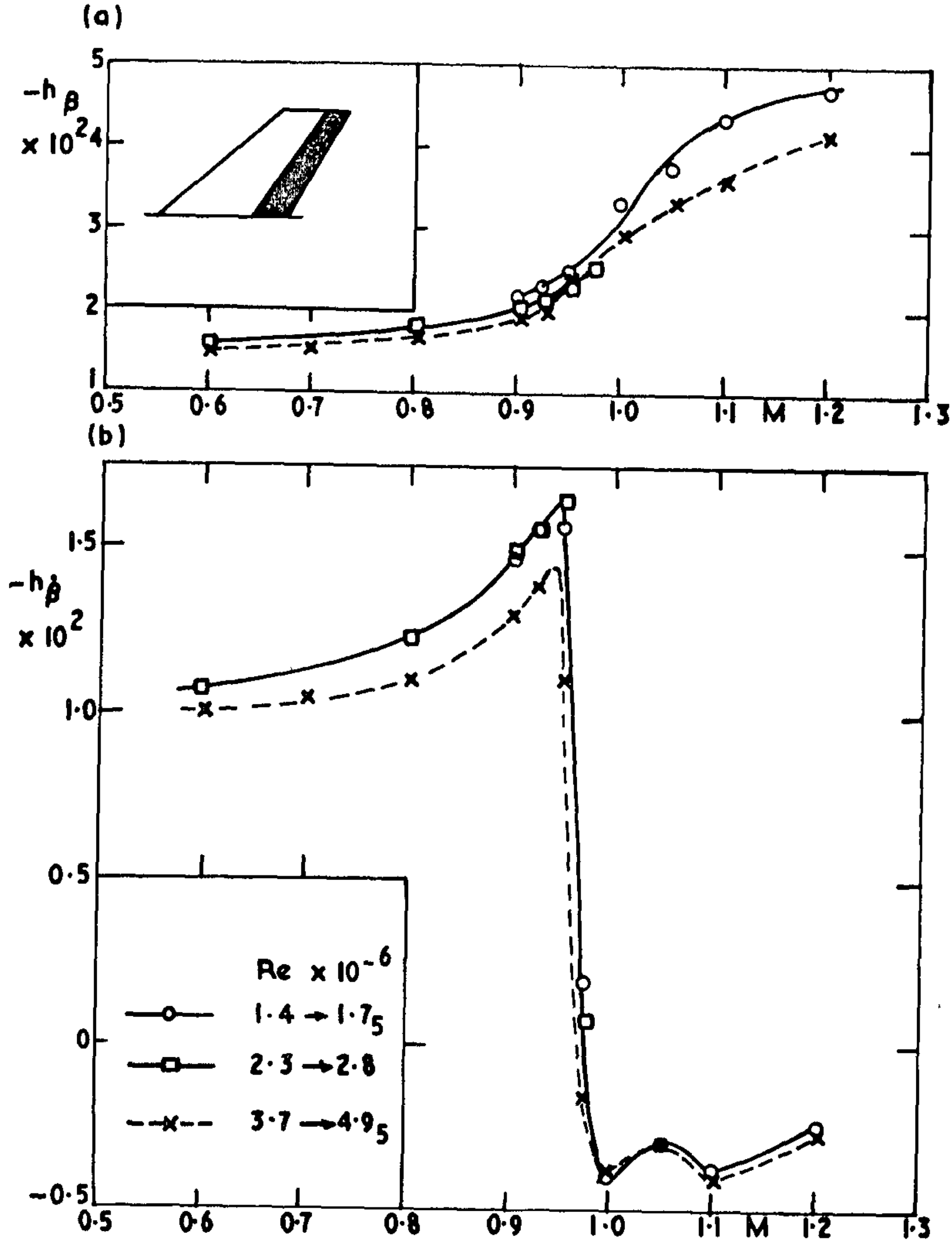
Effect on hinge-moment damping of fixing transition, E = 0·33: Ref. 19.

FIG.10



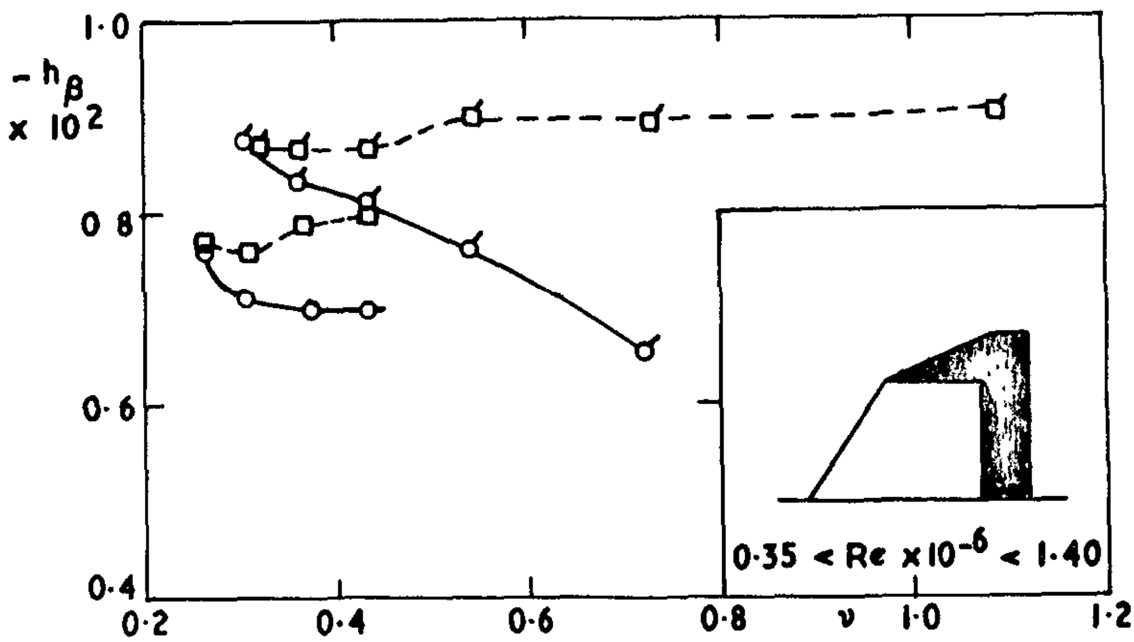
Effect on hinge-moment stiffness of fixing transition, E = 0·33 : Ref.19.

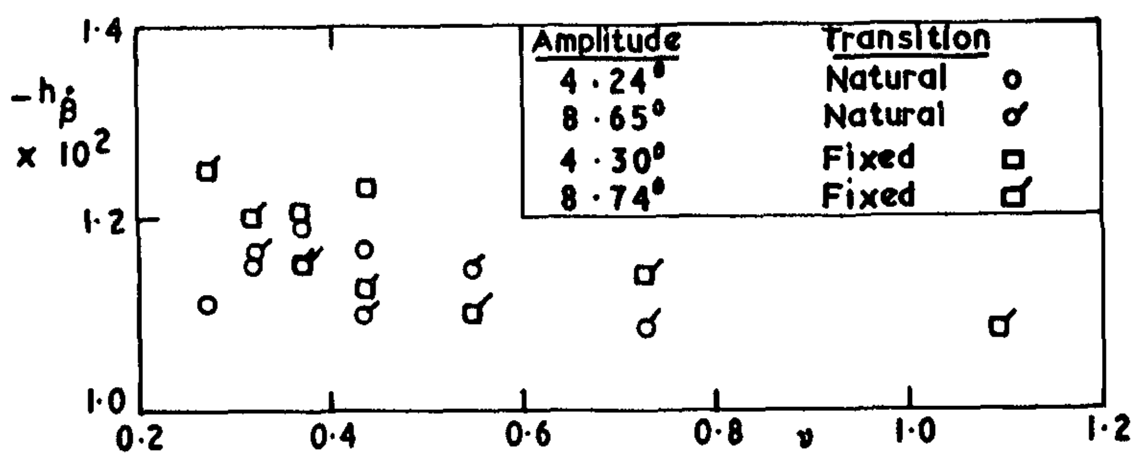
FIG. 11



Reynolds number effects on hinge-moment derivatives, $E = 0{\cdot}25$: Ref. 20.

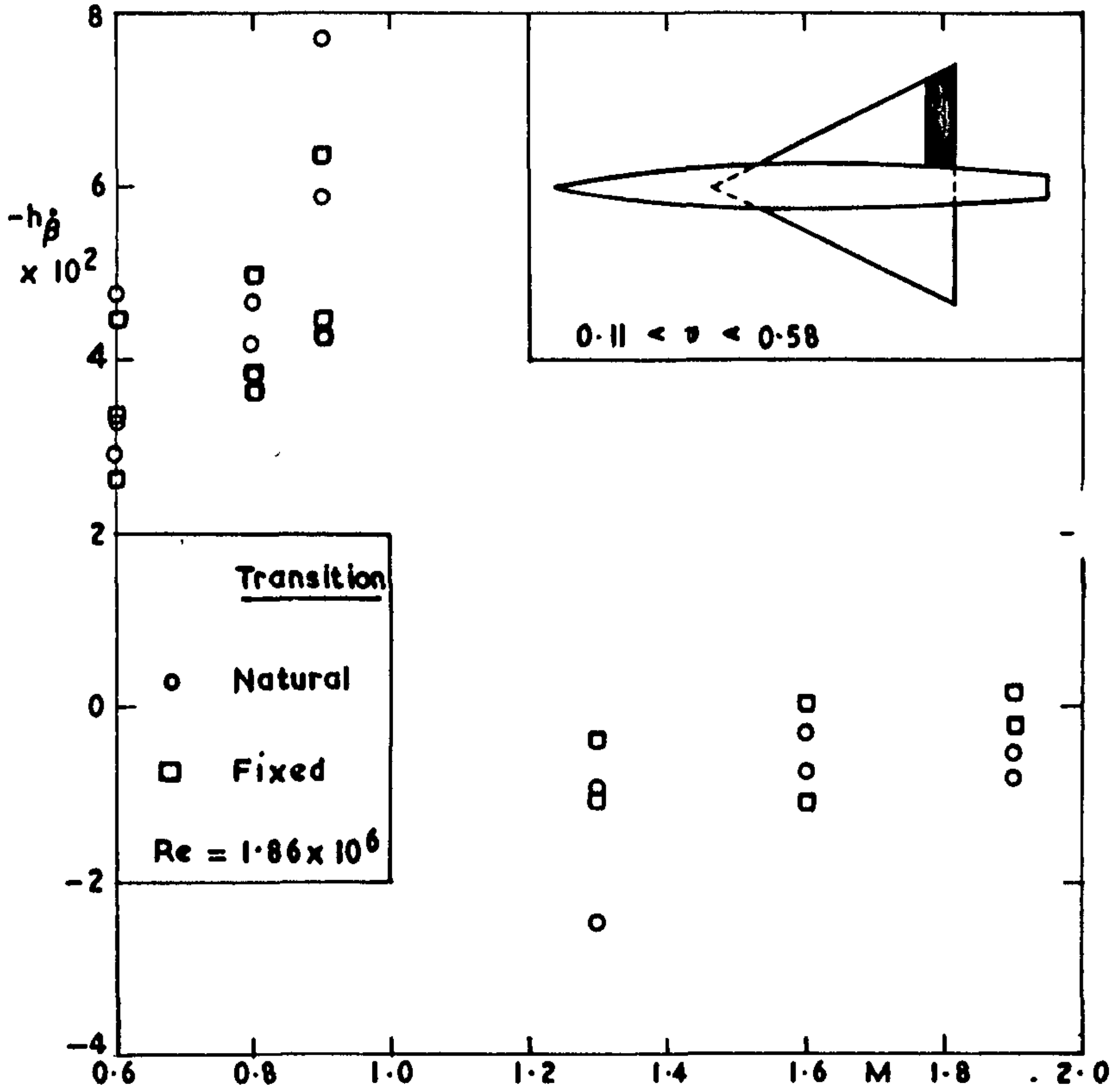
FIG. 12





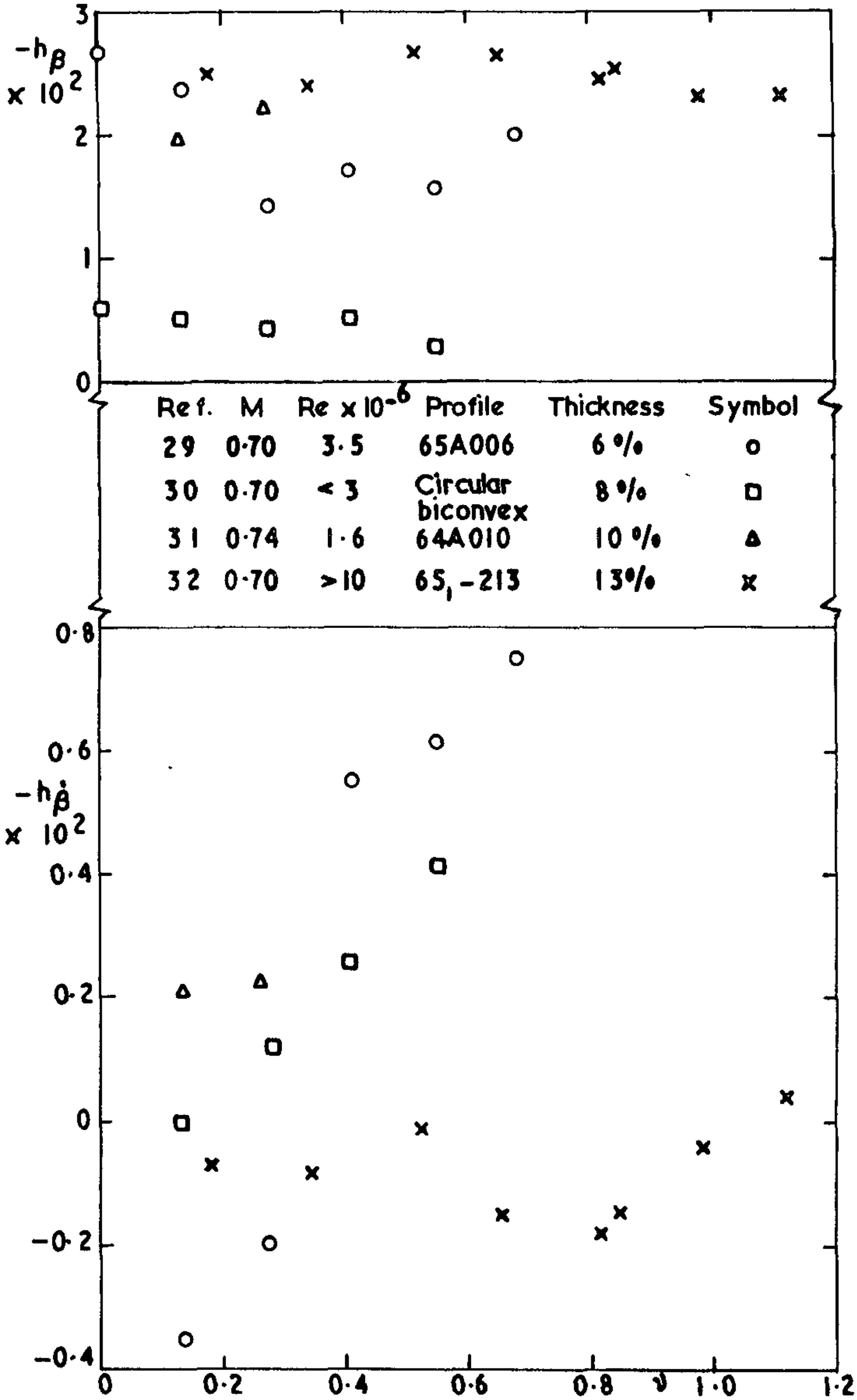
Effect of fixing transition at low speeds on the hinge-moments of a horn-balanced control surface: Ref. 2.

FIG.13



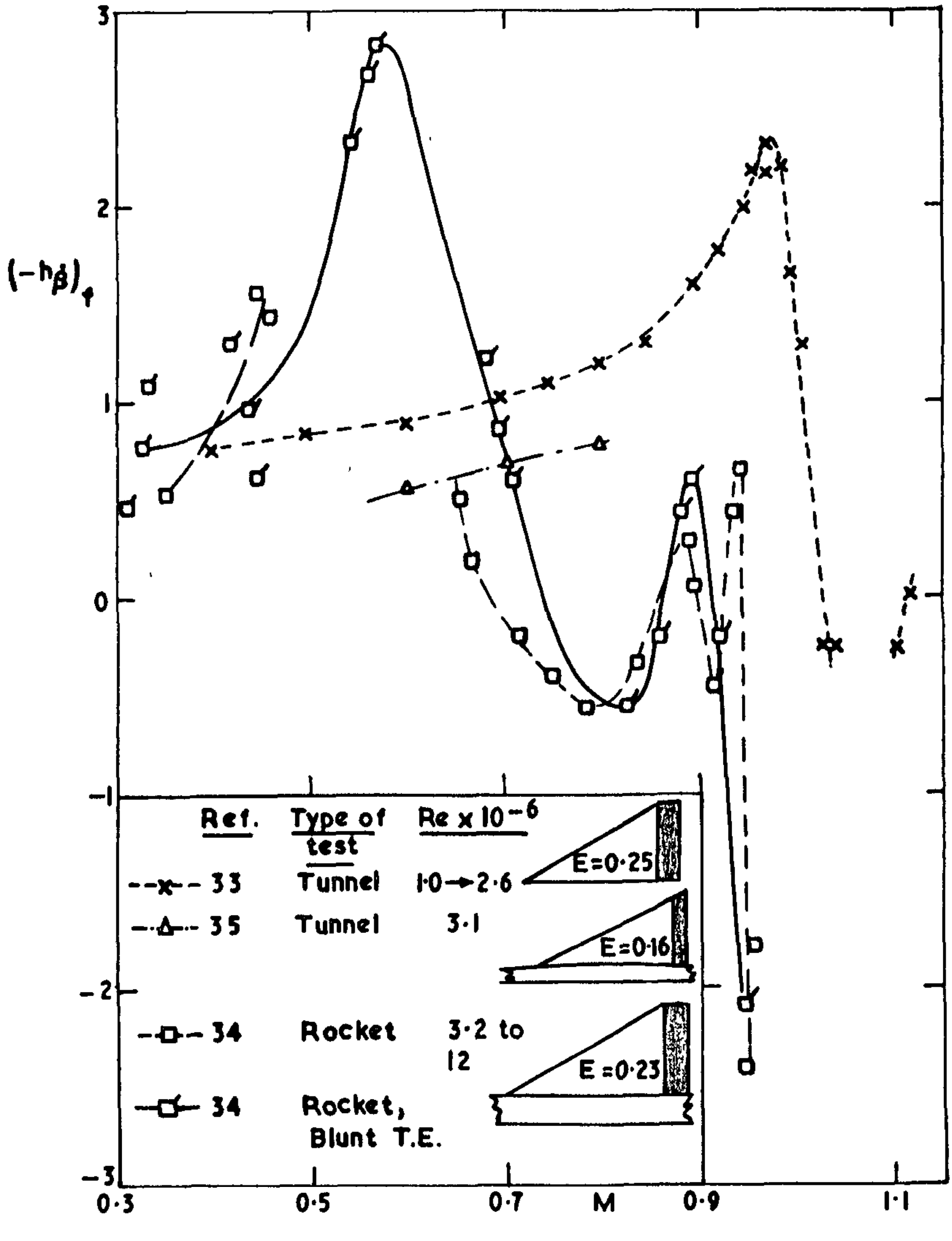
Effect on hinge-moment damping of fixing transition, E = 0·21:
Ref. 23.

FIG. 14



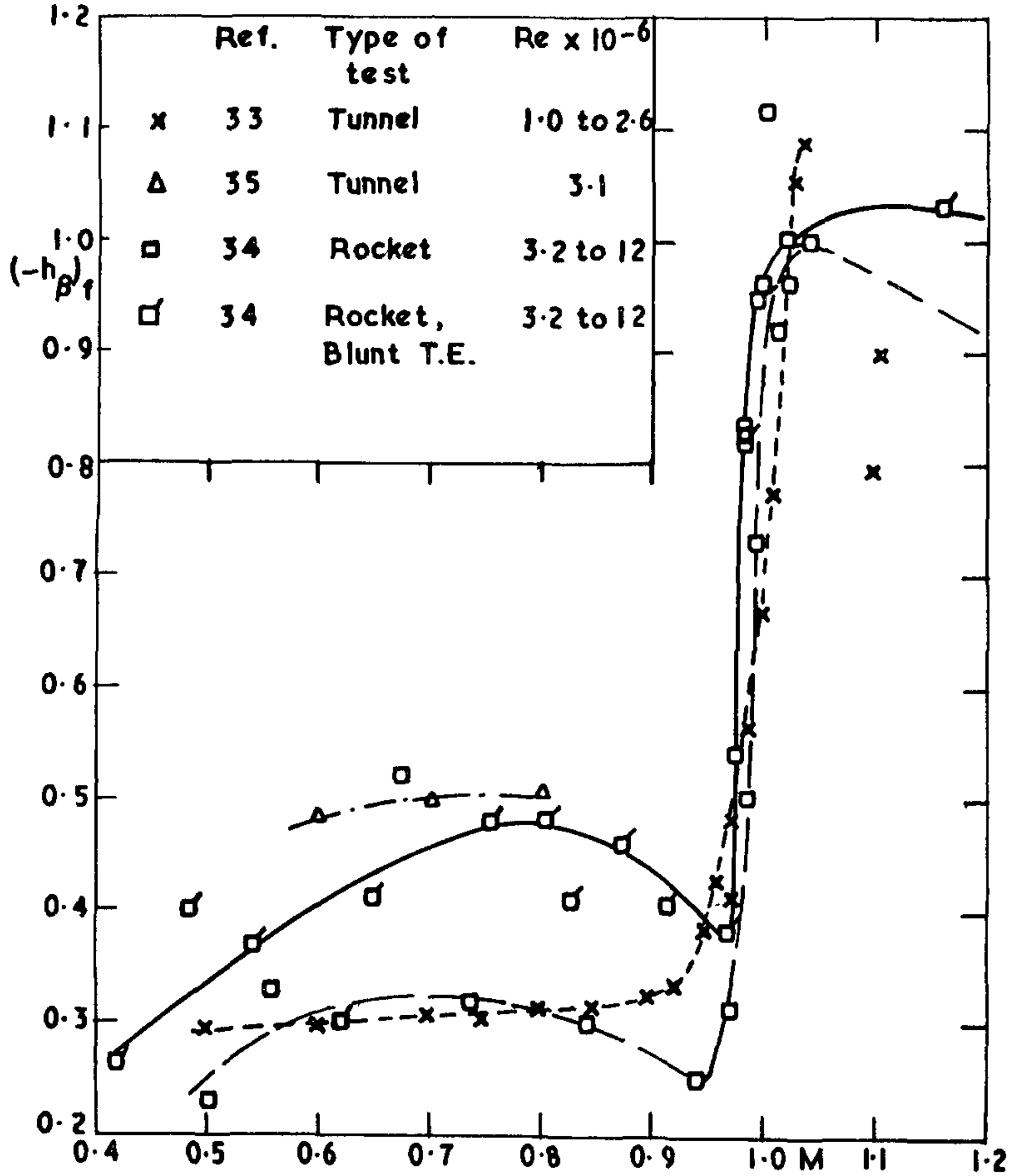
Comparison of hinge moments measured on four two-dimensional aerofoils with E = 0·25 : Ref. 29

FIG.15



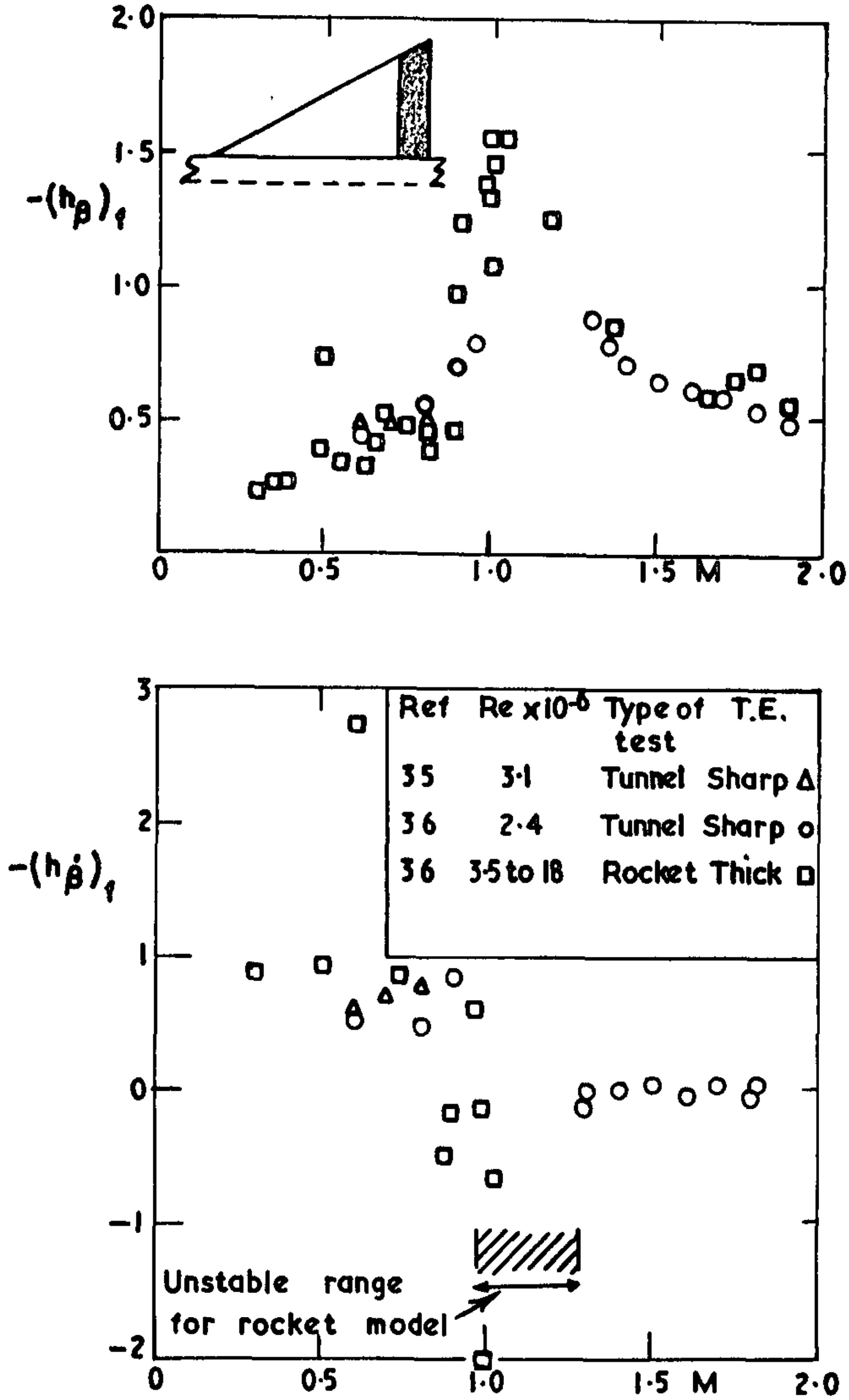
Comparison of damping derivatives measured in wind-tunnel and rocket tests.

FIG.16



Comparison of stiffness derivatives measured in wind-tunnel and rocket tests.

FIG.17



Comparison of results from tunnel and rocket tests on similar models: Ref. 36

A.R.C. C.P. No.1151
July, 1969
Moore, A. W.

SCALE EFFECTS ON OSCILLATORY
CONTROL-SURFACE DERIVATIVES

The limited evidence available indicates that provided boundary-layer separation is not a feature of the flow, wind-tunnel measurements of control-surface derivatives should be made without fixing boundary-layer transition on a model. Aerodynamic hinge-moment stiffness tends to increase with Reynolds number but decreases sharply when transition is fixed. The damping follows a similar pattern in two-dimensional tests but

with/

A.R.C. C.P. No.1151
July, 1969
Moore, A. W.

SCALE EFFECTS ON OSCILLATORY
CONTROL-SURFACE DERIVATIVES

The limited evidence available indicates that provided boundary-layer separation is not a feature of the flow, wind-tunnel measurements of control-surface derivatives should be made without fixing boundary-layer transition on a model. Aerodynamic hinge-moment stiffness tends to increase with Reynolds number but decreases sharply when transition is fixed. The damping follows a similar pattern in two-dimensional tests but

with/

A.R.C. C.P. No.1151
July, 1969
Moore, A. W.

SCALE EFFECTS ON OSCILLATORY
CONTROL-SURFACE DERIVATIVES

The limited evidence available indicates that provided boundary-layer separation is not a feature of the flow, wind-tunnel measurements of control-surface derivates should be made without fixing boundary-layer transition on a model. Aerodynamic hinge-moment stiffness tends to increase with Reynolds number but decreases sharply when transition is fixed. The damping follows a similar pattern in two-dimensional tests but

with/

DETACHABLE ABSTRACT CARD

with three-dimensional tests neither an increase in Reynolds number nor fixing boundary-layer transition appears to have any significant effect. It is recommended that this result is checked by further systematic tests including measurements when boundary-layer separation is a feature of the flow.

with three-dimensional tests neither an increase in Reynolds number nor fixing boundary-layer transition appears to have any significant effect. It is recommended that this result is checked by further systematic tests including measurements when boundary-layer separation is a feature of the flow.

with three-dimensional tests neither an increase in Reynolds number nor fixing boundary-layer transition appears to have any significant effect. It is recommended that this result is checked by further systematic tests including measurements when boundary-layer separation is a feature of the flow.

C.P. No. 1151

Produced and published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
49 High Holborn, London WC1V 6HB
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 B1 2HE
80 Chichester Street, Belfast BT1 4JY
or through booksellers

Printed in England

C.P. No. 1151

SBN 11 470399 X