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Loads on a Model during Starting and Stopping of an Intermittent Supersonic Wind Tunnel

By

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SUMMARY

Measurements are given of the loads on a model during starting and stopping of an intermittent supersonic wind tunnel at Mach numbers of 2.00 and 2.48. Qualitative agreement is obtained with a simple theory but a need is evident for further measurements at higher Mach numbers.

The use of a model loading coefficient in terms of tunnel stagnation pressure is proposed.

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1 Introduction

During the starting and stopping of a supersonic wind tunnel, the passage of a shock wave system through the working section is usually associated with the establishment or collapse of the flow. The passage of this shock wave system leads to flow separation from the tunnel walls, and consequent flow direction variations which may be quite violent in nature. A model mounted in the working section is thus subjected, during the starting and stopping of the tunnel, to flows of large incidence at Mach numbers (and consequently values of dynamic head) other than the steady value. It is well known that the resulting loads on the model may be considerably higher than the values during steady flow.

Some measurements have been made of the loads during starting and stopping in the R.A.E. no. 14 (9 in. × 9 in.) Intermittent Supersonic Wind Tunnel. The results are compared with the predictions of a simple theory.

2 Estimation of starting and stopping loads

Loads were measured on the wings only of the model shown in Fig. 1. Tests under steady conditions have shown that the wings behave virtually as isolated panels, and their relevant aspect ratio can thus be taken as unity. For an untapered unswept wing of unit aspect ratio, the maximum normal force coefficient curve slope occurs at a Mach number of $\sqrt{2}$. For a given stagnation pressure the maximum value of q, the dynamic head, also occurs at $M = \sqrt{2}$. Hence for a wing of square planform, the maximum loading per unit incidence will occur at this Mach number, for a given stagnation pressure.

Consider now a supersonic tunnel running at a nominal Mach number in excess of $\sqrt{2}$ with the flow not fully established but with the nominal Mach number attained at some point upstream of the model. In principle the flow can decelerate to a Mach number of $\sqrt{2}$ isentropically or through an inclined shock wave or by a combination of isentropic compressions and shock waves. If the flow is isentropic the maximum model loading per unit incidence will occur at $M = \sqrt{2}$. If the compression occurs asymmetrically in the tunnel nozzle, the reduction in Mach number will be accompanied by a change in flow direction given by the change in Prandtl-Meyer angle. There is thus a possible loading condition on a model set nominally at zero incidence given by the force at an incidence equal to this angle at a Mach number of $\sqrt{2}$. This will give the maximum loading for Mach numbers above about 2 but for lower Mach numbers the maximum loading will occur at lower values than $\sqrt{2}$. (It is obvious that the maximum loading for a nominal Mach number of $\sqrt{2}$ will occur at a value lower than $\sqrt{2}$.) However, the loads at the lower nominal Mach numbers will not be very large and the simple picture given will suffice for most purposes.

If the deceleration takes place through a single inclined shock wave it will also be accompanied by a flow deflection. The maximum value of q will not, in this case, be at $M = \sqrt{2}$ because of the entropy increase through the shock wave. However, calculations, taking into account the variation of normal force coefficient curve slope and flow deflection with Mach number, indicate that, for the square planform considered, the maximum load will occur at $M = \sqrt{2}$ for nominal Mach numbers above about 2.

For both isentropic and shock wave compression, values of an effective starting incidence, α_s, and normal force curve slope factor, k, can thus be calculated. The normal force curve slope factor is defined as the ratio of the normal force curve slope at a Mach number of $\sqrt{2}$ to that at the nominal tunnel speed, taking into account the variation in q, the dynamic head.

The effective starting incidence or flow deflection is given in Fig.2 and the normal force curve factor for unit aspect ratio in Fig.3 for a wing of square planform. In both curves the isentropic compression gives the larger effects. Since the isentropic compression is unlikely to occur fully, it is to be expected that the actual conditions will be somewhere between the two sets of results.

The normal force coefficient on a model during starting and stopping at a nominal incidence α can be expressed in terms of the two parameters, α_s and k as

$$C_N = k \frac{dC_N}{d\alpha} (\alpha + \alpha_s).$$

Thus by measuring the starting loads on the model over an incidence range both parameters can be determined.

3 Experimental method

Measurements of starting and stopping loads were made in the R.A.E. no. 14 (9" × 9") Intermittent Supersonic Tunnel at Mach numbers of 2.00 and 2.48. The model used is shown in Fig.1. A strain gauge balance, to which the wings are attached, is housed in the model body. The wing angle can be varied by rotating both wing and balance relative to the body, the balance measuring the force normal to the wing plane. Initially the tests were made using the normal A.C. strain gauge equipment with a rectified signal taken from the amplifer, the servo circuit not being used. These tests were not satisfactory because of the amplifier characteristics and further measurements were made using a D.C. amplifier and D.C. strain-gauge bridge supply. The output was displayed on a cathode ray tube and photographed. The trace displacement was calibrated by hanging weights on the balance. Marks were arranged on the traces to indicate the ends of the travel of the quick acting valve controlling the tunnel, and a timing trace of 50 c.p.s. was also displayed.

Measurements were made with the body at zero and 20° incidence with wing angles to body in the range ±20°.

4 Analysis of results and comparison with theory

A typical film record is shown in Fig.4. It will be noted that the unsteady loads are confined to a period towards the closed position of the valve. This is referred to in para.6. The unsteady loads are composed of an oscillatory component of frequency about 750 c.p.s. superimposed upon a more or less random variation. The high frequency component arises from the natural frequency of the balance and wing combination, and is regarded as being peculiar to the particular combination tested. Two values of loading have therefore been taken from each trace; that termed 'mean' is the maximum value on a mean curve drawn through the high frequency oscillation and the 'peak' value is the maximum displacement in the high frequency oscillation. Positive and negative values of each have been taken. It is considered that the so called mean value is applicable to the overall loading of a model, e.g. sting stressing, but that the peak value is appropriate to model components likely to have a high natural frequency.

In Figs.5 and 6, C_N, the coefficient of force normal to the wing plane, expressed in terms of exposed wing area, is plotted against α_W, the incidence of the wing to the free stream. The open symbols give the peak values of C_N, and the full symbols the mean values.

The two sets of points given on each graph are the positive and negative values of the loads. The two sets thus define the bounds of the range in which the load varies during starting and stopping. When, for example, no negative load occurs the point is plotted as zero since the load is zero before the tunnel starts. Also plotted are the steady values which are compared with steady values measured during normal running. As will be seen the results from the D.C. amplifier are about 25% down on the previous measurements at M = 2 but in reasonable agreement at M = 2.48. The disagreement is attributed to instability of the D.C. amplifier. The theoretical curves are obtained by applying the parameters α_s and k to the measured normal force curves. Any error in the absolute magnitude of the measurements is thus taken into account in the comparison with theory. No corrections are applied to the curves for the effects of body upwash.

The plots confirm the sort of physical picture described in para.2, in that two parameters are involved, an apparent incidence change together with an increased normal force curve slope. It will be noted that at M = 2.00 the mean loads on the positive side are greater than on the negative side. The M = 2.00 liner used was single-sided and the flow might be expected to have a preference for a direction towards the shaped liner so favouring the occurrence of positive loads. The mean loads at M = 2.48 where the liners are symmetrical are, in general, larger positive on stopping. A simple explanation for this is not evident. At large incidences (Figs.5(b) and 6(b)) the unsteady loads relative to the steady values are not so great as at low incidences presumably because of the reduction in normal force curve slope.

The peak loads depart from the steady loads by about twice the departure of the mean loads. If the aerodynamic loads are varying very rapidly this would be expected ('live' loading condition). It should be noted that, in general, the peak loads occur at isolated cycles of the high frequency oscillation.

In determining experimental values of α_s and k from the results the 'mean' loadings are used as being of wider application than the 'peak' loadings. A decision has to be made, however, as to whether to take the average values for any set of points or the maximum values. As the number of points available is limited and the starting and stopping flow is to some extent a chance phenomenon it is unlikely that the maximum values have been found. Furthermore the application of the results is to the stressing of models where some uncertainty is covered by safety factors. Average values of a set of points are therefore taken and the loads in stopping used, as being consistently larger at both Mach numbers. In the right hand graphs of Figs.5(a) and 6(a) the mean points lie sensibly parallel to the shock compression line. The values of k are therefore taken to be in agreement with the shock compression values of Fig.3. The corresponding values of α_s at M = 2.00 and 2.48 are respectively about 12 and 17 degrees compared with values from the shock compression curve of Fig.2 of 16 and 25 degrees.

5 Design values for model loading

5.1 Loading coefficient

In practice a knowledge of the load on a model set at zero incidence during starting and stopping is required. The results in Figs.5 and 6 give some confidence in the physical picture described in para.2 of the nature of the flow. The normal force coefficient on starting and stopping at zero incidence may then be expressed as

$$C_{N_s} = k \frac{dC_N}{d\alpha} \alpha_s$$

or defining a more general loading coefficient C_s in terms of stagnation pressure

$$C_s = \frac{qC_{N_s}}{H} = \frac{kq}{H} \frac{dC_N}{d\alpha} \alpha_s.$$

This coefficient is plotted in Fig.7 both for shock compression and for isentropic compression for a wing of unit aspect ratio. The shock compression curve has a maximum value at a Mach number of about 2.4. As would be expected from Figs. 2 and 3 the curve for isentropic compression gives considerably higher values above this Mach number. Also plotted are the measured 'mean' and peak values. The 'mean' values plotted are above the average values used to determine α_s and the points are in somewhat better agreement with the calculated shock compression curves than the ratio of measured to calculated α_s which is about 70%. The peak values are again of the order of twice the mean values.

There remains some doubt as to whether the decrease of starting and stopping loads at high Mach numbers predicted by the shock compression theory is realised. Bouwhuysen[1] has published some data on starting loads over a Mach number range from 1.4 to 3.1 but the loads are given simply in pounds on an unspecified model. The load is shown to be still increasing up to a Mach number of 3.1. If the load is scaled to agree with the measured points in Fig.7 at one Mach number it is found also to agree at the other. Some reliance may therefore be placed on a curve simply scaled from Ref.1. For the sake of consistency the chain dotted curve on Fig.7 derived from Ref.1 is scaled to pass not through the points plotted, but through points corresponding to the average values used to determine α_s in para.4. The value of C_s is 0.27 at M = 3.1 and extrapolation leads to a value of 0.3 to 0.35 at M = 4.5

5.2 Aspect ratio effects

It should be emphasised that the loadings in Fig.7 are for a wing of square planform. Theoretically the maximum normal force curve slope is proportional to aspect ratio and $\frac{1}{A} \frac{dC_N}{d\alpha}$ has a maximum value of 2 for an unswept wing. As the aspect ratio increases the Mach number at which this value occurs tends towards unity, and it is unlikely therefore that it will be attained. For models up to an aspect ratio of 6, $dC_N/d\alpha$ will probably have a maximum value of about 8. Simply scaling from Fig.7 this leads to a maximum loading coefficient up to M = 4.5 of about 1.3.* There may be some relief in that the value of α_s at which such a loading occurs will be large and the effect of aspect ratio will be diminished to some extent. (It can be seen that the load on a plate normal to a supersonic stream is relatively insensitive to the planform of the plate.) However a value of C_s approaching 1 will be difficult to meet structurally with thin wings at high stagnation pressures and more experimental work is clearly desirable.

5.3 Vibration effects

The presence of the high frequency components in the loads during starting and stopping indicates that small fins attached to a body will be critical as regards stress. It is suggested that such model parts should be stressed to twice the 'mean' loads of Fig.7.

*For the quasi-steady flow considered the maximum possible value of C_s is of course unity (full stagnation pressure on one surface and vacuum on the other).

If many runs are to be made fatigue is likely to be significant. A fatigue failure has already been encountered in the R.A.E. Intermittent Tunnels. This occurred on a control surface of aspect ratio 3 attached to a body. The control had been run at Mach numbers up to 2.5 and had been started at incidence. It survived about one thousand runs before failing, and was stressed to a loading coefficient of 0.5 with a safety factor of 2 on ultimate stress. On the basis of the loading criteria given here this failure would be expected.

6 Duration of unsteady loads

The timing traces and marks indicating the limits of the valve travel have been used to determine the period of the unsteady loads in relation to the valve open area. Assuming that the valve travels at a uniform rate, the curves of Fig.8 have been constructed. In these curves the valve area is expressed in terms of the critical area for starting, i.e. the area which will just pass the tunnel mass flow, allowing for the entropy increase behind a normal shock wave in the working section. Average times of the period of the unsteady load are shown. It will be seen that on starting the unsteady load begins when the valve is opened to the critical area. (The valve is some 11 ft downstream of the model position so that, at any rate in starting, the time lag between valve and working section is of the order of 1/100 second.) The so called quick-acting valve may be said therefore to operate in an essentially 'slow' manner, and the starting loads measured in the intermittent tunnel should also be applicable to a continuous tunnel.

In stopping the critical area will not be directly relevant. At both Mach numbers the unsteady loads begin when the valve area is about 1.3 times the critical area.

7 Conclusions

1 At Mach numbers up to 2.5 the 'mean' stopping and starting loads are of the same order as those predicted by a simple shock compression theory.

2 At Mach numbers above 2.5 the theory predicts a decrease in the loads. There is some evidence that this decrease is not realised in practice.

3 For low aspect ratio wings a value of loading coefficient (load on model per unit area divided by tunnel stagnation pressure) of 0.35 is suggested for Mach numbers up to 4.5. For higher aspect ratio models this coefficient may be appreciably larger.

4 The loading coefficient should be doubled for model components likely to have a high natural frequency and the possibility of fatigue must be considered.

5 The timing of the period of unsteady loads relative to the tunnel quick acting valve operating time shows that the motion of the valve is relatively slow. The measured starting loads should therefore be applicable to a continuous tunnel.

8 Further Work

A need is evident for further measurements of starting loads at Mach numbers above 2.5 covering a range of model planforms.

LIST OF SYMBOLS

A	Aspect ratio
H	Stagnation pressure
k	Normal force curve slope factor during starting or stopping
M	Mach number
q	Dynamic head
C_N	Normal force coefficient based on wing exposed area
C_s	Starting and stopping load coefficient $= \dfrac{\text{load per unit area}}{H}$
α	Incidence
α_B	Body incidence
α_W	Wing incidence to free stream
α_s	Effective incidence during starting or stopping

REFERENCE

No.	Author	Title etc.
1	van den Bouwhuysen J.N.A.	Starting loads in supersonic wind tunnels. Aeronautical Engineering Review Vol 13 No.1 January 1954.

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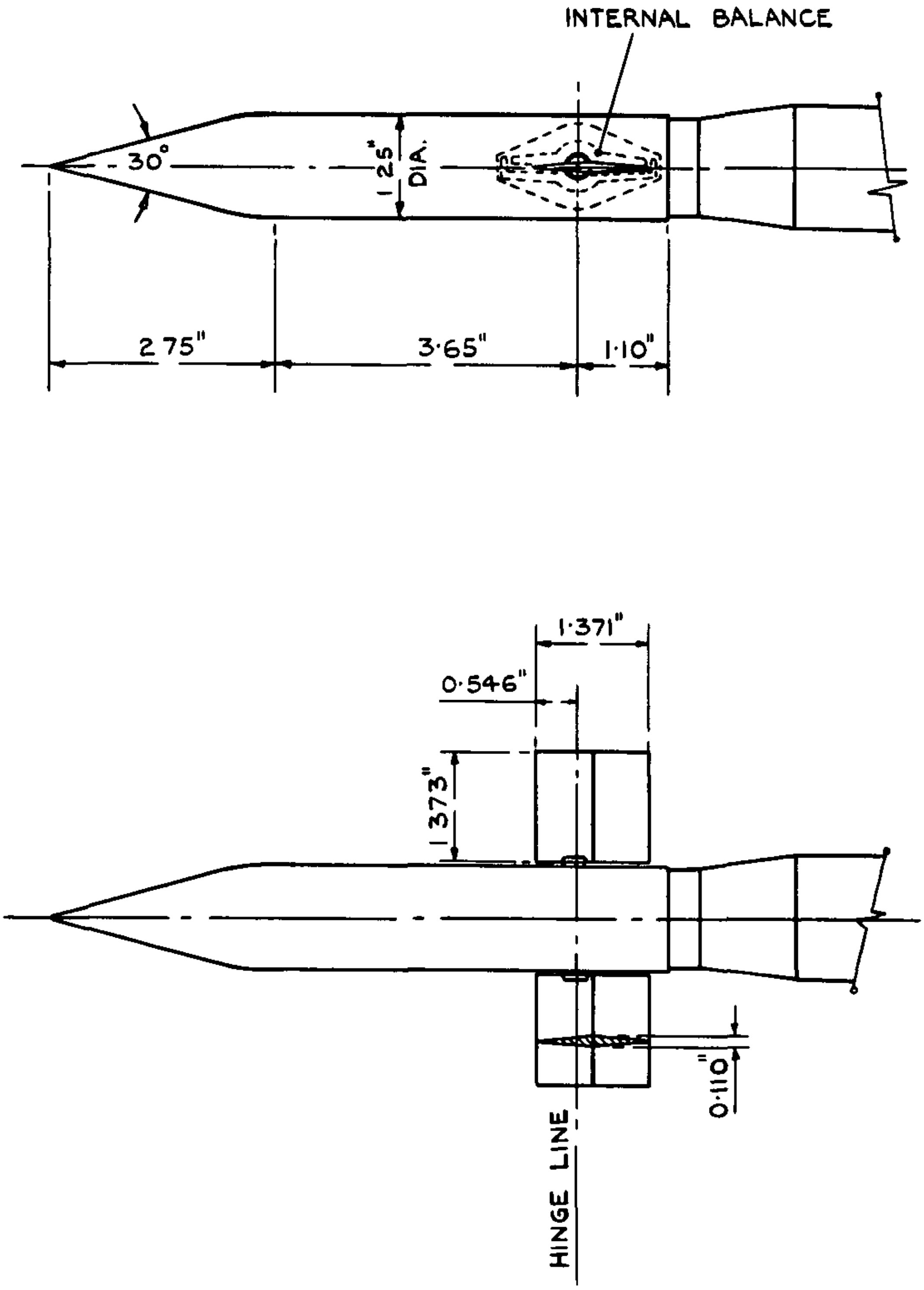

FIG.1. G.A. OF MODEL.

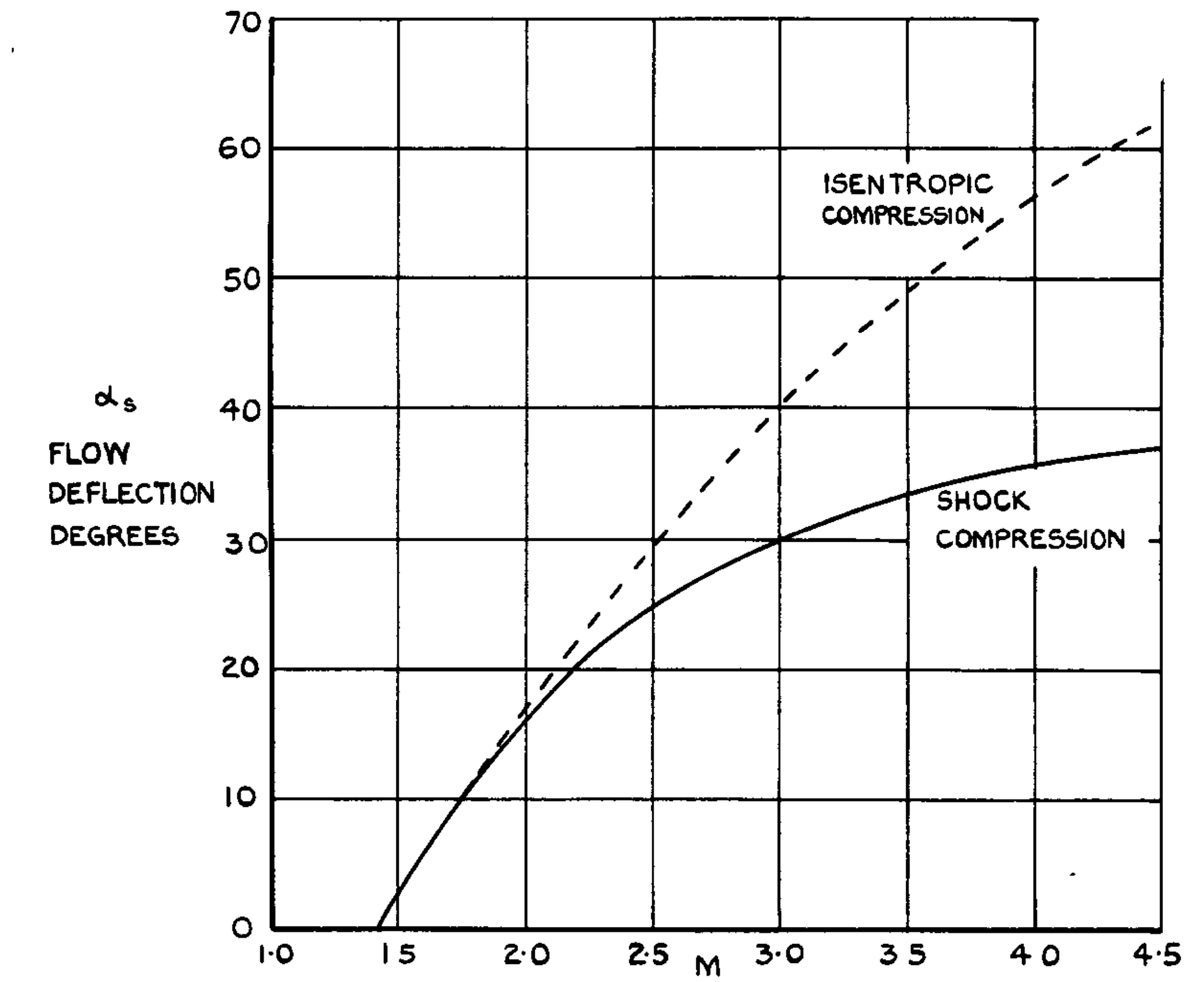

FIG.2. POSSIBLE FLOW DEFLECTION IN COMPRESSION FROM MACH № M TO A MACH № OF $\sqrt{2}$.

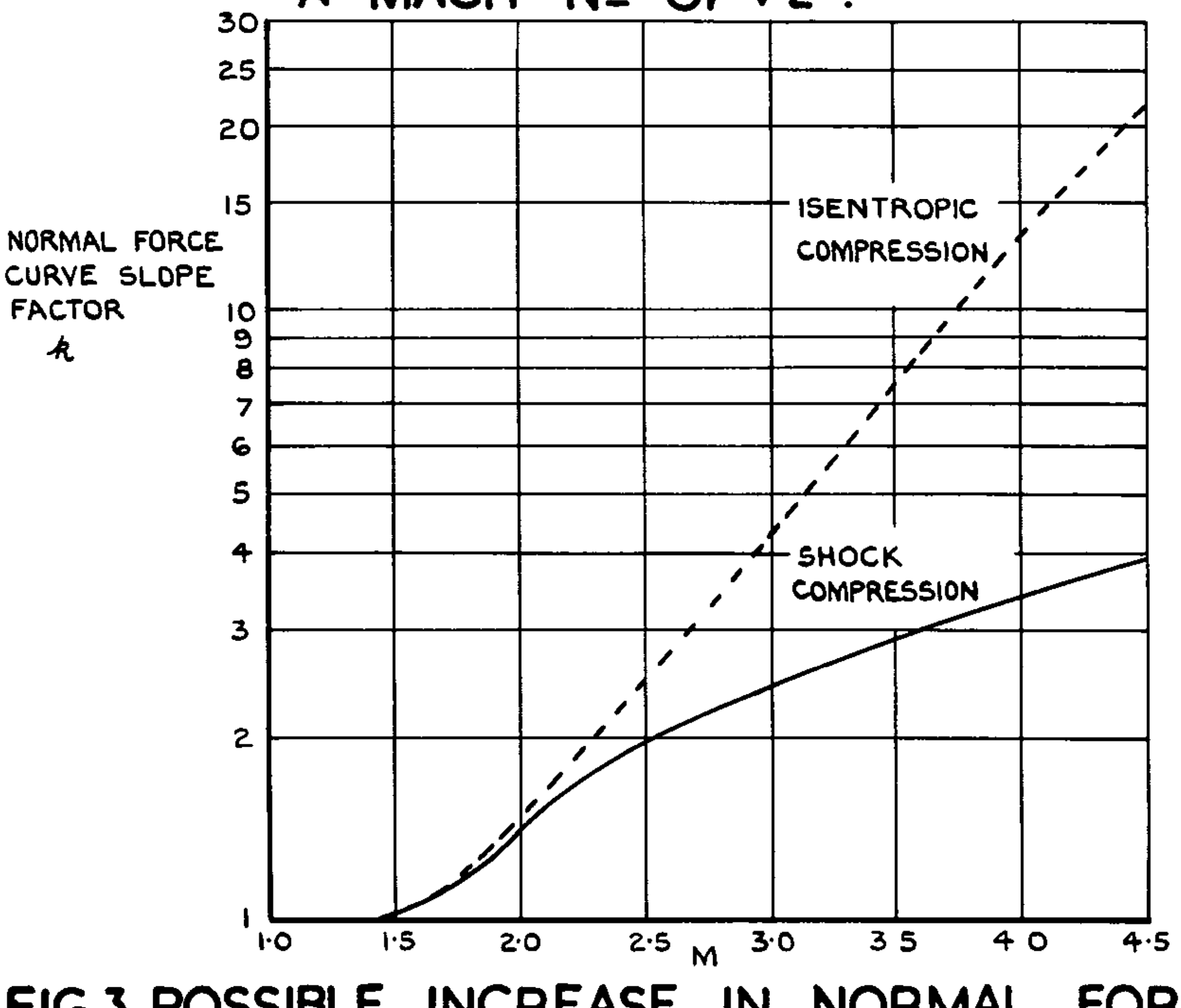

FIG.3. POSSIBLE INCREASE IN NORMAL FORCE CURVE SLOPE IN FLOW COMPRESSION FROM MACH № M TO A MACH № OF $\sqrt{2}$ — UNIT ASPECT RATIO.

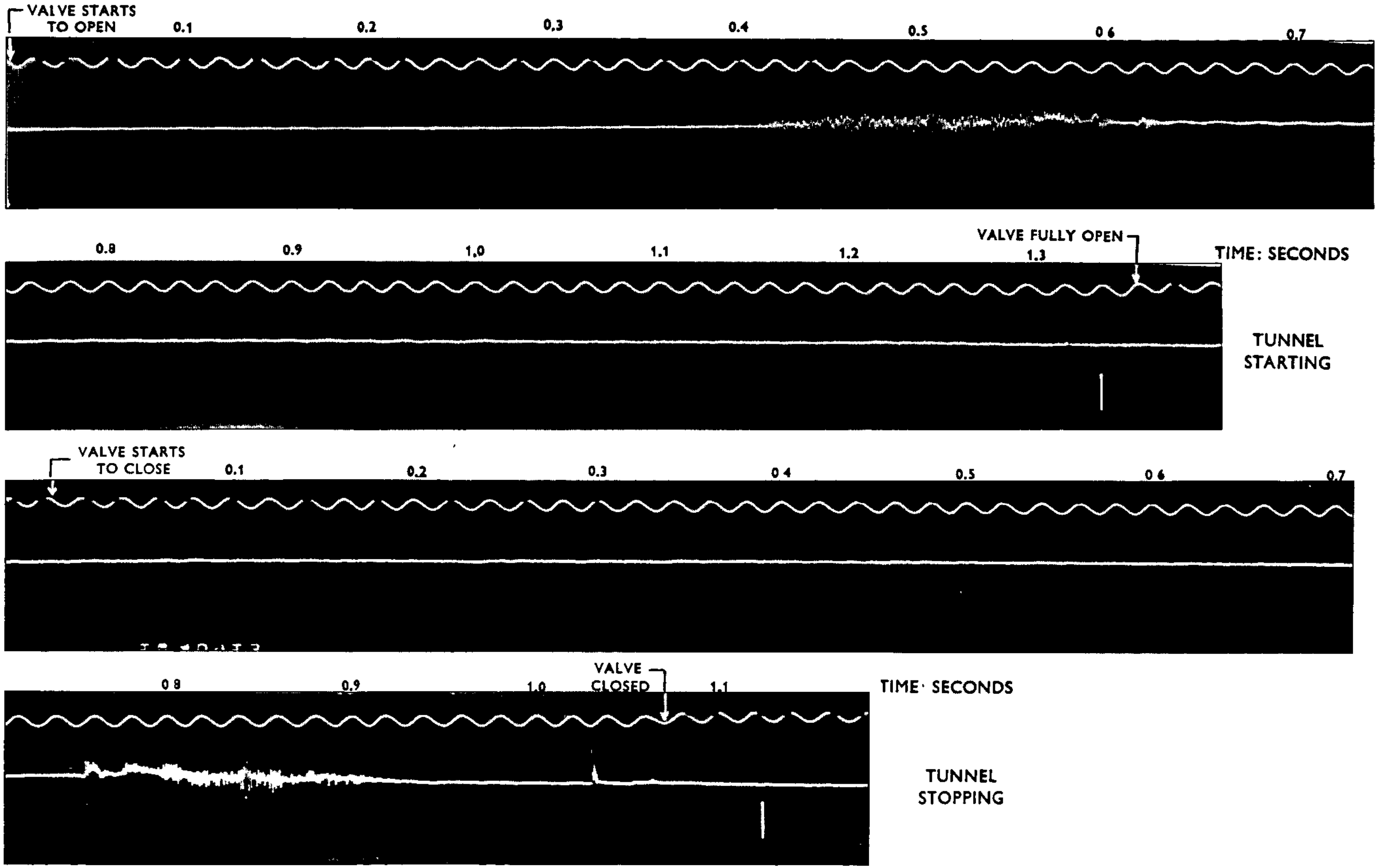

FIG.4. TYPICAL LOADING TRACES, $M = 2.0°$, $\alpha_B = 0°$, $\alpha_W = 15.7°$

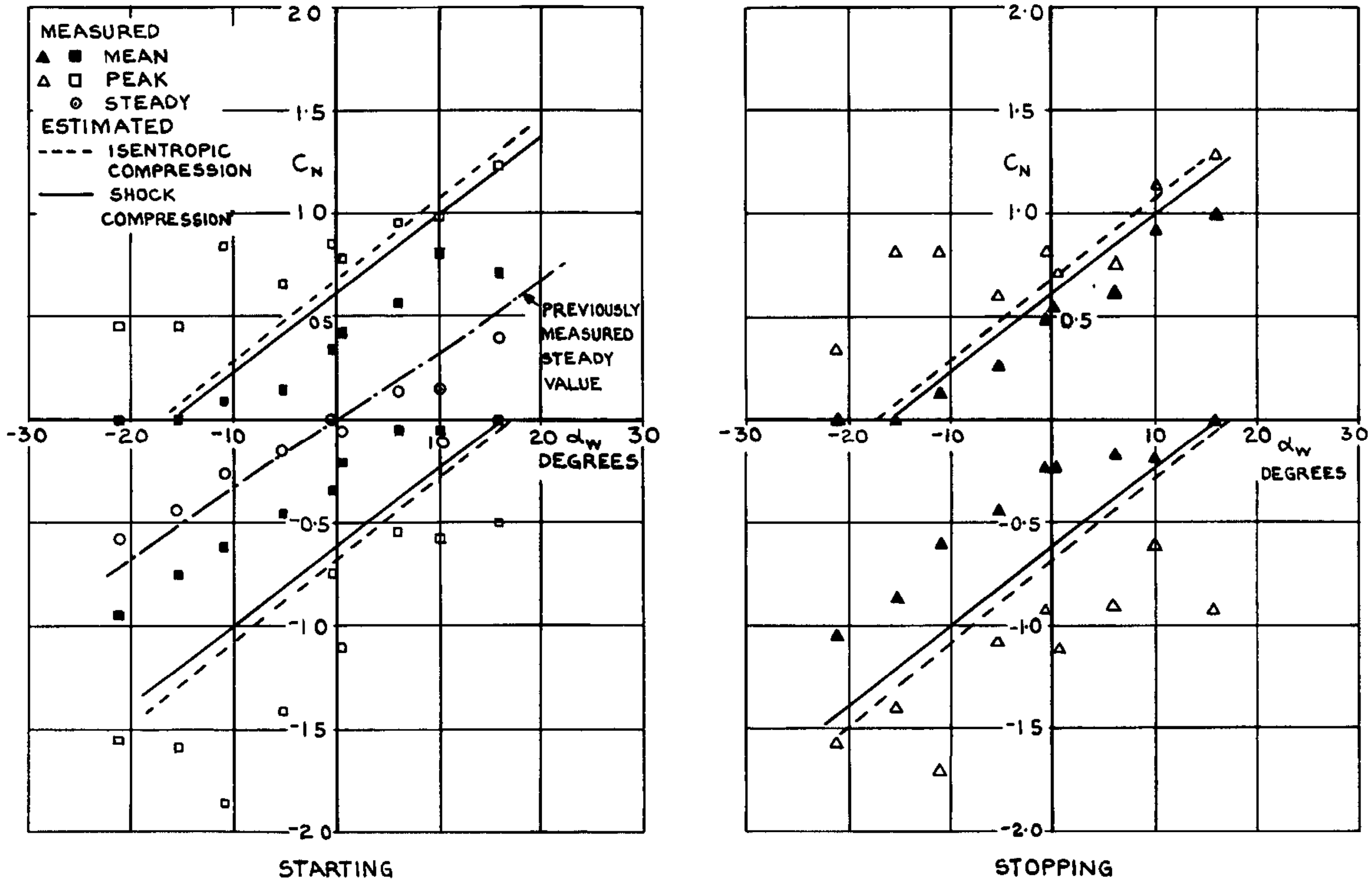

FIG. 5(a) STARTING & STOPPING LOADS AT M=2·00 α_B= O.

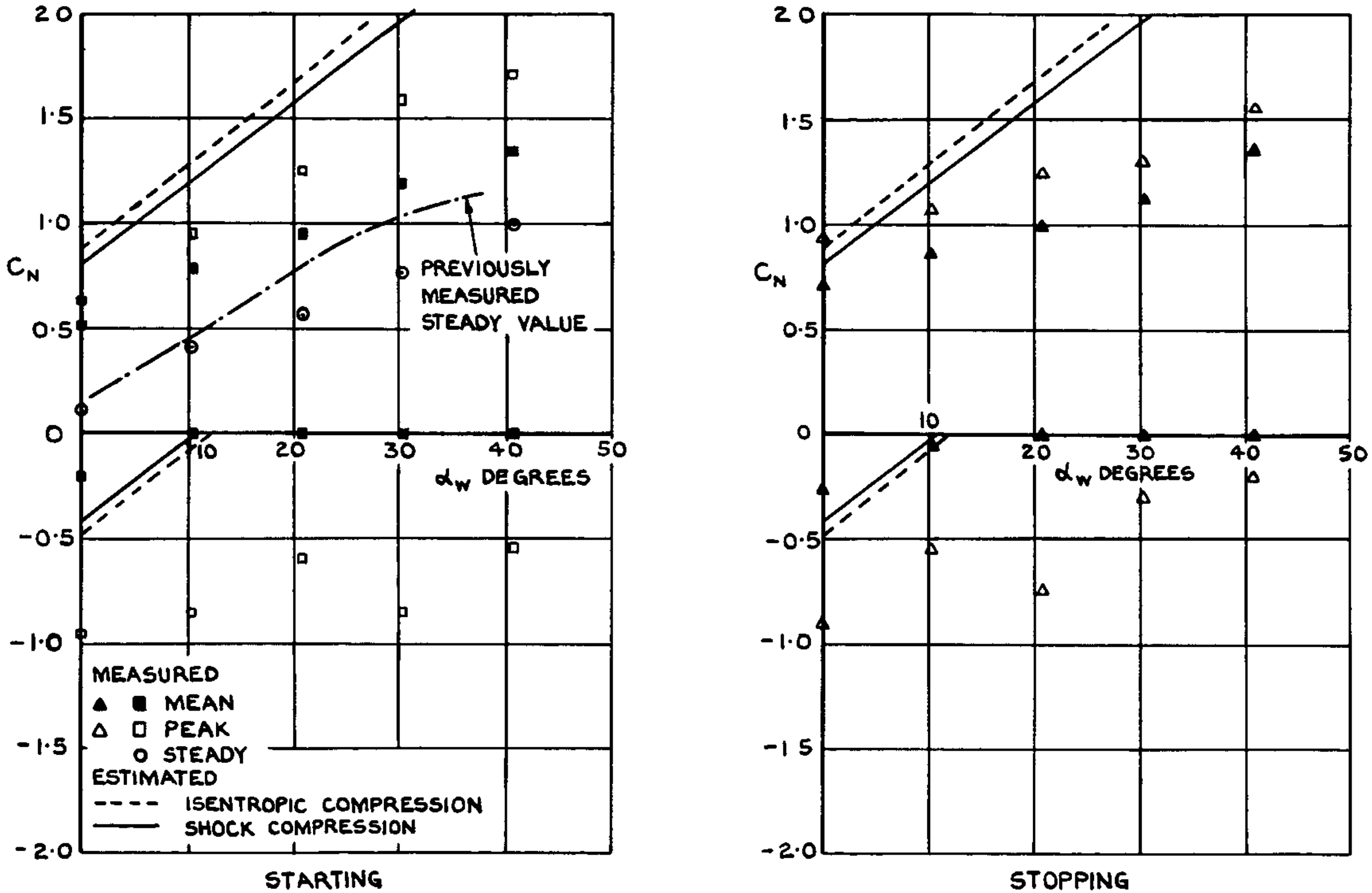

FIG. 5(b) STARTING & STOPPING LOADS AT M=2·00 $\alpha_B=20°$.

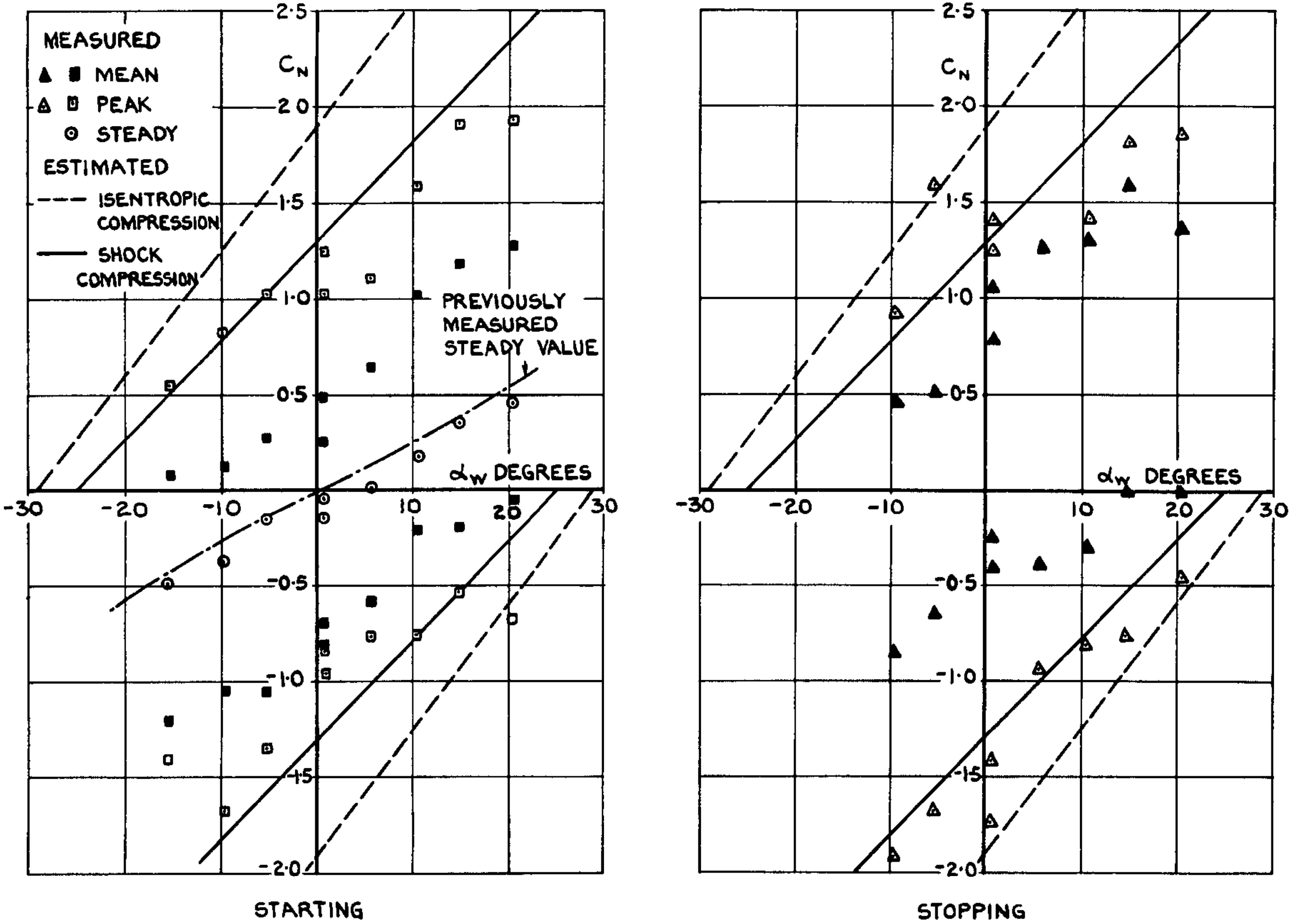

FIG. 6(a). STARTING & STOPPING LOADS AT M = 2·48 α_B = O.

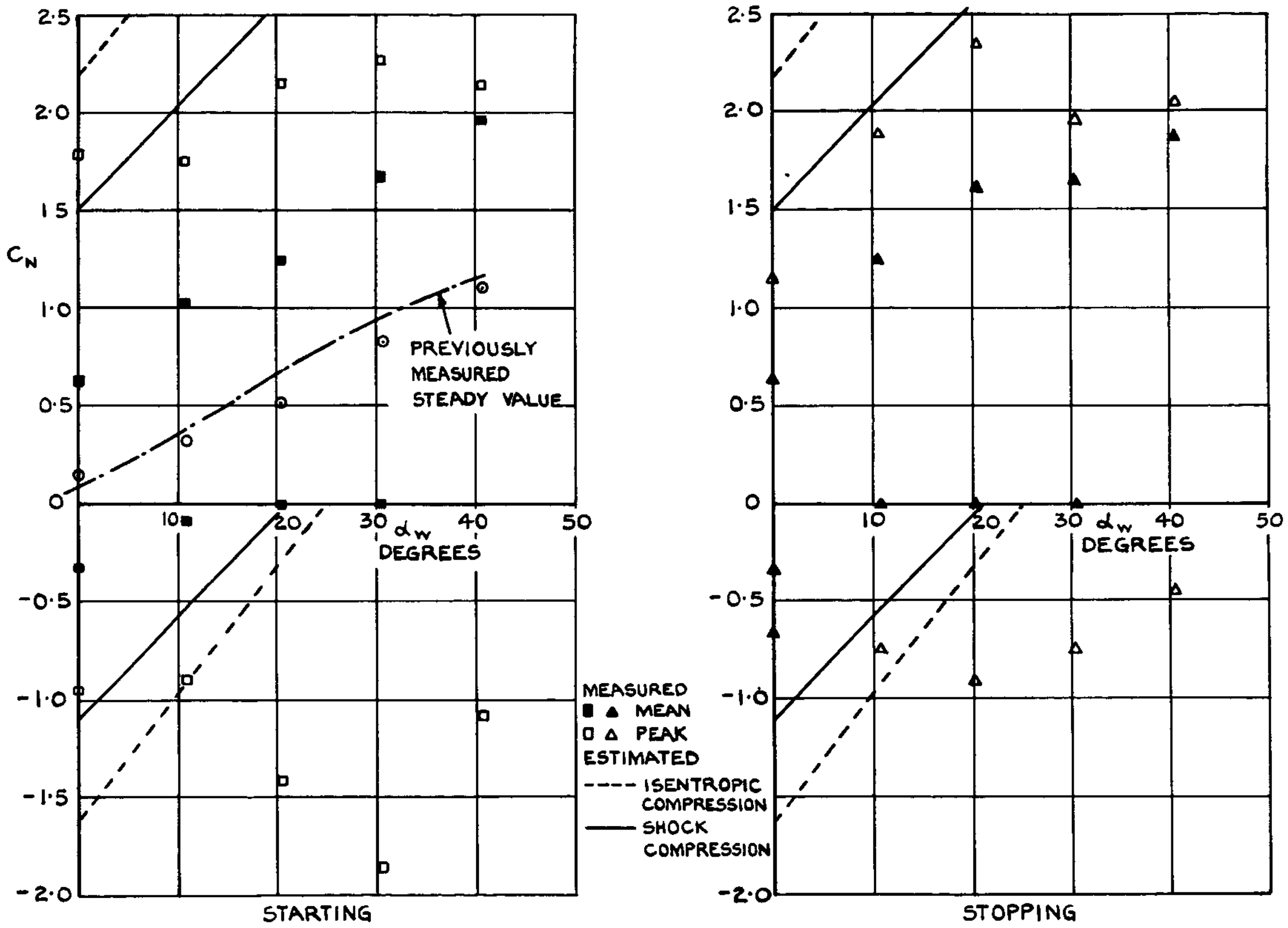

FIG. 6(b) STARTING & STOPPING LOADS AT $M=2{\cdot}48$ $\alpha_B=20^\circ$.

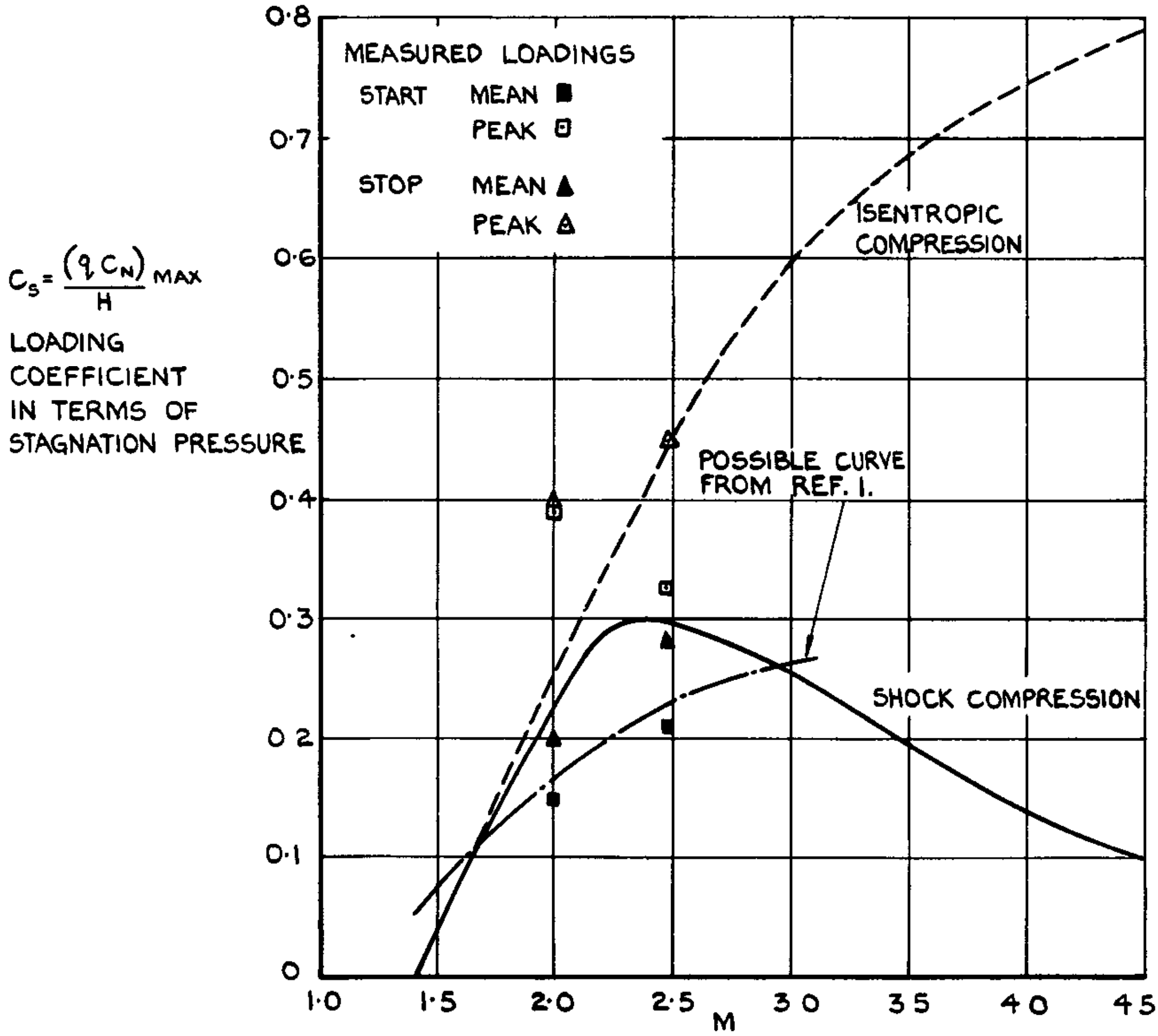

FIG.7. POSSIBLE VALUES OF LOADING DURING STARTING & STOPPING — UNIT ASPECT RATIO.

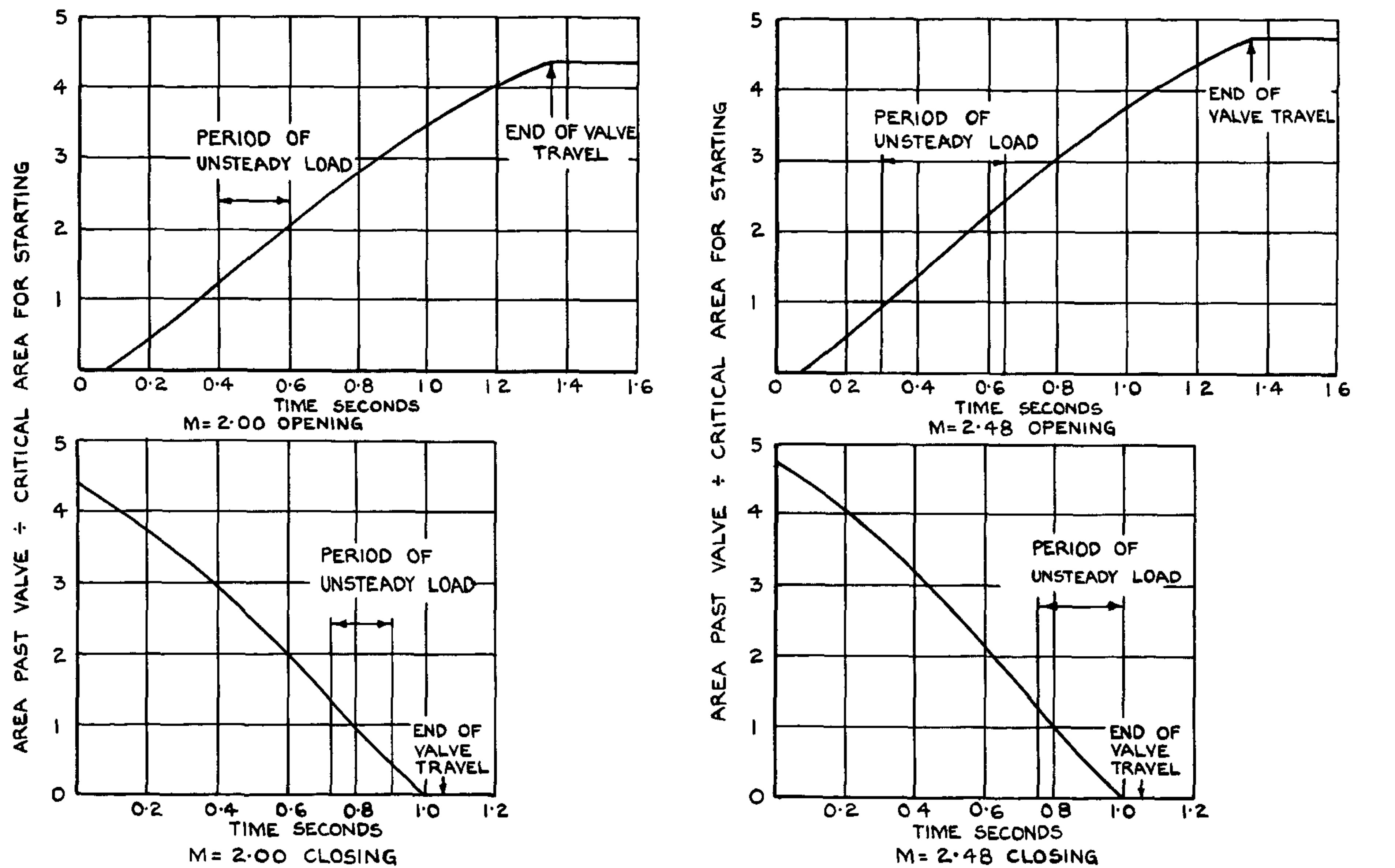

FIG. 8. OCCURRENCE OF UNSTEADY LOADS IN RELATION TO VALVE TRAVEL.

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