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Designing to Avoid Dangerous Behaviour of an Aircraft due to the Effects on Control Hinge Moments of Ice on the Leading Edge of the Fixed Surface

By

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Designing to avoid dangerous behaviour of an aircraft due to the effects on control hinge moments of ice on the leading edge of the fixed surface

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SUMMARY

The results of wind tunnel measurements of the hinge moments of a Viking elevator with simulated ice on the tailplane leading edge are used to explain uncontrollable pitching oscillations of the aircraft which occurred during a flight with ice on the tailplane leading edge. Reference is made to theoretical reports which show that with certain elevator (or rudder) hinge moment characteristics increasing oscillations in pitch (or yaw) are obtained.

It is suggested that the imposing of certain limitations on the control surface hinge moment coefficients will eliminate the possibility of a repetition of the Viking incident on future aircraft designs.

In order to achieve this it is recommended that for elevators and rudders the value of $-b_2$ should not be less than 0.10 (0.12 if they have an unshielded horn balance). For ailerons it is recommended that $-b_2$ should not be less than 0.075. The value of the elevator b_1 should be such that the stick free neutral point is not more than 0.05c aft of the stick fixed neutral point. For rudders the value of b_1 should be designed to be less than 0.05.

It is suggested that tests should be put in hand to determine the accuracy with which b_2 for an elevator can be measured in flight during quick routine tests. Should it prove practicable to obtain the needed accuracy, consideration should be given to framing a definite requirement for a lower limit for $-b_2$ on elevators with possibly an escape clause in certain cases, e.g. for power operated controls.

Very soon after this report was written Messrs. Vickers-Armstrongs Ltd., introduced a modification to the Viking elevator which, whilst still maintaining an adequate margin of stick free stability, has successfully cured the troubles due to ice.

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1 Introduction

Following a recent incident during a flight on a Viking aircraft when difficulty was experienced in controlling pitching oscillations which occurred when ice formed on the tailplane leading edge, the question has arisen of whether design rules can be formulated to prevent future aircraft types suffering from such trouble

In this note an attempt will be made to explain the reasons for the behaviour of the aircraft in these conditions, and design rules are suggested for avoiding such behaviour in future.

Guidance in interpreting the flight experience has been obtained from wind tunnel tests[1] on a Viking tailplane and elevator in which elevator hinge moments were measured with various types of ice formations simulated on the tailplane leading edge. The results of these tests showed that ice on the tailplane leading edge caused comparatively large changes in the elevator hinge moments in the direction of overbalance, i.e. b_1 became less negative (or more positive) and b_2 became less negative.

When considering possible variations of the basic hinge moments of controls it is essential to consider the variations from normal due to random manufacturing errors. The importance of the effects of such errors has been realised for a long time and designers have been warned of their possible magnitude[2].

It is obviously important that the effects of such variations in control hinge moments should not be allowed to cause dangerous handling characteristics of the aircraft.

An obviously dangerous hinge moment characteristic is a positive value of b_2, i.e. overbalance. Thus it appears desirable to design to a minimum value of $-b_2$ so that the effects of ice combined with the effects of manufacturing errors do not make b_2 positive.

If b_1 is large and positive in combination with a small (near zero) positive or negative values of b_2 for the elevator (or rudder) undamped stick free pitching (or directional) oscillations occur. These oscillations are caused by the induced movements of the control surfaces. When the aircraft is disturbed, giving a change in tail incidence, the comparatively large values of positive b_1, combined with a small value of $-b_2$, causes a large stabilising control movement. This overcorrects the disturbance and thus an increasing oscillation is set up.

This type of motion has been investigated theoretically for both pitch[3] and yaw[4]. The period of the oscillation is about 1-2 seconds for the pitching oscillations and about 1-5 seconds for the directional oscillations. Examples of such oscillations have been obtained in flight on quite a number of aircraft, even without ice present. In general, however, the motion has not been undamped.

When considering the possibility of the pilot being able to stop such oscillations, very important factors are the shortness of the period and the magnitude of the stick forces required to prevent the induced control movements. When the period is about 1 sec, it is possible for the pilot, in his attempts to damp out the oscillation to get out of step and actually move his control so as to increase the oscillation. The most satisfactory way of dealing with such oscillations appears to be to attempt to hold the stick (or rudder bar) fixed. If the value of b_1 is very large the pilot may not possess the strength to do this and this is the really dangerous condition.

Hence, in addition to imposing some limit on the value of b_2, it is necessary that some limit be placed on b_1 either to prevent the occurrence of unstable oscillations or to make the oscillations easily controllable when they do occur.

2 Tunnel measurements of the hinge moments of a Viking elevator

Elevator hinge moments were measured on a full scale starboard tailplane and elevator of a Viking aircraft in the large tunnel at R.A.E. The detailed results have been reported elsewhere[1] and only a brief summary will be given here.

Sketches of the various types of ice formations simulated in the tunnel tests are given in Fig.1. Type A is intended to represent the ice formation observed on the viking.

A brief description of the T.K.S. de-icing system as fitted on the Viking may be of assistance in understanding the significance of the various ice formations simulated. In the T.K.S. system, de-icing fluid is forced out through porous metal strips fitted along the leading edge of the wing or stabilising surface. In the case of the Viking tailplane there are two such strips on the inboard part and a single strip on the outer part of the span. If the flow of de-icer fluid is not sufficient, ice may form on the leading edge, except in the immediate neighbourhood of the porous metal strips. Type A represents such a formation with no ice on the metal strips and a rough ice formation elsewhere. Type B represents an extreme form of Type A. Here the surface is clear apart from two ridges formed one on each side of the leading edge. Type C simulates a smooth ice formation and was tried only on the horn balance.

Measurements of the elevator hinge moments were made over a range of elevator angles and tailplane incidences. Because of the large trailing edge andle ($22\frac{1}{2}$ deg.) the hinge moment curves were non-linear and the values of b_1 and b_2 were taken where the slopes were numerically the smallest, (i.e. minimum values of $-b_2$ were taken). The following table summarises the results and gives the changes (Δb_1 and Δb_2) in b_1 and b_2 in the various conditions when compared with the no ice condition.

TABLE I

Condition			b_1 $\left(\frac{\partial C_H}{\partial \alpha_T}\right)$	b_2 $\left(\frac{\partial C_H}{\partial \eta}\right)$	Δb_1	Δb_2
No ice			0.195	-0.055	-	-
With ice	A	on horn only	0.225	-0.035	0.030	0.020
" "	B	" " "	0.195	-0.035	0	0.020
" "	C	" " "	0.210	-0.035	0.015	0.020
" "	A	on tailplane only	0.250	0	0.055	0.055
" "	B	" " "	0.360	-0.030	0.165	0.025
" "	A	on both horn and tailplane	0.265	+0.020	0.060	0.075

It is interesting to note that Type B, which represents an extreme form of Type A, though it has a much larger effect on b_1, has a smaller effect on b_2. The results for Type A are probably most representative of a normal rough ice formation.

The Viking port elevator has a smaller horn balance than the starboard elevator. This will of course make the elevator hinge moments on the actual aircraft different from those given above.

3 Flight experience on the Viking

During a flight to investigate the efficacy of the Viking de-icing equipment, fairly severe icing conditions were encountered. The de-icing fluid flow was not sufficient to prevent ice forming, but the porous metal strips themselves remained free of ice. An ice formation similar to Type A of Fig.1 was observed.

When the auto pilot was de-clutched under these conditions the aircraft started to do uncontrollable pitching oscillations. Control was regained with the aid of the auto-pilot. When the ice had been removed from the fixed tailplane the behaviour of the aircraft was satisfactory though quite a lot of ice still remained on the elevator horn balance.

The violent pitching motion was an example of the elevator induced increasing oscillations described in para.1. The pilot was quite unable, by himself, to prevent the stick moving, i.e. b_1 was extremely large and positive.

In the case of the Viking the basic elevator (without ice) has a large positive b_1 and a rather small negative b_2 (cf. Table I) in order to give the aircraft a large gain in stability on freeing the stick. At climbing speed the gain in stability stick free compared with stick fixed is about 0.18c engine on and about 0.26c with the engines throttled. This was needed because the stick fixed stability of the aeroplane was very inadequate. It must be emphasised that this is a very undesirable state of affairs; in our view a designer should aim to get most of his stability stick fixed, and should only use the difference between stick free and stick fixed stability for making relatively small adjustments. The recommended maximum gain in stability on freeing the stick is 0.05c. Allowing for production variations, bad damping of the stick free short period oscillation might be expected on some Vikings even without ice.

The known effects of ice on the tailplane leading edge, which would make b_2 still smaller and possibly positive (overbalanced) and at the same time would make b_1 still more positive gives the conditions required for a dangerously undamped pitching oscillation.

Thus the Viking elevator had undesirable hinge moment characteristics which became dangerous when ice formed on the tailplane-leading edge.

Flight tests[5] made on a Viking fitted with a modified elevator with a b_2 of about -0.1, but with quite a large positive b_1, have shown that the short period stick free oscillation is damped with a variety of bad ice formations on the tailplane and horn balance.

4 Design values of b_1 and b_2

In para.1 it was stated that the trouble experienced on the Viking can be avoided by imposing restrictions on b_2 and possibly on b_1.

Fig.2 shows theoretically[4] derived boundaries of rudder b_1 and b_2 for damping of the rudder free oscillations. Similar boundaries can be drawn from the investigations of Ref.3. The boundary for increasing oscillations is of the same order for both rudders and elevators. The divergence boundary is critically dependent on the static stability of the aircraft whilst the increasing oscillation boundary is practically independent of this.

One method of avoiding undamped stick free oscillations is to make b_2 large and negative so that the combined effects of ice and manufacturing errors will not bring it into the increasing oscillations region, whatever the value of b_1. In order to do this the value of $-b_2$ with ice must be greater than about 0.1. This would make the minimum basic design value of $-b_2$ about 0.2. This is too large a value, if pure aerodynamic balance is to be used, for aircraft of more than about 20,000 lb all up weight.

Making b_1 negative enough to prevent ice and manufacturing errors making it positive is not practicable because of the large destabilising effects involved on freeing the stick.

Hence it is considered that the recommendayions should aim at preventing b_2 becoming positive, allow the possibility of increasing oscillations, but prevent b_1 becoming so large and positive that the pilot cannot easily control the motion by preventing the stick (or rudder bar) moving.

From the results of the tunnel tests on the Viking elevator given in Table I of para.2, it is seen that ice on the tailplane leading edge may change b_2 by 0.055 and ice on the unshielded horn balance may give a further change of 0.020.

Morgan in Ref.2 states that manufacturing errors may cause a variation in Kb_2 of up to $\pm$ 0.05 between controls made to the same drawings. These are extreme figures based on the standard of manufacture in war-time; an improvement in manufacture can be expected under peace conditions, and this may well reduce the limits to about $\pm$ 0.025.

Thus, given fairly careful manufacture, ice and manufacturing errors may combine to give a total reduction in $-b_2$ of 0.08 from the value normally realised in production. If the control has an unshielded horn balance there may be a further reduction of 0.02.

Making allowances for the fact that these figures are based on a single test, it appears desirable to recommend for elevators and rudders of aircraft on which ice may form on the tailplane or fin leading edges, that the normal basic value of $-b_2$ should not be less than 0.10 (0.12 where the control has an unshielded horn balance).

There is no information of the effect on the aileron hinge moments of ice on the wing leading edges. It is considered that the effect would be rather smaller than for the elevator as the control occupies less of the fixed surface chord. It is therefore suggested that a minimum value of $-b_2$ for ailerons should be 0.075.

Determining a maximum positive value of b_1 so that, when b_2 is about zero, the pilot can prevent the stick moving when pitching oscillations start is extremely difficult. The unknown factor is the change in incidence (or sideslip) that may occur before the pilot tries to stop the motion.

In the case of military aircraft a limit is imposed on the value of the elevator b_1 by the requirement that the stick free neutral point must not be more than 0.05c aft of the stick fixed neutral point. This means, very approximately, that b_1 must not be greater than $(-b_2/3)$. Experience with the Viking seems to suggest that this would be a sufficient restriction on the value of b_1 for elevators.

There is no comparable method of limiting the value of b_1 for rudders. As it is extremely difficult to measure b_1 in flight (see para.5) only a design recommendations can be made. It is considered that for rudders b_1 should not be designed to be greater than 0.05.

In general the value of b_1 for ailerons will be negative. It certainly will not be large and positive. It is therefore considered that no recommendation of limits for b_1 is necessary in the case of ailerons.

5 Practicability of flight tests

The question of checking that the recommendations are adhered to must be considered. It is obviously desirable that this should be done at an early stage during the prototype flight tests, if practicable, with occasional checks on some production aircraft

Of the three controls the elevator characteristics can be checked most easily. If the limitation on b_1 is made by specifying a certain minimum difference between the stick fixed and stick free neutral points, this will be checked automatically when determining the static longitudinal stability characteristics i.e. from the trim curves. The value of b_2 can be obtained from trim curves done at two C.G. positions in which the stick forces to trim at fixed trim tab settings are measured. If there is a means of shifting the C.G. position in flight b_2 can be measured very easily by trimming at a given speed with one C.G. position then measuring the change in stick force and elevator angle to trim at the same speed at another C.G. position, everything else remaining unchanged. Civil aircraft, in which passengers can be moved alont the aircraft to shift the C.G. position are very suitable for doing this. Tests are to be made shortly to determine the accuracy of measurements made using this quick method.

There is no quick method of measuring b_1 and b_2 for the rudder. Throttling back an engine on one side to obtain a yawing moment is objected to on two counts. Firstly, the technique is rather too elaborate for routine tests, and secondly because in the case of propeller driven aircraft there is an unknown change of incidence overthe fin. Thus in the case of rudders, the recommendation can be applied only to design values of b_1 and b_2.

The value of Kb_2 (K is the response factor) for ailerons can be determined from measurements of stick forces when rates of roll are measured. If this is done the method is straightforward, but is considered too elaborate just in order to do a routine check on the value of b_2. In this case again the recommendation can be applied only to design values.

In conclusion it should be stressed that any recommendations restricting in effect the closeness of aerodynamic balance can only be applied directly to controls with plain aerodynamic balance, manually operated. They obviously would not be applied directly to irreversible power operated controls. They should, however, be applied to the basic (no assister or tab locked) hinge moment coefficients of power assisted controls, spring tab controls, and pure servo tab controls.

The requirements suggested may form severe limitations on the use of plain aerodynamic balance on the controls of very large or very fast aircraft, in that the controls may be excessively heavy. They would force the designer of such aircraft to the use of power assisted, spring tab or pure servo tab controls, all of which can be made basically (tab locked) heavier than the plain control, or alternatively, to the use of irreversible power operation.

Whether the requirements are applied only to design values or whether they are applied to values realised in flight, it is considered desirable that future designs satisfy some such requirements if there is a possibility of the de-icing system failing or of the system being not fully effective in dealing with icing conditions.

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No.	Author	Title, etc.
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FIG. 1.

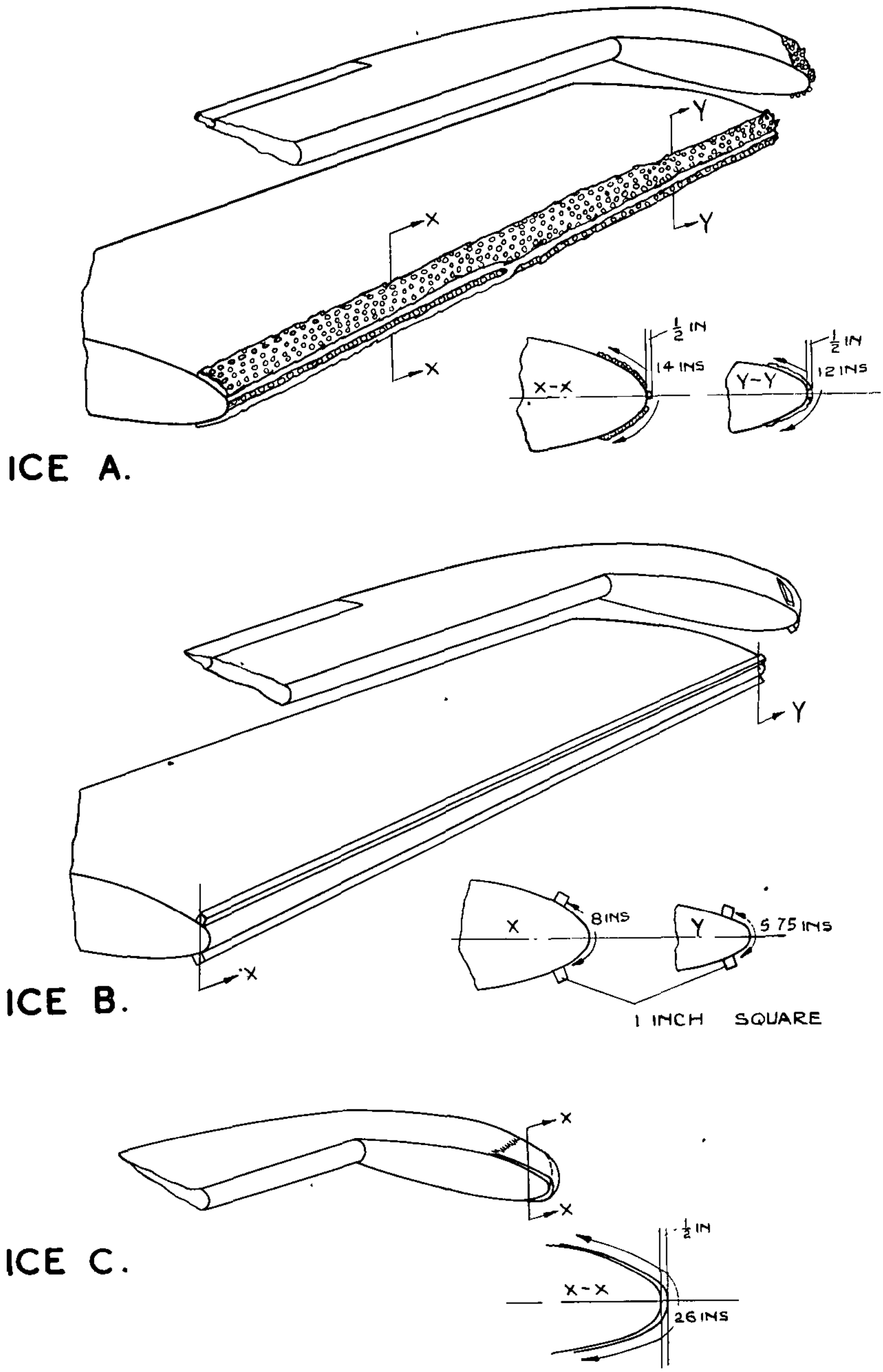

FIG. 1. ICE FORMATIONS TESTED IN WIND TUNNEL.

FIG. 2.

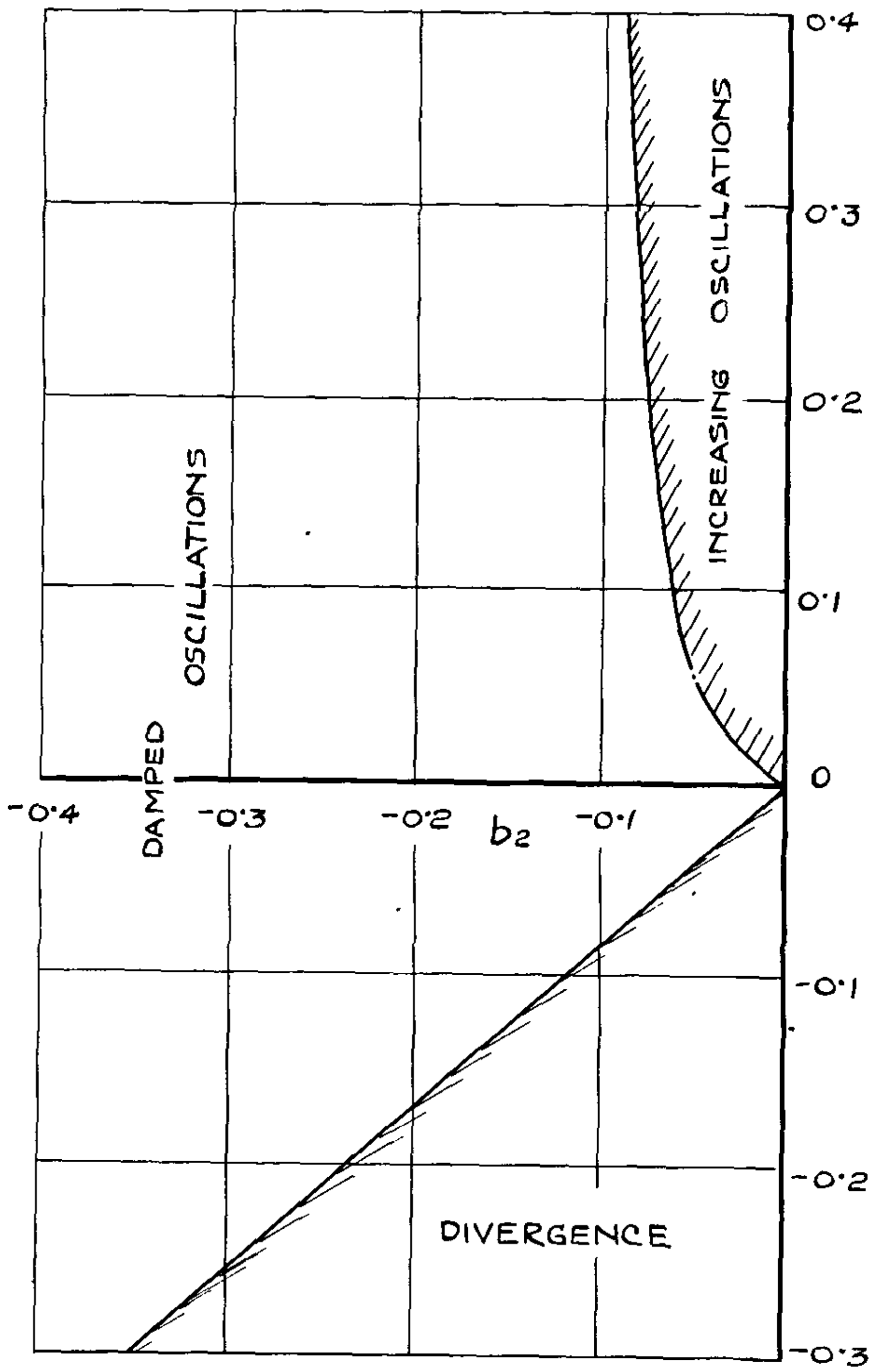

FIG. 2. BOUNDARIES OF RUDDER b_1 AND b_2 FOR DAMPED OSCILLATIONS (FROM REFERENCE 4)

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