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A. G. SMITH, B.Sc., A.R.C.S., D.I.C., and H. G. WHITE, B.Sc.

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Summary.—A review has been made of the evidence on take-off and landing porpoising instability of seaplanes. The basic types of porpoising and their occurrence have been examined; full-scale results have been correlated with model-scale and theoretical results.

Porpoising instability has been divided into three basic types, (*a*) forebody, (*b*) forebody-afterbody, (*c*) step instability. The first occurs during planing on the forebody only whenever the attitude decreases below a critical value. It is associated with a positive water pressure distribution over the forebody near the step; there is no flow on the afterbody. The instability corresponds theoretically to that of a single planing surface. The second type occurs during planing on the front and rear steps whenever the attitude exceeds a critical value. It is associated with a positive water pressure distribution over the forebody and afterbody in the neighbourhood of the steps only. There is no flow on the first 70 to 80 per cent of the afterbody. This porpoising corresponds to the theoretical case of two planing surfaces in tandem. The third type occurs when the water flow is not separated efficiently from the hull bottom at the main step. Large negative pressures alternate with positive pressures on the whole afterbody, the combination causing violent instability. Step instability is only present at high speeds but may occur down to quite low attitudes, and well below the stalling speed.

Full-scale stability limits are measured in both steady and accelerated speeds. Under operational conditions a 2 deg amplitude porpoise has been chosen as the maximum permissible for safety. Three degrees of stable range are then defined: (i) the minimum stable range, corresponding to the limits given by undamped porpoising of any amplitude—these limits are obtained from steady or accelerated speed tests; (ii) the minimum stable range during steady speeds where limits are drawn to exclude porpoising of under 2 deg; (iii) the operational stable range where limits are drawn to exclude porpoising of under 2 deg amplitude under accelerated conditions. The first is of predominantly research interest, the second is the operational case for zero acceleration (*i.e.*, over load take-off), the third is of greatest operational importance.

The stability limits are to some extent dependent on the degree of disturbance encountered, but once started, porpoising instability is independent of disturbance. Step porpoising is particularly sensitive to disturbance; in bad cases it often occurs at high speeds whenever the afterbody becomes even slightly immersed. A maximum value of disturbance should be laid down for design purposes.

Model tests at steady speeds give the minimum stable range. At high speeds the Royal Aircraft Establishment range is probably smaller than the full-scale because of the disturbance used and represents the extreme case. R.A.E. model limits are 1 to 3 deg higher than the full-scale limits on the same seaplane, but are otherwise in good qualitative agreement. The differences are probably due in part to the accumulated effect of differences in displacement, stalling angle and lift, damping, moment of inertia and radius of gyration, to differences in applied disturbance, and to scale effect. The first can be reduced by use of slipstream and care in aerodynamic design; the second by use of a laid down full-scale design disturbance.

The theory of porpoising instability will give accurate results for forebody instability if accurate values of the derivatives are available. There is not as yet sufficient accurate generalised data for this and experimental determinations are as lengthy as measuring the actual limits.

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* M.A.E.E. Report H/Res./173, received 22nd May, 1944.

AUTHOR'S NOTE†

This report was written at a time when the improvements in aerodynamic efficiency of seaplanes and increases of take-off and landing speeds were apparently causing the onset of high-attitude (stick back) instability at medium and high planing speeds. Little evidence was available, model or full-scale, on the nature of this instability or its origin, although considerably more was known about low-attitude (stick forward) instability. Investigations were therefore made to attempt to reach a rational explanation of the instability in terms of the physics of the motion, on the basis of which a research programme could be proposed, model and full-scale, to quantitatively assess the phenomena and give design guidance for its avoidance.

Since that time (1944) very considerable progress has been made on these lines, particularly in Great Britain and the United States of America, and many of the detail gaps left in this report have been filled in and problems solved. But the general conclusions stand; the only fresh development being intensive work in the U.S.A. on the long narrow hull in which forebody length is increased to compensate for reduction of beam. These later developments and their implications are discussed in some detail in reference M.A.E.E. Report F/Res/219, 'Water and Air Performance of Seaplane Hulls as Affected by Fairing and Fineness Ratio', August, 1950, by A. G. Smith and J. Allen.

It is particularly wished to acknowledge here the very big contributions made to the solution of the stability problems by H. G. White, co-author of this report, who was killed during consequent seaplane test flying in 1944.

A. G. Smith.

1. *Introduction.*—Increase of wing and beam loadings, use of shallow and faired steps, flaps, and other means to obtain the maximum aerodynamic cleanness are making conventional seaplanes less stable in take-off and landing. Propellers, wings and tailplanes are becoming more liable to damage from spray and greenwater.

The available full-scale, model-scale and theoretical evidence has therefore been reviewed to investigate these trends. Full-scale evidence collected by the Marine Aircraft Experimental Establishment is given greatest weight and model and theoretical evidence, as far as possible on the same seaplane or else of a systematic character, is used to supplement it.

The value of model evidence depends on its correct correlation with full-scale, which correlation is of growing importance as the amount of stability decreases. An examination has therefore been made of the correctness of model-scale results.

2. *Range of investigation.*—The first part of the report briefly reviews the various techniques of measurement and the definitions of porpoising instability used full-scale at the M.A.E.E. and model-scale in the R.A.E. and N.A.C.A. seaplane tanks.

The second part examines in detail the total evidence available. It is essentially factual and has been put into appendices.

In the third part are discussed the general nature of porpoising instability, the factors determining its presence and severity, the correlation of model and full-scale results. It concludes with some notes on possible changes of design necessary to avoid further increase of porpoising instability.

3. *Full and Model-Scale Testing Techniques.*—3.1. *Full-Scale* (*M.A.E.E.*).—Full-scale stability tests[1] are normally made in steady-speed taxying runs when conditions resemble those of model tests made in the R.A.E. Seaplane Tank. Such tests will give the maximum opportunity for any porpoising instability to develop.

Editor's note: references are made in the text to this Note and these are indicated by the insertion of †.

The speed is maintained constant for about 20 seconds with the stick in a fixed position. Elevator angles and attitudes are recorded. A series of runs is made over a range of elevator angles at each speed to establish the high and low attitudes at which instability begins, and also as far as possible the severity of porpoising.

The tests are made in winds of less than 5 knots and on a calm sea. The effect of wind on stability is believed to be important because of changes of displacement and applied moments, the effect of rough water or waves because of the applied disturbance.

There is always some disturbance due to sea or wind which helps to start porpoising. In a rough sea the pitching due to waves masks instability and can be severe enough to cause damage to propellers and tailplane. If porpoising instability does not occur a 2 deg amplitude disturbance is applied by means of the elevator. This is of the maximum order of disturbance found from waves* on large seaplanes whilst planing.

The steady-run technique has been modified in recent tests on the *Scion*[2] and *Saro*[3]. At each steady speed the elevator is moved steadily away from the neutral position until instability is started and then moved back until the porpoising is damped out. This method provides an alternative way of starting instability to that of a direct disturbance.

Results of these tests are plotted as attitude against water speed. Unstable points are plotted at their mean attitude on the arbitrary assumption that this corresponds to the attitude under the same conditions without porpoising. This assumption is fairly correct for small-amplitude porpoising, but as instability becomes more severe at extreme attitudes the mean attitude tends to lag behind what it would be without instability. The opposite effect occurs if the seaplane leaves the water during porpoising ; *e.g.*, the mean attitude is higher than that for no porpoising above the upper limit.

Both methods of disturbance lead normally to a mixture of stable and unstable points in the vicinity of the upper and lower limits, the thickness of this band of points being greater at the upper limit.

Any porpoising of undamped amplitude is taken to define an unstable region and limits are drawn on two bases according to the amplitude of porpoising. The minimum stable range is defined by undamped porpoising of any amplitude and an acceptable stable range by undamped porpoising of amplitude equal and greater than 2 deg. An earlier practice[4] was to count as unstable only divergent porpoising. The limitation of 2 deg is used because a small amplitude porpoise is accepted by most pilots. Its value is dictated by possible damage to propellers and tailplane at the hump speed region.

A new method of determining porpoising instability from take-off and landing records of attitude against speed has been developed recently[5]. The method permits quick measurements of the effect of such parameters as flaps, c.g. position and weight. A series of take-offs and landings is made, each at a fixed elevator angle for as long as safety permits. The attitude records are examined at five-knot intervals, and the mean attitude at each speed plotted as an unstable or stable point according as to whether or not undamped porpoising takes place. Stability limits are then drawn, first on the basis that an unstable region is defined by an unstable point of any amplitude, second on the basis of unstable points of over 2 deg amplitude. The first limits represent the minimum stable range and in practice closely agree with the minimum stable range from steady-run results[5]: the second limits represent the maximum operational stable range available for the given acceleration conditions, accepting a 2 deg amplitude limit. This range will generally be greater than the corresponding range from steady-run tests because of the effect of acceleration.

3.2. *R.A.E. Seaplane Tank.*—All stability measurements are made during steady-speed runs over the full attitude and speed range. The tests are made with dynamic models[6]. Full-scale conditions of wing and tailplane lift are ensured where necessary by changes of area or the addition of leading-edge slots. The model is free to pitch and heave but not to roll or yaw. The effect

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* Short seas. See section 7 for effect of long-period waves.

of slipstream has generally been represented by change of displacement and applied moment but recently tests have been made at full-scale T_C with propellers driven by compressed-air turbines[7].

The model is trimmed for each run by a fixed elevator setting and if instability does not start the model is disturbed. Originally[6] the steady runs were so timed that a residual disturbance of the water remained from the previous run to excite any inherent instability. If this proved insufficient a further disturbance was applied by the operator described as a severe nose-up angular displacement. The disturbance now employed[8,9,10] is a severe nose-down angular displacement of the order of 10 deg amplitude. It is applied by the operator direct to the model. This disturbance will often start porpoising instability not found by the earlier method, particularly at high speeds and attitudes. Similar results can be obtained with a train of waves which synchronise in period with that of any inherent instability. With this new technique of disturbance all tests are made in calm water conditions.

All measured points are plotted against speed at the attitudes corresponding to the elevator setting with no porpoising present. All undamped porpoising is defined as unstable, very small amplitudes only being ignored, and stability limits are drawn with respect to these.

3.3. *N.A.C.A. Seaplane tanks.*—Stability measurements are made both in steady-speed runs and on accelerated and decelerated-speed runs. They are made with dynamic models, modified where necessary for scale effects on $C_{L\max}$ and stalling incidence. Slipstream is generally represented by counter-weights and applied moments but some tests have been made with propellers driven by electric motors[12]. Further tests have been made representing the lift forces completely by a hydrofoil carried well behind the model. This has the advantage over the counter-weight method of varying lift correctly with change of attitude during porpoising.

The steady-run tests are made over a range of speeds, (*a*) with fixed elevator angle settings, (*b*) with change of elevator angle in one direction until instability starts and then reversal of direction until the instability is damped out. In the first method a 2 deg nose-up disturbance is applied to the model by the operator, in the second the change of elevator setting constitutes the disturbance.

All points are plotted against speed, and attitudes are plotted at the free-to-trim attitude with no porpoising present. This last condition is obtained if necessary by damping out the porpoising. All undamped porpoising is defined as unstable. Stability limits are drawn with respect to all such points.

The first method of test normally gives a mixture of stable and unstable points over a range of attitude at the upper and lower limits, the range being considerable at the upper limit. The second method of test leads to two upper limits, one determined by the onset of instability with increasing elevator angle, one by the damping out of instability with decreasing elevator angle. The decreasing attitude limit is normally much lower than the other.

A lower branch of the upper limit is also given by the limit drawn through the lowest attitude points showing instability when disturbed 2 deg. This is claimed to approximate closely to the decreasing trim limit[14].

Measurements with acceleration are made at conditions representing these of full-scale take-off and landings, but with the acceleration decreased to allow more time for observations. It is also kept constant for ease of operation. Runs are made at fixed elevator angles over the full elevator range at a series of weights and c.g. positions at each weight. No disturbance is applied.

No stable regions are drawn for each of these conditions. The whole take-off or landing run at a given set of conditions is defined as unstable if porpoising instability with an amplitude of 2 deg or over is encountered at any time. Limits are then drawn of the permissible range of c.g. positions at each weight and flap setting for which stable take-offs and landings are possible over a prescribed range of elevator angles. This elevator range is normally taken as from control column central to full-back, but the full-back position is sometimes reduced to the maximum considered necessary for normal handling in take-off and landing.

4. *The Nature of Porpoising.*—4.1. *Characteristics.*—Porpoising, basically, consists of a combination of oscillations in pitch and heave. It includes both stable and unstable oscillations, a stable oscillation being one which damps out. The pitching component only is normally measured full-scale and is the obvious characteristic. This is also used to denote the severity of porpoising. This maximum amplitude is normally of the order of 5 deg to 7 deg but tends to be larger for small seaplanes.

Porpoising instability does not always occur spontaneously even if the seaplane be running at an inherently unstable speed and attitude. Evidence full and model-scale indicates that there is a threshold degree of disturbance below which some instability may not start. This disturbance appears to be most effective when it is a nose-down angular displacement. As a result take-off tends to be more stable than landing since attitude changes are predominately nose-up on the former at high speeds, and nose-down in the latter because of stick movements (*i.e.*, violent porpoising at high speed and attitude is more liable to occur in a landing than in take-off).

The maximum amplitude of porpoising is independent of the order of the disturbance if resonance does not occur with a cycle of disturbances (waves) for it to build up. In take-off and landing runs there is often insufficient time for any instability to start or to build up. Maximum instability will however often occur in an overload take-off.

Instability generally occurs in two regions, one at high and one at low attitudes. It will occur during planing speeds of most present-day seaplanes if the stick is held more than half forward or more than three-quarters back. The limiting stable attitudes on an ideal seaplane would lie at or beyond the fully forward and back positions, and in fact such conditions were once closely achieved; the *Singapore* had a stable range of 8 deg over the whole take-off range. The latest N.A.C.A. testing technique used in accelerated runs requires stability for the stick central to full-back, but this range is still further limited if necessary to that required for normal handling only.

4.2. *Danger from Porpoising.*—Porpoising will lead to structural damage when the attitudes reached are such that spray or green water is thrown through the propeller discs or hits the wings or tailplane. These conditions are most often encountered in the region of the hump, at the low-speed end of which propeller clearance is small and at the high-speed end of which tailplane clearance is small. This tailplane clearance is least in the landing case. At speeds beyond the hump the propellers and tailplane are generally well clear, unless severe porpoising at high or low attitudes occurs. At high attitudes severe damage can quite easily result to the tailplane due to spray and green water. At extreme attitudes more severe structural damage can result because the seaplane comes off at or below the stalling speed and may fall back heavily on to the water out of control. A similar stalled impact case is most frequent during landings.

The limiting amplitude at which porpoising becomes dangerous may be quite low over the hump speed range and near take-off and landing speeds, but quite high in between. An arbitrary limit of 2 deg has been chosen at M.A.E.E. for the whole speed range, based on experience with present-day seaplanes[2, 3]. Experienced pilots will however often accept amplitudes up to 5 deg during the intermediate planing speeds, provided it is not divergent, and there is no danger of the seaplane leaving the water.

4.3. *Types of Porpoising Instability.*—Full-scale porpoising instability is at present classed at the M.A.E.E. as (*a*) normal forebody, (*b*) normal forebody-afterbody, and (*c*) step porpoising.

4.3.1. *Normal forebody instability.*—Normal forebody instability is basically determined by the water flow over the forebody of a hull. It is the same as that explored theoretically as single-step instability[15, 16, 17], Appendix II. The water forces take the form of positive but oscillating pressures occurring in the region of the main step[7, 8]. There is no flow over the afterbody.

All small-attitude porpoising above the hump speed is predominantly of this form, *i.e.*, most lower-limit porpoising. At high speeds it may develop into bouncing due to the dynamic lift at the peak attitudes being sufficient to lift the seaplane off the water. At the hump speed, when the critical attitudes on the lower limit may be quite high there is considerable interference from the afterbody due to rear step immersion. Also the airflow around both the forebody and afterbody may considerably influence the porpoising[19]. Recent N.A.C.A. tests made with and without afterbody showed that the afterbody only affected the lower limit in the hump-speed region[13].

Another form of forebody porpoising very occasionally met with full-scale, but more often model-scale, results from a big nose-down disturbance from a low attitude. The nose tends to be drawn under, with disastrous results. Full-scale it can occur in a bad fly-on landing.

4.3.2. *Normal forebody-afterbody instability*.—Normal forebody-afterbody porpoising can only occur in the presence of a second step and is basically determined by the combined hydrodynamic forces over the forebody and afterbody. It is probably the same as that explored theoretically as two-step porpoising[15], Appendix II. The water flow consists of positive oscillatory forces simultaneously present on both the forebody and afterbody[18]. The hydrodynamic forces on the forebody form a stable system in themselves and instability only results from the addition of the afterbody forces. This afterbody flow normally only exists on the latter 20 per cent, but can occasionally spread forward to 50 per cent as the result of an impact or high displacement. In any pitching oscillation the flow always spreads forward from the rear step and breaks away again towards the rear step.

Such instability only occurs at high attitudes forming most of the upper limit. At high speeds it may be replaced by step porpoising. At the hump-speed region it often merges into low-angle instability, due to the afterbody interference at the accompanying high attitudes. At high speeds again, it may be combined with forebody instability when porpoising is built up to such an extent that the seaplane is oscillating into both upper and lower limits. This might happen as a result of a very severe disturbance on continuous impact with a synchronous train of waves (a long swell in a calm sea).

4.3.3. *Step instability*.—Step-porpoising instability is associated with a front step geometry which does not produce efficient planing. By step geometry here is understood the general efficiency of the junction between forebody and afterbody in producing and maintaining a discontinuity of flow.

Step inefficiency generally only occurs at high speeds and attitudes. The attitudes must be such that there is afterbody immersion. The speed must be such that sufficient dynamic lift (air–water) can be built up to take the seaplane off the water, and can be well below the stalling speed. If normal forebody-afterbody porpoising be present, it is supplemented by the step porpoising, but the latter can occur in its absence.

The characteristic features of step porpoising are high suction forces periodically formed on the afterbody, and the violence of the porpoising which will cause the seaplane to leave the water every cycle. The water flow is present on forebody and afterbody, but the flow on the afterbody alternatively spreads from the rear to the main step with positive pressure and breaks away in the opposite direction with negative pressures. Such negative pressures have been measured at the M.A.E.E.[18] and noted in model tests[11, 20, 21]. The porpoising denoted as ‘ skipping ’ during a landing run, or ‘ jump take-off ’ during a take-off by the N.A.C.A. is probably step porpoising.

The airflow over the afterbody may also contribute to these high-attitude porpoising characteristics. R.A.E. tank tests on a dynamic and a resistance model of the *Empire* boat[19] showed that a considerable nose-up moment is built up at high attitudes and speeds due to the airflow over the afterbody. This was proved to be due to air forces and attributed to high suction forces in the expansion between the afterbody and the water when a stable non-eddying airflow is established there. This uniform flow is only possible below a maximum expansion angle and will depend also on the step depth, afterbody keel angle, attitude and Reynolds number. The data given suggests that the airflow over the whole afterbody is important, as well as over this particular region. When it is established this extra moment impairs the stability and introduces a step type of porpoise with a mean attitude higher than the trim attitude. The tank tests showed little signs of water flow on the afterbody. This instability is very similar to the step porpoise found with the faired step but the extraneous destabilising force appears to be predominately the periodic making of the airflow on the afterbody, rather than the water flow. It therefore seems possible that similar air forces may be present full-scale, which help the water flow to make on the afterbody as well as acting independently. Full-scale, however, the air forces will probably be less due to Reynolds number effect and also less for a pointed rear step (*Sunderland, Shetland*) than a transverse rear step (*Empire* boat). The predominant forces will probably be suction due to the water flow rather than airflow.

No theoretical analysis of such porpoising or in fact of any porpoising with discontinuous water pressures on the afterbody has so far been made.

5. *The Stability Limits and Hull-Bottom Design.*—The stability limits depend primarily on the form of the hull-bottom planing surfaces, secondly on the operational factors such as all-up weight, flaps, and lastly to some extent on the aerodynamic design. The first and third will be discussed in this section, the second in section 6.

Full and model-scale measurements show that there is not necessarily a sharp demarcation line between stable and unstable regions. There is usually a border line region of $\frac{1}{2}$ to 1 deg attitude full-scale due to variable conditions of disturbance and impossibility of repeating a set of conditions exactly. Model-scale gives much sharper limits under the conditions of severe disturbance used at the R.A.E.[8,9,10] and N.A.C.A.[13,14], and under the increasing and decreasing attitude technique used by the N.A.C.A.[11,13]. However N.A.C.A. model tests done by the simple 2 deg nose-up disturbance method give a scattering of stable and unstable points between the upper (increasing trim) and lower (decreasing trim) limits.

There can be different limits for the same seaplane on the evidence of different techniques of testing. It is important that this result be borne in mind when considering the evidence from various sources on stability limits. In general the N.A.C.A. decreasing-trim upper limit corresponds to that obtained with considerable disturbance, the increasing-trim limit with minimum disturbance. Other limits are situated with respect to these according to the degree and type of disturbance. The M.A.E.E. full-scale limit probably lies between the two, the R.A.E. at or below the lower[10].

5.1. *The Lower Stability Limit.*—The theory of lower-limit porpoising is covered by the treatment of a single planing surface[15], Appendix II; it therefore only holds above the hump speed when the afterbody is clear of the water, *i.e.*, in the presence of forebody porpoising.

For maximum stability for any given attitude it may be stated generally that the uncoupled derivatives z_z, m_q and z_w should be large, particularly z_z, the uncoupled derivative m_θ small, and the coupled derivatives as small as possible. This general rule only holds if the damping terms z_w and m_q are small compared with z_z, and if z_w and m_q do not differ unduly. Damping has maximum stabilising effect when the derivatives are equal. If m_q is large then no general rule can be applied and in particular cases the effect of damping can be destabilising.

The relative values of these derivatives are not known for seaplanes (due to lack of evidence). Calculations made[15,16,17,22] deal only with special cases or consider a range of possible values. These do show that all terms except z_w and m_q are predominantly hydrodynamic in content. In m_q the aerodynamic component predominates, in z_w it is about half the value.

The hull-bottom design forward of the step must therefore be such as to give maximum water forces for a given draft and attitude together with minimum nose-up hydrodynamic moment. It must therefore run at the required take-off attitudes with minimum applied nose-down moment. Maximum water reaction demands small dead-rise angle, sufficient beam and length of forebody to keep the nose and chines clear of the water surface under all conditions.

The aerodynamic design must be such as to keep the applied nose-down moments a minimum, and then to satisfy the damping requirements. The first demands small longitudinal air stability, the step aft of the centre of lift of the wing, and the c.g. as far back relative to the step as possible.

In practice for other reasons the c.g. is kept in front of the step as far as the lower limit stability permits. The stabilising effect of damping due to wings and tail is very dependent on the success in realising no associated nose-up hydrodynamic moments, and in keeping associated longitudinal air stability low. If the moment is high then the wings and tail are destabilising, even with zero longitudinal air stability. Adding a tailplane and wing to a hull is therefore generally stabilising, but additional tailplane or wing area may have little effect or even be destabilising. This is particularly so if the aerodynamic damping in pitch is much increased with respect to that in heave.

These qualitative deductions are generally confirmed by model and full-scale data, but full-scale data is very scanty (Appendix 1). Size of forebody[23] is approximately such that for $C_{\Delta 0} = 1 \cdot 0$, maximum present-day loading, forebody/beam ratio is 3 to $3 \cdot 5$.

Near the hump speed instability is subject to afterbody interference because of deep immersion and high running attitudes. The critical angle is considerably reduced on adding an afterbody[13]. Changes in the geometry of the afterbody have comparatively small effect, but generally any decrease of clearance further lowers the critical angle. Decrease of dead-rise raises the critical angle. Measurements show that the front 80 per cent of the afterbody is clear of water[14].

Model tests show that quite small interference to the water flow over the step can considerably lower the lower limit. A projection of any shape on the step, extending from the keel to the chine, and of the order of $\frac{1}{2}$ to 1 per cent beam in height and length, will lower the limit 3 to 4 deg. Similar obstructions immediately behind the step have no effect, even when made quite large. The decrease of critical angle is possibly due to backwards shift of centre of pressure tending to decrease the nose-up hydrodynamic moment. The zero effect when behind the step would be expected so long as the step was still sufficiently efficient to prevent the flow bending round it. This characteristic is made use of when applying step fairings.

Plan form and depth of step have little or no effect on the lower limit[13, 21, 22, 25].

5.2. *The Upper Stability Limit.—Normal Forebody-Afterbody Porpoising.*—The position of the upper limit due to forebody-afterbody instability will depend first on the clearance of the afterbody from the forebody wake and second on designing for maximum stability when afterbody immersion does occur. These two requirements are often contradictory.

Little quantitative data is available on the form of the wake behind the forebody. Very approximately theory and measurement[26], Appendix II, show that during a characteristic take-off the downwash extends for 2 to $2 \cdot 5$ times the beam behind the step. The roach is 3 to 5 times the beam behind the step, being closer at lower speeds and at small attitudes when static lift is more than 5 per cent of the total hydrodynamic lift. The mean downwash angle between the step and the minimum depression of the wake is of the order of 7 deg at the hump speeds to 3 deg near take-off. The mean upwash angle will be greater than the downwash for the first part of the planing range and the same order for the second part.

Maximum clearance therefore demands a short afterbody length, less than 2 to $2 \cdot 5$ times the beam, and the maximum height between the steps. Ideally the afterbody should be removed entirely but this is impossible with present-day designs.

The requirements for maximum stability with two-step continuous immersion have been investigated theoretically and practically. The theoretical treatment[15], Appendix II, is qualitative only in that little data on the correct value of the derivatives was available; also it has to be interpreted in terms of the wake formation behind the first step, which wake is neglected in the analysis.

The theoretical requirements for stability with continuous two-step immersion are (*a*) a short or very long afterbody, intermediate lengths being unstable; (*b*) the incidence of rear step to the local water flow should be as great as possible and preferably at least equal to that of the front step; (*c*) the height between the steps should be as great as possible, *i.e.*, front-step height and angle between forebody keel-line and line joining the two steps should be as large as possible; (*d*) the rear step should have the largest practicable beam; (*e*) radius of gyration should be small. Damping derivatives, air or water, are of little consequence. It is not possible to put quantitative values to these quantities because very little analysis has been made.

These qualitative requirements are brought together by systematic model tests[13,21,22], but in interpretation of these test results it is not always easy to tell whether the instability is forebody-afterbody or step porpoising. Length of afterbody is of primary importance in that for a given length the wake conditions largely influence the detail design. At low planing speeds clearance is zero because there must be afterbody immersion to keep down the attitude and the lower limit. Also there must be sufficient afterbody length for this purpose. The minimum satisfactory lengths are found to be 2 to $2 \cdot 5b$[13,21,22,23], when the rear step just comes on to the beginning of the upwash behind the front step. At high planing speeds clearance is the dominant factor, so that again the optimum length is 2 to $2 \cdot 5$ times the beam†.

Front step depth, afterbody keel angle, and height between steps are interdependent. For a given main-step depth and normal length of afterbody, afterbody keel angles of the order of 5 to 7 deg ($C_{\Delta 0} = 0 \cdot 8$ to $1 \cdot 0$) (afterbody length $2 \cdot 5b$), seem to lead to poor stability at all planing speeds[13 21]. Below 5 deg there is maximum stability at hump speeds and above 7 deg maximum stability at higher speeds. Again there appears to be an upper limit of the order of 10 deg above which stability is again less.

Main-step depth is important only in so far as it affects heights between the steps. It is stabilising in this respect but excessive height (above say 11 per cent beam) appears to lead to further instability on contemporary designs.

The effect of dead-rise on forebody-afterbody instability cannot be separated from its effect on step porpoising on the basis of present evidence and will be considered more fully under step porpoising. Generally increase of dead-rise from 15 deg to 20 deg raises the upper limits 2 to 3 deg but further increase has little effect[14].

Roughness on the main step of the order of 1 to 2 per cent beam lowers the upper limit very much at all speeds[24].

5.3. *Step Porpoising.*—Step porpoising generally results from inefficient planing, which inefficiency also shows its presence in the hump-speed region through poor cleanness over the afterbody hull bottom. It may be caused by insufficient discontinuity at the main step to separate the flow completely from the hull, and insufficient clearance or ventilation to prevent the flow again adhering to the afterbody when normal planing on the forebody only would normally be expected.

No theoretical examination of these conditions has been made.

Model test results[21, 25] do not differentiate between different types of porpoising; full-scale quantitative tests, Appendix I, have distinguished the different types of porpoising instability but are very limited in scope. A N.A.C.A. bulletin[27] does however distinguish skipping from two-step instability and its results give useful additional evidence in agreement with M.A.E.E. results. Some general qualitative rules can however be deduced.

The important factors are (*a*) main-step depth, (*b*) angle between keels of fore and afterbody, (*c*) ventilation of step and of afterbody, (*d*) main-step plan form, (*e*) dead-rise angle. The last three are concerned with ventilation.

The step depth and afterbody to forebody keel angle together decide the discontinuity on the hull bottom. Model and full-scale tests show that the necessary order of step depth is at least 5 per cent beam for a keel angle order of 8 deg; 7 per cent for 7 deg, 9 per cent for 6 deg; the afterbody length being $2 \cdot 5$ to 3 times the beam. They will increase for longer afterbodies. These step depths apply for a static loading condition of the order of $C_{\Delta 0} = 1 \cdot 0$, and would increase with further increase of loading†. A reasonable range is 9 to 11 per cent for safety. For half the loading about half the step depth has proved sufficient.

Artificial ventilation just aft of the main step[13, 27], whether natural or forced decreases the step depth necessary, but the volume of airflow required may be very large. On the full-scale *Coronado* natural ventilation reduced porpoising to some extent, the step depth being 6 per cent beam and afterbody keel angle 7¼ deg.

The amount of ventilation required would appear to depend on the airflow required under the afterbody to prevent undue suction occurring following separation of flow from the afterbody. Such capacity will be determined by the length and beam of the afterbody bottom, particularly near the rear step, and the dead-rise angle. Physically it appears that a large afterbody plan area, a small dead-rise angle, and a small keel angle would all increase the necessary ventilation. This required ventilation must come primarily from the region of the main step.

Generally therefore afterbodies should have large dead-rise angles and no flare, preferably plan forms of decreasing beam aft, large afterbody keel angles, and short lengths.

Main steps should be designed to provide the necessary natural ventilation. This means sufficient depth, the major requirement, in conjunction with the most favourable plan form. Extreme pointed steps will be better, swallow tails possibly worse, than transverse steps. Increase of dead-rise angle from forebody to the afterbody at the main step should be advantageous. Increase of loading will be bad because the resultant deeper immersion will reduce breathing capacity.

There seems to be no fundamental reason for the conventional form of step, so long as the form used is efficient. The addition of step fairings* is tantamount to using discontinuity of less than 90 deg, and full-scale experiments show that a 9 to 1 fairing[28] was critical, and a 6 to 1 satisfactory[18] at $C_{\Delta 0} = 0 \cdot 90$. The breakdown in efficiency was probably due to loss of ventilation.

The airflow over the entire afterbody may also have considerable effect on step porpoising, through its effect on ventilation requirements and supply[19].

The effect of wings will be of obvious importance since the seaplane normally leaves the water in the course of step porpoising. Without wing lift it is possible that the instability would be more violent in heave and the attitudes for instability may also be changed slightly. A 50 per cent increase in the slope of the lift curve will materially reduce the violence of high-speed high-attitude instability[14], possibly due to the decreased draft at higher attitudes and higher damping on heave. Damping from the tailplane would also be expected to affect the pitching oscillation.

Full-scale evidence analysed in Appendix I, Table 1 and Ref. 27 generally bears out these deductions. The most stable seaplane, the *Singapore*, has the shortest afterbody length (2 × beam) and the greatest after-keel to fore-keel angle (9 deg); its shallow step of 4·6 per cent beam is sufficient for the static beam loading $C_{\Delta 0} = 0 \cdot 33$ and the large afterbody angle. The least stable full-scale, the *Seal*[4], has long afterbody length. The *Lerwick*, Appendix I, compensates for a long afterbody (3.34 × beam) by a deep step (10·7 per cent beam) and fair afterbody keel angle (8 deg), but is still not too good near take-off and landing speeds. The G-boat has a shallow step (5·5 per cent beam) and fairly long afterbody (3·17 × beam) and a very low upper limit at high speeds. The *Sunderlands* I and III[18, 28, 30, 31] are quite good with 8 per cent beam step depth, 7 deg afterbody keel angle, 3·0 × beam afterbody length. The *Shetland*[3] is worse than a *Sunderland*; it has a longer afterbody (3·4 × beam) which is only partly compensated for a slightly deeper step (8·7 per cent beam) and bigger afterbody keel angle (7½ deg). The effective length of the *Sunderland* class hull is less because of the rear knife-edge step and linear tapering plan form of the afterbody. The *Coronado* was not satisfactory (step depth 6 per cent beam, $C_{\Delta 0} = 0 \cdot 9$) despite the very short afterbody (2·2 × beam), probably because of the small afterbody angle and small step depth†.

6. *The Stability Limits and Operational Factors.*—The operational factors found to be of importance are (*a*) all-up weight, (*b*) flaps, (*c*) slipstream, (*d*) c.g. position, (*e*) wind speed and roughness of water. These may not always have a direct influence on the stability limits but will affect the possibilities of such limits being encountered.

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* *See* Definitions.

6.1. *All-up Weight.*—The important factor is displacement or load on the water, but this can only be analysed full-scale in terms of all-up weight. An increase of all-up weight increases the displacement, increases or decreases the radius of gyration, and increases the mass moved. Increase of moving mass moves either limit $\pm \frac{1}{2}$ deg, but may considerably increase the severity. Increase of radius of gyration improves stability a little in the lower limit with forebody porpoising[22], but makes it slightly worse in the presence of afterbody interference (hump-speed region)[13]. It decreases the severity of porpoising.

Change of all-up weight is therefore closely the same as change of displacement. Collected model and full-scale evidence, mostly of British origin and analysed in detail in Appendix I, is tabulated in Table 2.

The lower limit is raised by increase of all-up weight. The order of change for forebody porpoising is 3 deg per 100 per cent change in $C_{\Delta 0}$ ($C_{\Delta 0} = 0 \cdot 5$) just above the hump speed ($C_v = 3$), to 1 deg per 20 per cent change in $C_{\Delta 0}$ ($C_{\Delta 0} = 1 \cdot 0$). The increase is at the most a half of this at high speeds, being a half at $C_v = 6$. Full-scale data, for the complete hull, Appendix I and Table 2, confirms the order of these results generally but decreases the rate of change at the hump speed. Model-scale data from the R.A.E. and N.A.C.A. tanks gives similar results. The R.A.E. data include the effect of a change from take-off to landing condition, because until slipstream was represented by propellers, the only difference was in displacement. The N.A.C.A results[11, 21, 22, 25] particularly emphasise that the effect of the afterbody interference is to reduce the weight effect on the lower limit at the hump speed. The maximum effect then occurs just above the hump. At high speeds the effect becomes negligible. No theoretical evidence is available.

There is an important exception. Model tests on the G-boat[9], Appendix I, showed that decrease of weight from $C_{\Delta 0} = 0 \cdot 71$ to $C_{\Delta 0} = 0 \cdot 65$ eliminated the stable range above 47 knots. This may possibly be due to the severe disturbance technique used in the R.A.E. tank (*see* section 7); as stated earlier (section 4) a seaplane may porpoise violently between the upper and lower limits both at the hump and at high speed if the limits be close together and the initial disturbance sufficient. Full-scale tests[29] on the G-boat showed little effect of weight, the limits agreeing generally with the model limits at the higher weight.

The effect of all-up weight on the upper limit is uncertain but less important. Generally model-scale evidence (all without slipstream present) shows that the upper limit is raised by increase in weight, but the net stability band is reduced. The N.A.C.A. tank evidence also shows that the effect on the increasing trim limit is negligible. Full-scale evidence is more contradictory. The step porpoise limit on the *Sunderland* type hull[1] is lowered considerably. The *Mariner*[32] limits are raised.

The weight of evidence is therefore in favour of raising the upper limit. The contradictions probably arise from considerations of the effect of displacement on draft and wake formation. Increase in weight which shields the chines at the main step and aft will decrease ventilation and probably lower step porpoising limits. On the other hand the wake will be deeper, and afterbody clearance greater, so that a rise in limit would be expected. By comparison with a single planing surface one would also expect the upper limit to follow the same characteristics as the lower, neglecting the effect of wake formation.

6.2. *Slipstream.*—The effect of slipstream is complicated because it involves large changes in displacement, airflow and aerodynamic damping. No theoretical data is available and there is no full-scale evidence which separates displacement effect from the remainder.

The N.A.C.A. model evidence[12] also does not separate displacement from the other effects. The results show a lowering of both limits of the same order as would be expected from the order of change of displacement except at the hump speed, where large decreases in limit were obtained suggesting an additional gain from the added aerodynamic damping.

The R.A.E. model evidence[7] shows that the factors excluding displacement made little difference ($\pm \frac{1}{2}$ deg) to the upper limit, but lowered the lower limit $1\frac{1}{2}$ to 2 deg at the hump, 1 deg at 60 knots. It is however doubtful whether the improvement at the lower limit hump is entirely due to increased tailplane damping since it still existed on removal of the tailplane, unless the additional damping due to the slipstream over the hull afterbody was in itself sufficient to produce the maximum damping effect possible.

The effect on afterbody ventilation seems to have been small with the models tested, but it is conceivable that on a critically ventilated afterbody addition of slipstream would be favourable. More tests are required to investigate this possibility, but it may account for part of the big difference on stability between take-off and landing.

Apart from stability, the slipstream does have an important effect on the spray characteristics, particularly below the hump speed, when spray from the bow blister is sucked into the propeller discs[7, 12]. This serves to demonstrate the possible effect on afterbody ventilation.

6.3. *Flaps*.—On the available evidence small flap angles up to 10 deg have negligible effect on stability: angles of the order of 30 deg lower the upper limit about 2 deg, less at the hump speed but more at take-off, and have little effect on the lower limit. The stability range for touch-down or take-off may therefore be seriously reduced. In addition the use of flaps tends to make the seaplane run at smaller attitudes, particularly over the hump in the presence of slipstream, so that lower-limit instability occurs.

Flaps reduce displacement, impart a nose-down moment, increase the air damping and vary the aerodynamic stability in pitch. The first should lower both limits, the second raise the lower limit, the third and fourth have variable effects depending on the damping, already present and the change of stability. Model tests without slipstream present (Table 3, Appendix I) show that the upper limit is lowered a mean of 2 deg by 20 deg of trailing-edge flap, the amount increasing with speed. In one case of a large flap angle of 48 deg, there was however no effect. On the *Sunderland* with Gouge flaps the lower limit was little affected except by 28 deg of flap.

Full-scale evidence (Table 3) generally shows a small effect of small flap angle (10 deg) on both limits. The effect on the *Shetland*[3] 1 : 2·75 scale model with 18 deg flap was serious because the small rise of the lower limit 1 deg and small decrease of the upper limit (1½ deg) combined to seriously reduce the take-off stable band of attitudes. Qualitative results on the *Mariner* show reduced stability with flaps down. On the other hand *Kingfisher* take-off was only feasible with flaps down, and the best *Coronado* landings were made with flaps down. In the last case use of flaps would make the touch-down attitude less for the same speed and so help to avoid step porpoising.

6.4. *C.G. Position*.—The collected evidence is given in Table 4 and Appendix I. No definite conclusion can be drawn as to the effect on either limit. Model-scale data suggests that the effect is negligible on the upper and the lower limit at high speeds. The maximum effect is at the hump but may be in either direction. Full-scale data is also limited but shows the same general results ; the lower limit can however be raised considerably at the hump speed by sufficiently forward c.g. movement. Theoretically forward and upward c.g. movement will raise the lower limit but have little effect on the upper limit.

The major effect of c.g. movement seems to be that on running attitude, so that with c.g. forward lower-limit porpoising instability and with c.g. aft upper-limit porpoising instability and in particular step porpoising are more likely to be encountered. The order of c.g. position for satisfactory performance is from 0·2 to 0·4 beam in front of the main step for a forebody-length/beam ratio of the order of 3·5.

7. *Correlation of Full and Model-Scale Stability Limits*.—Data on full and model-scale limits for seaplanes for which comparative data are available are given in Table 5. Detailed analysis is given in Appendix I. Full-scale limits are generally much lower than model-scale limits, whatever the model techniques used. The upper limit is from ½ to 4½ deg lower at the hump region and ½ to 3 deg lower at the take-off region, the mean difference being from 2 to 3 deg at the hump to 2 deg near take-off. The lower limit is 0 to 3 deg lower, or a mean of 1½ deg lower at the hump and 1 deg lower near take-off.

The effect of the revised disturbance technique of the R.A.E. tank is varied. On seaplanes with an inefficient step (faired-step *Sunderland*[33, 34] and *Shetland*[35], shallow-step *Lerwick*[36, 37]) both limits tend to be drastically changed so as to reduce or eliminate the stable region at high speeds. There is however little effect on the same seaplanes at low speeds, or on seaplanes with efficient steps and afterbodies. Occasionally the same disturbance technique will eliminate a stable range at the hump which exists without this disturbance[2, 38].

These differences between full and model-scale may be due to pure scale effect or incorrect representation of full-scale conditions.

The full-scale conditions which will have maximum effect in order of importance if incorrectly represented will be disturbance, displacement, flaps, aerodynamic damping and inertia.

The correct representation of full-scale disturbance is important. The different techniques used in model work show to what extent the limits obtained can vary. This evidence points to the presence of a threshold value of the nose-down disturbance beyond which (*a*) considerable upper limit instability at high speeds can appear, (*b*) complete instability may occur across a normally stable range of attitudes at hump or take-off. The incipient oscillations are a function of the initial disturbance but the final steady-state amplitudes of instability are independent of the disturbance. It follows that sufficient time must be allowed for such incipient oscillations to damp out. The present disturbance used by the R.A.E. tank is considerably in excess of that met with full-scale, unless an exceptionally heavy or synchronous wave formation is encountered. Also the smooth water condition of the tank tests are much more conducive to step porpoising, probably due to the lesser efficiency of step and afterbody ventilation. Full-scale, in a glassy sea, a heavy wash or swell will often start violent porpoising instability at high speeds which would seldom otherwise be obtained. The R.A.E. technique therefore will give limits representative of the worst conditions. full-scale.

The N.A.C.A. disturbance technique based on increasing and decreasing trim is possibly more representative of full-scale conditions in the absence of swells. The increasing trim upper limit is probably too optimistic for take-off, and the decreasing trim limit too pessimistic for landing. It is possible that a range of limits could be obtained depending on the degree and type of disturbance. For example, application of a large nose-down disturbance would probably lower the N.A.C.A. decreasing trim limit at high speed, or even produce porpoising instability right across the stable range[10].

It therefore appears that big differences do arise between model and full-scale limits on account of disturbance, but that considerably more investigation into an acceptable disturbance full-scale and its equivalent model-scale disturbance, is required before exact comparison is possible.

Correct displacement requires primarily correct representation of full-scale lift and therefore of correct slope of lift curve, maximum lift coefficient, stalling incidence, and slipstream. Lift characteristics have to be corrected when necessary by the addition of slots to postpone stalling and increased area to obtain full lift[10, 11, 13, 20]. Slipstream is best represented by propellers operating at correct T_c, because of the difficulties involved in correctly estimating it in the presence of the ground. Also, although trim attitudes have been correctly correlated with full-scale by using correct displacement (and moments), the model-scale upper limits were still much higher and the lower limit slightly higher than full-scale[35].

The representation of flaps has also to be carefully adjusted for scale effect, extension of the chord aft of the wing trailing edge often being required to give correct lift and moments.

The aerodynamic damping is very closely associated with true representation of slipstream. Increased air damping or slipstream will tend to lower the lower limit particularly at the hump[7], but its effect will depend largely on the damping already present. The effect on the upper limits is negligible. The effect on the nature of large-amplitude porpoising may be considerable.

The radius of gyration in pitch is normally accurately represented but the moving mass is often excessive. Theoretically this has no effect for errors of the order of 25 per cent but practically it has on occasions proved important[8, 22, 40]. Amplitude of porpoising increases with increase of moving mass and may therefore lead to different limits when a minimum amplitude is defined.

Model tests are normally made under steady-speed conditions, full-scale results are required under operational accelerated or decelerated conditions. Theoretically acceleration has no effect on the stability limits[15]. Practically full-scale[5] and model-scale [21,22] tests have shown the same result. There is however considerable difference in the violence of porpoising instability, and even on occasions in the incidence of instability. In the presence of acceleration or deceleration there is less time for instability to begin or build up, so that limits drawn with respect to a limiting amplitude of say 2 deg will show much greater instability than will steady-run limits. Comparison of model and full-scale results must therefore take acceleration effects into account. It can either be made under non-accelerated conditions, *e.g.*, model-scale steady-run limits and full-scale limits from accelerated runs drawn without distinction of amplitude, or by the new technique devised directly by the N.A.C.A. The latter is extremely useful in providing the operational answer but is subject to the effects of different degrees of acceleration in addition to different disturbances. In the limit zero accelerated conditions must approach steady-run conditions and these occur full-scale at full overload.

8. *Conclusions.*—8.1. *Nature of Stability Limits.*—Porpoising instability is at present normally found full-scale during take-off or landing at low attitudes over the higher two-thirds of the speed range when the stick is held much forward of central, and at high attitudes at high speeds when the stick is held more than half back. The upper and lower attitude limits of stability form a stable range which steadily decreases with increase of wing and beam loading, the use of shallow and faired steps, and other devices to reduce aerodynamic drag. The stable range is often reduced to the order of a few degrees at the hump speed and at take-off speed it can become zero. This decrease is the more serious at take-off in that with contemporary aircraft full-scale the upper limit decreases in attitude steadily as the corresponding speed is increased and the lower limit tends to remain at a fairly constant attitude. It follows that with these designs increase of take-off speed and decrease of beam make it difficult to run at reasonable take-off attitudes at high speeds without porpoising instability occurring†.

The instability is normally fairly mild at the hump but can cause severe spray damage to the propellers and tailplane. At high speeds it can be severe and cause complete loss of control, particularly in the landing case. The limiting amplitude for safety is taken as 2 deg over the whole speed range, but amplitudes up to 5 deg do little harm at intermediate planing speeds.

The beginning of instability is very dependent on the disturbances encountered and the time factor. Model and full-scale evidence show that much high-speed instability will only start after a nose-down disturbance and then only if that disturbance be sufficiently severe. The subsequent order of instability is, however, independent of the disturbance, as long as the incipient period is neglected. The full-scale order of disturbance depends on the scale of the seaplane, but it is generally much less severe than that given to models in the R.A.E. tank. The worst full-scale case is a glassy sea in no wind conditions in the presence of a swell or severe wash. Any long-period wave system can cause severe disturbance, particularly if it synchronises in period with that of possible seaplane porpoising. The decreasing trim upper limit of the N.A.C.A. is probably very close to this severe disturbance, the increasing trim upper limit to the undisturbed case. Considerably more experimental work is required to determine a maximum permissible disturbance full-scale for specific design purposes and to correlate this with model-scale disturbance.

In the normal full-scale condition of accelerated or decelerated motion, porpoising instability is often much less severe because of the shorter time available in any unstable condition and may not occur at all if no disturbance is met.

Full-scale stability limits are determined from both steady and accelerated speed measurements. The minimum stable range is defined by the limits corresponding to undamped porpoising of any amplitude, and is the same for all values of acceleration. This range corresponds to that measured model-scale in steady runs. The maximum operational stable range is defined by the limits corresponding to all undamped porpoising of over 2 deg amplitude, and will vary with the acceleration. It is a minimum when the acceleration is zero.

An alternative method of measuring stability developed by the N.A.C.A. is to define any take-off or landing as unstable in which porpoising of over 2 deg amplitude is encountered. This method is very useful for operational purposes, and the N.A.C.A. measure the stable range in terms of the c.g. range at one weight and the range of elevator angles for which such instability does not occur. It combines the effect of the features determining the stability limits in the presence of acceleration with those determining the running attitudes during take-off and landing.

8.2. *Comparison of Model and Full-Scale Limits.*—The full-scale upper limit is generally 2 to 3 deg lower in attitude and the lower limit 1 to 2 deg lower than the corresponding model-scale limit. The maximum discrepancy occurs at the hump and the minimum at high speeds. At take-off speeds the model stable range, as measured by the R.A.E. disturbance technique, may also be less than full-scale. The differences seem to be due in part to scale effect but can arise from the aggregation of errors due to incorrect representation of full-scale conditions. The important full-scale conditions which must be represented accurately model-scale are (*a*) disturbance technique, (*b*) displacement, (*c*) flaps, (*d*) aerodynamic damping, (*e*) radius of gyration and moment of inertia in pitch. The dynamic model fulfils most of these, and the use of propellers running at correct thrust avoids the necessity for doubtful calculations on aerodynamic derivatives. Inertia can be important in certain cases; radius of gyration is the more important factor but moving mass can be critical. Further investigation into possible scale effect is required.

It is important to emphasise here that dynamic model tests are invaluable as long as the possible differences from full-scale conditions are understood.

8.3. *Design for Stability.*—Porpoising instability has been separated into three types, all of which require separate design consideration. These are forebody, forebody-afterbody, and step-porpoising instability. The first is found with oscillatory water flow with positive pressures over the forebody only. It is independent of the afterbody and generally determines the lower limit above the hump. The second is associated with positive oscillatory pressures on forebody and afterbody at their respective step regions, and is that due to two planing surfaces in tandem. It probably constitutes most of the upper-limit porpoising at the hump and up to medium planing speeds. The third is due fundamentally to inefficient planing or clearance of flow from the afterbody and is generally associated with high positive and negative pressures on most of the forward part of the afterbody. It leads to violent porpoising on the upper limit at the higher speed range.

Theory and practice are in fair agreement on the guiding principles determining forebody porpoising instability, although considerable more full-scale evidence is required. Maximum stability is attained when the resultant nose up hydrodynamic moment is a minimum and at the same time the hydrodynamic forces for a given draft are a maximum. Draft should be as small as possible. There must be a minimum amount of air damping in pitch and heave beyond which no further gain is possible. Near the hump speed a strong afterbody lowers the lower limit the maximum amount so long as efficient planing is maintained.

Forebody-afterbody porpoising has not yet been analysed with much accuracy theoretically or full-scale. The limited amount of model-scale evidence is empirical only. The fundamental requirements are that (*a*) clearance of the afterbody from the wake behind the forebody should be a maximum (*b*) when afterbody immersion does occur the planing incidence should be as small as possible, the rear step as far above the front step as possible and the afterbody beam large but length very short or very long. Other factors are of little importance if efficient planing is achieved.

Step-porpoising instability requires an adequate discontinuity to break off the flow from the hull where required, and adequate afterbody clearance and ventilation to keep the flow separated. The first is achieved by an adequate change of keel angle; the second by step depth, change of keel angle, plan form of step and geometry of air space between afterbody and wake. The best solution is complete removal of the afterbody. All other factors are of secondary importance.

The design features to give the best stable range for contemporary[†] hull forms are summarised below.

Forebody Design.—(*a*) Length should provide adequate planing area to keep the chines clear at the hump: 3 to 3·5 beam is generally satisfactory for $C_{\Delta 0} = 0{\cdot}5$ to $1{\cdot}0$[†].

(*b*) Beam loading should not exceed $C_{\Delta 0} = 1{\cdot}0$ for boats or $1{\cdot}2$ for floatplanes with present accepted design[†].

(*c*) Dead-rise should be small at the step (order of 20 deg), and increased forward at about 5 deg per beam length.

(*d*) Flare is advantageous at the hump at large $C_{\Delta 0}$.

Afterbody Design.—(*a*) Length should be as short as possible, 2 to 2·5 beam with transverse rear step, 2·5 to 3·0 beam with pointed rear step.[†]

(*b*) The afterbody keel should rise at not less than 7 deg from the forebody keel at the step. If ventilation is poor or $C_{\Delta 0}$ high, increase up to 10 deg is advisable.

(*c*) Dead-rise angle should be 20 to 25 deg near the step for good hump stability. Warping of the afterbody is advisable for good ventilation and landing stability.

(*d*) There should be no flare.

(*e*) A pointed rear step in plan form helps ventilation (landing stability) but requires a longer afterbody for hump stability.

Step Design.—(*a*) Step depth for conventional designs should be at least 8 per cent beam for $C_{\Delta 0} = 0{\cdot}8$, after keel angle 8 deg, afterbody length 2·5 to 3·0 beam, pointed rear step. This is increased to 10 per cent for 3 to 3·5 beam afterbody length, reduced by 1 or 2 per cent for full forebody and afterbody warping, reduced 1 to 3 per cent with artificial ventilation at the step[†].

(*b*) Step fairings of 6 times the step depth defined above is permissible. With ventilation an 8 to 1 and possibly 10 to 1 fairing would be feasible.

(*c*) A pointed form of any plan shape will help landing stability but tends to raise the lower limit.

(*d*) Roughness on the bottom can lower both limits the order of 4 deg; behind the step it has no effect until it is large enough to be equivalent to a fairing—then it has no effect as long as the change of angle at the step is sharp and not less than about 20 deg, and there is adequate ventilation.

Operational Design.—(*a*) Increase in weight raises the lower limit considerably, the upper limit less so; stable range is reduced at hump and take-off and landing.

(*b*) Flaps up to 10 deg have little effect; greater angles trim the seaplane into the lower limit at low speeds and may lower the upper limit at high speeds.

(*c*) Centre of gravity position mainly affects the attitude to trim. Forward movement reduces hump stability, the stability disappearing at about 0·4 beam forward of the mean step position. Aft movement increases the possibility of step porpoising, especially in landing.

(*d*) A large radius of gyration in pitch helps the lower limit. There is little effect on the upper limit.

(*e*) Change of aerodynamic damping has little effect on either limit with tail and wings present. The addition of full slipstream increases hump stability 1 to 2 deg. Damping is essential for good lower-limit and step stability.

(*f*) High values of the slope of the lift curve and stalling angle damp upper limit stability.

(*g*) The worst sea conditions are a long swell on a dead calm sea in no wind; any long-period wave system can be bad. A head wind is stabilising.

8.4. *Improvements in Design.*—Improvement in porpoising stability requires full utilisation of the maximum gain to be obtained from detailed hull-bottom design, particularly with respect to dead-rise and step and afterbody ventilation†. Much more research is still required on such points. It appears that there is a definite limit to the possible gain unless ventilation proves effective in limiting step instability. Alternative hull forms would be such as to eliminate the afterbody so reducing the source of violent instability in landing, or to reduce beam loading considerably†. The former can be done by using a second planing surface disconnected hydrodynamically from the first; the only upper limit instability will then be the comparatively innocuous forebody-afterbody form. Preliminary tank tests have been made on such a solution[40]. The second solution can be obtained by providing an alternative water lifting surface. One method is by hydrofoils[41]; a second by using the flying wing seaplane[42] (probably in conjunction with a hydrofoil); a third by the use of retractable beam on the rear half of the forebody.

LIST OF SYMBOLS

α	Attitude of forebody keel to horizontal
$C_{\Delta 0}$	$\Delta_0 w b^3$
Δ_0	Static load on water
Δ	Load on water
w	Water density
b	Beam
C_v	$V/\sqrt{(gb)}$ (Froude Number)

Uncoupled Stability Derivatives

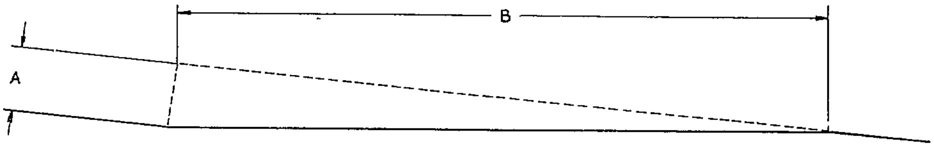
z_z	Lift due to draft
z_w	Lift due to rate of change of draft
m_θ	Moment in pitch due to pitch angle
m_q	Moment in pitch due to rate of change of pitch

Coupled Stability Derivatives

z_θ	Lift due to pitch angle
z_q	Lift due to rate of change of pitch
m_z	Moment due to draft
m_w	Moment due to rate of change of draft

DEFINITIONS

Fairing Ratio is defined as A : B where A and B are as in the sketch.



REFERENCES

No.	*Author*	*Title, etc.*
1	W. G. A. Perring and J. L Hutchinson	Full-scale and model porpoising tests of the *Singapore* IIc. R. & M. 1712. 1936.
2	H. G. White and A. G. Smith	Attitude and stability measurements on a half-scale *Sunderland* hull fitted to a *Scion* seaplane. A.R.C. 6481. (Unpublished.)
3	H. G. White and A. G. Smith	Stability tests on a large-scale model of the *Shetland* hull bottom. Current Paper 27.
4	G. Abel	Full-scale and model-scale porpoising on the *Seal*. A.R.C. 3375. (Unpublished.)
5	H. G. White and A. G. Smith	A method for determining the water stability of a seaplane in take-off and landing. R. & M. 2719. May, 1943.
6	L. P. Coombes	The use of dynamically similar models for determining the porpoising characteristics of seaplanes. R. & M. 1718. 1936.
7	D. C. Macphail and D. I. T. P. Llewelyn Davies.	Model investigation on the effect of slipstream on the longitudinal stability of flying boats on the water. A.R.C. 6609. (Unpublished.)
8	J. P. Gott	Note on the technique of tank testing of dynamic models of flying boats as affected by recent full-scale experience. A.R.C. 4378. (Unpublished.)
9	J. P. Gott	Further note on the tank testing of dynamic models of flying boats with special reference to the model of the G-boat. Aero. T.N. 962 (Tank).
10	J. P. Gott	Note on the comparison of British and American methods of tank testing dynamic models of flying boats. A.R.C. 6892. (Unpublished.)
11	R. E. Olson and N. S. Land	The longitudinal stability of flying boats as determined by tests of models in the N.A.C.A. tank 1. Methods used for the investigation of longitudinal stability characteristics. N.A.C.A. A.R.R. November, 1942.
12	J. B. Parkinson and R. E. Olson	Tank tests of a $\frac{1}{5}$ full size dynamically similar model of the army O.A.9 amphibian with water-driven propellers—N.A.C.A. model 117. N.A.C.A. A.R.R. December, 1941. A.R.C. 5757. (Unpublished.)
13	K. S. M. Davidson and F. W. S. Locke, Jr.	Some systematic model experiments on the porpoising characteristics of flying boat hulls. N.A.C.A. A.R.R. 3.F.12. June, 1943.
14	J. M. Benson and M. M. Klein	The effect of dead-rise upon the high angle porpoising characteristics of two planing surfaces in tandem. N.A.C.A. A.R.R. 3.F.30. June, 1943.
15	W. G. A. Perring and H. Glauert	The stability on the water of a seaplane in the planing condition. R. & M. 1493.
16	A. Klemin, J. D. Pierson and E. M. Storer.	An introduction to seaplane porpoising. A.R.C. 4132. (Unpublished.)
17	K. S. M. Davidson and F. W. S. Locke, Jr.	Porpoising: a comparison of theory with experiment. N.A.C.A. A.R.R. 3.G.07. July, 1943.
18	E. J. Evans, A. G. Smith, and R. A. Shaw	Water performance of *Sunderland* K.4774 with step fairing. R. & M. 2868. April, 1941.
19	C. B. Baker	Tank tests on a model of the *Empire* flying boat. A.R.C. 5213. (Unpublished.)
20	E. I. Stout	Tank tests of PBY, PB2Y3. Consolidated Aircraft Inc. Reports 2H–28–005, 2H–29–006.
21	Truscott and R. E. Olson	The longitudinal stability of flying boats as determined by tests of models in the N.A.C.A. tank II. Effect at variation of form of hull on longitudinal stability. N.A.C.A. A.R.R. November, 1942.
22	J. M. Benson and L. J. Lina	The effect of dead rise on the low angle type of porpoising. N.A.C.A. A.R.R. (WR. L–610). October, 1942.
23	F. W. S. Locke, Jr.	Correlation of the dimensions, properties, and loadings of existing seaplane floats and flying boat hulls. N.A.C.A. A.R.R. (WR W–41). March, 1943.

REFERENCES—*continued*

No.	*Author*	*Title, etc.*
24	J. M. Benson	Hydrodynamic stability tests of a flying boat and of a planing surface having a small downward projection (hook) in the planing bottom near the step. N.A.C.A. R.B. (WR L–58). January, 1943.
25	N. S. Land and L. S. Line	Tank tests of a dynamic model in N.A.C.A. tank No. 1 to determine the effect of length of afterbody, angle of afterbody keel, gross load and a pointed step on landing and planing stability. N.A.C.A. A.R.R. (WR L–400). March, 1943.
26	J. M. Shoemaker	Tank tests of flat and V bottom planing surfaces. N.A.C.A. T.N. 509.
27	J. B. Parkinson	Notes on the skipping of seaplanes. N.A.C.A. R B. 3127 (W.R, L–333). September, 1943.
28	G. J. Evans and R. A. Shaw	Water performance of *Sunderland* K.4774 with a 1 : 6 step fairing. R. & M. 2868 April, 1941.
29	R. A. Shaw and G. J. Evans	Porpoising tests on the G-class flying boat. A.R.C. 5070. (Unpublished.)
30	R. A. Shaw, A. G. Smith, W. Morris and G. J. Evans.	An investigation of the water performance of the *Sunderland* flying boat. A.R.C. 4391. (Unpublished.)
31	W. Morris	Note on the take-off characteristics of the *Sunderland* flying boat. A.R.C. 3728. (Unpublished.)
32	—	Tests of Glen Martin PBM–3 (*Mariner*) with the N.A.C.A. event recorder. Parts I, II and III.
33	—	Tank tests on a faired main step for the Short R.2/33 (*Sunderland*) flying boat. A.R.C. 3622. (Unpublished.)
34	—	Note on some tank tests on a modified bow form for the Short *Sunderland*. A.R.C. 4803. (Unpublished.)
35	—	Tank tests on the Short *Saro* R.14/40 flying boat. A.R.C. 5848. (Unpublished.)
36	—	Tank tests of the porpoising qualities of the Saunders-Roe R.1/36 flying boat. A.R.C. 3332. (Unpublished.)
37	K. W. Clarke, J. P. Gott and W. D. Tye	Further model porpoising tests on Saunders-Roe R.1/36 (*Lerwick.*) A.R.C. 4891. (Unpublished.)
38	C. B. Baker	Tank tests on the *Scion* seaplane. A.R.C. 4666. (Unpublished.)
39	R. Hills and K. W. Clarke	Tank and wind-tunnel tests on the Short *Sunderland* to compare attitudes with full-scale during take-off and landing. A.R.C. 4782. (Unpublished.)
40	J. R. Dawson and K. L. Wadlin	Preliminary tank tests with planing tail seaplane hulls. N.A.C.A. A.R.R. 3.F.15. June, 1943.
41	P. E. Naylor and A. G. Smith	The take-off and landing of a flying boat with a hydrofoil. A.R.C. 7331. (Unpublished.)
42	K. W. Clarke	Tank tests of a preliminary design of a hull-less seaplane. A.R.C. 2553. (Unpublished.)
43	Tank Staff	Further porpoising tests on *Seal* dynamic. Model for comparison with full-scale tests. A.R.C. 4074. (Unpublished.)
44	P. E. Naylor	The effect of weight variation on the water stability, trim and elevator effectiveness of a *Sunderland* III aircraft during take-off and landing. A.R.C. 7594. (Unpublished.)

APPENDIX I

Examination of porpoising characteristics of particular seaplanes

1. *Singapore IIc.*—The first full-scale stability tests[1] were made on the *Singapore* IIc to check the dynamic model results. The full-scale results are reproduced in Fig. 1a, together with the comparable model stability limits, and the complete model stability limits in Fig. 1b. The full-scale results are rather limited in scope, covering a c.g. rather than a speed range, and in those limits showed fair agreement with the model results in period and amplitude. However the attitudes for full-scale porpoising (40 to 50 knots only) are 1 deg to 2 deg lower than the model at the lower limit, and 0 deg to 1 deg lower at the upper limit.

The model evidence showed that 10 per cent mean chord movement of the c.g. aft lowers the upper limit 2 deg at 40 knots, 0 deg at 65 knots, but lowers the lower limit outside the minimum values possible with the elevator. A 10 per cent forward movement lowers the lower limit $\frac{1}{2}$ to 1 deg.

A 15 per cent increase in weight raises both limits about 1 deg; a 30 per cent increase in pitching moment of inertia raises the lower limit 1 deg.

These full-scale and model differences are all small compared with the big stable range of 8 deg but with a smaller range they would be important.

2. *The Seal.*—The full-scale and model-scale tests made on the *Seal*[4] are particularly interesting because, in the original analysis, even qualitative agreement could only be obtained between steady-run limits full and model-scale, when only full-scale points of over 3 deg amplitude, for which the amplitude was still increasing, were counted towards the limits. A repeat of the model scale tests[44] had confirmed the model limits.

These full-scale limits and the model limits based on all undamped porpoising are given in Fig. 2. The former neglect large numbers of porpoising points of steady amplitude less than 5 deg which lie inside them.

Comparable full-scale take-offs did not agree with these steady-run limits, showing instability in the stable range. Model tests confirmed that the same limits held with or without acceleration and it was therefore surmised that the full-scale porpoising inside the defined stability limits was due to forced oscillations set up by resonant wave systems. Model tests had shown this to be possible.

The full-scale take-off records have been re-examined by the new method of deducing stability limits from take-off measurements[5] and the new limits reproduced in Fig. 2. The new stable range is only 1 deg to $1\frac{1}{2}$ deg from 40 to 55 knots and even this range is of doubtful validity since insufficient evidence (four take-offs only) is available for accurate analysis. Re-examination of the steady-run points, counting all undamped porpoising as unstable, gives no region of stability with or without a 2 deg limiting amplitude.

The model results are in no doubt with the technique of testing used. The use of the new disturbance technique might conceivably give the same result as full-scale, by reducing drastically the stability at above 45 knots and 6 deg attitude, the upper limit being lowered. Some evidence for this is suggested by the build-up of steady oscillations in the model stable range when disturbance is due to a train of waves, but it is not stated whether these damp out when the wave system is no longer present.

Summing up, there is evidence to prove that the true full-scale stability range is very small, much smaller than is assumed by the first analysis. The model limits disagree, the upper limit at high speeds being 3 to 5 deg too high, but with the new disturbance technique this difference might disappear.

3. *The Lerwick.*—Insufficient steady-run tests have been made on the *Lerwick* to draw stability limits, but a considerable number of unpublished take-offs with different elevator positions have been recorded at different weights and flap positions. These take-offs are collected together in Figs. 3, 4 and 5 for 28,000 and 33,000 lb and flap angles 0 to 10 deg. They have been analysed for stability limits by the method of Ref. 5 and the deduced limits are given for all conditions in Figs. 3, 4 and 5 and collected together in Fig. 6.

The effect of 5 deg and 10 deg flaps is negligible on the lower limit, but 10 deg flaps lower the upper limit 1 deg within the speed range (40 to 60 knots), for which results could be interpolated. An increase of weight from 28,000 lb (normal) to 33,000 lb (overload) raises the lower limit 1 deg below 60 knots only, and appears to lower the upper limit about $\frac{1}{2}$ deg but no evidence is available at speeds below 70 knots.

It should be noted that the stable range is small (2 to 3 deg) so that these small effects are quite important.

The first tank tests[36] gave too wide a stable range and in particular did not show the presence of full-scale porpoising at high speeds and medium to high attitudes. The new model disturbance technique[37] was then introduced and showed up high-speed instability, which often took a predominantly heave form rather than heave and pitch. This form of porpoising was very critical to step depth and also damped out in rough water although not in calm. (Tests with this new technique are now always made with calm water.)

A hull form was finally evolved for the *Lerwick* and built full-scale (modification 56, Ref. 38), for which the stability limits with the new technique are as shown in Fig. 6. The model upper limit is 5 to 4 deg too high between 40 and 65 knots but only 1 deg above 70 knots. The model lower limit is in better agreement, being 1 deg too high below 55 knots and $\frac{1}{2}$ deg too low above 55 knots. The general effect of change of disturbance technique is to lower the upper limit about $\frac{1}{2}$ deg up to 65 knots, but above that to lower it about 3 deg. On the lower limit there is little effect.

4. *G-boat.*—The full-scale and model-scale stability results have been discussed from the model-scale standpoint in Ref. 9, where it was decided that fair agreement existed between model and full-scale if the model evidence was interpreted according to the latest stage of full-scale knowledge.

Full-scale steady-run tests[29] are not very systematic, being made at weights between 65,000 and 72,000 lb and at three c.g. positions. Not many points were obtained in each condition and all the available points have therefore been collected together in Fig. 7a in order to give an indication of the position of the limits and a rough comparison with model-scale. These form quite reasonable limits, and it should be noted that porpoising on the upper limit can be of large amplitude (up to 5 deg) but in the lower limit it is about $\frac{1}{2}$ deg to $1\frac{1}{2}$ deg. This lower limit would not therefore be recognised on the basis of the 2 deg amplitude limitation. The model tests made at 70,000 lb and 77,000 lb with the new disturbance technique[8], and the take-off limits were shown in Fig. 7a. Landing limits are given in Fig. 7b.

The full-scale take-off results give best agreement with the model tests at 77,000 lb, giving no indication of the complete absence of stability above 50 knots shown by the model limits at 70,000 lb. This big decrease of stability with decrease in weight on the G-boat appears to be a result of the use of the new technique in that it is unlikely that instability would be found with the old technique at the higher speeds, particularly in view of the full-scale results. In operations full-scale no porpoising has been reported for take-offs unless the stick has been pulled well back at the higher speeds. One conclusion would be that the new disturbance technique is too severe by comparison with the full-scale disturbances encountered and that in this particular case the change of weight of 70,000 to 77,000 lb is the critical range in which model-scale a certain degree of disturbance becomes effective in starting instability. A bigger disturbance at the higher weight might have had a similar destabilising effect.

Where comparable the model scale upper limits are 2 deg higher and the lower limits 3½ deg higher then the full-scale limits.

Full-scale stability limits in landing have been deduced from landing records[29] by the method of Ref. 5 and are given in Fig. 7b. Comparison with the model results again shows better agreement with the higher weight. Full-scale porpoising at high speeds at the higher attitudes is severe but at the lower attitudes very slight. The upper limit at high speeds is therefore quite well defined and important but the lower one is doubtful and of no importance. This upper limit is 3 to 4 deg below the model limit at 77,000 lb but above that at 70,000 lb. At the middle and lower speeds it is less well defined and there is more justification for assuming no stable range, except at very low attitudes, as found in the tank tests at 70,000 lb. However the full-scale porpoising in this intermediate region is much less severe than the model porpoising. In landings therefore, the new model disturbance technique is still too severe but less so than in take-offs. But no full-scale porpoising at low attitudes of touch down has ever been reported or found at the M.A.E.E.[29].

5. *Sunderland, Scion.*—The *Sunderland*[30] and *Scion*[2] are considered jointly because the *Scion* is a half-scale model of the *Sunderland.*

The full-scale *Sunderland* and *Scion* steady-run limits are in good agreement. The *Scion* limits are well established (*see* Fig. 8), but not much data are available for the *Sunderland,* particularly on the upper limit. Comparison with take-off stability[5] confirms the mild instability at low speeds and high attitudes for the *Scion* but again there is insufficient evidence on the *Sunderland,* although there are signs of this instability. More tests are being made on the *Sunderland* to establish these stability limits in take-off for various conditions.

The steady-run stability measurements at normal c.g.[2] are given in detail in Fig. 9 together with the stability limits based on a 2 deg limitation of amplitude. In this case the stability limits based on all undamped porpoising are very similar to these based on the 2 deg limit. The distribution of points illustrates the suggestion that the mean attitude of porpoising is not necessarily the same as the attitude to trim with the same elevator setting when no stability is present. The mean atttitude is always tending to be lower in the upper unstable region and higher in the lower unstable region.

Steady-run limits for c.g. forward and normal on the *Scion* are compared in Fig. 8. Forward movement of the c.g. raised the lower limit 1½ deg. at the hump speed and made the available stable range at the hump with c.g. forward very small. This was confirmed by take-off measurements.

Model results with the new disturbance technique[34,38] and also with the *Sunderland* model moved to a position further forward of the tank carriage to avoid carriage interference on air flow[19] are shown in Fig. 8. The *Scion* model limits[38] are quite different from the *Sunderland* model and full-scale limits. The absence of stability between 30 and 37 knots may be due to the new disturbance technique being too severe. Landing limits, obtained model-scale by omitting slipstream lift, do not show this instability. Full-scale steady runs show that mild instability may exist right across the attitude range at 25 knots, but the take-off[5] shows no instability. The difference between landing and take-off model-scale limits may again be due to the relatively increased severity of the disturbance with small displacement, this region being critical (*see* also G-boat). Excepting this unstable region the model *Scion* lower limit is 2 to 3 deg higher than the full scale limit. More recent tests on the *Scion* dynamic model at the R.A.E. lower the lower limit about 2 deg. The model upper limit is in agreement with that of the *Sunderland* but both are 2 to 4 deg higher than full-scale. The differences were due to weight and moment of inertia. The *Sunderland* model lower limit is in fair agreement with full-scale.

The *Sunderland* model limits have also been measured at overload[34] with the new technique and at 44,600 lb with the old technique (Fig. 8) and in the old position relative to carriage. The effect of change of disturbance technique introduced the possibility of mild porpoising in the previously stable region near the hump speed. This again points to the possibility of this region becoming unstable with the new technique if the displacement were much increased or stability weakened in any way. The results with a faired step are of special interest and are dealt with in connection with faired step instability. The effect of weight, model-scale, is to decrease the stable range by raising the lower limit and slightly lowering the upper.

Later tests[39] have been made on the *Sunderland* to establish the correct slipstream lift and moments and check the inconsistency of attitudes full and model-scale. Using these measured values the measured full-scale attitudes were obtained. No stability tests have yet been made using these new data, so that any possible change of limits is unknown.

6. *The Faired Step Sunderland.*—The *Sunderland* with the faired step[18] introduced a new kind of porpoising in full-scale tests and experiments have given some indication of the associated water flow over the hull bottom.

Results of the full-scale tests for steady runs and take-offs are given in Figs. 10 and 11. Fig. 10a gives steady runs with no fairing and Fig. 10b take-off stability limits for the no fairing case; Figs. 11a and 11b give the corresponding results for the different fairings. (Later results are given in Ref. 44 for a 1 : 4 fairing on a *Sunderland* III.) The fairings had no measurable effect on the lower or upper limits of normal porpoising but introduced the step-porpoise limit at high attitudes and speeds in steady runs only. Take-offs[30, 31] have been analysed by the method given in Ref. 5 to supplement the steady-run points of Refs. 18, 28 and 30 for a detailed analysis of the effect of the fairings on stability. The fairing extends the normal upper-limit porpoising to lower speeds but this is not very important since the porpoising is of a mild nature. The same mild porpoising was found on the full-scale *Scion* in steady runs with an unfaired *Sunderland* hull; so that a more powerful elevator on the unfaired *Sunderland* might have found this porpoising.

Analysis of the full-scale landing results[18, 28, 30] are given in Fig. 12. There are not enough points to establish a lower limit. The step porpoise is not found with the 1 : 3 to 1 : 6 fairings at 43,000 lb, but it occurs at quite low attitude with the 1 : 6 fairing at 50,000 lb although not very violently. This effect of displacement is in agreement with the reported porpoising of Service *Sunderlands* III at high loads at touch-down at slow speeds, and the beginnings of a bounce tendency at 49,000 lb in landings at the stall found in recent tests at the M.A.E.E. The step-porpoise limit with a 9 to 1 fairing at 43,000 lb coincides at high speed but extends down to 50 knots and the porpoising was also quite violent. At higher loads it would be very difficult to land with this fairing without porpoising badly. The absence of a step porpoise in take-off with the fairing would appear to be due to the much reduced displacement in take-off conditions.

The full-scale–model-scale comparison is given in Fig. 13 for take-off. The effect of the new model technique of disturbance is to eliminate the large stable range above 65 knots. Some of this may be due to change of weight. The full-scale lower limit is in good agreement with the model, but the upper limit is 3 deg lower and does not join up with the lower limit near take-off.

7. *The Shetland Hull on the Saro* 37.—The stability results for a large-scale model of the *Shetland* hull bottom have been discussed in detail[3]. The comparison of the large-model and tank-model results is given in Fig. 14. Fig. 15 shows the effect of c.g. travel, increase in weight and the use of flaps on the stability of the large model.

The tank-model take-off limits[35] have been found by the new tank technique and are compared with the corresponding large-model steady-run limits (*i.e.*, those for c.g. normal, 0 deg flap) at a weight of 120,000 lb. The lower limits show good agreement but the tank-model upper limit is too high and the more severe limits at 90 knots which suggest no stability at take-off for the tank model are not found in the large-model results. The large-model step-porpoising limit is in agreement with the tank-model upper limit from 75 to 85 knots.

The effect of moving the c.g. forward is to reduce the stable range very considerably over the hump (50 knots). The lower limit is raised 3 deg at 50 knots but is little changed above 70 knots. The normal upper limit is raised beyond the practical range of attitudes attainable ; and the step-porpoise limit is raised slightly, so increasing a little high-speed stability.

The effect of moving the c.g. aft is to narrow the stable range to $1\frac{1}{2}$ deg at 60 knots but to make little difference above 75 knots. The lower limit is raised 1 deg at 50 knots but is little changed above 70 knots ; the upper limit is slightly lower at 60 knots but is otherwise unchanged, and the step-porpoise limit is slightly lowered.

An increase in weight from 120,000 lb to 130,000 lb reduces the stable range over the whole speed range and to a minimum of 2 deg between 50 and 70 knots. The lower limit is raised 1 deg at 50 knots but is little changed above 70 knots ; the upper limit is lower, by 2 deg at 80 knots and 1 deg at 70 knots ; the step-porpoise limit is lowered by $1\frac{1}{2}$ deg.

The effect of increasing the flap angle from 0 deg to 15 deg is to narrow the stable range by 1 deg above 75 knots and to reduce it to $1\frac{1}{2}$ deg between 45 and 65 knots. The lower limit is unchanged at 50 knots but is 2 deg lower at 70 knots, the upper limit is lower by $1\frac{1}{2}$ deg over the whole speed range and extends down to 50 knots; the bounce-porpoise limit is $1\frac{1}{2}$ deg lower.

The stability limits shown in Fig. 15 are all drawn with reference to porpoising of more than 2 deg amplitude. It was found that over the hump (50 knots) porpoising of less than 2 deg amplitude could not be avoided. The mean attitude of porpoising in a step porpoise is higher than the steady running attitude and the bouncing porpoise is plotted at the steady-run attitude. If the steady-run attitude is not known then the step porpoise is plotted at a third of the amplitude away from the lower limit of the porpoise. This raising of mean attitude is the opposite to the effect of normal porpoising, which lowers the mean attitude of points inside the upper region of instability. The latter effect, which has been discussed in section 6 for the *Scion*, is confirmed by the *Shetland*.

APPENDIX II

Theoretical Evidence

1. *Introductory.*—The fundamental theoretical investigations of porpoising instability were made by Perring and Glauert in Ref. 15. The important parameters affecting instability were very roughly determined from hydrodynamic data based on measurements of the water forces acting on simple flat planing surfaces, and from generalised aerodynamic data. Two types of instability were investigated, one for a single planing surface and one for two planing surfaces in tandem, the second surface being continuously immersed. The results are necessarily qualitative only, in view of the data available, but do bring out the salient features.

This theory has been further applied (for the single planing surface case only) for later hydrodynamic and aerodynamic data[16, 18]. Similar results are generally obtained but their greatest value is in demonstrating the correct use of model data.

The theory has also been used successfully to theoretically check model results on the effect of dead-rise angle on the stability of a single planing surface[22]. The hydrodynamic data were obtained from complete tank tests on wedge-shaped planing surfaces covering the full range of dead-rise angle.

2. *Stability With a Single Planing Surface.*—Instability results from the interaction of pitching and heaving motions. These motions are generally stable if considered separately.

The theoretical single planing surface instability will only occur full-scale when there is no step or afterbody interference.

The derivatives determining the stability are the uncoupled ones: z_z, z_w, m_θ, m_q and the coupled ones: z_θ, z_q, m_z, m_w. The instability is set up by the interaction of the coupled derivatives. It appears, at first, that increase of the uncoupled and decrease of the coupled would be the leading rule for maximum stability but this is only approximately true because of the form of the stability equation. Increase of z_z and the damping terms z_w and m_q increases stability as long as m_z and z_w are not too large and in particular if z_w is not too large. Increase of damping must also be such as to make m_q and z_w more nearly equal. Increase of m_θ and the coupled derivatives always leads to instability. If the damping and/or m_θ are large then the results of increasing any specific terms are not predictable.

The true relative values of these derivatives is still unknown because of the lack of full-scale or model-scale data on complete seaplanes. No general rules can therefore be postulated.

Each derivative has a water and air component, but in all except m_q and z_w (the damping terms) the hydrodynamic forces predominate. Damping due to the tailplane is therefore very important and damping due to the wings fairly important. The form and size of the planing surface is important in so far as z_z and m_w can be kept large and m_θ kept reasonably low for any given planing condition.

Instability occurs below a critical attitude which decreases as the speed increases. The critical attitude is further decreased (or stability increased) by (*a*) decrease in dead-rise angle and to a lesser but important degree by (*b*) increased damping, (*c*) presence of nose-down hydrodynamic moments, (*d*) backward or downward movement of the c.g. relative to the step, (*e*) decreased air longitudinal stability, (*f*) increased moment of inertia. The effect of change of load on the water has not been theoretically examined but is known to be important in practice.

The destabilising effect of forward and upward c.g. movement acts in two ways, first by increase of longitudinal stability, secondly by change of moments relative to the step.

The stabilising effect of increased damping is not general. Excessive air damping will lead again to instability. The actual effect of increase in damping depends on the damping already present, and the relative value of this and the other forces involved. The addition of aerodynamic damping by means of wings and tailplane to a hull is very stabilising if the added longitudinal stability be kept low, just stabilising if the added longitudinal stability is excessive, but destabilising if an excessive nose up hydrodynamic moment is present. The change of degree of instability with attitude is much more pronounced in the presence of aerodynamic damping.

3. *Stability on Two Planing Surfaces.*—Theoretical results for this planing condition are not immediately applicable to true hull forms because the wake formation behind the first planing surface is not considered. The rear planing surface is assumed to be incident on the same water surface as the first. Results must therefore be interpreted in terms of the possible nature of this wake.

3.1. *Neglecting the Wake Formation Behind the First Surface.*—In contrast to the case of the single planing surface, no general rules on the relative effect of the different derivatives on stability can be deduced. For a limited range of attitudes of the first surface (less than 4 deg) increase of m_θ relative to z_z is stabilising, but above 4 deg applied moments to increase m_θ leads to instability. The damping terms z_w and m_q are again the only terms in which the aerodymanic components are important but increase of aerodynamic damping has negligible effect on stability. The addition of wings and tailplane also has negligible effect on stability.

Instability occurs above a critical attitude which tends to decrease slowly with increase of speed.

The critical attitude is lowered by any changes tending to reduce the strength of the aft planing surface relative to that forward. Decrease of (attitude) incidence, of rear step height above the front, of beam of the rear step all decrease the critical attitude. Change of distance between the steps is not important, but there is an intermediate range 2 to 5 beams in length, in which slight instability occurs.

Longitudinal air stability has no effect.

Decrease in radius of gyration improves stability.

The c.g. range from over the front step to a short distance aft is unstable.

3.2. *Effect of the Wake Behind the First Planing Surface.*—The wake behind a planing surface varies with speed, attitude and ratio of dynamic to static lift. When the ratio of dynamic lift (L) to displacement (Δ) is greater than $0{\cdot}95$ the maximum depression (Z) of the wake relative to the step is of the approximate order of (Ref. 26)

$$\frac{Z_{\max}}{b} = \sqrt{(C_\Delta \alpha)}$$

at a distance aft of the step of

$$\frac{x}{b} = \sqrt{\left(\frac{C_\Delta}{\alpha}\right)},$$

where b is the beam, and α the incidence of the planing surface. This result applies approximately for the planing region above $C_V = 4{\cdot}5$. Below this speed static lift is generally greater than 5 per cent, becoming 30 per cent at the hump speed. When L/Δ is less than $0{\cdot}95$ the wake is shorter (halved for $L/\Delta = 0{\cdot}7$) and the rise of water level after the trough is fairly abrupt. The upwash angle in this region is at least twice the downwash angle.

Under typical take-off conditions the approximate distance of the maximum depression behind the step would be from $2b$ at the hump speed to $2{\cdot}5b$ at medium planing speeds and $2b$ again near take-off. The value of the depression will vary from $0{\cdot}25b$ at the hump to $0{\cdot}2b$ near take-off.

Contemporary afterbody lengths are $2b$ to $4b$, the smaller lengths being favoured by U.S.A. designers, the longer by British designers. It follows that short afterbodies will be such that the rear step is just aft of the maximum depression and riding on the ' upwash '. This will be of the order of 5 deg to 8 deg at the hump speed and 2 to 4 deg at take-off. The longer afterbody will be such that the steps ride well up towards the crest of the ' upwash ' where the angle may be diminished considerably and the water surface near the normal water level or even above it.

The best afterbody characteristics for porpoising stability can now be roughly correlated with this wake formation to give the best hull geometry, bearing in mind that the planing angle of the second surface should be at least equal to that of the first and if possible greater when the difference in height between the steps is zero. If the height between the two steps be increased the angle can be smaller for the same stability. A short afterbody should therefore lead to greater stability, and the stability at the hump speed would be greater because of the greater upwash. For a long afterbody greater instability would be expected†.

TABLE 1

Weight and Dimension Data

Seaplane	Weight (lb)	Gross wing area (sq ft)	Span (ft)	Wing loading (lb/sq ft)	Beam (ft)	Beam loading coefficient $C_{\Delta 0}$	Forebody length/beam	Afterbody length/beam
Singapore IIc ..	26,600	1,759	79·5	15·1	10·88	0·33	2·53	2·04
Singapore III ..	27,000 31,150	1,759	79·5 (top)	15·4 17·7	10·88	0·34 0·39	2·53	2·01
Seal	6,400	438·5	—	14·6	3·20	1·46	4·22	3·37
Lerwick	28,000 33,600	845	81·0	33·0 39·6	8·525	0·72 0·87	3·33	3·34
G-boat..	70,000 77,000	2,340	134·3	29·9 32·4	12·0	0·65 0·71	3·20	3·17
Sunderland I	43,000 48,000	1,690	112·7	25·5 28·8	9·8	0·73 0·83	3·36	2·98
Sunderland II ..	43,000 50,000 60,000	1,690	112·7	25·5 29·6 35·5	9·8	0·73 0·85 1·02	3·36	2·98
Scion .. .. .. (½-scale *Sunderland*)	5,900	455	55·1	13·0	4·9	0·78	3·34	2·98
Saro 37, *Shetland* hull (1/2·75-scale *Shetland*)	5,700 6,200	340	50·0	16·8 18·4	4·54	1·07	3·52	3·4
Mariner	56,000	1,408	118·0	39·8	10·0	0·875	3·35	2·74
Coronado	68,600	1,779	115·0	39·6	10·5	0·925	3·00	2·18

TABLE 1—*continued*

Seaplane	Step depth at keel/beam	Main step shape	Rear step shape	Angle afterbody keel (deg)	Dead-rise angle at keel (deg)		Normal c.g. relative to step at keel in terms of beam
					Forebody	Afterbody	
Singapore IIc	4·6	V	Transverse	9·0	26	30·5	0·27
Singapore III	4·6	V	Transverse	8·5	26	30·5	0·27
Seal	6·25	Transverse	Knife edge	8·7	—	—	0·26
Lerwick	10·71	V	Transverse	8·0	29·5	22·0	0·20
G-boat	5·5	V	Knife edge	8·75	31·0	41·0	0·42
Sunderland I	8·0	V	Knife edge	7·0	31·0	41·0	0·31
Sunderland III	8·0	V	Knife edge	7·0	31·0	41·0	0·31
Scion .. .. .. (½-scale *Sunderland*)	8·0	V	Knife edge	7·0	31·0	41·0	0·31
Saro 37, *Shetland* hull .. (1/2·75-scale *Shetland*)	3·7	V	Knife edge	7·5	29·0	37·0	0·37
Mariner	4·6	Transverse	Knife edge	7·5	22·5	22·5	0·27
Coronado	6·0	V	Knife edge	7·25	22·5	22·5	0·37

TABLE 2A

Effect of Displacement on Stability Limits

Seaplane	Change of weight per cent	Conditions of test		Change of limits	
		Take-off (T.O.) or Landing (L)	Model (M.S.) or Full-scale (F.S.)	Upper limit	Lower limit
Singapore IIc	Increased 15	T.O.	M.S.	Raised ½° to 1°	Raised ½° to 1°
Singapore III	Increased 17	T.O.	M.S.	Lowered 0° to ½° above 50 knots	Raised 1°
Lerwick	Increased 20	T.O.	F.S.	—	Raised 1° below 60 knots
G-boat	Increased 10	T.O.	M.S.		Lowered 2° below 47 knots
				Stable range from 47 to 80 knots at 77,000 becomes unstable at 70,000 lb	
	Increased 10	L.	M.S.	ditto	
Faired-step *Sunderland* II	Increased 16	L.	F.S.	Step porpoise limit lowered 3°.	
Sarò 37 with *Shetland* hull bottom	Increased 8	T.O.	Half-scale	Step porpoise limit lowered 1½°. Normal porpoise limit lowered 1°	Raised 1° at low speeds. Lowered ½° high speeds
Saro R.2/33	Increased 8	T.O.	M.S.	Raised 1½° at 60 knots	
Sunderland III	Increased 25	T.O.	M.S.	Raised 2° at 60 knots to ½° at 70 knots	Raised 1½° at 40 knots at 0° at 50 knots
Sunderland III	Increased 20 Increased 14	T.O. L.	F.S. F.S.	Raised 1° at hump, 2° at T.O.	Raised 2° at hump, 1° at T.O. Raised 1° at hump, 2° at 50, 1° at T.O.
N.A.C.A. (Refs. 11, 25) . .	Increased 66 Increased 33	T.O. T.O.	M.S. M.S.	Raised 2½° at hump, 3½° at T.O. Raised 2° at hump and T.O.	Raised 5° at hump, 1° at T.O. Raised 5° at hump, 0° at T.O.

TABLE 2B

Take-off to Landing (*Model Tests only*)

Seaplane	Conditions	Change of limits T.O. L	
		Upper limit	Lower limit
Saunders-Roe R.2/33 ..	38,000 lb N.F.*	Raised 2° at 50 knots, 1° at 60 knots	Raised 2° at 40 knots, ½° at 65 knots
Short R.2/33	38,000 lb N.F.*	No change	No change
	38,000 lb 28° F.†	Raised 2°	Raised 1° at 40 knots. Unchanged at 50 knots
Saro R.1/36	25,000 lb Flap 40°	—	Raised ½°
Lerwick	28,000 lb Mod. No. 56 N.F.*	No change	Raised 2° at 40 knots to 0° at 60 knots
Scion	5,575 lb Sunderland float	Raised ½° at 40 knots to 1½° at 60 knots	Lowered ½° at 40 knots. No change above 45 knots

* N.F. = No flaps. † F. = Flaps.

TABLE 3

Effect of Flaps on Stability Limits

Full-scale evidence

Seaplane	Change of flap setting (deg)	Kind of flap	Take-off (T.O.) or Landing (L.)	Change of limits	
				Upper limit	Lower limit
Lerwick (Appendix I) . .	0– 5 0–10	Trailing edge split	T.O.	No effect Lowered 1°	No effect No effect
Sunderland (Appendix I)	0– 8	Gouge	T.O.	No effect	No effect
1 : 2·75 scale *Shetland* . .	0–15	Slotted trailing edge	T.O.	Normal limit lowered 1½°. Step limit lowered 1½°	Raised 1° above 65 knots

Model-scale evidence

Lerwick No. S.S.	0–20	Split trailing edge	T.O.	Lowered 1° hump speed to lowered 2° at take-off speed	Lowered ½° at intermediate speeds only
Lerwick No. S.S. . .	0–40	Split trailing edge	T.O.	—	Lowered ¼°
Sunderland	0–28	Gouge	T.O.	Lowered 2½°	Lowered 2°
Saunders-Roe R.2/33 . .	0–45	—	L.	Lowered ¼°	Lowered ¼° below 50 knots. Raised ¼° above 50 knots
Shetland (*Saro* 37) . .	0–30	Slotted trailing edge	L.	Lowered 3° above 60 knots	
Sunderland	0–28	Gouge	L.	Lowered ½° above 55 knots	Lowered 1¾°
Lerwick with S.S. . .	0–20	Split trailing edge	T.O.	No effect	No effect

TABLE 4

Effect of C.G. Position on Stability Limits

Seaplane	Movement of c.g. in terms of beam forward of step	Take-off (T.O.) or Landing (L.)	Model (M.) Full-scale (F.S.)	Change of limits	
				Upper limit	Lower limit
Singapore IIc	0·274 to 0·17	T.O.	M.	Lowered 2° at 40 knots, 0° at 65 knots	Lowered at least 2° outside obtainable attitudes
	0·274 to 0·38	T.O.	M.	No effect	Lowered 1° at 40 knots, ½° at 65 knots
Singapore III	0·274 to 0·36	T.O.	M.	Raised ½° to 1°	Lowered ½° above 45 knots
Scion	0·306 to 0·39	T.O.	F.S.	Lowered 1° near take-off	Raised 1½° at hump speed, 0° at take-off
Saro 37	0·369 to 0·44	T.O.	F.S.	Normal limit raised at lease 3° to outside obtainable attitudes. Step limit raised 1°	Raised 4° at hump speed, 0° above 60 knots
N.A.C.A.[23]	0·308 to 0·432	T.O.	M.	No effect	Lowered ½° at hump speed
	0·432 to 0·537			No effect	Lowered ½° at hump speed

TABLE 5

Comparison of Model-Scale and Full-Scale Limits

<table>
<tr><th rowspan="2">Seaplane</th><th rowspan="2">Condition of test
Model disturbance technique</th><th colspan="2">Comparison of limits</th></tr>
<tr><th>Upper limit</th><th>Lower limit</th></tr>
<tr><td><i>Singapore</i> IIc</td><td>Take-off
Old disturbance technique</td><td>Full-scale limit 0° to 1° <i>lower</i></td><td>Full-scale limit 1° to 2° <i>lower</i></td></tr>
<tr><td rowspan="4"><i>Seal</i></td><td rowspan="4">Take off
Old disturbance technique</td><td colspan="2">(1) <i>Full-scale limits based on divergent oscillations of over 3° amplitude</i></td></tr>
<tr><td>Full-scale limit 1½° <i>lower</i></td><td>Full scale limit: 3° <i>lower</i> at 30 kt, 0° <i>lower</i> at 55 kt</td></tr>
<tr><td colspan="2">(2) <i>Full-scale limits based on all undamped porpoising</i></td></tr>
<tr><td>Full-scale limit 0° <i>lower</i>, 40 to 55 kt</td><td>Little difference (40 to 55 kt)</td></tr>
<tr><td><i>Lerwick</i></td><td>Take-off
New disturbance technique</td><td>Full-scale limit: 4° to 5° <i>lower</i> from 40 to 65 kt, 1° <i>lower</i> above 70 kt</td><td>Full-scale limit: 1° <i>lower</i> below 55 kt, 1° <i>higher</i> above 55 kt</td></tr>
<tr><td rowspan="5">G-boat</td><td rowspan="3">Take-off
New disturbance technique</td><td>Full-scale 1½° <i>lower</i> from 45 to 60 kt (72,000 lb full-scale, 77,000 lb model-scale)</td><td>Full-scale 3° lower from 45 to 60 kt (72,000 lb full-scale, 77,000 lb model-scale)</td></tr>
<tr><td>No comparison with model at 70,000 lb</td><td>Full-scale 2° <i>lower</i> below 40 kt (72,000 lb model-scale, 70,000 lb model-scale)</td></tr>
<tr><td colspan="2">(<i>Note.</i>—Decrease of model weight from 77,000 to 70,000 lb. eliminates stability above 40 kt)</td></tr>
<tr><td rowspan="2">Landing
New disturbance technique</td><td>Full-scale 1° to 2° <i>lower</i> where comparable</td><td>Full-scale 1° to 2° <i>lower</i> where comparable</td></tr>
<tr><td colspan="2">Full-scale limits at 72,000 lie between model-scale 70,000 and 77,000 lb</td></tr>
<tr><td rowspan="2"><i>Scion</i> with <i>Sunderland</i> hull</td><td rowspan="2">Take-off
New disturbance technique</td><td>Full-scale 3° <i>lower</i> above hump speed</td><td>Full-scale 4° <i>lower</i> above hump speed</td></tr>
<tr><td colspan="2">(<i>Note.</i>—No stability on model in region of hump speed)</td></tr>
<tr><td><i>Sunderland</i> I</td><td>Take-off
Old disturbance technique</td><td>Full-scale 3° <i>lower</i></td><td>Full-scale 1° <i>lower</i></td></tr>
<tr><td rowspan="3">Faired step <i>Sunderland</i> (4 to 1 ratio fairing)</td><td>Take-off
Old disturbance technique</td><td>Full-scale 3° <i>lower</i></td><td>Full-scale in good agreement</td></tr>
<tr><td rowspan="2">Take-off
New disturbance technique</td><td>Full-scale 2½° <i>lower</i> below 40 kt</td><td>Full-scale ½° <i>lower</i> below 40 kt</td></tr>
<tr><td colspan="2">(<i>Note.</i>—Above 55 knots there is no stability model-scale, 3° to 5° full-scale)</td></tr>
<tr><td rowspan="2">Effect of faired step</td><td>Take-off
Old disturbance technique</td><td><i>Full-scale:</i> No difference to normal limit but additional step-porpoise limit introduced at combined high speeds and attitudes
<i>Model-scale:</i> Normal limit lowered 1°, no step porpoising.</td><td><i>Full-scale:</i> no difference
<i>Model-scale:</i> no difference</td></tr>
<tr><td>Take-off
New disturbance technique</td><td><i>Model-scale:</i> No stability with faired step above 40 kt. No comparable tests without fairing available.</td><td>ditto</td></tr>
<tr><td rowspan="2"><i>Saro</i> 37 with <i>Shetland</i> hull</td><td rowspan="2">Take-off
New disturbance technique</td><td>Full-scale 2° <i>lower</i></td><td>Full scale ½° lower</td></tr>
<tr><td colspan="2">(<i>Note.</i>—Model scale above 90 kt there is no stability, <i>cf.</i> faired-step <i>Sunderland</i>)</td></tr>
</table>

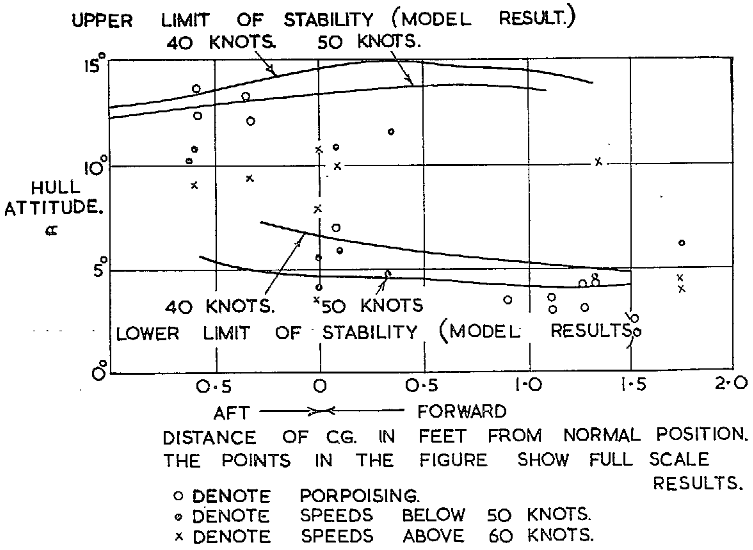


FIG. 1a. Full-scale and model-scale stability of *Singapore* IIc.

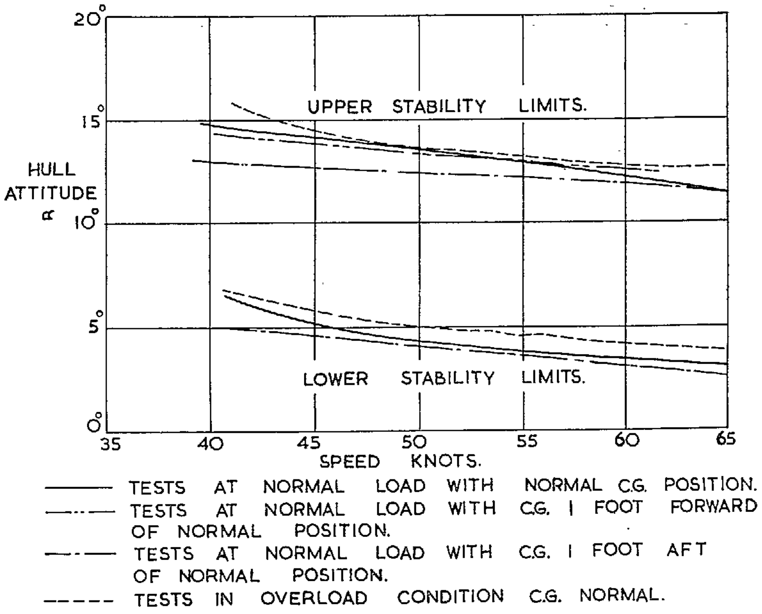


FIG. 1b. Curves showing limiting attitude for stability. Model stability limits of *Singapore* IIc.

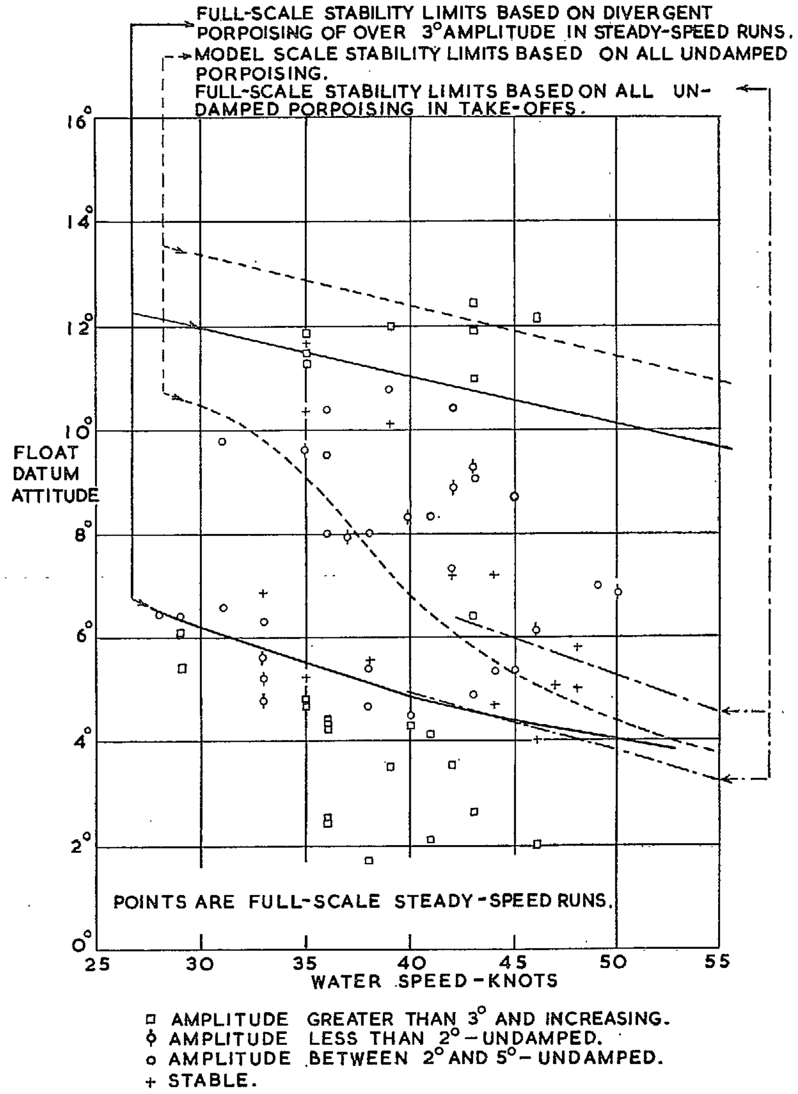
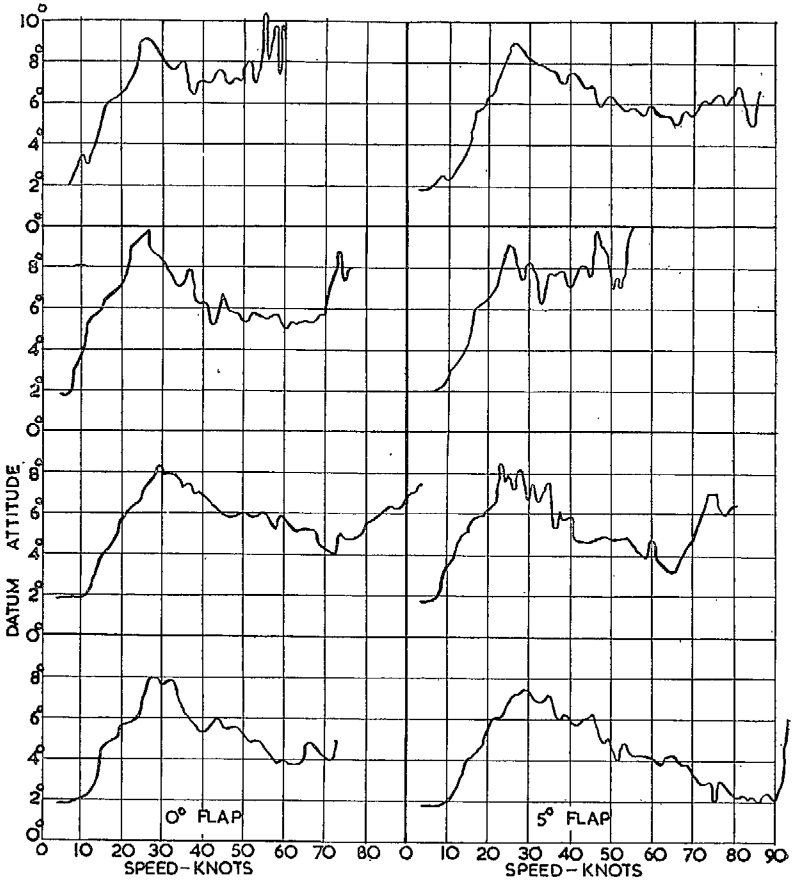
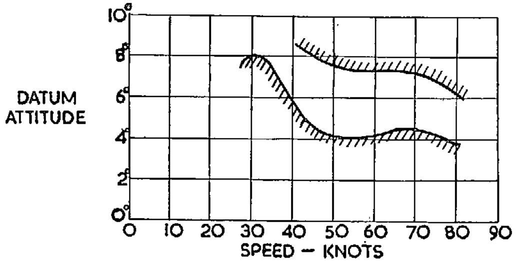


FIG. 2. *Seal* stability. Model and full-scale.

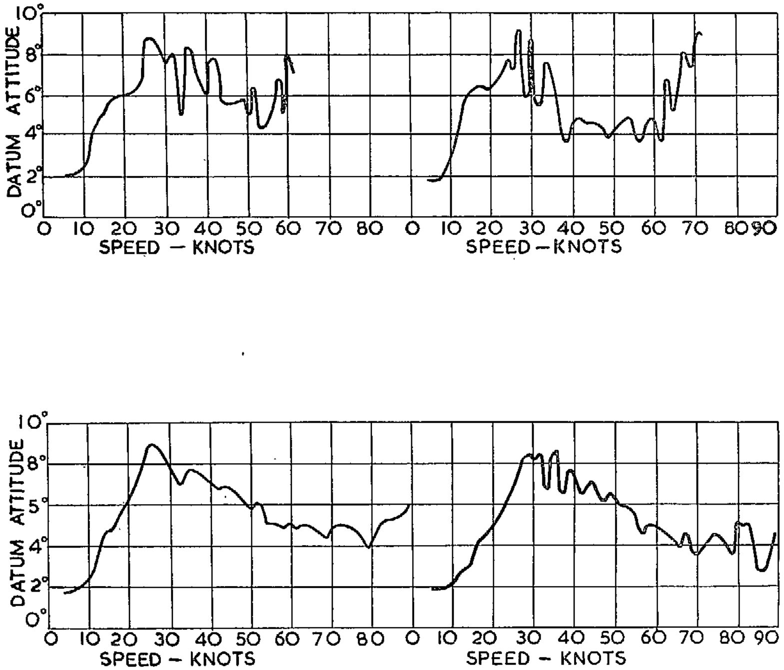


TAKE-OFF ATTITUDES AGAINST WATER SPEED.

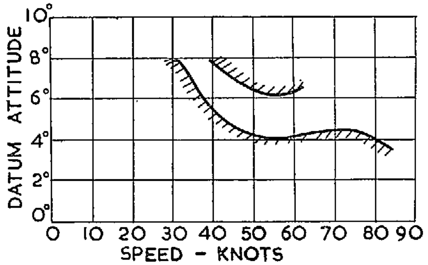


STABILITY LIMITS DEDUCED FROM TAKE-OFF ATTITUDES

FIG. 3. Full-scale stability of *Lerwick* at 25,000 lb. Normal c.g.



TAKE-OFF ATTITUDES AGAINST SPEED



DEDUCED STABILITY LIMITS FROM TAKE-OFFS.

FIG. 4. Full-scale stability limits of *Lerwick* at 25,000 lb. 10 deg flaps. Normal c.g.

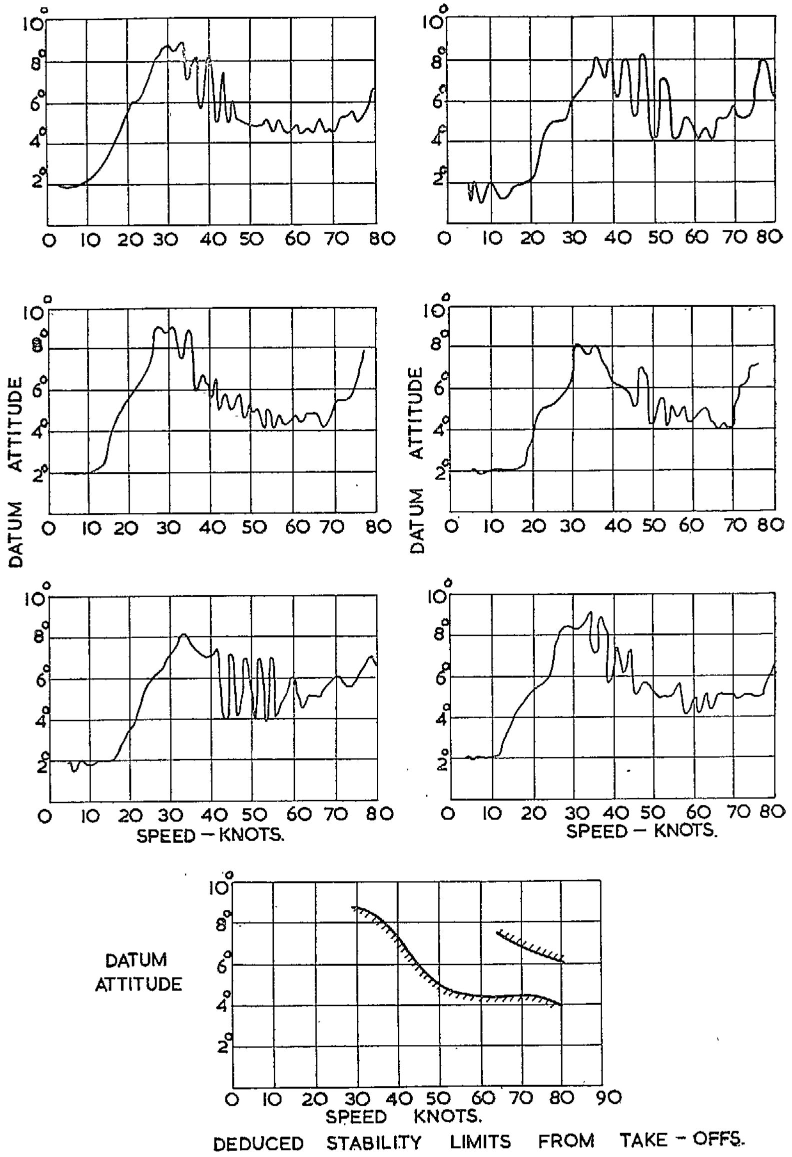


FIG. 5. Full-scale stability limits of *Lerwick* at 33,000 lb. 10 deg flap. Normal c.g.

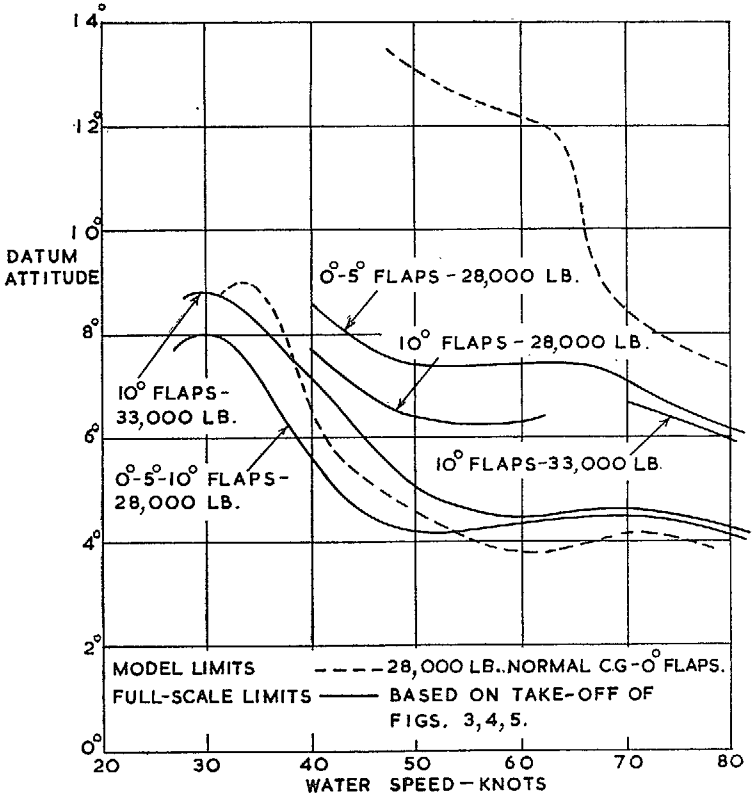
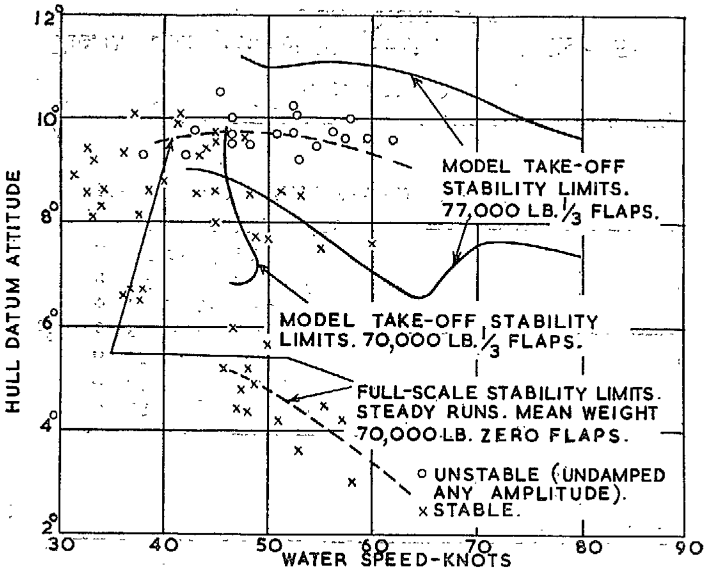
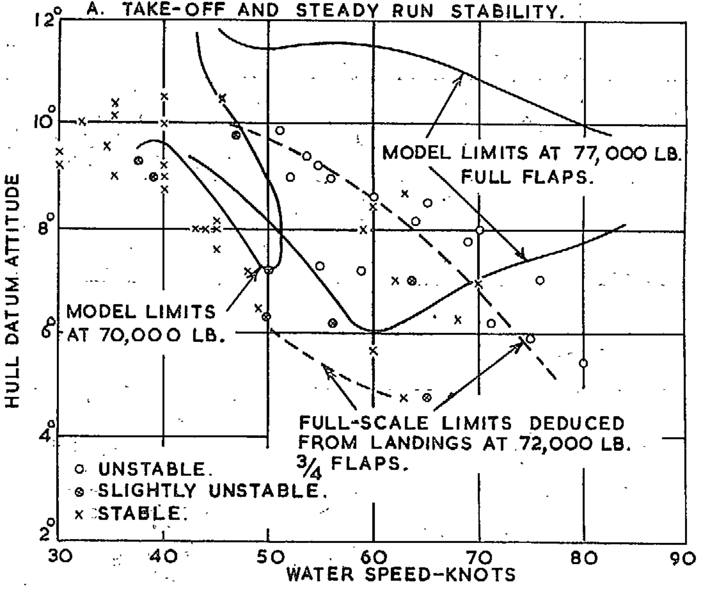


FIG. 6. Full-scale and model-scale stability limits of *Lerwick* in take-off.

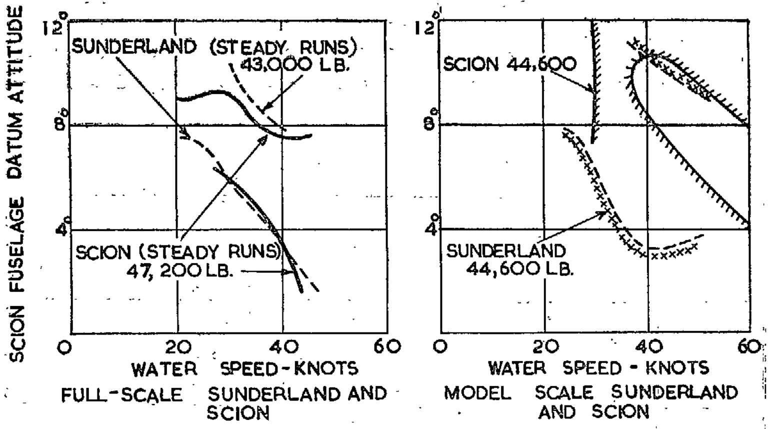


A. TAKE-OFF AND STEADY RUN STABILITY.



B. LANDING STABILITY.

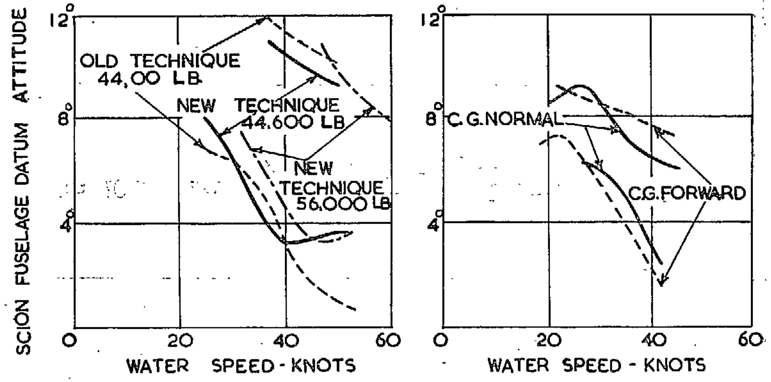
FIG. 7. Full-scale and model-scale stability of G-boat.



FULL-SCALE SUNDERLAND AND SCION

MODEL SCALE SUNDERLAND AND SCION

NOTE :- ALL SPEEDS AND ATTITUDES TO SCION SCALE
SUNDERLAND SPEED IS $\sqrt{2}$ x SCION SPEED
SUNDERLAND DATUM ATTITUDE IS SCION DATUM ATTITUDE LESS 1·6°



MODEL SUNDERLAND DIFFERENT WEIGHTS AND TECHNIQUES

FULL-SCALE SCION EFFECT OF C.G. MOVEMENT 47,200LB

FIG. 8. Stability limits in take-off conditions of *Sunderland* I, *Scion* (half-scale *Sunderland*). Full and model-scale.

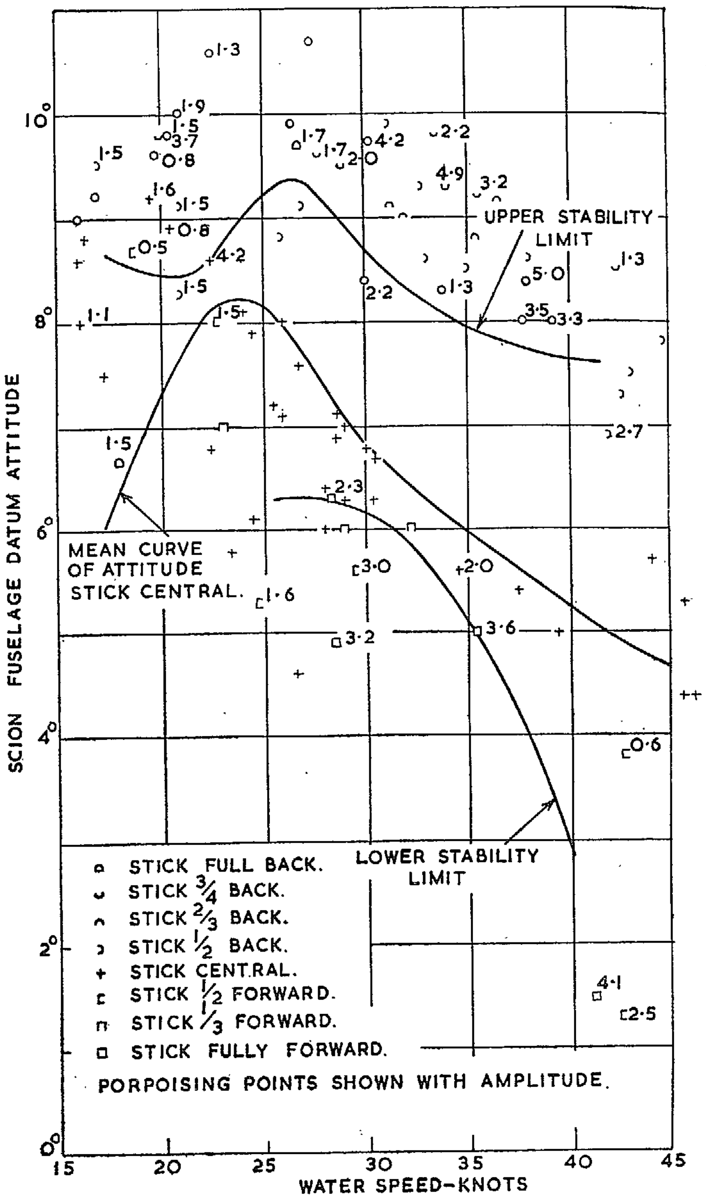


FIG. 9. Steady-run stability points and limits of *Scion* at 5,900 lb. Normal c.g.

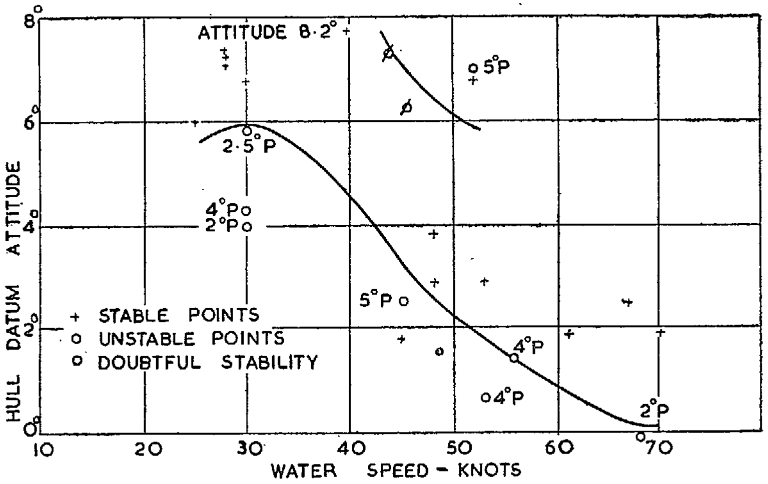


FIG. 10a. *Sunderland* stability in steady runs. No fairing. 43,000 lb. 0 deg flap.

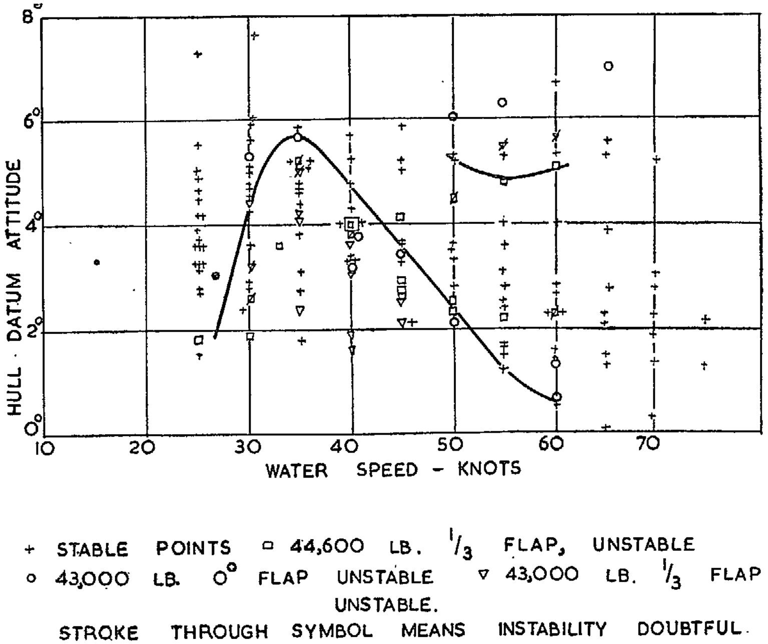


FIG. 10b. *Sunderland* stability in take-off. No fairing.

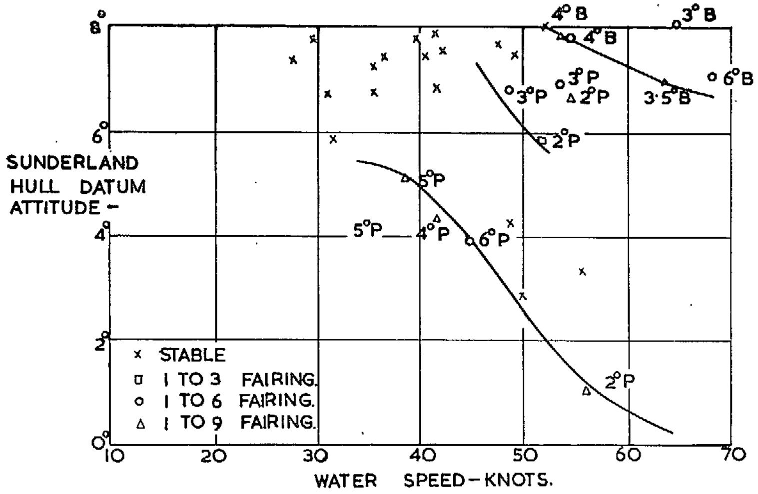


FIG. 11a. *Sunderland* stability in steady runs. 43,000 lb. 0 deg flap. Different step fairings.

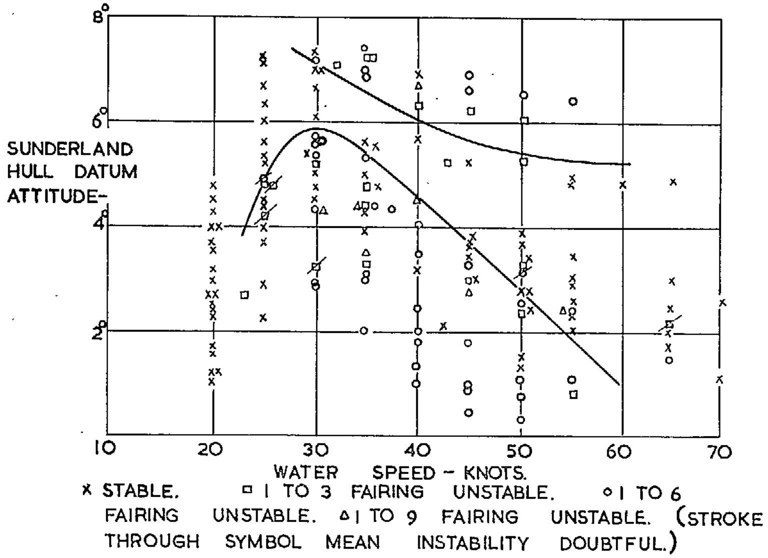


FIG. 11b. *Sunderland* stability in take-off. 43,000 lb. 0 deg and 1/3rd flap. Different step fairings.

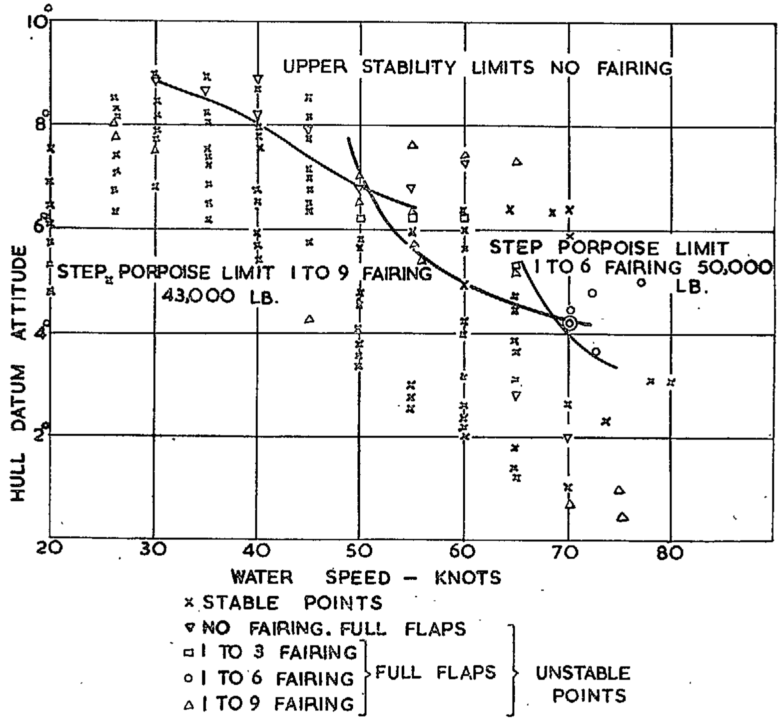


FIG. 12. Stability of *Sunder'and* in landing with different step fairings.

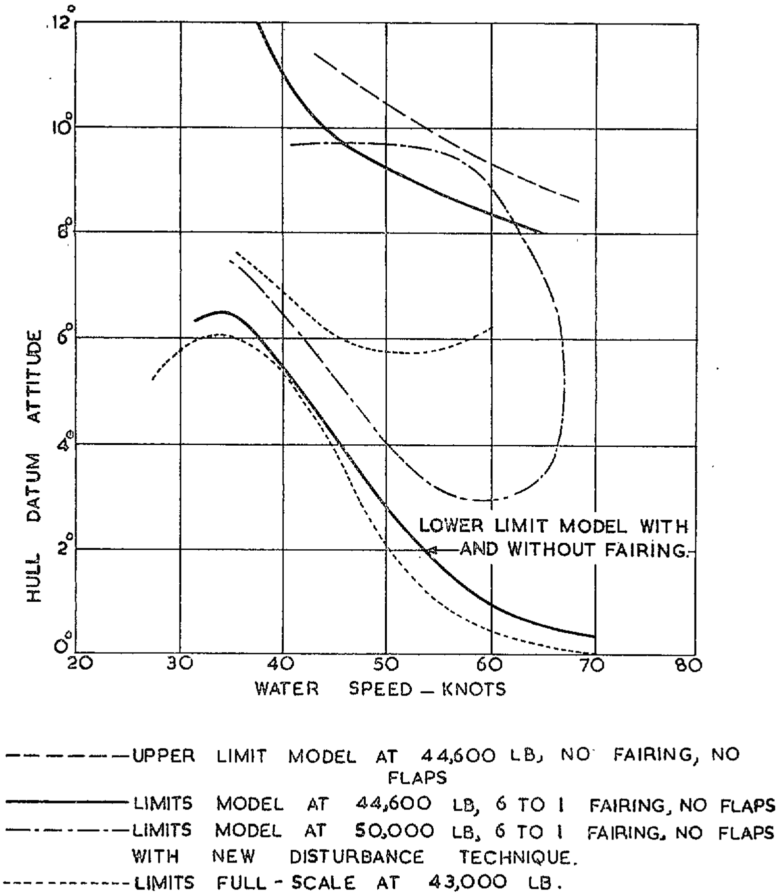


FIG. 13. Faired-step *Sunderland*. Stability in take-off. Model and full-scale.

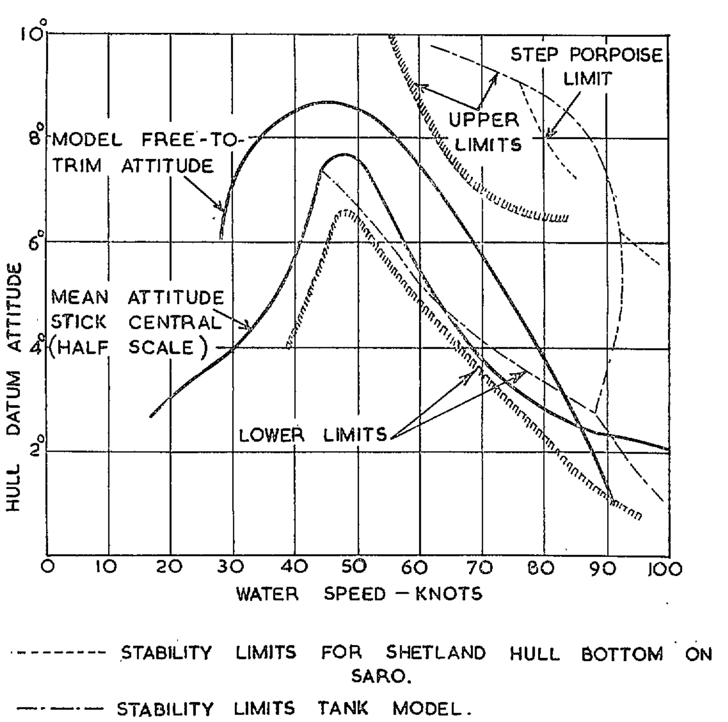


FIG. 14. *Shetland* stability in model take-offs and in *Shetland-Saro* steady runs. 120,000 lb. Normal c.g.

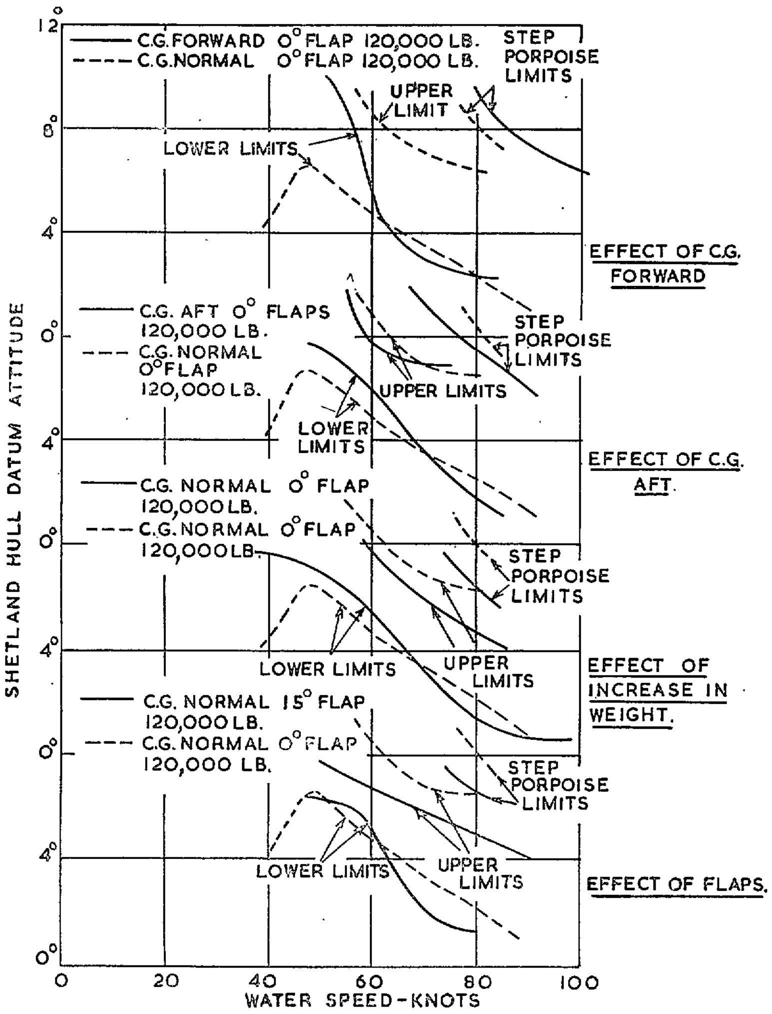


FIG. 15. *Shetland* stability in steady runs. Effect of c.g. travel, weight, and flaps. *Shetland* hull bottom attached to *Saro* 37.

(59844) Wt. 17/680 K.5 5/54 Hw.

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