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A Survey of Scale effects on the Hydrodynamic Testing of Seaplane Models

By

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A SURVEY OF SCALE EFFECTS ON THE HYDRODYNAMIC TESTING OF SEAPLANE MODELS

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SUMMARY

A general survey is made of all the factors where true dynamic similarity cannot be achieved in model tests of seaplane hulls and the likely effects on test results are discussed with reference to towing tank models and medium size research aircraft.

In resistance tests the correction for Reynolds Number effects requires more investigation and the artificial production of a turbulent boundary layer is the most likely means of achieving the required improvement in accuracy.

Pressure effects are likely to affect the break away of flow at small discontinuities such as extreme fairings with resultant errors in both stability and resistance test results. More accurate and systematic full scale data than at present available is needed before methods of allowing for this can be satisfactorily developed.

(21380)

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TABLE I

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1. INTRODUCTION

The well known practice of testing models of aircraft and ships has long been an accepted technique in research and development work. It serves the purpose of providing data on which theoretical analysis can be guided and checked and of answering immediate practical problems, where theory cannot be readily applied.

The success of model tests depends on the achievement of true dynamic similarity between model and full scale conditions, or when this is impossible, on making accurate corrections either during the tests or to the results obtained. There are generally several parameters where the correct scale value cannot be achieved and the purpose of this report is to discuss these factors in connection with the hydrodynamic testing of seaplane hulls and floats, both with reference to model tank tests and to the use of small aircraft to provide data for the design and development of larger ones.

A considerable amount of work has been done on this subject in the past, but a further review appears to be necessary because the changes now taking place in the design of seaplanes have altered the relative importance of different factors. For example the fairing of steps to reduce air drag has increased the importance of factors affecting the separation of flow at relatively small step discontinuities.

Current British seaplane research is limited mainly to model scale work and this survey is intended to form a guide to the further development of model testing techniques and to indicate the items most requiring attention when further full scale or medium scale work is planned. (Medium scale refers to sizes such as would be used for a special research aircraft).

2. DYNAMIC SIMILARITY

Table I gives two sets of scaling factors applicable to hydrodynamic tests of seaplane hulls and floats, which give the conditions of dynamic similarity, the first based on the assumption that gravity is an important factor i.e. that the Froude number, V^2/gb ($= C_V^2$) is maintained constant and the second ignoring gravity but introducing an arbitary velocity scale.(z). The second system is used for testing in the high speed planing region, where experimental evidence show the forces and flow conditions (excluding spray formation) to be independent of Froude number, and the scale of velocity is dictated by the maximum testing speeds obtainable with the apparatus available. (This system is not generally applicable to stability tests where complete models with wing and tailplane are used as the lift conditions will not be correct).

The second system is also applicable where two aircraft of different sizes are Involved, such as a medium scale research aircraft and a full scale project. In such cases the aerodynamic characteristics can very rarely be made to correspond exactly, and the relation between total lift and forward speed will not generally be that required for true hydrodynamic correspondence. In this case, the scale of velocity (z) will be estimated from representative velocities such as the unstick speed (assuming the same attitude at both scales).

In both systems, the factor of density is fixed by the necessity of using water and air as the two fluids in the test set up (no towing tank where this does not apply is known to exist), In both systems, the conditions already referred to above effectively control the scales of all other parameters if truly similar conditions are to be achieved. Examination of Table I will show that some factors are also governed by immediate practical conditions and the optimum scales are not achieved, e.g. atmospheric pressure, kinematic viscosity, surface tension, and, in some cases, radius of gyration.

In the remainder of this report the first scaling system is used, but the second can be applied with only small changes to the formulae.

3. REYNOLDS NUMBER

As is well known, dimensional analysis of the factors governing the flow of a viscous fluid show that for similarity of conditions the Reynolds Number ($RN = \frac{VL}{\nu}$) must be constant. From Table I it is seen that V is proportional n3 and L is proportional to n. Hence if Reynolds Number be constant ν must be proportional to $n^{3/2}$ but where the same fluid is used at all scales ν is constant and hence Reynolds Number is proportional to $n^{3/2}$ in actual tests.

3.1. REYNOLDS Number effect on skin friction forces

The usual approach to this problem in resistance tests on both seaplanes and ship models is based on the formula

$$D_t' = (D_t - D_f)\, n^3 + D_f' \qquad (a)$$

where n = the ratio of linear dimensions at two scales

D_t = total drag } at one scale
D_f = friction drag }

D_t' = total drag } at the second scale
D_f' = friction drag }

i.e., the pressure drag (total drag - friction drag) is scaled up simply, but the actual value of the friction drag at each scale must be calculated independently by the relation

$$\left.\begin{aligned} D_f &= \tfrac{1}{2}\rho v^2 C_f\, S \\ D_f' &= \tfrac{1}{2}\rho v'^2 C_f'\, S' \end{aligned}\right\} \qquad (b)$$

where v = mean velocity over the wetted surface

C_f = the appropriate total skin friction coefficient

S = the wetted area.

This approach has been adopted in ship testing in the last few years, and is found to be relatively accurate but has not been widely applied in seaplane tests until recently (Reference 1) for the following practical reasons.

3.1.1. Wetted Areas

One reason is the difficulty of measuring the wetted area accurately. At one time this was virtually impossible, but the use of the water flow indicator (Reference 2) enables the wetted areas and the relative areas of laminar and turbulent flow to be indicated readily though testing becomes somewhat laborious.

An underwater photographic method is used quite successfully in the N.A.C.A. tank at Langley Field, but this does not give any data on the state of turbulence. Where the nature of the boundary layer is reliably known, the photographic method gives all the required data and is much less laborious and time consuming than the R.A.E. indicator method,

Where S is measured satisfactorily, it is, of course, converted from one scale to another in the ratio of n^2.

3.1.2. Mean Velocity

A further difficulty is the evaluation of v. It has been the practice to use the free stream velocity, both in evaluating the

Reynolds Number (Paragraph 3.1.3.) and in expression (b). It is, however, known that the pressures on the planing bottom are almost universally above atmospheric and it is therefore impossible for the **actual** velocity, at any point, to be as much as the free stream velocity.

An approximate mean velocity may be calculated as follows (Reference 3.)

Let p = mean pressure on the wetted surface minus atmospheric pressure

v = mean velocity at the wetted surface

VP free stream velocity

Δ 3 load on water

S = wetted area

β = deadrise angle

a = forebody keel angle relative to undisturbed water surface.

From Bernouilli

$$p + \tfrac{1}{2}\rho v^2 = \tfrac{1}{2}\rho V^2$$

$$p = \frac{A}{S \cos \beta \cos a}$$

whence the mean velocity $v \left\{ = V^2 - \frac{2\Delta}{(S \cos \beta \cos a)\rho} \right\}^{\frac{1}{2}}$ (c)

This is easy to evaluate for a simple vee bottom and a reasonable estimate should be possible for the more complex case of a warped forebody and wetted afterbody, provided the geometry of the wetted areas is measured reasonably accurately, expression (c) being replaced by

$$v = \left\{ V^2 - \frac{2\Delta}{\Sigma(\delta S \cos \beta' \cos a')\rho} \right\}^{\frac{1}{2}} \qquad (c')$$

where β' and a' are local values and δS an elementary wetted area.

For this purpose, the wetted area required does not include the spray region, as the pressure in this is not appreciably different from atmospheric, and its contribution to drag is doubtful, The importance of this correction is greatest at high attitudes where the drag is large and hence its measurement most important. Brief calculations based on the data of Reference 1 show that v/V may be of the order of 80 to 85% in some cases and, as expression (b) involves v^2, errors of up to 35% arise if the correction is, ignored. To convert to any other scale, the value of v is scaled up as to n^2 i.e. $\frac{1}{2}\rho v^2 S$ is scaled up as n^3 and therefore

$$\frac{D_f'}{D_f} \underset{v}{=} n^3 \frac{C_f'}{C_f} \qquad (d)$$

It is, however, necessary to evaluate $\frac{1}{2}\rho v^2 SC_f$ to permit the values of D_f and $(D_t - D_f)$ to be found.

The use of a mean velocity is by no means accurate, as the pressure distribution on the planing bottom varies very appreciably from the stagnation line (where the velocity will be a minimum), to the trailing edge where the velocity will be nearly equal to the free stream velocity in many cases. It is, however, considered impracticable and of little value to attempt to estimate the velocity distribution more accurately as its effect on the boundary layer conditions are not sufficiently understood to enable more detailed information to be applied.

3.1.3. Skin Friction Coefficient

The major factor affecting the accuracy of expression (b) is the accuracy with which the akin friction coefficient, Cf, is known for each scale. Much work has been done on the relationship between Cf and Reynolds Number for both laminar and turbulent flow, the former having been extensively analysed theoretically, and the latter, which does not lend itself to mathematical treatment very readily, has been the subject of many experimental investigations and the empirical results obtained are widely used. (Figure 1).

Recent work at N.P.L. (Reference 4) in which the actual drag of flat plates and pontoons has been measured, shows the relation between turbulent skin friction and Reynolds Number to be more complex than is suggested by the Schoenherr line which is very widely used in ship tank testing techniques.

The principal difference suggested by the N.P.L. work is that there is an effect due to the length/beam ratio of the wetted area of the model, though the origin of this is not explored. This influence has also been confirmed by the work in Reference 5 where the C_f values were obtained by the pitot traverse method in the boundary layer near the side of the model and in the wake behind the model (Reference 6).

For the seaplane planing bottom the problem is far too complex to attempt to apply the corrections for variation of length/beam ratio owing to the fact that the available data is based on rectangular wetted areas which have no resemblance to the seaplane case. The use of the Schoenherr line would appear to be quite justifiable to obtain answers within reasonable limits and it is in fact the present day basis of extrapolation used in ship tests, while improvements in the accuracy of seaplane resistance measurements to that at present achieved in ship tanks would be a very considerable step forward from the present position, Reference 7, which is the full scale/model scale correlation over a large range of scales obtained on a special ship, the "Lucy Ashton", is a good example of contemporary ship work.

On the assumption that the Schoenherr line for turbulent flow and the Blasius line for laminar flow are sufficiently accurate for use, the problem then arises of the position of transition from laminar to turbulent flow and the selection of the correct Cf value between the laminar and turbulent values. The size of model used in the R.&E. towing tank generally gives results in the region of Reynolds Numbers between 10^5 and 5×10^6 in which region transition almost always occurs in such a way that appreciable areas of both laminar end turbulent flow exist, (assuming the smooth model surface generally obtained with phenoglaze is used), (Reference 1).

In Reference 1, where the current British technique is outlined, it has been assumed that a Reynolds Number on which accurate comparisons with the flat plate data may be based, is obtained by measuring a mean wetted length (weighted for area) parallel to the keel. The free stream velocity V is used instead of the mean velocity v (expressions c and c'), and it has been assumed that the point of transition in any stream line bears a simple relation to the Reynolds Number, i.e. a C_f/RN line was drawn (Figure 1) between the laminar and turbulent lines to cover the transition region. It is, however, well known that the point of transition in any boundary layer system depends on several factors besides Reynolds Number, the principal ones being surface roughness and local pressure gradient, while others suoh as mean pressure may have secondary effects.

The surface obtained on most models is very smooth, and it is not likely that such roughness as does exist, has any serious effect.

The pressure gradient has, however, a considerable effect and in aerofoil work it is found that, with a smooth surface and reasonable nose radius, transition very rarely occurs in the area of high negative pressure gradient immediately behind the leading edge, but is very rapid where the positive pressure gradient occurs.

In the case of the seaplane planing bottom, most of the water enters the boundary layer at the stagnation line, where the maximum pressure occurs, and flows entirely in a negative pressure gradient while in the boundary laye, layer, until it eventually leaves the system at the step or chine. The magnitude of the pressure Gradient varies considerably with the attitude and speed of the model, and so its effect on the Reynolds Number at which transition occurs will vary considerably from one test to another,

The use in Reference 1 of a simple line for the C_f/RN relationship in the transition region suggests that such a simple line exists but it should be remembered that practically all the tests leading to this were done at one attitude only on a simple vee wedge. More exhaustive tests carried out in the R.A.E. tank on simple wedges, though not published, show this to be impracticable, These results have, however, only been plotted with Reynolds Numbers and Cf values calculated from the mean wetted length and free stream velocity. A *re-analysis* of these points with the corrections referred to above, may give more consistent results, but this is not considered likely as the scatter is so large.

A further source of error is that the direction of flow is not in fact parallel to the keel. A recent brief test (not previously reported), with silk tufts on a perspex model, in which the direction of flow was noted visually by the position of the tufts, showed that the flow was in fact, inclined at an angle away from the keel, the angle being of' a similar order to the keel attitude of the model. This is also shown in Figure 5 of Reference 8, though it is not commented on by the authors,

A selection of illustrations of earlier vee wedge results using turbulence indicator methods (Reference 2) are reproduced in Figure 2. In these the black areas show the wetted edges, stagnation lines and regions of turbulent flow while white areas are regions of laminar flow (or the unwetted region ahead of the wetted edge). Examination of these examples shows that laminar flow persists at the keel over the whole wetted length *in* nearly all cases, where turbulence is not artificially enforced, and in one case, laminar flow appears to have been re-established behind a region of enforced turbulent flow. It is concluded from these observations that fresh water (water not previously affected by boundary layer conditions), enters the boundary layer at the keel of the model along its whole length behind the stagnation line and produces a laminar flow area along each side of the keel. This effect till, of course, be greater at higher attitudes and. will acquire more importance where long wetted lengths are involved, unless the boundary layer conditions are controlled by some means.

Analysis of the conditions controlling the relative areas of laminar and turbulent flow would require a detailed knowledge of the direction of flow, the effect of pressure gradients and the rate of spread of turbulence *across* the streamlines.

It is considered that the analysis of this problem is too complex to be practicable and the obvious solution is that used in many ship tanks *in* recent years, i.e. to produce turbulence over the whole of the wetted area so that reference may always be made to one C_f/RN line,

In the corresponding full scale case some areas of laminar flow will exist at the stagnation line and at the keel, but owing to the relatively large Reynolds Numbers transition will be almost immediate, and practically the w-hole wetted area will be covered by turbulent flow.

In ship tank pmctice, turbulence-is often produced by means of a thin wire stretched around the ship near to the bow, but this cannot be used on seaplane models due to the movement of the forward wetted edge and hence the necessity of re-psitioning the wire for every test.

A technique in use by the Stevens Institute of Technology (Hoboken, New Jersey) is to tow thin struts in the water ahead of the model, so that the eddying and turbulent wake of the strut provides the water from which the model boundary layer is formed and turbulence is assured, This method is, however, open to some question, as energy is being provided to the boundary layer of the model by means of the strut, and not as a result of friction at the model surface, hence the relationship between Reynolds Number and the total skin friction may not be exactly the same as when transition is produced in the boundary layer itself. Another possible small error from this method is that the strut will impart some forward velocity to the water near the model (with a corresponding rearward velocity at each side).

In the N.A.C.A. towing tank at Langley Field, no steps are taken to produce turbulence, but the flow is often found to be turbulent, even when very smooth models are tested at relatively low Reynolds Numbers (Reference 8). The reason for this is not known here, but it may be connected with the short time between tests (this tank is noted for a rapid running routine), or small amplitude, relatively high frequency, vibration of the model supporting structure. This is seen in Figure 3 of Reference 8, to be of a type where minor vibrations would be difficult to prevent.

The method which would appear most practicable for use in the R.A.E. tank is similar to the ship method in that the turbulence producer is secured to the model and not towed in front of it. As the flow is in general backward and outward from the keel, a line of a suitable rough material placed along the keel and a short distance on either side suggests itself. Whilst the flow outward from the keel does not cover the complete planing bottom, turbulence spreads sideways across the streamlines and it is likely that practically the whole wetted surface aft of the stagnation line could be made turbulent in this manner.

It may prove necessary to add a further strip of turbulence producer, parallel to the keel, part way towards the chine, which would stimulate turbulence in any areas not affected by the keel strip, and would also ensure turbulence in the spray area. The exact nature of the roughness and its orientation will require some development work in the tank, but it is felt that a simple method which is easy to apply should not be difficult to find.

3.2. Reynolds Number effect on spray

Considerable importance is generally attached to the shape of spray formation of a seaplane, as it is essential to avoid serious damage to propellers, wings, tailplane etc., and to avoid any large amount of water being taken into engine air intakes. Tests to investigate this spray formation are normally carried out on the longitudinal stability models by photographing the actual spray and measuring up the photographs by reference to a grid painted on the side of the model.

There is a considerable difference in the appearance of the spray between model tests and full scale aircraft. In the model case, the blister spray is normally an unbroken sheet of water while the forward spray sometimes tends to break up into relatively large drops. The corresponding full scale case generally consists almost entirely of drops much smaller relatively speaking than any drops occuring in the model tests.

The local Reynolds Number in the flow area from which the spray originates (based on a representative distance between the keel and the chine and a velocity of the same order as the free stream velocity) is of the order of 3×10^6 or less in model tests, and results in mainly laminar flow regardless of the pressure gradient. The corresponding Reynolds Number for an aircraft of only 10,000 lb. weight is of the order of 10^8 at which value turbulent flow invariably results. The spray is a relatively thin sheet of water and probably consists almost entirely of water originating from the boundary layer in contact with the planing surface. It is therefore likely to break up into small drops much more readily when this boundary layer is turbulent than on the model scale where it is assumed to be laminar. It is often considered that the difference between full scale and model scale spray form is due to surface tension, but the effect of surface tension is such that any element of water takes up a shape in which it has the minimum surface area. This would tend to retain the water in a sheet when this sheet is thick (i.e. in the full scale case), and to break up into drops when the sheet is thin (model case).

It is noted in Reference 3 that production of very slight turbulence (by means of a thin strut ahead of the model), transformed the spray and wake from a typical model from the normal model condition to give a very striking resemblance to the full scale case.

A brief reference is made in the Appendix of Reference 9 to tests done in the Stevens Institute tank, where a wetting agent was added to the water to reduce the surface tension to about $\frac{1}{3}$ of the normal value. This again transformed the spray to give the appearance of full scale conditions. No further details of these tests can be traced and it is possible that other influences were involved and the validity of either of these two cases cannot be established without more data than is available.

The effects on the spray envelope of this difference between model and full scale are in general found to be unimportant as the overall form is practically the same in each case. One possible effect of the state of turbulence on the spray formation would occur if the chines were appreciably round, as it is likely that turbulence would reduce tne effect of surface tension in causing the flow to stick round the curve, so tests at model scale where turbulent flow exists would give a closer resemblance to the full scale case than otherwise. This is discussed later (Paragraph 5).

In all configurations of conventional seaplanes on which data is available, the chines in the area affecting spray formation are relatively sharp and no scale effect on sticking has yet been noted. It is, however, important that the chines of a model should be as sharp as possible even though the exact scaled down radius of curvature from the full scale case may be impossible to achieve. The desired effect is often achieved by the addition of thin metal strips projecting very slightly through the chine, at an angle of between 100° and 120° to the model planing bottom.

4. ATMOSPHERIC PRESSURE

It will be noted from Table I that pressures are soaled in the ratio of (n) for true dynamic similarity, but of necessity, atmospheric pressure is nearly constant and, as all known towing tanks are open to the atmosphere, model tests have to be carried out at atmospheric pressure. The principal effect of this will be in the behaviour of water flowing round any curved surface to which it is adhering as a result of suctions. The magnitude of suction required to cause this adherence may be such that at model scale the pressure will be reduced below atmospheric by a moderate amount, whereas to obtain the same effect at a larger scale the scaled up suction would require to be more than one atmosphere which is clearly impossible. The result is that where the flow breaks away at the large scale, sticking may occur in model tests with quite drastic effects on the resulting flow pattern down-stream from the point in question, as well as on the force over the particular area.

Even if the absolute pressure does not fall to zero, cavitation will occur if it approaches the vapour pressure of the water and again the full suction will not be achieved and break away will probably occur. Cavitation will occasionally occur in model tests and is believed to do so where hydrofoils are concerned, but ii is not common on conventional seaplanes, and in any case the pressure at which it occurs will be the same at all stiles, and not at the correctly scaled value. These effects are most likely to occur in tests on conventional seaplanes where there is flow past a highly faired step and where the water tends to flow up the side of the aircraft or round the counter during yawing tests, (directional stability work),

The sticking at model scale may be prevented by placing "breaker strips" (Reference 2) *cross the direction of flow in the ares. concerned, These are thin wedge shaped strips placed so that the water flows up a gradual slope and then leaves the strip in a way resembling that over a very shallow step. The flow is thus held a short distance from the original surface and air is allowed to enter the gap and destroy suctions which would have resulted in sticking. Model tests can, therefore, give two extreme cases i.e. where the maximum sticking occurs and where no sticking occurs. It is, however, not impossible for sticking to affect the flow seriously at full scale, particularly where the step is highly faired and also in yawing tests (Reference 10 is an example where this is believed to be the case).

The problem now resolves itself into one of establishing the degree of sticking which is likely to occur at full scale, and attempting to interpolate between the two extreme cases available in the model tank. No exact method of doing this has been suggested, and the judgement of the operator in placing the breaker strips for tank test is a controlling factor.

It would appear on first examination that model testing should be done with no breaker strips, presenting the most pessimistic case (sticking is very rarely advantageous) and so ensuring that a full scale aircraft would be better, but this would often result in quite acceptable fairings being abandoned with resultant loss from the aerodynamic point of view.

5. SURFACE TENSION

Any assessment of the effects of surface tension is made difficult by the fact that as *far* as can be found no serious theoretical or experimental work has been done on the effects of surface tension, in connection with the motion of a body at or near the free surface of a liquid, Dimensional analysis of the parameters affecting flow where surface tension is assumed to be significant, results in the conclusion that, for exactly equivalent conditions, as well as Reynolds Number and Froude Number requiring to be kept constant, the surface tension num$\frac{\gamma}{\rho L v^2}$ (where γ is the surface tension having the dimensions of force per unit length) should be constant. To achieve this the value of the surface tension requires to be reduced for the model scale in the proportion of n^2, but as the same fluid is used at both scales, the same surface tension is constant.

An attempt has been made to reduce the surface tension in a towing tank and very brief reference is made to this in Reference 9. In this case a reduction of $\frac{1}{3}$ was made, but for a model scale of 1/20 a reduction of 1 to 400 is required. As these tests were limited to a value of $\frac{1}{3}$ it is assumed that further reduction was not practicable and it suggests that a method of reducing surface tension to the correct value would be very difficult to find.

Any scale effects which result from surface tension may also be influenced by the Reynolds Number effects, as it is difficult to believe that surface tension would have as much influence where the flow is turbulent, as where it is laminar. Unless, therefore, model tests are made with turbulence producers fitted, surface tension may have some influence apart from the possible effect on spray form (referred to in Paragraph 3.2.). There is no definite evidence of any serious effects occuring in seaplane or ship tanks, but it is possible, however, that, with step fairings having small angles of discontinuity, surface tension may prevent break away at model scale, where its influence would be negligible at full scale. The significance of this is not yet known because the refined fairings now considered practicable for seaplanes have not received much attention in past model tank work.

The work most relevant to this is that carried out full scale on a Sunderland V with a faired ventilated step and reported in Reference 11. It is also planned to test a scale model of this aircraft in the R.A.E. towing tank for stability and spray characteristics. This Will give an indication of any difference between model and full scale governing the break away at a refined step though it will not, of course, yield positive evidence as to whether such differences as may occur are due to surface tension. It is very unlikely that surface tension would produce any effects of consequence at any scale likely to be used for actual flying aircraft.

6. DISCUSSION OF STABILITY TESTS

The stability of a seaplane is dependent on whether or not all forces and moments acting on it in any particular condition form a stable system. The individual forces and the manner of their variation are not evaluated in the course of a stability test, though some of them are measured during resistance testing. It is, therefore, necessary that all relevant factors are correctly represented during the test as no correction to the conclusions is possible.

6.1. Model

All parts of the model affecting stability are easily made accurately geometrically similar at any scale (see Reference 2 for constructional methods) and the all up weight is adjusted to the correct scale value. Some difficulty is experienced in obtaining the correct radius of gyration in wooden models, but a recent investigation (Reference 12) has shown such errors as do occur to be unimportant.

6.2. The Aerodynamic Forces

The aerodynamic forces and moments are carefully measured and adjusted before stability testing is commenced. It is not necessary in anv particular test for the wing and tail to be identical to the full scale project, provided their lift and pitching moment characteristics are correct. This generally results in the use of leading edge slats etc., as the model scale Reynolds Numbers am very low compared with full sale. No difficulty is however generally encountered in producing a reasonably good representation of full scale conditions (Reference 2).

6.3. Planing Forces

No knowledge of any scale effects directly affecting the planing forces on a seaplane bottom exists except where the shape of the water surface is involved. This occurs in connection with afterbody planing if scale effects produce sticking on a step fairing so affecting the flow down-stream (see Paragraph 4). In an extreme case, this can result in a complete failure to break away model scale which does not occur at full scale, Break away can be enforced by the use of a small breaker strip or an artificial increase of the step size, but the question of whether or not break away will occur at full scale must first be established, and it does not appear that this can be done satisfactorily by tank tests alone.

Some full scale work has been done on extreme step fairings, the latest being reported in Reference 11, but the corresponding model has yet to be tested.

Tank tests have been done on the Princess flying boat (Reference 13), with a faired step and the full scale aircraft appears to have satisfactory stability characteristics in sheltered water operation, This result leads to the conclusion that with the step discontinuity used sticking occurs neither at model nor full scale. There is, however, no evidence that the effect would have been the same at both scales if the discontinuity had been reduced in severity. As far as is known, no other tank tests associated with the corresponding full scale tests have been completed with extreme fairings and the subject appears to require considerable investigation.

It is probable that final development of the step form and fairing may have to be carried out at much larger scale than towing tank models. If it is then found that the required discontinuity to produce break away is appreciably smaller at full scale than model scale, it will be necessary to test tank models with breaker strips at the step after the actual step design has been evolved from previous full scale knowledge.

6.4. Friction Forces

It has been pointed out earlier that friction forces are not in general correctly represented at model scale, but that subsequent corrections are possible where the forces themselves are the object of the test, This is, however, not possible in stability tests. The actual drag component of the friction forces becomes unimportant as the stability model is attached to the carriage of the tank, and its forward movement is controlled by the mass and power of the carriage, those being very much greater than the mass and power involved in the model. As the line of action of the friction forces is considerably below the C.G. of the model (at which point the model is pivoted), an error in the pitching moment results. If therefore the friction forces are not correctly represented due to the wrong skin friction coefficient the pitching moment and its manner of variation are not correctly represented. This will obviously affect both the trim curves and stability limits obtained in any test.

The trim curves themselves are often dismissed as of secondary importance, but they have considerable significance in assessing the acceptability of any stability limits, and also in the selection of the load on water and attitude ranges to be used for resistance tests on the appropriate model ofthesame aircraft. In some oases, where laminar and transitional flow cover appreciable proportions of the model wetted surface, the resultant total C_f value may be approximately equal to the corresponding full scale Cf value, as the turbulent Cf value at high Reynolds Number falls to the same order as the laminar flow value at much lower Reynolds Number. (Figure 1).

The only form of boundary layer control which appears to be practicable in model tests, is to make the whole boundary layer fully turbulent. This would result in C_f values very much higher than in the corresponding full scale case, and is obviously not applicable, but in general any C_f value below the fully turbulent case would require selective turbulence simulation over part of the wetted area, and the complexity of this would make its application to stability testing impracticable.

Simple calculations based on the data of Reference 1 show that an error of 50% in the value of Cf will give an error in the pitohing moment equivalent to movement of the C.G. by about 0.03 beams in the worst case, which occurs at or a little above the hump speed. Examination of Figure 1 suggests that errors of more than 50% in C_f are unlikely to occur and the effect on stability limits and trim curves is not likely to be serious,

6.5. Test Conditions

A further scale effect not referred to earlier is the difference between the completely calm no wind condition of the seaplane tank, and the actual water and wind conditions encountered at full scale. Even if perfectly calm conditions existed full scale the change of attitude of the aircraft during a take-off run results in its arriving at any particular point with some angular velocity which does not occurinthe carefully controlled tank tests or, if it is allowed to occur, the angular velocity is incorrect as the time history of the take-off is wrongly represented due to the rapid acceleration of the carriage.

The technique used in the N.A.C.A. towing tank is to test at constant speed with both increasing and decreasing attitudes produced by steady movement of the model elevator. Difficulties are obviously to be encountered in the selection of the rate of elevator movement and no further allowance for sea conditions can be made by this method.

Full scale conditions usually involve at least a small chop or swell on the water surface, and where open sea operation is contemplated, very large long swells are bound to be encountered. It is possible to test models with various wave systems in the towing tank, but this becomes extremely laborious and only particular cases of wave length and height may be tested, whereas infinite variations of these may be encountered in actual sea conditions.

The technique in the R.A.E. tank has been to subject the model to a considerable instantaneous nose down pitching moment. The difficulty however, is to establish the desirable magnitude of the disturbance. This is normally defined as the change in attitude produced at the instant of disturbance.

Reference 14 gives an account of some recent work on the subjeot done in connection with the high length/beam ratio models being tested in a current research programme. It is found in each case that an increase in the magnitude of disturbance has an increasing effect on the stability limits until a certain critical disturbance is reached. This disturbance is very large, but further increases of disturbance produced no further effect on stability whatever. The critical disturbance is however different at various conditions of speed, attitude, etc. The conclusion reached in Reference 13 is that standardisation between various model tests can only be achieved if this maximum critical disturbance is used in all cases. This would appear to be representative of the worst possible sea conditions, and it is believed to cover any combination of length and height of swell etc. The model test, however, is bound to be pessimistic in that it assumes no wind, whereas large swells are normally associated with at least a moderate wind which generally has a relieving effect, provided the short chop produced by the wind is not excessive.

Furthermore, the established technique of landing on water with a large swell is to alight along the crests so the worst conditions are avoided full scale.

6.6. Model Scale/Full Scale Data

Examples of model and full scale limits extracted from References 15, 16 and 17 are reproduced in Figures 3 and 4. In both these cases, the disturbances were limited to arbitrary values (in general less than the maximum critical values) and the full scale limits are obtained in relatively calm water.

The deterioration of model stability with disturbance is clearly seen, and Figure 3 shows that a 5^o disturbance affects the whole of both upper and lower limits, whereas an increase to 7^o produces further deterioration in one region only, and negligible effect elsewhere. On first examination, none of the model stability limits show any direct connection with the corresponding full scale limits. A general difference in attitude of both limits is noted in the review of previous model and full scale tests in Reference 18, and occurs in every known case where comparison has been made. This difference in attitude affects both trim curves and stability limits, and in every case the attitudes are higher in the model tests. This maybe due to the error in pitching moments, due to skin friotion forces referred to above, and suggests that the C_f value in most model tests is lower than in the corresponding full scale case, though, as stated above, available data indicates this effect to be too small to produce the discrepancies shown. If an allowance is made for the difference in angle in examining Figures 3 and 4, the full scale limits would appear to fall between the undisturbed and disturbed cases.

The foregoing factors suggest that comparison between models may be made quite reliably from longitudinal stability limits, obtained either with or without applied disturbance, depending whether the full scale aircraft is required for sheltered water or open sea operation. This will permit the selection of the best of a series of models, but prediction of exact full scale stability characteristics is very difficult and much depends on the experience and judgement of the person making the assessment. It is somewhat unfortunate that of more recent seaplanes, with fazed steps, very few have been tested at both model and full scale. The current full scale tests on the Princess flying boat should help a great deal, as comprehensive model tests were carried out previously, but detailed investigation of any serious scale effects which are found, may prove impracticable. A special research aircraft used in conjunction with model tests, would, however, prove much more fruitful in this matter, as modifications could be made much more readily both model and full scale, and the necessary instrumentation for the plotting of wetted areas, pressures, forces etc., could be provided.

6.7. Directional Stability Tests

The remarks in sections 6.1 to 6.6 have referred to longitudinal stability tests but most of them are also relevant to directional stability tests with some change in relative importance.

The method of performing these tests is described in Reference 14 and differs in principle from longitudinal stability tests in that the model is not left free in yaw but is constrained and the sense of the yawing moment in any position is noted by the observer controlling the model.

Any errors in the moment of inertia in yaw, however large, are therefore of no consequence and the resultants of the various steady forces and moments are the only relevant factors.

The nature of the results of directional stability tests and observation of the associated flow conditions indicate that the major influence is that due to water sticking to the side of the after-body and the rear part of the fuselage which occurs in the higher speed range when the model is yawed a certain amount.

The preceding remarks in sections 4 and 6.3. arc relevant to this case, and suggest that the suctions which result are likely to be disproportionately large at model scales. The addition of breaker strips (Reference 14) to destroy these suctions results in the complete elimination of the corresponding instability. Another case is therefore encountered where two extremes may be tested in the model tank with the actual full scale use lying in between.

The scale effect described is, however, only important in relation to the magnitude of the yawing moments and, as any directional instability is unacceptable at the higher speeds, the angle of yaw at which the effect occurs is of major importance.

This angle of yaw must depend primarily on the shape of the trough left in the wake of the forebody and, provided tests are carried out at the correct Froude Number (or velocity coefficient), and no sticking occurs at the main step or forebody chine, it is unlikely to be affected by any scale effects.

A region of instability is found in the low speed or displacement range, but, as this is inherent in floating bodies at low speeds, and disappears before the higher speeds are reached, its exact limits are not Of great importance.

This low speed instability is caused almost entirely by the pressures acting on the forward part of the hull and these are unlikely to be influenced by any of the known scale effects mentioned above.

The interpretation of directional stability test results is difficult because no technique for performing directly equivalent full scale tests is available, and very little model work has been done previously. The principal value of the tests is in the comparison of different models and, provided this is limited to the angles at which stable and unstable equilibrium is encountered no serious scale effects are known to exist.

The development of appropriate full scale tests is desirable, but they would of necessity be very limited in scope compared with the model tests.

7. DISCUSSION OF RESISTANCE TESTS

In resistance testing the values of the forces and moments are the items of interest and the dynamic properties of the model are completely irrelevant. It is also immaterial whether the forces and moments conduce to stability or instability. In this case correction of the results for known scale effects is possible after completion of testing, provided the model and full scale conditions are accurately known.

7.1. Planing Forces

Most of the remarks in section 6.3, in connection with planing forces, apply equally well to resistance tests as to stability. The main conclusion is that planing forces are subject to scale effects only where flow conditions are affected by the question of whether or not break away occurs at any particular point. Such an effect will produce errors in the planing lift, pitching moment and drag (due mainly to change in wetted area). It may, therefore, be necessary to use breaker strips at the main step, or in equivalent positions where extreme fairings are used, if the suggested scale effect on break away is found to be of serious consequence.

7.2. Friction Forces

The principal scale effect found in resistance testing is due to the Reynolds Number effect on skin friction forces, and is discussed in detail in section 3.1, where the conclusion is reached that the stimulation of turbulence over the whole planing surface is the only practicable method whereby an exact knowledge of boundary layer conditions on the model can be achieved.

It is also necessary to know the corresponding full scale conditions as well. It is fairly well established that the flow conditions are virtually fully turbulent but surface irregularities on the planing bottom (plating joints, rivets, etc.) must also add to the total drag a little. A common practice in ship work is to add an increment of 0.0004 to the C_f value to be used. This is dealt with in Reference 7 where it is shown that 0.0004 is in general an over-estimate, but it is clear that an accurate correction requires much more full scale data than is at present available in either ship or seaplane work.

The usual practice of presenting test results in the form of non-dimensional parameters is convenient in many ways, but very misleading if it is not made clear at what scale the particular values are applicable, It is also necessary to permit change to any other scale to be made. For instance, the practice of indicating drag as $\frac{R}{\Delta}$ makes corrections for Reynolds Number impossible. It would seem more logical to separate the pressure and friction drag components at model scale and present them separately, i.e.

$$R = R_p + R_f \qquad (e)$$

where R_p = pressure drag

R_f = friction drag

The pressure drag can conveniently be presented as $\frac{R_p}{\Delta}$ but the friction drag cannot be so simply treated. One possible method of presentation is to indicate friction drag in the following form.

$$R_f' = \left\{ \frac{R_f}{b^y} \right\} b'^y \qquad (f)$$

where b = the model beam

b' = the full scale beam

and y = a constant

The model results would then be presented as plots of $\frac{R_f}{b^y}$

This is based on the method of scaling up suggested by Gruson in Reference 19, and again described in Reference 20. It is here assumed that the C_f/RN line for turbulent flow approximates to $C_f = k\,(RN)^x$ typical values of the constants giving $C_f = 0{,}072\,(RN)^{-0.2}$ for the range of Reynolds Numbers 10^5 to 5×10^7.

A comparison with the Schoenherr line over the range 10^5 to 10^{10} suggests that the constants should be approximately $0.042\,(RN)^{-0.16}$ though the comparison at the higher Reynolds Numbers is very much open to question, due to lack of data. If only model scales were concerned, the earlier set of values would be the best mean. (Figure 1).

We now have:

$$R_f = \tfrac{1}{2}\rho V^2 S\ C_f \qquad (g)$$

$$= \tfrac{1}{2}\rho V^2 S\ k\ (RN)^x$$

$$\frac{R_f}{R_{f'}} = \left\{\frac{\rho}{\rho'}\right\}\left\{\frac{V}{V'}\right\}^2\left\{\frac{S}{S'}\right\}\left\{\frac{RN}{RN'}\right\}^x$$

$$= n^{3 + {3}/{2}\ x} \qquad (h)$$

whence if x = -0.2

$$\frac{R_f}{R_{f'}} = n^{2.7}$$

or if x = -0.16

$$\frac{R_f}{R_{f'}} = n^{2.76}$$

The error in value of $\frac{R_f}{R_{f'}}$ due to the uncertainty in the value of x is rather large and more full scale data is required to find an appropriate value.

The value of 2.7 will be used hereafter as it is known to be reasonably accurate over the range where most data is available, expression (f) therefore becomes $R_{f'} = \left\{\frac{R_f}{b^{2.7}}\right\} b'^{2.7}$. The data which it is then necessary to present to permit scaling up to any scale include $\frac{R_p}{\Delta}$ and $\frac{R_f}{b^{2.7}}$

Corrections to pitching moment based on Reynolds Number are also required if great accuracy is needed. Good estimates can be made if the effective moment arm of the drag forces about the model C.G. can be estimated. This arm is relatively small and the correction should rarely be large.

Most of the scale effects previously mentioned will have some effects on the apparent lift of the planing surface, due to its inclination to the horizontal but, in general, these effects will be negligible, and no useful purpose will be served by discussing them in detail until most of the more important factors referred to above have been established by accurate model and full scale tests over considerable ranges.

All the foregoing remarks concerning pressures and forces indicate that correction for scale effects is relatively straightforward provided the model scale conditions are known with sufficient accuracy, and it is to this end that immediate work needs to be directed though accurate data at at least two widely different scales on a typical aircraft is required to verify some of the assumptions made.

Previous tests are of very little use in this matter as none of those of which the results are available in sufficient detail were performed with controlled boundary layer conditions. The most recent work on this is reported in Reference 21 which is an attempt to apply the method outlined. in Reference 1 to a small high speed flying boat. The results, while showing fair correlation over certain limited ranges have a scatter of up to ± 25% of the total drag when the whole range of tests is considered.

The need for a systematic model scale investigation in this subject is apparent, the main requirement being that all the variables requiring investigation are introduced and investigated individually. Firstly control of the boundary layer to give fully turbulent flow with negligible drag from the turbulence stimulator must be developed on models with no pressure effects present, The next step is to introduce typical pressure gradients to a flat model (with effectively all parallel flow) and finally to proceed to a typical vee wedge. The eventual application to actual seaplane models cannot be discussed profitably until the above work is done.

8. CONCLUSIONS

8.1. Longitudinal stability tests

The only scale effect likely to cause serious error when calm water stability is considered is that connected with the "sticking" of flow round corners such as occur at the step with extreme fairings etc. This scale effect is likely to arise from the incorrect scale atmospheric pressure and possibly fmm surface tension effects. Break away can be enforced at model scale but model tests will not show what will happen at full scale. Full scale data with extreme fairings is essential.

It is not practicable to do systematic rough water tests in the seaplane tank but the rough water stability of different models may be compared by the "maximum disturbance" technique. Prediction of full scale rough water stability from tank tests is almost impossible at present and much more full scale data is essential to permit model stability tests to be interpreted properly.

8.2. Directional stability tests

If the tests are limited to establishing the angles at which stable or unstable equilibrium occurs, large scale effect errors are not likely to arise. If the magnitudes of the yawing moments are required large errors are to be expected, mainly due to atmospheric pressure effects.

8.3. Resistance tests

The major scale effect in resistance tests is due to the Reynolds Number effect on skin friction. Accurate correction of test results requires:-

(a) an exact knowledge of the boundary layer conditions which can be best achieved by causing turbulent flow to exist over the whole wetted area,

(b) allowance for the difference between the mean velocity of flow at the model surface and the free stream velocity,

(c) allowance for deviation of the direction of flow from the normally assumed path (parallel to the keel) and the entry of fresh water into the boundary layer at the keel,

The conclusions relating to sticking during longitudinal stability tests (section 8.1.) also apply to resistance tests as the whole flow pattern on the afterbody is affected.

The present method of non-dimensional presentation of results while generally convenient. can be misleading where scale effects occur and needs further development from this point of view.

Medium and/or full scale data of high accuracy is needed in order to verify tho accuracy of model tests.

LIST OF SYMBOLS

n = scale of linear dimension

z = scale of velocity

b = beam of seaplane or model

v = mean velocity of flow

V = free stream velocity or velocity of seaplane or model

C_f = coefficient of skin friction

D_t = total drag

D_f = friction drag

D_t', D_f', etc. refer to a second scale

P = pressure

P_v = vapour pressure

L = a characteristic length

RN = Reynolds Number = $\frac{VL}{\nu}$

S = wetted area

a = keel attitude relative to the still water surface

β = deadrise angle

y = surface tension

ρ = density

ν = coefficient of Kinematic viscosity

a = the load on water

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TABLE I

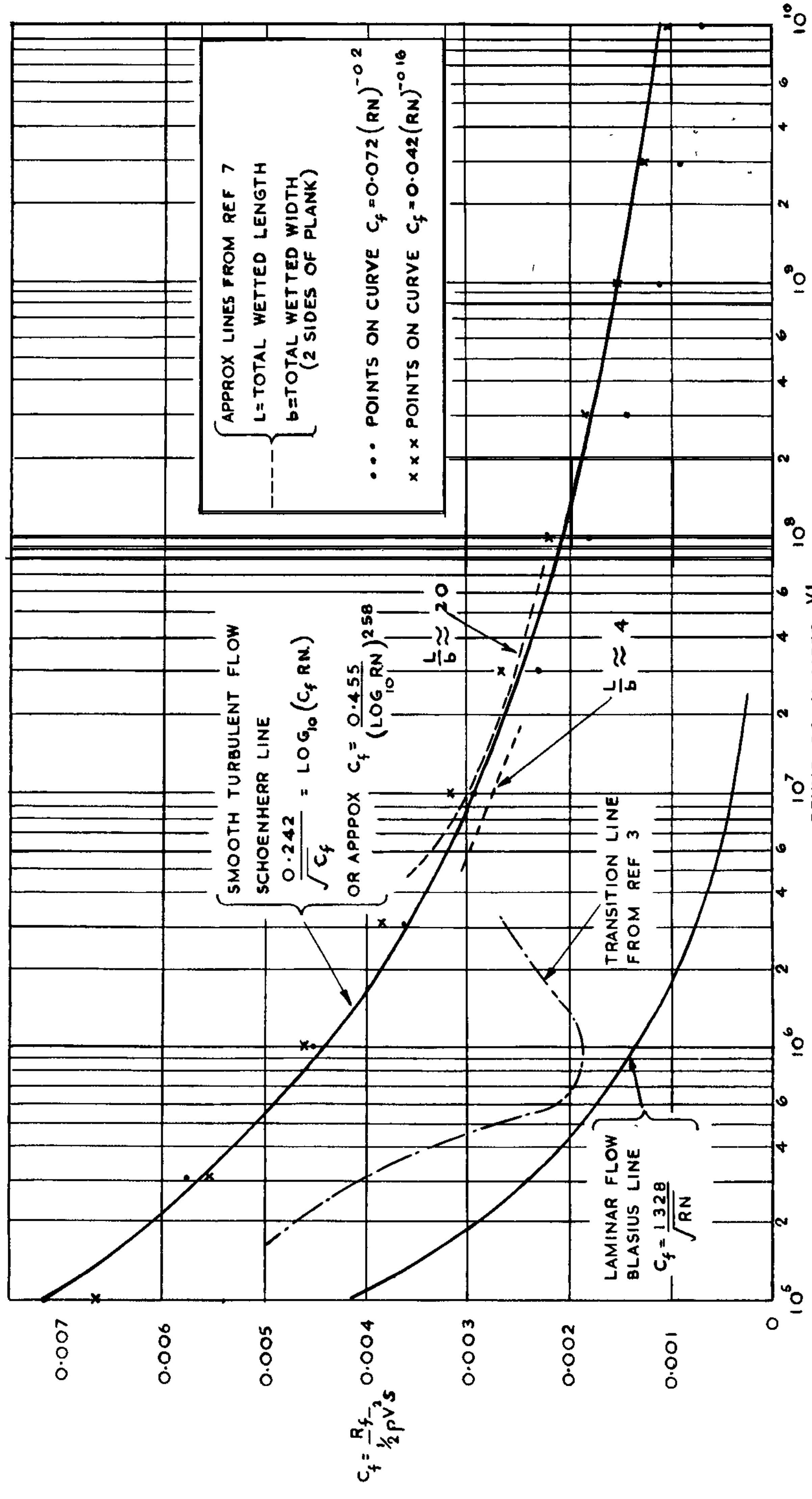
TABLE OF SCALING FACTORS FOR DYNAMIC SIMILARITY

Quantity	Dynamic similarity including "g"		Dynamic similarity neglecting "g"	
	Derivation of scale	Scaling factor	Derivation of scale	Scaling factor
Length (L)	Nominal scale	$1 : n$	Nominal scale	$1 : n$
Density (P)	To permit use of air and water in test system.	$1 : 1$	To permit use of air and water in test system,	$1 : 1$
Linear acceleration (A)	Correct value for "g"	$1 : 1$	$A \alpha \frac{V}{T}$	$1 : \frac{z^2}{n}$
Linear velocity (V)	$V \alpha \frac{L}{T}$	$1 : n^{\frac{1}{2}}$	Second. nominal scale	$1 : z$
Time (T)	$L \alpha AT^2$ $\therefore T \alpha \left(\frac{L}{A}\right)^{\frac{1}{2}}$	$1 : n^{\frac{1}{2}}$	$T \alpha \frac{L}{V}$	$1 : \frac{n}{z}$
Angular displacement (8)	$\theta \alpha \frac{L}{L}$	$1 : 1$	$\theta \alpha \frac{L}{L}$	$1 : 1$
Angular velocity ($\dot{\theta}$)	$\dot{\theta} \alpha \frac{\theta}{T}$	$1 : n^{-\frac{1}{2}}$	$\dot{\theta} \alpha \frac{\theta}{T}$	$1 : \frac{z}{n}$
Angular acceleration ($\ddot{\theta}$)	$\ddot{\theta} \alpha \frac{\theta}{T^2}$	$1 : n^{-1}$	$\ddot{\theta} \alpha \frac{\theta}{T^2}$	$1 : (\frac{z}{n})^2$
Mass (M)	$M \alpha \rho L^3$	$1 : n^3$	$M \alpha \rho L3$	$1 : n^3$
Weight (Wt)	$Wt \alpha Mg$	$1 : n^3$	$Wt \alpha MA$	$1 : n^2z^2$
Force (F)	$F \alpha MA$	$1 : n^3$	$F \alpha MA$	$1 : n^2z^2$
Pressure (P)	$P \alpha \frac{F}{L^2}$	$1 : n$	$P \alpha \frac{F}{L^2}$	$1 : z^2$
Kinematic viscosity (ν)	$\nu \alpha \frac{L^2}{T}$	$1 : n^{3/}$	$\nu \alpha \frac{L^2}{T}$	$1 : nz$
Power (HP)	$HP \alpha FV$	$1 : n^{7/}$	$HP \alpha FV$	$1 : n^2z^3$
Power loading (Total weight) (Total power)	$\alpha \frac{Wt}{HP}$	$L : n^{-\frac{1}{2}}$	$\alpha \frac{Wt}{HP}$	$1 : z^{-1}$

TABLE I (Contd.)

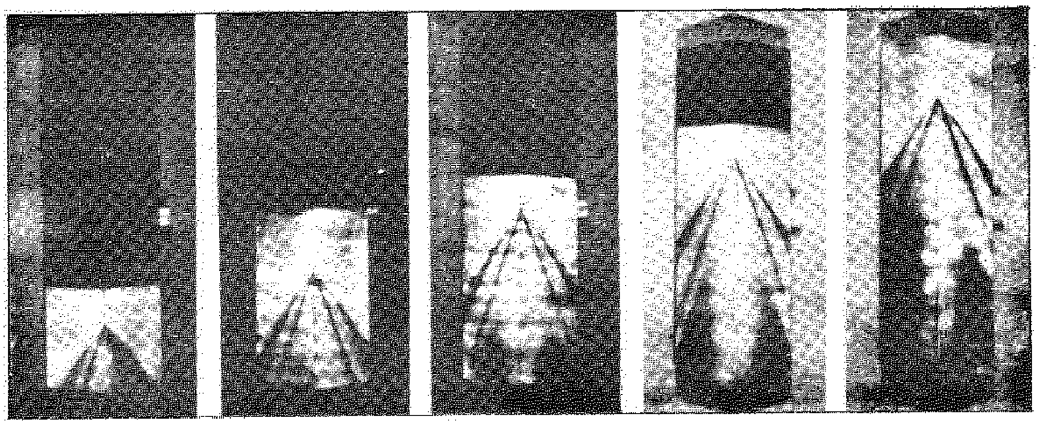
Quantity	Dynamic similarity including "g"		Dynamic similarity neglecting "g"	
	Derivation of scale	scaling factor	Derivation of scale	Scaling factor
Radius of gyration (k)	$k \alpha L$	1 : n	$k \alpha L$	1 : n
Moment of inertia (I)	$I \alpha k^2M$	$1 : n^5$	$I \alpha k^2M$	$1 : n^5$
Beam loading = $C_{\Delta_0} = \frac{wt}{wb^3}$	$= \frac{Wt}{\left(\frac{Wt}{L^3}\right) L^3}$	1 : 1		
Velocity coefficient = $C_V = \frac{V}{\sqrt{gb}}$	$= \frac{V}{\sqrt{AL}}$	1 : 1	-	-
Coefficient Of fluid friction $C_f = \frac{F}{\frac{1}{2} \rho V^2S}$	$C_f \alpha \frac{F}{\rho V^2L^2}$	1 : 1	$C_f \alpha \frac{F}{\rho V^2L^2}$	1 : 1
Surface tension	$\gamma \alpha \frac{F}{L}$	$1 : n^2$	$\gamma \alpha \frac{F}{L}$	$1 : nz^2$
Surface Tension No.	$\frac{\gamma}{\rho Lv^2}$	1 : 1	$\frac{\gamma}{\rho Lv^2}$	1 : 1
Reynolds Number	$\frac{VL}{\nu}$	1 : 1	$\frac{VL}{\nu}$	1 : 1
Froude Number	$\frac{V^2}{gb} = (C_V)^2$	1 : 1	-	-
Cavitation Number	$\frac{P - P_V}{\frac{1}{2} \rho v^2} = \frac{P}{P}$	1 : 1	$\frac{P - Pv}{\frac{1}{2} \rho v^2} = \frac{P}{P}$	1 : 1
wing loading	$\frac{F}{L^2}$	1 : n	$\frac{F}{L^2}$	$1 : z^2$

FIG. 1.

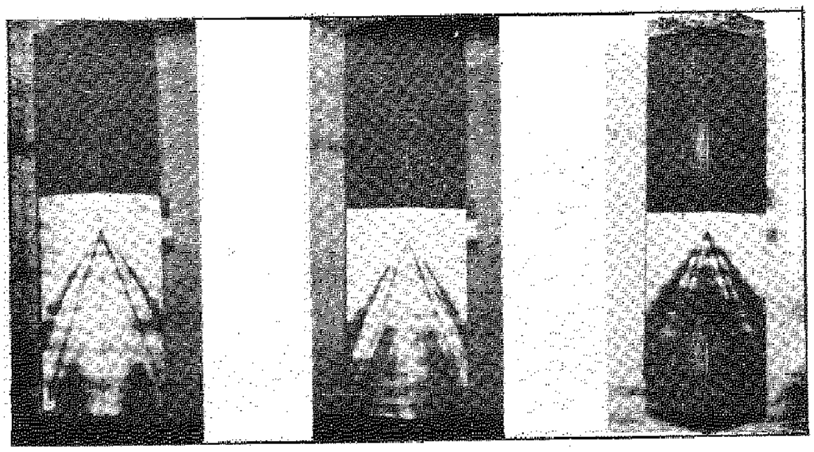


SKIN FRICTION COEFFICIENT / REYNOLDS NUMBER CURVES

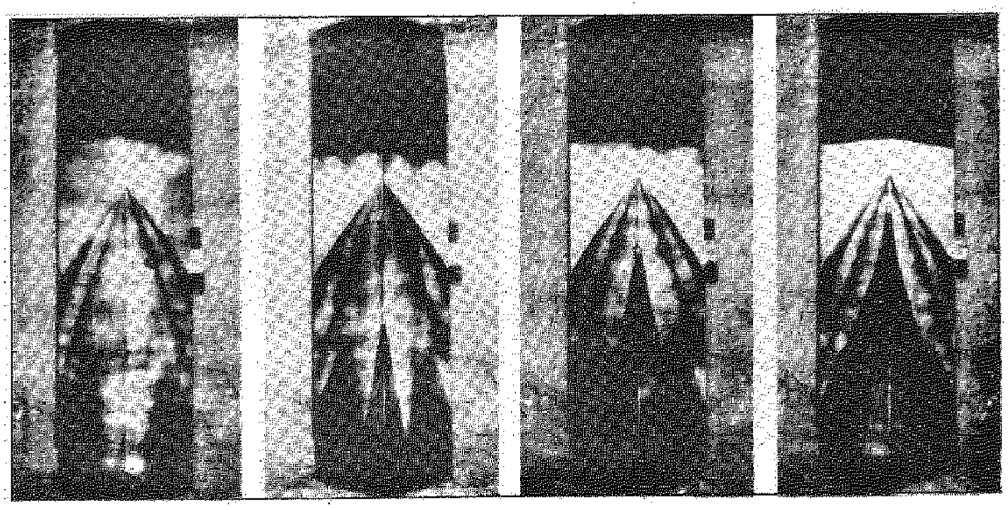
FIG. 2



EFFECT OF INCREASING REYNOLDS NUMBER AT CONSTANT SPEED. $\tau = 6^\circ$

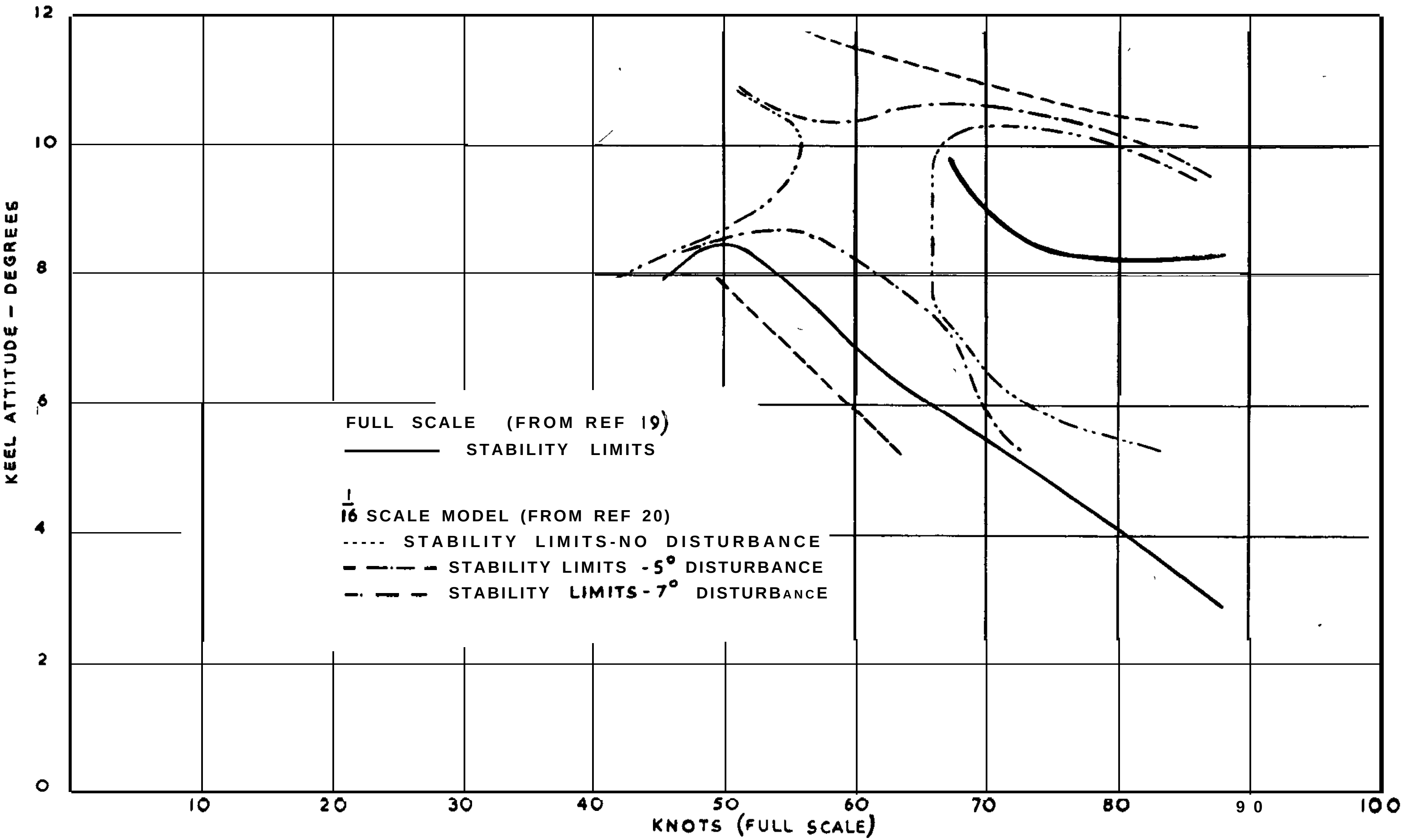


EFFECT OF INCREASING REYNOLDS NUMBER WITH CONSTANT WETTED LENGTH. $\tau = 6^\circ$



EFFECT OF A SMALL PROTRUBERANCE ON KEEL. $\tau = 6^\circ$
REYNOLDS NUMBER ON KEEL = $2 \cdot 65 \times 10^{-6}$

ILLUSTRATIONS OF FLOW CONDITIONS FROM PREVIOUS MODEL TESTS.

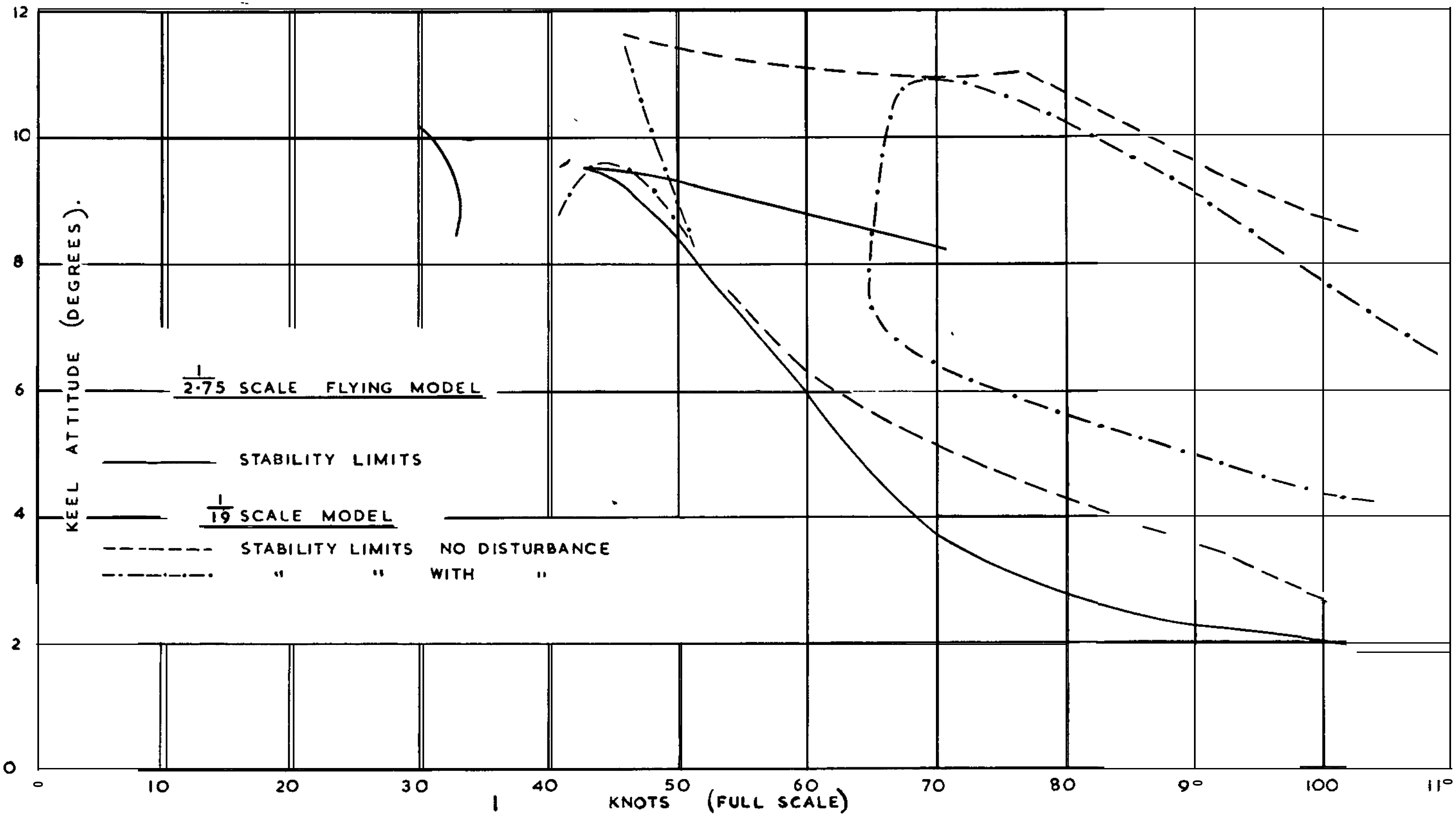


MODEL AND FULL SCALE STABILITY LIMITS FOR SEAFORD.I .

(TAKE OFF, ZERO FLAP)

FIG. 3.

F 16.4.



MODEL AND $\frac{1}{2\cdot75}$ SCALE STABILITY LIMITS FOR SHETLAND.
(TAKE OFF AT 130,000 LBS, ZERO FLAP)

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