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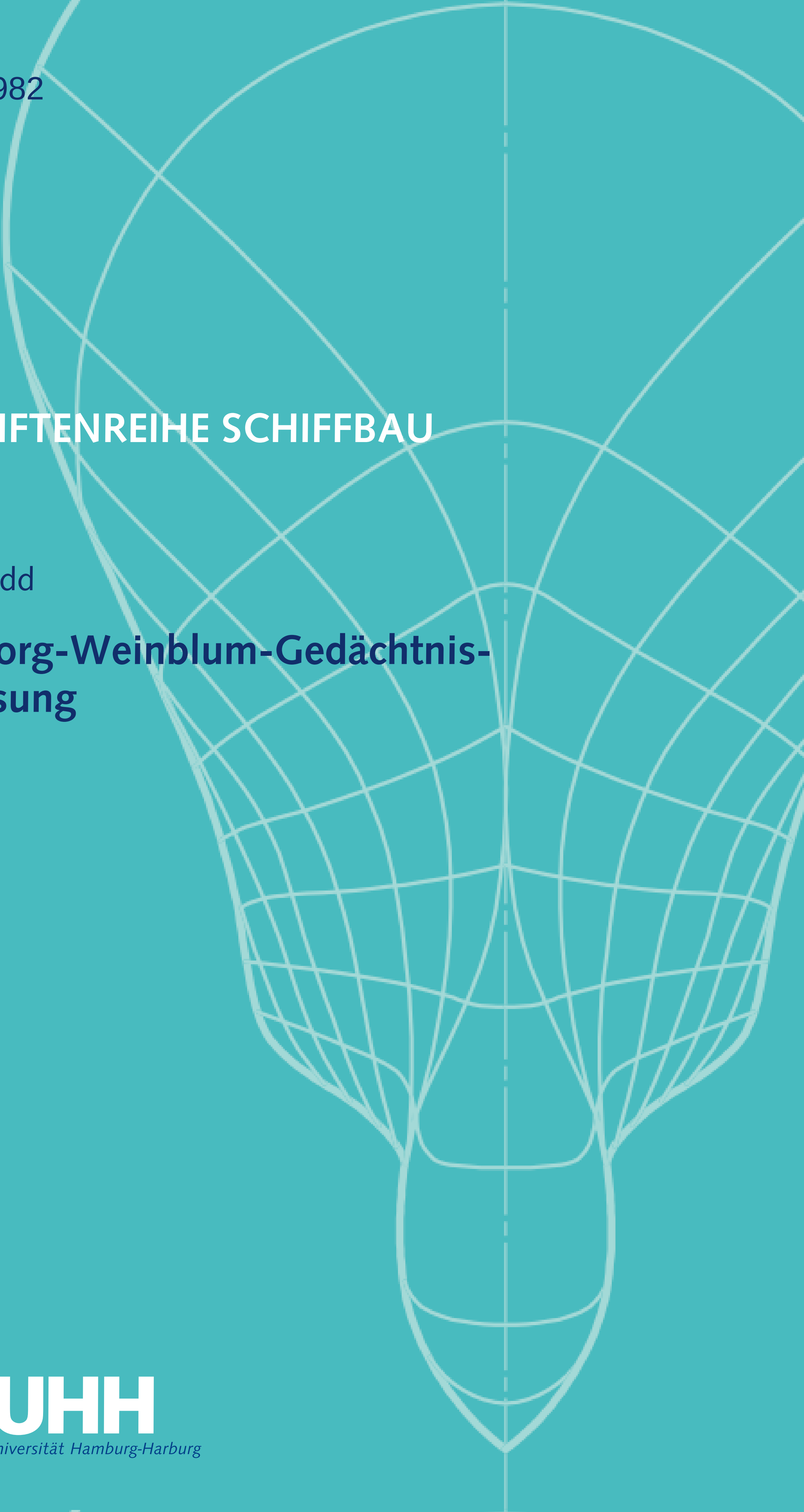

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V. Georg-Weinblum-Gedächtnis-Vorlesung

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Some Effects of Scale in Ship Model Testing -V. Georg-Weinblum-Gedächtnis-Vorlesung

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Fifth Weinblum Memorial Lecture

Some Effects of Scale in Ship Model Testing

by G E Gadd

This lecture is the fifth in the series in honour of the memory of Professor Georg Weinblum. I am sure my audience is well aware of the very great contributions to many aspects of ship science that he made, both directly in his own work and in the inspiration he gave to others. It is unnecessary therefore for me to say more of the public aspects of his career: instead I will make only a few personal remarks. The influence which Professor Weinblum had and continues to have was due not only to his scientific achievements but also to the warmth and kindness of his personality. As an example of this I cite the fact that the encouragement he gave over many years to the work of my countryman, Mr Wigley, by contributing to the discussion on most of his papers, did not stem simply from a cold professional interest - he was deeply affected by the news of Wigley's death, and on his next visit to London took pains to find the place where his ashes had been scattered, so that he could pay his last respects to his old friend. Even in my very limited personal acquaintance with him, during my first term of serving as Secretary of the ITTC Resistance Committee, I experienced something of this warmth. Although he was not still officially a member of the Committee, Admiral Brard so valued his advice that he wanted him to be invited along to our meetings as an honourary member. He played an active part at our meeting in Paris in February 1973. Sadly it was to be the last such meeting he attended. I had invited him to the London meeting of the following year, but only 10 days before he died he wrote me a letter regretting that his state of health would prevent him from attending. The last sentence of this letter was "Have a good time and try to promote science!" It is a good motto for all who are engaged in ship research.

My subject today is "Some Effects of Scale in Ship Model Testing". Everyone knows of course that a ship model tested at the correct Froude number must necessarily be at a far lower Reynolds number than the full scale ship, and that the most important scale effects are due to this difference. However it is not the Reynolds number difference which causes the most obvious difference in appearance between the flows round a ship and its model. I refer to the far greater extent of white water that can be seen on the full scale, even when the sea is very calm. Those of us who test ship models must sometimes wonder, when we compare photographs of model and ship, whether or not this difference matters, but our doubts are usually pacified by the reflection that prediction methods based on the assumption that it doesn't matter do work tolerably well. The foam which is such an obvious visible feature of the flow round the ship must, we feel, be of only minor importance in the total energy balance.

There are however situations where foam or spray is of direct concern, not because of any contribution it may make to resistance, but because, as stated in Saunders' book[1] "Hydrodynamics in Ship Design", "it can be most objectionable as a means of obscuring vision, wetting decks under certain wind conditions, and forming ice in freezing, windy weather". He was referring to "bow feather", the spray thrown up at a bow which is not sharp. We recently carried out tests at NMI to investigate what scale effects might be present in such a case. Two models, one 7m long and the other 1.1m long, were constructed to the shape shown in fig 1. They were intended to run with either the 10° half angle or the 20° half angle end forward. The ends of the smaller model were cut off square to a width of 5mm, corresponding to a 32mm width blunting on the larger model. The latter had in addition detachable end pieces to make the two ends sharp, as shown in fig 1. A grid of lines was marked on both models with a spacing of 20mm in the smaller case and the corresponding spacing of 126mm in the larger case. Thus if the flow patterns had been the same at the two scales, photographs of the two models from a similar viewpoint would have appeared the same.

In fact this was very far from the case. With the large model run at 4 m/s a great deal of spray was created by the square cut-off bow, especially with the 10° half angle end forward. The smaller model at the Froude scaled speed of 1.6 m/s generated no spray at all, though a film of water did climb up the forward face of the bow to a rather lesser scaled height than the upward jet at the bow of the larger model. This film however clung to the surface of the model, and extended only a short distance downstream of the bow, whereas with the large model spray fanned out from a region close to the intersection of the bow and the water surface, as indicated in fig 2. It appeared from the photographs that the spray comprised individual drops of water torn out from the water surface, rather than a smooth continuous sheet.

The trajectories of these drops were a little outwards from the plane of the flat lateral faces of the wedge bow. Thus the spray could be fully deflected by either a long horizontal spray rail placed at A in fig 2 or by a much shorter one at B. However the projection of the rail at A needed to be as much as 50mm to be effective, whereas a 25mm thick rail sufficed at B.

The photographs are consistent with the supposition that the spray is made up of particles fanning out from the spray root with an initial speed equal to the water speed at the root. Thus in the case of the large model at 4 m/s, with the 10° half angle end forward, the photographs showed the water elevation at the spray root in the bow wave to be 0.11m, implying a speed there of 3.72 m/s. Let this be V_o. When viewed from the side the particles emerge from the spray root along all directions from vertical to horizontal, though viewed from the front their direction is a little inclined outward from the vertical. If this latter inclination is not too large, the trajectory of a particle ejected from the spray root at an angle α to the horizontal will be approximately

$$h = x\tan\alpha - x^2/2\cos^2\alpha$$

where h is the height of the particle above its point of origin when its horizontal distance from it along the inclined face of the wedge is x, the lengths being made non-dimensional by multiplying by g/V_o^2. The envelope of such trajectories is

$$H = \tfrac{1}{2}(1-x^2)$$

This is plotted in fig 2, where the grid painted on the model is indicated. The circle points are taken from a photograph showing the limit of spray penetration against a background of the grid. It can be seen that the agreement with the theoretical envelope is good.

We may speculate as to the cause of this disruption of the water surface near the spray root, involving the ejection of fluid particles. It seems likely to be associated with the sharp curvatures of streamlines passing through this region. Whereas with a pointed bow a streamline in the surface just to one side of the centre plane will be smoothly curved, as in fig 3, the corresponding streamline in the blunted bow case will be much more abruptly curved. In particular there is likely to be a region of sharp convex curvature just to the side of the blunted bow. This can mean that the static pressure locally can get less with increasing depth beneath the surface, the dynamic effects due to streamline curvature more than outweighing the hydrostatic pressure gradient due to gravity. Under these conditions G.I. Taylor[2] has shown that the flow can become unstable. The situation is analogous to the case of Taylor-Görtler instability[3] of boundary layers on concave surfaces. Here the rotationality of the flow means that any fluid particles which become displaced outwards radially will be moving faster than the ambient flow speed at their new positions, at which the pressure gradient in consequence is insufficient to force them back to where they started from, as indicated in fig 4(a). For the free surface irrotational flow case instability as in fig 4(b) can occur as follows: If surface tension were sufficiently weak to allow a fluid particle to become detached from the main body of the fluid, its trajectory would be a curved path either exactly following or curving away from the fluid surface according to whether the pressure gradient into the fluid were zero or negative. Sufficient surface tension will prevent this from happening, and viscosity will tend to reduce the rate of amplification of disturbances, as Bellman and Pennington[4] show.

In the present experiments, run at the same Froude number for the large and small wedge models, surface tension forces are relatively much more important on the small scale, for which the non-dimensional quantity t_1, equal to $T/\rho V^2 L$ (where T is surface tension, ρ density, V speed, and L length) is 40 times larger than for the large model. It is not surprising therefore that the surface is much less disrupted with the small model. Moreover with the large model the initial disturbances which, it is suggested, become amplified in the convex surface flow region, may be much larger than for the smaller model. This is because they may arise from the cascade of water tumbling just ahead of the bow, associated with the fountain effect of water deflected upwards along the blunt bow edge. Whether the water from such a fountain breaks up at the top and descends in irregular lumps, or remains attached as a film to the surface of the model, depends again on surface tension, the relevant parameter now being t_2, equal to $T/\rho g L^2$. Even if V is increased to reduce t_1 to the same value for the small model as for the large one, t_2 will still be much larger for the small one, so differences in spray behaviour would still be expected to occur. Aerodynamic and viscous forces may also play a part in this complicated flow situation, and will differ in importance at the two scales, causing still further differences in spray behaviour. Thus when the small model was run faster, it was found that there was still far less disruption of the water at the foot of the bow than for the large model. The water remained more as a film on the surface of the model, and being more subject to viscous forces, did not penetrate upwards nearly as far as the envelope H in fig 2.

The very strong effects of scale found for the "bow feather" flow naturally prompt the question as to whether other cases of spray formation, for example the spray sheets thrown up by a planing hull, are subject to similarly large scale effects. This however does not appear to be the case. At the V shaped intersection of the bottom of a planing hull with the water the spray formed is more in the nature of a thin sheet adhering to the hull surface rather than a hail of drops. In fact according to the Oxford English Dictionary, which defines spray as "water or other liquid dispersed by impact etc in fine mist-like particles", it would not be describable as spray at all. This is probably because the streamline curvatures at the spray root, except possibly at its forward extremity, are concave to the air-water interface, so that the conditions for Taylor instability do not exist. The situation is different where the spray sheets impinge on chines or spray rails, and here there is commonly far more white water on the full scale than on the model.

I want next to consider another situation where there is a marked difference in appearance between the flows at full scale and model scale, namely the breaking bow wave in front of a full form shp. There has been considerable controversy concerning the causes of wave breaking. The classical Stokes theory for steady irrotational waves predicts a limiting form with sharp crests containing an angle of 120°. However Banner and Phillips[5] point out that "it is very difficult, even in the laboratory, to generate a wave train that approaches this configuration", and that " the waves tend to become very unsteady as the curvature of the crest increases, so that even a small perturbation results in breaking". They note however that the Stokes theory implies a stagnation point at the sharp crest. With wind generated waves, surface drift due to the wind means that a stagnation point can occur even when the wave is not sharply cusped, and they consider this to be the important condition for incipient wave breaking. The experiments they performed in support of their ideas were made with a standing wave generated in a small flume by a horizontal bar laterally across the flow beneath the surface, and they concentrated attention on the first wave crest and on the influence that a wind over this wave could have. However with such an arrangement it is certainly possible, as in the later experiments of Duncan[6], to produce wave breaking without any surface drift generated by wind. Duncan shows a condition of incipient breaking, where either a steady non-breaking wave is possible, or, if an initial disturbance is introduced and then removed, a steady breaking condition can be achieved (fig 5). From the measured wave elevations it is evident that the undisturbed crest speed in this incipient case is as much as half the free stream speed, throwing doubt on the validity of the criterion proposed by Banner and Phillips.

At first sight this cannot apparently be a case of Taylor instability, since even for the limiting Stokes form of maximum wave height the local vertical pressure gradient at the crest is only reduced to half the hydrostatic value. At the crest in this maximum wave case the wave height must be $V^2/2g$. For a wave whose height is k times this, where k is a little less than 1, the crest velocity becomes appreciable, equal to $(1-k)^{\frac{1}{2}}V$. If we suppose that the vertical pressure gradient is still close to half the hydrostatic value, this implies that the radius of curvature at the crest is $2(1-k)V^2/g$. The forms of such waves for $k = 1$ and $K = 0.87$, according to the calculations of Salvesen and von Kerczek[8], are shown in fig 6. A circle of the theoretical radius of curvature for the half hydrostatic pressure gradient is drawn to touch the crest of the lower wave, and it can be seen that the numerically calculated profile certainly has a radius of curvature of this order of magnitude. However a circle of half this radius is also drawn to touch the crest, and it is clear that a not unduly large local distortion of the wave profile, such as might occur in a fluctuating manner due to unsteadiness in the oncoming stream, could suffice to reduce the radius of curvature to a point where Taylor instability might become a possibility.

This conjecture is perhaps supported by Dagan's finding[9] that whereas flows which satisfy Taylor's instability condition are always unstable, disturbance waves can still grow even if this condition is not met provided the flow is contractive, i.e. elements of surface area contract as they move downstream. Such a condition occurs between the trough and crest of a wave, particularly in large amplitude cases. Thus any slight instability could become amplified and lead to a locally sharp surface curvature occurring near the crest.

It seems to me therefore entirely possible that Taylor instability, or the modified form of it considered by Dagan, is the ultimate cause of incipient wave breaking. The essential characteristics of this form of instability are that the rate of amplification of disturbances is reduced by increased viscosity, and that instability only occurs at all if the surface tension is not too large. The effect of a superimposed surface drift, as considered by Banner and Phillips, would on this view not primarily be due to its producing a stagnation point at the surface, but rather to an enhanced instability, produced by the shear, of the Taylor-Görtler kind mentioned earlier.

Experiments quite analogous to those of Banner and Phillips, but made on the bow wave of a ship model rather than on two dimensional waves in a flume, have been reported by Kayo and Takekuma[10]. They also produced a surface shear, by towing a thin plastic sheet in the surface ahead of the model, and they showed that this increased the extent of bow wave breaking and increased the model's resistance. However they advanced a new explanation for the cause of wave breaking, arguing that it was analogous to boundary layer separation. They pointed out that even without the plastic sheet, there is, at the water surface ahead of the wave breaking region, a thin region of fluid which, relative to the model, moves much more slowly than the main oncoming flow. This fluid therefore has a reduced total head, and the imposition of an adverse pressure gradient by the bow will cause flow reversal. Such a retarded fluid layer is clearly evidence of an anomalous surface film effect. No towing tank can in practice maintain a perfectly clean surface. This is easily demonstrated by introducing a number of small air bubbles into the surface. On perfectly clean distilled water, or on water poured from a tap into a container and tested straight away before a contaminated surface can form, such bubbles would last for no more than 1 second on average. In towing tanks it is typical for them to last 5 seconds, and periods of 15 seconds or more are sometimes found on occasions when surface blooms occur. The stabilization of bubbles depends on the so called Marangoni effect, that where a surface film is locally stretched its surface tension rises, so leading to a contraction again. The effect is due to the surface contaminant, which lowers surface tension, having its concentration locally reduced in a stretched area of the surface. The immobilizing of the surface layer by such films can be strikingly demonstrated in a small flume, by lowering a thin horizontal plate spanning the flume till it just touches the surface. Ahead of the plate a region of completely flat surface will form, terminated upstream by capillary waves. This effect has been investigated by Scott[11] and it represents another instance of the Marangoni effect. The laminar boundary layer developing under the immobile surface film exerts a traction on it which is opposed by surface tension gradients caused by variations of surface concentration of the contaminant. Presumably just ahead of the barrier the contaminant molecules are packed closer together than in the oncoming stream. The presence of the thin laminar boundary layer is revealed by die carefully introduced behind the upstream capillary waves: such die will scarcely move at all in the surface, though where it descends below it, even by as little as 1mm, it is swept along with the main flow. The forward extent of this stagnant layer, however, reduces markedly with increasing speed. Thus in recent experiments in a small flume at NMI it was found to be 0.6m at 0.2 m/s, reducing to 0.3m at 0.3 m/s, and vanishing entirely at 0.5 m/s. It seems unlikely, therefore, that the mechanism suggested by Kayo and Takekuma plays a major part in bow wave breaking except for small models at low speeds.

I return therefore to the suggestion that Taylor-Dagan instability is a more significant cause of bow wave breaking, and that this instability can be enhanced or reduced by the introduction of shear at the surface. The case of an adverse shear produced either by wind currents[5] or by a towed plastic sheet[10] has already been discussed. We recently conducted experiments at NMI with a ship model in a towing tank where shear of either sign could be introduced. The adverse shear was produced as in ref 10 by towing a plastic sheet ahead of the model. It had similar effects except that they were significant only for Froude numbers below 0.22. At higher speeds the surface of the breaking bow wave was already so violently turbulent without the plastic sheet that the latter had little effect. Shear of the opposite sign was then introduced by towing a lateral horizontal wire ahead of the model just below the surface. A striking reduction of bow wave turbulence was observed at a Froude number of 0.18. Correspondingly the coefficient of residuary resistance was reduced from $1.135.10^{-3}$ to $1.073.10^{-3}$, whereas it was increased to $1.263.10^{-3}$ by the plastic sheet. (A considerably greater proportional increase in residuary resistance occurred in the experiments of ref 10, the difference presumably being attributable to the differences of hull form).

Although I have argued against the hypothesis of Kayo and Takekuma that a surface film ahead of the main bow wave plays a major part in wave breaking, surface films may well be important in another sense. It was pointed out earlier that surface tension could prevent surface breakup when Taylor instability conditions are present. If the Marangoni effect is significant, however, a more powerful mechanism for reducing turbulence at the surface may operate. Thus Davies[12] shows that surface films can suppress the smaller scale eddies produced by a mechanical stirrer just under the surface. He attributes this to the resistive action of the Marangoni effect on the stretching and contracting of elements of the surface by the turbulence. It is presumably due to this effect also that the turbulent boundary layer profile on a vertical flat plate aligned with the flow and piercing the surface becomes modified close to the surface, as can be seen from fig 7 showing the results of recent measurements made in a small flume at NMI.

All this may provide a key to the understanding of "free surface shock waves". This is the name that Inui and his co-workers[13] give to the type of bow wave they often observe on small models of order 2m in length. These waves resemble shock waves in supersonic flow in that they are characterised by a sharp front at which a rapid change of velocity direction occurs. For oblique waves, the wave crest angle increases as speed is reduced[14], as though the wave were a hyraulic jump on a shallow water flow whose equivalent water depth depends only on the geometry of the bow. Behind the ship, contours of constant total head show[13] regions of head loss close to the water surface extending laterally outboard of the central viscous wake. This is very similar to what is observed behind larger models with breaking bow waves[15], as can be seen from fig 8. However Inui and Miyata[16] sharply distinguish between free surface shock waves and bow wave breaking, partly because there is not always much visual evidence of breaking for their small models. Evidently there is dissipation of energy however, and anomalous surface film effects might provide the mechanism for this. If it were possible to perform ship model experiments in a tank with a perfectly clean uncontaminated surface it might be that free surface shock waves would not occur.

If these views are valid we should expect that increasing scale would probably make the wave resistance coefficients increase a little in the incipient bow wave breaking region. This is because the decreased relative importance of surface tension effects and of viscous damping would lead to greater surface instability, and as we have seen, when instability is increased artifically by a towed plastic sheet, some increase of resistance results. However reduced turbulence can possibly be associated with an alternative form of energy dissipation due to surface film effects, and at a larger scale, may be compensated for in part by greater undulations of the wave surface downstream, as in Duncan's incipient wave breaking case[6] shown in fig 5. (It is perhaps for the latter reason that theoretical calculation methods[17] which assume potential flow can give at least qualitatively correct predictions of variations of wave resistance with hull form, when in reality these variations are associated with different degrees of wave breaking). Thus despite considerable differences in the surface appearance of bow waves at different scales, the associated differences of resistance may not be very serious.

We are not always concerned only with resistance however. A few years ago we had to test at NMI a hull form which was almost the same as one tested earlier in Japan. It then emerged that the Japanese ships were experiencing vibration troubles which were attributed in part to the effect of air bubbles being swept under the ship and into the propeller aperture. These bubbles were entrained from the bow, when the bulbous bow was only half immersed at ballast draft, and they had been observed to occur in the Japanese model experiments[18,19]. Accordingly we looked for them in our model experiments, but there were none to be seen. A photograph of our model in the ballast condition showed a film of water climbing over the bulbous bow, and then turning steeply downwards. Ripples developed on this film, but the disturbance was not large, though on the full scale ship there is very violent foaming and entrainment of bubbles. Dr Baba has very kindly supplied me with a clear photograph of one of the pictures reproduced in ref 19, and it is evident that the water surface over the bulb in his experiments was such more disturbed than in ours, though there was still no obvious evidence of air entrainment such as occurred on the full scale ship. However the greater degree of disturbance in Dr Baba's model experiments may explain why his experiments showed bubbles being swept under the hull whereas ours did not. The most probable explanation of this difference between the two experiments is that there may have been small differences in the bulb shapes, since the two hull forms were not absolutely identical, though they were very similar. However an alternative explanation which is just possible is that differences in surface film properties between the two test tanks may have been the cause. Perhaps in future bubble persistance times should be recorded when inter-tank comparisons are made.

My final topic concerns a possible scale effect on the drag of an immersed transom in cases where there is eddying flow behind it. Tamura[20] has considered this problem for tanker forms, where the ratio of immersed transom area to wetted area is small, of order 0.002 to 0.004. He recommended the assumption of a constant base drag coefficient related to base area of 0.03. In support of this proposal he presented calculations for base drag coefficients at model and ship scales using the aerodynamic data collected by Hoerner[21]. These calculations actually suggested that the coefficients would be a little larger on the ship than on the model, but Tamura considered the difference too small to be worth taking account of.

In some cases the transom area is a much larger fraction of the wetted area, and here it is more important to know what scale effects may be present. There is considerable evidence that for transoms which are much wider than they are deep the scale effects can be large, and that tests at model scale, when extrapolated by conventional methods, can underestimate the resistance penalties associated with eddying flow behind the transom. Thus it has been reported[22] that certain yacht forms suffered no resistance increase on the model scale when the aftermost portion was cut off to form a transom stern, whereas on the full scale there was a large drag penalty. Again fig 9, reproduced from ref 23, shows that the resistance coefficient curve for HMS "Penelope", which has a large transom, is much flatter at the low speed end than the curve deduced from model results. The mean level of the full scale curve is higher than that of the model prediction curve either because of insufficient roughness allowance for the latter or of insufficient appendage drag allowance, but the difference in shape between the two curves could well be due to an underestimation of the base drag penalty at the lower speeds. Further evidence[24] comes from experiments made at NMI with a 3.2m long model of R.V. "Athena", a round bilge high speed form with a transom stern as shown in fig 10, in comparison with earlier measurements on a 5.7m long model of the same form, made at DTNSRDC. As can be seen from fig 11, the residuary resistance for the smaller model was some 20% lower than for the larger model at the lowest speeds, though at high speeds, when the flow had smoothly cleared the transom, the coefficient was a little higher for the smaller model. The Reynolds number at the lowest speed with the smaller model was $4.2.10^6$ based on LBP, so there is little reason to suspect significant areas of laminar flow on the model, since the transition fixing studs fitted are known[25] to be very effective turbulence stimulators for hull forms with such small angles of entrance as in the present case. Accordingly it seems that the scale effect must be caused by an increase in the base drag coefficient with increased scale. It is estimated[24] that at the lowest speeds the base drag contribution to the drag coefficient of the smaller model is of order $1.5.10^{-3}$ based on hull wetted area (or of order 0.15 based on base area). Thus it forms the larger part of the residuary resistance. The discrepancy between the two resistance curves at the lowest Froude number is about $0.4.10^{-3}$, so if this is primarily due to a change of base drag coefficient, the latter would have to increase by order one quarter for a change of Reynolds number from $4.2.10^6$ to $1.1.10^7$. Such a change is much larger than that indicated by Hoerner's aerodynamic data, either for two or three dimensional base flows.

As with all experimental data, of course, one has to bear in mind the possibility of experimental error, or of the effects of small inaccuracies in model manufacture, etc, so further evidence is required before it can be concluded definitely that the scale effect is as large as it appears. Moreover the effect, if it exists, appears to be confined to wide shallow transoms. For deep transoms at low Froude numbers recent experiments at NMI have shown no great increase of base drag coefficient with increasing scale. Bluff pontoons, as sketched in fig 12, like the buoyancy pontoons of oil rig support vessels, have been tested at two widely differing scales, the model in one case being 3m long and in the other 10m long. Various stern shapes have been used, including a sharp cut-off transom. The residuary resistance curves for the small and large models are not very different, though it is possible that a small increase of base drag for the larger model is masked by a corresponding small decrease in the drag of the fairly blunt head form. Furthermore, direct measurements of the base pressure coefficients seemed to show little effect of scale, though it was difficult to obtain precise values because of considerable flow unsteadiness and because there were appreciable (and unexpected) variations of pressure with variation of position over the base.

Accordingly if the "Athena" findings are correct, we must look for an explanation which differentiates between wide shallow transoms and deep ones. In either case there is turbulent mixing at the boundary of the so-called "dead fluid" region, and this is a process tending to draw fluid from the base and create a low pressure there. Variations in boundary layer thickness on the body upstream of the base will modify the turbulent mixing process, and this explains the tendency for base drag coefficients in the absence of a free surface to increase somewhat with increasing Reynolds number. We have to consider how it might be possible for such a tendency to become amplified by free surface effects.

At first sight a possible cause might seem to be a modification by surface tension of the entrainment processes at the edge of the "dead fluid" region, related to the way in which turbulence is modified at a free surface, as shown by Davies' experiments[12] and the results of fig 7. Such effects would be expected to be greatest for small models at low speeds. However experiments made in a small flume at NMI appear to disprove this conjecture. Various double models with blunt transom bases were tested both deeply immersed and with the water level at their horizontal planes of symmetry, as in fig 13. The Froude numbers being low, the water surface remained nearly flat, so apart from any possible surface tension effects on the eddying motion, the flow round the lower half of a fully immersed model should have been the same as that round the model in the surface. Base pressure measurements showed no significant differences between the two conditions, so surface tension effects seemed to have little influence on the tendency to entrain fluid out of the base region.

It may be that the effect only becomes significant at non-negligible Froude numbers, when there is an appreciable lowering of the water level behind the transom, though the transom is still partially immersed. With the deep transom of course a high Froude number would be needed before this change of level became a significant fraction of base depth, and the pontoon experiments discussed above did not extend to such speeds. The eddy structure in such a case also differs from that with a shallow transom. As sketched in fig 14, prominent eddies with vertical vorticity can be seen with a deep transom, whereas with a shallow one the vorticity must be primarily horizontal. When the water level at the transom becomes lowered by increased speed in the latter case, the flow immediately behind the transom resembles a turbulent bore. One may speculate that at the smaller scales something like the effects which surface tension and viscosity have on small-scale breaking bow waves also operate here to tend to reduce the turbulence and inrease the base pressure. An objection to this idea is that the Froude number at which the flow completely clears the transom does not seem to be scale dependent. However by the time this condition is reached the "turbulent bore" is quite steep. As was seen in the case of the plastic sheet experiments with bow wave breaking, there was little effect at higher speeds when the bow wave was already very turbulent.

All this is of course conjectural, and many more detailed flow studies will be needed before the complicated physical processes involved can be fully understood. Such understanding is however necessary if we are to make reliable predictions for full scale conditions from model results. Thus we must make it our aim to "try to promote science", the aim set before us by Professor Georg Weinblum, which he pursued so constantly and effectively in his own researches.

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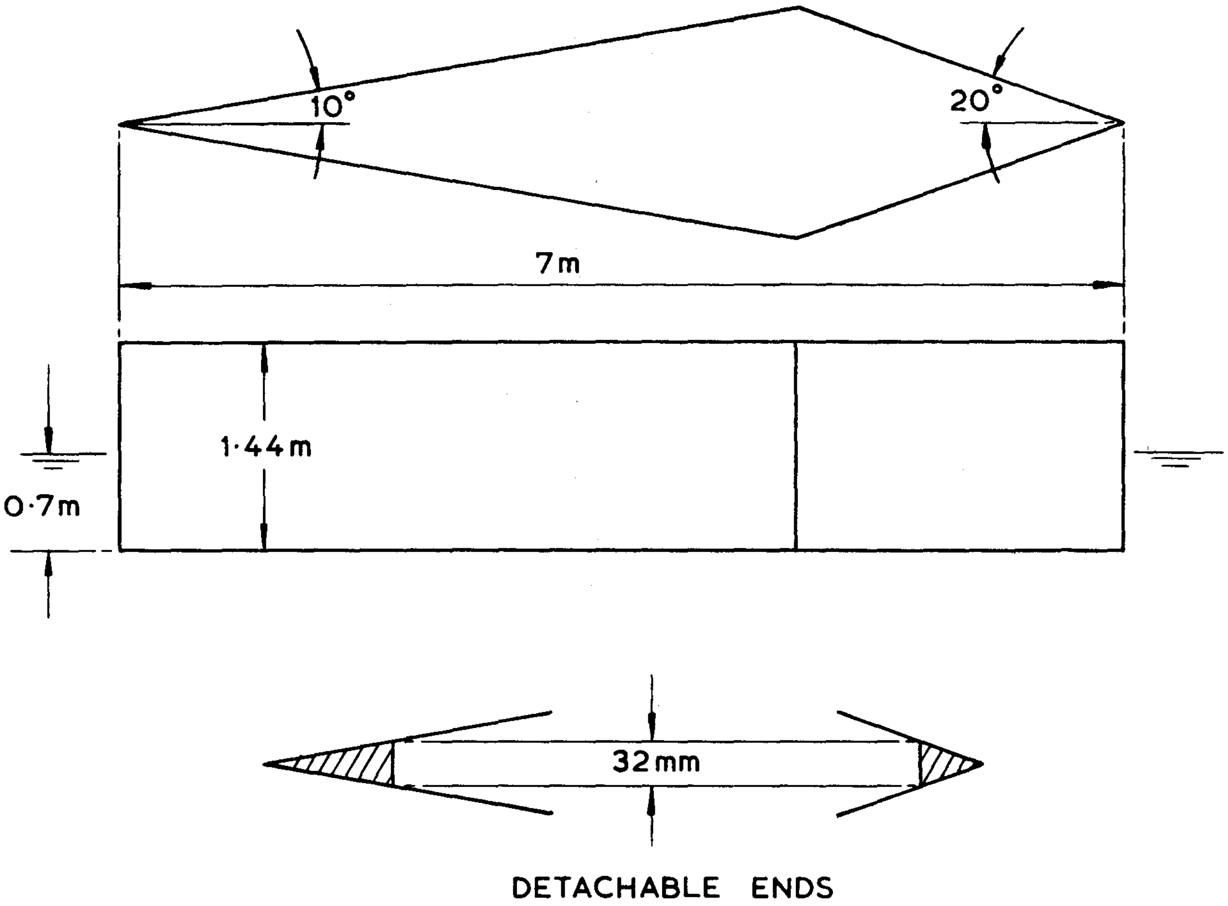

SKETCH OF LARGER WEDGE MODEL

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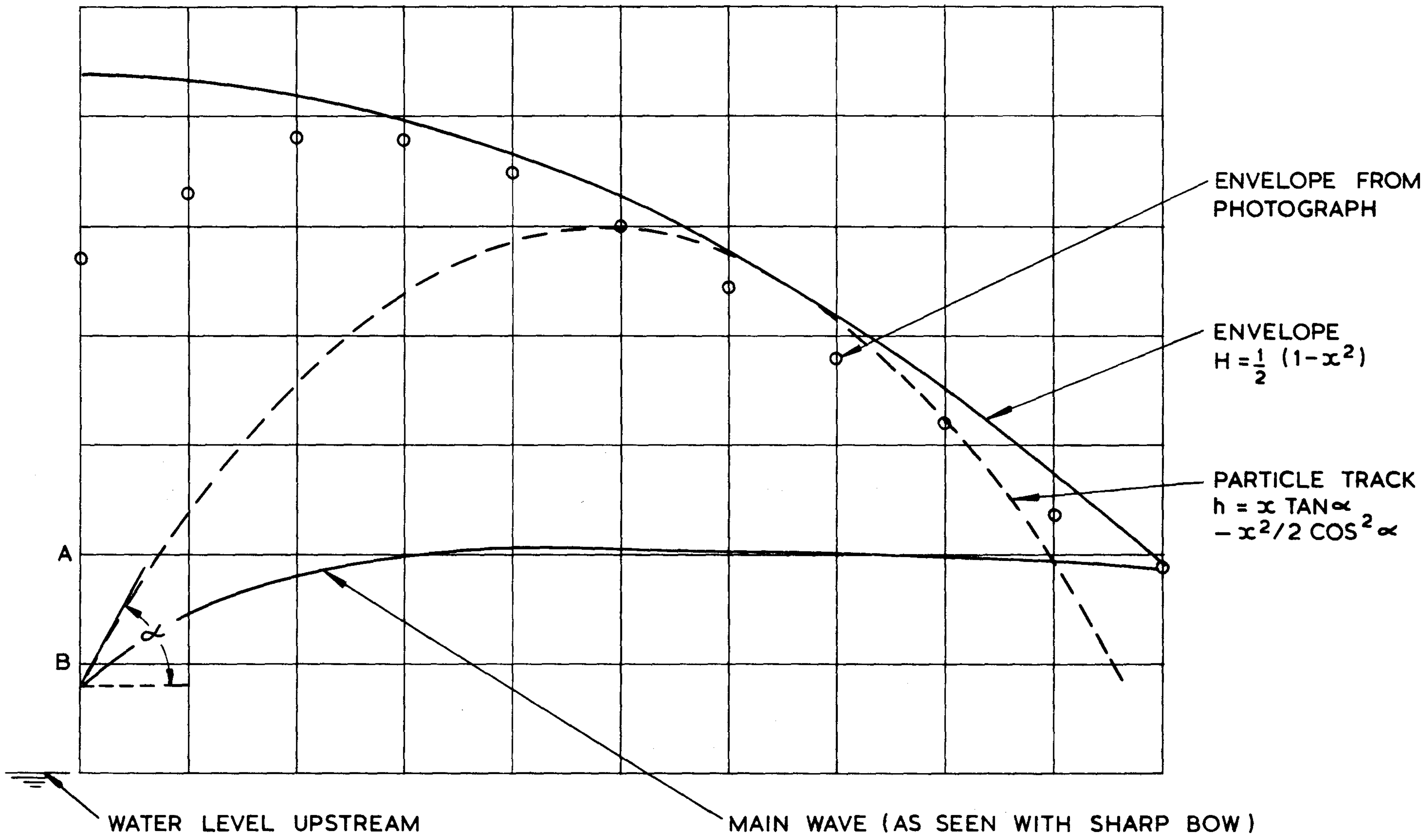

SPRAY FORMATION WITH LARGE 10° WEDGE

FIG. 2

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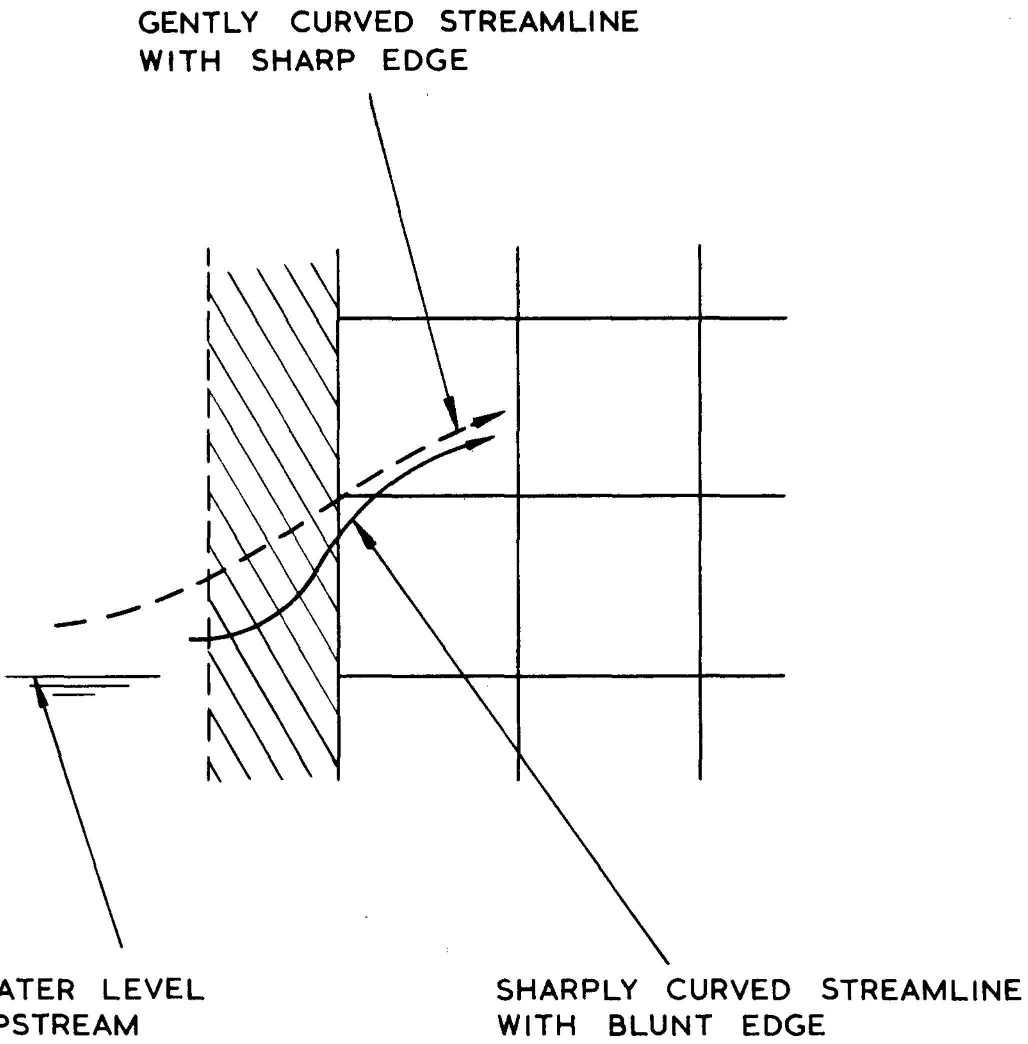
FIG. 3



STREAMLINES WITH SHARP AND BLUNT EDGE

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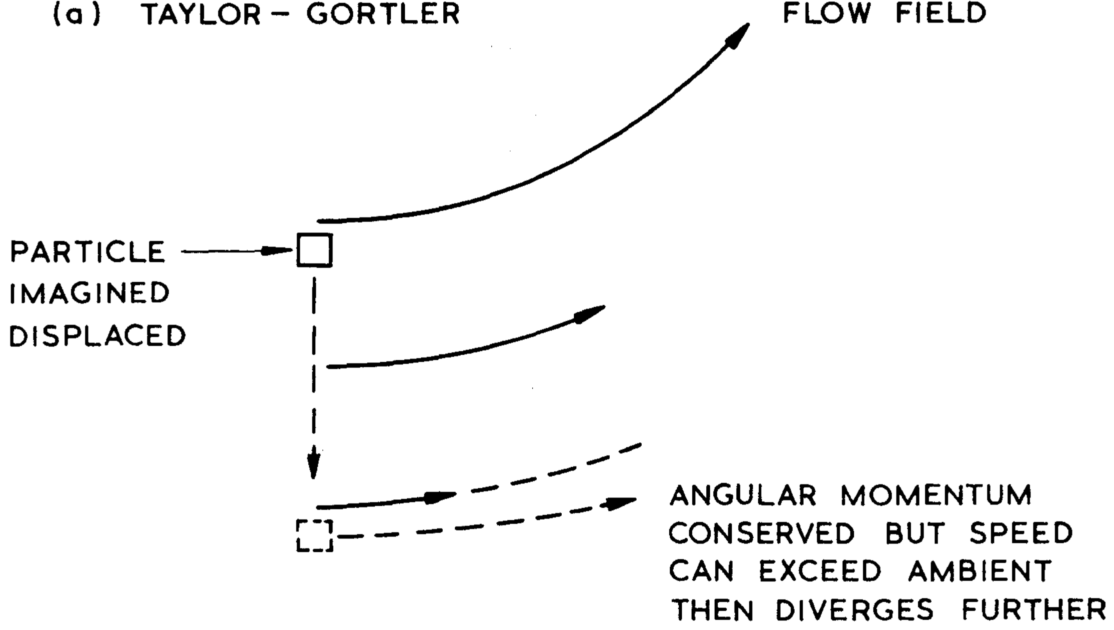
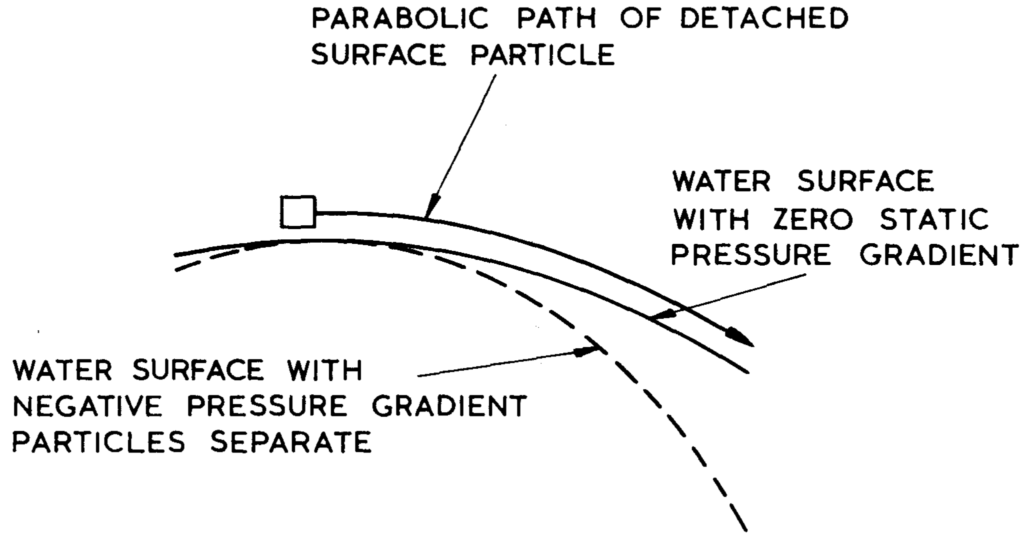
FIG. 4

(a) TAYLOR – GÖRTLER

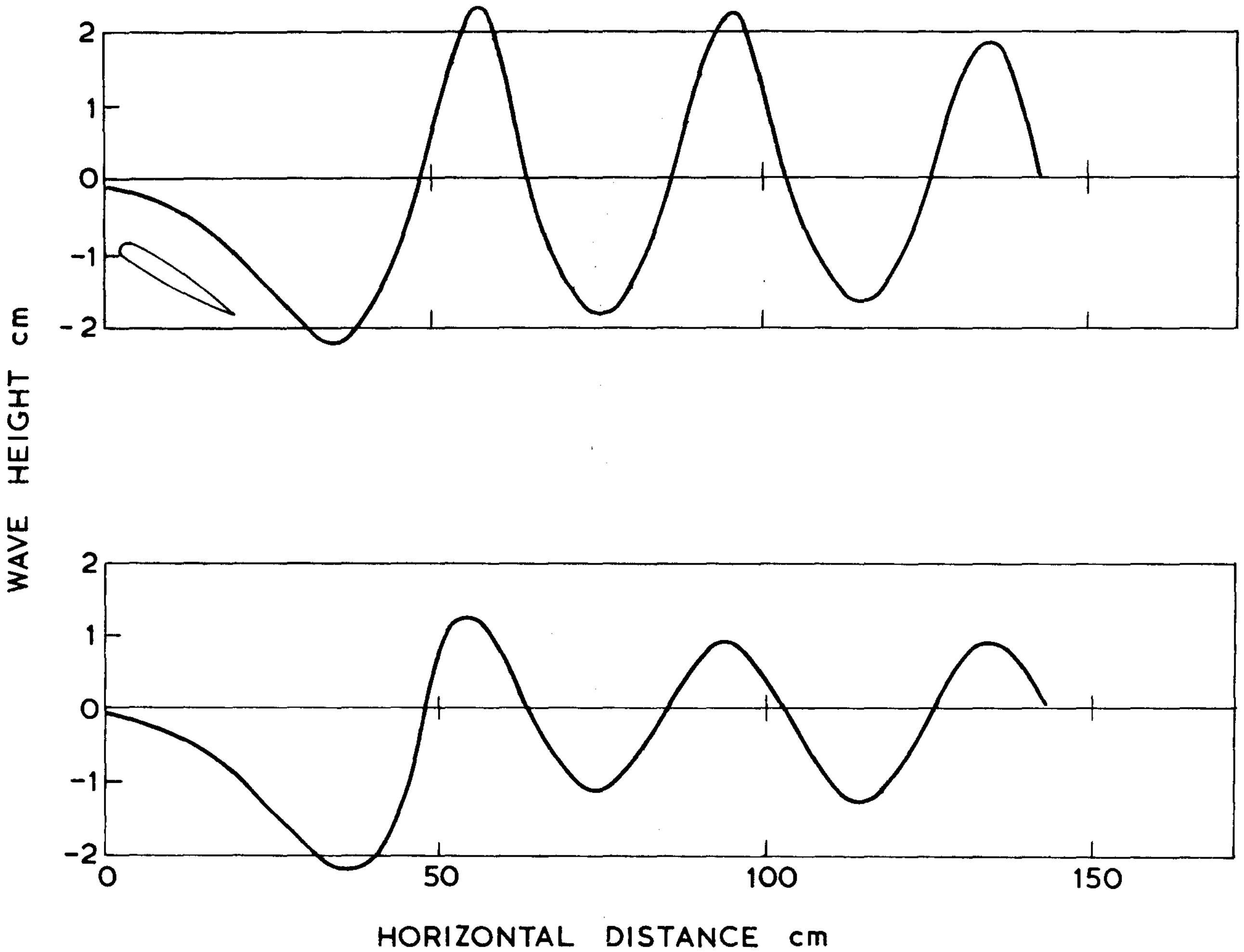


(b) TAYLOR INSTABILITY AT FLUID SURFACE



TYPES OF INSTABILITY

FIG. 5



DUNCAN'S MEASUREMENTS OF NON-BREAKING WAVE (TOP) AND BREAKING WAVE (BOTTOM) UNDER SAME CONDITIONS

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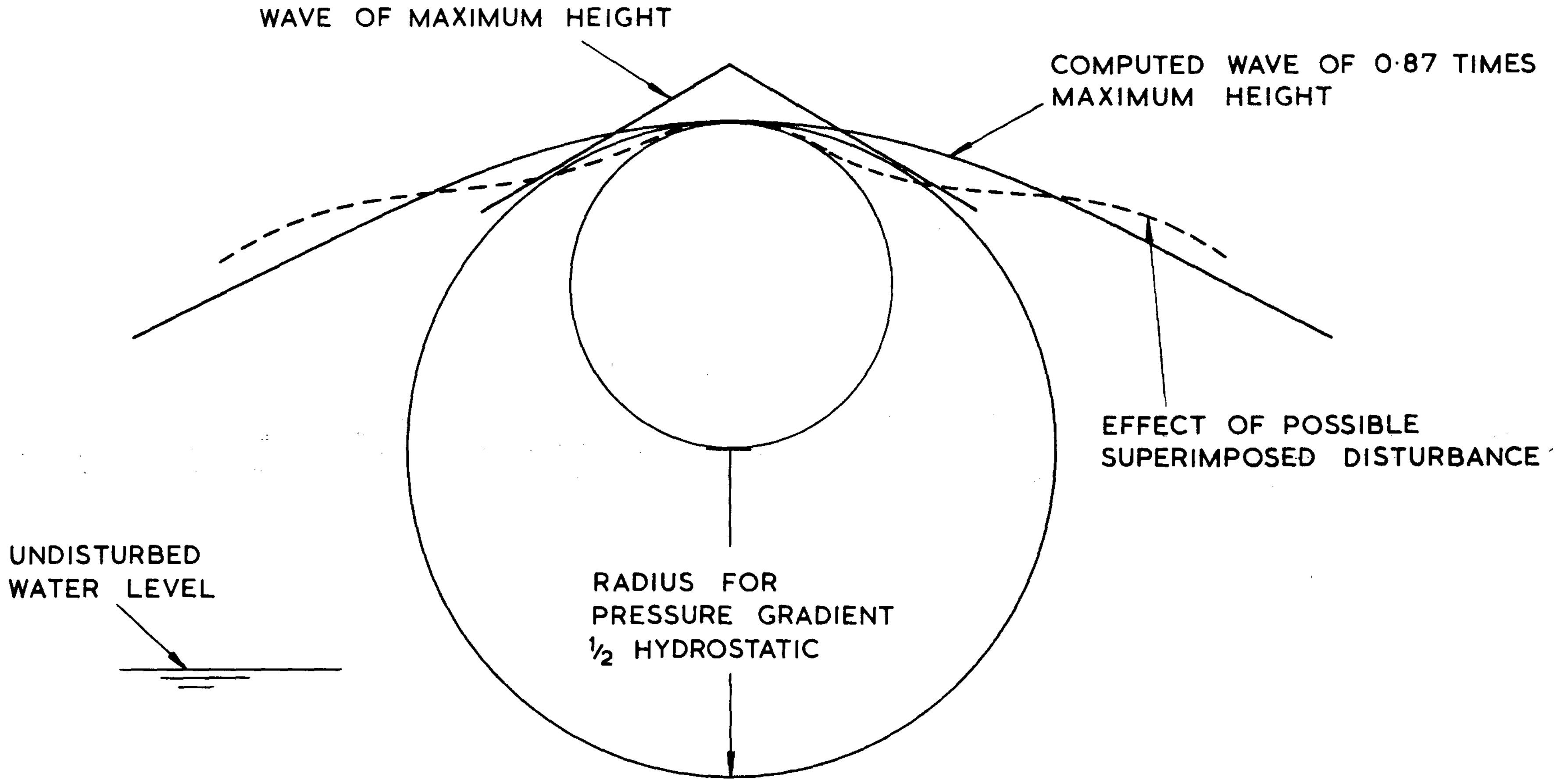
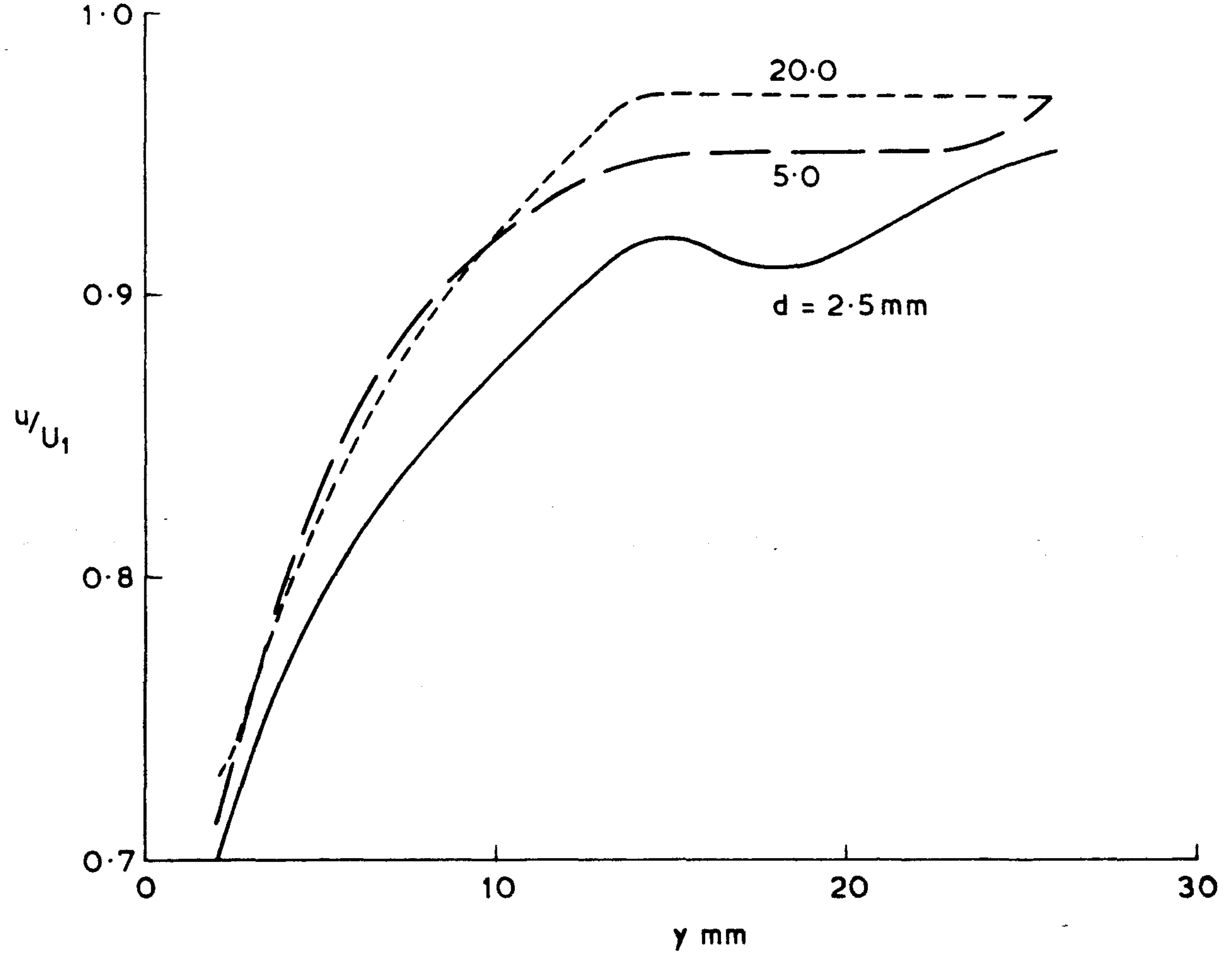
FIG. 6

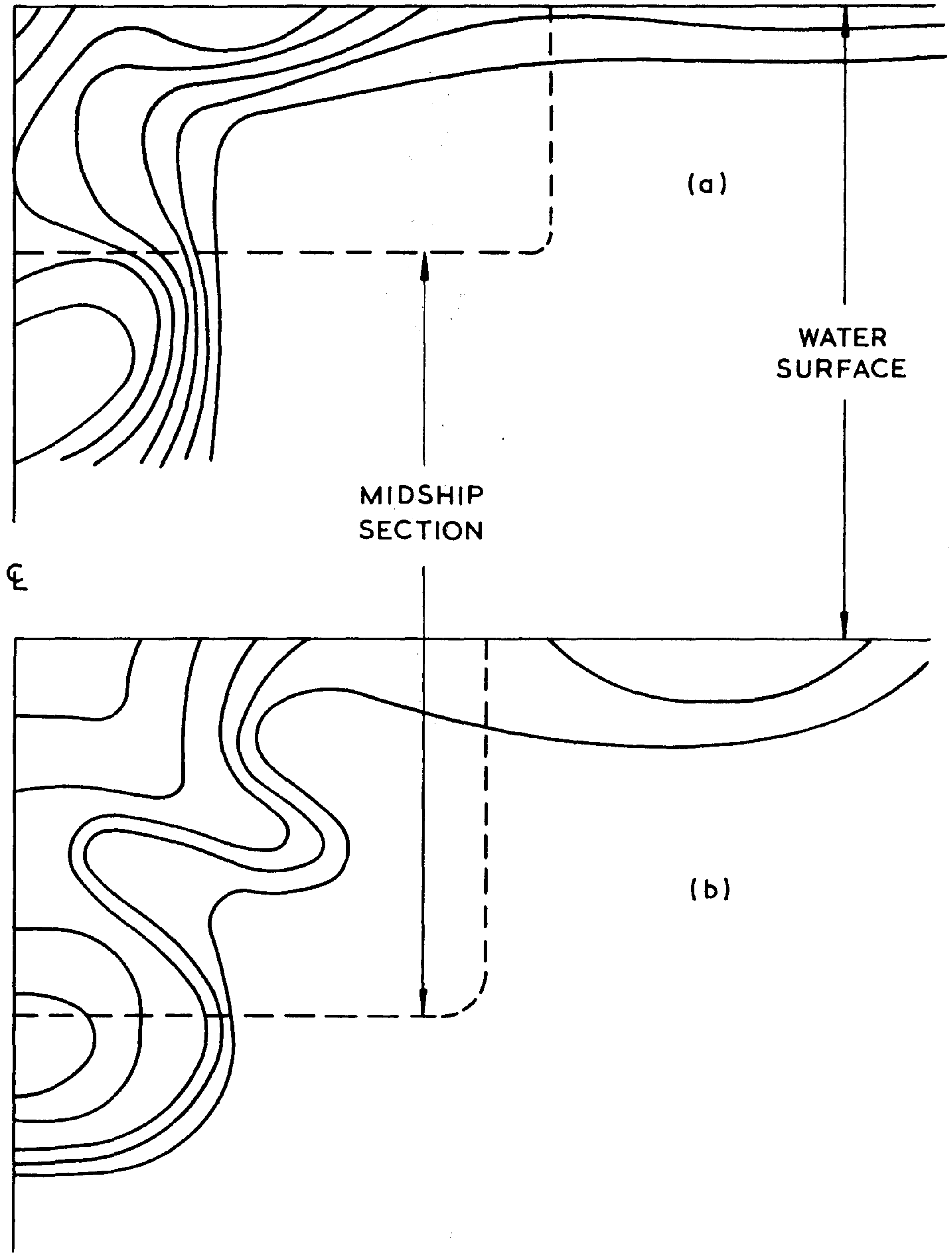


CONDITIONS NEAR A WAVE CREST

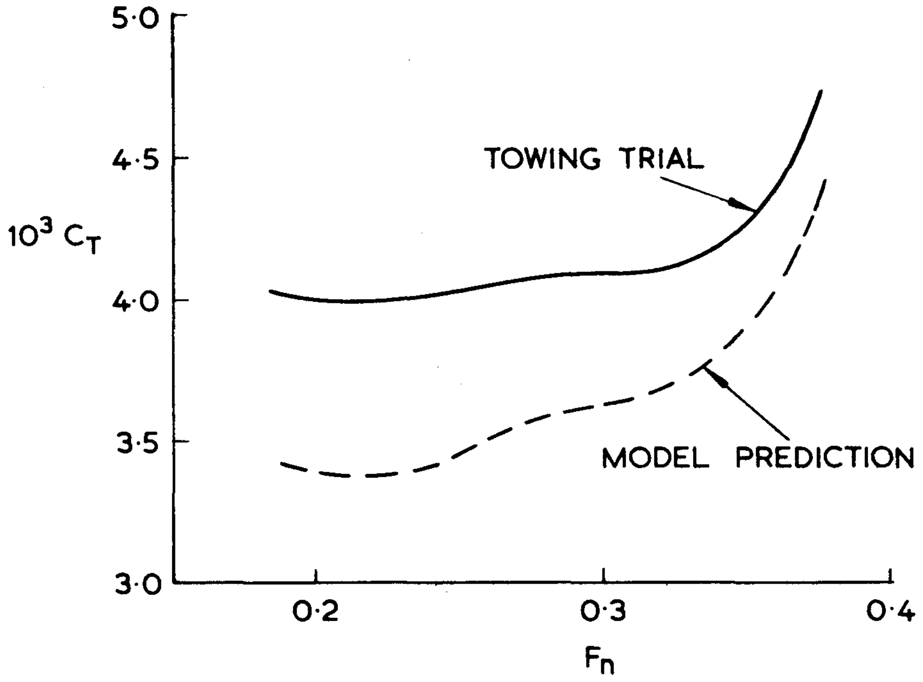
FIG. 7



BOUNDARY LAYER PROFILES ON A VERTICAL
WALL AT VARIOUS DEPTHS d BELOW THE WATER SURFACE

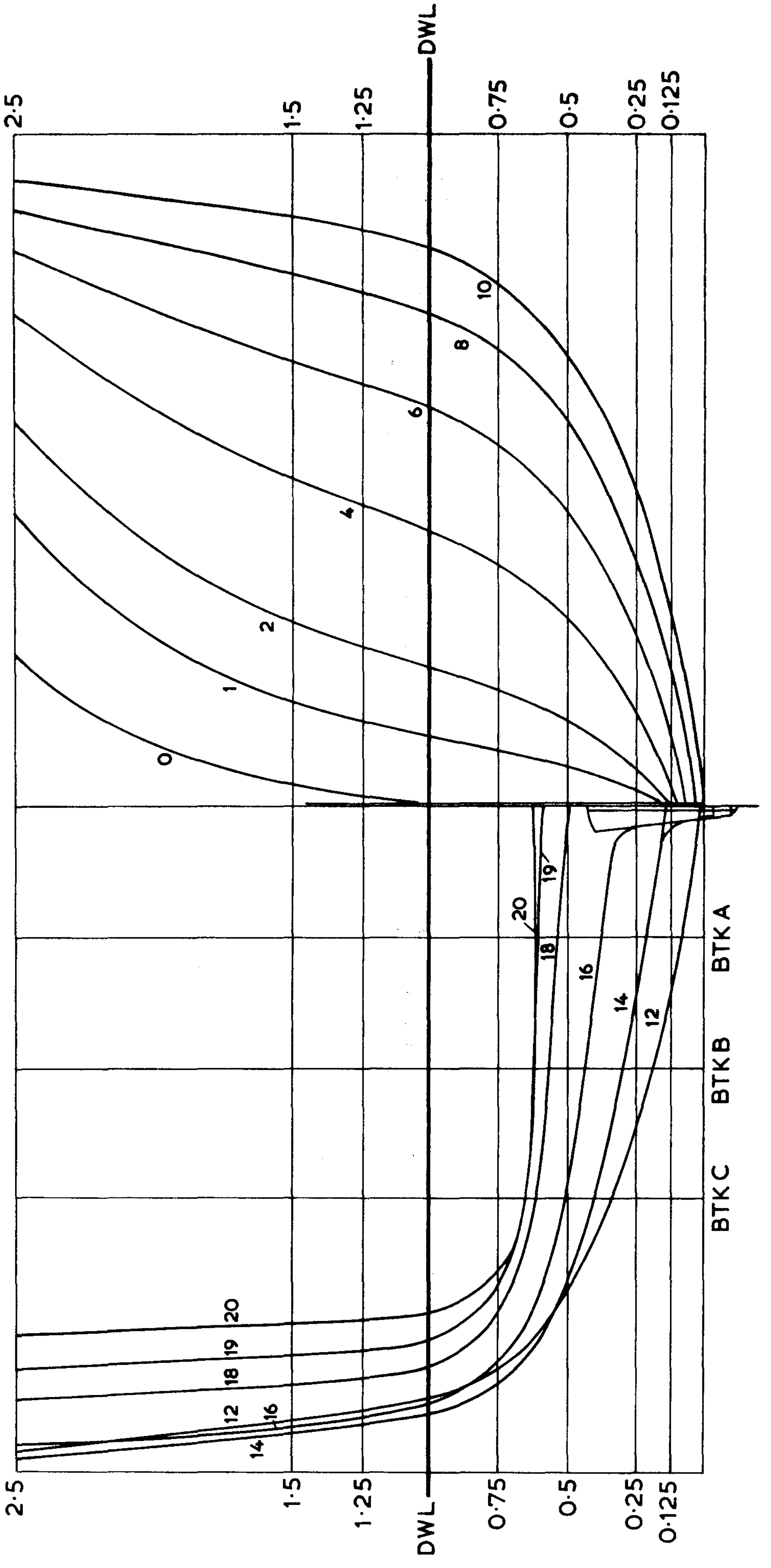


SKETCHES OF TOTAL HEAD CONTOURS BEHIND SHIP MODELS (a) WITH "FREE SURFACE SHOCK WAVES" (REF. 13) AND (b) WITH BREAKING BOW WAVES (REF. 15)



RESISTANCE CURVES FOR
H.M.S. PENELOPE, FROM REF. 21

FIG.10



BODY SECTIONS OF R.V. "ATHENA" MODEL

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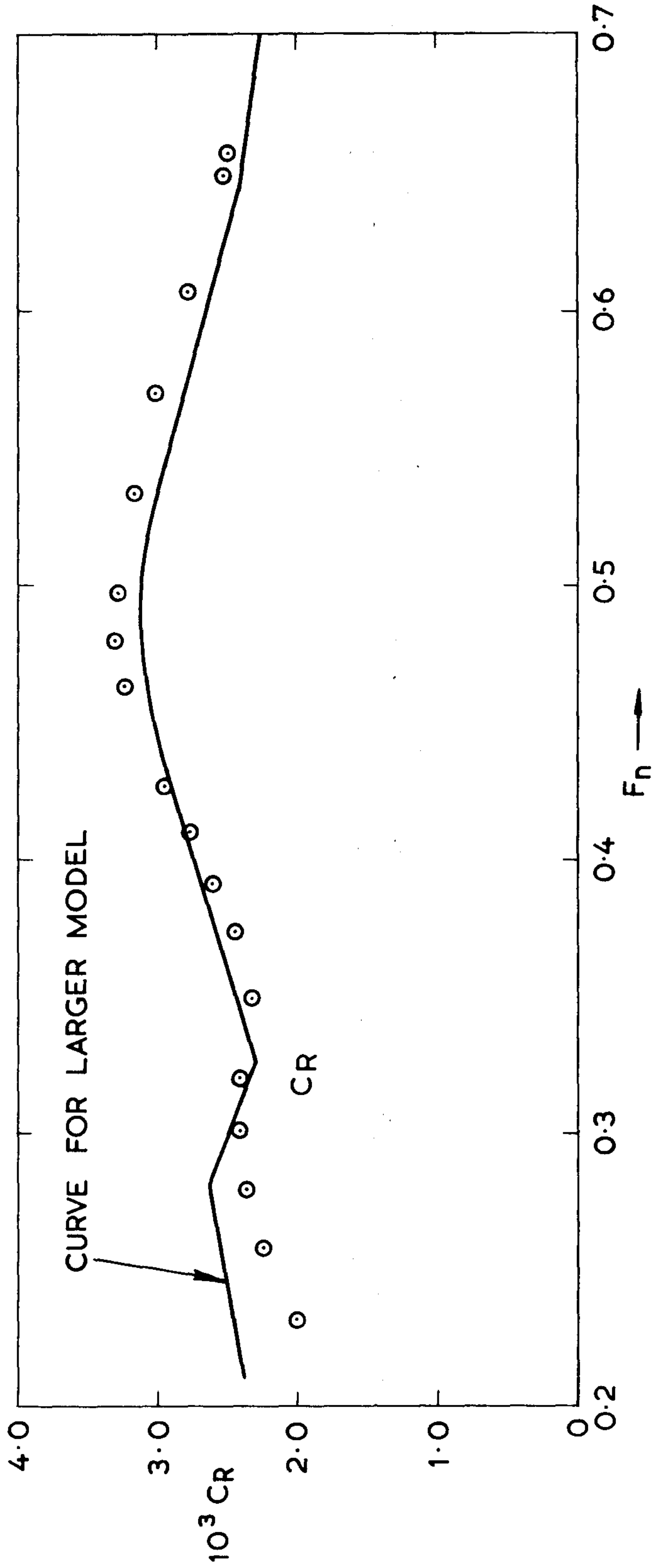
FIG. 11



RESIDUARY RESISTANCE OF MODELS OF R.V. "ATHENA"

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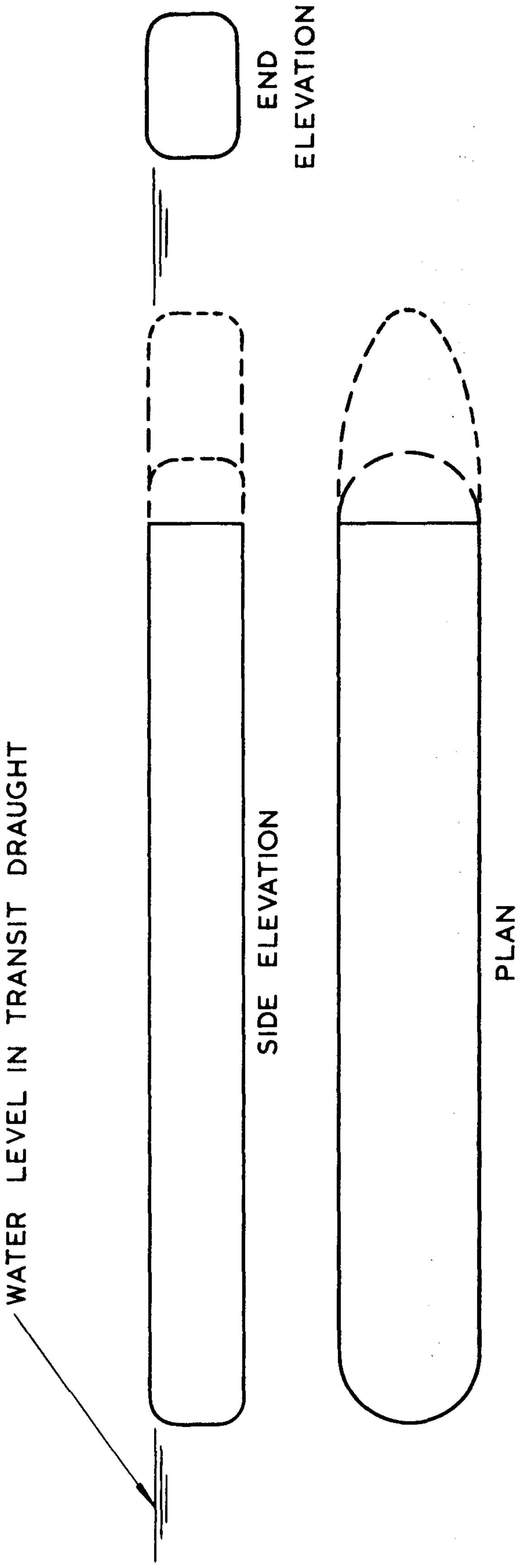
FIG.12



BLUFF PONTOONS WITH ALTERNATIVE STERN SECTIONS

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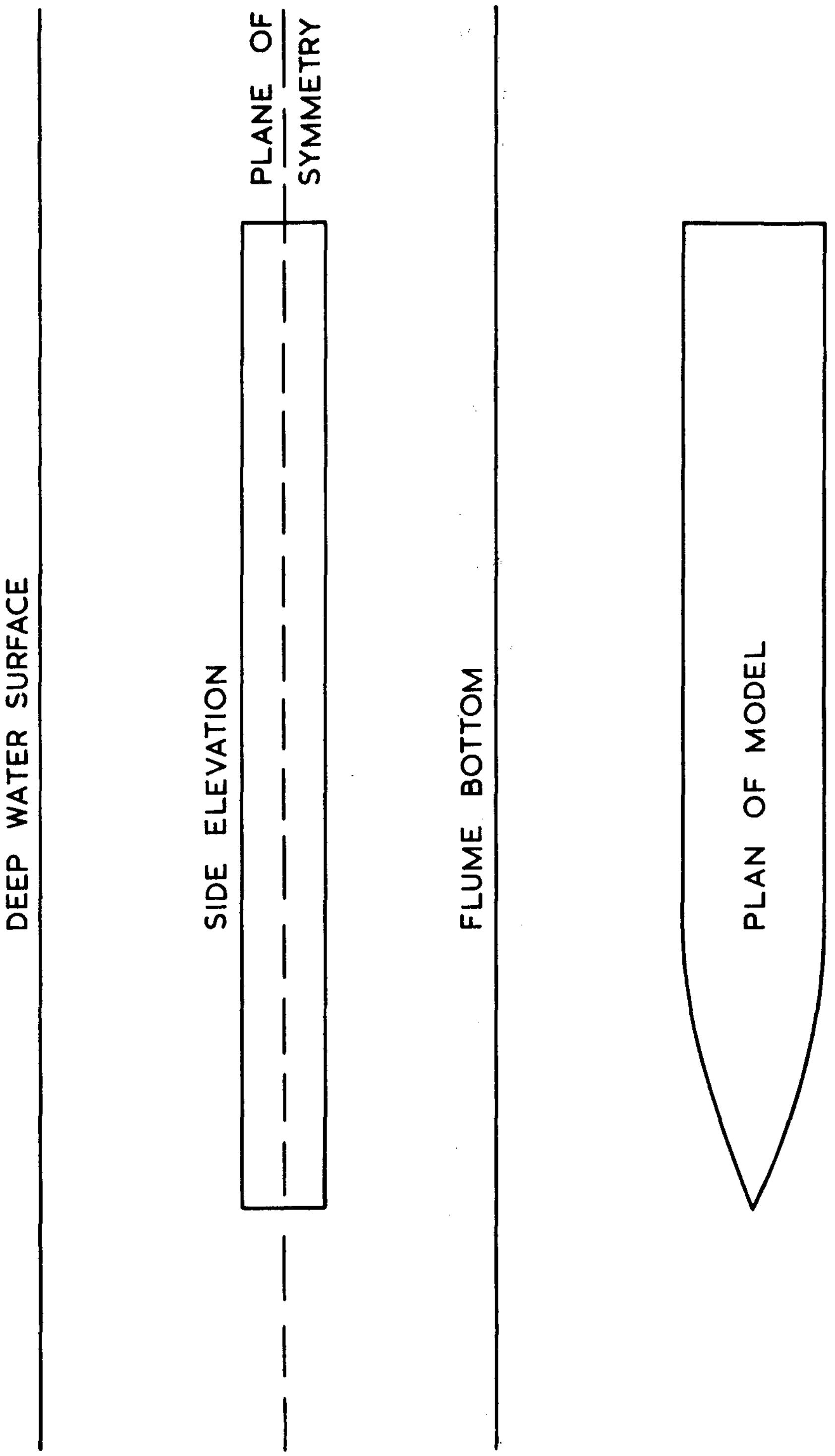
FIG. 13



DOUBLE MODEL EXPERIMENTS

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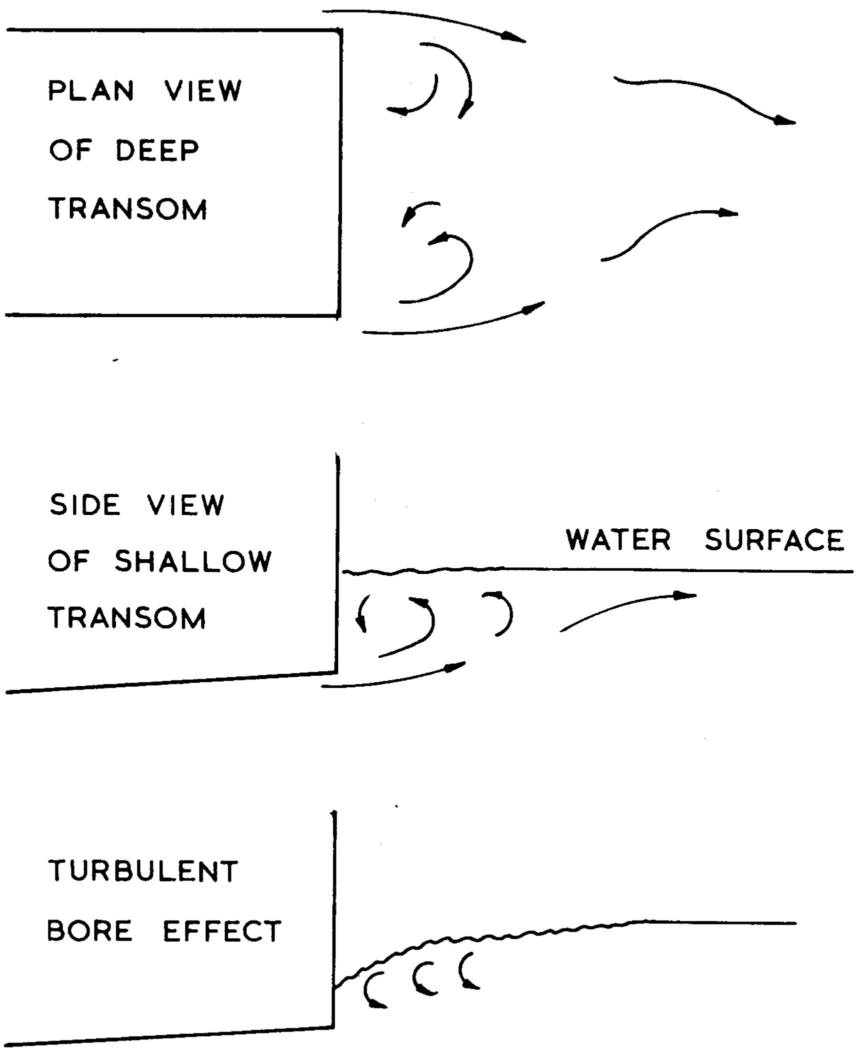
FIG. 14



EDDIES BEHIND TRANSOMS