spicules, foraminiferan shells and algal fragments. However, the majority of the particles were unrecognizable, varying from 0·5 to 10 μ in diameter, but mostly about 1 μ (that is, of just colloidal dimensions), and showed a strong tendency to form a layer at air/water interfaces.

After drying at 105° C., 4 c.c. of the residual fluid reduced to 0·17 gm. of total solids, of which 0·135 gm. was due to the salt present in the water, leaving 0·035 gm. of other solids probably corresponding to the particulate matter. The dried residue was tested for cellulose, protein and pentose with negative results. Both protein and pentose (among other substances) can produce stable foams by adsorption in the form of a rigid interfacial layer; but since this layer need be of only molecular thickness, the amount of stabilizing material does not have to be very large, and might remain undetected by the methods used. However, it was obvious that the food content of the foam was negligible compared with that already available on the shore.

While the evidence obtained was partly in support of Miss Pope's suggestions[1], there was no evidence that the apparent stabilizing particles were derived from living organisms broken up by the waves: they might have originated from detritus or fæcal matter. Furthermore, it does not seem essential to postulate the presence of a substance causing marked lowering of the surface tension. The properties associated with foam formation appear to be surface rigidity and a sharp rise in surface tension when the surface area is increased, rather than low surface tension by itself[2]. It is possible that the drag of the wind on the water compressing the surface film and causing it to 'solidify' is a contributory factor towards the formation of foam.

I am indebted to Dr. D. J. Crisp for advice on this matter.

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[1] Pope, E. C., *Aust. Mus. Mag.*, **10** (11), 365 (1952) (noted in *Nature*, **171**, 913 (1953)).

[2] Adam, N. K., "The Physics and Chemistry of Surfaces", 142 (3rd edit., Oxf. Univ. Press, 1941).

Wave Riding of Dolphins

PREVIOUS discussions[1] of the wave riding of dolphins have been based on the assumption that it was necessary for a dolphin to have a weight greater than that of the displaced water in order to be able to ride a wave while totally immersed. It is the purpose of this communication to clarify this point and to show that it is the total weight of the dolphin which is significant rather than the excess weight.

From the hydrodynamic point of view, it is most convenient to consider the steady-state case in which the dolphin and the wave are stationary and the main body of water is moving with the wave velocity. Within the linearized theory of steady waves, streamlines of the flow are lines of constant pressure, and this relation may be expected to hold approximately for any steady-wave system. The simplest correct approximate way of computing the ideal force on an immersed body in such a flow is as a buoyant force, equal to the volume times the pressure gradient evaluated at the centre of the immersed volume. This pressure gradient equals the fluid density times ($g \cos \theta + u^2K$), where u is the local velocity of the flow and θ and K are the inclination and curvature of the streamline, and this gradient is directed normal to the streamline. This buoyant force is opposed by the force $W \cos \theta - L$ (see Fig. 1), where W is the total weight of the immersed body and L is the hydrodynamic lift. This gives the relation:

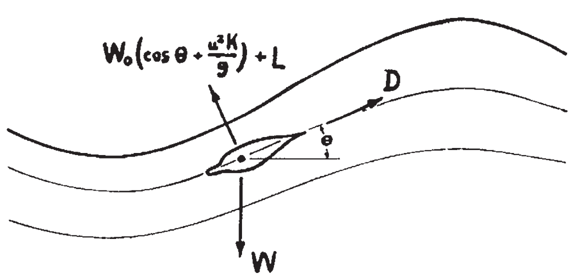

Fig. 1. Dolphin in a wave

$$L + \frac{W_0}{g} u^2K = (W - W_0) \cos \theta, \qquad (1)$$

where W_0 is the weight of the displaced fluid, the hydrostatic buoyant force on the body. Balance of forces in the direction of the streamline gives:

$$D = W \sin \theta, \qquad (2)$$

where D is the hydrodynamic drag. For a wave rider planing on the surface, the equations would be the same but with $W_0 = 0$. The force opposing the hydrodynamic drag is independent of any buoyant force, which only affects the amount of hydrodynamic lift needed. Thus it is the total weight which is significant, and not the excess weight. The totally immersed dolphin may be at a slight disadvantage over a surface wave rider because the maximum value of θ is less below the surface than on the surface. However, the dolphin is at a significant advantage because it has very much less hydrodynamic wave drag and drag due to lift.

An alternative method of calculating the forces in this case would be to separate mathematically the effect of the gravitational field. From this point of view the drag force is opposed by a force equal to the displaced mass of fluid times the space derivative $u\, du/ds$ of $\frac{1}{2}u^2$ along the streamline, in addition to a force $(W - W_0) \sin \theta$. In view of the relation $g \sin \theta = u\, du/ds$, the two approaches may be seen to be equivalent. A third equivalent point of view is that an immersed body with no excess weight would be acted upon by a force which would give it the same acceleration as the fluid in the same vicinity.

For fore-and-aft stability the dolphin must be in a part of the wave for which K is positive, and it may be expected that this is normally the case. The hydrodynamic lift is thus generally somewhat less than $(W - W_0) \cos \theta$ and may be zero or of either sign.

In any event, the practical difficulty discussed by Woodcock and McBride, the difficulty of having to assume laminar flow, disappears. Added significance is given to their remark that this wave-riding force should be taken into account in any estimate of the dolphin's capacity for sustained work. With moderate velocities and reasonably large wave inclinations, the dolphin has amply sufficient thrust from this source to overcome drag with turbulent flow.

The opinions contained in this communication are the private ones of the writer and do not necessarily reflect the views of the United States Navy.

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Office of Naval Research,
U.S. Embassy, London. Aug. 14.

[1] Woodcock, A. H., *Nature*, **161**, 602 (1948). Woodcock, A. H., and McBride, A. F., *J. Exp. Biol.*, **28**, 215 (1951).