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Measurement of the Wave-making Resistance of a Ship by Means of an Electric Analogy

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(Abstract)[1]

1. So long as we assume that the disturbance produced by the wave motion is infinitesimal, p, the pressure in a fluid, satisfies the equation of Laplace, the same type of equation as defines φ, the electric potential. If, therefore, we can provide the same boundary condition to the distributions of these two quantities, there must exist an equality relation between the pressure and the potential. Accordingly we find it possible to reduce a hydrodynamical problem of wave-making resistance of a ship to a simple measurement of an electric quantity. This is the principle of the electric analogy of wave problems.

This technique may be not only able to dispense with the calculation of ship waves which is so much complicated but by taking the wave-profiles observed in the model basin as the boundary conditions, we shall be enabled to obtain the data of the wave resistance of a ship in a form completely separated from the skin friction when we analyse model ship experiments.

2. As mentioned before, p is a harmonic function and is determined uniquely if the boundary conditions are specified. The boundary conditions, on the other hand, are:

(i) on the free surface, p equals a constant, which can be identified to zero at our choice, and

(ii) as we go down the water ($z \to \infty$), the disturbance by the waves dies out and p tends to $\rho g z$ in an asymptotic manner, ρ being the density of the water.

And if we assume that the disturbance is completely negligible below the depth $z = h$, which is not small compared with the wave-length, then the boundary problem for p can be visualized by Fig. 1. Now if we put, in place of both the wave-profile which is the surface elevation calculated or observed and the contour of equal pressure at the depth of practical infinity $z = h$, the metallic plates corrugated into the forms of these curves, keep the electric potential at 0 and $\rho g h$ and fill electrolyte in the space between them, then p will be represented by φ at the points corresponding to each other, so we have only to measure φ in order to know the pressure distribution.

However, there still remains a difficult problem: in spite of the fact that the pressure field generated by the waves around the ship is of three-dimensional character, the electric potential distributed in the electrolytic basin is two-dimensional: x and z, cf. Fig. 1. In other words, instead of the combined system of transverse and diverging waves starting from both sides of the ship (let us suppose that I indicates the wave-profile on the central plane), we are going to measure in the electrolyte the pressure, so to speak, caused solely by the transverse waves extending perpendicularly to the direction of motion of the ship, neglecting the effect of the

[1] The original paper was published in Japanese in *Zôsengaku Kenkyu* (Studies of Ship-building), Kyushu University, No. 5-6 (1949).

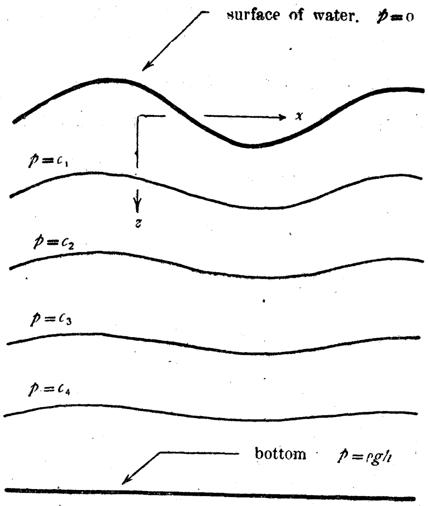

Fig. 1

diverging component. Afterwards we shall be able to estimate the error owing to this simplification.

Another inconvenience accompanying this analogy is that we cannot magnify the scale in z direction in order to increase the accuracy of moulding the pole-plates and of probing the equipotentials, simply because this transformation is not conformal.[1]

3. With a view to visualizing the use and the limit of this analogy, the following experiment has been carried out. As the profile of I the series of wave-patterns C, E, G, I and K, the waves calculated theoretically by Wigley for the geometrically simple ship form with infinite draft have been chosen.[2] If we denote the speed of the ship by c ft/sec, by l the length of the curved entrance or run (7.5 ft) and by L the length of the ship (16 ft), then for the wave-patterns C, E, G, I and K, $c/\sqrt{gl}$ is equal to 0.694, 0.675, 0.592, 0.512, 0.433, respectively and $c/\sqrt{gL}$ equals 0.475, 0.463, 0.405, 0.350 and 0.297.

As the pole-plate II, on the other hand, which corresponds to the bottom or more precisely to the equal-pressure surface at an infinite depth, we used a straight strip of plate. This was partly for simplicity on one hand, but on the other as we may safely assume that the form of the plate II would be hardly decisive for the final value of the wave resistance, because the symmetric part of the pressure does not contribute to the resistance.[3]

Measuring p at various points on the central plane of the ship and integrating, we can obtain the values of R_w, the total wave resistance of the ship, for various Froude

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1) There may be a possibility that the increase of the accurary introduced by magnifying the scale of z can compensate the error in violating the conformality. This is, however, another problem to be checked in future.

2) Wigley, *Proc. Roy. Soc.*, vol. 144 (1934).

3) For the case of G only, the equal-pressure surface calculated on the basis of the two-dimensional flow of an ideal fluid around the ship in was employed for the plate II in order to verify this assumption. No marked differences, however, cannot be observed in the final result, cf. Fig. 5.

numbers. Further, if we compare them with the theoretical result of Wigley, we can arrive at some conclusions about the utility, the scope and at the same time about the error of the analogy.

We made the copies of Fig. 2 of Wigley's paper, magnifying in such a fashion as 1 ft in the scale attached to the original figure corresponds to 30 mm for C, E and to 36 mm for G, I, K, respectively. The difference between the maximum crest and trough was thus found roughly equal to 46 mm for C and 22 mm for K. And strips of phosphorous bronze, 90 cm of length, were corrugated into the profiles of these surface elevations.

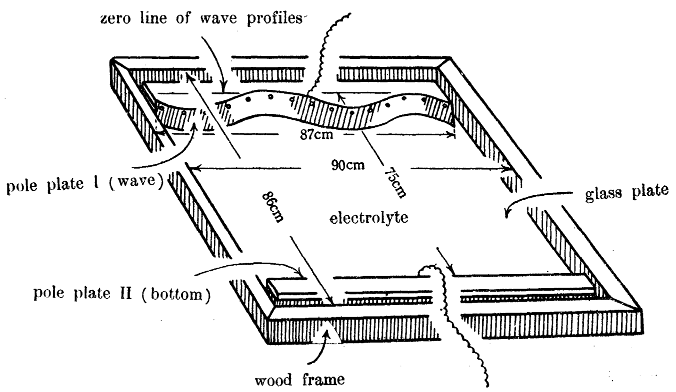

Fig. 2 General Arrangement of Electrolytic Basin

The general arrangement of the electrolytic basin is shown in the photograph and Fig. 2. Filling the basin with $CuSO_4$ solution (0.2 %), the equipotentials were detected with the accuracy of ± 1 mm in reference to the scale of section-paper placed under the glass plate. Fig.'s 3 and 4 show the electric circuit and the series of the equipotentials for the wave-pattern C, respectively, where the percentage attached to each contour denotes the value of φ when we put $\varphi = 0$ on I and $\varphi = 1$ on II ($z = 25$ ft). Below the line of 60 % the contours were so straight that it was found needless to continue the detection.[1]

4. Since on the φ-curves of 0 and 100 % p equals 0 and ρh lb ($\rho = 1.94 \times 32.2$ lb/ft^3, $h = 25$ ft for C, E and 21 ft for G, I, K), respectively, we know readily the actual value of p in lb/ft^2 for each of the percentage of the contours. By means of this map of equipotentials or rather equipressures we can read the value of p at every point we need. Integrating the component of p parallel to the direction of motion of the ship all over the wetted surface, we can obtain the total wave resistance R_w in lb. In Fig. 5 the curve of R_w/c^2 calculated by Wigley (*loc. cit.* Fig.'s 5A and 5B) and the points obtained by the present measurement are reproduced for ready comparison.

In view of the errors accompanying shaping of the poles, levelling of the glass plate and various other inevitable causes,[2] the agreement of C, E and G with the

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[1] As to the technique of measurement the following literature was very useful. Bradfield, Hooker and Southwell, *Proc. Roy. Soc.*, vol. 159 (1937).

[2] When we were working at this experiment Japan was in her worst condition; our present opinion is that this measurement must be and can be repeated with more accuracy and refinement.

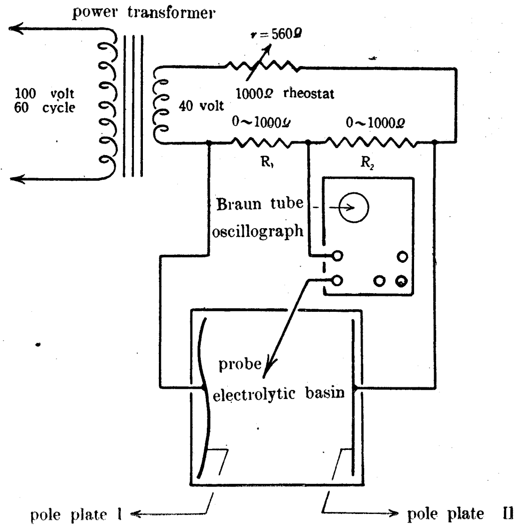


Fig. 3 Electric Circuit

theory is not disappointing, but I and K are much smaller than the exact values. This remarkable discrepancy reminds us of the notice by Havelock that the greater part of the wave resistance in lower speed is due to the diverging wave system in contrast to the fact that in higher speed the transverse system plays an essential rôle.[1] If the discrepancy for I and K results really from neglection of the diverging system, a question which has to be answered in future, Havelock's opinion seems to suggest a limitation of this analogy.

The idea of this experimentation is due to Professor Yamada of the Institute.

[1] Havelock, *Proc. Roy. Soc.*, vol. 82 (1909).

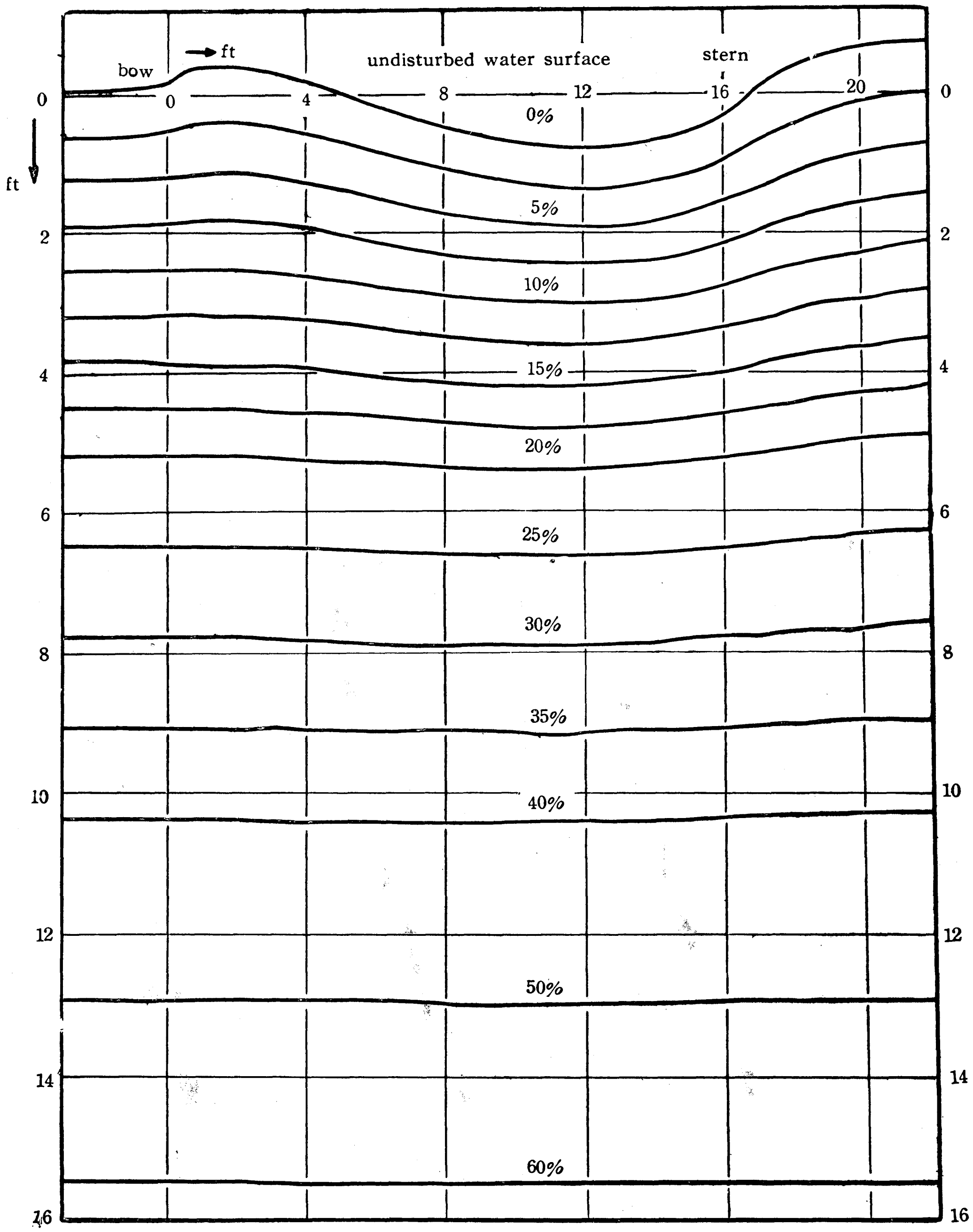
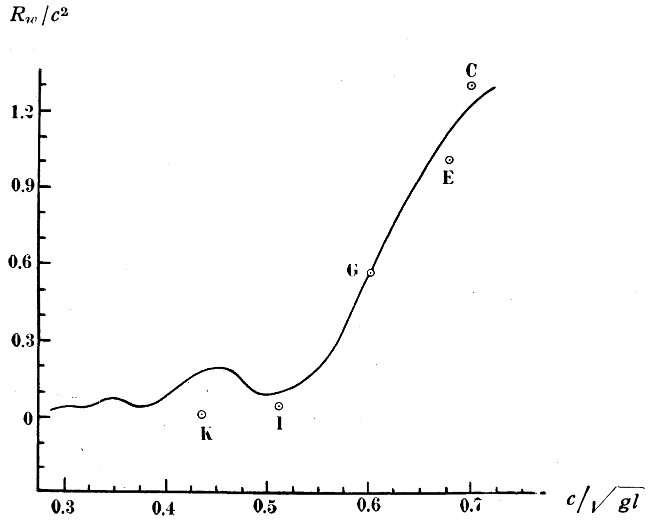


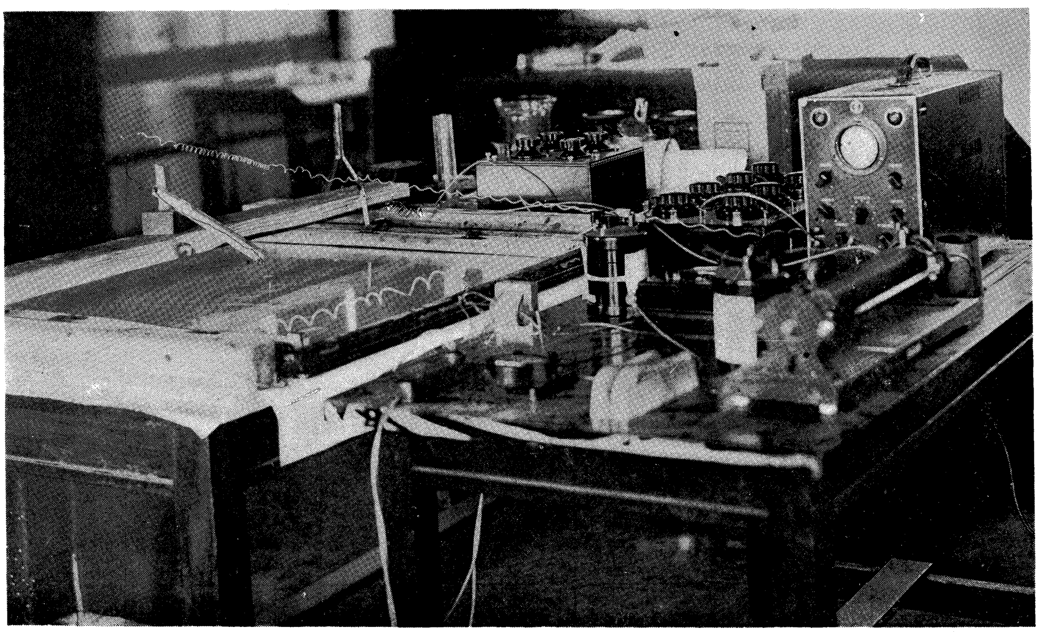
Fig. 4 Contours of Equal Pressure for Wave Pattern C

Fig. 5

R_w : total wave resistance in lb
c : speed of ship in ft/sec
l : length of curved entrance or run (7.5 ft)

—— : theory (Wigley)
⊙ : measurement (present method)





General View of Equipment

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