speed occur at lower speeds in shallow water, and are more pronounced ; the resistance is occasionally reduced when the speed is increased.

5. The changes of resistance produced by shallowness are accompanied by corresponding changes in the speed of revolution of the engines and in the trim of the vessel. These are illustrated by the curves in fig. 52, Plate VI., which are taken from a paper read before the I.N.A. by the writer in 1909, giving the results of some trials on H.M. torpedo-boat destroyer “ Cossack.”

The data obtained from the various shallow water experiments are capable of extension to ships of similar types by the application of the law of comparison at corresponding depths (pro­portional to the linear dimensions) and at corresponding speeds. The influence of shallow water on the speed of a large number of ships can be thus obtained; but the data at present available are insufficient to enable a general law, if any exists, to be determined.

A further modification in the conditions arises when a ship proceeds along a channel of limited breadth and depth. Some interesting experiments were made in this connexion by Scott Russell on the resistance of barges towed in a narrow canal. He obtained (by measuring the pull in the tow rope) the resistance of a barge of about 6 tons displacement, for a mean depth of the canal of about 4½ ft., as follows:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Speed in miles per hour . | 6·19 | 7'57 | 8∙52 | 9·04 |
| Resistance in pounds . | 250 | 500 | 400 | 280 |

At the critical speed (8·2 m. per hour) corresponding to the depth, the resistance was in this case reduced; and at a higher speed a further reduction of resistance was observed. It is stated that the boat was then situated on a wave of translation extending to the sides of the canal, and which was capable of travelling unchanged for a considerable distance; the resistance of the boat was then almost entirely due to skin friction.

When the speed of a ship is not uniform, the resistance is altered by an amount depending on the acceleration, the inertia of the ship and the motion of the surrounding water. In the ideal conditions of a vessel wholly submerged in a perfect fluid, the force producing acceleration is the product of the acceleration with the “ virtual mass,” which is the mass of the vessel increased by a proportion of the displacement; *e.g.* for a sphere, one half the displacement added to the mass is equal to the virtual mass. The effect of acceleration on a ship under actual conditions is less simple; and the virtual mass, defined as the increase of re- sistance divided by the acceleration of the ship, varies considerably with the circumstances of the previous motion. The mean value of the virtual mass of the “ Greyhound,” obtained by Froude from the resistance experiments, was about 20% in excess of the displacement. This value is probably approximately correct for all ships of ordinary form, and is of use in estimating the time and distance required to make a moderate alteration in speed; the conditions during the stopping, starting and reversing of ships are generally, however, such as to make this method inapplicable.

Propulsion.

The action of a marine propeller consists fundamentally of the sternward projection of a column of water termed the propeller race; the change of momentum per unit time of this water is equal to the thrust of the propeller, which during steady motion is balanced by the resistance of the ship.

Assuming in the first place that the passage of the ship does not affect and is uninfluenced by the working of the propeller, let V be the speed of the ship, *v* that of the propeller race relative to the ship, and *m* the mass of water added to the propeller race per second. The thrust T is then equal to *m* (v-V), and the rate at which useful work is done is TV or *m*V (v-V). Loss of energy is caused by (*a*) shock or disturbance at the propeller, (*b*) friction at the propeller surface, (c) rotational motions of the water in the race, and *(d)* the astern motion of the race. Of these (*a*), (*b*) and *(c)* are capable of variation and reduction by suitable propeller design; though unavoidable in practice, they may be disregarded for the purpose of obtaining the theoretical maximum efficiency of a perfect propeller. The remaining loss, due to the sternward race, is equal to *⅛m(υ-N)2∖* whence the whole energy supplied to the propeller in unit time is expressed by ⅛w(≠-V2) 2V

and the efficiency by The quantity *υ-V* is commonly termed

the *slip,* and the *slip ratio* ; the latter expression being denoted by *s*, the theoretical maximum efficiency obtained on this basis j—$

becomes 1 „ It appears, therefore, that the maximum efficiency should be obtained with minimum slip; actually, however, with screw propellers the losses here disregarded entirely modify this result, which is true only to the extent that very large slip is accompanied by a low efficiency. The foregoing considerations show that, with a given thrust, the larger *m* the quantity of water acted upon (and the smaller, therefore, the slip), the higher is the efficiency generally obtained.

The type of propeller most nearly conforming to the fundamental assumption is the jet propeller in which water is drawn into the ship through a pipe, accelerated by a pump, and discharged aft. The “ Waterwitch ” and a few other vessels have been propelled in this manner; since, however, the quantity of water dealt with is limited for practical reasons, a considerable sternward velocity in the jet is required to produce the thrust, and the slip being necessarily large, only a very low efficiency is obtained. A second type of propeller is the paddle, or stern-wheel which operates by means of floats mounted radially on a circular frame, and which project a race similar to that of the jet propeller. Certain practical difficulties inherent to this form of propulsion render it unsuitable or inefficient for general use, although it is of service in some ships of moderate speed which require large manoeuvring powers, *e.g.* tugs and pleasure steamers, or in vessels that have to run in very shallow water. The screw, which is the staple form of steamship propeller, has an action similar in effect to the propellers already considered. Before proceeding to discuss the action of screw propellers, it is desirable to define some of the terms employed. The product of the revolutions and pitch is often called the speed of the propeller ; it represents what the speed would be in the absence of slip. Speed of advance, on the other hand, is applied to the forward movement of the propeller without reference to its rotation; and is equal to the speed of the ship or body carrying the propeller. The difference between the speed of the propeller and the speed of advance is termed the slip ; and if the two former speeds be denoted by *υ* and V respectively, the slip is v-V and the slip ratio y — V

(or properly the apparent slip ratio) ——. This notation corresponds to that previously used, v-V being then defined as the absolute velocity of the race; it is found with propellers of the usual type, that zero thrust is obtained when ∑j=V, provided that the “ conventional pitch, which for large screws is approximately 1∙02 times the pitch of the driving surface, is used in estimating ν. The pitch divided by the diameter is termed the pitch ratio.

The theories formulated to explain the action of the screw pro- peller are divisible into two classes—(i.) those in which the action of the screw as a whole is considered with reference to the change of motion produced in the water which it encounters, the blade friction being, however, deduced from experiments on planes; and (ii.) those in which the action of each elementary portion of the blade surface is separately estimated from the known forces on planes moved through water with various speeds and at different angles of obliquity; the force on any element being assumed uninfluenced by the surrounding elements, and being resolved axially and circumferentially, the thrust, turning moment, and efficiency are given by summation. Professor Rankine in *Trans. Inst. Naυ. Archs.,* 1865, assumed that the propeller impressed change of motion upon the water without change of pressure except such as is caused by the rotation of the race. In Sir George Grecnhill's investigation (*Trans. Inst. Nav. Archs.,* 1888) it is assumed conversely that the thrust is obtained by change of pressure, the only changes of motion being the necessary circumferential velocity due to the rotation of the screw, and a sufficient sternward momentum to equalize the radial and axial pressures. These two theories are both illustrative of class (i.) ; and this idea was further developed by Mr R. E. Froude in 1889, who concluded that the screw probably obtained its thrust by momentarily impressing an increase of pressure on the water which eventually resulted in an increase of velocity about one-half of which was obtained before and one-half abaft the screw. A lateral contraction of the race necessarily accompanies each process of acceleration. These general conclusions have been in some degree confirmed by experiments carried out by Mr D. W. Taylor, *Proceedings of the {American} Society of Naυal Architects, &c.,* 1906, and by Professor Flamm, who obtained photographs of a screw race in a glass tank, air being drawn in to show the spiral path of the wake.

In *Trans. Inst. Nav. Archs.,* 1878, Froude propounded a theory of the screw propeller illustrative of the second class above mentioned, the normal and tangential pressures on an elementary area being deduced from the results of his own previous experiments on obliquely moving planes. He was led to the following conclusions regarding maximum efficiency:—(1) The slip angle (obliquity of surface to the direction of its motion) should have a particular value (proportional to the square root of the coefficient of friction) ; and (2) when this is so, the pitch angle should be 45°. The maximum efficiency obtained from this investigation was 77 %. This theoretical investigation, though of importance and interest, does not exactly represent the actual conditions, inasmuch as the deductions from a small element are applied to the whole blade, and, further, the considerable disturbance of the water when a blade reaches it, owing to the passage of the preceding blade, is ignored.

The must complete information respecting the properties of screw propellers has been obtained from model experiments, the law of comparison which has been shown to hold for ship resistance being assumed to apply equally to screw propellers. No frictional correction is made in obtaining the values for large screws from the model ones; as stated by