come to rest at the end of the starboard roll, the centre of gravity of the water should have again reached the middle line, and the righting couple should be neither increased nor diminished by the water-chamber, except in so far as it affects the displacement and the vertical position of the centre of gravity. The same process is repeated on the ship’s roll back from starboard to port. Thus the water-chamber reduces the angle of roll of the ship chiefly by modify­ing the righting couple acting upon her throughout the rolling; it increases the righting couple which opposes the motion as the ship heels over, thereby reducing the amount of the heel, and on the return roll it lessens the righting couple and causes the ship to move more slowly than she otherwise would, so that she acquires less angular momentum on reaching the upright, and therefore tends to roll less deeply the other way.

Two water-chambers were originally contemplated in the old *Inflexible,* but the space occupied by one of these was required for other purposes, and only one, the smaller of the two, which was 51 ft. long (across the ship), and 14 ft. wide (fore and aft), was finally fitted. This was shown to reduce the rolling by about 25%. Several ships have since been fitted with this device.@@1

In addition to trials at sea to ascertain the diminution of roll by this means, still-water rolling experiments were carried out in the “ Edinburgh ” and compared with the results obtained with a model water-chamber on a linear scale of loaded so that its period and stability corresponded to those of the ship. A close agreement was observed between the behaviour of the model and the ship; and this enabled the experiments to be carried out over a larger range of conditions than would have been practicable with the ship alone. The model was supported on knife edges and connected to a paddle partially immersed in the water of a tank; this was adjusted to represent to scale the natural extinction of roll in the ship without

the water-chamber. The length of the chamber (in the ship) was 16 ft.; and widths of 43 ft., 51½ ft. and 67 ft. were successively given to it. The displacement of the ship was about 7500 tons; the period 10 seconds; and the metacentric height 7∙52 ft. On experimenting with different depths of water, it was found that the maximum extinctive effect at all angles of roll was obtained with the depth at which the period of motion of the water from side to side of the tank is equal to the period of the ship. The best depths were found to be 2∙3 ft. and 3∙35 ft. with breadths of 43 ft. and 51½ ft. respectively, thus agreeing closely with the theoretical formula, ν = √*gh*, for the speed of a solitary wave across the water-chamber. In these circum­stances the water rushed across the tank in a breaking wave or bore, and consumed energy in its passage and through its violent impact with the sides of the tank. With other depths, the motion of the water, at moderate angles, took the form of a slope gently alternating from side to side at small angles of roll ; and the effect was practically non-extinctive. With the critical depth the growth of the resistance to rolling commenced almost at zero angle; but, with other depths, the extinction was nearly nil, until a certain angle of roll was attained, whose amount increased with the departure from the critical depth. At the larger angles of roll, the disadvantage of the departure from the critical depth was not marked. The resistance of the chamber increased considerably with the breadth; the value of the 51½-ft. chamber was roughly twice and that of the 67-ft. chamber three times that of the 43-ft. chamber.

In order to compare the effect of water-chambers with that of other methods of extinction, it is observed that the resistance due to the former increases slowly at large angles of roll. The effectiveness of bilge keels, on the other hand, increases rapidly as the angle of roll increases. It was found that, with 12° roll, the resistance of the water­chamber was equivalent to that of 2 ft. of additional bilge keel ; but at 17½° the water-chamber was relatively about half as effective. With 3° of roll, however, the water-chamber was about 9 times as

effective as the additional bilge keel. Fig. 31 shows the comparative rates of extinction under the various conditions.@@2

Water-chambers have been successfully employed to limit the rolling motions at sea in ships of the old “ Inflexible,” “ Edinburgh" and “ Admiral ” classes, and in other warships and merchant vessels.

Sir John Thornycroft devised an arrangement for overcoming the rolling motion of a ship amongst waves, consisting of a weight carried from side to side so as always to oppose the heeling couple caused by the wave slope. The weight was automatically worked by apparatus controlled by two pendulums (or their equivalent), one of which—a long period pendulum—remained vertical, and the other —a short-period pendulum—placed itself perpendicular to the effective wave slope. The gear was fitted on a yacht of about 230 tons displacement, the moving weight being 8 tons; and the net effect in this case was to reduce the rolling by about one-half. (See *Trans. Inst. Nav. Archs.* 1892.)

An interesting application of the gyroscope to the diminution of rolling was devised by Dr O. Schlick, and fitted by him to the S.S. “ See-bar.” The principle of its action, the details of the gear, and a description of the trials are given in papers read before the Inst. Nav. Archs. in 1904 and 19o7. Particulars of the “ See-bar ” were: length 116 ft., breadth 11∙7 ft., draught 3∙4 ft., displacement 56 tons, metacentric height 1∙64 ft., and period of double roll (gyroscope at rest) 4·14 seconds. The fly-wheel of the gyroscope was one metre in external diameter, weighed 1100 lb, and it was run at 160θ revolutions per minute ; its axis was initially vertical, and the casing containing the wheel was capable of revolving about a horizontal athwartship axis, the centre of gravity of the apparatus lying slightly below this axis. A brake was fitted to control the longitudinal oscillations of the casing. When the wheel was revolving and the axis held by the brake, no effect was produced upon the motion of the ship ; but when the axis was allowed to oscillate freely in the middle-line plane the period of roll was lengthened to 6 seconds, but no other extinctive effect was obtained. By suitably damping the longitudinal oscillations of the gyroscope, however, by means of the brake, a large extinctive effect upon the rolling was experienced; and during the trials made, the apparatus stopped practically all rolling motion.

The equations for the pitching motions of a vessel arc identical in form with those for rolling; and the preceding remarks are, in general, equally applicable to pitching. In a large number of ships the period for pitching is approximately one-half of that for rolling; but the angles attained arc considerably less. Where control over the longitudinal positions of weights is possible, *e.g.* in small sailing vessels, weights are removed as far as possible from the ends in order to shorten the period, the safety of short ships and boats being secured when the deck is maintained as nearly as possible parallel to the wave slope (ν. remarks by Froude *ante*).

The single period for heaving and dipping oscillations is equal to τ when W is the displacement in tons, and T" the tons per inch

immersion. When proceeding across waves of apparent semi-period T1, forced heaving oscillations of semi-amplitude αψτiτp are obtained, where T is the single period of dip, and *2a* is the vertical distance between the statical positions of the ship on crest and in trough of wave. These oscillations combine with the free dipping oscillations due to the circumstances of the initial motion, the resultant motion being of interest in connexion with the longi- tudinal bending moments in the ship caused by the waves. (See section *Strength.)*

Pitching or rolling is frequently the cause of dipping oscillations, and the motion is then termed uneasy; this action may be of im- portance in ships whose sides near the water-line have a considerable slope to the vertical, since any rolling motion is then accompanied by vertical oscillations of the centre of gravity. It may also be shown that forced dipping oscillations of considerable amplitude are ob­tained when the period of roll (or pitch) in such cases approximates to twice the dipping period; the complex nature of the resistances attending the motion of the ship has, however, prevented a complete investigation being made.

Interference also occurs between the rolling and pitching movements of a ship, when the centres of gravity of the wedges of immersion and emersion for moderate angles of heel are separated by a considerable distance longitudinally; and occasionally uneasy rolling of a peculiar character is caused thereby.

*Resistance.*

The resistance of a ship in steady motion, or the force exerted by the surrounding water on the hull, opposing its progress, is equal and opposite to the thrust of the propellers. The ship is subjected to a system of balanced forces, each of which is in some degree affected by the others. It is convenient, however, first to confine attention to the resistance of the hull, assuming the

@@@1 See paper on “ A Method of Reducing the Rolling of Ships at Sea ” in *Trans. Inst. Nαυ. Archs.* 1883.

@@@2 See paper entitled “ The Use of Water-Chambers for Reducing the Rolling of Ships at Sea,” *Trans. Inst. Nav. Archs.* 1885.