THE EFFECT OF SHOCK ON SHIPS' MACHINERY.

A new problem for naval machinery designers has been introduced with the present war. This concerns the effects of non-contact under-water explosions which although of a transient nature, are of a magnitude unexpectedly large. In most engineering design, parts have to withstand sustained loads or regular periodic forces and safe stresses are determined by yield, creep or fatigue limits. In the case of explosions the machinery parts may have to withstand the peak forces for less than one hundredth of a second perhaps only once in the lifetime of a ship and the yield or proof stress at the appropriate rate of loading forms the criterion of strength. The estimation of the forces that may act on any particular part leads into a branch of physics and mechanics seldom met by naval engineers. The problem is made more difficult by the fact that one's senses are of little use in forming an idea of what occurs, so that it is necessary to depend on delicate instruments capable of recording faithfully the sequence of events during the critical minute fractions of a second.

When an underwater explosion occurs it sends a 'pressure pulse' radially outwards in all directions, travelling at approximately the normal speed of sound in water, *i.e.*, about 5,000 feet per second. (In air the speed is 1,100 feet per second and along a steel rod 16,700 feet per second.) At each point in the water reached by this pressure pulse there is a sudden rise in pressure followed by an exponential fall for a few thousandths of a second. It is the arrival of this pressure pulse at the surface of the sea which causes the shimmer on the surface growing in the case of shallow explosions into the symmetrical dome called the 'spray dome.' Nearly all shock damage is caused by the impingement of the pressure pulse on the shell of a ship, but there are subsequent effects of the explosion which may in particular cases cause further damage.

Secondary Pulses.

The globe of gas formed by the detonation of the explosive expands rapidly and due to the kinetic energy given to the immediately surrounding water it continues to expand beyond the point at which its pressure is equal to the hydrostatic pressure in the water. Thus, an oscillation of the bubble about its equilibrium size is set up and at each minimum a secondary pressure pulse is sent out. The energy contained in these secondary pulses is much less than that in the initial pulse, but since the gas bubble is in general formed upwards by gravity, a secondary pulse may emanate from a point very much closer to a ship and thus cause more severe damage locally than the main pressure pulse alone. The time interval between pulses depends on the size and depth of the explosion and is about half a second to a second for explosions commonly experienced. The spectacular plumes of spray which are thrown up after a sufficiently shallow explosion are probably caused by secondary pulses occurring when the gas bubble has nearly reached the surface. An explosion which sends up a tremendous plume is more impressive than one where only the spray dome is seen, but this forms little criterion of the shock damage likely to result unless the ship happens to be directly over the point where the plume would occur.

In ships subjected to the first magnetic mines it was usually reported that there were two explosions within a second of one another. Since it was unlikely that in each case two magnetic mines had exploded, it was at first thought that the two apparent explosions were caused by the difference in time taken by the waterborne and airborne sound to arrive. In one case, an officer started off for the engine room on feeling the shock from the first explosion and about a second later was injured by what was thought to be a second explosion. It is now realised that these effects were due to secondary pressure pulses.

When the main pressure pulse impinges on the hull of a ship the first effect is to set the shell plating in motion. Within a fraction of a second, points on the plating reach a velocity of several tens of feet per second and any small items mounted directly on the plating (*e.g.*, the measuring instruments used in determining this) must be capable of withstanding accelerations of several thousand g. The plating tends to bend between its supporting frame, and in a ship which has been subjected to a severe explosion the plating becomes permanently dished in between the framing up to a maximum of several inches, showing the ribs and giving rise to the expression the ' hungry look.' In less severe explosions the plating may dish elastically and the hull may appear untouched after the explosion although internal gear may have suffered more or less severely from shock.

Resistance.

Heavy masses mounted almost directly on the bottom framing offer a resistance to the motion of the framing by their inertia, their own accelerations being governed by the force which the surrounding plating exerts in coming to rest. A few thousandths of a second after the pressure pulse has impinged on the point on the ship's hull nearest to the explosion, the outer shell must have an undulating surface over an area near to this first point, while beyond this area no movement of the plating has yet occurred. The undulations must consist partly of the more heavily loaded frames lagging behind the lightly loaded ones and superimposed on this the various stages of the dishing referred to above.

Within twenty or thirty thousandths of a second the whole of the shell of the ship has been set in motion by the arrival of the pressure pulse meanwhile the points at which the pressure pulse first arrived have already started to oscillate with a number of superimposed frequencies determined by the stiffness of the shell plating, framing and seatings and by the various masses involved. It is this initial oscillation of a machinery item mounted near the ship's skin which usually determines whether or not it will be damaged. If it can withstand the maximum acceleration and deceleration to which it is subjected during this period, it will probably survive anything to which it is subjected thereafter. A machine weighing about a ton may be subjected to a maximum acceleration of several hundred g, and a maximum deceleration of about half the maximum acceleration, from an explosion of such severity that the bottom is just not holed and may move upward nearly six inches in this time.

Oscillations.

As the ship's bottom at various points moves upward during this period, it deforms the section of the ship and tends to set the ship's structure above in motion. The energy from the explosion which was originally received by the ship's shell is thus distributed throughout the ship, but the parts nearest to the first point of impingement of the pressure pulse receive their motion earliest. Thus oscillations are set up in the various sections of the ship due to the inward motion of the ship's shell before the upper parts have started to move. The ship gradually starts to vibrate as a whole with two or more nodes due to the greater velocities imparted to the structure in the vicinity of the explosion and to the different times at which the various sections of the ship start to move. The frequency of vibration of the various sections of the ship may be of the order of 10 to 50 cycles and that of the flexural vibrations of the ship as a whole which is usually called whipping may be 2 to 3 cycles per second. Everything within the ship must also have a damped oscillation at its own natural frequency, due to the sudden application of motion.

Thus there are at least six distinct types of motion set up when a ship is subjected to the pressure pulse from a non-contact underwater explosion. These are:—

(1) Initial motion of the shell plating. Maximum acceleration several thousand g.

(2) Initial motion of objects mounted on the bottom framing. Maximum acceleration largely dependent on the mass, several hundred g for a mass of about 1 ton.

(3) Vibration of sections of the ship. Maximum acceleration less than one hundred g.

(4) Whipping of the ship as a whole. Maximum acceleration, say 5 g.

(5) Vibration of all parts at their own natural frequencies. Maximum accelerations are dependent on the frequency and the lower the frequency the less the acceleration.

(6) In addition, since the nett momentum given to a surface vessel is mainly upwards, the ship as a whole will rise in the water until brought to rest by gravity.

Damage cannot occur unless sufficient relative motion between the relevant parts has taken place to cause the necessary strain for failure of individual items, or in other cases the fouling of moving parts, the opening of switches, etc. For items supported only at definite points this means that there must be relative motion between the supports and the centre of gravity of the main body. In an elastic body the acceleration is directly proportional to the relative motion that has already occurred at any given moment. Hence the maximum acceleration which the main body receives forms a criterion of whether or not failure will occur.

The maximum acceleration which an item receives is dependent on its flexibility, rigid items receiving greater accelerations than flexible ones from the same surrounding motion. For an understanding of the problem of shock it is useful to have a numerical idea of the natural frequencies of various common fittings. A rough guide is given by the fact that the natural frequency in cycles per second is between 3 and 4 times the reciprocal of the square root of its deflection in inches under its own weight. Thus an item which deflects ·010 inch under its own weight has a frequency between 30 and 40 cycles per second, and for a frequency of 3 or 4 cycles per second it would deflect one inch under its own weight. Castings used for auxiliary machinery may have natural frequencies of several hundred cycles per second and small rigid fittings several thousand. Resilient mountings fitted in H.M. ships normally have frequencies between 20 and 40 cycles per second.

Where the natural frequency of an item is substantially less (say one third or less) than the frequency with which the supporting structure is vibrating, the maximum acceleration given to it is much smaller than that of the supporting structure and tends to be directly proportional to the maximum upward velocity of the surrounding structure and to its own natural frequency. This upward velocity of the surroundings is due to the momentum given by the pressure pulse which is mainly upwards. It can be considered as made up by the upward velocity of the ship as a whole and the local component of the velocity of the whipping vibration, both of which are of considerable duration compared with the natural period of common flexible fittings.

The reduction in maximum acceleration below that of the surroundings is due to the longer time taken by the flexible items to reach the velocity of the surrounding structure and must entail relative movement between the items and the surrounding structure. The maximum relative movement tends to be directly proportional to the maximum upward velocity of the surroundings and inversely proportional to its own natural frequency. For an upward velocity of 10 ft. per second and a frequency of 20 cycles per second it is about one inch (the maximum acceleration in this case being about 40 g).

On the other hand, comparatively rigid items must move with the surrounding structure. For items with natural frequencies four or more times as great as that with which the surroundings are vibrating, there is practically no relative motion between the item and the structure, both receiving the same maximum acceleration. The mass of the item, however, affects the vibration of the structure and where the mass is large the maximum acceleration of both are substantially reduced.

Where the natural frequency of the item and the frequency with which the structure is vibrating are more nearly equal there is a tendency towards resonance. Due, however, to the rapidity with which most of the vibrations are damped out and the changes of frequency of vibration which are continuously occurring in the early stages the maximum acceleration is seldom increased to as much as double that of the surrounding structure. The whipping vibration of the ship as a whole is frequently sustained for many seconds, but due to the extremely low frequency of this compared with typical internal fittings, there is little chance of resonance. Most fittings are amply strong to withstand the comparatively small accelerations and decelerations associated with this vibration (say 5 g) and are not adversely affected by the large displacements (a few feet perhaps) involved.

Effect on Personnel.

Human beings, however, respond quite differently from machines to the various effects of underwater explosions. In the first place, they are extremely flexible, and in the second they have no holding down bolts. With regard to the first there have been a few unfortunate exceptions, where men standing with braced legs on rigid parts of the structure close to the outer shell of the ship have had ankles, knees or spines damaged. With slightly bent legs this does not occur. In general, the main factor affecting the crew, is the maximum velocity which they attain, since, in the absence of holding down arrangements, this determines how far they will be flung into the air, and it is from this that most casualties arise. The human senses are therefore apt to judge the relative severities of explosions largely by the amount of whipping because this is at a frequency which can be observed and lasts for an appreciable period, it is also the most likely cause of injury. On the other hand it is difficult to form a measure of the high accelerations to which the more rigid fittings are subjected for a very short period immediately after the arrival of the pressure pulse.

In this brief article many factors have been omitted, but sufficient has been said to show that the broad principles of design to withstand shock must be:—

(*a*) Avoidance of brittle materials;
(*b*) Giving machines sufficient strength to withstand the maximum forces or accelerations to which they are subjected; or
(*c*) Reducing the maximum forces or accelerations to which machines are subjected by the introduction of a suitable degree of flexibility, where relative motion can be accepted.