The Stability of Submarines.

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The purpose of this paper is to place on record the results of calculations made to determine the conditions of stability of submarine vessels in varying circumstances which may occur on service. Accidents have happened to many submarines, and in some instances have been accompanied by loss of life. After investigating possible causes of accident, the author was convinced that one of the chief was the singular variation in stability and buoyancy produced by changes in the draught of water and the "trim" of submarines. He was led, therefore, to undertake the detailed calculations of which the principal results are now stated and illustrated.

Either by accident or intention, submarines may reach considerable depths below the surface and be exposed to severe external fluid pressures. Ample structural strength must be provided to meet these pressures and to prevent deformation of the vessels. In order to fulfil this object with moderate weights of structures, submarines are made "cigar-shaped," with circular or nearly circular cross-sections. The cigar-shape is usually somewhat disguised by light superstructures built above the upper surface of the hull proper, and carrying decks or platforms, which add to the comfort and convenience of the crews when the vessels are floating at the surface—in the "awash" condition —at their lightest draught. In that condition water is excluded from the spaces between the superstructures and the cigar-shaped hulls, and the buoyancy and stability are sensibly increased.

The other extreme condition at the surface is that when a submarine has been "trimmed" for diving, and floats with a very small portion of her hull above water. This is effected by admitting water-ballast into tanks specially constructed for the purpose and of known capacity. The final adjustments of draught and trim during the process of trimming require great care. All openings into the interior are closed and secured in a watertight manner before trimming is commenced. Water is also allowed to enter the spaces between the superstructures and the cigar-shaped hull, and to remain in free communication with the surrounding water, so that the lightly constructed superstructures may sustain no external pressure when the vessel is submerged.

Diving is accomplished by giving the submarine headway, and so manipulating horizontal rudders that the bow is depressed. The "stream-lines" developed in the water by the onward motion produce downward pressures on the upper surface of the hull towards the bow; the vertical component of these pressures overcomes the vertical component of the rudder pressures and the small "reserve of buoyancy" which the submarine retains, and the vessel moves obliquely downwards until the desired depth below the surface is reached. The horizontal rudders must be then manipulated by a skilled steersman in such a manner that further motion (although really along an undulating course) is practically at a constant depth below the surface. When headway ceases, both rudder pressure and stream-line motions disappear, the small reserve of buoyancy reasserts itself and the submarine rises to the surface.

This general statement may be illustrated by figures for an actual submarine, resting on official evidence given at the enquiry into the foundering of submarine A8 at Plymouth last year.

In the awash condition, at the lightest draught of water, the reserve of buoyancy was about 13 tons (excluding the conning tower), the corresponding displacement exceeding 200 tons; so that the maximum reserve of buoyancy was about 6 per cent. of the displacement. The minimum reserve of buoyancy accepted for any class of war-ships at their deep-load draught has been about 10 per cent. in low-freeboard American "monitors," many of which vessels foundered. For "breastwork monitors" in the Royal Navy the corresponding reserve was 30 per cent. of the load displacement; for high-freeboard war-ships and passenger steamers it is from 80 to 100 per cent.; for cargo steamers it varies from 25 to 40 per cent. The contrast between submarines at their lightest draught and other types of ships at their deepest draught, shown by these figures, indicates the acceptance of altogether exceptional conditions in submarines, and the necessity for their cautious management in the awash condition at the surface, when the apertures on the upper surfaces are kept open.

These apertures are closed and secured before the vessels are trimmed for diving by admitting water-ballast. In the diving condition the reserve of buoyancy is extremely small. For submarine A8 it is said to have been 800 pounds, the corresponding displacement being about 220 tons. In other submarines of about the same displacement the reserve of buoyancy in the diving condition has been only 300 to 400 pounds. Consequently there is a necessity for extreme care in the final stages of trimming.

The cigar-shape of the hulls involves very rapid changes in the areas and moments of inertia of the planes of flotation as the draught of water is increased in passing from the awash to the diving condition: the stability is greatly reduced, and every member of the crew has to remain in his station.

No weights must be allowed to shift. All the conditions, in fact, differ from those which prevail in ships of ordinary form as they pass from the extreme light draught to the deep-load, for in such ships the outlines of transverse sections approximate to the vertical, except near the bow and stern, over the range between these extreme conditions, and the areas and moments of inertia of planes of flotation do not vary greatly.

These general statements may be illustrated by the comparison of a small cruiser of ordinary form with a submarine. The cruiser is about 260 feet long at the water-line, 37 feet broad, and 14 feet 6 inches mean load-draught, the corresponding displacement being about 2000 tons. The submarine has an extreme length of 150 feet, is 12·2 feet in extreme breadth, and has a displacement of 300 tons in the diving condition. In the light (awash) condition the submarine draws about 18 inches less water than in the diving condition, and has a displacement of about 284 tons. When awash the length at the water-line is 94 feet, and breadth extreme 8·2 feet; when in the diving condition the corresponding measurements are 41 feet length and 3·6 feet breadth. These figures differ widely from the length of 150 feet over all and 12·2 feet maximum breadth. In the cruiser, within the corresponding range of draught (18 inches) there is practically no change in length and breadth extreme at water-line, and these dimensions are practically identical with the extreme dimensions of the vessels. Fig. 1 illustrates the contrast

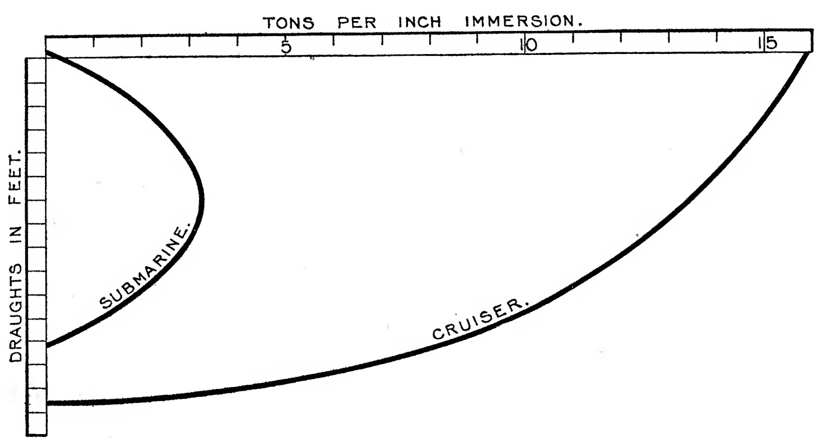

Fig. 1.

between the cigar-shape and the ordinary ship-shape. Horizontal measurements to the curves on that diagram, at any draught of water, measure the area of the corresponding plane of flotation, and the number of tons required to immerse the vessel one inch. It is obvious that the small area of the plane of flotation at the lightest draught, its rapid diminution as the draught is increased, and the critical condition when trimmed for diving, all render possible the establishment of vertical dipping oscillations in submarines by comparatively trifling disturbances in the water-surface surrounding them.

Fig. 2 shows the "metacentric diagrams" for *transverse* inclinations of the two vessels, constructed in the usual manner. MM shows the *locus* of the metacentre of the cruiser, and BB that of the centre of buoyancy as the draught of water varies. The curves *m, m, m* and *b, b, b* show the corresponding *loci* for the submarine. The intercept between these curves on any vertical ordinate represents the height of the metacentre above the centre of

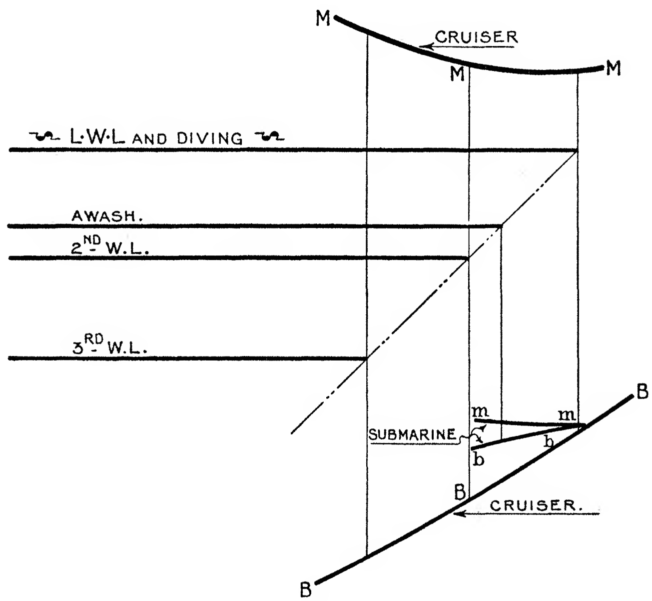

Fig. 2.

buoyancy at the corresponding draught of water. For the submarine in the awash condition this height is 0·32 foot, and in the diving condition it is 0·01 foot. Stability is obtained by disposing the weights so that the centre of gravity of the vessel and its contents lie below the axis; and in some existing submarines in their diving condition the vertical distance between the axis and the centre of gravity, or metacentric height, is said to be about 9 inches. When submerged, this measure of stability, of course, applies to inclinations from the vertical in any direction.

For the cruiser the height of the metacentre above the centre of buoyancy is 7·7 feet at the load water-line, and 8·6 feet for the water-line (18 inches below the load) corresponding to the awash condition of the submarine. The centre of gravity of the cruiser is about 2 feet below the metacentre and $5\frac{3}{4}$ feet above the centre of buoyancy in the load condition; the metacentric *locus* is nearly horizontal from the load to the light condition, and the centre of gravity rises a few inches as coals and stores are consumed.

Fig. 3 shows the metracentric diagrams for *longitudinal* inclinations. For the submarine awash the metacentre is 37 feet above the centre of buoyancy;

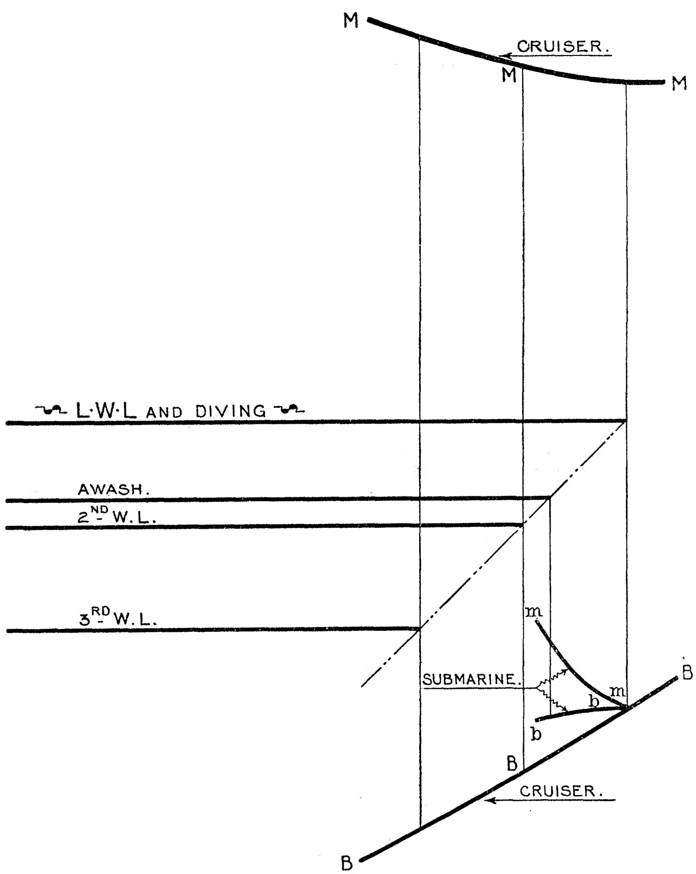

Fig. 3.

in the diving condition it is only 1·25 feet above. For the cruiser floating at a water-line 18 inches below the load draught, the height is 352 feet; at the load draught it is 328 feet. Expressed in terms of the length over all, the heights of metacentres above centres of buoyancy are 0·25 and 0·0083 times the length respectively for the awash and diving conditions, as against 1·35 and 1·26 times the length for the cruiser at corresponding draughts. These figures indicate the relatively small longitudinal stability of the submarine, and the necessity for avoiding any movements of weights when the vessel is in the diving condition or submerged.

Reference has been made above to the effect upon stability produced by the addition of superstructures. Fig. 4 illustrates this effect for transverse inclina-

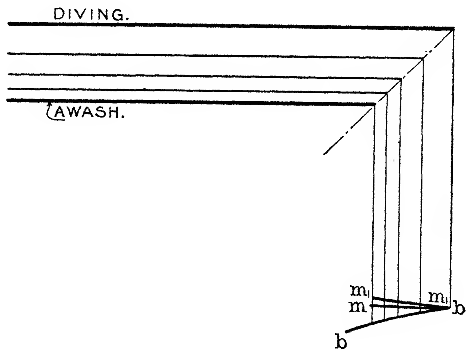

FIG. 4.

tions, *m m m* being the metacentric *locus* without superstructure, and m_1 m_1 m_1 the *locus* with superstructure closed and water excluded from spaces between it and the cigar-shaped hull. In the awash condition the height of the transverse metacentre above the centre of buoyancy is increased about *one-sixth* by the superstructure. The effect of the superstructure upon longitudinal stability is much more marked, as will be seen from fig. 5. In

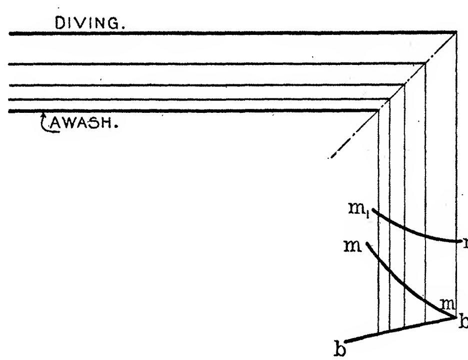

FIG. 5.

the awash condition, closing the superstructure increases the height of metacentre above the centre of buoyancy by fully 50 per cent.

It will be obvious from these diagrams that the maintenance of the full reserve of buoyancy is essential to the safety of a submarine when proceeding at maximum speed at the surface. In the case of A8, owing to special circumstances, this condition was not fulfilled, and the vessel proceeded at full speed on the surface with her ballast-tanks partly filled with water and with only 6 tons reserve of buoyancy as against the maximum reserve of 13 tons. In consequence of this deeper draught the longitudinal metacentric height was reduced from 12 feet to $8\frac{1}{2}$ feet and the power of resisting changes in longitudinal trim was correspondingly diminished. Since that accident took place, definite orders have been given by the Admiralty that the maximum reserve of buoyancy shall always be secured before submarines are driven at full speed on the surface. The precaution is obviously necessary.

When a submarine is in the diving condition with all apertures closed and crew stationed, the metacentric height (as above stated) is very small, and the trim may be sensibly and rapidly disturbed by small external forces. Consequently very moderate angles of helm given to the horizontal rudders by the operator will produce sensible changes of trim; and, as the pressures on the rudders vary as the *square* of the speed of the vessel, increase in speed with consequent increase in rudder pressures demands greater skill and precaution on the part of the helmsman. A very small amount of trim "by the bow" in association with moderate speed when submerged will bring a submarine to a considerable depth below the surface in a very short time. Experience proves that with trained and disciplined operators at the helm, and with moderate speeds such as have been accepted hitherto, submarines can be worked at fairly constant depths below the surface. On the other hand, many cases have occurred where submarines have reached considerable depths and have touched bottom in consequence of slight accidents or failure in control. These considerations point to the conclusion that much higher speeds than have been obtained hitherto when submerged must be accompanied by greatly increased risk; and it may be questioned if the gain in offensive power, obtained by increased speed, justifies the change in these circumstances. For large submarines it is universally agreed that automatic appliances for regulating depth below the surface are not to be trusted, although they are successful in locomotive torpedoes.

Close approximations can be made to the pressures developed on the horizontal rudders of a submarine moving at a given speed, and to the corresponding changes of trim produced in the vessel. Similar approximations cannot be made at present to the pressures and inclining moments consequent on the stream-line motions in the water surrounding a submarine when she moves ahead. This matter can only be dealt with by direct experiment on models and submarines. In the course of the enquiry into the foundering of A8, this conclusion was universally accepted. Differences of opinion existed as to the primary cause of that accident. It was obvious that the deeper draught, the lessened stability and the open hatch all conduced to the disaster; but experienced witnesses asserted that they were not of opinion that the vessel could have been made to dive suddenly as she did if she possessed as much as 6 tons reserve of buoyancy. Others equally experienced entertained the opinion that this was the real cause of the accident. After a careful analysis of the evidence the author was convinced that the latter opinion was correct. It was stated at the time that the Admiralty proposed to have experiments made at their experimental tank and on actual submarines in order to settle this difference of opinion. Up to the present time no results of such Admiralty experiments have been published: if they have been made, this silence is much to be regretted on scientific grounds, and no reason is seen for refusing the information. It has been stated authoritatively that experiments of the kind have been made on models of submarines at the Experimental Establishment of the United States Navy at Washington, and that the results have confirmed the opinion expressed by the author.

In connection with the enquiry into the loss of A8 it was made known that her commanding officer recognised the fact that lessened stability must accompany deeper immersion, and that he trimmed the vessel 4° by the stern (lifting the bow about 4 or 5 feet) in the belief that this change would make the vessel less liable to be driven under water by the stream-line action on the bow.

In considering all the circumstances the author was consequently led to investigate the variations in stability accompanying changes of trim in submarines, and to compare them with corresponding changes in other ships. The technical term "trim" here used means the difference in draught of water at the bow and stern: it has no relation to "trimming" for diving. It was obvious, of course, that the cigar-shape must introduce variations in stability with change of trim much greater than those which would occur in vessels of ordinary form, and it was known that in ordinary vessels the changes of trim which occur in service are not of practical importance. Figs. 6 and 7 give the results obtained for the submarine awash and for the cruiser at load draught, when changes of trim take place by the bow and stern, up to 6° from the "even-keel" condition. In order to compare the two types more closely, the heights of metacentres above centres of buoyancy for the even-keel condition are treated as "unity" in both cases, although they differ widely, as above stated. Ordinates to the curves at any angle of trim measure the relative heights of the corresponding metacentre above the centre of buoyancy. Fig. 6 shows these heights for transverse inclinations and fig. 7 those for longitudinal inclinations. In both cases the effect of superstructures is omitted.

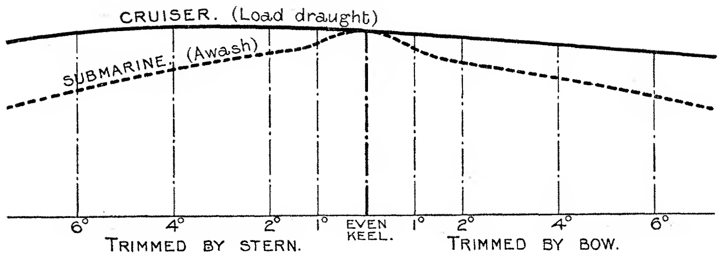

Fig. 6.

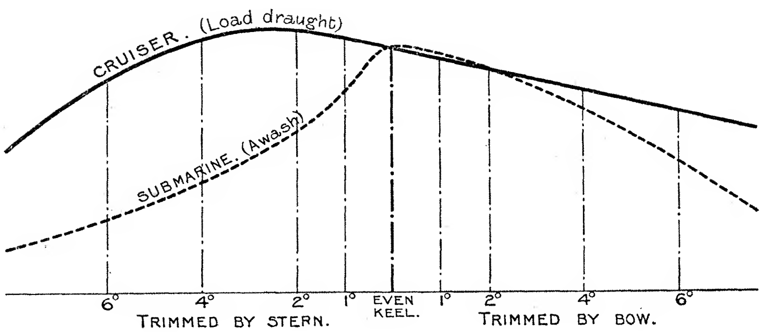

Fig. 7.

Longitudinal stability is more important and the results may be briefly summarised. Taking 4° trim by the stern, the height of the metacentre above the centre of buoyancy in the submarine is only 45 per cent. of the height when the vessel is on an even keel. For the cruiser the corresponding figure is 100 per cent.: that is, there is practically no change in longitudinal stability within the limit of trim mentioned. If the superstructure came into play in the submarine the percentage of the metacentric height at 4° by the stern to the height on even keel would exceed 50 per cent. It will be seen, therefore, that for a cigar-shaped vessel departures from even keel are accompanied by serious decrease in longitudinal stability, and it may be doubted whether the depressing effect of the stream-line motions at the bow would be reduced to an equal extent, if at all, by raising the bow to the extent done in the case of A8. The latter point, however, is determinable only by direct experiment.

Fig. 8 represents three conditions of draught and trim for the submarine dealt with in the calculations.

The foregoing statements lead to the conclusion that in the design of submarines the calculations for stability require to be worked out by naval architects to an extent which is not necessary for ships of ordinary form, and that each departure from precedent must be most closely scrutinised and exhaustively considered. It is true, no doubt, that for the diving and

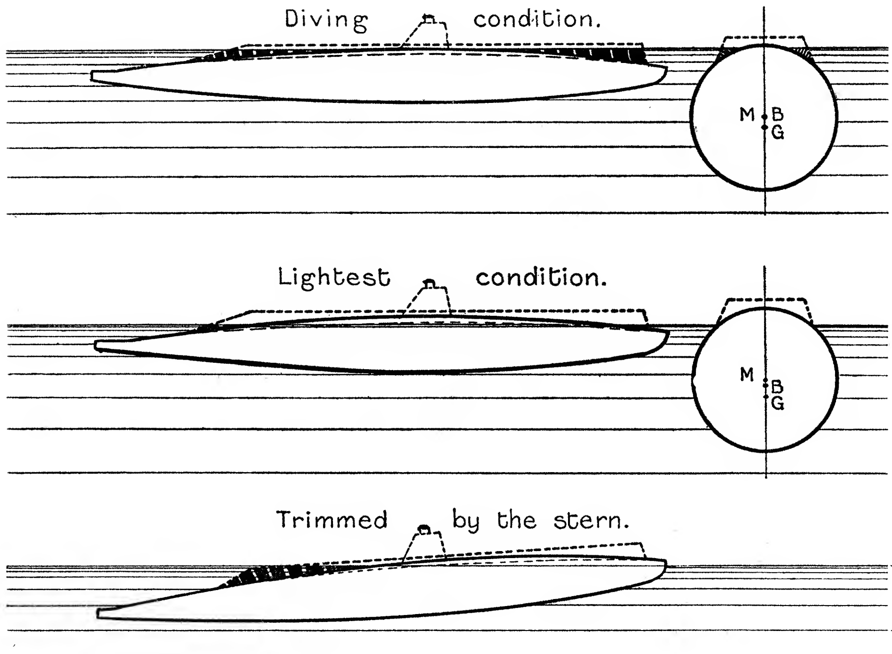

Fig. 8.

submerged conditions the essential point is to deal accurately with questions of weight and position of the centre of gravity, since stability *in all directions* when submerged depends upon the relative positions of the centres of gravity and buoyancy, and moderate "metacentric heights" have to be accepted. On the other hand, it is certain that equal attention should be directed to the conditions of stability in the awash condition, and in the stages of immersion between it and the diving condition. Submarine design is not a task to be entrusted to amateurs or imperfectly informed persons. Skilled naval architects alone should undertake the work, and the results of their investigations should be put into the form of simple practical rules for the guidance of officers and men. From the nature of the case—in consequence of the singular forms of the vessels, the small reserves of buoyancy, and the exceptional variations in stability which must be accepted in order to obtain the power of rapid submergence—considerable risks must be taken. It is, therefore, the duty of all concerned to give all possible assistance to officers and crews in the form of information and instructions based on thorough investigation and experiment.