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The Effect of an Underwater Explosion on the Hull

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CHAPTER X

THE EFFECT OF AN UNDERWATER EXPLOSION ON THE HULL

The experience of naval wars has shown that when underwater explosions of mines, torpedoes, and bombs occur at any one area of the hull of a ship, the destruction of that area is often accompanied by the impairment of the general longitudinal stability of the hull in another area. This impairment is manifested in the appearance of corrugation and rupturing of the deck, sides, and bottom along a narrowly defined segment of the length of the hull.

This phenomenon, which was first observed during the First World War and later when the British minelayer Khanter [Hunter?] was sunk by a mine in 1937, was repeatedly observed during World War II in the case of both naval vessels and merchant ships which were either sunk or damaged as a result of underwater explosions.

It is to be assumed, of course, that impairment of the integrity of the hull in the area not subjected to the direct action of the underwater explosion might be avoided by the appropriate strengthening of the hull in that area.

In this connection there arise certain questions as to the degree of strengthening of the hull which is indispensable to avoid its being damaged outside of the area of destruction from the direct action of the underwater explosion, and as to the practical expediency of such a strengthening of the hull, taking into account the resulting increase in weight to the detriment of other tactical and technical characteristics of the ship.

In what follows we set forth the general order of such a solution and treat the most important deductions, arising from that solution which bear upon the question of guaranteeing the general longitudinal stability of the hull against the action of underwater explosions (For a more detailed treatment of this point, see Yu. A. Shimanskiy Vliyaniye podvodonovo vzryva po obshchuvu prochnost' korpusa korablya (The Effect of an Underwater Explosion on the General Stability of a Ship's Hull): OBORONGIZ 1944)

I - THE GENERAL CHARACTER OF DYNAMIC STRAINS IN THE HULL

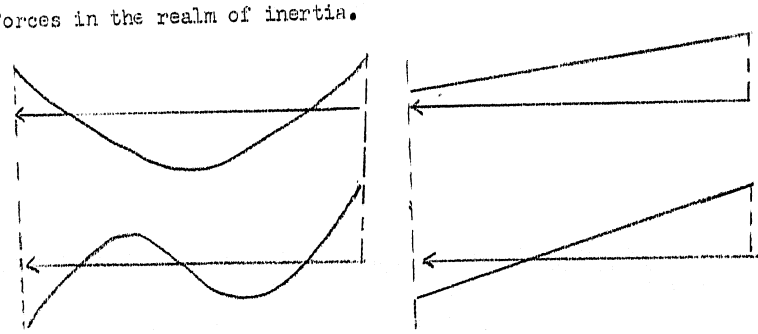
(Here we are considering only those dynamic strains in the hull produced in the vertical (diametrical) plane; i.e., pitch and roll and the vertical vibration of the hull. As to other possible strains in the hull (i.e., strains on the horizontal plane), they are less dangerous from the point of view of the general stability of the ship, and for that reason they are not considered here. In this connection we should point out the undemonstrability of the existing opinion which holds that the impairment of the general stability of the hull from an underwater explosion is a result of the longitudinal strains in the hull).

1. From the point of view of structural mechanics, the hull of a ship may be considered as an elastic girder of varying section, with an uneven distribution of mass along its length, lying on an elastic foundation (the buoyancy of the hull).

When a dynamic load -- that is, a load rapidly fluctuating in time -- acts on such a girder, the latter undergoes the following strains, all varying in form and character (see figure 48):

(a) Strains of a vibratory nature, taking the form of strains in the bend of the girder under the action of the inertia forces of the masses of the girder (figure 148 a).

When analyzing these strains in the hull, the latter may be considered as a completely free (unsupported) girder, since the fluctuations in the reactions of the elastic foundation of the girder (i. e., the fluctuations in the forces of buoyancy of the hull) resulting from these strains, are small by comparison with the forces in the realm of inertia.



(Figure 148)

(b) Strains in the hull considered as a solid body, produced by the action of the external load, the inertia forces of the mass of the girder, and the reactions of the elastic foundation (forces of buoyancy of the hull) (figure 148 b). These strains are accompanied by a corresponding bending of the girder.

2. With each of these two kinds of dynamic strain in the hull, bending forces are created in its sections which may prove dangerous for the stability of those sections. The relative degree of danger for the stability of the hull, represented by these two kinds of dynamic strain in it, is determined by the effective duration of the dynamic load which produced the strains. If the duration

of the action of this load is of the same order as the periods of the particular elastic vibrations of the hull, those strains of a vibratory nature will be that much more dangerous. If the duration of the action of this load is of the same order as the periods of the ship's pitch, those dynamic strains in the hull considered as a solid body may be that much more dangerous for the stability of the hull. In each separate instance, the relative degree of danger to the stability of the hull, represented by these and other dynamic strains, must be determined by the appropriate computation. In this connection, the visible effect produced on the hull by the dynamic load at the time of the underwater explosion, cannot be overemphasized. Comparatively greater observed strains in the hull considered as a solid body resulting from an underwater explosion, may be accompanied by a bending of the hull which is less then the bending of the hull resulting from strains of a purely vibratory nature, which may be less noticeable.

3. The sharp distinction made above, between strains in the hull of a vibratory nature, and strains in the hull considered as a solid body, appears in actuality only after both of these strains take on the character of completely free vibratory strains, such as they become after the cessation of the action of the external forces which produced them. Under these conditions, the strains in the hull considered as a solid body (the pitch and roll of the ship) and the strains in the hull of a vibratory nature (vibration of the ship) will act independently of each other.

In the first moments when the external forces which produced both of these strains, are still acting on the hull, the strains may not be treated as being fully independent of each other, since the appearance, at that time, of strains of a vibratory nature depends upon those inertia forces of the masses of the hull which are produced by the accelerations in the hull resulting from the strains in it as a solid body, which strains were produced by the action of the external forces. Also, in that period during which external dynamic forces are acting on the hull of the ship, very great bending moments are being developed. For this reason, the analysis of the dynamic strains in the hull, having as its basic aim, in a given instance, the ascertaining of the greatest bending moments for the sections of the hull, must be carried out on the basis of a coordinated investigation of both kinds of strain in the hull. The magnitude of these bending moments, which will appear in different sections of the hull at different times, can be found only by means of adequately strenuous labors of computation.

4. Despite the great external difference between the two kinds of dynamic strain in the hull which we have dealt with, they are completely similar from the point of view of mechanics, so that the same methods of computation may be applied in studying them.

For the solution of the problem that has been posed, we are applying the method of reduction, developed in detail in the preceding chapters. Also we are utilizing certain deductions made in those chapters, which bear upon the present instance of the action on the hull of a dynamic load.

II - STRAINS, ACCELERATIONS, AND BENDING MOMENTS IN SECTION OF THE HULL PRODUCED BY THE ACTION OF AN UNDERWATER EXPLOSION

1. The strains in a hull, produced as a result of the action

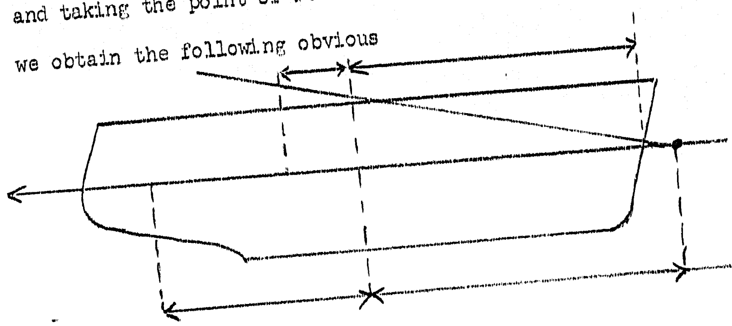
on it by a given load, may be considered as the sums of mutually independent strains, produced in the form of its greatest free vibrations, determinable by the corresponding normal functions.

As was pointed out above, for the present problem it is necessary that we compute the component strains in the hull, both those of a vibratory nature and those produced in the hull considered as a solid body; and, consequently, it is necessary to find the normal functions corresponding to both of these strains.

Owing to the practical difficulties attendant upon discovering the normal functions corresponding to the vibratory strains in the hull at the highest harmonic frequencies, and owing, also to the relatively slight effect of such strains on the total dynamic strains in the hull, we shall limit ourselves to a computation of the vibratory strains in the hull at the first two harmonic frequencies only. These normal functions may be found by the usual methods applied to the analysis of vibrations in the hull, which were explained in Chapters I and II. This being the case, we may consider them here as known, denoting them by the symbols ε_1 and ε_2 respectively. We may likewise consider as known, for each of these normal functions, the corresponding reduced masses of the ship, M_{1np}, M_{2np} the reduced coefficients of rigidity (and the half periods of free vibration $t_{1,1}$, $t_{1,2}$) and the half periods of free vibration K_{1np}, K_{2np}. As to the normal functions which specify the forms of the strains -- that is, the forms of the greatest free vibrations in the hull considered as a solid body -- they are easily obtained by means of using the deductions made in Section 6 of Chapter II, Part I.

It was shown that the greatest free vibrations in the hull considered as a solid body, were its gyrations around two horizontal axes, removed from the center of gravity of the ship by distances X_a and $X_б$ determined by the equation (48) on page 74.

Finding the position of these axes of gyration by equation (48), and taking the point of reduction at the bow extremity of the ship, we obtain the following obvious



(Figure 149)

formula for the normal functions specifying the forms of the greatest free vibrations in the hull considered as a solid body (Cf. figure 149):

$$f_a = 1 - \frac{x}{c - X_a} \qquad (1)$$

$$f_б = 1 - \frac{x}{c + X_б}$$

where x = distance of the section from the bow extremity

c = distance of the center of gravity of the ship from the bow extremity.

The reduced masses, reduced coefficients of rigidity, and frequencies and half periods of vibration of the hull which correspond to these normal functions, are determined by the following equations (for denotation, see section 6, Chapter II, Part I):

Reduced masses:

$$M_{a\,np} = \int_0^l m_x f_a^2\,dx = \frac{P}{g}\,\frac{X_a^2 + r^2}{(c - X_a)^2}, \qquad (2)$$

$$M_{\sigma\,np} = \int_0^l m_x f_\sigma^2\,dx = \frac{P}{g}\,\frac{X_\sigma^2 + r^2}{(c + X_\sigma)^2}. \qquad (3)$$

Reduced coefficients of rigidity:

$$K_{a\,np} = \frac{S(X_a + b)^2 + P(R - a)}{(c - X_a)^2} \qquad (4)$$

$$K_{\sigma\,np} = \frac{S(X_\sigma - b)^2 + P(R - a)}{(c + X_\sigma)^2} \qquad (5)$$

Frequencies:

$$p_a^2 = \frac{K_{a\,np}}{M_{a\,np}} = \frac{1}{M}\,\frac{S(X_a + b)^2 + P(R - a)}{r^2 + X_a^2}, \qquad (6)$$

$$p_\sigma^2 = \frac{K_{\sigma\,np}}{M_{\sigma\,np}} = \frac{1}{M}\,\frac{S(X_\sigma - b)^2 + P(R - a)}{r^2 + X_\sigma^2} \qquad (7)$$

Half periods:

$$\tau_a = \frac{\pi}{p_a}; \quad \tau_\sigma = \frac{\pi}{p_\sigma} \qquad (8)$$

2. Each of the four component strains in the hull that were shown above, and the corresponding accelerations in the sections,

may be found by utilizing the method of reduction explained in Chapter IV, Part I, after which the total strains and accelerations are found by the equation:

$$\varphi_{xt} = \sum \varphi_n f_n , \tag{9}$$

$$\dot{j}_{xt} = \sum \dot{j}_n f_n , \tag{10}$$

where φ_n, $\dot{j}_n$ = the functions of time t, corresponding to the normal function f_n, which determine the strain and accelerations at the point of reduction.

In using equations (9) and (10), it is necessary to take into account the different character of the fluctuation in time and along the length of the hull, of each of the terms in these equations. With these equations it is possible to construct, for each selected section of the ship, curves of fluctuation in time and acceleration and, in this way, to find the greatest of their values. It is also possible to construct, for a given moment in time, curves of fluctuations of strains and accelerations along the length of the hull.

With the dynamic strains in the hull determined by equation (9), the following forces are produced in the hull sections, causing the bending of the hull. The inertia forces of the masses of the ship, equal to $m_x \dot{j}_{xt}$, where m_x = mass of the linear unit of the length of the ship, and $\dot{j}_{xt}$ = magnitude of the total acceleration in the section of the ship, determined by equation (10). The forces depending upon the fluctuation of the forces of buoyancy, owing to the vertical strains in the section of the hull, equal to

φ_{xy} , where y = ordinate (width) of the loaded waterline, and φ_{xt} the magnitude of the total strains in the section of the hull, determined by equation (9)

Owing to the action of the above mentioned forces on the sections of the hull, bending moments are created which may be computed with the aid of the following equation:

$$M_{xt} = \int_0^x \int_0^x (-m_x j_{xt} - \varphi_{xt} y)\, dx^2. \qquad (11)$$

For the moments of time $t < T$ - that is, up to the moment of cessation of the external load which has acted on the hull -- it is necessary to take into account the action of this load as well (leaving out the inertia forces and the forces of buoyancy). However, if this load is applied to only one of the extremities of the hull, the equation (11) for the bending moments may be left unchanged, on condition that the integration with the upper varying limit provided for in that equation, is carried out beginning with the other extremity of the hull -- the one free from the load.

Using equation (11), it is possible to construct, for any selected section of the hull, a curve of fluctuation in time of the magnitude of the bending moment, and to find the maximum value of the bending moment in this section. Also, it is possible to construct a curve of the fluctuation of the bending moment along the length of the hull, for each selected moment of time t.

For the computation of the bending moments in the hull sections, equation (11) may be presented in a form which is more convenient

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for practical application.

Substituting the values of strain φ_{xt} according to equation (9), and acceleration j_{xt} according to equation (10), we obtain

$$M_{xt} = -\sum j_n \int_0^x \int_0^x m_x f_n \, dx^2 - \sum \varphi_n \int_0^x \int_0^x y f_n \, dx^2 \qquad (12)$$

where f_n = normal functions

φ_n, j_n = respectively, the strain and acceleration at the point of reduction, corresponding to the function f_n;

y = ordinates (widths) of the loaded waterline

m_x = masses of the linear unit of the length of the hull.

The integral with the varying upper limit which figures in the equation, does not depend upon the time t, for which, according to this equation, the magnitude of the bending moments in the hull sections are computed. This greatly simplifies the computation and the determination of the maximum values of the bending moments in the hull sections for the various values of time t.

The masses m_x, figuring in the first term of equation (12), must be treated in the same way as they were treated in ascertaining the forms of the greatest vibrations in the hull; that is, in determining the form of the functions f_n corresponding to them. If, in determining these functions, the masses of additional water were taken into account to one degree or another, that same computation for the additional masses of water is required also in equation (12), in order that the curves of the bending moments constructed according to tat equation be made duly continuous. In addition, for making these curves continuous it is necessary that in the second term of this equation, the symbol for the totals include only the strains in the hull considered as a solid body (functions f_α and f_σ), hull strains of a vibratory nature being excluded from these totals. This requirement is dictated by the fact that, for ascertaining the forms of the latter strains, it was assumed that they were not accompanied by fluctuations in the forces of buoyancy of the hull.

The stresses occuring in the hull sections at the time of the dynamic strains we are considering, are to be determined by means of dividing the computed bending moments by the corresponding moments of resistance of the hull sections.

Taking the indexes of the bending of the hull in its terminal sections as equal to zero, we obtain the following equation for computing the ordinate of the elastic bending curve of the hull:

$$\eta = \frac{1}{E}\left[\int_0^x\int_0^x \frac{M_x}{I_x}\,dx^2 - \frac{x}{l}\int_0^l\int_0^x \frac{M_x}{I_x}\,dx^2\right]. \qquad (13)$$

3. In order to find the functions φ_η and j_η (figuring in the reduction in the above equation) which specify the limits of fluctuation in time of the strains and accelerations at the point of reduction, it is necessary to know the point of application and the limits of fluctuation in time for the dynamic load which acted on the hull at the time of the underwater explosion.

In reality, however, the magnitude and character of the fluctuations in time of the dynamic load acting on the hull at the time of the underwater explosion, cannot be known, in view of the fact that they vary within very great limits, depending upon the many changing conditions under which a ship's hull may be subjected to the action of underwater explosions.

In order to estimate the general longitudinal stability of a ship's hull from the point of view of resistance to underwater explosions, and to develop means of construction which will contribute to increasing the resistance of the hull to the action of underwater explosions, one may propound a practical solution of the problem, making certain tentative assumptions with regard to the magnitude and character of the load acting on the hull at the time of the underwater explosion. As a result, the computation of the stability of the hull against the action of underwater explosions, acquires a tentative character which, however, does not rule out its practical significance, since such computations are often applied in shipbuilding practice.

4. The load which acts on the hull at the time of an underwater explosion fluctuates in time according to a certain law increasing from zero to a maximum, and then decreasing to zero again in the course of a certain time $\phi(t)$. The function expressing the load may be treated trigonometrically and presented in the following form:

$$\phi(t) = \sum F_n \sin \frac{n\pi t}{T},$$

where

$$F_n = \frac{2}{T}\int_0^T \phi(t) \sin \frac{n\pi t}{T}\, dt.$$

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Since the value of the function $\phi(t)$ is unknown -- but bearing in mind that in the given instance only the first term of the series contains the analytically significant value of this function -- we assume that the load acting on the hull at the time of an underwater explosion, fluctuates in time according to the equation:

$$F = F_{max} \sin \frac{\pi t}{T}, \qquad (14)$$

where F_{max} = maximum magnitude of the load

T = duration of the action of the load

Considering underwater explosions of such a kind that an area of the hull is destroyed, one may make the assumption that the greatest magnitude of the load which has acted, at the time of such an explosion, on the entire remaining area of the hull, is proportional to the resistance of the hull to destruction in the area of the explosion. For the general stability of the hull outside the area of the explosion, the most unfavorable kind of explosion is one which takes place at one of the extremities of the hull (in addition to this, the magnitude of the reduced load is the greatest) and which is accompanied by the complete destruction of that extremity. In the case of a destroyed area of not very great length, one may assume that the section of the hull delimiting this area is destroyed only as a consequence of the action of the shearing force (that is, disregarding the effect of a certain bending moment acting on this same section).

On the basis of the assumptions made above, we obtain the following equation for the maximum magnitude of the concentrated load producing a dynamic strain in the hull at the time of an underwater explosion:

$$F_{max} = \frac{I \sum t}{\mu} \tau_{kp}.$$

where I = moment of inertia at the area of the hull section under consideration

μ = static moment of that portion of the same section which lies along one side of the neutral axis, with respect to that axis

$\sum t$ = sum of the thicknesses of the vertical walls of the section

τ_{kp} = magnitude of the relates stress producing the destruction of the vertical walls of the section (the appropriate yield point of the materials, or Euler's formula for stress).

We tentatively assume that the section for which the greatest magnitude of dynamic load is to be computed is located at a distance of approximately $0.1\ l$ from the low extremity of the hull, with l = full length of the ship.

We may make an assumption of this kind since, in the designated area of the bow extremity of the ship, the magnitude of the force computed by equation (15) varies with sufficient regularity.

The duration of the action of the load T, figuring in equation (14) has a great effect on both the magnitude and the character of the dynamic strains in the hull. Curve 1 in figure 13 shows the dependency of the coefficient of dynamism of the load K, which specifies the magnitude of the greatest strain, on the relationship

$$a = \frac{T_1}{T}$$

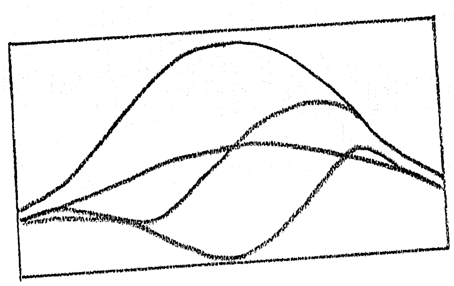
The duration of the action of the load T has an even greater effect on the magnitude of the maximum acceleration produced by the action of this load on the hull section.

An examination of equation (10) for acceleration leads to the conclusion that with the diminution of the time of action of the load T, the total accelerations in the hull sections diminish rapidly. Moreover, their maximum values are attained in the area of application of the load. During the very brief action of a large load, similar to the phenomenon of a blow, these accelerations may attain very great magnitudes in comparison to the accelerations encountered in engineering practice. However, owing to the short duration of the action of such accelerations, and also to the very small amplitude of the strains corresponding to them, although they are physiologically unpleasant and painfully felt, they are not dangerous for the stability of the individual ship structures, and are less dangerous for the general stability of the whole ship.

The adverse effect of such accelerations on ships' instruments may be easily counteracted by the use of suitable shock-absorbers.

The effect of the duration of the load T on the bending moments which it creates in the hull sections, yields to analytical examination only with the greatest difficulty, since these bending moments are created as a result of a fluctuation in the forces of buoyancy at the time of the dynamic strains in the hull, and as a result, also, of the action of the inertia forces of the masses of the ship, the magnitude and distribution of which are determined by the magnitude and distribution of the accelerations in the hull sections.

Completed numerical computations substantiate the a priori assumption that for a floating ship, the most dangerous period of duration of the action of a load, from the point of view of the bending of the hull, is that period during which the strain in the hull corresponding to the first harmonic frequency of its free vibrations, reaches its maximum; that is, at $a = \frac{\tau_1}{T} = 0.6$, [redacted] $T = 1.67\tau_1$ where τ_1 = half period of free vibration of the hull in the first harmonic frequency (figure 150).



(Figure 150)

An underwater explosion near a ship may act on the hull both in the form of a wave of condensation and rarefaction, spreading through the water with great speed during the briefest period of its action, and in the form of a direct hydraulic impact of moving masses of water during a longer period of its action. If the underwater explosion is accompanied by the destruction of that part of the ship in the area of the explosion, its effect on the whole ship is as though absorbed by the destruction of that part of the ship.

At the same time, the duration of action on the whole ship by corresponding forces is increased.

Thus the duration of action of the forces acting on the hull at the time of an underwater explosion, may vary within very great limits; and the effects of underwater explosions on the hull may, accordingly, be various.

In a given case one must consider the most dangerous instance of an underwater explosion; that is, one must take, for the duration of its action, $T = 1.67\,\tau_1$.

As regards the moment of time t_2, for which one must compute the bending moments, one may, with sufficient accuracy for practical purposes, take the value of this time as $t_1 = 0.75T$

Although in certain sections of the hull the maximum bending moments may be reached at values of time t differing somewhat from $t = 0.75T$, these bending moments do not materially differ from the values obtained at $t = 0.75T$, and for this reason it is not necessary to compute them with the very highest degree of accuracy, requiring correspondingly extensive labors of computation.

At $\alpha = \frac{\tau_1}{T} = 0.6$ and $t = 0.75T$ the strain and, consequently, the bending of the hull corresponding to the first harmonic frequency of its free vibrations, reach a maximum.

5. On the basis of the assumptions made above regarding the point of application and the limits of fluctuation in time of the load acting on the hull at the time of an underwater explosion, functions φ_n and j_n, figuring in equations (9), (10, and (11)

are determined by the following equations, deduced in Chapter I, Part I:

Strain at the point of reduction (bow extremity of the hull):

$$\varphi_n = \frac{\varphi_{n\,cT}}{1-a_n^2}\left(\sin a_n \frac{\pi t}{\tau_{1n}} - a_n \sin \frac{\pi t}{\tau_{1n}}\right). \qquad (10)$$

Accelerations at the point of reduction:

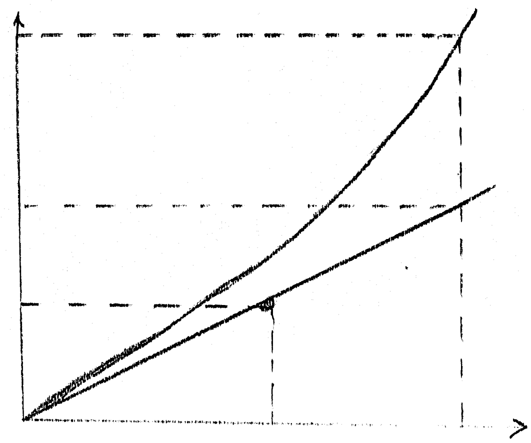
$$j_n = -\frac{\pi^2}{\tau_{1n}^2}\left(\varphi_n - \varphi_{n\,cT} \sin \frac{\pi t}{T}\right),$$

where $\varphi_{n\,cT} = \frac{F_{max}}{K_{n\,\pi p}}$ static strain at the point of reduction corresponding to the normal function f_n, where F_{max} = greatest magnitude of the load acting on the hull at the time of an underwater explosion, and $K_{n\,\pi p}$ = reduced coefficient of rigidity corresponding to the normal function f_n (cf. Para.1.)

$a_n = \frac{\tau_{1n}}{T}$ tentative denotation, in which τ_{1n} = half period of free vibration of the hull corresponding to the normal function f_n (cf. Par. 1), and T = duration of the action of the load.

III - GENERAL CONCLUSIONS

Computations made on the basis of the most unfavorable assumptions, as indicated above, show that the maximum bending moments produced in the hull sections by an underwater explosion, may considerably exceed those bending moments which are obtained by the conventional computations of the longitudinal stability of the hull by positioning the ship on the base of a wave. This disparity becomes particularly noticeable in those areas of the length of the hull in which the curve of the bending moments for the position of the ship on the base of the wave, drops sharply. In these areas of the hull, the bending moments created by an underwater explosion may be from 2 to $2\frac{1}{2}$ times as great as the conventionally computed bending moments obtained by positioning the ship on the base of a wave. Since, in the conventional computation of the longitudinal stability of the hull, the norms for the allowed stresses are equal to from 50 to 40% of the yield point of the material -- that is, the coefficients of safety, relative to the yield point of the material, are from 2 to $2\frac{1}{2}$ - the greatest stresses in the hull sections at the time of an underwater explosion, will not exceed the yield point of the material and, consequently, the conventional computation of the longitudinal stability of the hull by positioning a ship on a wave, should adequately guarantee the stability of the hull, even in the case of an underwater explosion. Obviously, however, such a conclusion will be correct only where there is a strict proportionality between the magnitudes of the bending moments and the stresses they have created in the hull sections. Otherwise, the bending moments occurring in the hull at time of an underwater explosion will create stresses in the hull sections which exceed the yield point of the material; that is, the underwater explosion may be accompanied by the impairment of the integrity of the hull outside the area of its direct action. What was said above is illustrated



(Figure 151)

in Figure 151, in which the bending moments are laid out along the horizontal axis, and the stresses corresponding to them are laid out along the vertical axis. Where there is a strict proportionality between the bending moments and the stresses, their relation to each other will be defined by the straight line OA, passing through point C, which corresponds to the bending moment as per the conventional computation of the longitudinal stability of the hull, and its related stress, equal to from 50 to 40% of the yield point of the material. Where this bending moment is increased from 2 to $2\frac{1}{2}$ times -- that is, where the bending moments correspond to the conditions of an underwater explosion -- the stresses should increase by just that much and, consequently, reach the yield point of the material (poind D). In the absence of proportionality between the bending moments and the stresses, their relation to each other will be defined by a certain curved line OE; and in this case the stress corresponding to the bending moment produced by an underwater explosion will exceed the yield point of the material (point F).

On the basis of what has been said above, it may be supposed that the impairment of the integrity of the hull outside the area of direct action of the underwater explosion, could not take effect -- or, in any case, the likelihood of the appearance of this phenomenon would be considerably lessened -- if, in all sections of the hull, an adequately strict proportionality were preserved between the bending moments acting on those sections, and the stresses -- up to the critical bending moment at which the stress in the hull section reaches the yield point of the material. For these conditions to be fulfilled, it is necessary that all of the upper, external structural members of the hull be guaranteed against these compression stresses equaling the yield point of the material. Otherwise, the sectional areas of these members will enter into the computation of the equivalent girder with reducing coefficients less than unity, and proportionally smaller as the compression stresses acting on them are larger. As a result, the proportionality between the bending moments and the stresses will be impaired. Moreover, the stresses will increase more rapidly than the bending moments, as is shown by the curve OE in Figure 151.

The requirement deduced above, concerning the necessity of guaranteeing the resistance of basic structural members up to stresses equalling the yield point of the material of those members, has by no means been adequately complied with in contemporary hull construction.

2. Verified computations carried out for ships which had undergone the kind of damage from underwater explosions which we were considering above, have shown that the resistance of the upper, external structural members proved itself by no means adequate from the point of view of the requirement mentioned above. On the basis

of the conventional computation of the general longitudinal stability of the hull for a ship positioned on a wave, the norms for the allowed stresses, determined by the computation of the sign function of the load acting on the hull, are from 40 to 50% of the yield point of the material. According to this, from the point of view of formal computation, there is no necessity for completely guaranteeing the resistance, even of such fundamental structural members of the hull as the deck stringer and the sheer strake. This applies with even greater force to the extremities of the hull, where the computed stresses usually fall far short of the norms indicated above. Thanks to this, the material of the structural members of the hull is not adequately employed with regard to the various possible overloads on the hull, which it is not calculated for, but which may occur in practice -- for example, on the occasion of an underwater explosion, of running aground on a sandbar, or of the impairment of the integrity of certain structural members as a result of war damage, etc.

What was said above concerning the necessity of guaranteeing the resistance of the fundamental longitudinal members of the hull against compression stresses equal or near to the yield point of the material, should be fully applied to all hull structures, with the aim of the greatest possible increasing of the maximum resistance of these structures against those possible overloads which cannot be foreseen and for which one may not make computations, but to which the structural members may be subjected under the varying conditions of a ship's service.

In particular, for example, the resistance of the structural members of a ship's skin -- that is, the deck, the bottom, the sides, and the bulkheads -- must be guaranteed, not only against the conventionally computed load, but also against a critical load; that is, against a load which creates in the sections of these structural members, stresses equalling the yield point of the material.

3. On the basis of the data derived above it is possible to draw the following conclusions regarding the guaranteeing of the general stability of the hull against the action of underwater explosions.

(a) The reason for the impairment of the integrity of the hull in the area outside that of the direct action of an underwater explosion, is the bending of the hull in the vertical plane, occurring as a result of the dynamic strains in the hull considered as a solid body, and the strains of a vibratory nature, occurring as a result of the dynamic load applied to the hull at the time of the underwater explosion.

(b) In order to avoid the impairment of the integrity of the hull outside the area of the underwater explosion -- or, in any case, to reduce to a minimum the likelihood of the appearance of this phenomenon -- it is necessary that the resistance of the fundamental longitudinal members be guaranteed compression stresses in them, equalling the yield point of the material of these members.

(c) In the construction, and in the computation of the stability, of all ship structures, including the hull in all the extent of its length, it is necessary to obtain the greatest full utilization of the construction material; that is, the greatest full guarantee of resistance of its structural members, not only against the action of a conventionally computed load, but also against the action on it of a critical -- that is, a destructive --load, which evokes the yield point of the material in its structural members. This is necessary in order to achieve, without the expenditure of new material, the maximum degree of resistance in the projected structure, against such loads, which are quite possible in actual practice, but which cannot be foreseen or taken into account in computations (underwater explosions, running aground on a sandbar, etc.)