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THE EFFECT OF AN UNDERWATER EXPLOSION ON A SHIP

ABSTRACT

This article contains a synthetic account of an underwater explosion and its effects. It presents diagrams of the gas bubble radius in the function of explosive charge mass and detonation depth as well the values of pressure on the front of a shock wave in the function of range and mass of TNT charge: 1, 10, 50, 250, 1000 kg (following T. L. Geers and K. S. Hunter). It also presents a classification of underwater explosions and their effect on a ship's hull. It includes the classification of modern sea mines throughout the world and also contains a diagram which can be used to estimate the effects of a shockwave on a ship's hull in the function of TNT charge mass, following the Cole's formulas.

Key words:

underwater explosion, sea mine, gas bubble, wave, pressure, Cole's formulas.

INTRODUCTION

An explosion is a collection of violent occurrences causing instantaneous disturbance in the balance condition of a system, which is accompanied by a change of the potential energy into potential mechanical action would be better performed by expanding gases occurring in the compressed condition prior to the explosion. The effect of this action is the rise of a pressure wave called a shockwave or detonation wave, which, in water reaches a velocity of up to 8000 m/s, and its pressure at the wave front reaches a value of 100 MPa or higher. The underwater explosion

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differs substantially from an explosion in air because its a bubble of gas formed in water. A thorough analysis of such a phenomena requires simultaneously taking into account such factors as detonation run, properties of the medium, distribution and propagation of the detonation wave, energy dissipation, propagation and pulsation of the gas bubble, reverberation of the shockwave from bottom and surface, movement of the water area bottom, wave interference, cavitation and many other factors [3, 14]. During an explosion in water the explosive material having solid state transforms into a gas product having a volume equal to the volume of the explosive material, temperature of 3300 K and pressure reaching 14000 MPa. It takes approximately 10^{-7} s for this pressure to reach maximum value. Under such a high pressure a gas bubble is formed and a spherical shockwave, which at the beginning propagates radially at a speed of 5000–8000 m/s which then decreases to the sound velocity of approximately 1500 m/s. Together with the distance covered, the pressure value on the shockwave front diminishes. The gas bubble is opposed by the hydrostatic pressure of the surrounding water, which causes the so called pulsation. The gas bubble expands and shrinks alternately, moving at the same time towards the surface as the hydrostatic lift force acts on it (fig. 1). When the gas bubble reaches the surface of the water it violently releases the carried gases into the atmosphere throwing them up into the air together with hectoliters of water and vapor.

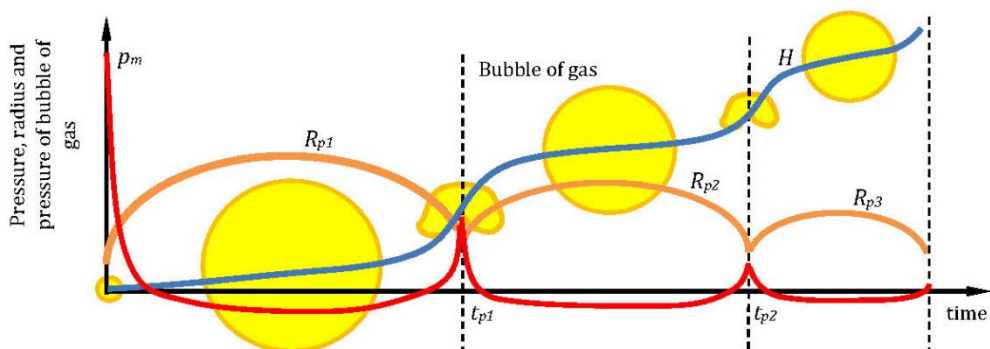


Fig. 1. Parameters of an underwater explosion [14]

The mathematical model of an underwater explosion is extremely complicated. As far as calculation possibilities are concerned two types of underwater explosion are distinguished. In the first case the charge is placed so close to the hull that it is within the reach of the gas bubble. The effects of such an explosion can be

estimated based on statistics however it is difficult to consider them using computation methods. In the second case the hull is beyond the reach of the gas bubble and is loaded only with the pressure wave moving in the liquid.

MINE THREATS IN WATERS OF THE WORLD

The first time sea mines were used was during the Crimean war (1853–1856) by the Russian fleet. Modern mines are smart devices, capable of movement, and self-burying on the sea bottom, which makes them undetectable. They are equipped with various sensors which react to changes in pressure, magnetic field, electric potential and hydrodynamic field. They are also capable of self-regulation depending on the ambient conditions [12, 13]. They can be deployed individually or in groups, forming an intelligent mine barrier capable of recognizing opponent's ships (friend or foe system). Among the many divisions and classifications of mines the basic classification, presented in figure 2, is based on the location of the mine in the water and the way it responds to a passing vessel.

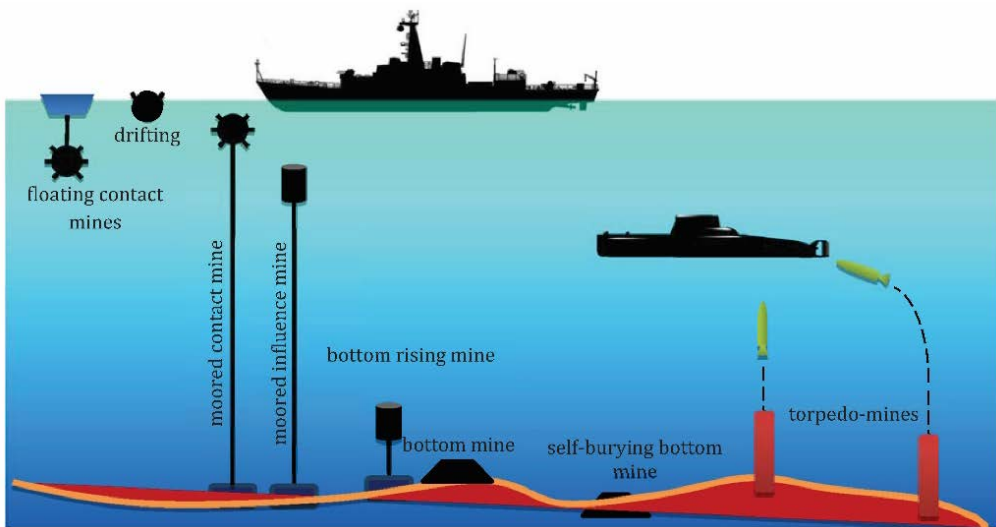


Fig. 2. Classification of sea mines

Table 1. Selected sea mines of the world and their equivalents expressed in kg TNT [12, 13]

Moored mines — fixed				Bottom mines — fixed			
Country	Name	Depth [m]	Mass (explosives) [kg]	Country	Name	Depth [m]	Mass (explosives) [kg]
France	<i>H 30</i>	1–500	300	France	<i>MCC 23</i>	150	530
Spain	<i>MO-90</i>	5–340	300		<i>TSM 3530</i>	100	1000
Germany	<i>DM 11 UMC</i>	1–500	40	Germany	<i>FG 1</i>	60	535
Russia	<i>AMG-1</i>	13–100	262		<i>DM 61</i>	60	450
	<i>GM</i>	10–200	300	Russia	<i>AMD-1000</i>	4–200	782
	<i>KAM</i>	10–40	300		<i>MDM-1</i>	12–120	1120
	<i>KSM</i>	10–210	300		<i>MDM-5</i>	8–300	1350
	<i>Lira</i>	25–250	250		<i>Serpey</i>	8–50	750
	<i>M-08</i>	6–110	115		<i>UDM-2</i>	–	800
	<i>M-26</i>	6–139	240	Sweden	<i>BGM 100</i>	5–100	105
	<i>PM-1</i>	15–25	230	GB	<i>M Mk 2</i>	9–36	462
	<i>PM-2</i>	45–290	245		<i>Sea Urban</i>	5–200	600
Active, mobile and remotely controlled mines					<i>Stonefish</i>	10–200	500
Denmark	<i>MTP 19</i>	3–20	300	Italy	<i>Manta</i>	2.5–100	150–180
Russia	<i>KRM</i>	40–100	300		<i>MN 102</i>	5–300	630
	<i>MDS</i>	4–150	480		<i>MR-80</i>	5–300	380–865
	<i>SMDM-1 and 2</i>	4–150	480 and 800		<i>MRP</i>	6–300	620

THE EMPIRICAL DESCRIPTION OF THE DETONATION WAVE IN WATER

The underlying foundation for describing the pressure wave in water are works by R. H. Cole [2] from 1948, who was the first to publish the results of an experiment carried out in an exercise range, for which he derived simple empirical formulas. In some approximation it can be assumed that the initial velocity of the shockwave is proportional to the pressure on its front and is [3]

$$v_p = 0.7p_m \quad [\text{m/s}], \quad (1)$$

where:

p_m — pressure at the front of the wave [MPa].

Particles of water, which have reached such velocity act on the particles of an adjacent layer, imparting velocity and acceleration to them, which causes them to slow down and the pressure value on the wave front to decrease. As a consequence the shockwave is dissipated in all directions at the speed [3]

$$v = \frac{v_c}{1-4.2 \cdot 10^{-6} p_m} \quad [\text{m/s}], \quad (2)$$

where:

v_c — speed of sound in water [m/s].

Duration time of pulsation depends on the explosive charge mass and detonation depth. The pulsation lasts until the gas bubbles reach the surface. The duration time of the second pulsation is approximately 70%, and approximately 50% of that of the first pulsation. The duration time of the underwater explosion was determined for TNT using the Cole's formula [2]

$$t_p = 0,3 \frac{\sqrt[3]{m}}{1+0.1H} \quad [\text{s}], \quad (3)$$

and its longest radius of the gas bubbles as

$$R_{pmax} = 1.53 \sqrt[3]{\frac{m}{1+0.1H}} \quad [\text{m}], \quad (4)$$

where:

m — explosive charge mass [kg];

H — depth [m].

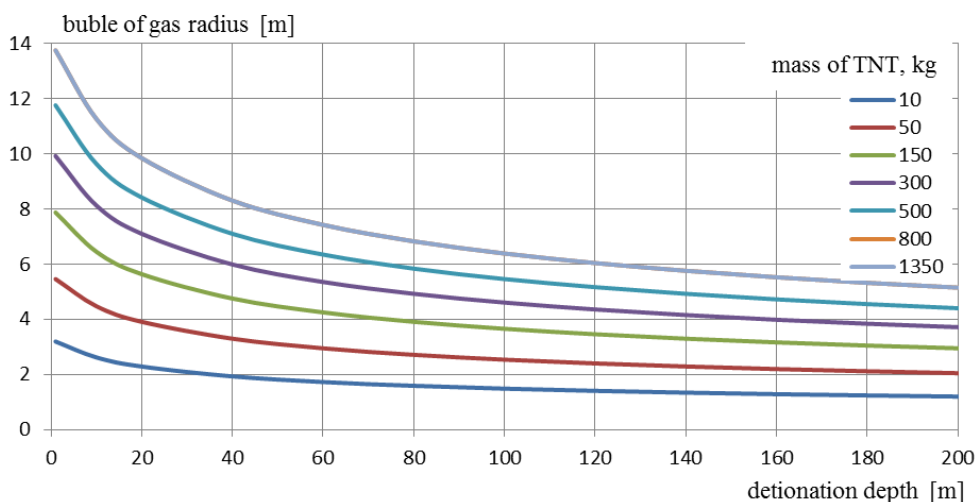


Fig. 3. The gas bubble's radius in the function of explosive charge mass and detonation depth

The explosive charge mass in small mines and torpedo warheads reaches 300 kg, in medium mines it is up to 500 kg (the largest ones 800–1350 kg). Thus in the case of small and medium mines even when an explosion takes place close to the surface and the range is higher than 12 m the hull of a ship is beyond the reach of the gas bubble. When only the wave pressure acts on the hull, determination of this load can be based on the empirical formulas presented by various authors. These formulas were derived from measurements and tests carried out in exercise ranges [2]:

$$p_{max} = K_1 \left(\frac{\sqrt[3]{m}}{R} \right)^{A_1}; \quad (5)$$

$$p(t) = p_{max} e^{-\frac{t}{\theta}}; \quad (6)$$

$$\theta = K_2 \sqrt[3]{m} \left(\frac{\sqrt[3]{m}}{R} \right)^{A_2}, \quad (7)$$

where:

t — time [s];

R — distance from an explosive [m];

K_1, K_2, A_1, A_2 — coefficients for an explosive obtained through experimental investigations.

These formulas reflect the nature of the explosion very well. They can be used to determine values of pressure on the shockwave front in water in the function of distance from the detonation epicenter, explosive charge mass, and time. The values of coefficients K_1, K_2, A_1, A_2 have been determined by many authors in publications [1, 2, 5, 6, 7]. Figure 4 presents the pressure values on the shockwave front in the function of distance and TNT mass of 1, 10, 50, 250, 1000 kg determined following formulas by T. L. Geers, K. S. Hunter [9].

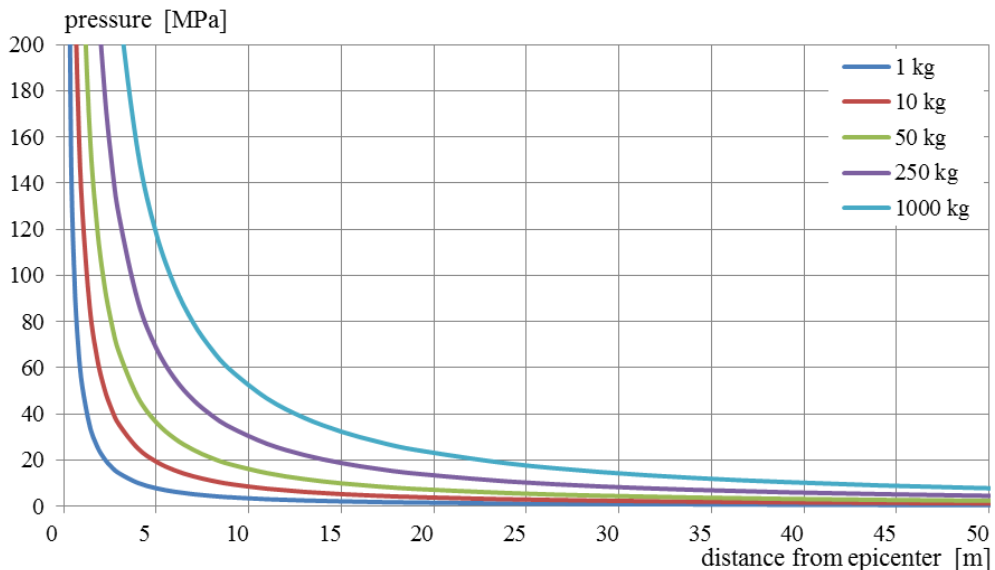


Fig. 4. The pressure values on the shockwave front in the function of distance and TNT mass of 1, 10, 50, 250, 1000 kg following T. L. Geers, K. S. Hunter [9]

THE CLASSIFICATION OF THE ACTIONS OF UNDERWATER EXPLOSION ON A SHIP

Sea mines and torpedoes, depending on their designation, and mode of detonating the explosive material, act on a ship's structure in various ways. Explosions caused by them can be generally classified as contact and those that influence the latter can be subdivided into near and far-distance. The effects of these actions will differ and they depend on several factors such as explosive charge mass, distance of the hull from the epicenter, size of vessel and its structure, place of the explosion (bow, amidships, stern, port side, starboard side), detonation depth, reverberation of the detonation wave from the bottom and many other factors. Each explosion imparts acceleration of high values to ship structure nodes which causes mass forces to deform and tear apart its shell plating together with the mechanisms.

Contact explosions occur when the part of the hull below the waterline is within the action range of the gas bubbles, which means that no matter how much of the explosive material there is the detonation occurs within the distance of 0–12 m. Most often it is an explosion directly on the shell plating of the hull initiated by a contact or inertial fuse as the result of the hull being hit by a torpedo or a mine. For a small, single-compartment vessel, such an explosion usually ends up with its sinking but a multi-compartment vessel can retain buoyancy and stability after such an explosion. An explosion caused by a contact mine filled with 100–200 kg TNT will blow a hole in the shell plating, having a radius of 1–3 m. A further space having a radius of up to 10 m is the space of destruction of mechanisms, installations and pipelines, the space of cracks in frames of appliances, and breaking of securing bolts. And a strong shock is recorded in the whole vessel. Gases and products of high temperature enter the vessel magnifying the damage. Medium size vessels can be damaged at the place of explosion. In the event of explosion in the forward part of a vessel it will be revolving round the axis running through its bow. The effects of contact explosions are very serious even for large vessels and even if the vessel is in the can-be-repaired condition, it will be out of use for several months [3].

If a sea mine, at the moment of detonation following contact with the hull, is floating on the sea surface (hitting a drifting mine) the damage to the ship is much smaller as the largest part of the explosion energy is dissipated in the air, and the resulting hole has a smaller diameter. In such a case the vessel should not break apart or sink. It can retain moving capability, and can continue to be operated after shipyard repair.



Fig. 5. Zones of destruction in a contact explosion: 1 — breach, 2 — structure bursting, 3 — zone of damage to structure and mechanisms

An example of a contact explosion is an Iwo Jima amphibious-assault ship — USS ‘Tripoli’ LPH-10, who on 18 February, 1991 hit a LUGM-145 mine in the Persian Gulf. The exploding mine whose weight was 145 kg and worth below \$ 1000 made a breach having dimensions 16 by 20 m. The ship was repaired within a month and the cost of repairs was \$ 3 500 000.



The magnitude of the mine damage to *Tripoli*, in drydock at Bahrain, is clear in this

Fig. 6. Damage to the hull of the USS ‘Tripoli’ LPH-10 [17], LUGM-145 mine [18]

An influence explosion occurs if it takes place at a certain distance away from the ship’s hull, long enough for the ship’s shell plating not to be touched by a gas bubble. In such a case it is only the pressure wave that acts on the ship hull. **Close distance explosions**, within 2–20 m, having the pressure acting the hull of 8 MPa results in penetration of the hull. The penetration, in such a case, have a linear character and occur along strengthening frames and longitudinals. As the gas bubble does not have contact with the ship, the explosion products do not enter the inside of the ship and there is no direct action by high temperature. Mechanisms and appliances are

usually displaced and broken away from the foundations and their casings are cracked. In the short distance influence explosion the damage zone is much larger than in the case of the contact explosion [3].

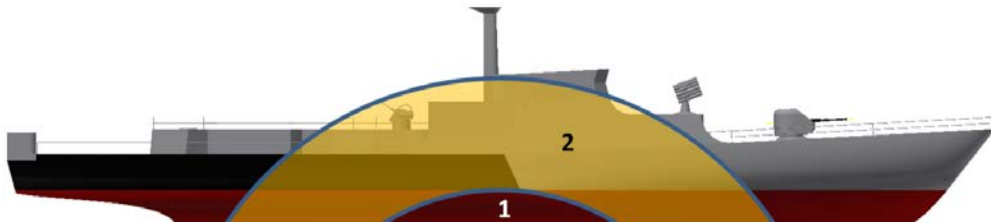


Fig. 7. Zones of destruction in a close distance influence explosion: 1 — linear cracks, 2 — zone of damage to structure and mechanisms

The pressure wave striking the hull causes a bulge, whose direction follows the gas bubble's pulsation. The largest destruction occurs as a result of explosions underneath the keel, amidships. Explosions in the vicinity of the bow or stern usually do not cause the vessel to sink. This is illustrated by the results of accelerations obtained in the course of numerical simulations of the action of the pressure wave caused by the explosion of a 250 kg TNT charge at a depth of 15 m on the hull of a project 206 FM mine-hunter for tests ahead of the bow, behind the stern and off the beam at a distance of 20 m (fig. 8, 9 and 10) [10]. One of the most dangerous short distance explosions is an explosion of bottom mines in shallow water regions. The pressure wave reverberating from the bottom considerably intensifies ship destruction.

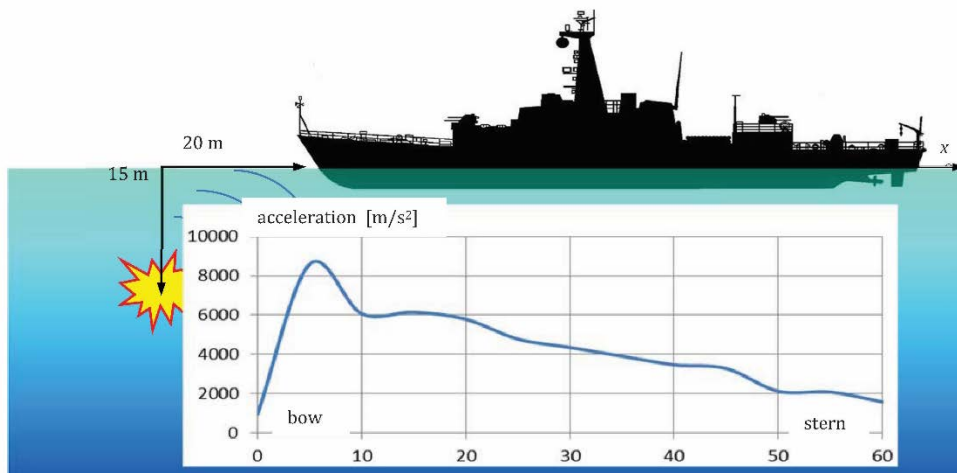


Fig. 8. The values of acceleration on the keel of the 206 FM mine-hunter for an explosion 20m ahead of the bow, depth of 15 m, 250 kg TNT [10]

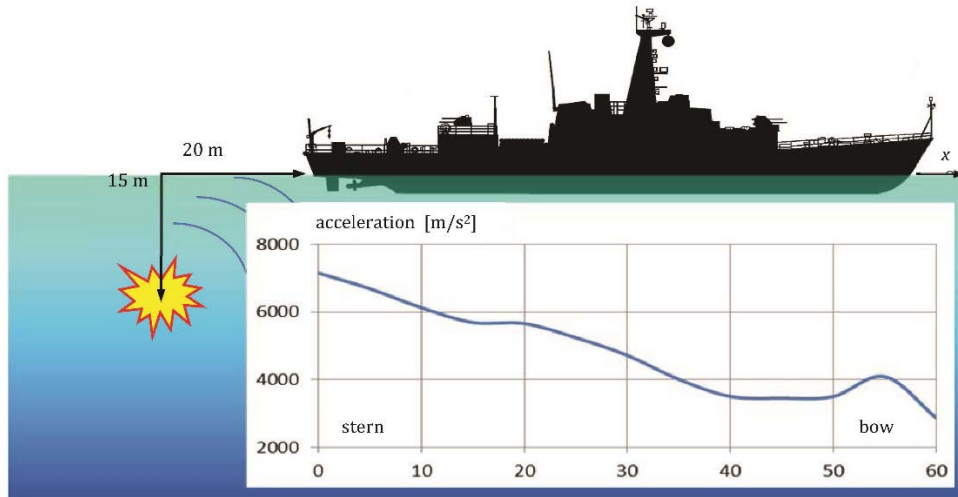


Fig. 9. The values of acceleration on the keel of the 206 FM mine-hunter for an explosion 20 m behind the stern, depth of 15 m, 250 kg TNT [10]

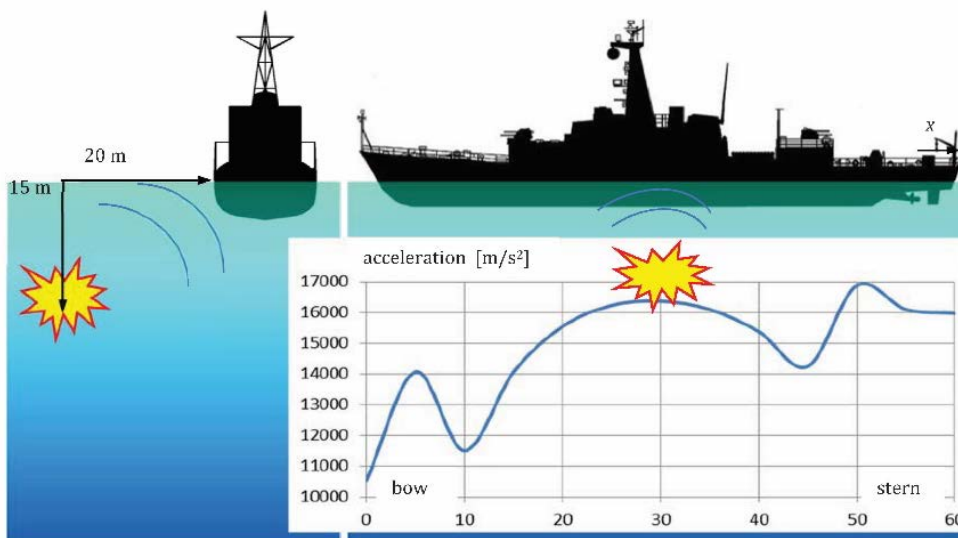


Fig. 10. The values of acceleration on the keel of the 206 FM mine-hunter for an explosion 20 m off the beam, depth of 15 m, 250 kg TNT [10]

An example of the short distance influence explosion is the Ticonderoga-class guided missile cruiser — USS 'Princeton' CG-59, which on 18 February, 1991 off the Libyan coast struck a MN-103 Manta mine, filled with 170 kg of explosive material, worth approximately \$ 1000. The explosion caused damage to the hull and shipboard mechanisms estimated \$ 24 000 000. Repairs took two months.



Fig. 11. The Ticonderoga-class guided missile cruiser — USS 'Princeton' CG-59[19] and a MN-103 Manta mine [20]

Detonations of mines at a distance of more than 30 m away from the ship's hull are referred to as long distance influence explosions. The place of explosion (bow, amidships, stern) does not have such a big impact on its effects as in the case of a short distance explosion. In long distance explosions there do not occur cracks in the hulls plating, but it can sustain deformation in the form of indentation. The pressure wave falling on the hull imparts high acceleration values to its structure nodes, which lead to damage to appliances and mechanisms. The area of damage is wide, and practically covers the whole vessel (fig. 12). The most damage is to the hull below the waterline on the side of the explosion.

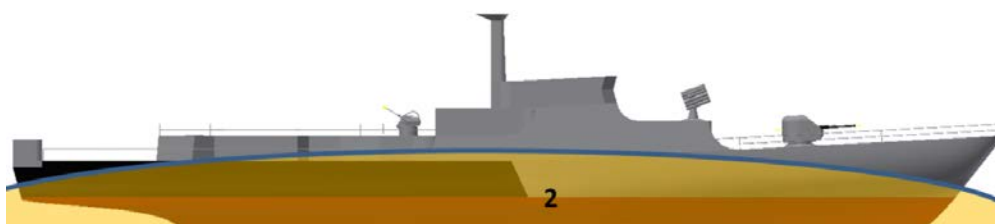


Fig. 12. Zones of destruction in a long distance influence explosion: 2 — zone of damage to structure and mechanisms

In its further parts and on higher decks the intensity of damage decreases due to lower acceleration values. This is presented by spectral acceleration characteristics of ship decks in a long distance influence explosion underneath the keel (fig. 13). These characteristics should be treated as an illustration as in reality they

depend on many factors such as action, direction of explosion, distance, amount of explosive charge, sea state, dimensions, geometry and rigidity of hull, structure bonds, dimensions and mass of appliances, method fixing of appliances on foundations and their shock absorption and many other factors [3].

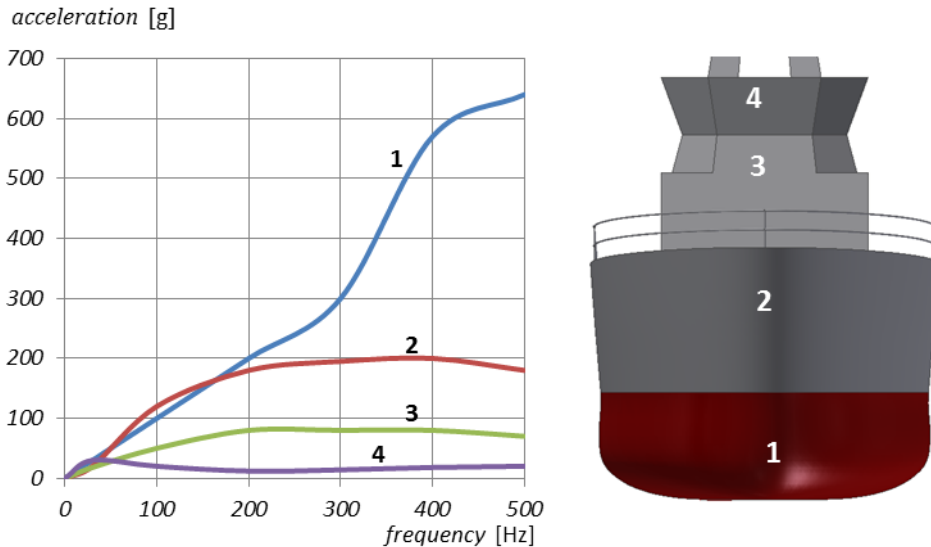


Fig. 13. Spectral acceleration characteristics of ship decks in a long distance influence explosion underneath the keel

The appliances most sensitive to action of high acceleration are electric appliances such as: electricity switchboards, switches, electronic devices, etc. These failures can cause the vessel to come to a standstill, however the crew should be able to bring the vessel to harbor on their own. Shipyard and other repairs are unavoidable. The effects of influence explosions can be minimized by appropriate structural design the vessel. This is especially important in designing warships, especially ships like mine-sweepers, and mine-hunters who, due to their designation have to be capable of surviving multiple underwater explosions.

As a result of unceasing armed conflicts both warships and weapons used to fight them have been in constant development. For this reason rich countries carry out exercise range tests of the action of underwater explosions on a ship using decommissioned vessels or prototypes during which state of the art measuring appliances are used. Data obtained this way considerably facilitates and support designing new vessels resistant to explosions. Figure 14 presents photos of examples of such exercise range tests.



Fig. 14. An influence explosion off the beam of the guided missile cruiser USS 'Arkansas' CGN-41, 17 March, 1982 [3] and an influence explosion off the beam of the aircraft carrier USS 'Theodore Roosevelt' CVN-71, 19 September, 1987 [22]

Progress in computer technologies and the methods of finite elements have resulted in extending the range of use of numerical simulations across the range of issues relating to explosions. Investigations in this area are carried out all over the world, e.g. [4, 15] as well as in Poland [1, 5–8, 10–12]. Numerical simulations, marine exercise range experiments as well as investigations on ships hull impact strength together with equipment to underwater influence explosions have made it possible to estimate the effects of these explosions depending on the value of the falling pressure wave. Table 2 lists the effects of the shockwave having the pressure 0–500 MPa, generated off the beam as a result of the underwater influence explosions of charges weighing 300–1000 kg TNT, on the ship [3].

Table 2. Effects of action of shockwave on a ship caused by an influence explosion [3]

Pressure [MPa]	Effects of action of shockwave on a ship
0–0,4	Safe for all vessels
0–2	Safe for warships
2–4	Lighting lamps cracking, damage to sensitive electronics, cracking of elements made from brittle materials
4–6	Damage to electronics, switchboards, electric appliances. Light injuries sustained by crewmembers, possibility of partially losing maneuver and combat capabilities
6–8	Serious damage to electronics, switchboards, electric appliances, failure of generators, cracking of mechanism casings. Numerous injuries among crew members, considerable lowering of maneuver and combat capabilities
8–12	Deformation and cracking of the hull. Serious damage to mechanisms and appliances, foundation bolts breaking. Numerous injuries among crew members, cases of death. Loss of maneuver and combat capabilities. Docking and shipyard repairs necessary

Pressure [MPa]	Effects of action of shockwave on a ship
12-16	Considerable deformation and cracking of the hull and bulkheads, flooding of compartments. Destruction of mechanisms and appliances. Numerous cases of death among crew members. Total loss of maneuver and combat capabilities. Many months docking and shipyard repairs necessary
16-27	Likelihood for the ship to sink. Cracking of bulkheads and widespread destruction of mechanisms and appliances. High number of death cases among crew members. If the ship does not sink she can be considered for repairs
250-350	Possible immediate sinking of the ship. If the ship does not sink, the destruction is so serious that she will be beyond repair
350-500	Possible breaking of the ship, her capsizing and sinking. If the ship does not sink, the destruction is so serious that she will be beyond repair
above 500	Immediate sinking

CONCLUSIONS

It can be noticed from the list of effects of the shockwave on the ship caused by an influence explosion that every floating vessel should retain maneuvering and combat capabilities without any major loss when the value of the pressure wave is up to 4 MPa. Cracking of bodies of appliances and mechanisms appears at a pressure of up to 8 MPa. At the pressure ranging 12 MPa deformation and cracks in the hull are recorded. If the pressure wave reaches 16 MPa on the shell plating of the hull extensive cracks will occur and the ship can sink. Using the empirical formulas describing the detonation wave the safe distance of the ship from the epicenter can be calculated for a specific mass of the charge and determine explosion parameters (mass and distance) for characteristic pressure values 4, 8, 12 and 16 MPa. Assuming the charge mass as 150 kg for small mines, 300 kg for medium mines and torpedoes, 500 and 800 kg for large ones and 1200 kg for the largest it is easy to determine the damage they will cause in the function of distance of the hull from the epicenter, following for example the Cole's formula (fig. 15, table 3). Analyzing these dependencies it can be assumed that explosions of sea mines containing even 800–1300 kg of TNT at a distance over 80 m do not pose any major threat to warships. For small mines containing up to 150 kg of TNT the safe distance is 50 m.

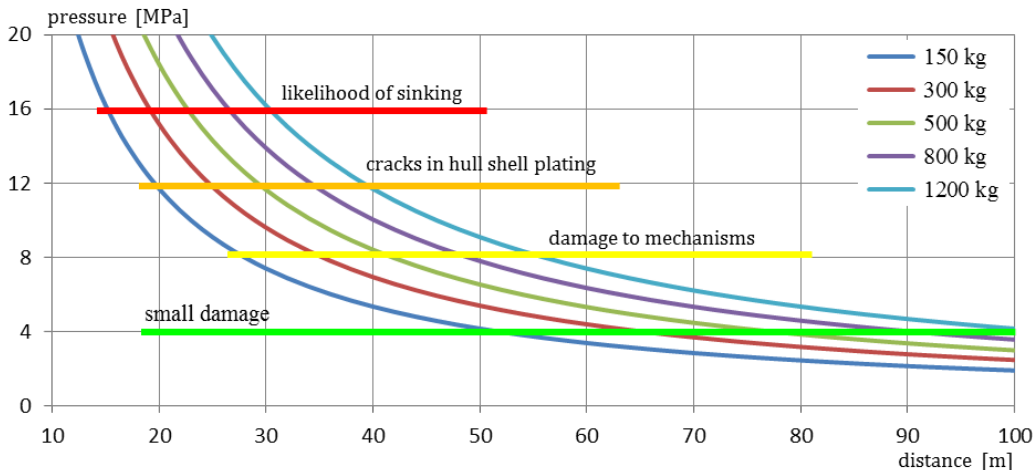


Fig. 15. The effects of the shockwave on the ship hull in the function of TNT mass: 150, 300, 500, 800, 1200 kg following the Cole’s formula

Table 3. The dependence of the distance from the explosion epicenter to the ship in the function of explosive charge mass contained in the mine and the corresponding to them effects of the shockwave on the ship

Detonation wave pressure [MPa]	Mine mass (TNT) [kg]					Explosion effects
	150	300	500	800	1200	
	Distance following the Cole’s formula [m]					
4	51	65	78	90	102	Safe for warships
8	28	35	42	49	56	Damage to mechanisms and appliances
12	19	24	30	34	39	Deformations and likelihood of cracks in hull shell plating
16	16	19	23	27	30	Total loss of maneuver and combat capabilities. Likelihood of ship sinking

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ODDZIAŁYWANIE WYBUCHU PODWODNEGO NA OKRĘT

STRESZCZENIE

W artykule zamieszczono syntetyczny opis wybuchu podwodnego i jego skutki. Przedstawiono wykresy promienia pęcherza gazowego w funkcji masy ładunku i głębokości detonacji oraz wartości ciśnienia na froncie fali uderzeniowej w funkcji odległości i masy ładunku TNT wynoszącej 1, 10, 50, 250, 1000 kg (według T. L. Geersa i K. S. Huntera). Przedstawiono klasyfikację wybuchów podwodnych i ich oddziaływanie na kadłub okrętu. Przedstawiono klasyfikację współczesnych min morskich świata. Opracowano wykres umożliwiający szacowanie skutków oddziaływania fali uderzeniowej na kadłub okrętu w funkcji masy ładunku TNT według wzorów Cole'a.

Słowa kluczowe:

wybuch podwodny, mina morska, pęcherz gazowy, fala, ciśnienie, wzory Cole'a.