1477. Analysis of the pressure wave parameters caused by TNT underwater explosion forced on the hull of minehunter

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Abstract. The paper presents the parameters of the pressure wave incident on minehunter hull structure modeled on the simplified vessel hull of Kormoran II project. The pressure wave is caused by the sea mine explosion on wet board of the ship and propagates in the sea. To describe the pressure wave procedure pressure formulas which can be implemented on programs CAE based on the Finite Element Method (FEM) was used. The way of modeling short – term issues using FEM and constitutive equations describing the explosion of TNT in the sea was described. Naval mines used by the Polish Navy were characterized. Equivalents of selected explosives in relation to the TNT were posted. Geometry of mine destroyer was mapped as a shell – beam model. The results of the pressure wave incident on the hull as a function of charge weight and the location of the epicenter of the explosion was presented. Formulated conclusions and comments.

Keywords: impact resistance of the structure, a model of the pressure wave, underwater explosion, short – term process, FEM, CAE, Kormoran II.

1. Introduction

In September 2013, Inspectorate of Polish Navy Armament signed a contract to build new ships for combating and setting mines codenamed "Kormoran II". She has to be adapted to operate in the Polish economic zone, as well as in tactical operations in the Baltic and the North Sea. Basic assumptions tactical – technical shown below [1]:

- displacement: max: 850 tons;
- length: 58.00 m;
- width: 10.30 m;
- forecastle deck height: 6.40 m;
- the height of the main deck, aft: 4.70 m;
- draft: 2.60 m;
- speed: not less than 15 kt;
- range: not less than 2,500 nautical miles.

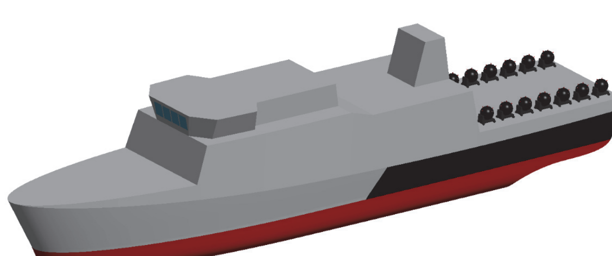

Fig. 1. The Kormoran II minehunter designed for the minefield setting

Due to the destination of the ship should be examined cases in which the ship may be exposed to the sea mine explosion. It is therefore necessary to distinguish underwater explosion (UNDEX) derived from the enemy charge and the explosion on board in case of a failure while setting up mine warfare. The effects of explosions are difficult to predict. In case of contact explosions which are explosions on board of the ship, it is possible to determine the pressure distribution derived from such an explosion by using the CONWEP procedure which is not described further.

2. Underwater explosion

Nowadays, many CAE programs uses CONWEP procedure to simple calculations for free explosions in the air. The value of pressure is determined by the program based on the weight of the load and then using TNT equivalents calculated for the respective loads. A similar situation can be applied to underwater explosions. In order to properly calculation of pressure wave incident on the structure shall be familiar with the phenomenon, analytical description of the pressure wave used by the program and simplifying assumptions.

Underwater explosion is a rapid equilibrium violation caused by detonation of explosive in water. During explosion the charge is converted from solid into product of volume equal to volume of explosive material, temperature range $T \approx 3300$ K and pressure $p \approx 14000$ MPa. With so much pressure gas bubble is formed which causes a spherical shock wave that propagates in the medium [3, 4]. The first of the researchers of this phenomenon was the R. H. Cole whose works are the basis for further research. The parameters of the shock wave and the gas bubble parameters are being investigated further. Currently the main of researchers are T. L. Geers, K. S. Hunter and C. K. Park. Most previous publications describes the behavior of gas bubbles, often omitting same shockwave. In this work, omit the description of the bubble in order to focus on the pressure wave from the detonation. This wave in the initial stage moves at a speed of the order of $v \approx 5000$ – 8000 m/s. Then, the water molecules act on the water layer adjacent losing speed and travel further the speed of sound in water, which is approximately $c_o \approx 1500$ m/s. Pressure impulse was described by researchers in various ways. It is hard find a universal solution, however, due to the development of measuring instruments in this work decided that for the calculations related to underwater explosion the latest models, i.e. model developed by Geers'a and Hunter will be best to use. Figure 2. Shows the profiles described by researchers over the years [5].

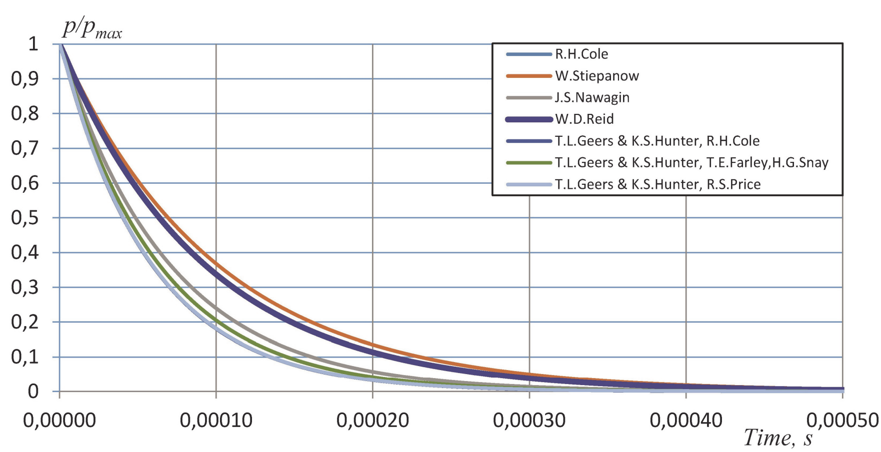

Fig. 2. The pressure wave profiles described by researchers over the years [5]

Cole formulas are described below. They were determined by the measurement of detonation of 70-136 kg of TNT. Profile of the pressure wave is described by the following formula:

$$p(t) = 52{,}3\left(\frac{\sqrt[3]{m}}{r}\right)^{1{,}13} \cdot e^{-\frac{t}{\theta}}, \tag{1}$$

$$\theta = 0{,}093\sqrt[3]{m}\left(\frac{\sqrt[3]{m}}{r}\right)^{-0{,}22}, \tag{2}$$

where: m – charge mass, kg, r – distance of epicenter, m, p_{max}peak pressure, MPa, θ – time constant, ms, t – time, ms.

Cole models were presented in 1948. Since that time was corrected by J. S. Navagin W. Stiepanow, and T. L. Geers and K. S. Hunter, the latter formulas are described below:

$$p_{max} = P_c\left(\frac{a_c}{r}\right)^{1+A} \cdot e^{-\frac{t}{\theta}}, \tag{3}$$

$$\theta = v_c\left(\frac{a_c}{r}\right)^{B}, \tag{4}$$

where: a_c –charge radius, m, $P_c = 1.42$, $v_c = 0.992$, $A = 0.13$, $B = 0.18$.

Table 1. TNT equivalent for various explosives [2]

Explosive	Density ρ (g/cm^3)	Heat of explosion Q (kJ/kg)	Pressure p (MPa)	Detonation speed D (m/s)	TNT$_e$ (Q)	TNT$_e$ (p)	TNT$_e$ (D)
TNT	1,64	5569	19,0	6950	1,00	1,00	1,00
Hexogen	1,8	6334	34,7	8754	1,14	1,83	1,26
Hexotol 90/10	1,61	6232	25,6	7910	1,12	1,35	1,14
Hexotol 80/20	1,6	6150	24,2	7745	1,1	1,27	1,11
Hexotol 70/30	1,59	6070	22,7	7580	1,09	1,19	1,09
Octogen	1,9	6538	39,3	9100	1,17	2,07	1,31
Octol 90/10	1,75	6438	30,3	8320	1,16	1,59	1,2
Octol 80/20	1,71	6342	27,8	8050	1,14	1,46	1,16
Octol 70/30	1,7	6242	26,7	7900	1,12	1,41	1,14
Octol 60/40	1,7	6156	25,3	7680	1,11	1,33	1,11
Pentryt	1,77	6400	33,5	8300	1,15	1,76	1,19
Tetryl	1,68	5920	24,5	7560	1,06	1,29	1,09
PBX-9011	1,77	6168	29,9	8700	1,11	1,57	1,25
HMX/PU 80/20	1,43	5856	19,3	7334	1,05	1,02	1,06
RDX/PU 80/20	1,57	5735	23,4	7778	1,03	1,23	1,12
RDX/PU 70/30	1,38	5436	16,7	6961	0,98	0,88	1,00
NM	1,13	6435	12,5	6523	1,16	0,66	0,94
NGL	1,59	6606	24,6	7580	1,19	1,29	1,09
DATB	1,79	5498	25,9	7520	0,99	1,36	1,08
PETN/PU 90/10	1,65	6406	26,3	7950	1,15	1,38	1,14
PETN/PU 80/20	1,5	6034	21,5	7465	1,08	1,13	1,07
PETN/PU 70/30	1,39	5682	16,5	6957	1,02	0,87	1,00
PEP (85/15)	1,5	6186	21,5	7600	1,11	1,13	1,09
SEMTEX	1,4	6372	19,8	7220	1,14	1,04	1,04
C-4	1,66	6650	25,7	8370	1,19	1,35	1,2
COMP. B	1,72	6000	28,1	8052	1,08	1,48	1,16
LX-17	1,91	4407	31,6	7630	0,79	1,66	1,1
LX-14	1,83	6452	36,3	8958	1,16	1,91	1,29

In the case of explosions of any material other than TNT it is possible to use a TNT equivalent. The equivalent is very difficult to determine because of the multitude of comparative parameters. In practice the heat of explosion, detonation speed and pressure coming from the explosion at a test distance are compared. As the table shows the equivalents determined on the basis of various parameters differ significantly. A good solution is to use average values.

Attention to the complexity of the explosion and the phenomena attendant should be paid. In the performed simulations cavitation, pulsation, reflections from the bottom and displacement of gas bubble to the surface have been omitted. Also only non-contact explosions was used because the effects of contact explosions are difficult to predict. Proper phenomenon of underwater explosion is shown in the Fig. 3.

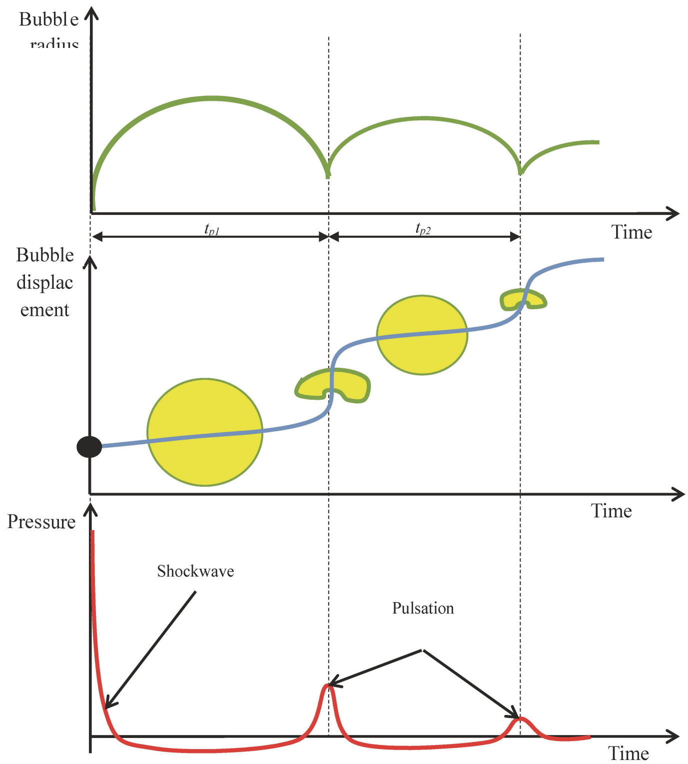

Fig. 3. Underwater explosion phenomena [7]

As can be seen from Figure 3, the explosion create pressure pulse called the shockwave. The gas bubble is minimal in this time. Inside the bubble are highly compressed gases which cause expansion of the bubble to the point where the pressure within the bubble is equal to the hydrostatic pressure of water, and then begins to be compressed again due to the compressibility of the gas. At the same time the gas bubble moves to the water surface. Reduction of hydrostatic pressure causes gas bubbles expansion again which causes another pressure pules called pulsation. The above phenomenon is repeated until the movement of the bubble to the surface is completed [3].

3. Minefields threats in the world

Naval mine is the explosive charge with protective devices, responsive and incendiary placed in the watertight hull used to destruction of the underwater part of the hull of the ship. Among the many divisions and classifications of mines fundamental division concerns the mines places in the water and how it responds to the vessel. Typical classification is shown on Fig. 4, [6].

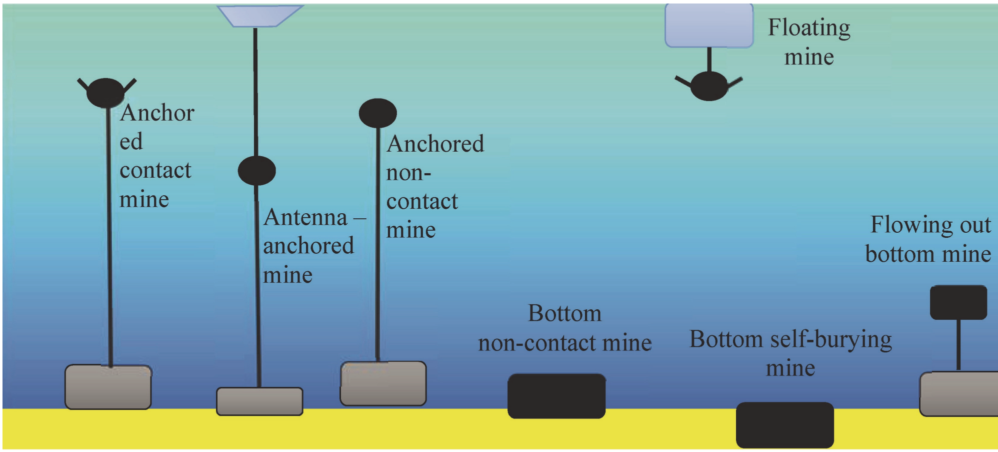

Fig. 4. Classification of naval mines

Naval mines were first used in the Crimean War (1853-1856) by the Russian fleet. Modern mines are intelligent devices, capable of movement, and to bury itself in the bottom, which makes them undetectable. They are equipped with various sensors alternating magnetic field, electric potential and improved hydrodynamic field sensors capable of self-regulation depending on external conditions. They can work individually or in groups, acting in an intelligent minefields, able to recognize the enemy ships (IFF system). The Polish Navy uses 4 types of sea mines (Table 2 and Figure 5) with a mass of TNT from 110 to 400 kg. Navies of the world use mine with similar masses, but you can find much larger amounts of up to 1350 kg of TNT. Selected mines are presented in Table 2.

Table 2. Polish Navy mines

Name	Depth, m	Mass of TNT, kg
OD – Okrętowa duża	12	250
OS – Okrętowa średnia	10	110
MMD – 1 – Mina Morska Denna 1	20	190
MMD – 2 – Mina Morska Denna 2	50	400

Table 3. Mines used by other countries Navy [6]

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

Fig. 5. Polish Navy Mines (Source: Laboratory of Underwater Weapons Polish Naval Academy)

4. Preparation of FEM simulation

The task of explosions, should be regarded as an appropriate task described by the equation of motion. Recognition of this phenomenon using the finite element method requires the use of an appropriate equation in the form:

$$\mathbf{M}(\mathbf{U})\ddot{\mathbf{U}} + \mathbf{C}\dot{\mathbf{U}} + \mathbf{K}(\mathbf{U}, \dot{\boldsymbol{\varepsilon}})\mathbf{U} = \mathbf{F}(t, R, m_{TNT}), \tag{5}$$

where: $\mathbf{K}$ – stiffness matrix; $\mathbf{M}$ – matrix of inertia (density matrix); $\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K}$ – damping matrix, where α and β are constant coefficients; $\mathbf{U}, \dot{\mathbf{U}}, \ddot{\mathbf{U}}$ – displacement, velocity and acceleration vector; $\mathbf{F}$ – load vector; $\dot{\boldsymbol{\varepsilon}}$ – strain rate vector; t – time; R – distance from epicenter; m_{TNT} – TNT charge mass.

In the task load vector **F** have been set as a time-varying pressure wave in accordance with equations (1), (2) or (3), (4). Other expressions of equation (5) in this work are omitted, because they describe the structure reaction while this work refers only to load.

Polish Navy is currently using 4 types of sea mines. Among other, uses OS mine which contains 110 kg TNT (Source: Laboratory of Underwater Weapons Polish Naval Academy). The paper examined a case in which such a charge detonates around the ship of Kormoran II project. Using CAD programs reflected outer shell of the ship, and then implements it into CAE program in which the relevant calculations were carried out.

Due to the very short load time very high attention should be paid to the finite element size and time step choice. The calculations of explosions are complex and lengthy because of fact that for large structures character of the load can be omitted. To compare waveforms pressure from analytical solutions or experiments the relationship can used:

$$I^{+} = \int_{0}^{t_a} [p(t) - \gamma H] dt, \tag{6}$$

where: t_a – time of the first positive pulse pressure wave, s; γH – hydrostatic pressure, Pa.

As is apparent from Fig. 6 the I^{+} individual waveforms can be close to each other but maximum can be undercut. Due to the fact that in the present time step, one of the nodes has been dispensed with a lack of symmetry of the load has been shown. Properly selected time step and the size of the element shown in Fig. 7.

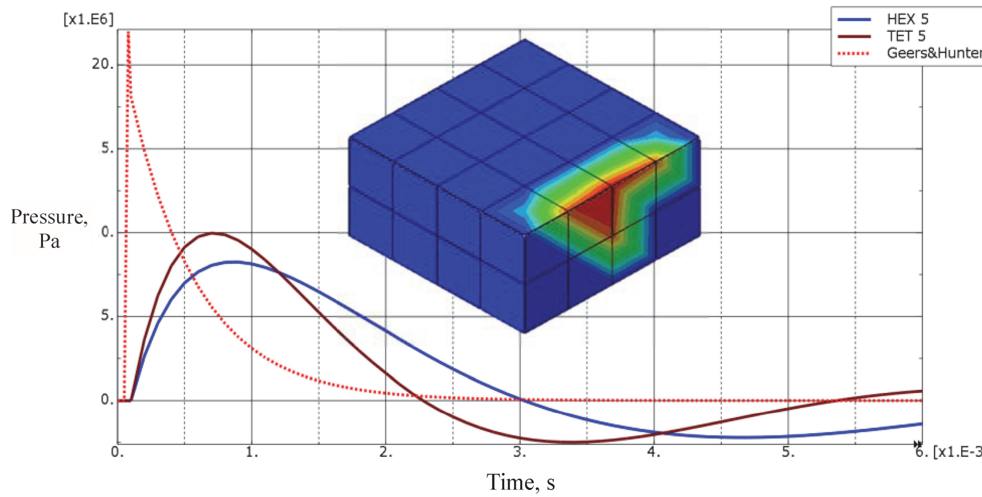

Fig. 6. An example of incorrect element size and time step [5]

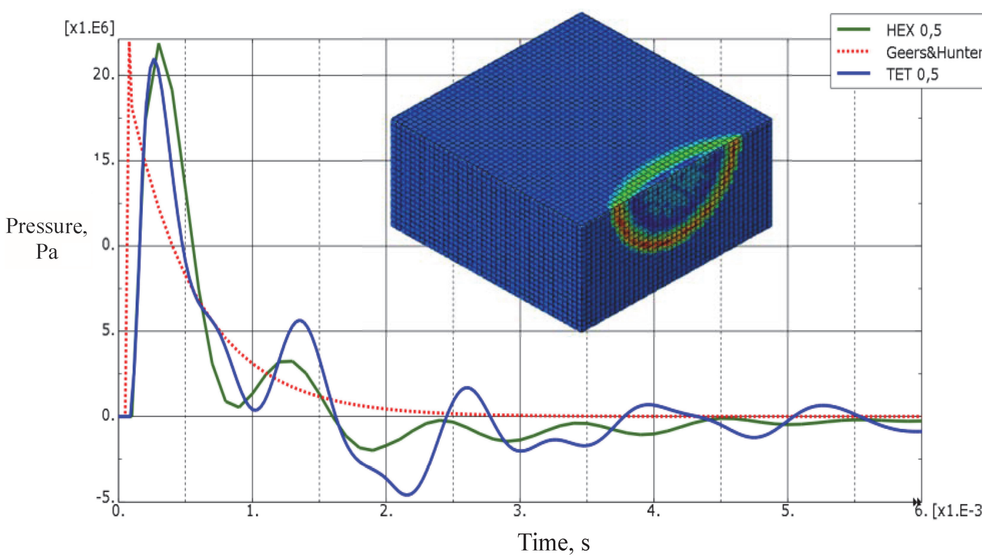

Fig. 7. Proper time step and element size [5]

Charge was placed at a distance of 9 m below the keel of the ship. According to equation (3) the pressure on the front of the shock wave is 25.67 MPa. The pressure calculated by the program was 29 MPa. The difference results from the strong relationship between the size and shape of mesh elements. In the paper [5] the effect of mesh size and shape on the propagation of the shock wave were analyzed. It was found that the 4 - nodal tetragonal of size of 0.5 m elements are best to use.

The pressure distribution of non-contact mine explosion in the acoustic medium in different time points were shown. The pressure wave reaches the ship's hull and it is reflected resulting in a negative pressure. The decrease of pressure can lead to cavitation under the keel of the ship. In this case, if the ship is treated as a beam supported continuously, due to cavitation a discontinuity of the support will appear and the ship would be load with the forces of gravity. In this work, this phenomenon is omitted.

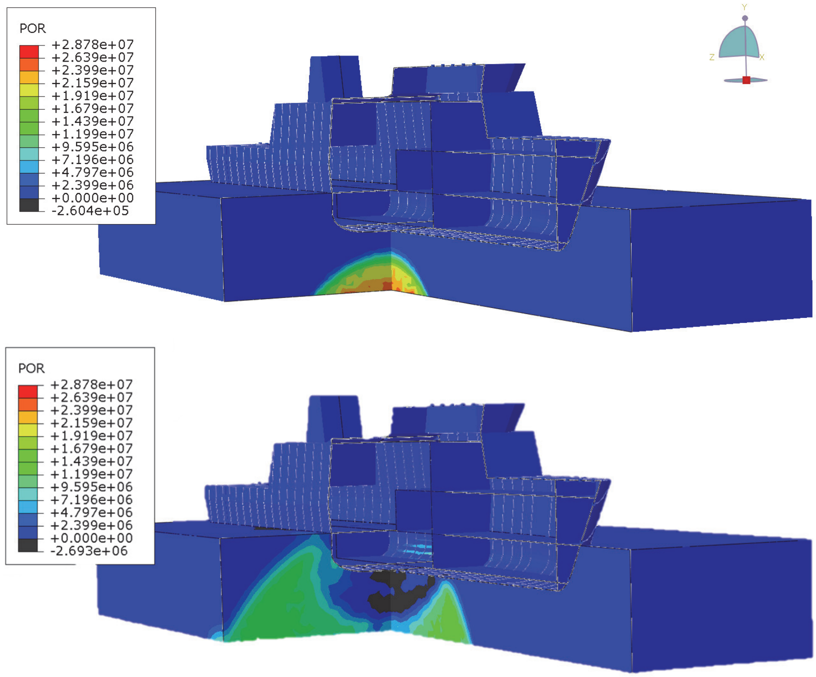

Fig. 8. Pressure distribution of non-contact TNT explosion under the keel of the ship

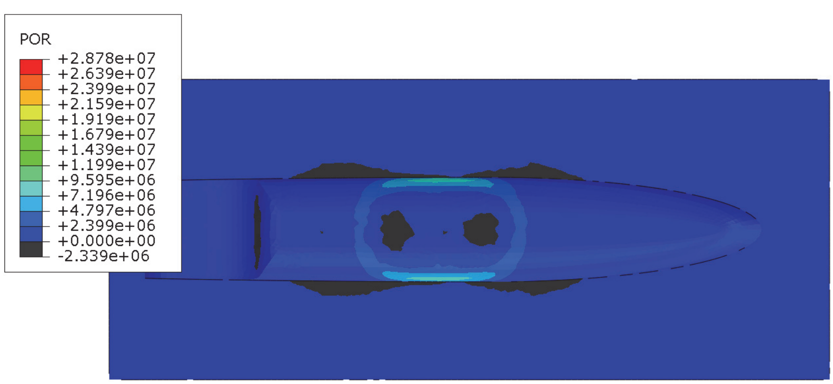

Fig. 9. Pressure distribution of non-contact TNT explosion under wet surface of the ship

5. Conclusions

Study describes the phenomenon of underwater explosion. The model used in the study is the latest model of the shock wave in this type calculations. Problems that results from the application of the acoustic medium and its response for the given load. Also highlights the FEM equation that describes the dynamics task. The complexity of this task depends on the author and expected results. In case of underwater explosions weight loss, elements self – contact or hardening of the material due to the strain rate can be included. The influence of various parameters on the results will be examined in further publications.

Using the presented method of modeling underwater explosion can also designate an approximate movement parameters for the foundations of the devices inside the ship. Omitting the effect of cavitation and other phenomena can have a significant impact on the response of the structure. However, is assumed, that for steel the most important is a first shock wave, which is described in this article.

It should also be used carefully presented equivalents of TNT. A multitude of methods for their determination as well as errors due to incorrect modeling of acoustic mesh elements can significantly affect the obtained results.

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