AREA OF IMPACT OF UNDERWATER EXPLOSION ON DIVERS

Institute of metal science, equipment, and technologies with Hidroaerodynamics centre “Acad. Angel Balevski” – Bulgarian Academy of Sciences, Sofia, Bulgaria

nika0611@abv.bg, aleksandar_kolarov@abv.bg

Abstract: Underwater swimmers can be amateurs without criminal intent, as well as poachers, underwater treasure hunters, or underwater saboteurs carrying out terrorist acts or gathering intelligence pose new challenges to the underwater safety of water transport in ports, coastal and offshore facilities and other sites of the critical coastal infrastructure. While the former category is usually handled with police-type techniques using non-lethal weapons, a lethal force could be used at some stages when dealing with terrorist divers. In this context, it is of theoretical and applied interest to identify the areas in which the underwater explosion leads to different types of impacts on divers. The material proposes an approach to assess the strength of the underwater blast caused by means of warning and protection from underwater swimmers, which could be used in the construction of specific protection systems for harbors, naval bases or element of the critical coastal infrastructure against unauthorized access by divers.

Keywords: DIVER, UNDERWATER EXPLOSION, GAS BUBBLE, PRESSURE IN THE WAVE, DAMAGING EFFECT

1. Introduction

Underwater swimmers pose new challenges to the departments and agencies authorized to provide underwater safety of water transport in the waters of ports and coastal and offshore facilities and other sites of the critical coastal infrastructure. Divers can be amateurs without criminal intent, as well as poachers, underwater treasure hunters, or underwater saboteurs carrying out terrorist acts or gathering intelligence. While the former are usually handled with police-type techniques using non-lethal weapons, a lethal force could be used at some stages when dealing with terrorist divers. For these purposes, remote-controlled underwater charges, hand-held underwater grenades, underwater pneumatic devices, etc. are often used in warning and physical deterrent or destruction subsystems. In this context, it is of theoretical and applied interest to identify the areas in which the underwater explosion leads to different types of impacts on divers. The fact that the detection distance of divers with the help of specialized sonars - from 500 to 700 meters - is comparable to the radius of impact of underwater explosive devices, which significantly limits the time to decide what means to use, makes the preliminary practical determination of peak pressure of the underwater sound wave in the impact area important and necessary.

2. Prerequisites and means for solving the problem

In the first type divers, the techniques police-type with non-lethal weapons are usually used for influencing offenders. In combating terrorist divers at some stage it is possible to use the funds to a lethal outcome. The underwater explosion of a bomb or a grenade can either alert the diver to float or to force him to float. They can also effectively induce lethal outcome for underwater swimmers. Table 1 shows the limit values characterizing the blast effect on the diver wearing a neoprene standard suit [1].

<table>
<thead>
<tr>
<th>Peak pressure, [psi]</th>
<th>Peak pressure, [kPa]</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 2000</td>
<td>&gt; 13800</td>
<td>Death</td>
</tr>
<tr>
<td>500 - 2000</td>
<td>3450 - 13800</td>
<td>Death or serious injury</td>
</tr>
<tr>
<td>50 - 500</td>
<td>345 - 3450</td>
<td>Possible serious injury</td>
</tr>
<tr>
<td>&lt; 50</td>
<td>&lt; 345</td>
<td>The probability of injury is low</td>
</tr>
</tbody>
</table>

According to published results [1, 3], it can be concluded that the peak pressure of underwater sound wave with a value of 230 dB re 1 µPa will be fatal for the diver and in the range 206 to 226 dB re 1 µPa would cause various organ and tissue damages, which in the most cases require the diver to rise to the surface. In this context, the measurement of the power of the underwater explosion of means for countering divers and underwater swimmers and the evaluation of its striking effect (lethal and/or non-lethal) as a function of distance, depth of sailing, scuba equipment and others have great practical application in the design of underwater bombs, grenades, and setting the tactical use.

The problem can be formulated as: How to evaluate the power of an underwater explosion and, accordingly, the area of non-lethal and lethal impact on underwater swimmers for the purpose of the tactics of using explosives?

The use of mathematical apparatus does not allow to take into account all the parameters and their interdependence and does not guarantee accurate results. Therefore, measuring the strength of the underwater explosion as a means of countering divers and underwater swimmers and assessing its damaging effect (deadly or non-lethal) as a function of the distance, the relief, and structure of the bottom, the depths of sailing and the positioning of the blasting device. The abovementioned function factors have sufficient applications in the design and tactics of use of underwater effectors.

This is confirmed by the differences in results calculated with some empirical formulas (Table 2).

Table 2: Impact zones on divers

<table>
<thead>
<tr>
<th>Lethal Range</th>
<th>Change Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 kg</td>
<td>1 kg</td>
</tr>
<tr>
<td>1. Re=7.17 W(^{-0.5}) (blast and wave)</td>
<td>1m</td>
</tr>
<tr>
<td>2. Re=3.75 W(^{-0.5}) based on P=13800 kPa (US Navy Diving manual)</td>
<td>1.47m</td>
</tr>
<tr>
<td>3. Le=512 Pa-s (50% mortality for 80kg manual, Richardson)</td>
<td>1.3m</td>
</tr>
<tr>
<td>4. Le=516 Pa-s (5% mortality for 80kg manual, Richardson)</td>
<td>2.3m</td>
</tr>
<tr>
<td>Physical injury / Deterrent range</td>
<td>5. R=18.35 W(^{-0.5}) (blast and wave)</td>
</tr>
<tr>
<td></td>
<td>6. R=18.35 W(^{-0.5}) based on P=3450 kPa (US Navy Diving manual)</td>
</tr>
<tr>
<td></td>
<td>7. Le=215 Pa-s (no mortality for 80kg manual, Richardson)</td>
</tr>
<tr>
<td>Non-injury range</td>
<td>8. R=85.25 W(^{-0.5}) based on P=345 kPa (US Navy Diving manual)</td>
</tr>
<tr>
<td></td>
<td>9. Le=14 Pa-s (Christian and Gouin)</td>
</tr>
<tr>
<td></td>
<td>(Nedwell)</td>
</tr>
</tbody>
</table>

The material proposes an approach to assess the strength of the underwater blast caused by means of warning and protection from underwater swimmers, which could be used in the construction of specific protection systems for harbors, naval bases
or element of the critical coastal infrastructure against unauthorized access by divers.

3. Solution of the examined problem

3.1. Measurement of characteristics of the underwater explosion

An explosion occurs through the explosive conversion of explosive gas in a result of a chemical reaction that takes place at very high temperature 3000°C and pressure over 150,000 atm. The distribution of this pressure at the explosion of detonating substances (TNT) is carried out in all directions with the supersonic velocity of several thousand meters per second from 4500 to 8000 m/s. As a result, the shock wave is created, which differs from the ordinary acoustic wave due to the large amplitude and the explosive character of the pressure. At the first shock wave pressure is the same as of the detonation products, and its initial velocity in water is about 85% of the one of the charge detonation. At a distance of about ten radii of the mass of explosive (aligned to form a sphere) the pressure decreases and the velocity of sound in water reaches its constant average value, i.e. about 1500 m/s. Energy losses at underwater explosion are negligible because the energy of the blast, transformed into a shock wave, is used mainly for a displacement of the water mass, and the temperature of the surrounding water mass is increased slightly. It is assumed that approximately half of the explosion energy is converted into heat, and the other half is emitted in a pulse as sound pressure. One of the significant features of explosion of detonating substances under water is the formation of vapor-bubble. Possessing a positive buoyancy, it pulsed with radial pulsation of the gas field caused by dynamic cyclic expansion and contraction floats to the surface of the sea, where sprays. The maximum radius and the pulsation period of the gas bubble are interconnected and depend on the hydro-static pressure of the blast depth, which increases in proportion to the depth and on the density of water [2]. The distance between the receiver and the point of detonation greater than 91.4 m is in effect for the empirical formula of the pulsations period [1]:

\[
T = 2.1W^{0.15}(h + 10.07)^{0.8},
\]

where \( T \) [s] - pulsations period; \( W \) [kg] - charge size.

The empirical dependency between relationships of the periods of the first, second and the third pulse of the gas bubble:

\[
3.1: 2.1: 1 = 0.76: 0.55
\]

is obtained during multiple studies [3]. The maximum pressure in the gas bubble at the end of first pulse is about 10–20% from the shock wave pressure, which in the second and the third pulse (can reach up to 10) causes repeated hydraulic shocks with the periodicity 0.1–0.15 seconds. In the process of shock wave propagation from the blast center, the shock wave front undergoes deformations as a result of losses from its expansion, the thermal conductivity of the water, and the mechanical processes related to its compressibility and elasticity. The initial pressure and velocity of the shock wave decrease gradually to sound values, and its front from oval one becomes steeper, i.e. in the area of high pressures and the small velocities. In this way, at an adequate distance from the blast center, the non-linear processes in the shock wave front disappear and its propagation begins to obey the laws of acoustics. The energy dissipation of acoustic radiation at the expense of its transformation into heat is not usually taken into account due to the weak influence of this factor on the magnitude of absorption, i.e. the movement of the acoustic wave in a real environment is considered as an adiabatic process. Experimental researches have shown that the pressure in the shock wave is changed as a bell curve (pulse), which is approximated sufficiently accurately by the formula [4]:

\[
p = p_m e^{-t/T}
\]

where \( p \) [atm] (1 atm = 101.32 kPa) - pressure in the shock wave;

\( p_m \) - peak pressure; \( t \) [s] - time; \( \Theta \) - time parameter which depends on the charge size \( W \) and the distance from the blast center:

\[
\Theta = 97.6W^{0.22}
\]

where \( W \) [kg] - charge size.

The peak pressure is determined by means of experimentally obtained formula [1]:

\[
\left(\frac{W}{r}\right)^{0.22}
\]

where \( r \) [m] - distance from the blast center.

The spectrum of explosive depends on the blast amount and depth. The spectrum of the explosive signal is characterized by large subsonde in the frequency domain due to interference. The position of the first maximum of the frequency scale \( f_1 \), and also the distance between adjacent peaks in the spectrum \( \Delta f \) are associated with the first pulse period of the gas bubble \( T_1 \) by means of the proportion [2]:

\[
f_1 T_1 = \Delta f T_1 = 1
\]

The periodicity of interferential minimums is observed at frequencies up to 3–5 kHz. At higher frequencies, the main energy carrier of the signal is the explosive shock wave. After transformation, the importance of the energy spectrum of the explosion is obtained:

\[
|S| = \frac{P_m^2}{f^2 + \Theta^2}
\]

This formula shows that in the low-frequency domain \( (\omega/\Theta) \) the energy spectrum does not depend on the frequency, and for \( (\omega/\Theta) \) it decreases proportionally to \( 1/\omega^2 \). Based on the study of the sound waves propagation in the frequency interval from 16 Hz to 60 kHz, for the coincident of absorption \( \beta \) of the acoustic energy in the seawater the empirical formula is obtained [5]:

\[
\beta = 0.036 * f^{2.5} [\text{dB/km}],
\]

where \( f \) is the frequency in kHz.

The sound wavefront undergoes reflection from both the sea surface and the bottom when propagating in shallow water areas up to 100 m. The interference of the direct wave with multiple reflected waves can lead to different results in measuring the amount of otherwise identical explosive charges, and by the same distance because the parameters of seawater as a hydro-acoustic channel are numerous and continuous variable. The approximate shape of the shock wave pulse received on the receiver as a result of interference with the reflections from the bottom and the sea surface is shown in Fig. 1.
In the typical case of conducting researches, when the distance between the source (explosion) and the receiver $R$ is greater than the depth of the blast $h_1$ and the receiver $h_2$, the acoustic pressure amplitude can be determined by means of the formula [6]:

\[
p_a = \frac{\rho A \omega}{R} \sin \left( \frac{2 \pi r}{\lambda} \right)
\]

The formula (9) analysis shows that if the source depth and the distance to the receiver are saved, and only the depth $h$ is changed, one will observe both the zones with the zero pressure and the ones with the maximum pressure as a result of the interference of the waves direct and reflected from the sea surface. Ninety-nine percent of the energy of the wave incident on the sea surface is reflected with a negative sign. This fact leads to the following practical conclusions:

- It is appropriate the relatively small depth (4–5 m) to be chosen for the explosion depth comparable to the radius of the first vapor bubble to avoid the influence of repeated hydraulic impacts.
- It is necessary for the receiver depth to be increased simultaneously with shortening the distance between it and the source to obtain higher sound pressures.

3.2. Sensors for measuring the characteristics of the explosive source

The sensors for pressure measuring are widely used in order to measure the characteristics of the explosive sources. The sensitive element of these sensors is made of quartz, piezo, tourmaline and fluoro polymer. Basic requirements for these sensors are the sensitivity increased to high frequencies, the high stability, the ability to supply a long cable, and to work in a hostile environment. Applications for measuring the strong shock wave using a long cable for transmitting data to the processing system must be carefully calculated to ensure the necessary frequency response. The long cable capacity behaves like a low pass filter and for reason of that. It must be taken into account in determining the output voltage and current of sensor. As a rule, a higher current is required to provide a higher voltage at the long cable output (20 mA to power the long cable).

To provide 1 V at the estimated pressure output, the frequency response of the sensor needs to be five times larger than that of the current and the cable. For this purpose, the sensors are combined with an electron block and compensatory acceleration sensor elements, which ensure the necessary frequency response. The sensors with the frequency compensation hold time of a few microseconds to react and not self-excitation, which provides an accurate measurement of the shock wave. Characteristics of a tourmaline sensor of company “Aerospace & Defence Division” (Fig. 2) are given in Table 3.

Tourmaline sensors are delivered with a cable length for measurement conditions, but their disadvantage is that they can be used to measure the sound pressures from the source no greater than 100 MPa. For the measurement of higher pressures, the fluoro-polymer sensors are used which have the characteristic impedance close to that of the water.

4. Results and discussion

4.1. Scheme of measuring the power of an underwater explosion

It is known that both the instantaneous pressure and the blast constant depend on the blast mass $W$ and the distance to the explosion point $r$. In this connection, the performance of practical measurements of the explosive source should include two stages:

- The first stage is the preparation of measurement, i.e. determining the blast mass, the choice of the measurement scheme, the choice of the blast area, determining the explosion depth, the hydrophone depth, and the distance between the blast point and the measurement point $r$. The distance is determined so as to be greater than the one at which the value of the instantaneous pressure of the blast would be greater than the maximum scale of measuring instrument;

- The second stage involves measuring the instantaneous pressure and recording the signal from the blast for subsequent processing. The measurement scheme is shown in Fig. 3, where PXI is the console for the digitization of the signal, its writings in the file, and the software for processing and displaying the signal.

4.2. Results:

The values of the results measured by the above scheme are shown in Table 4:

Table 4: Results of the measurements
The correspondence between the measured results and the calculated by empirical formulas for different charges are shown in Fig.4, Fig.5 and Fig.6:

<table>
<thead>
<tr>
<th>No</th>
<th>Weight of the explosion, kg</th>
<th>$P_{70}$ (measured instrumentally at 70 m) dB/μPa</th>
<th>$P_{t}$ (calculated by the formula of 1 m) dB/μPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>200.8</td>
<td>237.7</td>
</tr>
<tr>
<td>2</td>
<td>0.75</td>
<td>201.6</td>
<td>238.48</td>
</tr>
<tr>
<td>3</td>
<td>0.75</td>
<td>202.2</td>
<td>239.19</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>200.8</td>
<td>237.7</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>201.6</td>
<td>238.48</td>
</tr>
</tbody>
</table>

Fig.4. Measured peak shock wave pressure at a charge of 0.5 kg

Fig.5. Measured peak shock wave pressure at a charge of 0.75 kg

Fig.6. Measured peak shock wave pressure at a charge of 1.0 kg

The shape and the parameters of an underwater explosion obtained experimentally by the scheme are shown in Fig.7 and Fig.8.

5. Conclusion

- Tactics of using underwater swimmers against objects of the coastal and the off shore infrastructure (oil and gas platforms, submarine cables and pipelines, etc.) as well ships and hydro-technical equipment in the region of ports shows that the depth of their sailing is expected to be in the range between 5 and 40 m;
- The distance between the sensor and the charge is determined to be greater than the distance at which the value of the instantaneous pressure of the blast would be greater than the maximum scale of measuring instrument. The measuring scheme of the underwater explosion power should provide registering and recording the pulse pressure within the range 345–13 800 kPa;
- In conducting the experiments, it is necessary waves on the sea to be less than 1 ball, the area depth to be more than 40 m, and the distance between the sensor and the explosion to be greater than 91.4 m;
- It is appropriate measurements to be made at the sensor depth equal to the expected depth of diver sailing and at various types of bottom – sand, rocks, mud, and others ceteris paribus;
- If the results are significantly deferent from the ones estimated in advance by means of the mathematical formalism, it is necessary repeated positioning the explosion to the sensor, as depth and/or a distance varies in order to reduce the influence of interference.

6. References


