

## Underwater explosions

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### Abstract

An underwater explosion is an extremely complex physical and chemical process. As the explosive charge detonates, it causes the sudden release of chemical energy and produces high-temperature and high-pressure gas that quickly diffuses around underwater. The shock wave generated by an underwater explosion propagates radially in water and its peak pressure of the shock wave is related to the charge and relative explosive distances. Underwater explosion load can be divided into impact load and bubble action load, which can cause local or global damage to a ship or submarine. Hence, the measurement of underwater explosion load is very important for ship designing purposes. In the present short review various aspects of underwater explosions are presented in some detail.

### Introduction

The research and literature of underwater explosion have been fully studied since the beginning of the Second World War. The development of modern underwater weapon equipment led the researchers to pay much attention to the issue of how to research and improve the capacity of explosives and enhance the energy release. High energy density materials are one of the research hotspots in the field of underwater weapons.

For a long time, researchers have made great progress and important research results. The name of Cole has to be remembered. In 1948 Cole collected and summarized a large number of experimental data and gave an empirical formula for the shock wave pressure and bubble pulsation load of underwater explosion [1]. Much later, Zamyshlyayew modified the empirical formula proposed by Cole [2]. In 2014, with the help of smooth particle hydrodynamics (SPH) method and water column impact theory, Ming gave the prediction formula of bubble jet load of underwater explosion [3]. However, there are still many difficult problems to be overcome and solved so far due to the difficulty and complexity of this problem. The reason is that, on the one hand, it is related to the high cost requirements of underwater explosion experiments, and required experimental safety, and qualifications. On the other hand, near-field underwater explosion wall pressure peaks are high, and it may be directly affected by underwater explosion detonation products. It cannot fully meet the needs of pressure load measurement of underwater large equivalent-weight charge and close range or contact explosion wall.

Note that high-intensity sound in the sea can be generated by using chemical explosives, air guns, or electrical discharges. Chemical explosives have been used as signal sources for single, but reproducible, broadband high-amplitude signals. The characteristic feature of a signal from a chemical explosive is the formation of a high-frequency shock wave followed by the low-frequency pulsation of a gas bubble. On the other hand, more low-frequency air gun signals have found applications in studies of the seabed, where

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return signals from layers in the seabed provide information about characteristic structures of interest in prospecting for oil or gas.

A chemical explosive in most cases consists of the elements C, O, H, and N in various combinations. Some of the explosives used are TNT (trinitrotoluene,  $C_7H_5O_6N_3$ ), Tetryl ( $C_7H_5O_8N_5$ ), RDX ( $C_3H_6N_6O_6$ ), and PETN ( $C_5H_8O_{12}N_4$ ). Also, the explosive pentolite (consisting of 50% TNT and 50% PETN) has been used extensively to produce underwater, high-intensity sound due to its reproducible signals. The energy available in TNT, for instance, is around  $4.5 \cdot 10^6$  J/kg. The frequently used SUS (Signal, Underwater Sound) charges are mostly TNT in about 0.82 kg amounts. The detonation process in the explosives is most frequently started by a shock wave produced by an especially sensitive explosive which is used as a primary material to start the detonation process. In the detonation process, a detonation front will move with high velocity through the explosive transforming into reaction products under very high pressure.

In underwater acoustics, the spectrum of interest ranges from below 1 Hz to far above 1 MHz. This broad frequency range and the demands for acoustic power, bandwidth, size, weight, and depth of operation are a challenge to sonar system manufacturers. Fortunately, a broad variety of sonar system designs covering various applications are now available.

### Underwater explosions

Underwater explosion chemistry involves rapid detonation, creating a high-temperature, high-pressure bubble of gaseous products and steam within water. This process causes shock waves due to water's high density/incompressibility, often producing a blue flash from water ionization. Common materials like TNT (2,4,6-trinitrotoluene,  $C_7H_5N_3O_6$ ) use redox reactions to release energy, while additives like aluminum powder are used to increase the total energy output [4].

The detonation process creates a shock front which advances at the speed of several thousand meters per second. This shock front is termed "detonation wave" and chemical transformation resulting from detonation occurs simultaneously with the progression of this wave. When this wave reaches the boundary of the explosive material and surrounding medium, the pressure is transmitted through the boundary at a finite pressure and velocity. In the case of underwater explosions, the surrounding medium is water, which can be regarded as a homogeneous fluid incapable of sustaining shear stresses. A shock wave traveling through water has two distinct physical characteristics: (1) shock wave velocity and, (2) local particle velocity. At the pressures considered, the speed of sound wave in water is independent of peak pressure and is approximately 1440 m/s.

Trinitrotoluene (TNT) is commonly used to generate, characterize, and study underwater explosions. It has a specific energy of 4500 kJ/kg and for the purpose of calibration; the specific energy released by other explosive compounds is often expressed in the form of equivalent mass of TNT. Upon detonation, TNT forms nitrogen, water, carbon monoxide, and solid carbon and generates a large amount of pressure (on the order of 14,000 MPa). The surrounding medium compresses by this pressure and radiates a high-pressure disturbance, which falls off rapidly which is called explosive decay.

Generally, the study of underwater explosion consists of two main research fields: shock waves and explosion bubbles. Many experimental, analytical, and numerical works exist on both fields. An underwater explosion generates an initial shock wave propagating radially outwards which is followed by a large bubble containing hot gaseous products of the explosion. It is to be noted that subsequent secondary shocks may be encountered every time the bubble reaches a minimum volume. The shock wave has the first damaging effect on a nearby solid structure (e.g. ship, submarine, etc.) because of the very high pressures associated. The

explosion products will then form a high-pressure gas bubble. Due to inertia, the bubble over-expands and has a very low pressure inside. Since the ambient pressure is now larger, the bubble will collapse. If expansion and collapse occur near an underwater structure, the bubble will create, under certain conditions, a high-speed re-entrant water jet towards the structure. This jet always originates on the farther side of the bubble with respect to the structure. The jet then penetrates the bubble and impacts on the other bubble wall, creating a toroidal bubble. The pressures involved in this jetting process are not as high as the pressures generated by the shock wave, but the duration is much longer. This mechanism is believed to create the second damaging effect. In general, the physics associated with the shock waves are of the order of milliseconds, whereas the flow physics associated with the bubbles are of the order of seconds [5].

### Explosives used for underwater purposes and measurements

Underwater explosions (UNDEX) utilize specialized high explosives designed to produce high-intensity shock waves and gas bubble energy, often using formulations like RDX (Royal Demolition Explosive, Cyclonite,  $C_3H_6N_6O_6$ ), HMX (High-Molecular-Weight RDX, Octogen), PETN (Pentaerythritol tetranitrate), or aluminized explosives (e.g., HBX, Torpex (Torpedo Explosive)) to enhance performance [4]. Some composite formulations are also employed such as;

COMP B: RDX/TNT/WAX 59.4/39.6/1.0,

H-6: RDX/TNT/AL/WAX 45.1/29.2/21.0/4.7,

PBXN-103: AP/AL/PNC/MTN/RESOURCINOL/TEGDN38.73/27.19/6.92/24.36/0.36/2.44,

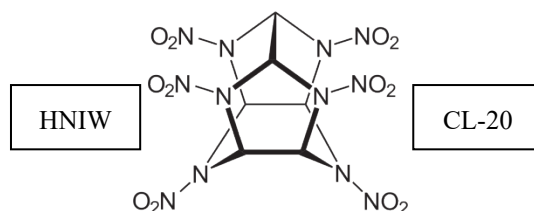
HBX-1: RDX/TNT/AL/WAX,

HBX-3: PBX/TNT/AL/WAX 31/29/35/5.

These explosives are chosen for their water resistance and, frequently, for their high density to maximize damage against vessels, typically measured against a TNT equivalent.

Accurate determination of bubble loading parameters is crucial for optimizing explosive formulation design and enhancing energy utilization efficiency. Aluminum powder is the most commonly employed metal fuel in aluminized explosives [4]. The energy release from aluminum powder combustion significantly influences the underwater explosion bubble loading characteristics of aluminized explosives. Liu *et al.*, in their study [6], developed a non-isothermal combustion model for aluminum powder with derived governing equations under detonation conditions. A novel equation of state (JWL-Al EOS) was formulated for detonation products, which was incorporated with aluminum secondary combustion [6]. This theoretical framework was integrated with bubble dynamics equations in order to establish a computational approach for underwater explosion bubble loading. Then it was experimentally validated through systematic testing.

2,4,6,8,10,12-Hexanitro-2,4,6,8,10,12-hexaazatetracyclo[5.5.0.0<sup>3,11</sup>.0<sup>5,9</sup>]dodecane is a relatively novel explosive known as CL-20 or HNIW. The effects of explosive composition parameters and water depth on the underwater explosion bubble loading of CL-20-based aluminized explosives have been systematically investigated [6].



Investigations of Liu *et al.* have revealed that the proposed computational method for bubble loading demonstrates high accuracy. They have observed that the Al/O ratio modulates the complete bubble pulsation cycle, where the first bubble period demonstrates an initial increase which is followed by reduction as the Al/O ratio increases, while aluminum combustion rate shows monotonic decline. Conversely, increasing water depth shortens the first bubble period but accelerates aluminum combustion rate. Bubble energy exhibits positive correlation with water depth, but with rising Al/O ratio it increases and then decreases [6].

In another work, Liu *et al.* studied the underwater explosion process of hexanitrohexaazaisowurtzitane (CL-20)-based polymer bonded explosives (PBXs) with and without aluminum powders [7]. They performed experiments employing two kinds of explosives with aluminum contents of 0 and 15%. In their study, they designed an experimental installation to study CL-20-based explosive and CL-20 based aluminized explosive in underwater explosion. The images of pressure histories, bubble periods and bubble pulses of shock wave were obtained. Additionally, the shock wave energy, bubble energy and total underwater explosion energy of two kinds of explosives were calculated. The underwater explosion process was well-simulated by the AUTODYN software. The results show that when aluminum content increases from 0 to 15%, the total underwater explosion energy increases from 1.4 times TNT equivalent to 1.7 times TNT equivalent. In the process of bubble pulsation, the light is produced in the bubble of CL-20 based aluminized explosive when the time is from 49.5 ms to 49.8 ms. The peak pressures of aluminized explosives and non-aluminized explosives are 15.16 MPa and 15.51 MPa, respectively. The secondary pressure wave bubble pressures are 2.25 MPa and 2.35 MPa, and the bubble periods are 50.20 ms and 46.76 ms, respectively. The maximum bubble radii are 67.87 cm and 60.27 cm, respectively. The simulated overpressures of aluminized explosives and non-aluminized explosives are 14.90 MPa and 15.14 MPa, respectively. The secondary pressure wave bubble pressures are 2.16 MPa and 2.27 MPa, the bubble periods are 49.32 ms and 45.90 ms, and the maximum bubble radii are 66.32 cm and 58.89 cm, respectively. The shock wave and bubble parameters obtained by calculation are in good agreement with the experimental results.

The images of gas bubble in underwater explosion have been obtained by high-speed photography. The pictures showed the bubble generation, expansion and contraction. Meanwhile, the difference between CL-20-based explosive and CL-20-based aluminized explosive about bubble had been shown. When the time was from 49.5 ms to 49.8 ms, the bubble of CL-20-based aluminized explosive emitted light inside the bubble, but the CL-20-based explosive had no light in bubble. Thus, the point was that the energy released by secondary reactions could heat detonation products.

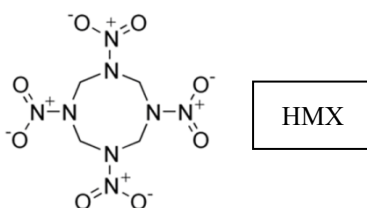
The pressure histories of shock wave were measured by a sensor. By means of the above methods and results, the different parameters of underwater explosion and underwater explosion energy were obtained. Hence, the addition of aluminum powder helps to attain the purpose to increase time constant, bubble pulse period, maximum radius of bubble and explosion energy. So, by compared with CL-20-based explosive, one observes that the bubble pulse period, maximum radius of bubble, shock wave energy, bubble energy and total underwater explosion energy increase by about 7.4%, 12.6%, 15.9%, 33.3%, 22.6%, respectively. The

underwater explosive energy of CL-20-based explosive is 1.4 times TNT equivalent. The total underwater explosion energy of CL-20-based aluminized explosive with 15% aluminum is 1.7 times of TNT equivalent.

The entire evolution of the bubble was well-simulated by the AUTODYN software. Computed bubble pulse properties agreed well with measured bubble pulse properties for all the cases studied, with an average error of peak pressure of shock wave bubble period approximately 1.79 %, peak pressure 3.70 %, and maximum radius 2.30 %. However, the numerical results of bubble images did not show the light emission in the bubble. It was different from the experimental images. They believe that this simulation work needs some further research.

In the work of Liu *et al.*, the underwater explosion energy output characteristics of hexanitrohexaazaisowurtzitane (CL-20)-based aluminized explosives with different aluminum powder particle sizes were reported too. Powder particle size (D50) is quite important for how to improve the energy release level and formulation design of aluminized explosives [4]. In the paper, four experimental samples of CL-20-based aluminized explosives with aluminum powder particle sizes including 2, 13, 24, and 43  $\mu\text{m}$  were designed. The experiments were carried out through an underwater explosion tank and compared with explosives containing lithium fluoride of the same particle size. The results show that the burning of aluminum powder promoted the shock wave propagation and bubble expansion. The results reveal that aluminized explosives have a lower and then higher decay rate compared to lithium fluoride-containing explosives. For the experimental range of aluminum powder particle sizes, with an increase in D50, the peak shock wave pressure first increased and then decreased, reaching the maximum at 24  $\mu\text{m}$ . While, the shock wave and loss energy gradually increased, whereas the bubble energy, energy utilization, and underwater explosion total energy all gradually decreased. To a certain degree, the energy output structure can be regulated by adjusting the D50 under the premise of constant total energy of explosives. The experimental results improve the understanding of how D50 affects the underwater explosion parameters of aluminized explosives, which is of great significance for improving their energy utilization [7].

Xiang *et al.*, in one of their works, interested in the performance of detonation and underwater explosion (UNDEX) of a six-formula using HMX-based aluminized explosive by detonation and UNDEX experiments [8]. The detonation pressures, detonation velocities, and detonation heat of HMX-based aluminized explosive were measured. The reliability between the experimental results and those calculated by an empirical formula and the KHT code have been verified. UNDEX experiments were carried out on the propagation of a shock wave and a bubble pulse using a cylindrical HMX-based aluminized explosive (1 kg) underwater at a depth of 4.7 m. Based on the experimental results of the shock wave, the coefficients of similarity law equation for the peak pressure and attenuation time constant of shock wave were found to be in acceptable agreement. The bubble motion during UNDEX was simulated using MSC.DYTRAN software, and the radius-time curves of bubbles were determined. The effect of the aluminum/oxygen ratio on the performance of the detonation and UNDEX for an HMX-based aluminized explosive was discussed [8].



The paper by Jiao *et al.* mentions underwater explosion experiments for CL-20 based aluminized explosives for different explosive percentages (EP), with HMX based aluminized explosive used as a comparison [9]. The difference of energy release in the two kinds of explosives has been discussed.

To control the explosion energy output by optimizing explosive components is a key requirement in a number of different application areas. The effect of different Al/O ratio on underwater explosion of aluminized explosives has been studied in detail. However, the effect of explosive percentage in the same Al/O ratio is rarely researched, especially for hexanitrohexaazaisowurtzitane (CL-20) based aluminized explosives. In this study, they performed the underwater explosion experiments with 1.2-kilogram of explosives in order to investigate the explosion energy released from CL-20 and Octogen (HMX) based aluminized explosives. The percentage of the explosive varied from 5% to 30% and it is observed that the shockwave peak pressure ( $p_m$ ) grows gradually; shock wave energy ( $E_s$ ) continues increasing, bubble energy ( $E_b$ ) increases then decreases peaking at 15% for both formulas, and the total energy ( $E$ ) and energy release rate ( $\eta$ ) peak at 20% for CL-20 and 15% for HMX. This paper outlines the physical mechanism of  $E_b$  change under the influence of an aluminum initial reaction temperature and reaction active detonation product percentage coupling. With the explosive percentage changing from 5% to 30%, the underwater explosion  $p_m$  gradually increases,  $E_s$  continues to increase,  $E_b$  increases then decreases peaking at 15% for both formulas,  $E$  changes at almost the same rate as  $E_b$  peaking at 20% for CL-20 and 15% for HMX. On the other hand,  $\eta$  reaches the highest at 20% for CL-20 and 15% for HMX. The optimal explosive percentage of explosive (CL-20 or HMX)/AP/Al/HTPB) formulas is 15 to 20% when the Al/O ratio is 0.71. The energy release of CL-20 formula is more than the HMX formulas where  $E_s$  is 9.3% higher, whereas  $E_b$  is 4.8%,  $E$  is 6.1%, and  $\eta$  are 3.7% higher, respectively [9].

The result reveals that CL-20 is superior as a new high explosive and has promising application prospects in the regulation of explosive energy output for underwater explosives [9].

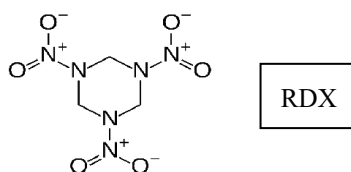
Makhov investigated the possibilities of increasing the shock wave energy of an underwater explosion by introducing the explosive having a positive oxygen balance into the composition of the energetic material [10]. For the calculations, relatively new compounds were chosen as explosive oxidizers, such as 3,6-dinitro-1,4-bis(trinitromethyl)-1,4-dihydropyrazolo[4,3-c]pyrazole; 4,4,5,5-tetranitro-2,2-bis(trinitromethyl)-2H,2H-3,3-bipyrazole, and 2-dinitromethyl-5-nitrotetrazole. The function of explosive fuel was performed by the well-known powerful substances HMX and CL-20. The calculations have shown that compositions containing these explosive oxidizers should have high values of the TNT equivalent, in terms of shock wave energy and the most noticeable increase in the TNT equivalent [10]. The expectation is that use of these explosive oxidizers should have some positive effects in the case of aluminized compositions [10].

To explore the application of the micro-sized B-Al (boron-aluminum) compound powder in enhanced blast explosive (EBX) and thermobaric explosive (TBX) [4], three HMX-based explosives containing B-Al (coded as, PF-1, PF-2 and PF-3) were designed and prepared by Gao *et al.* [11]. The ignition and combustion characteristics of various samples (micro- and nano-sized B, B-Al compound powders with and without HMX) under different pressures and atmospheres were studied by a laser ignition technique and combustion experimental system. The flame evolution images and emission spectral characteristic parameters of the ignition and combustion process were obtained. The structures of detonation reaction zone of ideal and non-ideal explosives were studied by PDV (photonic doppler velocimeter), and the characteristic parameters and explosion reaction mechanism of wave profile were obtained. The energy output characteristics of explosives containing B-Al composite were evaluated by air blast and underwater explosion tests. The results clearly show that nano-sized B has better ignition and combustion characteristics than micro sized B; the ignition and combustion property of B-Al compound powder with HMX is obviously superior to that of B-Al compound powder. PBX-1 is an ideal explosive, and the reaction zone width is 44ns, while PF-1 and PF-3 are typical non-ideal explosives, having the reaction zone widths of 112ns and 102ns, respectively. In the air blast and underwater explosion test, under the detonation of HMX, the combustion of micro-Al can promote the afterburning effect of micro-B, which releases a great amount of combustion heat, then generates expansible

products with higher temperature and pressure, and finally increases the duration of fireball and total energy in underwater explosion [11].

The laser ignition and combustion characteristics of four samples were studied under five operating conditions. The results show that nano-sized B has better ignition and combustion characteristics than micro-sized B; the ignition and combustion property of B-Al compound powder with HMX is obviously superior to that of B-Al compound powder. The reaction zone structures of various explosives were studied by PDV. Results show that the reaction zone width and length of PBX-1 are 44 ns and 0.30 mm, respectively, which is an ideal explosive with obvious C-J point. The reaction zone width and length of PF-1 are 112 ns and 0.70 mm, respectively; the reaction zone width and length of PF-3 are 102 ns and 0.65 mm, respectively, which have no obvious reaction zone terminal point and belong to the typical non-ideal explosives. In the air blast test, under the detonation of HMX, the combustion of Al powder drives the combustion of B powder, releasing a large amount of combustion heat. At the same measuring position, the shock wave overpressures of PF-2 and PF-3 are greater than that of PF-1, and the duration of blast fireball is longer. In particular, PF-3 with 20% B-Al compound powder has the longest blast fireball duration. This indicates that B powder has stronger combustion intensity and greater energy release than Al powder. The combustion of B-Al compound powder prolongs the high temperature and pressure duration of the secondary reaction of explosives containing B-Al and enhances the after-effect explosive power. Whereas, in underwater explosion test, the energy of explosive detonation is expressed as shock wave energy and bubble energy. Among the three specimens, the total underwater explosion energy in descending order is PF-3, PF-2 and PF-1, and the total underwater explosion energy of PF-2 and PF-3 is larger than PF-1. This result reveals that in HMX-based explosives containing B-Al, the detonation heat of HMX can increase the temperature of detonation products and improve the combustion environment of metal powder, consequently, the secondary reaction of B-Al compound powder releases a large amount of reaction heat, which increases the bubble energy through the pulsation of bubbles, thereby increasing the total energy of underwater explosion [11].

Xiang and coworkers performed a series of experiments to understand the underwater explosion (UNDEX) performance of RDX/AP-based aluminized explosives, six formulations of the explosives were prepared, with Al content varying from 30% to 55% and ammonium perchlorate (AP) content from 45% to 20% [12]. A series of UNDEX tests that used a 1 kg cylindrical charge was conducted underwater at a depth of 4.7 m. The pressure histories of the shock wave produced at different positions and the bubble periods were measured. The coefficients of the similarity law equation for the shock wave parameters were fitted with experimental data. The effect of the aluminum/ oxygen (Al/O) ratio on the performance of the energy output structure for RDX/AP-based aluminized explosives is discussed. The bubble motion during UNDEX was simulated using MSC.DYTRAN software, and the radius-time curves of the bubbles were determined. The results show that AP influences the detonation reaction mechanism of RDX/AP-based aluminized explosives, which causes different UNDEX performances. The bubble energy of the RDX/AP-based aluminized explosive was higher than that of RDX-based and HMX-based aluminized explosives [12].



The results of Ziang *et al.* showed that the value of  $\theta$  for the RDX/AP-based aluminized explosives decreases linearly with increases in the Al/O ratio, which is different from that of RDX- and HMX-based

aluminized explosives. The logarithmic values of  $p_m$ ,  $\theta$  ( $\theta$  is the time required by the peak pressure  $p_m$  to fall to  $p_m/e$ , where  $e = 2.718$ ),  $I$  and  $E$  of the shock wave show excellent linearity with the scaled distance. The RDX/AP-based aluminized explosives in the present study exhibit higher  $E_b$  values, that on average of more than 15%, compared with those of RDX- and HMX-based aluminized explosives. Moreover,  $E_b$  approaches an average of 78% of the total energy in the UNDEX test. It has been obtained that  $E_b$  does not follow a direct relationship between detonation heat and bubble energy. These different UNDEX performances indicate that the detonation reaction mechanism of RDX/AP-based aluminized explosives differs from that of RDX-based aluminized explosives. Evidently, AP provides more oxygen and enhances the combustion efficiency of the Al particles, which consequently causes the release of more energy in the detonation products. The entire evolution of the bubbles was well-simulated by the MSC.DYTRAN software. The bubble radius history showed that the numerical period and the maximum radius of the bubble were smaller than the experimental and empirical results, respectively. The errors indicate that the volume-acceleration model may not be suitable for studying RDX/AP-based aluminized explosives [12].

Yin *et al.* tried to investigate the effect of nano-aluminum powder on the characteristics of RDX-based aluminized explosives underwater closed-filed explosions [13]. The scanning photographs along the radial of the charges were gained by using a high speed scanning camera [13]. The photographs of two different aluminized explosives underwater explosions have been analyzed, the shock wave curves and expanded curves of detonation products were obtained. Furthermore, the change rules of shock waves propagation velocity, shock front pressure and expansion of detonation products of two aluminized explosives were investigated, and also the parameters of two aluminized explosives were contrasted. The results show that the aluminized explosive which with nano-aluminum whose initial shock waves pressure propagation velocity, shock front pressure are smaller than the aluminized explosive without nano-aluminum and has lower decrease rate attenuation of energy [13].

In order to analyze the effect of aluminum fiber contents on the underwater explosion performance of RDX-based explosives, Lin *et al.* measured and obtained the pressure-time curves of composite explosives with different aluminum fiber contents by underwater explosion experiments [14]. Peak pressure, impulse, shock energy, and bubble energy were obtained by analyzing the curves. The results show that the peak pressures of composite explosives decrease with increasing aluminum fiber contents. The shock impulse of the 30% aluminum fiber composite explosive was found to be the highest in all composite explosives. The effects of the 20% and 40% composite explosives are nearly equal to that of the 30% explosive, and the different values of shock impulse among them do not exceed 5%. The specific shock energy of the 20% aluminum fiber composite explosive is the highest in all composite explosives. The bubble energy and explosion energy of composite explosives increase with increasing aluminum fiber contents [14].

Zhao and coworkers employed a finite element software (LS-DYNA) in order to numerically investigate the damage of stiffened plates due to underwater explosive loads provided by RDX-based aluminized explosives [15]. A finite element analysis model of fluid-solid coupling was established in order to study the elastoplastic dynamic buckling behavior of a stiffened plate structure. The effects of the RDX-based aluminized explosive energy release rate, shockwave energy, bubble energy and shockwave pressure on damage have been discussed. A connection is established between aluminum content, the energy output of the underwater explosion and the response of the stiffened plate [15].

In the work of Lin *et al.*, a new non-ideal explosive was obtained by adding aluminum fiber to RDX [16]. Pressure-time curves were measured in different regions by underwater explosion experiments of aluminum - fiber explosive and RDX. Peak pressure, impulse, shock wave energy, bubble impulsion period and bubble

energy were all obtained by analyzing the curves. The peak pressure of the new explosive is lower than that of RDX in the same regions. Whereas, the shock wave impulse becomes larger and the distance does not much affect the difference. Compared with RDX, the specific shock wave energy of the new explosive was obtained to be decreased by 2%~5.2%. On the other hand, the specific bubble energy rises by 9.4%~23.36%, the specific explosion energy increases averagely by 3.5%. The specific bubble energy is 55%~60% of the explosion energy, which is higher than the ratio 50%~53% of RDX. The specific explosion energy is 74%~84% of explosion heat, which is lower than the ratio of 89%~95% of RDX [16].

HNIW(CL-20), HMX and RDX have been examined in the small scale underwater test by Košík *et al.* Pressure curves of detonating materials were obtained. Then, the comparison between HNIW, HMX and RDX pressure waves parameters were estimated [17]. Applicability of the small scale underwater test for high explosives examining became proved.

Presented results let the investigators to find that small scale underwater explosion test is a good tool for comparing high explosives blast parameters [17]. Proposed procedure may be useful for small quantities of explosives used (ca 16.5 g of each explosive). It is possible to compare such parameters as shock energy and bubble energy. Calculation of absolute values of energies is also possible. They proceeded the experiments on one fixed settings of the arrangement (according to Standard). Small scale underwater test is flexible and it lets on many different settings (one can vary detonator-sensor distance, water temperature, detonator position, etc.). It lets for every kind of detonation initiation (excepting detonating cord). Investigators have planned such possibilities to be used in further experiments. There is no significant difference between bubble energy equivalents for HNIW, HMX and RDX. The difference appears for shock wave energy equivalents HNIW is ca 8.7 % more efficient than RDX, and HMX is ca 3.5 % more efficient than RDX [17].

### Measurement technology of underwater explosion load

Underwater explosions have found extensive application in technology, acoustics and physics. However, underwater explosion is an extremely complex physical and chemical process. The shock wave generated by underwater explosion propagates radially in water and its peak pressure of the shock wave is related to the charge and relative explosive distances. The value of underwater explosion load is related to the charge and explosion distance or relative explosive distances. Note that relative explosive distances =  $R/R_0$ ,  $R$  is the distance from the detonation center of the explosive to the measuring point,  $R_0$  - the radius of spherical charge [18]. For the same explosive charge, the peak pressure of shock wave increases with the decrease of relative distance, and it may reach MPa or even GPa level. The volume occupied by the explosive gas products is usually called bubbles, and the pressure generated by the bubble collapse jet is sometimes even greater than the shock wave pressure. Underwater explosion load can be divided into impact load and bubble action load, which can cause local or global damage to ship or submarine.

The charge of prototype underwater explosion is usually hundreds or even thousands of kilograms. Such underwater explosion experiment not only costs a lot but also brings great difficulties to measurement technology and safety. Researchers usually use small equivalent-weight explosives. Small equivalent-weight explosion is a micro charge explosion that can be used for laboratory operation and research.

Bubbles have intrigued mankind for many centuries and many problems relating to bubble dynamics remain unsolved or are not yet well understood up to the present day [18]. Oscillating bubbles can be found in many fields of engineering ranging from cavitation on ship propellers, underwater explosions to even micro bubbles in medical treatments, etc. Initially, spherical symmetrical bubble oscillations were investigated. Much later, it

was discovered that in many cases the bubble assumes a nonspherical symmetric configuration during the collapse phase. Several experimental and numerical studies have clearly shown that if a bubble oscillates near a solid surface (if buoyancy can be neglected and in a stationary ambient flow), a jet will be formed in the bubble. This jet originates from the side that is facing away from the solid and traverses the bubble with great speed until it impacts on the opposite bubble wall. Then, the bubble is slightly repelled from the solid surface during its expansion phase and strongly attracted towards it during its collapse phase.

On the other hand, if a bubble oscillates near a free surface, again under the assumption of zero buoyancy and no ambient flow, a jet directed away from this surface can be formed during the collapse phase of the bubble [19], [20].

The bubble as a whole will be repulsed by the free surface. Even in the absence of any surface in the vicinity of the bubble, a jet still can be formed in large bubbles due to the effect of gravity. This jet always is directed upwards (in opposite direction to the gravity vector). (For an overview of the phenomena discussed above, see [21]).

To the best knowledge of the authors, the dynamics of a bubble depicting the combined effects of a free surface, solid surface and gravity have not yet been reported in the literature. This situation can typically occur when an underwater explosion occurs near a floating ship. In this article a method based on the boundary integral method (BIM) was introduced and broadly described. The authors report that the proposed modification of the BIM method makes use of the fact that the free surface can act as a negative mirror if the free surface remains relatively flat during the underwater explosion. The above assumption is valid for a reasonably deep submerged explosion bubble [22].

The article by Li *et al.* summarizes the measurement of underwater explosion impact load and bubble pulsation load [23]. The value of underwater explosion load is related to the charge and explosion distance or relative explosive distances ( $R/R_0$ ,  $R$ -explosive distances,  $R_0$  -the radius of spherical charge) [23].

There are several types of pressure-history gauges for measuring air blast pressure waves. Each gauge type measures a different physical aspect of the pressure effects (e.g., piezoelectric, piezoresistive, capacitive gauges, etc.). In addition, there is a wide range of peak-pressure and/or impulse measurement/assessment options, which employ rudimentary mechanical means that offer pressure/impulse peak value indications ("bikini" measurements, soda-can collapse, metal sheet/bar bending, etc.).

Brill *et al.* developed diaphragm gauges in order to measure blast impulses [24,25]. These gauges can be used to measure blast in air, water, soil and other environments. Such instrumented gauges were used in blast tests of the Israeli Home Front Command that were conducted in January, 2008. In these tests, the diaphragms were positioned on the foundations of a structure, in front of which hemispherical TNT bare charges were detonated at various distances. The measurement results were collected and analyzed (strain commencement times, residual strains, and final central deflections, etc.) in order to gather data on the blast impulses acting on the structural foundations under various conditions. It was found that under the conditions of the present experiments (measurement on shallow buried foundations), the major factor determining the level of the impulse on the structural foundations is the ground blast wave induced by the air blast wave. In particular, the impulse load on the buried structure was much greater when there was an above-ground structure above it, from which the blast wave reflected into the soil.

The present research concerns the dynamic load on a structure foundation using copper diaphragms as gauges to measure the impulse of explosive loading. It describes the calibration of these gauges and their use to measure impulse on the foundation of a structure loaded by explosive detonation of hemispherical TNT bare

charge. The pressure wave took approximately 1.5 ms to travel through the ground to the depth of the gauges [24,25].

This study of Rajasekar and coworkers numerically analyzes the characteristics of shock wave propagation and attenuation in different mediums of explosion near the air-water interface (free surface) [26]. They studied and discussed flow physics, like shock wave propagation, reflection, transmission, and cavitation qualitatively and quantitatively. Also, the numerical simulation was carried out with air, water, and TNT (tri nitro toluene), which were modeled using the ideal gas, Mie-Gruneisen (shock), and Jones-Wilkins-Lee (JWL) equation of state, respectively. The Coupled Eulerian-Lagrangian model is employed. In an explosion above the air-water interface, the shock wave propagates and reaches the free surface. Due to the acoustic impedance of water, the incident shock wave reflects, and part of the shock wave is transmitted into the water. Since the acoustic impedance of water is much higher than that of air, this free surface acts like a solid wall. On the other hand, in the case of an explosion below the interface, the incident shock wave reaches the free surface and the shock wave reflects as an expansion wave, thus resulting in cavitation. In an explosion at the free surface, shock wave propagates in both air and water. In the work propagation and attenuation of shock wave were studied. Hence, the free surface near the medium of explosion plays a significant role in the characteristics of shock propagation and attenuation effects [26].

Qu and Zhou investigated the implosion of composite cylindrical shells in underwater blasts. It is a process in which a structure collapses inward onto itself and releases energy via outwardly radiating pressure pulses [27]. Relevant issues include incident loading, elastic buckling, plasticity, damage, and release of impulsive waves. When the research was in an early stage, the experimental studies had primarily focused on the structural response of composite tubes including the load threshold for buckling and material damage and the release of impulsive waves from the collapse site. The latter is of concern as it is a source of potential damage for surrounding assets. The computational simulations have tracked and complemented the development of experiments, focusing on the effects on structural response of material, layup, and loading. It has been shown that filament-wound glass-fiber composite structures offer superior resistance to damage and yield lower postcollapse energy release compared with carbon-fiber composite structures. One focus has been on the development of quantitative relations between structural response in terms of deflection, energy dissipation, and intensity of released pressure pulses and input conditions in terms of initial incoming load intensity, internal air pressure, fiber orientation, and structural design attributes. The overarching objective is to establish criteria and load-structure-performance relations for the design of structures with enhanced, tailored, and adaptive performance offerings. The chapter by Qu and Zhou reviews the progress in experimental investigations and presents recent computational studies on the response of composite cylindrical structures during an implosion event [27].

Bjørnø and Levin have investigated underwater explosions using small amounts of chemical explosives [28]. Most investigations using conditions of underwater explosions are performed as full-scale tests. This is mainly due to the fact that reliable measurements of pressure waves taken at a short range from the detonation of small amounts of chemical explosives are extremely difficult, if not impossible, to perform. Their experiments based on a number of tests where small amounts of explosives, ranging from 0.2 to 6 g were detonated. The scaling law for underwater explosion shock waves was generalized, which includes short distances and very small charge weights typical of laboratory conditions. In the study, empirical expressions for the peak pressure, time constant, impulse and energy flux density as a function of charge weight and distance have been worked out. An excellent agreement was found between the peak pressures, calculated by using the empirical expression and the corresponding values calculated using Kirkwood-Bethe's theory for underwater

shock waves [28]. The conclusion of the authors is that is that small scale (laboratory) underwater explosion tests, give valid useful results and may be used instead of traditional full scale tests in a number of fields.

The paper of Rungsiyaphornrat and coworkers reported their study that investigated numerically two gaseous bubbles merging into a single coalesced bubble as in underwater explosions [29]. This explosive phenomenon is modeled using a boundary integral method. Two configurations, which are in-phase and out-of-phase explosions, are simulated and compared with available experimental results. They found that the thickness of the liquid film between the two bubbles determines the coalescence criterion. Bubble shapes and periods of oscillation are predicted well, as compared to those of the experiments.

In this work, the researchers assumed that the bubbles only contain a non-condensable gas, which can be described as ideal and the expansion and compression of this gas as adiabatic. The internal bubble pressure,  $p$ , as a function of the bubble volume,  $V$ , is  $p=p_0V_0V^\gamma$  where  $p_0$  and  $V_0$  are the pressure and volume at the time of inception of the bubble (they are obtained empirically). The ratio of the specific heats,  $\gamma$ , equals 1.25 for the gaseous explosion products resulting from a TNT explosion

In this paper, they have presented the numerical results on merging of two gaseous bubbles as in underwater explosions using the boundary integral method. For the study, two explosions occur in either the in-phase or the out-of-phase configurations. When the film thickness between two bubbles becomes smaller than the critical thickness defined as the coalescence criterion (based on experiments), the bubbles merge into one [29].

Wang *et al.*, in one of their studies, used elastic mesh technique (EMT) for 3D BIM simulation with an application to underwater explosion bubble dynamics [30]. The proposed elastic mesh technique (EMT) is a mesh regulation technique, which is based on the assumption that the segments of a mesh are elastic. EMT can be employed in conjunction with the boundary integral method (BIM) for the simulation of three-dimension bubble dynamics. It is to be mentioned that problems relating to severe mesh distortion as the bubble evolves are a common occurrence. With EMT, the mesh is advanced not by the material velocity, but the optimum shift velocity obtained by minimizing the total elastic energy stored in every segment of the mesh at each time step. In doing so, the prohibitively small time stepping associated with small meshes without EMT in order to maintain numerical stability is mitigated to a large extent. An important feature to be mentioned is that the EMT scheme accords the user the flexibility to implement a non-uniform optimum constitutive relation governing the elastic behavior of mesh segment and which can be further varied with time. Tests were performed for an underwater explosion bubble exhibiting the dynamics of strong jet development with and without EMT for comparison, and the consideration of incorporating EMT as a hybrid system serving as an alternative to the required mesh refinement which is computationally intensive. A full three-dimension simulation of explosion bubble(s) in the presence of the free surface was further carried out to elucidate the associated flow physics [30]. The present suggested method is based on the idea that if the mesh is made of elastic ribbons, it should be able to automatically adjust its shape optimally, namely all segment lengths are close to be equal. Strictly, the optimum mesh is found to minimize the total elastic energy stored in each segment of the mesh. This approach has a distinct advantage in that it “actively” seeks the optimum mesh for computation at each time step. It also implies that, this algorithm can in principle accept a not-so-uniform initial mesh and optimize the distribution during the whole simulation. Another advantage of the present method is that it leaves the user the option to choose proper constitutive relation of the elastic mesh, or even different relations for different part of the mesh. The EMT suggested in the article can be easily implemented with boundary element method to establish a robust and accurate tool for three-dimensional bubble dynamics simulations [30].

Zhang *et al.* have investigated the influences of initial and boundary conditions on underwater explosion

bubble dynamics [31]. Numerical and experimental methods are combined in this paper to study the bubble dynamics generated by an underwater charge explosion with different initial charge shape, detonating styles and boundary conditions [31]. Outdoor experiments were carried out to employ sunlight with the assistance of lamplight to get clearer pictures of bubble motion. The results have shown that the charge detonating stage is not finished instantly but takes some time to explode fully. The explosion begins from its detonating end and finishes at the other end, which results in its uneven distribution of initial normal velocity. So instead of following the traditional method of treating the charge explosion instantly, a real charge explosion model has been built in this paper with the combination of LS-DYNA and the boundary element method (BEM). LS-DYNA is used to solve the charge initial detonation and the BEM to solve its subsequent bubble motion. The researchers have managed to model the linking relationship between these two methods. The convergence study has been firstly taken with different meshes. In this paper, charges with different slenderness ratios from 0.99 to 20 are chosen to carry out the experiments and their corresponding numerical results are put forward. It can be found that in both experimental and numerical results, the initial charge shape and its detonating style would affect its following bubble dynamic behavior. When the cylindrical charge is horizontally installed and end detonated, an oblique jet leaned to the detonating end would be formed and a horizontal migration process is also observed during the whole bubble pulsating stage. The bubble dynamic behaviors near different solid boundaries are further studied and the numerical results coincide well with the experimental ones [31].

In a theoretical and experimental study, Hawass *et al.* investigated underwater explosion performance of some selected explosive compositions [32]. The thermo-chemical calculations have been carried out using EXPLO5 code to determine the underwater explosion parameters for different selected explosive mixtures. In the experimental part, preparation of the different types of explosive mixtures based on melt cast explosive (TNT) and plastic bonded explosives (PBXs) based on polyurethane binder system were presented. The effect of different aluminum weight percentages for the selected explosive mixture has been investigated with respect to the impulse and the resulted deformation. Their conclusion was that PBX based on RDX in addition to 25 wt% aluminum and 30wt% ammonium perchlorate produces the highest underwater explosion performance from all the tested samples. This explosive mixture seems to be a suitable candidate in order to replace the traditional well known TNT in the underwater explosive applications [32].

In this paper, Wang *et al.* investigated emulsion explosives [33]. Rules for the change of output energy of emulsion explosives with different oxygen balance, aluminum powder content, charge condition, decoupling media etc., were studied by using an explosion water pool. The  $p-t$  curves and peak pressure values were obtained. The effects of all these factors on shock wave energy, bubble energy and total energy were obtained. The results show that output energy of emulsion explosives without aluminum powder is lower than that of standard TNT explosives. The total energy of emulsion explosives with zero oxygen balance is only 86 % of that of TNT. In the experiment, output energy of the explosives tends to increase with the increase of aluminum powder content. With aluminum contents from 10 % to 15 %, the total energy is 1.05 and 1.14 times of that of TNT, respectively. Energy efficiency is affected with change of decoupling coefficient and media [33].

Xu *et al.* performed an underwater explosion test to determine the detonation properties of metallized explosives containing aluminum and boron powders [34]. An oxygen bomb calorimeter (PARR 6200 calorimeter, Parr Instrument Company, USA) is used to obtain the heat of combustion of the metal mixtures. As the content of boron powders is increased, it was observed that the heat of combustion of the metal mixtures increases, and the combustion efficiency of boron decreases. The highest value of the heat of combustion is 38.2181 MJ/kg, with the boron content of 40%. All metallized explosive compositions (RDX/Al/B/AP) have higher detonation energy (including higher shock wave energy and bubble energy) in water than the TNT

charge. The highest total useful energy is 6.821 MJ/kg, with the boron content of 10 %. It is 3.4 % higher than the total energy of the RDX/Al/AP composition, and it is 2.1 times higher than the TNT equivalent [34].

The article by Cichra and Doherty provides methods for estimating the performance of underwater explosives. It mainly focuses on evaluating some crucial parameters, (like shock wave energy and bubble energy), for understanding the underwater explosion (UNDEX) performance of energetic materials [35].

Swisdak's article provides a comprehensive guide to underwater explosion phenomena. It supplies compiled tables, charts, and graphs for calculating shockwaves and bubble behavior produced by underwater detonations [36].

In Stromsoe and Eriksen's article, the change in postdetonation free energy has been used for assessment of the sum of shock and bubble energies of aluminized explosives in underwater applications [37]. As has been suggested for CHNO explosives the detonation pressure also seems to be a significant factor in this case. For compositions with a high Al content it is probable that additional energy becomes available from reaction of Al with water in the surrounding medium [37].

The change in postdetonation free energy, rather than the often used change in detonation enthalpy, is suggested as a measure of the underwater performance of high explosives. Results of a correlation analysis of data from 11 explosives are presented. It is suggested that the detonation pressure is also a significant factor for the energy available for mechanical work, but this can not be verified by the present data. However, in the partition of energy between shock wave and bubble the detonation pressure is the dominant factor.

It is known that aluminized-high explosives are to give better underwater performance. In the experiments of Adapaka *et al.*, all explosive formulations for underwater targets are filled into warheads and shells by casting method [38]. TNT, a high explosive is used as casting medium due to its lower melting point. Plastic bonded explosives are fast replacing TNT-based high explosive formulations for the reasons that they are more insensitive and low vulnerable explosives with better shelf life. Few aluminized plastic bonded explosive formulations based on RDX, aluminum, and HTPB have been processed, varying the aluminum content from 0 to 35 % and evaluated underwater. The present paper discusses the experimental methodology adopted to evaluate the above formulations for their ballistic parameters, viz., peak over pressure and impulse [38]. Explosion bulge tests have been conducted with each explosive formulation and extent of bulge in test plates is presented and compared with a standard underwater explosive, viz., HBX-3.

This 1996 report by Bocksteiner evaluates the underwater explosive performance of Australian-manufactured PBXW-115, which is a polymer-bonded explosive [39]. The study provides detailed data on shock energy, bubble energy, and overall explosive performance compared to standard explosive compositions, confirming its properties for weapon systems.

In this paper, some of the interesting results obtained and discussed in the course of a large number of experiments carried out at IDL Chemicals Hyderabad [40]. A linear correlation was found between underwater energies and Trauzl lead-block values. The correlation of the total energy was found to be better than the correlation of shock and bubble energies individually. Also, variation of underwater energies with depth was observed. The shock energy decreased with depth but bubble energy increased with depth, for three different types of explosives. Moreover, the effect of firing explosives with and without boosters was studied. In the case of an aluminized slurry explosive there was a slight increase in shock energy and no change in the bubble energy, when initiated with boosters. In the case of a powder explosive, the shock energy was found to decrease by 15 % and the bubble energy by 4.7 %, when initiated with boosters. An attempt was made to study the statistical behavior of underwater testing. The shock energy distribution appeared to be non-normal. It indicated

the possibility of the presence of two modes. The bubble energy distribution was normal and its variability was found to be very low. The total energy distribution was also non-normal on account of shock energy distribution. The need for standardization of various testing parameters (such as the depth of the charge, the distance between the charge and the transducer, the geometry of the cartridge and the type of initiation), are considered to get repeatable and internationally comparable results. They have contemplated that there is a need to develop a complementary theory and additional measurements (if possible) to make the system more complete and acceptable for measuring the strength of explosives [40].

The effect of Al/O ratio on detonation performance and underwater explosion of RDX-based aluminized explosive were measured by test, and the test result was verified by KHT code [41]. In the research, Xiang *et al.*, the influence law of Al/O ratio on detonation pressure, detonation velocity and heat was analyzed. Underwater explosion experiments were carried out on shock wave propagation and bubble pulse of 1 kg cylindrical RDX-based aluminized explosive under water 4.7 m. The coefficients of similitude equation for peak pressure and attenuation time constant were fitted. The results of study indicate that the detonation pressure and velocity reduce linearly with the increasing of Al/O ratio and the detonation heat achieves a maximum value when Al/O ratio equals to 0.997. When Al/O ratio equals to 0.366, the peak pressure and shock wave energy reach the maximum value, whereas the shock wave impulse and flux density reach the maximum value when Al/O ratio equals to 0.633, and the first bubble pulsation period and radius reach the maximum values when Al/O ratio equals to 0.997 [41].

The performance of detonation and underwater explosion (UNDEX) of a six-formula HMX-based aluminized explosive was examined by Xiang by means of detonation and UNDEX experiments [42]. All the detonation pressures, detonation velocities, and detonation heat of HMX-based aluminized explosive were measured. Then the reliability between the experimental results and those calculated by an empirical formula and the KHT code was verified. UNDEX experiments were carried out on the propagation of a shock wave and a bubble pulse of a 1 kg cylindrical HMX-based aluminized explosive underwater at a depth of 4.7 m. Based on the experimental results of the shock wave, the coefficients of similarity law equation for the peak pressure and attenuation time constant of shock wave were found to be in acceptable agreement. The bubble motion during UNDEX was simulated using MSC.DYTRAN software, and the radius-time curves of bubbles were determined. The effect of the aluminum/oxygen ratio on the performance of the detonation and UNDEX for an HMX-based aluminized explosive was discussed [42].

This article by Szturomski contains a synthetic account of an underwater explosion and its effects [43]. 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 of 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 [43].

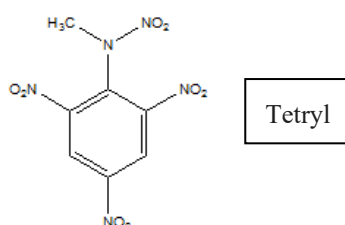
Xing *et al.* in their study investigated the influence of aluminum powder content on the metal-driving capability and underwater explosion energy of HMX/RDX-based aluminized explosives [44]. Through the preparation of polymer-bonded explosives (PBX) with aluminum content ranging from 0 to 15 %, they conducted explosive-driven metal plate test and established JWJ-Miller equation of state model incorporating aluminum secondary reactions for underwater explosion simulations using LS-DYNA. Experimental results demonstrated that increasing aluminum content in aluminized explosives resulted in a gradual decline in metal-driving capability, with an 8% reduction observed at 15% aluminum content. Underwater explosion simulations

revealed that where the aluminum–oxygen ratio reached 0.15, the shock wave energy of 1.846 MJ/kg achieved. Bubble energy showed a positive correlation with aluminum content. When the aluminum content is 15 %, the aluminum formulation exhibited a prolonged bubble pulsation period (249.6 ms) and an expanded bubble radius (107.4 cm). The research validates the effectiveness of the JWJ-Miller equation in modeling non-ideal detonation characteristics of aluminized explosives. The results have revealed that the impact of aluminum powder on explosive performance is not only reflected in its heat value but also in the timing of energy release. These findings provide critical theoretical guidance for the design of high-energy explosive systems requiring optimized performance [44].

This paper by Vadhe *et al.* reviews the current status and future trends of aluminized explosives [45] having a major focus on cast compositions, which encompass both the melt-cast trinitrotoluene (TNT) based and the slurry cast polymer-based compositions. It discussed in detail the widely reported RDX and HMX based aluminized compositions with TNT used as a binder. Various researchers have suggested a 15–20% Al content as an optimum from the viewpoint of velocity of detonation. A higher Al content, however, is incorporated in most of the compositions for a sustained blast effect, due to the potential of secondary reactions of Al with detonation products. The effect of the aluminum particle size on performance parameters (velocity of detonation, etc.) is included. There are some recent works on nanometric Al based compositions, and the results obtained by various researchers suggest mixed trends for RDX-TNT compositions. Studies on nitrotriazol and TNT based compositions bring out their low vulnerability. Also, detailed discussions on some of the interesting findings on ammonium dinitramide and bis(2,2,2-trinitro-ethyl)nitramine (BTNEN) based compositions are included. The review brings out superiority of polymer based aluminized explosives, as compared to conventional TNT based compositions, particularly, with respect to low vulnerability. In general, aluminized plastic bonded explosives find numerous underwater applications. Ammonium perchlorate (AP) is also incorporated, particularly, for enhancing underwater shock wave and bubble energy. The results suggest hydroxyl-terminated polybutadiene appears to be the binder of choice. However, nitrocellulose, polyethylene glycol, and polycaprolactone polymer based compositions with energetic plasticizers, like bis-dinitropropyl acetal/formal (BDNPA/F, 1/1 mix), trimethylol ethane trinitrate, and triethylene glycol dinitrate are also investigated. Polyethylene glycol and polycaprolactone polymer based compositions are found to be low vulnerable, particularly, in terms of shock sensitivity. Highly insensitive polymer bonded nitrotriazol based compositions are being pursued all over the globe. The highly insensitive CL-20/AP combination meets the demands of high density and high velocity of detonation. Glycidyl azide polymer and poly nitratomethyl methyl oxetane appear to be binders of interest for plastic bonded explosives in view of their superior energetics. The authors suggest further research for the vulnerability aspects of these compositions. Also, brief information on plastic bonded and gelled thermobaric explosives is included [45].

### Bubble dynamics

While nearly half the explosive energy goes into the shock wave, for tetryl, the energy amount was measured to be 46%, most of the residual energy is found in the gas bubble [46].



The gas bubble expansion after the shock wave emission is associated with energy emitted in the form of pressure waves which propagate radially from the bubble. Since the pressure of the reaction products in the gas bubble, after the detonation and shock wave emission, is substantially higher than the hydrostatic pressure at the detonation site, the gas bubble expands continuously for a relatively long period. During the bubble expansion, its gas pressure decreases gradually down to the hydrostatic pressure, but the bubble expansion continues due to the inertia in the outward flowing water. When the pressure in the gas bubble falls below the absolute environmental pressure, the difference between the bubble pressure and the environmental pressure gradually stops the bubble expansion. The bubble boundaries now contract at an increasing rate. This inward motion continues until the gas compressibility and the increasing pressure in the gas bubble stop the inward motion of the bubble boundary and its environment. The bubble now has its first minimum radius and a new expansion and contraction cycle may start again. In nearly 80 % of the bubble pulsation time, the pressure in the bubble will be below the hydrostatic pressure. Depending on the explosive detonation depth, gas bubble oscillations may persist for a number of cycles. In spite of the fact that an oscillating gas bubble, due to Bernoulli effects, will receive a repulsive force from a free surface and will be attracted toward a rigid boundary, the buoyancy effects on the bubble makes it to migrate toward the water surface. The speed of migration is highest when the bubble has its minimum radius. The period,  $T_n$  (unit: s), for the gas bubble oscillation depends on the detonation depth,  $d$  (unit: m), and on the amount of explosive  $W$  (unit: kg) [46].

In this paper of Wang *et al.* the importance of the development of analytical theory and experimental methods for understanding the correlation between the explosive properties and bubble dynamic characteristics in underwater explosions has been emphasized [47]. It has prime importance for engineering application value for underwater weapons and ships. Based on the assumption of an instantaneous explosive detonation, they introduced the Jones–Wilkins–Lee equation of state to describe the high-pressure state in an explosion bubble and established the initial conditions for the bubble dynamics calculations. The paper deals with numerical methodology to model and study the bubble dynamics produced by an underwater explosion when it occurs in an infinite medium, i.e. no interaction with any surrounding obstacle as the free surface, the seabed or deformable structures (surface ship or submarine). Numerical simulation of this class of problems requires a large mesh domain and a long time scale. In order to reduce the computing time they used the bi-dimensional axisymmetric multi-material arbitrary Lagrange Euler formulation developed by the authors. Considering the high-Mach-number flow and high pressure at the initial boundary of the explosion bubble, the Lezzi–Prosperetti equation with second-order Mach accuracy was used. Thus, an analytical model and a calculation method of the explosion bubble dynamics for an explosive detonation were established. Note that this direct link between the detonation parameters and the bubble features is significant for the subtle design, selection, and optimization of explosives' properties. A micro-equivalent explosive bubble pulsation experiment was carried out in a water tank using a customized experimental system, which can offer nearly boundary-free condition to mitigate the reflective wave effects on bubbles. Three types of explosives were used in the experiment: the research department explosive (RDX), the pentaerythritol tetranitrate (PETN), and the hexanitrohexaazaisowurtzitane (CL20). Finally, the experimental results and the practicability of the experimental system were analyzed and the influence of the explosive type on the dynamic characteristics of the explosion bubbles and the differences between the theoretical and experimental results were compared. The results showed that the proposed explosion bubble dynamics model and calculation method have high accuracy and practicability. The proposed model can be used for explosives with known detonation parameters and equation of state parameters. The detonation parameters, velocity, and pressure are linked to the bubble features, namely, pulsation period and the maximum radius, directly. The designed experimental system, which is capable of simulating infinite water for the explosion of micro-equivalent explosives, was stable and easy to use. Comparisons with empirical and

theoretical formula are performed in order to corroborate the numerical results. Particularly, the spatial convergence, the influence of the domain size and the boundary conditions are studied in order to propose a consistent methodology with the explosion bubble phenomena. The work is significant for the subtle design, selection, and optimization of explosives' properties [47].

It is worth mentioning that the detonation of an explosive charge in water results in the propagation of a shock wave through the water, and also in the formation of a high-pressure and high-temperature gas bubble from the detonation products [48]. Due to the initial gap between the pressures of the gas and the water, the bubble expands rapidly until its internal pressure gets into equilibrium with the hydrostatic pressure of the surrounding water. Due to inertia effects in water, this expansion phase goes on and leads to a pressure drop of the gas inside the bubble below the hydrostatic pressure. Depending on the size of the explosive charge, the gas volume may exceed the initial volume by orders of magnitude. When the fluid velocity around the bubble vanishes, the gas globe begins to contract what increases the pressure inside. After this first phase of expansion and contraction, the bubble exhibits several pulsations due to pressure difference in the gas and the water. Owing to buoyancy forces, the bubble tends to migrate toward the surface. The pulsations of the bubble generate long time secondary shock waves of less magnitude than the primary shock wave.

The paper by Barras *et al.* deals with a numerical methodology to model and study the bubble dynamics produced by an underwater explosion when it occurs in an infinite medium, *i.e.* no interaction with any surrounding obstacle as the free surface, the seabed or deformable structures (surface ship or submarine). High explosive detonation is simulated using an Eulerian formulation, with a fixed mesh. For underwater explosion, they considered two different fluid media (gas for the detonation products and liquid for the sea water around it), with interface reconstruction method between the two materials. Numerical simulation of this class of problems requires large mesh domain and long time scale. In order to reduce the computing time reasonably they used the bidimensional axisymmetric multimater Lagrange Euler formulation. Comparisons with empirical and theoretical formula are performed in order to corroborate the numerical results. Particularly, the spatial convergence, the influence of the domain size and the boundary conditions are studied in order to propose a consistent methodology with the explosion bubble phenomena. The interface is computed inside each element based on volume fraction of each material within the element [48].

This study of Hung *et al.* [49] investigated the linear and nonlinear dynamic responses of three cylindrical shell structures subjected to underwater small charge explosions in a 4m × 4m × 4m water tank. The dimensions of the cylindrical shell structures were 90 cm × 30 cm × 1 mm (length×diameter×thickness). Both ends of the cylindrical shell were mounted with thick plates to provide support and also create an enclosed space. The three cylindrical shell structures were un-stiffened, internally stiffened and externally stiffened, respectively. The experiments involving the dynamic response of the cylinders subjected to underwater explosion (UNDEX) were performed under different standoff distances, varying from 210 to 35 cm. A small quantity of explosives was used to generate the shock loading. The plastic deformation of the cylindrical shell was observed at a standoff distance of less than 50 cm. Other conditions were tested to examine cylinder linear response. Dynamic analyses were performed for the experimental model using FEM and compared with the test results. The accelerations and dynamic strains of cylindrical shells obtained from the experiment were compared with those obtained by FE analysis. Finally, problems related to small-scale UNDEX experiments performed in small water tanks were analyzed.

In this study, by Rong the volume-acceleration model was introduced to determine the initial conditions for bubble motion during underwater explosions [50]. Required subroutines, which define the initial and boundary conditions of the fluid field, were developed based on the MSC.DYTRAN software. Numerical simulations

were compared with the results of validated experimental data. It was found that the calculated shapes of the bubbles are in excellent agreement with the experimental results. Using the interaction between a bubble and a free surface as a basis, it was simulated and then analyzed the dynamic behavior of a bubble near a free surface, including the ring rebound of the bubble and the spray dome of the free surface. The computed spray dome heights were found to be consistent with the results from empirical formulas. The dynamic behavior of the bubble and the spray dome of the free surface were systematically studied and summarized in accordance with the principle that bubble motion and the spray dome are closely related to standoff distance. The results of this study may serve as a reference for understanding bubbles formed by underwater explosions and those generated by lasers. They also have valuable implications for correlative theory research and engineering calculations [50].

This 2005 article by Klaseboer *et al.* details experimental and numerical studies of underwater explosion bubbles near rigid or resilient structures [51]. In the experiments, high-speed photography and a 3D boundary element method (BEM) were employed to analyze the jet formation, bubble migration, and structure interaction. Over all, this paper deals with an experimental and numerical study of the dynamics of an underwater explosion and its associated fluid structure interaction. Experimental studies of the complex fluid structure interaction phenomena were carried out in a specially designed test pond. The pond is equipped with a high-speed camera and pressure and displacement sensors. The high-speed camera was used in order to capture the expansion and collapse of the gas bubble created by the explosion. Design of the experiments consists of several different structures, including both rigid and resilient plates of circular shape. The deformation of the plates was measured with a non-contact laser telemetry device. The numerical simulations of the explosion bubble interacting with a submerged resilient structure were performed using a three-dimensional bubble dynamics code in conjunction with a structural code. The bubble code is based on the boundary-element method (BEM) and has been coupled to a structural finite-element code (PAM-CRASH™). The experimental results were compared against the numerical results for different bubble structure configurations and orientations. Several physical phenomena that have been observed, such as bubble jetting and bubble migration towards the structure are discussed [51].

Zhang *et al.*, in this 2008 paper, presented a 3D BEM approach to study underwater explosion bubble problems [52]. The dynamics of bubble(s) in four different arrangements have been simulated. For the simplest Rayleigh bubble case strict comparison is made with the analytical solution of Rayleigh equation, and there is a very good agreement. They considered the effects of gravity on the bubble behavior, and some numerical analyses were carried out for the evolution of a bubble near a free surface and the interaction of two bubbles.

The fluid is assumed to be inviscid and incompressible and the flow irrotational. A time-integration boundary-integral method is used to solve the Laplace equation for the velocity potential to calculate the shape and position of the bubble. In this investigation, to improve the accuracy of the solution, the high-order triangular elements with curved sides and surfaces defined by six nodes are used to discretize the boundary surface. Meanwhile, the singularity of the double-layer potential is eliminated by recasting the principal-value integral of the double-layer potential when the influence coefficient matrix is calculated. The material velocity vector at any node can be obtained by the potential of adjacent nodes with an appropriate weighted method. Elastic mesh technique (EMT) (which is a new mesh regulation technique), is further applied to maintain the regularity of the triangular-element mesh used to discretize the dynamic boundary surface during the evolution of explosion bubble(s). All these efforts are to make the present approach viable and robust, and which is validated by computations of several bubble dynamics problems. Numerical analyses are carried out for the evolution of a bubble near a free surface and the interaction of two bubbles with a floating structure near a free surface. The robustness of the algorithm is demonstrated through simulating bubble jets near a free

surface producing sharp free surface spikes and bubble(s) collapsing nearby a floating structure close to a free surface [52].

This work by Bui *et al.* presents the development of a numerical strategy that combines the fast Fourier transform on multipoles (FFTM) method and the boundary element method (BEM) to study the physics of multiple bubbles dynamics in moving boundary problems [53]. The recent FFTM method can be employed to speed up the resolution of the boundary integral equation. However, one major drawback of the method is that its efficiency deteriorates quite significantly when the problem is spatially sparsely populated, as in the case where multiple bubbles are well separated. To overcome this deficiency, a new version of FFTM with clustering is proposed (henceforth called FFTM clustering). The new algorithm first identifies and groups closely positioned bubbles. The original FFTM is then used to compute the potential contributions from the bubbles within its own group, while contributions from the other separated groups are evaluated via the multipole to local expansions translations operations directly. They tested the FFTM clustering on several multiple bubble examples to demonstrate its effectiveness over the original FFTM method. Considerably vast improvement over the standard BEM has been noticed. The high efficiency of the FFTM clustering method allows one to simulate much larger multiple bubbles dynamics problems within reasonable time. Some physical behaviors of the multiple bubbles are also presented in this work.

In short it is demonstrated that FFTM is an accurate and efficient method to simulate multiple bubbles in the moving boundary problems especially when the number of bubbles is large or the complex topology of the bubble shapes is approximated with a large number of nodes and elements. However, a major drawback of the method is that its efficiency deteriorates quite significantly when the problem is spatially sparsely populated [53].

The ability of predicting material failure is essential for adequate structural dimensioning in every mechanical design. For ships, and particularly for military vessels, the challenge of optimizing the toughness-to-weight ratio at the highest possible value is essential to provide agile structures that can safely withstand external forces. Vannucchi exploring the case of underwater explosions, some of the fundamental mathematical relations for foreseeing the behavior of naval panels to such solicitation presented in this article [54]. A broad state-of-the-art survey links the mechanical stress-strain response of materials and the influence of local reinforcements in flexural and lateral-torsional buckling to the hydrodynamic relations that govern the propagation of pressure waves prevent from blasts. Also, some numerical simulation approaches that have been used in the computational modeling of underwater explosions are reviewed. For that purpose, focusing on Eulerian and Lagrangian fluid descriptions, Johnson-Cook and Gurson constitutive materials for naval panels, and the solving methods FEM (Finite Element Method), FVM (Finite Volume Method), BEM (Boundary Element Method), and SPH (Smooth Particle Hydrodynamics) are discussed. The confrontation of experimental tests for evaluating different hull materials and constructions with formulae and virtual reproduction practices allow a wide perception of the subject from different yet interrelated points of view [54].

The outline of the paper of Klaseboer *et al.* [55] is as follows; firstly the basic equations that govern the dynamics of the bubble described and some examples are given of bubbles oscillating near free surfaces. Special emphasis is placed on the second oscillating phase of bubbles, which has often been ignored in previous works. Also the effects of gravity are investigated in this section. The theoretical framework for the proposed 'negative mirror' method is given. A comparison is given with an existing axial symmetrically code which produces nearly identical results. Also basic equations, and the simplified model using negative mirror images to represent the free surface were considered, (no floating structure has been introduced yet). In Section 4 the dynamics of (large) bubbles near a free surface and a (fixed) floating structure are investigated. Several

examples showing very complex bubble behavior can be observed under certain circumstances and investigates the complex behavior of underwater explosion bubbles when they interact with both a free water surface and a solid floating object like a ship [55].

This paper, by Zhang published in Applied Ocean Research, investigates the complex fluid-structure interaction (FSI) between a pulsating underwater explosion bubble and a deformable structure. The study is significant for its use of a coupled numerical approach to predict how bubble dynamics—specifically the high-speed liquid jet and secondary pressure pulses—cause structural damage [56].

The response of a lightweight torpedo when subjected to an underwater explosion (UNDEX) is an important criterion for multidisciplinary design. This paper investigates the effect of structural stiffeners on the performance of a lightweight torpedo [57]. The finite element package ABAQUS was used to model the UNDEX and the fluid–structure interaction (FSI) phenomena, which are critical for accurate evaluation of torpedo stress levels. The pressure wave resulting from an underwater explosion was modeled using similitude relations and it was assumed to be a spherical wave. Various explosive weights and explosion distances were explored to determine the critical distance both for an un-stiffened and a stiffened torpedo. Once it was established that the stiffened torpedo performed better under explosive pressure loads, various configurations were studied to determine the optimal number of ring and longitudinal stiffeners. A final configuration was obtained for the torpedo that had minimum weight and was least sensitive to small manufacturing variations in the dimensions of the stiffeners. This paper presents details of the torpedo and fluid models and the finite element analysis method for fluid–structure interaction [57].

Chen *et al.* considered how to moderate ship the damages caused by the underwater explosions which is of great interest to the modern ship designers [58]. This investigation explores the protective effects of a layer of rubber sandwich with the square honeycomb core coated onto ship hull. Two slender steel scaled ship models were manufactured and tested. One model was coated with a layer of rubber coating while the other kept intact. A series of comparative tests were carried out to comprehend the dynamic performance of the protective layer when both shock wave and bubble pulse loading were considered. Modal characteristics of both models were measured firstly and then live UNDEX tests were made on the free floating ship models. Both the acceleration and strain peaks were selected as the major comparative criterions. The free field and wall pressure were also monitored. Detailed discussions on test results have shown that the protective rubber layer is capable of moderating damage of the ship body caused by shock wave while not very effective in reducing the whipping damage excited by bubble pulse [58].

### Miscellaneous

This paper by Zhang *et al.* starts with the importance and basic physical phenomena of underwater explosion, explaining the background and significance of ship damage and protection research under underwater explosion loads, research progress and status, as well as key challenges [59]. To address these challenges, the paper elaborates on popular underwater explosion theories, models and methods. In terms of theoretical and computational research, a unified theory of bubble dynamics is presented, as well as a transient strong non-linear gas-liquid-solid fully coupled model and numerical method for underwater explosion, which have been used to develop a fundamental industrial software FSLAB capable of solving practical problems in fluid-structure interaction. In terms of experimental research, underwater explosion surrogate experimental methods and model testing methods are elaborated. Based on this, theoretical analysis, computational and experimental results in the field of ship damage and protection under underwater explosion loads are presented and discussed, aiming to provide references for underwater explosion-related research [59].

Zhang *et al.* published in 2008 an article [60], in which the results based on the potential flow theory and the boundary element method (BEM) to calculate the dynamics of an underwater explosion bubble near boundaries, and in conjunction with the finite element method (FEM). It is employed to compute the interaction between a bubble and an elastic–plastic structure. A complete 3D underwater explosion bubble dynamics code is developed; the simulated results compare well with an underwater explosion experiment. With this code, the interactions between an underwater explosion bubble and elastic–plastic structures such as a flat plate, a cylinder and other simple structures are calculated and analyzed. Besides, the damages caused by the after flow, pulsating pressure, and jetting load on the structures are also calculated, with or without a free surface. From the time history of the pressure and stress of the structure, it can be observed that the stress reaches its maximum value when the bubble collapses, which proves that the pressure and jet impact induced by the collapse of the bubble can result in severe damage to the structure. In particular, the 3D analysis code is applied to some engineering problems, for example it is used on a surface ship to study the interaction between a bubble and a complex elastic–plastic structure. Under the bubble load, the low-order eigenfrequency of the ship is aroused usually, leading to the so-called ‘whipping’ effect, because the pulsating frequency of the bubble ‘matches’ the low-order eigenfrequency of the ship. The ship moves up and down with the expansion and collapse of the bubble respectively. Meanwhile, the power of the bubble generated by a near-field underwater explosion in short range is discussed, and some important conclusions which can be applied to project application field are drawn [60].

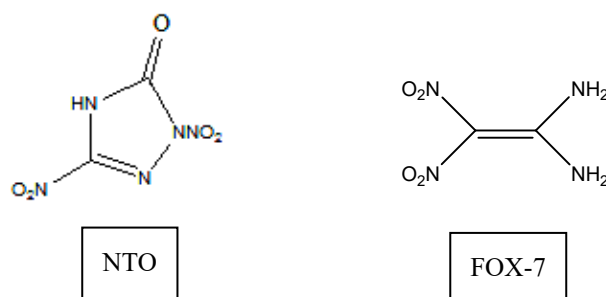
A numerical study of two gaseous bubbles merging into a single coalesced bubble as in underwater explosions is investigated in this paper. This explosive phenomenon is modeled using a boundary integral method. Two configurations, which are in-phase and out-of-phase explosions, are simulated and compared with available experimental results. The thickness of the liquid film between the two bubbles determines the coalescence criterion. Bubble shapes and periods of oscillation are predicted well, compared to those of the experiments [61].

Huang *et al.*, focused their attention to previously rarely studied fact that is the shape of a high-explosive is an important factor in the near-field and/or contact explosions. In this paper, they first conducted experiments to study the directional effects of the underwater explosion shock wave of slender explosives [62]. A numerical model based on the multi-material arbitrary Lagrangian Eulerian (MM–ALE) technique is then developed to study the influence of the explosive slender ratio on the generated shock waves. Then the numerical model is validated by experiment data. After that, tests have been conducted with constant-mass cylindrical explosives with slender ratios ranging from 2.0 to 9.2. By comparing with the center-detonated spherical explosive, the peak pressure, pulse duration, impulse and energy flux of the underwater explosion of slender explosives are analyzed in detail. Furthermore, the effectiveness of the fluid–structure interaction algorithm is verified through the experimental data of a plate subjected to underwater contact explosion. Finally, the response of plates subjected to the underwater explosion of a slender explosive at different azimuths is studied. The interaction between the plate and the directional loads is analyzed. Finally they conclude that the loads and structure responses of the near-field underwater explosion of slender explosives are different from those of spherical explosives. The analyses and results provide a reference for the near-field underwater explosion loads and structural response studies [62].

In this paper, Wang *et al.* investigated emulsion explosives [63]. Rules for the change of output energy of emulsion explosives with different oxygen balance, aluminum powder content, charge condition, and decoupling media etc. were studied by means of an explosion water pool. The  $p$ – $t$  curves and peak pressure values were obtained. The effects of all these factors on shock wave energy, bubble energy and total energy

were given. The results show that output energy of emulsion explosives without aluminum powder is lower than that of standard TNT explosives. The total energy of emulsion explosives with zero oxygen balance is only 86 % of that of TNT. In the experiment, output energy of the explosives tends to increase with the increase of aluminum powder content. Such that, with aluminum contents from 10 % to 15 %, the total energy is 1.05 and 1.14 times that of TNT, respectively. Energy efficiency is affected with change of decoupling coefficient and media [63].

In order to investigate the metal driven abilities of two newly designed HMX-based aluminized explosive compositions, (XL: 31% HMX, 31% FOX-7, 30% Al, 8% binder; EL: 31% HMX, 31% NTO, 30% Al, 8% binder), were considered and multiple cylinder tests were conducted to gain the cylinder wall expansion process and evaluate Gurney energy [64]. Then the parameters of JWL-Miller equation of state were determined based on experimental expansion data. For evaluating the underwater explosion power of XL and EL, the authors numerically simulated the propagation of shock wave and bubble pulsation under water. The experimental and modeling results showed that the metal driven ability and underwater explosion overpressures of XL were obviously better than EL, but the specific bubble energy of XL was only about 3% higher than EL. Compared with NTO (3-Nitro-1,2,4-triazol-5-one), FOX-7 better improve metal driven capacity, underwater explosion power and secondary combustion rate of aluminized explosives. Those conclusions may provide useful suggestions for designing HMX-based insensitive aluminized explosives [64].



The non-ideal behavior of aluminized explosives significantly affects the characteristics of underwater explosion shockwaves, rendering the classical model for underwater explosion shockwaves difficult to apply. In this paper, Kan *et al.* analyzed the underwater explosion shockwave characteristics of a new generation of aluminized explosives [65]. Then, they proposed a non-ideal explosive underwater explosion shockwave model incorporating a non-ideal explosive shockwave parameter correction function controlled by the Al/O ratio. First, they conducted underwater explosion tank experiments to obtain four groups of Al/O ratios of shockwave parameters of underwater explosion with aluminized explosives and analyzed the effect of the Al/O ratio on them. Subsequently, the equation of state of aluminized explosives calculated and established a one-dimensional simulation model of underwater explosion. Then the reliability of the mesh quality and equation of state were verified using the experimental data. Finally, they used the model to calculate the underwater explosion shockwave parameters of aluminized explosives with Al/O ratios of 0.1–1.3. Based on data analysis, they established a calculation model of the pressure peak and energy flow density of the underwater explosion shockwave of aluminized explosives containing non-ideality correction functions. Their results reveal that the shockwave pressure peak and energy first increase and then decrease with an increase in the Al/O ratio. They obtained that the non-ideal behavior of aluminized explosives makes the shockwave energy of underwater explosion more sensitive to the Al/O ratio. The proposed model can better predict the experimental results and can be of high practical value as a general structure for underwater explosion shockwave models of other aluminized or metallized explosives [65].

Grządziela interested in modeling of impact arising from underwater detonation and associated specific sea loads due to waving and dynamical impacts [66]. Sea waving can be sufficiently exactly modeled by means of certain statistical methods. Much more problems arise from modeling impacts due to underwater explosion. Knowledge of a character of impulse loading which affects ship shaft line can make it possible to identify potential failures by means of on-line vibration measuring systems. The problem of influence of sea-mine explosion on hull structure is complex and belongs to more difficult issues of ship dynamics. Underwater explosion is meant as a violent upset of balance of a given system due to detonation of explosives in water environment. This paper presents a proposal of identification of a degree of hazard the ship's hull forced from underwater explosion. Presently, a theoretical analysis was made of influence of changes of hull structure in vicinity of hull. The main problem of naval vessels is a lack of dynamical requirements of stiffness of the hull. Modeled signals and hull structure were recognized within sensitive symptoms of three sub models: model of hull structure, model of impact and model of propulsion system. All sub models allow testing forces and their responses in vibration spectrum using SIMULINK software and FEM models

The results of testing allowed performing simulations of a similar nature to the actual loads of underwater explosions. Virtual model of the hull of the ship responds in a similar manner to the real impacts. Most simulations were performed to calculate or estimate the strength of the hull of plastic deformation. Load model of 2 or 3 bulbs allows assessing the potential occurrence of resonance at any point of the hull. This is important in the design process because the stiffness of the fixing or changing the mass of the foundation, can arrange the marine device from the potential risks coming from the resonance of an underwater explosion [66].

In an article by Geers and Hunter, a model for a moderately deep underwater explosion bubble is developed that integrates the shock wave and oscillation phases of the motion [67]. A hyper acoustic relationship is formulated that relates bubble volume acceleration to far-field pressure profile during the shock-wave phase, thereby providing initial conditions for the subsequent oscillation phase. For the latter part of the work, equations for bubble-surface response were derived that include wave effects in both the external liquid and the internal gas. The equations were then specialized to the case of a spherical bubble, and bubble-surface displacement histories were calculated for dilational and translational motion. Agreement between these histories and experimental data is found to be substantially better than that produced by previous models [67].

The process of an underwater explosion near a ship hull is typically accompanied with the impinging of water jet, the penetration of high-speed fragments, the propagation of shockwaves among multilayer structures, the interaction of stress waves in structures and other extremely complex phenomena [68]. The fluid dynamics are usually strongly nonlinear such as discontinuity, saltation, etc., while the structure undergoes large-deformation, tearing and even breaking, thus the whole process is very complex. As the source of energy in underwater explosions, the charge properties are directly related to the energy release and subsequently the structural damage. At present, Ming *et al.* tried to manage the understanding of underwater contact explosion loading which is still relatively incomplete. Moreover, the hole size, damage mode, failure criteria and other factors related to the damage phenomenology are as yet unresolved, but widely studied.

The damage process of ship structures subjected to underwater contact explosions is characterized by strong nonlinearity, thus there are great challenges in solving such problems. Firstly, the full Smoothed Particle Hydrodynamics (SPH) method for the fluid and structure interaction (FSI) is established based on compressible SPH fluid dynamics and SPH shell. Furthermore, the normal flux method is introduced to treat the interface. However, given the immaturity of the SPH shell in dealing with the fracture of complex structures, an SPH-FEM (Finite Element Method) coupling method for FSI is proposed with the "glue" treatment applied at the interface. The validity of above two methods has been verified by an underwater contact explosion

experiment. Afterwards, the pressure-time relationship within six charge radii is fitted based on the axisymmetric SPH simulation. On this basis, the flat plates subjected to underwater contact explosions were studied in detail with the application of a combined damage variable. Three stages in the damage process, namely localized bulging, discing and petaling, were observed, and the crack and deflection were found to be sensitive to the changes of peak pressure and impulse respectively. Finally, complex models of a stiffened plate and a ship were established to further study the damage characteristics.

Mainly, the shock loading of underwater contact explosions and the induced damage characteristics of a flat plate, a stiffened plate and a complex ship structure have been studied in this paper. Firstly, the full SPH method and SPH-FEM coupling method for the fluid and structure interaction are detailed. Meanwhile, the normal flux method and the proposed “Glue” algorithm are respectively used to treat the interface of the fluid and structure in the above two methods [68].

Note that the necessary comprehension of the materials behavior goes beyond traditional steels, whereas modern designs utilize advanced metallic alloys, composite structures (either purely polymeric, as in the case of small and medium sized boats, or in a sandwich layout composed by metal sheets and foam cores) and wood [69]. Also, the usage of innovative materials, such as polymers reinforced by natural fibers, have been addressed in the literature, on one hand presenting inferior mechanical properties to carbon or glass fiber, and on the other having enhanced sustainability. In addition, the diverse existent hull architecture requires the designer not only to master different materials, but also to understand the response of the vessel itself as a composition of the several interlinked structural elements built with those materials, such as panels, stiffeners, and girders.

The ability of predicting material failure is essential for adequate structural dimensioning in every mechanical design. For ships, and particularly for military vessels, the challenge of optimizing the toughness-to-weight ratio at the highest possible value is essential to provide agile structures that can safely withstand external forces. Exploring the case of underwater explosions, the present paper by Vannucchi summarizes some of the fundamental mathematical relations for foreseeing the behavior of naval panels to such solicitation. A broad state-of-the-art survey links the mechanical stress-strain response of materials and the influence of local reinforcements in flexural and lateral-torsional buckling to the hydrodynamic relations that govern the propagation of pressure waves prevent from blasts. In the article, numerical simulation approaches so far used in computational modeling of underwater explosions are reviewed, especially focusing on Eulerian and Lagrangian fluid descriptions, Johnson-Cook and Gurson constitutive materials for naval panels, and the solving methods FEM (Finite Element Method), FVM (Finite Volume Method), BEM (Boundary Element Method), and SPH (Smooth Particle Hydrodynamics). The confrontation of experimental tests for evaluating different hull materials and constructions with formulae and virtual reproduction practices allow a wide perception of the subject from different yet interrelated points of view.

Addressing the mechanics embraced by underwater explosions, the present survey underlines essential mathematical relations from the hydrodynamics of subsea explosions, to the propagation of high pressure waves and bubbles, to the behavior shown by materials and structures commonly used in shipbuilding. The validity of these methods has been checked through the high correlation of purely analytical formulations with several experimental works, in spite of the fact that some discrepancies among authors have also been identified, such as the constants used for determining peak pressure as a function of the charge load.

The variety of computational numerical resources applied in this area have permitted the constitution of advanced research studies that are able to mirror UNDEX, conditions considering complex wave force

transmission mechanisms and progressively accurate material responses in parallel, thus ratifying the forefront role played by virtual simulations in related engineering problems.

Moreover, the confrontation of the late efforts in improving and perfecting the precise reproducibility of constitutive models to real situations, with the reported advanced material characterization and hydrodynamic studies, show that this traditional but ongoing research field has kept its evolving pace and still presents a remarkable development potential [54].

It is known that when a composite structure is exposed to underwater explosion, it experiences two important phases. In the first phase, the composite structure is impacted locally by the underwater explosion shock with a very short time duration (in milliseconds), and in the second (and perhaps more devastating) phase the composite structure is deformed globally by the underwater explosion bubble with a much longer time duration (in seconds) [70]. As the charge is detonated underwater near the structure, the effect of underwater explosion bubble becomes very significant, and it should be carefully considered.

This paper by Gong and Khoo deals with the transient response of a glass-epoxy composite submersible hull subjected to underwater explosive bubble. The boundary-element method (BEM) was used to simulate the physical process of the explosion bubble growth, contraction and collapse while the finite element method (FEM) was used to calculate the response of glass-epoxy composite structure to the high pressure induced by the underwater the explosion bubble. The coupled BEM–FEM was used to handle the interaction of the composite structures and the underwater explosion bubble. With the coupled code, the mutual effects of relative location between the bubble and the composite submersible hull were investigated. Also the transient responses (such as stresses and internal energy densities) of the composite submersible hull to the underwater explosive bubble can be predicted for different charge weights and charge distances. From the results obtained, some insights to the dynamical problem of the interaction between underwater explosion bubbles and composite structures are deduced.

The present modeling and simulation facilitates the investigations of the stiffened composite submersible hull subjected to underwater explosion bubble. The results show that the underwater explosion bubble produces the large deformation of the hull around the standoff point after the bubble collapses and reaches its minimum volume beneath the composite hull; it also exerts the global effects on the composite submersible hull with higher stress response in the longitudinal direction [70].

Recently, behavior of plate specimens subjected to underwater explosion is getting more and more popular interest of metal forming community and ship designers. Rupture of the original explosive molecule into various product molecules associated with the evolution of large amount of heat generated results in a shock front in the water medium, which is followed by a gas bubble pulsation [71]. The interaction of the shock wave with a plate imparts energy to it, which is dissipated in the form of deformation. The intensity of explosion determines whether a plate undergoes elastic deformation, yielding, plastic deformation or fracture. When the deformation is in the elastic range, the stress developed in the plate is given as a function of the material and shock wave parameters. As the intensity of explosion progressively increases, the elastic to plastic transition occurs over a specific shock factor. Obviously plastic deformation is a function of geometric and material properties of the plate and shock pulse impulse. Deflection-time history reveals the reloading effects of the shock wave. As the deforming plate absorbs maximum energy, depending on its strength and ductility, it undergoes fracture. Terminal strain to fracture is considered as the criterion for explosive shock performance of ship materials.

In the present article, theory of underwater explosion phenomena was reviewed with special emphasis on

the interaction of shock waves with plane plates. The plates undergo more damage by reloading than by the primary pulse. Note worthy that the elastic stress due to the primary pulse, the yield onset and the extent of permanent deformation of thin plates are predictable for non-contact explosion. Explosion bulge test serves as the qualification test for ship materials. Flawed bulge explosion test specifies the minimum plastic strain [71].

It is obvious that design of ship plates against underwater explosions is a mandatory requirement of warship construction. While non-contact underwater explosions of small intensity induce dynamic stresses that die with time, those of moderate intensity cause permanent or inelastic deformation, whereas those of severe intensity lead to rupture. The intensity of the explosion increases with the explosive charge quantity and decreases with stand-off [72]. Therefore, a range of combinations of explosive charge quantity and stand-off may deliver the same amount of shock energy to the plate. However, the energy-coupling factor between a shock wave and the plate is the maximum only for a specific configuration of the explosion. This leads to the so-called effective shock factor, which forms the basis for assessing the elastic-plastic behavior in the plating. In this article, permanent deformation of plate is predicted by analytical and empirical methods. Whereas contact explosion damage is predicted as a function of target material parameters and explosive parameters together with an energy-coupling factor [72].

The purpose of this study by Zhang *et al.*, was to establish a model adequacy assessment method for dynamic response of hull structure subjected to underwater explosion [73]. A numerical model is established and experiments are carried out to assess the shock response of the hull structure. An experiment data processing method suitable for this study is proposed. The numerical calculation results and the processed experimental data are first compared graphically to verify initially the accuracy of the numerical model. Subject matter expert score for qualitative analysis is obtained from the comparison of time series and the quantitative validation metric is calculated. Four validation metrics are introduced to represent the different time and frequency domain characteristics of the signals. To establish the relationship between subject matter expert score and validation metric, probabilistic neural network is used. The total probability formula is used to synthesize the overall model adequacy score of the model [73].

This investigation by Chen *et al.* explores the protective effects of a layer of rubber sandwich with the square honeycomb core coated onto ship hull [74]. Two slender steel scaled ship models were manufactured and tested. One model was coated with a layer of rubber coating while the other kept intact. A series of comparative tests were carried out to comprehend the dynamic performance of the protective layer when both shock wave and bubble pulse loading were considered. Modal characteristics of both models were measured firstly and then live UNDEX tests were made on the free floating ship models. The acceleration and strain peaks were selected as the major comparative criteria. The free field and wall pressure were also monitored. Detailed discussions on test results reveal that the protective rubber layer is capable of moderating damage of the ship body caused by shock wave while it is not very effective in reducing the whipping damage excited by bubble pulse.

Although, it is very promising in energy absorbing, the metal sandwich structure is designed mainly to resist contact or near-field explosions, which seem very intense and powerful. As for far field explosions, sandwich structure with metal core seems not effective in elastic regime as in plastic regime for the compressive strength seems too large in this situation. Even though, the assumption that sandwich with soft core can lower the momentum transmitted into the main structure seems very attractive. With an eye to this, the idea that coats the hull with a layer of protective soft rubber sandwich is investigated in this paper. Such protective coatings are shaped and sized to conform to the entire underwater hull surface and most effectively protect different compartments covered by sections of the covering which are mated and interconnected. The soft protective hull

coatings are constructed in order to provide the desired shock mitigating and shock absorbing capabilities. Aimed at the question whether the rubber coatings can function as expected, two slender ship models were designed with one being coated while the other not. A series of comparative tests were carried out, including modal and underwater explosion tests. Details of the experiments are given and results discussed.

The main outline of this paper of Chen *et al.* is as follows: The structure and geometry of scaled ship models as well as rubber coatings are introduced firstly. The main tests procedures of both modal and underwater explosion tests are introduced in succession. Then, the acceleration, strain and pressure history of two models are compared and analyzed. At the end, an overall evaluation is made on the soft coating technique in underwater explosion protection [74].

Shape of charge liners has a great effect on formation of a metal jet and its penetration into a target. In this paper by Zhang *et al.*, three different shapes of a charge liner, namely, conical, hemispherical and spherical-segment, are chosen to investigate their effect on damage response of a plate to underwater explosion [75]. A Smooth Particle Hydrodynamic (SPH) method based on mesh-free Lagrange formulation was applied to simulate an entire process of a shaped-charge detonation, formation of a metal jet as well as the penetration on a steel plate. Initially, a SPH model of the shaped charge with a spherical-segment liner was developed, and its results were compared with the experimental data to verify the effectiveness of this method. Then, numerical simulations of shaped charges with different liners have been performed to study the damage characteristics of a steel plate subjected to underwater-explosion shock loading and the metal jet. It was found that for the shock wave the peak value of the radial pressure is larger than that of the axial pressure during the detonation process; the level of pressure in the spherical-segment case was higher than that of the other two cases. After the detonation, the metal jet was gradually produced under the effect of the detonation wave. Three types of the metal jet - a shaped charge jet (SCJ), a jetting projectile charge (JPC) and an explosive formed projectile (EFP) – were formed corresponding to three cases with conical, hemispherical and spherical-segment liners. The obtained results have revealed that the velocity and length of the SCJ in the conical case are greater than that of the other cases, and it therefore may lead to a larger penetration depth. In addition, the EFP has a better motion stability for a velocity difference in the spherical case is lower than that of the other two cases. Subsequently, the shock wave arrives at the plate earlier than the metal jet, which will cause deformation of the plate. Due to higher pressure, the shock wave in the spherical-segment case has a stronger damaging effect on the plate than that in the other two cases. Finally, the metal jet reaches the plate thus causing a hole. Because of a wider jet head, the EFP results in a more serious damage to the plate. The suggested analysis and its results provide a reference for structural design of shaped charge warheads [75].

The paper of Petrov and Schmidt is devoted to numerical investigations of processes accompanying an underwater explosion near the free surface [76]. In the study, a model of evolution of liquid and gas separated by free surface is implemented. The model enables one to take into account cavitation in rarefaction waves propagating through the liquid. Thus, the study is directed at phenomena of propagation of compression and rarefaction waves in the liquid and in the gas. The interaction of the waves with each other and with the moving free surface, and the cavitation due to pressure drop in the liquid, are consideration of interest as well. Governing equations are solved by a numerical method based on Godunov-type high resolution scheme. Location of the free surface is determined utilizing information on distribution of the liquid volume fraction taking into account compressibility of both media. Computations of underwater explosion near the free surface have demonstrated robustness of the proposed algorithm.

In this paper, the liquid (water the case under study) is considered as a barotropic medium which obeys the Tait constitutive equation, while gas is considered an ideal perfect medium. Besides, an attempt is made to

introduce the stiffened gas model as the constitutive equations for both water and gas. In the present paper a combined Euler-Lagrange algorithm is proposed which allows to simulate multiphase flow structure induced by underwater explosion near the free surface. This method provides description of propagation of compression and rarefaction waves, as well as their interaction with each other and with deformable free surface, inception of cavitation in the bulk of the liquid due to pressure drop in rarefaction waves [76].

In recent years, shock trials for surface ships have been conducted in many countries for qualification of ship integrity, systems and subsystems in response to shock [77]. A ship trial identifies design and construction deficiencies that negatively impact ship and crew survivability. Such a trial also validates shock hardening and performance of shipboard equipments. However, live-fire ship shock trials and underwater explosion testing are both complex and expensive. As a possible alternative, numerical modeling and simulation may provide viable information on the details of dynamic characteristics of ships, including at the component and sub-component levels. In the article ship shock analyses were conducted using a finite-element-based coupled catamaran-type ship with a fluid model. This model is also applicable to underwater explosion (UNDEX) simulation for movements of a high-speed catamaran-type ship. Catamaran-type ship shock modeling and simulation were performed and the simulation results were compared with the empirical data. The high-speed catamaran-type ship shock analysis approach is presented and the important parameters are presented and discussed [77].

## Conclusion

This article summarizes the various aspects of the underwater explosions emphasizing measurement of underwater explosion, impact load and bubble pulsation load, based on the data piled up in the laboratory scale and environmental scale. Also various simulation techniques applied to underwater explosions excerpted from the relevant literature are mentioned including the discussions of the investigators.

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