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Response of Dome-enclosed Box-type Structure to Underwater Explosion

O.R. Nandagopan*, Sameer Abdul Azeez, and C.G. Nandakumar#

Naval Physical & Oceanographic Laboratory, Kochi – 682 021, India
#Cochin University of Science & Technology, Kochi – 682 022, India
**E-mail:* ornandaguopan@yahoo.co.in

ABSTRACT

In the development of underwater sensor systems, the sensor arrays are configured for different shapes like cylindrical, rectangular and spherical depending on the requirement. The rectangular shaped box–type structure discussed here has both top and bottom ends open. Flanges stiffen the top and bottom ends, and gussets are used to connect the flanges with the structure. In this paper, the box-type structure is subjected to non-contact underwater explosion in a shock tank to study the peak free field pressure on the structure. To simulate the actual conditions, the structure is placed in free flooded area and covered with a dome. The free-field peak pressure on the dome and structure are plotted with time. The measured pressure curves are in agreement with the empirical predictions reported in literature. It is concluded that around 85 per cent of the shock impulse acting on the dome is transmitted to the box-type structure. The dome and box-type structure withstood the explosive load, thereby validating their design.

Keywords: Underwater explosion, sensor structure, structural response, shock wave

1. INTRODUCTION

Military standards prescribe that underwater structures are to be designed to withstand shock loads resulting from non-contact underwater explosion[1]. The sensor array structures are also designed accordingly. Generally, these structures are configured in various shapes like cylindrical shell structures, spherical shell structures and box-type structures. These structures, which are placed in the free-flooded area of ships or submarines, are referred to as wetted surface type. They are also classified as 'water-backed' structures as against 'air-backed' structures referring to the pressure hulls of ships and submarines, which have water on one side and air on the other.

The studies on structural response to underwater explosion on 'water-backed' structures are relatively few. Rajendran and Lee[2] have established the damage potential due to noncontact underwater explosion for air and water backed plates. A few experimental studies on underwater explosion have been reported in literature for cylindrical shell structures. Li[3], *et al.* carried out underwater explosion on two types of cylindrical shells in a circular lake and observed that main hull sand-filled cylindrical shell is more difficult to be damaged by the shock wave loading than an unfilled cylindrical shell. Li[4], *et al.* examined the propagation of the shock wave and the bubble pulse of an underwater explosion in a water pool, and estimated the dynamic response of a cylindrical shell. Numerical simulations performed using MSC. DYTRAN were compared with experimental data and it was found that the artificial bulk viscosity had a significant effect on the peak pressure of the shock wave. On the other hand, not much literature is available on the response of spherical structures and box-type structures to underwater explosion. Popplewell[5,6] has studied the vibrations of box type structure and its response to traveling pressure wave utilizing finite element methods. In this paper, in order to validate the design process of underwater sensor structures, a typical sensor array structure having box-type configuration is subjected to non-contact underwater explosion in shock tank. To simulate the actual scenario, the structure is kept in the free-flooded area and covered with an acoustic dome.

1.1 Effects of Underwater Explosion

According to Cole[7], an explosion is a chemical reaction in a substance which converts the original material into a gas at very high temperature of the order of 3000 °C and pressure of 50,000 atm (5 GPa), the process occurring with extreme rapidity and evolving a great deal of heat. If water is considered to be a compressible media, pressure applied at a localized region in the fluid is transmitted as a wave disturbance to other points in the fluid with a large but finite velocity. For propagation of waves from a spherical source, the amplitude decreases with distance from the source.

Kowsarinia[8], *et al.* presented techniques for calculation of free-field blast parameters such as pressure and impulse in underwater explosion and prediction of bubble pulsation parameters. These were compared by experimental results of underwater detonation of Hexogen explosive charge. Liu[9], *et al.* utilised the flow-out boundary and variable step-size multi-material Euler algorithm to analyse numerically the whole process of shock wave generation and propagation, as well as the bubble formation and impulse of underwater explosion.

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Huang[10], *et al.* carried out numerical simulation of underwater explosions using a one-dimensional 'wedge' model of ANSYS-AUTODYN explicit software for nonlinear dynamics. In this study, the effects of charge depth, charge mass, and mesh density on the shock wave and bubble pulse parameters are performed for four different explosives, TNT, H-6, pentolite, and PETN. Holt[11], *et al.* studied the spatial and temporal acoustic response of the bubble cloud resulting from a 13.6 kg PBXN-111 charge detonated at 15.2 m depth and used the bubble population estimates to develop a model for the bubble population resulting from an underwater explosion. Singh[12] has theoretically studied the propagation and attenuation of spherical shock waves in water using Whitham's method and energy hypothesis method, and found that energy hypothesis is quite agreeable with experimental data compared to the higher values obtained with Whitham's method.

Underwater explosion is found to affect the structures of ships and submarines in terms of the impact loading of the primary shock wave as well the following bubble pulses. Shin and Santiago[13] predicted the underwater shock response of a two-dimensional mid-section model of a surface ship with a coupled surrounding fluid model. Shin[14] has also carried out a three-dimensional analysis of a surface ship finite element coupled model with a surrounding fluid model subjected to a far-field underwater explosion. Lihua[15], *et al.* used the Arbitrary Lagrangian-Eulerian (ALE) Finite Element Method to solve the fluid-structure interaction problem in the explosion shock and estimated the damage situation of ship rudder in underwater explosion impact load. Zhang[16], *et al.* proposed a calculation method on the dynamic bending moment of bubble to evaluate the impact of underwater explosion bubble load on the longitudinal strength of surface ships. By considering the wave effect they established an evaluation method of the total damage of a ship. Andrzej[17] performed ship shock modeling and simulation, and compared the predicted results with ship shock test data obtained from sea trials. This study attempted to find out the order of pressure occurring in the construction of the hull subjected to shock loads, and thereby identify risks from excess of pressure tolerated in the internal nodes of the hull, which are the bearings of marine propulsion, technical equipment and armaments.

In many cases, the structural response due to underwater explosion has been studied using numerical techniques, particularly using explicit integration based codes. A number of benchmarks for structural response to underwater explosion solved using various codes have been compiled by Mair[18]. The numerical modeling and simulation in all these cases is an alternative to the actual experimentation. In this paper, the free field pressure due to underwater explosion, on sensor structure is obtained experimentally. This free field pressure is comparatively less than the free field pressure on acoustic dome since the shock wave is passed through acoustic dome.

2. EXPERIMENTAL STUDY

2.1 Estimation of Shock Pressure

As a result of underwater explosion, primary and secondary shock waves are formed. The primary shock waves are generated because of localized compression of surrounding water media. Secondary shock waves generated by the oscillating bubble of detonation products (gas bubble) are of low intensity but of longer durations[19].

As per Cole[7], the formula used to describe the primary shock wave for an underwater TNT explosion is generally of the form

$$P = P_m e^{(-t/\theta)} \tag{1}$$

Where P_m is the peak shock wave pressure and θ is the time constant of exponential decay. For TNT,

$$P_m = 21600\ (w^{1/3}/R)^{1.13} \tag{2}$$

P_m is in psi, w is the charge weight in pounds, and R is the standoff distance in feet.

For the PEK explosive of 30 g, the peak pressure value is calculated, taking into account the fact that shock effect of 1 g of PEK equals that of 1.17 g of TNT[20]. The expected peak free-field pressure on the dome due to 30 g of PEK placed at a distance of 0.95 m is estimated to be 2302 psi (15.87 MPa).

2.2 Experimental Setup

The box type structure is shown in Fig. 1 and has dimensions of 900 mm × 300 mm × 650 mm with the top and bottom ends open. End flanges are provided at the top and bottom, and are connected to the longitudinal sides by means of gussets. There are 27 holes of 36 mm diameter each and multiple holes of smaller diameter on both the longitudinal sides of structure. The structure is made of stainless steel and weighs about 250 kg.

Figure 1. Box-Type structure.

The dome shown in Fig. 2 is also made of stainless steel which is acoustically transparent. It is 2500 mm in length. The maximum height is 1180 mm and the maximum width is 620 mm. The thickness of the dome material is 2 mm and it is stiffened by angles placed inside the dome all around. The box-type structure is placed inside the dome such that its longitudinal axis coincides with that of the dome.

The non-contact underwater explosion was conducted in a shock tank capable of testing heavy structures. The explosive used was plastic explosive kirkee (PEK). The main constituent of PEK is tetryl (85%). The detonator used was MK-79 Electric, which was ignited by an electric current of 0.556 amperes.

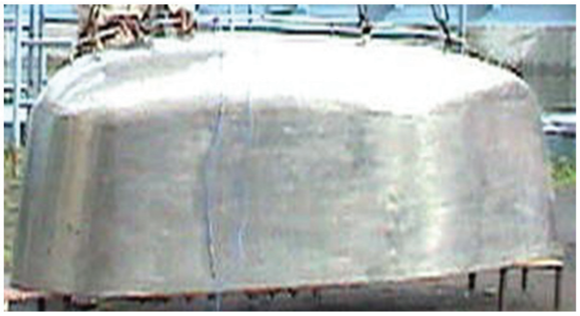

Figure 2. Acoustic dome.

Figure 3 indicates the schematic arrangement of experimental setup. To simulate actual scenario, the structure and dome are connected at the bottom flanges with an intermediate fixture using 16 sets of M20 and M18 fasteners. This is to ensure the transfer of inertia forces from dome to structure as in real condition. A pressure blast gage is pasted over the dome (Point-A in Fig. 3) to measure the free-field pressure in the vicinity of the dome. Similarly another pressure blast gage is mounted over the structure along the longitudinal side (Point-B in Fig. 3) to measure the free-field pressure near the structure. The free end of the pressure blast gage is connected to the data acquisition system with pre-amplifiers. The structure with the dome is lifted with the overhead crane and slowly immersed in water to a depth of around one metre. The complete arrangement is held with overhead crane to simulate free-free condition.

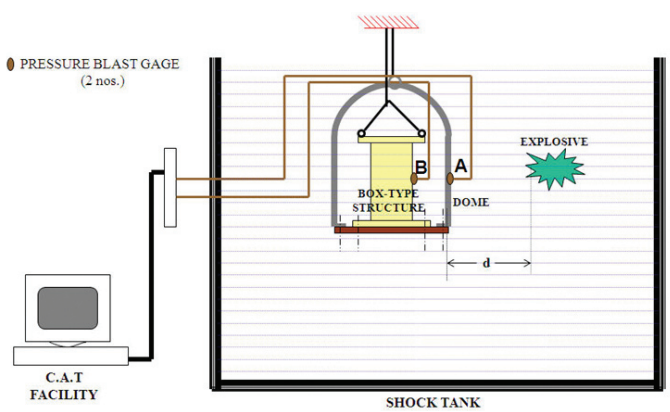

Figure 3. Schematic of experiment.

The weight of explosive charge and distance between the dome and explosive are calculated with the reference of MIL-E-16400 G (Navy)[21]. Totally 10 trials are conducted. In each of the trials, 30 grams of PEK is placed at a distance of 0.95 metre from the dome housing the box-type structure. The explosive is placed at the required location by suspending it from one of the ends of an L-section beam whose other end is fixed to the top of the dome.

2.3 Experimental Procedure

The box-type structure with dome is submerged in the shock tank at a depth of around one meter using an overhead crane. PEK is detonated in the tank, and the pressure blast gages pasted on the dome and structure recorded the free-field pressure in psi at every 20 microseconds. During the experiment, free-field pressure over period of time is plotted for 10 ms. This recording is done for the pressure gages placed at both the dome and the structure. The Computer Aided Test (CAT) facility then did the analysis and plotted the shock response spectrum. Ten trials are carried out using this setup.

As a result of the explosion, a white plume burst into the water surface. This is followed by the 'slick', a black plume caused by gaseous products. After the experiment, the dome and structure are retrieved using the overhead crane.

2.4 Instrumentation

The instrumentation included mainly of pressure blast gages, pre-amplifiers and a 2-channel data acquisition system. Two numbers of underwater pressure blast gages are used in each test, one to measure the free-field pressure acting on the dome and the other at the box-type structure. These gages have capacity to measure peak pressure of 5000 psi with a sensitivity of 1 mV / psi and to withstand peak mechanical shock of 20000 g. They are connected to the data acquisition system by means of electrical cables.

The data acquisition system consists of a personal computer based computer aided test (CAT) system operating on Windows 98 and transient analog to digital convertor (ADC) cards. The software used is GHI Systems, Inc. CAT System, which is a level-1 Windows based software for data acquisition.

3. RESULTS AND DISCUSSIONS

On completion of each trial, visual inspection is carried out on dome and structure. Pressure blast gages are checked for its continuity. Results obtained from each trial is recorded and tabulated in Table 1. Since the pressure blast gage records the pressure in psi, equivalent peak free – field pressure in SI unit is also indicated within the bracket. In order to get variation of free field pressure with respect to time, the recorded data is shown through plots. The trial outputs for dome are shown in Fig. 4. Similarly variation of free field pressure with respect to time for structure is shown in Fig. 5. To compare the free field pressure on dome and structure, the recorded data from trial 1

Table 1. Values of peak free-field pressure

Trial no.	Peak free-field pressure at dome in psi (MPa)	Peak free-field pressure at structure in psi (MPa)
1	2617.34 (18.05)	2271.12 (15.66)
2	2402.74 (16.57)	2098.94 (14.47)
3	2100.48 (14.48)	1837.27 (12.67)
4	2451.76 (16.90)	2086.31 (14.38)
5	2383.98 (16.44)	2055.72 (14.17)
6	1969.71 (13.58)	1703.65 (11.75)
7	2295.33 (15.83)	1983.11 (13.67)
8	1989.56 (13.72)	1686.38 (11.63)
9	2364.75 (16.30)	1998.61 (13.78)
10	1997.44 (13.77)	1701.52 (11.73)

is plotted together in Fig. 6. The free field pressure is recorded using pressure blast gages positioned on dome and structure. The distance between dome and explosive is 0.95m. It is evident from Fig. 4, that the pressure blast gage attains the peak free field pressure when the shock wave reaches the pressure blast gage. Hence the peak free field pressure is attained after 1.45 ms (approx) in case of dome. In case of structure, the peak free pressure is attained after 1.7 ms (approx) from the time of explosion. The difference in time between the peak pressure on dome and structure is due to the separation of dome and structure along the line of explosion. This is seen from Fig. 6. Considering the sensitivity of 1 mV/ psi of pressure blast gage, disturbances in the water is picked up by the pressure

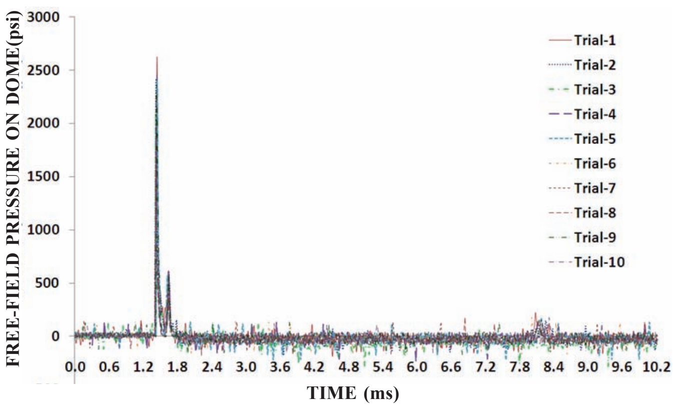

Figure 4. Free-field pressure on dome.

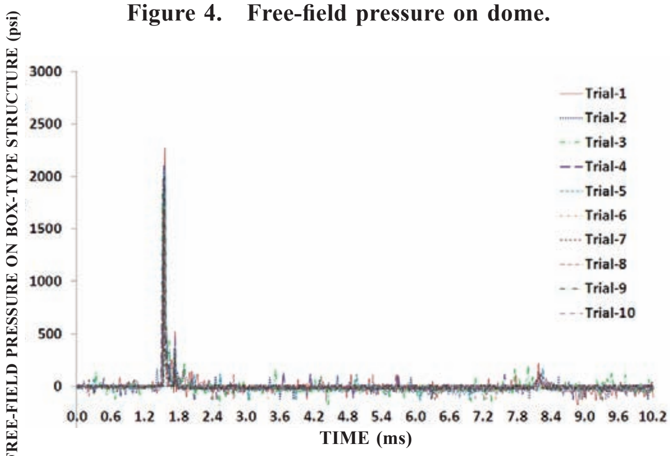

Figure 5. Free-field pressure on box-type structure.

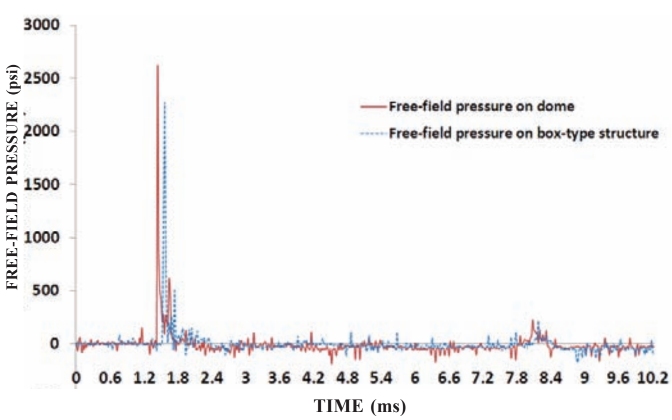

Figure 6. Free-field pressure on dome and box-type structure for trial no. 1.

blast gage and accordingly variation in free field pressure is recorded with time in Figs. 4 to 6.

From Fig. 4, it can be seen that the maximum peak pressure obtained on the dome during the trials is 2617.34 psi and the minimum is 1969.71 psi. This corresponds to a variation of 13.7 % and 14.43 % respectively from Cole's prediction. The peak pressure of 2295.33 psi obtained during trial no. 7 is the closest to Cole's prediction with a difference of only 0.29 %. The deviations observed from the theoretically estimated value is attributed due to disturbances in the positioning of explosive due to wind flow and subsequent disturbances on the water surface in shock tank. However, as the deviations are limited within 15 %, it is not expected to be significant as far as structural design for underwater shock is concerned.

From Fig. 5, it can be observed that the maximum and minimum values of peak pressures on the box-type structure obtained during the trials are 2271.12 psi and 1686.38 psi respectively. Comparing the values of peak pressures on the dome and that on the structure, shown in Table 1, it is seen that a large proportion of the peak pressure is transmitted across the dome to the structure, corresponding to a maximum of 87.47 % and a minimum of 84.52 %. This shows that the dome structure does not offer much resistance to the advancing shock wave. Hence structures placed in free-flooded area may not call for consideration of the full shock load in the structural design.

From the plots of peak pressure, it is evident that the primary shock wave is a steep fronted wave of high amplitude but of very low duration (180 - 200 micros). The secondary shock waves of a lower intensity but longer durations are also seen in these plots. It is seen that the plots are as per the standard curves enunciated by Cole[7]. The other small pressure fluctuations seen in the graph could be due to the disturbances of the medium, which are also picked up by the pressure blast gages.

The free-field pressures acting on the dome and structure are together shown in Fig. 6 for trial no. 1. It is observed that the peak pressure on the dome occurred at a time instant of 1.44 ms whereas that on the box-type structure occurred at 1.56 ms. This difference of 0.12 milliseconds corresponds to the travel time of the peak pressure wave across the separation distance between the incident surfaces of the dome and box-type structure.

4. CONCLUSION

The experimental procedure described in the paper presents an effective method to carry out the evaluation of response of free-flooded structures to non-contact underwater explosion. The predicted value of shock pressures acting on the dome is found to be in agreement with the value obtained from Cole's empirical calculations within a deviation of less than 15 %. The nature of the pressure plots obtained also follow the theoretical estimations reported in literature. One of the major observations from the experiment, is the fact that the shock impulse acting on the dome is almost (around 85%) transferred to the box-type structure. Hence it is concluded that structures placed in the free-flooded area may not call for consideration of the full shock load. The box-type structure and enveloping dome withstood the explosive load, thereby validating their design.

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Contributors

Dr O.R. Nandagopan obtained his PhD from Cochin University of Science & Technology, Kochi, presently working as a Scientist 'G' at Naval Physical & Oceanographic Laboratory (NPOL), Kochi. His area of specialization is underwater structures. His significant contributions are in the area of winches and handling systems for towed and dunking sonar systems for Indian Navy. Interested area of work is biomimicry and product realization.

Mr Sameer Abdul Azeez obtained his MTech (Industrial Engg. & Mgmt.) from Indian Institute of Technology Kharagpur. Currently working as scientist at the Naval Physical and Oceanographic Laboratory (NPOL), Kochi. He has been working in the areas of design, analysis, simulation, development and testing of engineering subsystems of sonar systems for the Indian Navy. His major contributions are in the areas of airborne sonar systems and application of systems engineering concepts. His research interests include: Structural dynamics, machine design and systems engineering.