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# Effect of External Water Flow on Response of Cylindrical Shell Subjected to Under Water Explosion

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## ABSTRACT

This article deals with response of cylindrical shell subjected to loading of Under Water Explosion (UNDEX) when water current is introduced to the surrounding environment. Cylindrical shells as one of main basic structural elements in construction of marine and submarine facilities are prone to UNDEX threat. Due to vicissitudes of conducting experiments in this field and also complicated inherent of fluid-solid interaction phenomenon, numerical models can be used as an effective tool for scrutinizing the problem. In this study, a submerged thin walled cylindrical shell and its surrounding water discretized by coupled shell Lagrangian elements and Eulerian cells respectively. Simulations are performed in AUTODYN hydrocode. For better perceiving of phenomenon, studies are done for two various explosive charge stand-off distances. Results show that introduction of flow to water, can tangibly change the symmetrical configuration of flow- less problem. Due to intricate interaction of water flow and explosion bubble, distribution of UNDEX overpressure and impulse is disturbed and this leads to un-symmetric deformation of cylindrical shell. Also amplitudes of deflection are reduced obviously by increasing flow velocity.

## 1. Introduction

Shell structures, especially cylinder ones have extensive usages in marine and submarine industries. Due to round geometrical shape of cylindrical shells, their resistance against lateral loading is relatively higher than other plane shell-plating structures. Main body of various submarine vessels can be approximated by cylindrical shell. Submerged cylindrical shells are exposed to tangible high hydrostatic pressures due to depth of sea. But sometimes these structures are prone to be threatened by Under Water Explosions (UNDEX). Level of pressures of UNDEX loadings is very higher than of hydrostatic water pressure and its substantial rapid dynamic behavior makes it very destructive phenomenon. UNDEX response evaluation and design of this type of structures is a main priority. Many nonlinear sources such as rapid large deformation of materials, interaction of structure-fluid (FSI) and large amount energy conversion lead to that structures' analysis subjected to UNDEX loading be a very complicated task. Analytical models cannot play an impressive role among various engineering methods and experimental procedures can be very tedious, expensive and dangerous tools for obtaining feasible results. Numerical simulations by careful consideration of meticulous aspects of this method and being cognizant about the complicacies are extant in UNDEX problem can be implemented as a trade-off way for exploring intricacies of UNDEX and FSI problems, simultaneously.

Numerous researchers devoted their efforts to investigate UNDEX problem and its effect on structures. Experimental method is a main and robust tool for this purpose. Some scaled down models of simple engineering problems have been testes in UNDEX pools. Usually, these researches are associated by numerical simulations. Hung et al.[1] investigated the dynamic response of cylindrical shells to under water blast empirically. They used a pool as a simulating medium for conducting UNDEX tests. Also a numerical study was accomplished using DAA approximate method for considering fluid-solid interaction. Cylindrical panel's deformation was studies by Ramajeyathilagam et al. [2] by experimental and numerical methods. DYNA3D code was implemented for numerical analysis. Some simplifications may aid analytical models to predict structural response subjected to underwater blast. Dynamic buckling of stiffened shells under transient lateral shock wave loading surveyed by Pedron and Combescure [3]. Wierzbicki and Hoo fat [4] by analytical study assessed damage parameters of cylinders under impact and explosive loadings.

One of the basic and main assumptions in previous references is being calm and stationary condition of water that even is not mentioned explicitly in articles. Other nonlinearities involved UNDEX-FSI problem are enough to be not handled by ordinary engineering methods and if flow of surrounding water is introduced into model, some considerations will be necessary. Meanwhile water currents are relevant in ocean and river applications and their speed may be tangible in a way cannot be neglected in advance and accurate design stages. By this new problem definition, spherical propagation of incipient shock wave is not acceptable and simulations must be performed from initiation of explosive charge detonation. In recent years, numerical procedures have found their way in highly rated mechanics problems and their puissant in solution of this type of events makes them a relatively cheap and powerful tool for tackling such difficulties. Hydrocodes among a lot of numerical packages available commercially or written privately; are developed for engaging with problems such as: explosion, blast, impact, penetration or perforation. This new introduced problem may be handled by using AUTODYN hydrcode. By the best knowledge of authors, there is no published research that concerns explosion in flowing water and its effect on structures.

In this article using a high fidelity multi-physics numerical model prepared in AUTODYN environment, above discussed problem is analyzed. For modeling of explosion of TNT charges in water depth, JWL equation of state is utilized. Simulations are performed for various flow velocities and two stand-off distances are chosen for better perceiving the problem. Cylindrical shell as a very useful structure in marine application is assumed to be the target resisting against the UNDEX loading. Finally, results are graphed for more illustrative comparisons.

## 2 . Problem Description

A thin walled cylindrical shell with 300 mm, diameter, 1000 mm length and 2 mm thickness dimensions is selected for studying water flow in longitudinal direction effect on structure. Cylindrical shell made from 4340 steel. Inside of cylinder is assumed to be filled by atmospheric air. Due to symmetry respect to the plane parallel to current direction, only half of problem is needed to be modeled. Two 23 and 106 grams TNT charges are used to make UNDEX from two different 1 and 1.5 m stand-offs, respectively. Flow velocities are varied from 0 (stationary condition) to 6 (m/s). Figure 1 shows a schematic of proposed problem.

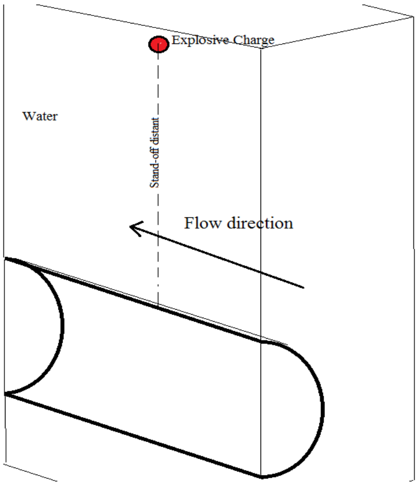

Figure 1: Problem Schematic.

## 3. Numerical Assessment

Explosive loading on structures usually associates with fluid-solid interaction phenomenon. High pressure of explosive detonation impacts adjacent particles of intermediate medium and the shock pulse propagates in environment. Nature of intermediate medium has serious effect on the history of explosive loading and must be counted in numerical procedures. Water as a relatively dense and incompressible environment makes some complicacies are not observable in air blast cases. So modeling surrounding water is necessary for getting accurate results. Explosion essence in water affected by incompressibility and after first shock loading, second and even third pulses consequence. First shock overpressure is very high but its endurance is short but in other hand second pulse has relatively long endurance and low overpressure amplitude making considerable impulse. Interaction of underwater shock wave with structure can be more intricate in comparison by air blasting loads. One of most important aspects of intermediate medium modeling is high deformation of fluids in comparison by structural elements. For avoiding distortion of fluid elements, Eulerian Approach must be utilized while Lagrangian method is suitable for capturing shell structures.

In this article, both of water and cylindrical structure are discretized by Eulerian cells and Lagrangian shell elements, respectively. For better tracking of FSI, Eulerian cells are refined in vicinity of structure. There are 324000 fine cells in water model while 3600 shell elements are employed for constructing cylindrical structure. Shell and surrounding Eulerian network are fully coupled.

Explosion is a highly nonlinear energy conversion event and for analyzing this problem, particular equation of states (EOS) are required. Accurate prediction of initiation of detonation in explosive material needs to fine grids may not be possible in 3-

D problems. Fortunately AUTODYN capability in modeling 1-D wedge problems may be implemented to reach highly accurate results. Incipient moments of explosion that deals with detonation wave propagation in explosive, may be simulated in 1-D wedge axial symmetry and results of this analysis can be remapped into high fidelity 3-D model. By means of this method there is no need to refine numerically high cost 3-D problem to visit fine grid requirements of detonation process. Figure 2 depicts numerically discretized model.

In cases, when loading is very rapidly applied on structures, behavior of structural materials can considerably modified particularly for metal ones. Steels are sensitive to high strain rate effect and this fact must be accounted in their numerical modeling. Johnson-Cook as a successful rate sensitive plasticity model for rates up to 10000/s, is implemented here for 4340 steel. Linear equation of state (EOS) is assigned to shell structural elements. Explosive charge that is assumed fabricated from TNT has very negligible mechanical strength and only a robust EOS is required. Often Jones-Wilkins-Lee (JWL) EOS has been utilized in literature for this purpose. In the case of water, polynomial equation of state can be a suitable one for handling fluid behavior in explosive loading. Required materials properties and related equations for sake of concise are tabulated in Table 1-4.

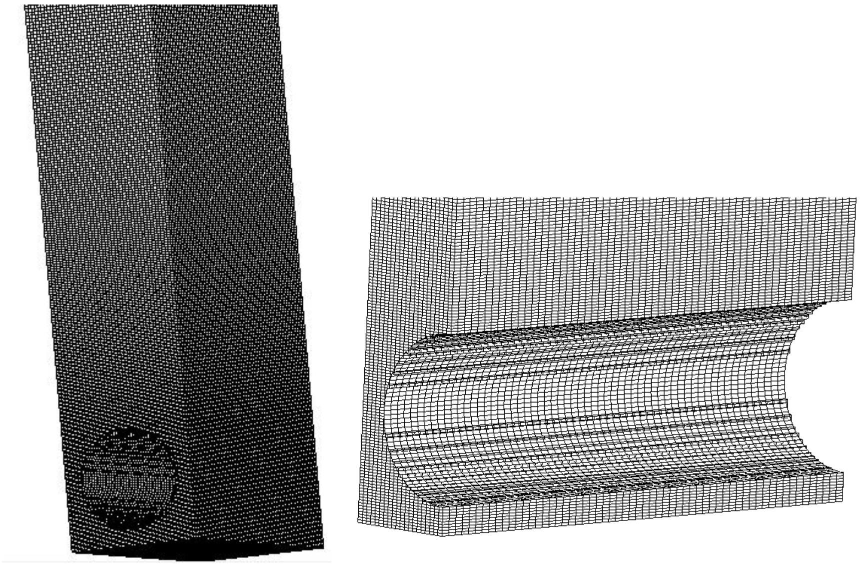

**Figure 2: Numerically discretized model. (Left: Whole model mesh, right: magnified shell vicinity zone, note: Eulerian grids in internal portion of cylinder are omitted for sake of clarity)**

**Table 1. 4340 steel employed properties.**

| Mathematical relation and parameters definitions | Quantities of parameters |
|---|---|
| $\sigma_y = (A + B\varepsilon_p^n)(1 + C\log\varepsilon_p^*)(1 - T_H^m)$<br>$\sigma_y : Dynamic\ \ yield\ \ stress,$<br>,<br>$\varepsilon_p : Effective\ \ plastic\ \ strain\,,$<br>$\varepsilon_p^* : Normalized\ \ plastic\ \ strain\ \ rate,$<br>$T_H^m : \dfrac{T - T_{room}}{T_{melt} - T_{room}}, normalized\, Temprature$ | A=792 MPa |
| | B=510 Mpa |
| | C=0.014 |
| | n=0.26 |
| | m=1.03 |
| | $T_m$=1793 $^0$K |

**Table2 . Linear Equation of State, 4340 steel.**

| Mathematical relation and parameters definitions | Quantities of parameters |
|---|---|
| p=Kμ<br>p=Pressure<br>μ= $\dfrac{\rho}{\rho_0} - 1,\ \rho : density$ | K=159 GPa |
| | $\rho_0 = 7830\ kg/m^3$ |

**Table 3. Polynomial EOS for Water.**

| Mathematical relation and parameters definitions | Quantities of parameters |
|---|---|
| $p = A_1\mu + A_2\mu^2 + A_3\mu^3 + (B_0 + B_1\mu)\rho_0 e$<br>e: specific energy<br>μ: As defined in Table 2 | $A_1$=2.2 GPa |
| | $A_2$=9.54 GPa |
| | $A_3$=14.57 GPa |
| | $B_0$=0.28 |
| | $B_1$=0.28 |
| | $\rho_0 = 1000\ kg/m^3$ |

**Table 4. JWL EOS for TNT.**

| Mathematical relation and parameters definitions | Quantities of parameters |
|---|---|
| $p = C_1(1-\frac{\omega}{r_1 v})e^{-r_1 v} + C_2(1-\frac{\omega}{r_2 v})e^{-r_2 v} + \frac{\omega e}{v}$<br>v= specific volume | $C_1$=373.7 GPa |
| | $C_2$=3.74 GPa |
| | $r_1$=4.15 |
| | $r_2$=0.9 |
| | $\omega = 0.35$ |
| | $\rho_0 = 1630\ kg/m^3$ |

## 4. Results and discussions

After numerical calculations results presented in this part. Due to interaction of water flow with explosion bubble, spherical geometry of bubble deviated from symmetrical configuration and sphere of explosion gases elongated in flow direction, nominally. Also from resistance of flowing water in counter direction of bubble, a little increase of pressure observable in this side. By further propagating of UNDEX bubble, effect of flow enhanced and distribution of pressure will be more asymmetrical. Figure 3 shows a caption from normal view on symmetry plan of pressure field contour after progressing bubble roughly half way to reach shell. It is worth noting that departing from symmetrical loading is outstanding in velocities more than 4 (m/s). This may be returned to this fact that velocity field induced from UNDEX in shock front is in this order. Naturally by passing this velocity, flow dynamic pressure will have more puissant effect.

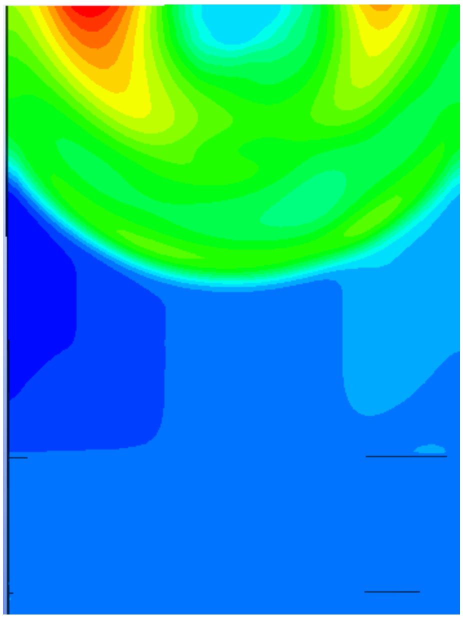

Figure 3: UNDEX bubble pressure field in 6(m/s) flow vel. *(Current direction from left to right*).

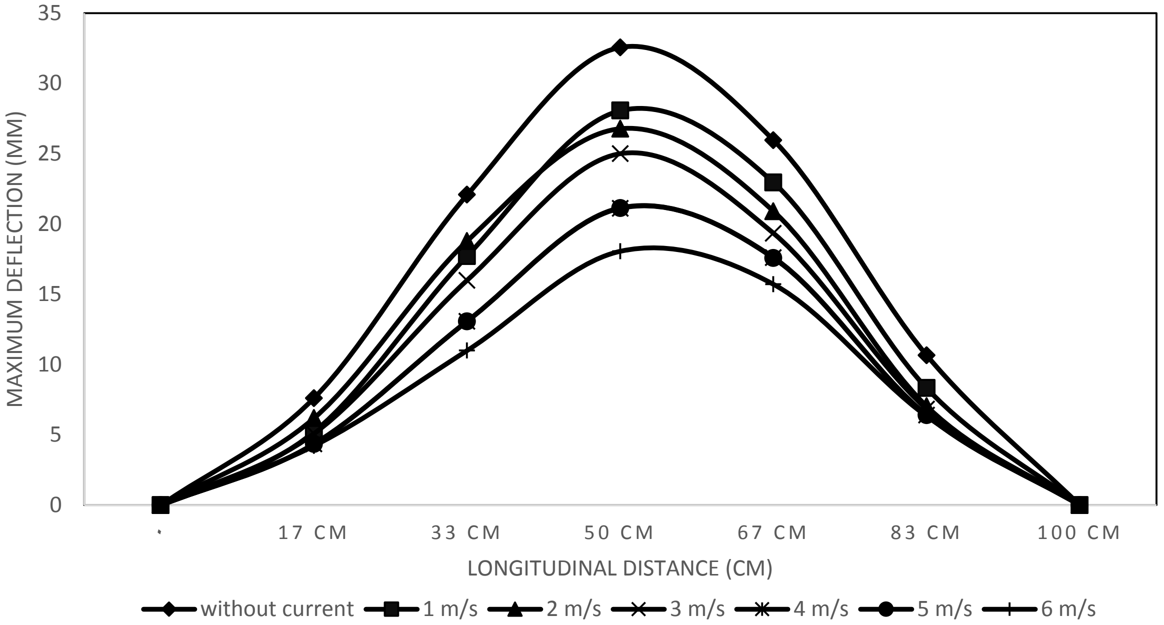

Figure 4. Deflection of symmetrical middle line of shell exposed to shock front for 1m stand-off and various flow velocities.

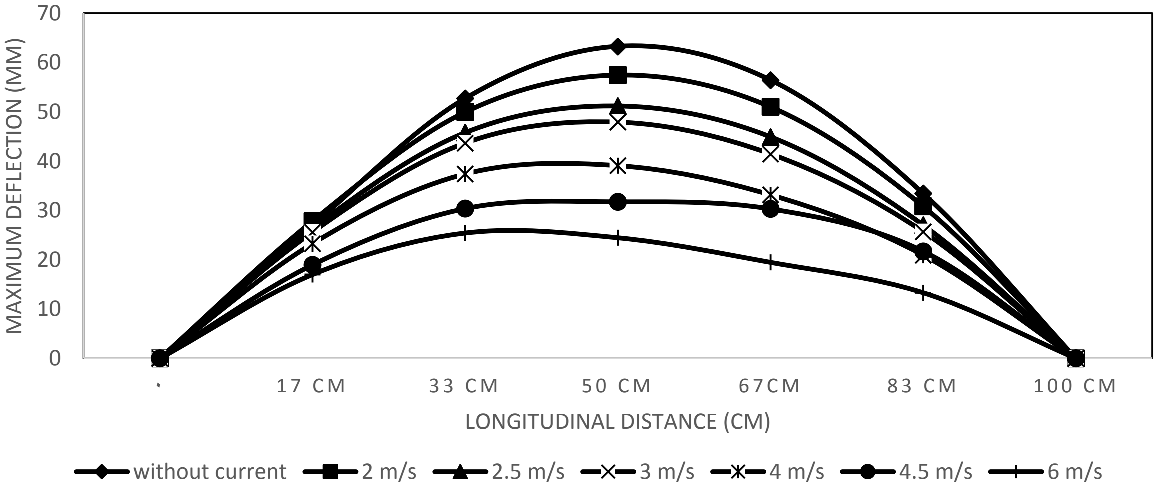

Figure 5. Deflection of symmetrical middle line of shell exposed to shock front for 1.5 m stand-off and various flow velocities.

Figures 4 and 5 depict variation of shell deflection for 1 m and 1.5 m stand-offs respectively, along the line located on the symmetry plane which is in side fronting shock wave of explosive charge. In flow-less case deflection function has a symmetrical configuration. By enhancing flow velocity, deflection apex deviates from center of graph and migrate to flow direction. This apex migration is more tangible for 1 m stand-off distance. This is due to nature of local distribution of pressure in near distant explosions. Deflection function also is sharper in this stand-off. As can be expected, energy of UNDEX absorbed by water current and fewer amount of energy imparted into the structure. So amplitudes of deflections are reduced significantly by escalation of flow velocity. Maximum of deflections for 6 m/s velocity is near to half of flow-less case.

In higher stand-off distant (1.5 m) deflection curve is flattened slightly. In farther distances of explosive charge standing, distribution of pressure are more uniform on entire of line of symmetry. As figure 5 shows, in this case up to 3 (m/s) current velocity, symmetry configuration of curve retained but by passing this velocity, a slight warping of curve is observable. In 4.5 (m/s) velocity a more robust symmetric curve is constructed again. This may be result of coincidence of UNDEX induced velocity and flow current velocity. At 6 (m/s) flow velocity more tangible deviation from symmetric curve is observed. But in this case maximum point of curve translates to counter direction of flow. Due to considerable complicacy of UNDEX bubble interaction with flow in various velocities, it is not easy task to justify this phenomenon, but stagnation of pressure in one side of bubble that confronts with flow velocity may produce more overpressure in this side and more deformation morphed in this spot. For 1.5 m stand-off, reduction of deflections in 6 (m/s) is near to one third of flow-less case.

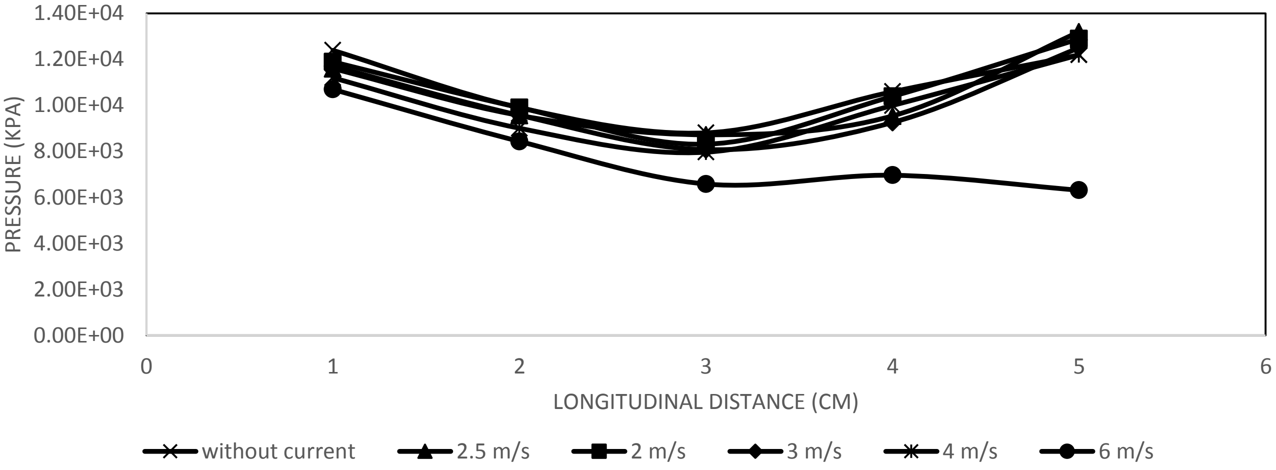

Figure 6. Pressure variation along symmetrical middle line of shell exposed to shock front for 1 m stand-off and various flow velocities.

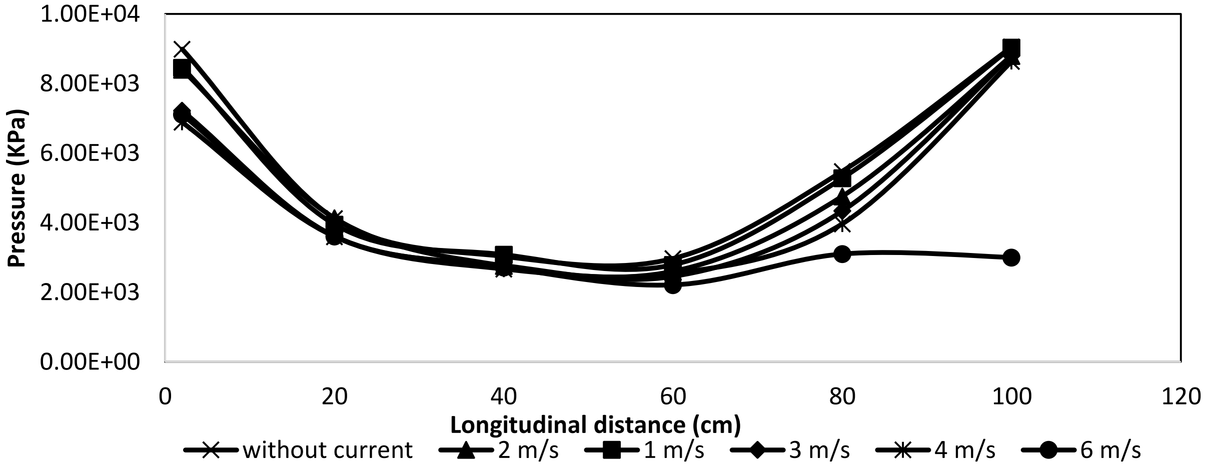

Figure 7. Deflection of symmetrical middle line of shell exposed to shock front for 1.5 m stand-off and various flow velocities.

Pressure variation along the symmetrical middle line at instant that maximum pressure is occurred, are illustrated in figures 6 and 7. As can be seen, peak pressure variation is not very sensitive to flow velocity. Only at 6 (m/s) a tangible deviation can be observed in exit port of current from model. Previous studies [5, 6, 7] have confirmed that peak pressure has not only main role in deformation of structures subjected to explosive loading. In other hand, time of applying pressure or its integration over time which is defined as impulse may be indexed as a noticeable parameter that causes to significant deformation of structures. Impulse in mathematical form can be shown as follows:

$$\mathrm{Im} = \int_{0}^{\infty} p(t)dt \qquad (1)$$

Above improper integral in explosive loadings converges to a specified quantity, because of exponential decadence nature of pressure history. For better perceiving pressure history of an underwater explosion, figure 8 proposes a sample graph. Because of incompressibility and higher viscosity of water, this history has intrinsic differences with its in air explosion (INEX) counterpart. Often after near distant and powerful UNDEX there are other pressure pulses interpreted as second, third and … pulses. Usually integration is done on a bonded time interval up to moment when pressure decays to zero. Figure 9 depicts variation of impulse for various flow velocities in two different stand-offs. As can be seen by increasing velocity, effective impulse will be subsided along the cylindrical shell. As integration over time makes fluctuations in time history weaker, there is no considerable change in spatial impulse profile along the shell and it seems this parameter for every current velocity is almost constant. It can be roughly construed that in farther stand-offs slop of impulse curve vs. velocity is steeper, result of more time of bubble exposition to current and imparting its energy into the surrounding medium.

A three dimensional caption of deformed cylinder subjected to UNDEX in 6 (m/s) flow velocity and 1 (m) stand-off is shown in figure 10.

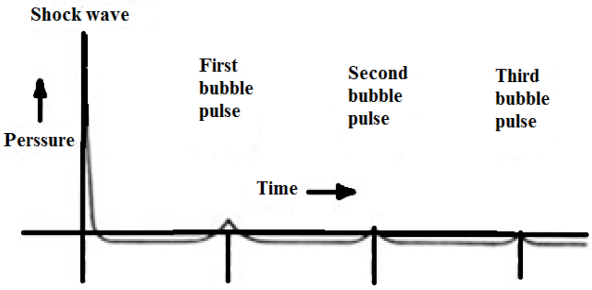

Figure 8. A sample UNDEX pressure history notice to second and third pulses resulted from oscillatory nature of bubble dynamics.

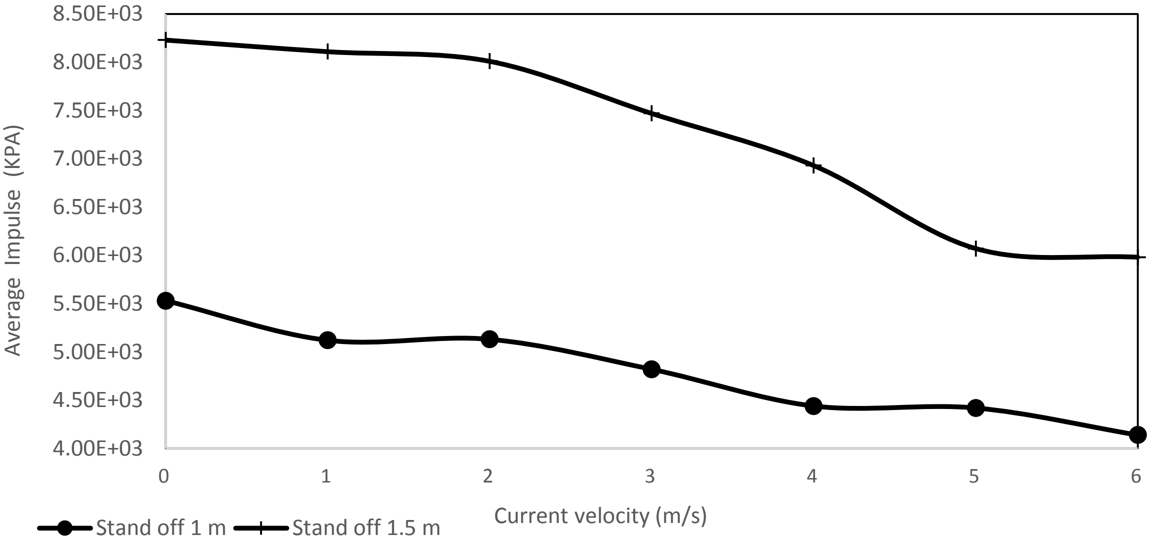

Figure 9. Variation of impulse as a function of surrounding water velocity, for two stand-offs. (*Note that for farther distant higher charge is used for more tangible deformation*)

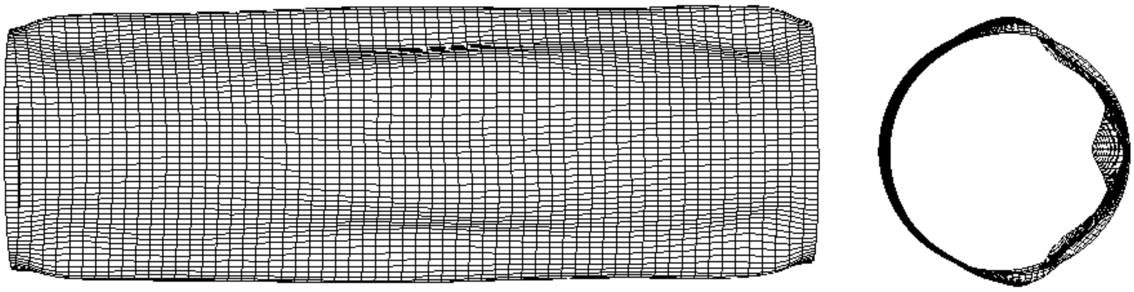

Figure 10. Three-dimensional embodiment of deformed shell in 6 (m/s) flow and 1 m stand-off.

## 5. Conclusion

A study for evaluation of water flow effect on UNDEX and FSI problem is fulfilled using high fidelity numerical procedure. As results show UNDEX phenomenon can be significantly affected by external flow. Furthermore, problem of FSI can be modified due to complicate interaction of UNDEX bubble, flow and structure. Investigation of numerical calculations illuminated that structural deformation morphology can tangibly be changed by introduction of external flow to surrounding medium. It is logical to be assumed that for UNDEXs with lower charges and farther stand-offs this effect can enhance. Finally, it is noteworthy that because of experimental challenges in conducting real scale tests for surveying water flow effect on UNDEX, numerical methods can be implemented successfully for better perceiving this elaborate problem.

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