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SIMULATION OF UNDERWATER BLAST LOADING ON NAVAL SHIP STRUCTURES USING AUTODYN

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ABSTRACT

Naval vessels are highly susceptible to underwater explosions (UNDEX) generated by torpedoes, mines, and depth charges. Non-contact underwater explosions produce shock wave loading, gas bubble oscillation effects, hull whipping, and structural damage. Due to the high cost and risk of full-scale experiments, numerical simulation is essential for evaluating structural response. This study presents a nonlinear explicit finite element simulation of underwater blast loading on a frigate-class naval vessel using ANSYS AUTODYN. Both the initial shock wave and secondary bubble pulsation phases are modeled, incorporating fluid–structure interaction (FSI). Material behavior is represented using the JWL equation of state for TNT and the Johnson–Cook model for ship steel. Results demonstrate that secondary bubble pulsation significantly contributes to hull whipping and structural stress development. The developed methodology provides a robust framework for naval shock-resistance design.

Keywords — Underwater explosion, UNDEX, bubble pulsation, explicit dynamics, fluid–structure interaction, Johnson–Cook model, naval structures.

1. INTRODUCTION

Naval ships operating in hostile environments are exposed to underwater explosive threats. When an underwater detonation occurs near a vessel, two primary loading mechanisms arise:

Initial high-intensity shock wave

1. Secondary gas bubble oscillation

While the shock wave induces local structural damage, bubble pulsations can excite global hull vibrations known as whipping. The resonance between bubble frequency and hull bending modes may cause severe structural failure.

Because experimental underwater blast testing is expensive and logistically complex, computational simulation has become the preferred method for predicting ship response. Explicit finite element methods are particularly suitable for highly transient blast phenomena involving large deformation and fluid–structure interaction.

This study develops an explicit dynamic simulation framework to analyze underwater blast loading on a naval frigate structure.

Underwater explosion to a surface ship

UNDERWATER EXPLOSION PHYSICS

A. Shock Wave Phase

Immediately after detonation, a high-pressure gas sphere forms and generates a compressive shock wave that propagates through water. The shock front is extremely thin and characterized by:

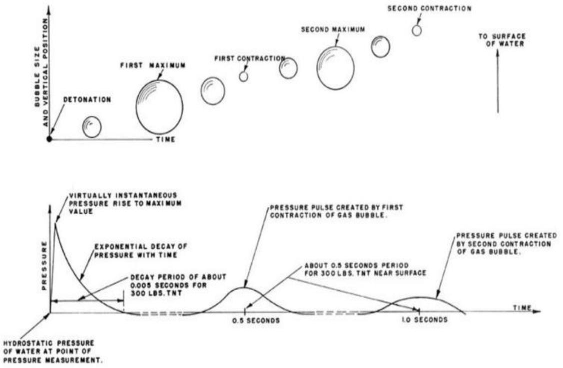
- Rapid pressure rise
- Exponential decay
- High impulse transfer

Numerical modeling employs artificial viscosity techniques to represent the discontinuous pressure jump while satisfying Rankine–Hugoniot conditions.

B. Bubble Oscillation Phase

Following shock wave emission, the detonation gas bubble expands due to internal pressure and collapses under hydrostatic forces. Each collapse generates a pressure pulse. The first and second bubble pulses are typically dominant.

The bubble oscillation period and maximum radius depend on explosive charge mass and depth. Secondary pulses may induce hull resonance and contribute significantly to whipping response.



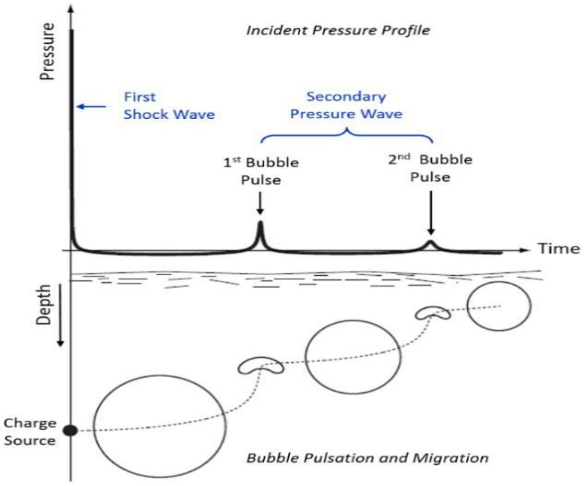
The relationship between oscillation of migration bubble and related pressure propagation caused by underwater explosion. (Resource from: Submarine report No.58 (BRAND, 1945)

2. LITERATURE REVIEW

It is important to figure out accurately the pressure which loads the ship hull during the bubble migration process before starting any finite element analysis. In this chapter, the underwater explosion and resulting bubble pulsation and migration phenomena will be presented first; then the approach commonly used to calculate the pressure due to the shock wave phase will be detailed. In the third part of this section, the bubble oscillation phase will be investigated, and the different existing methods to calculate the resulting pressure field will be reviewed.

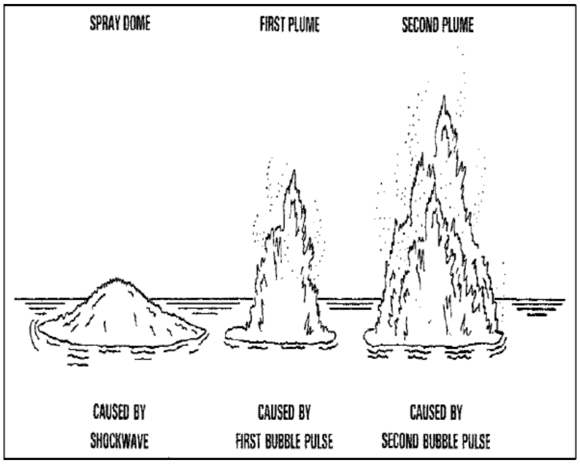
1. Bubble phenomenon

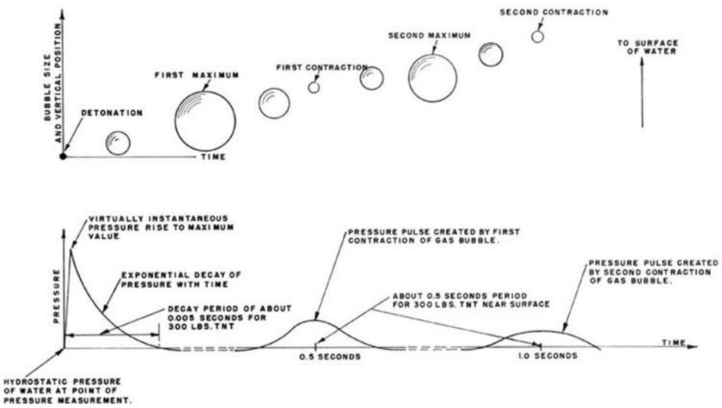
During the bubble migration process, in order to have balance with hydrostatic pressure, it is obvious that the bubble volume increases while the internal pressure is decreased, this alternative motion can be assumed as a mass-spring system as well. The bubble oscillation and migration process is illustrated in as proposed by (Snay, 1956). This figure clearly shows that the pressure level evolution is closely related to the bubble oscillation phenomenon. First of all, when the charge explodes, a high and compressed gas pressure arise in the small bubble. At the same time, the so-called first shock wave, which related pressure can be represented by a nonlinear exponential decay, happens in an extremely short time period.



The evaluation of incident pressure and bubble migration process (Snay, 1956)

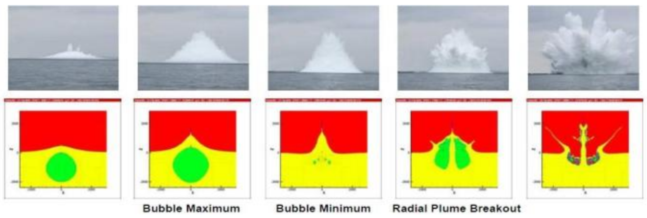
With the progression of studies, the shock response of non-contact UNDEX became an important issue not only for the naval ship but also for the merchant vessel and the different phenomena associated to an UNDEX was discussed: impact of the shock wave, cavitation near the ship hull, hull beam whipping, etc. Thomas (Vernon, 1986) used spherical explosion bubble theory to predict the whipping response of a surface ship submitted to bubble pulsations; he pointed out that the bubble pulse frequency and ship hull bending natural frequency can coincide, leading to a severe loading scenario. On the other hand, practical measurement methodologies and simulation methods have been developed over the past 20 years describes with more detail the relationship between bubble oscillations and the incident pressure evolution (BRAND, 1945); this figure shows clearly that a pressure peak occurs each time the bubble radius reaches its minimum.





The relationship between oscillation of migration bubble and related pressure propagation caused by underwater explosion. (Resource from: Submarine report No.58 (BRAND, 1945)

Surface Phenomena for underwater explosion (Source from: (Costanzo, 2010))



UNDEX Plume Above-Surface Effects (Costanzo, 2010)

The sea free surface has an influence on the propagation of the shock wave which reflects on it. Hollyer (Hollyer, 1959) highlighted the fact that the free surface acts as a reflecting boundary regarding the spatial propagation of the shock wave.

2. NUMERICAL MODELING APPROACH

A. Explicit Time Integration

Explicit solvers are preferred for blast simulations due to:

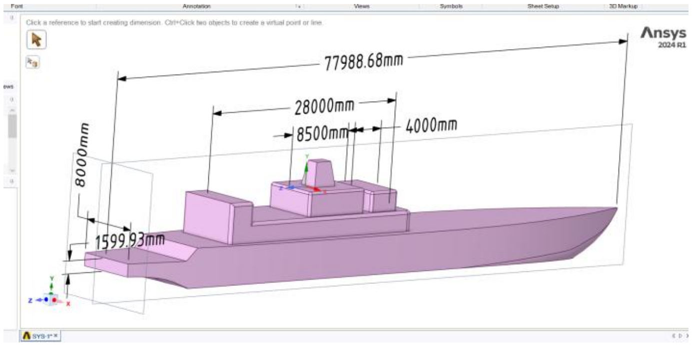
- Large nonlinear deformation
- High strain rate effects
- Complex contact interactions
- Fluid–structure coupling

The explicit central difference integration method ensures stable time stepping for highly transient phenomena.

Space claim:

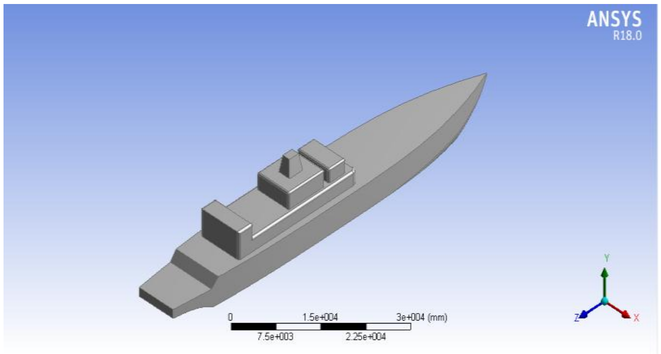
SpaceClaim is a solid modeling CAD (computer-aided design) software that runs on Microsoft Windows and developed by SpaceClaim Corporation. The company is headquartered in Concord, Massachusetts.

SpaceClaim Corporation markets SpaceClaim Engineer directly to end-user and indirectly by other channels. SpaceClaim also licenses its software for OEMs, such as ANSYS Flow International Corporation CatalCAD, and Ignite Technology which markets a version of SpaceClaim for jewelry design



Click a reference to start creating dimension. Ctrl+Click two objects to create a virtual point or line.

Geometry of ship details



Geometry

3. Finite element method:

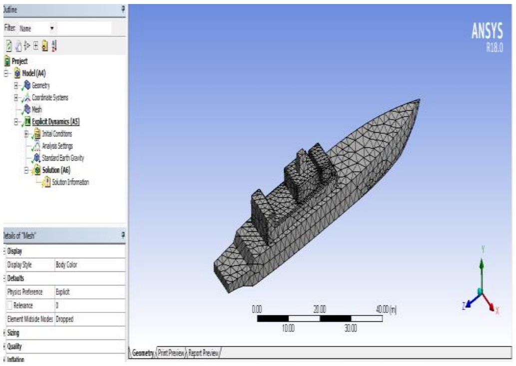
The finite element method (FEM) is a numerical technique for solving problems which are described by partial differential equations or can be formulated as functional minimization.

Values inside finite elements can be recovered using nodal values. Two features of the FEM are worth to be mentioned:

1) Piece-wise approximation of physical fields on finite elements provides good precision even with simple

approximating functions (increasing the number of elements we can achieve any precision).

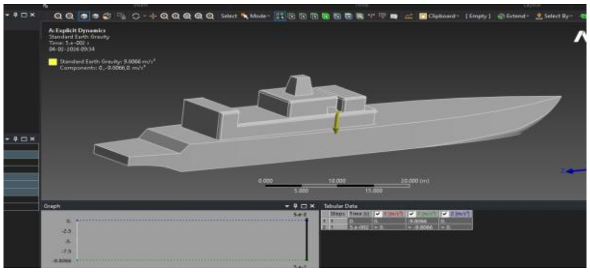
2) Locality of approximation leads to sparse equation systems for a discretized problem. This helps to solve problems with very large number of nodal unknowns



Mesh

4. EXPLICIT DYNAMICS:

With the implementation of an explicit solver in ANSYS Workbench there is another advanced analysis type available in this versatile user interface. The phrase "Explicit" refers to a type of time integration used to perform dynamic simulations. Explicit methods are more accurate and efficient for simulations involving shock wave propagation, large deformations and strains, non-linear material behavior, complex contact, fragmentation and non-linear buckling.

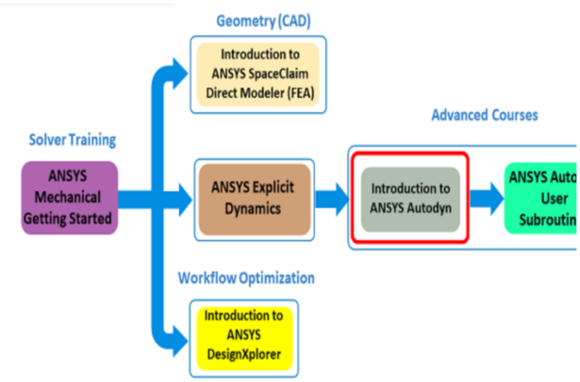


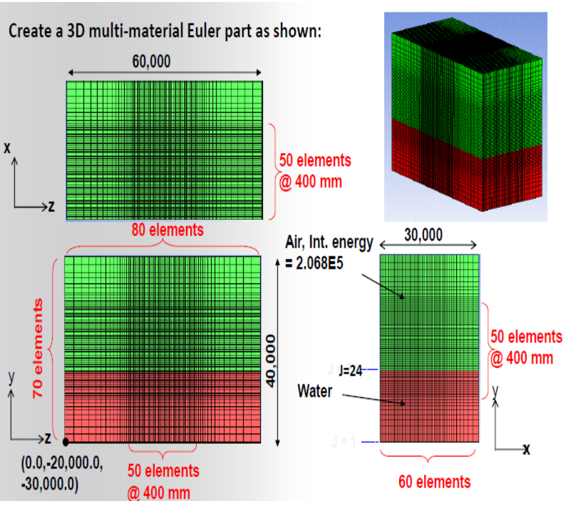
Standard Earth gravity

Ansys AUTODYN:

In today's operations, explosive blasts are just as much about precision control as brute force. For efficiency, miners must use enough explosives to fragment and move as much material as possible—but the amount of explosive energy is constrained by budgets and limits on blast vibrations. If timed correctly, shock waves reinforce and amplify one another to produce maximum fragmentation and movement of rock, ore, coal and other materials

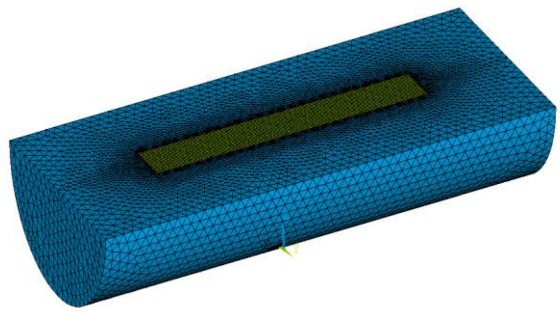
Select from a vast library of material models and understand the material requirements needed based upon the state (solid/liquid/gas) and characteristics of a material (reactivity, porosity, ductility, pressure dependency, etc.) Use Autodyn within the Workbench Environment to take advantage of efficient model setup afforded by Ansys Mechanical.





Model Preparation

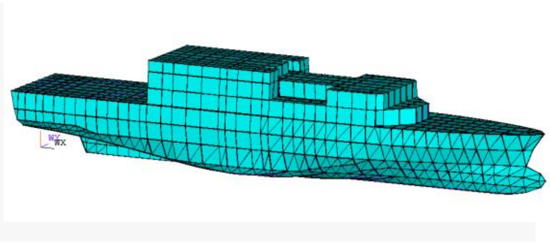
model created using ANSYS pre-processor with the same dimension as mentioned the distance from explosive to the structure remains 50 m, and the charge is kept at the midship under the bottom. Moreover, with the consideration of the interaction between the structure and the sea water, it is necessary to create a fluid mesh in ANSYS plots the interface mesh between the structure and the fluid. Lastly presents the fluid-field mesh surrounded the semi-cylinder, knowing that 50 m is considered as the radius of fluid-field mesh in this case.



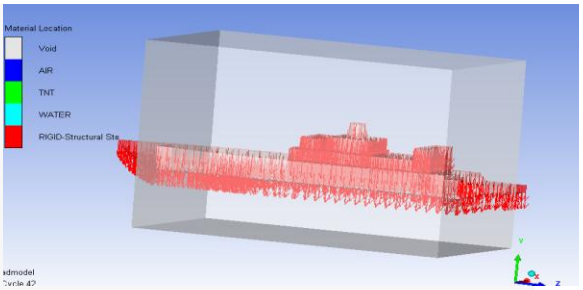
Ship Information

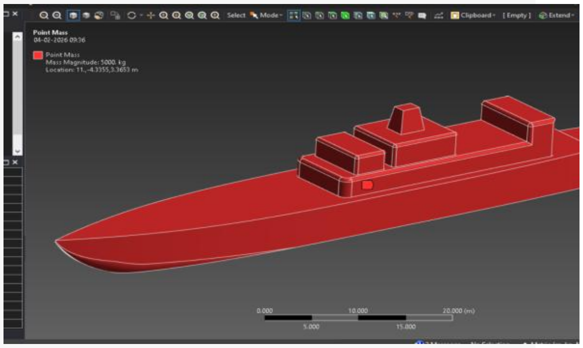
Frigate ship which is provided by STX Europe is considered as the reference ship for the following study. As listed in Table 5-1, the overall length of the frigate ship is 95 m, its breadth is 40 m, and its draft is 4.75 m.

Length overall	95.0 m
Breadth	40.0 m
Draught	4.75 m



With the consideration of fluid-structure interaction (FSI), it is necessary to create in ANSYS a fluid-field mesh and an interface mesh between fluid and structure meshes. Represents the design of fluid-field and structure meshes. In this plot, the pink stands for the interface mesh between fluid and structure mesh, whereas the blue mesh represents the sea water with the radius of 40 m surrounding to the ship.





Point Mass
04-02-2026 09:36
Point Mass
Mass Magnitude: 5000. kg
Location: 11.,-4.3355,3.3653 m

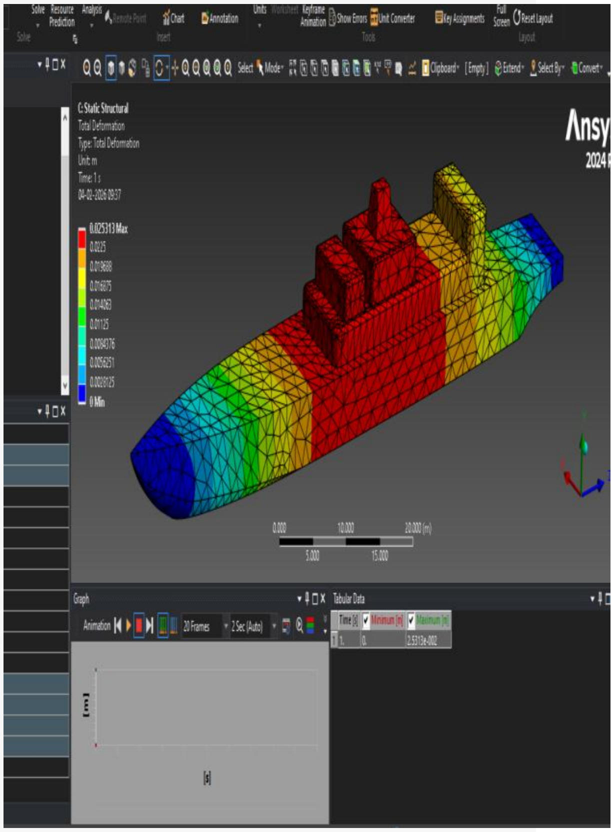
Point mass of ship

5. Analysis Process

With the limitation of ANSYS, it is necessary to apply reaction forces into nodes instead of pressure loads to shell element if we want to implement transient response analysis.

Therefore, the results retrieved from the static analysis are presented. Since the charge is located below the midship section, reaction forces are more significant amidships as it is confirmed. Moreover, the free surface constraint is represented by green triangles where the pressure load is zero.

According to the distribution of reaction force curves, it is clear that the trends are like pressure loads distribution with the time evolution.

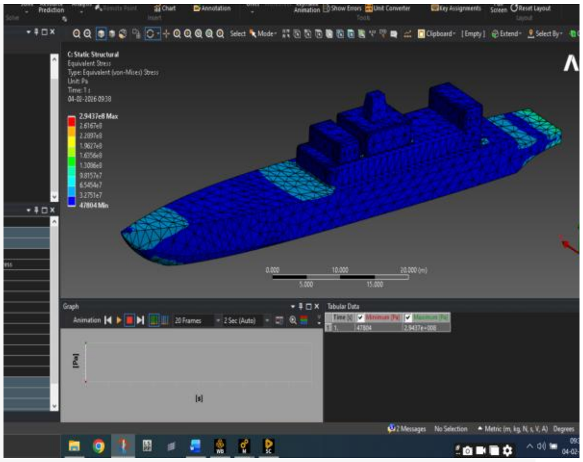


C: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1 s
04-02-2026 09:37

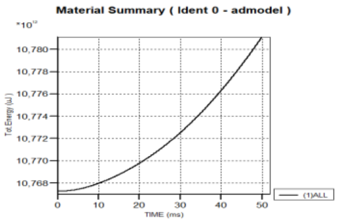
0.025313 Max
0.0225
0.019688
0.016875
0.014063
0.01125
0.0084376
0.0056251
0.0028125
0 Min

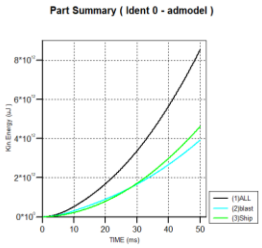
	Time [s]	Minimum [m]	Maximum [m]
1	1.	0.	2.5313e-002

Deformation of ship

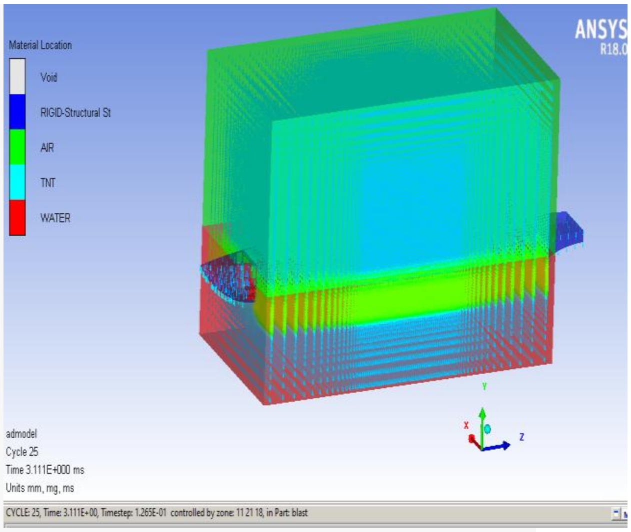


Equivalent stress

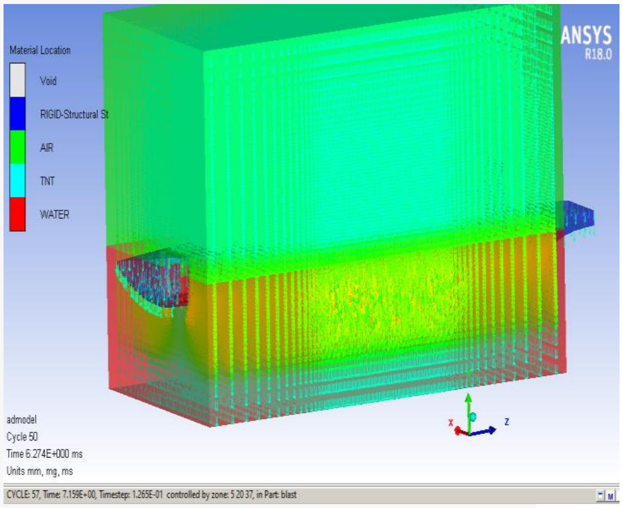




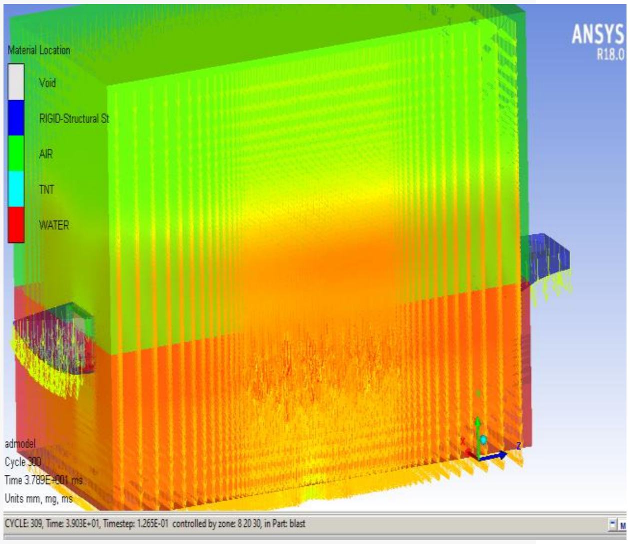
Although the results depicted seem to be more realistic regarding the displacement amplitudes than the one observed for the semi-cylinder, the same problem than the one encountered in the semi-cylinder study can be observed, that is the displacement is not zero at the initial time.



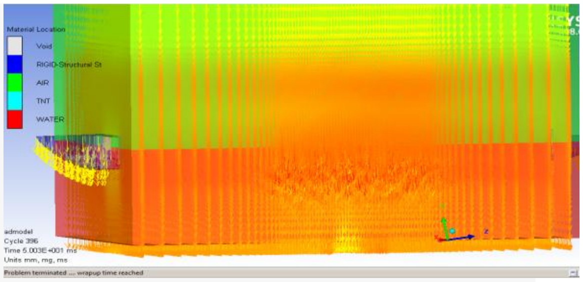
CYCLE: 25, Time: 3.111E+00, Timestep: 1.265E-01 controlled by zone: 11 21 18, in Part: blast

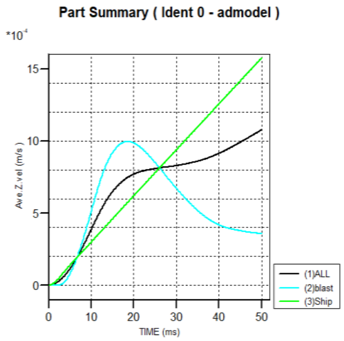


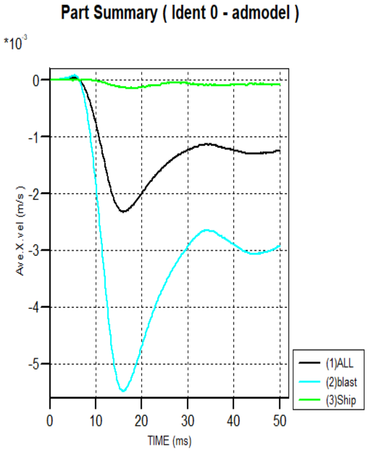
CYCLE: 57, Time: 7.159E+00, Timestep: 1.265E-01 controlled by zone: 5 20 37, in Part: blast

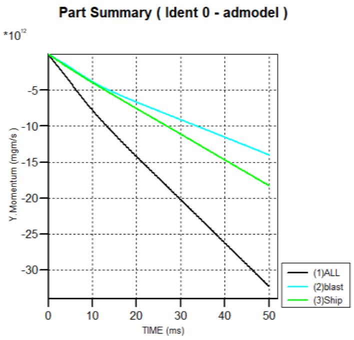


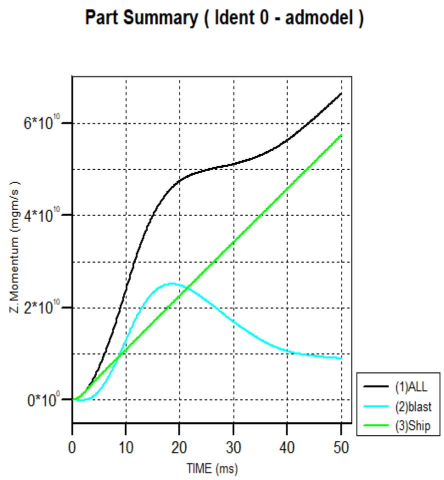
CYCLE: 309, Time: 3.903E+01, Timestep: 1.265E-01 controlled by zone: 8 20 30, in Part: blast

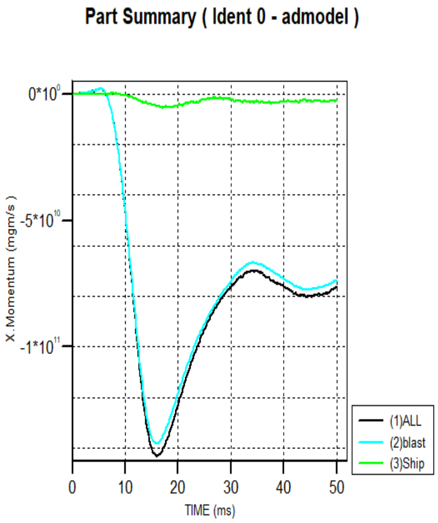

Material Location
Void
RIGID-Structural St
AIR
TNT
WATER
admodel
Cycle 396
Time 5.003E+001 ms
Units mm, mg, ms
Problem terminated .... wrapup time reached

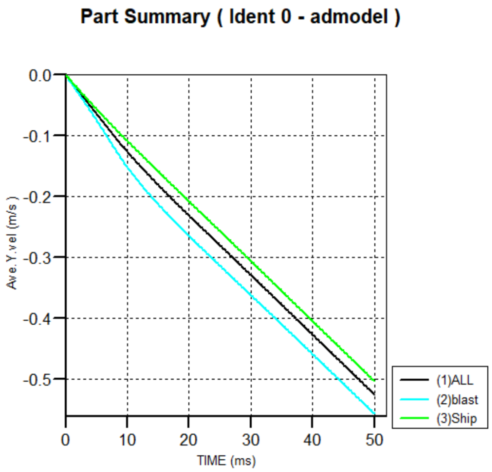

Part Summary (Ident 0 - admodel)
*10^-4
15
10
5
0
Ave.Z vel (m/s)
0
10
20
30
40
50
TIME (ms)
(1)ALL
(2)blast
(3)Ship


Part Summary (Ident 0 - admodel)
*10^-3
0
-1
-2
-3
-4
-5
Ave.X vel (m/s)
0
10
20
30
40
50
TIME (ms)
(1)ALL
(2)blast
(3)Ship


Part Summary (Ident 0 - admodel)
*10^12
-5
-10
-15
-20
-25
-30
Y Momentum (mgm/s)
0
10
20
30
40
50
TIME (ms)
(1)ALL
(2)blast
(3)Ship


Part Summary (Ident 0 - admodel)
6*10^10
4*10^10
2*10^10
0*10^0
Z Momentum (mgm/s)
0
10
20
30
40
50
TIME (ms)
(1)ALL
(2)blast
(3)Ship


Part Summary (Ident 0 - admodel)
0*10^0
-5*10^10
-1*10^11
X Momentum (mgm/s)
0
10
20
30
40
50
TIME (ms)
(1)ALL
(2)blast
(3)Ship


Part Summary (Ident 0 - admodel)
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
Ave.Y vel (m/s)
0
10
20
30
40
50
TIME (ms)
(1)ALL
(2)blast
(3)Ship

Reference Frames

A hybrid Eulerian–Lagrangian formulation is used:

Lagrangian domain: Ship structure

Eulerian domain: Water and explosive

This approach allows modeling of expanding detonation gases without mesh distortion while maintaining structural accuracy.

7. MATERIAL MODELS

A. Water

Water is modeled using a compressible equation of state (EOS) relating pressure to density and internal energy.

B. High Explosive (TNT)

TNT detonation products are modeled using the Jones–Wilkins–Lee (JWL) equation of state:

$$\boldsymbol{P = Ae^{-R_1 V} + Be^{-R_2 V} + \omega \frac{E}{V}}$$

where:

$\boldsymbol{A, B, R_1, R_2, \omega}$are empirical constants

$\boldsymbol{V}$is relative volume

$\boldsymbol{E}$is internal energy

C. Ship Steel – Johnson–Cook Model

The ship hull steel is modeled using the Johnson–Cook constitutive law:

$$\boldsymbol{\sigma = (A + B\varepsilon^{n})(1 + C\ln \dot{\varepsilon})(1 - T^{m})}$$

This model accounts for:

Strain hardening

Strain rate sensitivity

Thermal softening

Damage evolution is incorporated using accumulated plastic strain criteria.

8. SHIP MODEL AND FSI SETUP

A. Ship Geometry

A frigate-class vessel is modeled with the following principal dimensions:

Parameter	Value
Length Overall	95 m
Breadth	40 m
Draft	4.75 m

The explosive charge is positioned 50 m below midship.

B. Fluid–Structure Interaction

A surrounding water domain with a radius of 50 m is generated. An interface mesh couples the Eulerian water field to the Lagrangian structural domain, enabling two-way pressure transfer.

9. ANALYSIS PROCEDURE

The computational workflow consists of:

Defining TNT charge and detonation parameters

Assigning JWL EOS to explosive

Creating Eulerian water domain

Assigning Johnson–Cook steel model

Establishing fluid–structure interaction

Performing transient explicit simulation

10. RESULTS AND DISCUSSION

A. Pressure Distribution

Impulse from the secondary bubble phase contributes substantially to structural loading.

B. Structural Deformation

Maximum displacement occurs at the midship bottom region where the charge is located. Hull bending behavior indicates whipping response initiated by bubble pulsation.

C. Equivalent Stress

Von Mises stress concentrations are observed near:

- Bottom plating
- Structural stiffeners
- Midship structural connections

Secondary bubble oscillation produces comparable or greater energy input than the initial shock in terms of structural vibration.

11. CONCLUSION

A comprehensive explicit finite element framework for underwater blast simulation has been presented.

After analyzing the most important existing methodologies, it is the most suitable approach in order to predict the whipping response on ship structures submitted to the underwater explosion. In this study, a complete scheme is developed in order to perform the structure response by means of explicit and implicit numerical methods. The main conclusions drawn from the present research are summarized below:

Simulation results show:

High peak pressure during initial shock

Significant secondary pressure peaks during bubble collapse

According to pressure load distribution diagram gathered from ansys AUTODYN simulation, it is clear that the impulse *I* of first and second bubble which means that the energy is much higher during the bubble oscillation phase. Furthermore, the total energy diagram obtained from AUTODYN points out that the energy increases dramatically within secondary bubble pulsation phase; hence, it has been demonstrated that secondary bubble pulsation phase has the significant influence on ship structure.

Major findings include:

1. Secondary bubble pulsation significantly influences hull whipping.
2. Explicit dynamic solvers are essential for accurate transient blast modeling.
3. Coupled Eulerian–Lagrangian formulation effectively captures fluid–structure interaction.
4. Johnson–Cook modeling accurately represents high strain-rate steel behavior.

The methodology can be used for naval shock-resistance design and survivability assessment.

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