USE OF MSC/NASTRAN IN PREDICTING STRUCTURAL RESPONSE TO AN UNDERWATER EXPLOSION

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ABSTRACT

The prediction of the response of submerged structures to underwater explosions requires solving a fluid-structure interaction problem. This paper is based on experiences with MSC/NASTRAN's interface with the USA (Underwater Shock Analysis) code. The phenomena associated with an underwater explosion and how MSC/NASTRAN/USA is used to solve the problem will be discussed. As a validation, analytical results will be compared to a test. The statements and opinions herein are those of the author and do not necessarily represent Newport News Shipbuilding.

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INTRODUCTION

Purpose

The purpose of this paper is to demonstrate the use of MSC/NASTRAN and USA (Underwater Shock Analysis) in predicting the response of a submerged structure to an underwater explosion. An analysis of an actual test is used to show validation.

Background

U.S. Navy warships are designed to survive near miss explosions. Significant loadings on submerged structures are transferred from underwater explosions through the water. It was discovered in World War I and II that this shock loading from a "missed" shot could still disable a warship by damaging vital equipment.

Research and development in underwater explosions have defined the chain of events that occurs in the fluid due to an underwater explosion. The explosion produces an initial compression wave that travels through the fluid. This shock wave has the same properties as an acoustic wave and travels through the fluid at the speed of sound. The explosion also produces an expanding gas bubble that sets up a flow field in the fluid and causes additional shock waves as the bubble collapses and re-expands.

The USA code provides fluid boundary elements on the structure that transfer the varying fluid pressures into structural loads and structural displacements into fluid pressures. An accurate fluid-structure interaction is critical to the analysis. In 1989 MSC/NASTRAN was interfaced with USA, and provided Newport News Shipbuilding with the capability to predict the response of structures to underwater explosions.

MSC/NASTRAN provides a wide range of structural modeling elements and techniques and USA provides fluid boundary elements that handle the interaction of the structure with the surrounding fluid.

THE UNDERWATER EXPLOSION

Sequence of Events

When an underwater explosion occurs, a great amount of gas and energy is produced. A sudden increase in pressure causes the water surrounding the explosion to propagate a compression wave known as a shock wave. This shock wave travels radially away with a velocity approximately equal to sound velocity in water.

As the shock wave propagates rapidly, the gases form a bubble that expands spherically from the explosion source. Depending upon the explosive weight and depth the bubble will expand to a maximum. Due to the momentum of the expansion, the bubble has exceeded the equilibrium point and the hydrostatic pressure of the fluid begins to collapse the bubble. The gas bubble contracts, gaining momentum, passes the equilibrium point again, then collapses on the trapped gases. This produces a second "explosion" effect known as the bubble pulse.

Each bubble pulse causes the chain of events to repeat. The expanding and contracting bubble will continue oscillating, and send out shock waves until the energy is damped out or the bubble migrates, due to buoyancy, to the surface of the water and the gases are vented.

The Shock Wave

As stated above, the high pressure developed during the explosion of the charge causes a compression of the surrounding water. The compression propagates and is known as the shock wave.

An exponential function is usually used as the mathematical approximation of the shape of the shock wave, $p(t) = P_o e^{(-t/\theta)}$. A great amount of experimental work has been done to find the relation between the two characteristic parameters P_o and θ.

Water flow velocity is associated with the propagation of the acoustic compression wave. The water particle velocity due to a plane wave is $v(t) = p(t)/\rho_o C_o$, which is the pressure history divided by the density of water and the speed of sound in water.

For a more typical spherical shock wave, the water particle velocity is,

$$v(t) = \frac{p(t)}{\rho_o c_o} + \frac{1}{\rho_o R}\int_0^t p(t)dt$$

The first term is the same as the plane wave; the second term is the result of spherical flow, and is the afterflow term.

The shock wave will reflect off nearby boundaries such as the water surface (a free surface) or the ocean bottom (an elastic surface). The reflection from the free surface produces a tension wave that propagates downward reducing the water pressure and cutting off the increased pressure around the structure due to the initial shock wave. Typically, the pressure near the surface is reduced to zero and an area of bulk cavitation is formed. Reflection off the bottom is a compression wave that adds additional load to the structure.

The Gas Bubble

The high pressure produced by the explosion pushes the water radially outward from the explosion. Gas expansion forms a bubble, and as the bubble expands the gas pressure decreases. Due to flow momentum, the expansion continues well beyond the pressure equilibrium between the gas and surrounding water. The bubble keeps expanding until the gas pressure is nearly zero.

The surrounding water under hydrostatic pressure begins to collapse the fully expanded bubble. The collapse accelerates, and again due to momentum the pressure equilibrium point is passed. The bubble continues to collapse on the trapped gas and compresses it to a minimum radius. The high pressures cause the gases to detonate once more, emitting a second shock wave and starting a second bubble. The second shock wave is called the bubble pulse since it creates a pulse in a pressure time history.

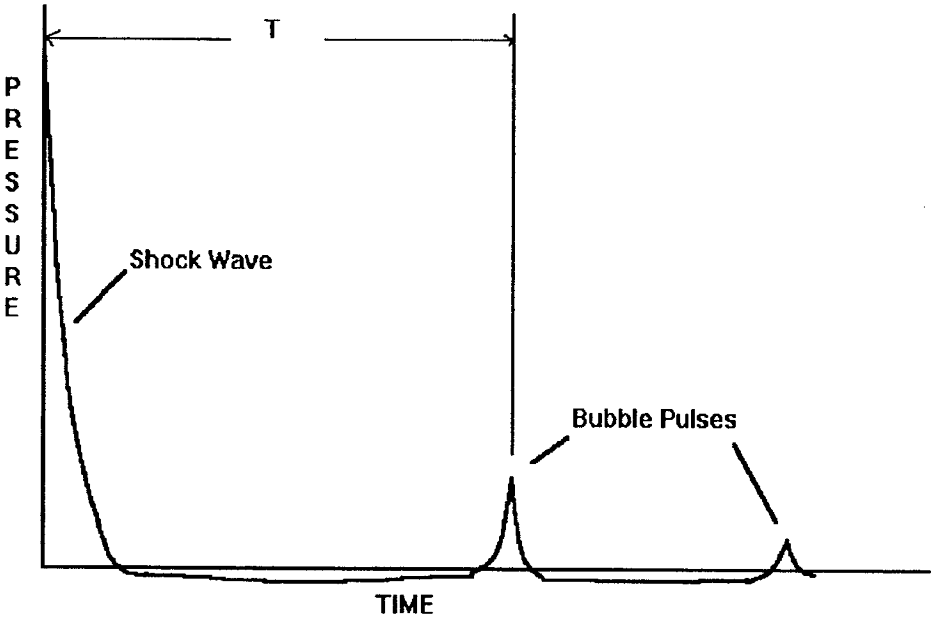
The expansion and contraction of the bubble affects the surrounding water pressure and particle velocity. The water flow due to the expanding bubble is equal to the afterflow term in the particle velocity equation for a spherical shock wave. Hence, the exponential decaying pressure time history for the shock wave includes the water flow due to the expanding bubble. The contraction of the bubble causes the water to flow back towards the charge source, creating an underpressure in a pressure time history. The bubble pulse causes another sharp increase in the pressure time history.

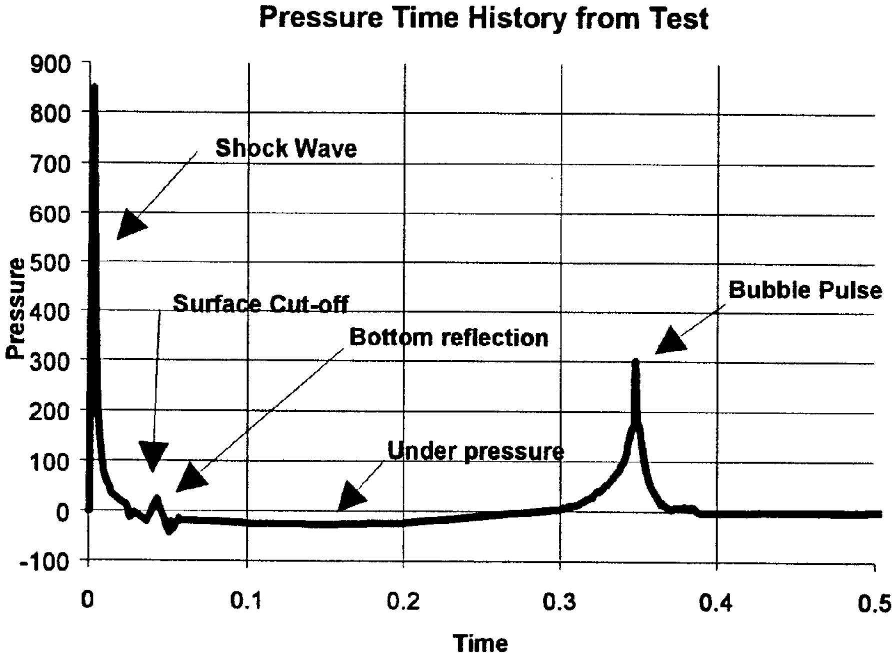
The frequency of the bubble pulses, tuned to structural frequencies, can excite vibration modes in a submerged structure causing large motions or forces to be produced. The period of the bubble pulses was determined experimentally to be,

$$T = 4.36\frac{W^{\frac{1}{3}}}{(H+33)^{\frac{5}{6}}}$$

where W is the charge weight and H is the charge depth.

The total pressure time history is shown below.





MSC/NASTRAN and USA

The Structure Model

MSC/NASTRAN is used to model the submerged structure. MSC's wide range of elements such as various rods, bars, beams, plates, and rigid elements makes it well suited for effective modeling of the structure. Since the boundary conditions are the fluid boundaries, the entire submerged structure must be modeled. MSC's diverse element types enable an efficient model to be built that concentrates on detail where necessary.

Due to the bubble pulse, it is desirable to determine the free vibration modes of the structure before the direct time integration of the fluid-structure problem is solved. MSC/NASTRAN has powerful dynamic solution capabilities.

To interface with USA the structural code must be flexible and open. MSC/NASTRAN's DMAP alter capabilities allows such an interface.

All analyses are approximations and experience has shown that the accuracy of the structural model is the most critical part of the approximation.

In summary, MSC's diversity, flexibility, and reliability makes it well suited for interfacing with USA and solving the fluid-structure interaction problem.

The Fluid Model

The USA code provides the fluid model using surface membrane elements connected to the wet structural nodes. USA treats the surrounding fluid as an infinite acoustic medium.

USA performs the fluid-structure interaction using the Doubly Asymptotic Approximation (DAA) method. DAA approaches the exact boundary-element solution for both high frequency and low frequency structural motions and makes a smooth transition between the two. The DAA approach is suitable for this class of problems with accuracy sufficient for engineering analysis.

Fluid-Structure Interaction

The equation of motion is,

$$M_s \ddot{x} + C_s \ddot{x} + K_s = f$$

$$f = -GA_f (p_i + p_s)$$

where

M_s = *structural mass*
C_s = *structural damping*
K_s = *structural stiffness*
x = *structural motion*
f = *force*
G = *fluid structure transformation matrix*
A_f = *Fluid area,* M_f = *fluid mass*
p_i = *incident shock pressure wave*
p_s = *scattered pressure wave (reflection of structure)*

The DAA equations of equilibrium are,

$$M_f \dot{p}_s + \rho c A_f p_s = \rho c M_f \dot{u}_s$$

$$G^T \dot{x} = u_i + u_s$$

u = *fluid particle velocity.*

The structural velocity times the fluid-structure interaction matrix is equal to the fluid particle velocity, due to the incident wave and scattered wave.

Substitution of the above into the equation of motion yields the equations that are integrated in the solution,

$$M_s \ddot{x} + C_s \dot{x} + K_s x = -GA_f (p_i + p_s)$$

$$M_f \dot{p}_s + \rho c A_f p_s = \rho c M_f (G^T \ddot{x} - \dot{u}_i)$$

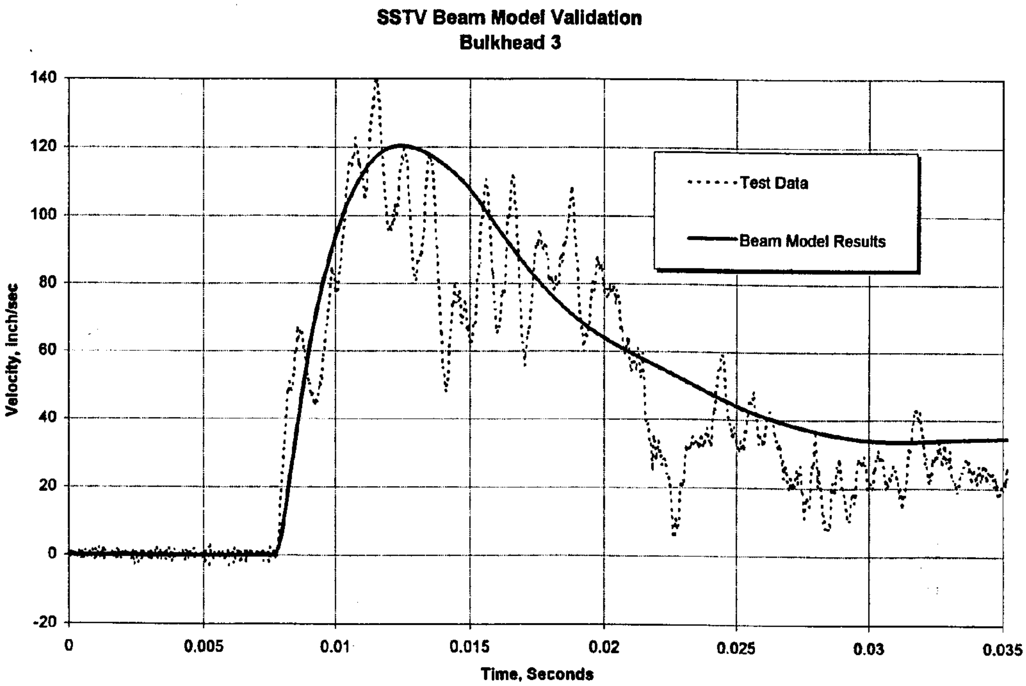
VALIDATION

Overview

Two tests are used for validation of the analysis tool. The first test is a measure of the underwater vehicle's response to the direct shock wave. The second test is a long flexible cylinder subjected to an underwater explosion, where the charge weight and test depth is such that the first bending flexure mode of the cylinder is excited into vibration by the timing of the bubble pulse.

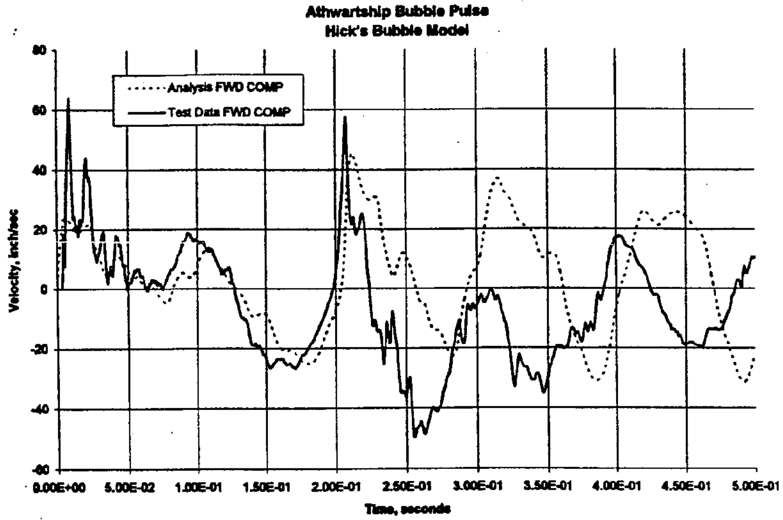
Direct Shock Wave

The USA/NASTRAN model of the test vehicle is a beam model of the structure with USA surface-of-revolution elements for the fluid elements. The plot of the analysis data below shows acceptable correlation with the test data. The high frequency content of the test data is due to local shell effects that the beam structural model doesn't represent.

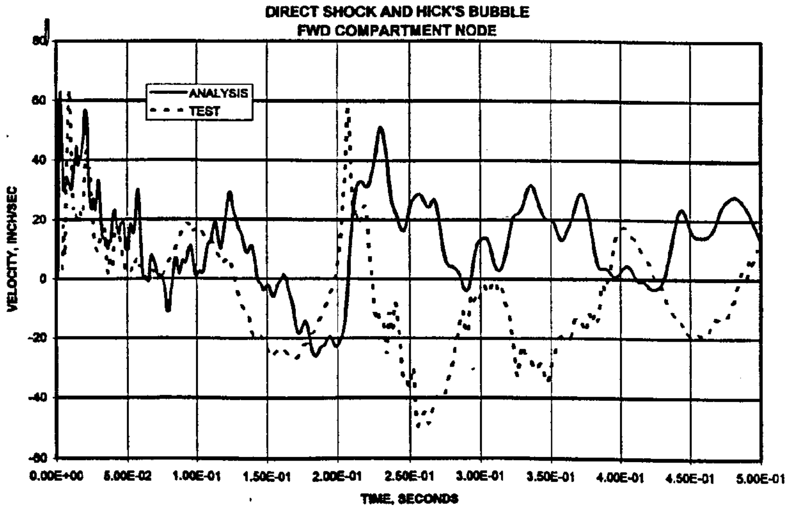


Bubble Pulse Model

In test two, the same modeling technique is used. However, two types of loading representations are used. In the first analysis of test two, the Hicks bubble model provided in USA/NASTRAN is used. In the Hicks bubble model, only the low frequency water flow caused by the expanding and contracting bubble is accounted for. The plot below, for the first low frequency cycle, shows adequate correlation with the test data. Generally, this is acceptable for design purposes.



In the second analysis of test two, the pressure time history of both the direct shock wave and the bubble pulse is input as the loading. The below plot shows adequate correlation with the direct shock peak, and good correlation with the bubble pulse response; however, the timing is not as accurate as the Hick's bubble model.



CONCLUSION

The underwater explosion is a complex phenomenon that produces both a sudden (shock wave) and a low frequency loading (gas bubble) on a structure. Free surface and bottom reflections further complicate the problem.

USA/NASTRAN has been shown to have adequate correlation, for design purposes, with test data of both the shock wave and bubble pulse loading. Experiences with analyses of underwater shock problems, not shown in this report, has demonstrated that the quality of the structural model is the most critical aspect. MSC/NASTRAN provides a wide range of high quality structural elements to facilitate accurately representing the structural model.