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# Numerical Analysis of Vertical Water Impact of a Spherical Projectile

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*Abstract*: Information related to the water impact forces is crucial in the design of missiles, seaplanes, aircraft, and spacecraft and also has relevance to the design of marine structures that must withstand slamming loads. In this paper numerical modeling of vertical water impact of a spherical projectile is presented using LS-DYNA explicit dynamics software package. The LS-DYNA package allows the fluid to be modeled using an Eulerian formulation. The LS-DYNA predictions for impact coefficient are compared with the analytical and experimental data.

*Key-Words*: Water impact, Spherical projectile, Impact coefficient, Eulerain-Lagrangian coupling

## 1 Introduction

The study of hydrodynamic impact is one of the application areas of FSI (fluid-structure interaction) field. Information related to the water impact forces, particularly during the initial stages when maximum impact loads occur, is crucial in the design of missiles, aircraft, and spacecraft [1] and also has relevance to the design of marine structures that must withstand slamming loads [2]. To design jettison objects entering into the water, the impact forces should be accurately computed. If poorly designed, the body may be destroyed or precise control and guidance electronic circuits may be malfunctioned by strong elastic waves.

It has been recognized that there are fundamental differences between ground and water impacts. The crash-resistant subsystems designed for rigid surface impacts, such as landing gears or sub floors in aircraft, are not as effective in water since the structure undergoes a different loading mechanism. Water displaces and provides a reasonably uniform loading on the base of the structure, but a rigid surface results in more direct and concentrated loading of the frame members. Moreover, the water behavior to allow a reliable prediction of reactive forces against various geometries of the impact head when subjected to a dynamic loading simulation involves great deal of complexity. The behavioral characteristic of water are more complicated than those of other common engineering materials. Thus making generalized behavior conditions are extremely difficult to determine with reliable accuracy. Usually the study of the phenomenon is dealt with experiments, empirical laws, and lately, with finite element simulations [3-6]. These simulations are performed by means of special codes that allow the fluid-structure coupling. The codes have their origin in Lagrangian finite element programs developed for crash analysis improved with possibility of interacting with Eulerian spatial description, which is of particular interest in fluids. Critical points in this type of modeling are the fluid-structure interaction algorithms, constitutive modeling of the fluid and time efficiency of the computation.

Studies of the impact of a solid sphere on a horizontal liquid surface are categorized in two sections: those which are concerned with the formation of the cavity and splash, and those which are concerned with the force of impact on the sphere. This study concentrates on the second aspect.

In the present work, Numerical modeling of vertical water impact of a spherical projectile is done using LS-DYNA explicit dynamics software package. The LS-DYNA package allows the fluid to be modeled using an Eulerian formulation. The structure can be modeled using Lagrangian formulation which is coupled to the fluid using Eulerian-Lagrangian coupling algorithms. Finally the results are compared with the analytical and experimental data.

## 2 Impact Coefficient

An important pioneering work in splash and impact can be attributed to von Karman [7]. He studied this phenomenon in order to find the forces exerted on a sea plane float during landing. The non-dimensional parameter which governs impact force is the impact or slamming coefficient, which is defined as:

$$C_S = \frac{F_I}{\frac{1}{2}\rho V^2 A_x} \tag{1}$$

where $F_I$ is the impact force, $\rho$ is the density of the fluid, $V$ is the initial impact velocity and $A_x$ is the projected area of the projectile.

Von Karman does not take into account the deformation of the free surface around the outside of the sphere. He also assumed that the mass of the body is increased, due to the addition of a mass of water, which is seen to travel with the body at its instantaneous speed. This increase of mass is known as the added or virtual mass. In computing added mass, he used flat plate approximations instead of using the more complex spherical equations.

Miloh [8] used an asymptotic solution for early stages of constant velocity water entry of a sphere which would take into account the 3-dimensional effects of a spherical body in finding added mass and introducing a correcting surface wetting factor for compensating the undisturbed free surface assumption. The impact coefficient is then obtained as:

$$C_s(\tau) = \frac{8\sqrt{2}}{\pi} C_w^{\frac{3}{2}} \tau^{\frac{1}{2}} - 2.38 C_w^2 \tau - 2.09 C_w^{\frac{5}{2}} \tau^{\frac{3}{2}} \tag{2}$$

where $C_w$, a correcting surface wetting factor, and $\tau$, dimensionless depth, are defined as below:

$$C_w = 1.327 - 0.154\tau \ , \quad \tau = \frac{Vt}{R} \tag{3}$$

where R is the sphere radius.

Experimental results for the early stages of vertical water impact of a sphere (Moghisi and Squire [9] and Laverty [10]) show that equation (2) yields a good approximation for the impact coefficient.

In this paper the LS-DYNA predictions for impact coefficients of a spherical projectile are compared with Miloh and experimental impact coefficients.

## 3 Eulerian and Arbitrary Lagrangian-Eulerian Formulation Capabilities in LS-DYNA

In LS-DYNA it is possible to apply the Eulerain formulation for fluid flow analysis, where the fluid flow through the fixed mesh in space is observed, while in the Lagrangian formulation the mesh follows the material flow. In Eulerian solving procedure, a node may change its position during one computational time step because of node loading. After the time step the analysis stops and all the nodes of the Eulerian mesh that have been displaced are moved to their original position (mesh smoothing) and the internal variables (stresses, flow fields, velocity field) for all nodes that have been moved are computed (interpolated) so that they have the same spatial distribution as prior to the mesh smoothing (advection).

The Arbitrary Lagrangian-Eulerian (ALE) solving procedure is similar to Eulerian procedure. The only difference is the mesh smoothing. In the Eulerian formulation the nodes are moved back to their original positions, while in the ALE formulation the positions of the moved nodes are calculated according to the average distance to the neighboring nodes [11].

Although the Lagrangian formulation allows easy tracking of free surfaces and interfaces between different materials, its weakness is its inability to follow large distortions of the computational domain. Eulerian formulation facilities the treatment of large distortions in the fluid motion. Its main drawback is the difficulty to follow free surfaces and interfaces between different materials or different media (e.g., fluid-fluid and fluid-solid interfaces). ALE formulation is particularly useful in flow problems involving large distortions in the presence of mobile and deformable boundaries [12].

# 4 Simulation Approach

In simulating water impact of a spherical projectile in LS-DYNA, sphere and water model are defined and An Eulerian-Lagrangian coupling algorithm is used to couple these two models.

## 4.1 Sphere Model

The spherical projectile is modeled as a lagrangian solid with 120,000 hexahedral constant stress elements. The sphere is defined as a rigid body. The diameter of the sphere is 5.72E-2 m. Elasticity modulus, E, and Poisson's ratio, $\nu$, should be defined for determining contact parameters. The properties of the sphere are the same as a standard billiard ball that Laverty [10] has used in running his experiments and are given in table 1. Fig.1 shows the sphere model.

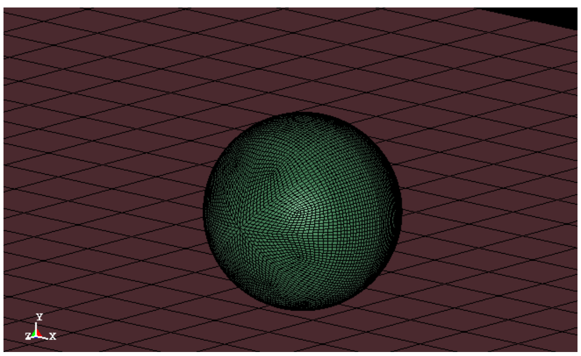

Fig.1 Sphere Model.

## 4.2 Fluid Model

For impacts of objects into water, an Euler mesh representing a void or air must be modeled on top of the water to allow the water to form the wave that occurs in an impact. Since the air is assumed to have only little influence on our simulation it can be modeled as void. The void part has to be given the same material data like the water. One point integration solid element formulation 12 (single material with void) is used to model the Eulerian material (water) and void. MAT_NULL card is used to define water behavior in which viscosity can be defined for water. This model avoids deviatoric stress calculation. The equation of state which gives the relation between the change of volume and the change of pressure is used. If only the parameter $C_1$ in EOS_LINEAR_POLYNOMIAL card is defined as bulk modulus of water, a linear relation between pressure and volume will be obtained. The properties of water are given in table1.

The dimensions of the water and void block are 0.8×0.8×0.6m and 0.8×0.8×0.5m respectively. Elements with edge length of 0.02 m are used. The vertical height mesh seed is given a one-way bias of 0.2. 88000 hexahedral Eulerian elements are employed to define water and voids.

| | | |
|---|---|---|
| Water | Density (Kg/m$^3$) | 1000 |
| | Bulk modulus (GPa) | 2.06 |
| | Viscosity (Pa.s) | 1.79E-2 |
| Sphere material (Phenolic resin) | Density (Kg/m$^3$) | 1700 |
| | Elasticity modulus (GPa) | 12 |
| | Poisson's ratio | 0.35 |

Table 1 Water and Phenolic Resin Properties.

## 4.3 Coupling

The coupling between the fluid (slave) and the structure (master) is done by CONSTRAINED_LAGRANGE_IN_SOLID. In this Arbitrary Eulerian-Lagrangian coupling algorithm, the Eulerian mesh and the Lagrangian mesh are coupled through an ALE interface surface. The interface serves as a boundary for the following Eulerian material during the analysis. The ALE interface moves as the Lagrangian structure deforms. Thus, the Eulerain mesh boundary also moves. In order to preserve the original Eulerian mesh and make it follow the structural motion, the Eulerian grid points can be defined as ALE grid points.

The Lagrangian mesh is finer than Eulerian mesh to prevent leakage in the coupling. Flow through the structure is prevented by applying penalty forces to the fluid and structure. As soon as a Eulerian node peneterates into a Lagrangian structure, a force of recall is exerted on the contravening node and put it back on the surface of the structure. Penalty forces are calculated proportionally to the penetration velocity and depth to behave like a spring system. There is a constant known as the penalty factor, pf, affecting the penalty forces. A comparison between the results for pf=0.5 and pf=0.05 has been made.

### 4.4 Continuum Treatment

In CONTROL_ALE card, Eulerian is selected as continuum treatment. The number of cycles between advections is chosen as 1 with a Van Leer Advection method. Smoothing is turned OFF.

### 4.5 Hourglass Control

The solid and shell Eulerian elements in LS-DYNA have only one integration point at the center of the element. This makes the program. very efficient since each element requires relatively little processing, but it also introduces the problem of hourglassing. With a single integration point, some of the deformation modes of the element have no stiffness associated with them and are called the zero energy or hourglass modes.

One of the method in LS-DYNA for controlling hourglassing is viscous damping. The viscous method damps out hourglass modes and is carefully tuned so that other modes of deformation are not affected. A parameter known as hourglass coefficient, HQ, can be used to control hourglssing. The default value of hourglass coefficient is 0.1. Increasing the hourglass coefficient helps preventing hourglass. However, excessively large values can cause numerical problems. As the null material has no shear stiffness, it is recommended to use a reduced hourglass coefficient. $HQ=10^{-4}$ gives the best results.

## 5 Results

The Acceleration of the spherical projectile is required to compute the impact coefficient. Due to the presence of high frequency signals seen in the numerical acceleration time histories, data must be filtered using a low-pass digital filter. By applying a filter to LS-DYNA data and increasing its frequency cutoff incrementally, all high frequency oscillations, which are not present in the experimental data, are removed and a comparison can be made. In this study a Butterworth digital low-pass filter is applied. The filtered accelerations are used to compute the impact coefficients.

As the velocity curve is relatively simpler than the acceleration curve, some data required to find the fundamental acceleration pulse are obtained from the velocity curve. Fig.2 shows the velocity changes of sphere during impact for pf=0.5 and pf=0.05. Because of impact forces, the velocity reduces to 3.9 m/s at a time of 0.0034 seconds for pf=0.5 and 0.0024 for pf=0.05. Thus, the fundamental frequency is about 1/T or 294Hz and 416 Hz for pf=0.5 and pf=0.005 respectively. To extract the fundamental acceleration pulse, the lowest filter frequency should be above the fundamental frequencies. 300– and 420– filters are used for pf=0.5 and pf=0.05, respectively.

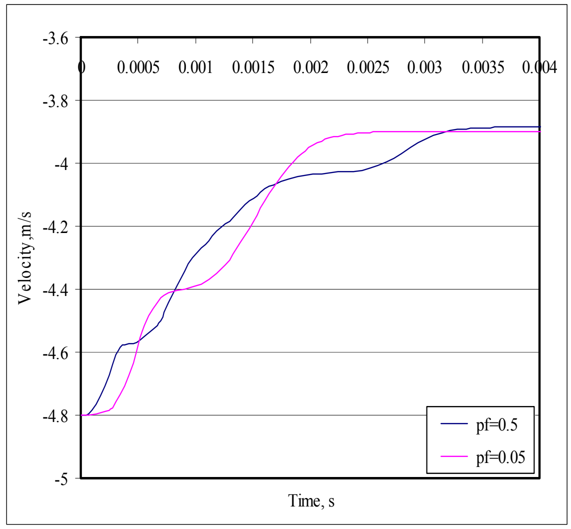


Fig.2 Velocity during Impact for pf=0.5 and pf=0.05.

An approximation of the maximum acceleration of the fundamental pulse is obtained from the maximum slope of the velocity curve between 0.0007 and 0.0017 seconds, which gives a maximum acceleration of about 440 $m/s^2$ for pf=0.5, which is equal to an impact coefficient of 2.48.

Fig. 3 Shows the impact coefficient plot as a function of the nondimensional depth, D(t)/R (D(t) is the instantaneous immergence depth and R is the sphere radius), which compares Miloh and experimentally observed impact coefficients with raw and filtered impact coefficient predictions of this analysis. In computing nondimensional depth for Miloh, it is assumed that the velocity is constant during the considered course of entry (D(t)/R=Vt/R). As Laverty takes into account gravity and buoyancy forces in computing experimental impact coefficient, a deviation of experimental data from analytical happens for $\tau > 0.3$.

## 6 Conclusion

Although, the filtered LS-DYNA predictions overpredict the impact coefficient of the spherical projectile, they follow the overall trend of analytical and experimental results. When pf=0.5, large oscillations are observed in the impact coefficient results. In this case the water nodes "spring away" from the rigid surface and large spikes occur in the contact force. If penalty factor is reduced to 0.05, water nodes will properly follow the structure. Despite the difference between raw impact force coefficient plot, the velocity curve shows that Changing the value of penalty factor does not have significant effect on the maximum acceleration.

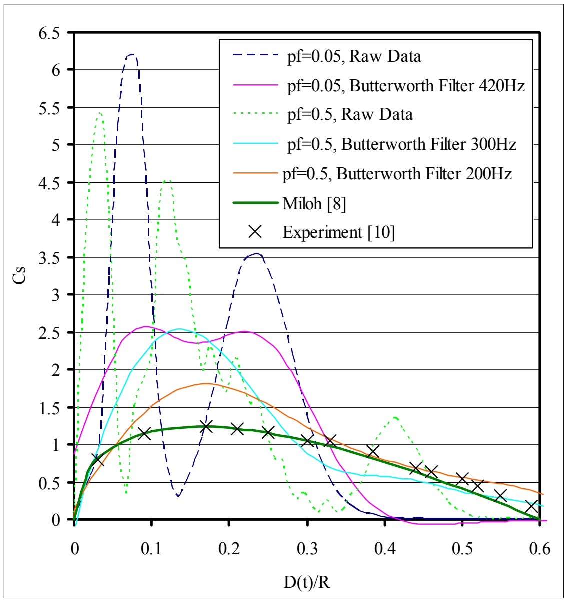


Fig.3 Impact Coefficient as a Function of Nondimensional Depth.

From equation 2.2, the maximum of impact coefficient occurs at $\tau$=0.18 which is equal to 1.23. The rise times of analytical and numerical plots are about the same. From the 300Hz-filtered data for pf=0.5 a maximum impact coefficient of 2.53 at $\tau$=0.14 is predicted. The value of the maximum acceleration is close to the approximated value obtained from the velocity curve.

If the minimum value of the fundamental frequency obtained from the velocity curve is not considered and a 200Hz-filter is applied to raw data for pf=0.5, the maximum value of impact coefficient will be closer to the analytical result. It seems that without a strong fundamental understanding of filtering techniques, the quality of engineering decisions made from impact analysis will reduce.

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