An impact study of a capsule with a rigid wall using the SPH approach

Ionut-Cosmin ONCESCU*[,1], Alexandru-Mihai CISMILIANU[1],
Florin FRUNZULICA[2]

*Corresponding author
[1]INCAS – National Institute for Aerospace Research "Elie Carafoli"
B-dul Iuliu Maniu 220, Bucharest 061126, Romania
oncescu.ionut@incas.ro*, cismilianu.alexandru@incas.ro
[2]"POLITEHNICA" University of Bucharest, Faculty of Aerospace Engineering,
Polizu Street no.1-6, RO-011061, Bucharest, Romania
ffrunzi@yahoo.com

DOI: 10.13111/2066-8201.2015.7.4.14

Received: 05 October 2015 / Accepted: 12 November 2015

The 36th "Caius Iacob" Conference on Fluid Mechanics and its Technical Applications
29 - 30 October, 2015, Bucharest, Romania, (held at INCAS, B-dul Iuliu Maniu 220, sector 6)
Section 2. Numerical Analysis

Abstract: *Impact problems have always been of interest in the Aerospace industry because events such as "bird-strikes" occur quite often and necessary studies must be performed to observe the behavior of structures during the impact. This paper performs a study of an impact between a capsule filled with a liquid, modeled with SPH approach (Smoothed-Particle Hydrodynamics), and a rigid wall using the explicit nonlinear analysis. We also apply a rotation to the capsule to study how it affects different values such as impact pressures and structural stress. Another important aspect of this problem is the fluid-structure interaction and how different parameters influence the spill pattern of the fluid. We present some numerical results obtained for the above-mentioned cases.*

Key Words*: contact-impact, SPH, numerical simulations*

1. INTRODUCTION

Impact problems are important and difficult to analyze because of their non-linear behavior in which we have large structural deformations. In this paper we will simulate an impact problem which consists of a hollow sphere, filled with a liquid such as water, that hits a rigid wall at a certain speed. Before the impact occurs there are certain steps that must be performed such as a launch and ballistic calculation to obtain the angle and the speed at which the ball hits the wall; in our case these steps have been performed but they will not be detailed in this paper because our main focus is the impact problem, therefore we will consider the input data is already known. Another important aspect of this problem is the material from which the sphere is made, in our case we consider the material to be an isotropic polymer and for a future work we will consider the part to be 3D printed using the Fused Deposition Modeling [1] method from an Acrylonitrile-Butadiene-Styrene (ABS) polymer. The fluid contained in the ball was modeled using the Smooth Particle

Hydrodynamics (SPH) because we want to observe the spill pattern after the impact on each case. A description of the impact analysis and the modelling problem is also provided in this paper, the 3D printed material behavior was simulated using the theory presented in a previous paper [2].

2. IMPACT ANALYSIS

Impact problems require a nonlinear type of analysis; the nonlinear response could be caused by any of several characteristics of a system, like large deformations and strains, material behavior or the effect of contact or other boundary condition nonlinearities. In our analysis there are several phenomena's involved, an impact problem which will ultimately leads to the structural failure of the sphere, a fluid flow and a fluid-structure interaction. To solve these problems we will use an explicit solver from LS-Dyna, because we want to run the simulation at a small time-step to better capture the phenomena.

In this paper we will use the penalty based method for defining the impact – contact conditions between the finite elements and SPH particles. When defining a contact between 2 elements, we must define the contact surfaces. First of all there are 2 types of contact surfaces or interfaces, one is called the SLAVE, and the other one is called the MASTER interface. The nodes that can be found on the slave surface are called slave nodes and vice-versa for the master nodes. The standard penalty method is the most used method for impact-crash problems, suited for explicit and implicit programs. The method consists of placing normal interface springs between all penetration nodes and the contact surface [3], see figure below.

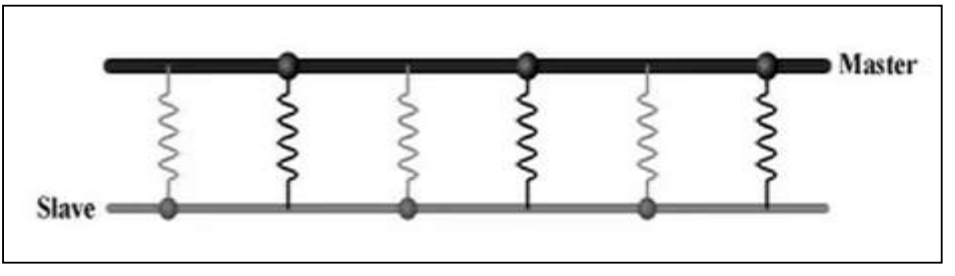

Figure 1. Slave-Master surface contact definition

The standard penalty formulation is the most used algorithm for the contact interfaces. In applying this penalty method, each slave node is checked for penetration through the master surface. If the slave node does not penetrate, nothing is done. If it does penetrate, an interface force is applied between the slave node and its contact point. The magnitude of this force is proportional to the amount of penetration. This may be thought of as the addition of an interface spring [3]. For example if a slave node n_s has penetrated a master segment then we apply a force vector $\overline{f_s}$ that is equal to:

$$\overline{f_s} = -\bar{l}k_i\bar{n}_i \ \text{, if } l < 0 \tag{1}$$

Where k_i is the bulk modulus of the material, l is the length of the penetration and $\overline{n_i}$ is normal of the master surface at the contact point.

The bulk modulus factor depends on the volume, area of the solid finite element and a factor K given by the user which basically represents the spring stiffness; care must be taken when choosing this factor because when we have a contact between materials with low stiffness, such as foam, the parts that collide could pass each other. The standard value used in this problem was chosen $K = 0.1$.

Another important factor of this problem is the time step, during a cycle the solver passes through all the finite elements and updates the global time step based on the smallest length of a finite element L_c and the speed of sound c_{3D} through that element

$$\Delta t_c = \frac{L_c}{c_{3D}},\ c_{3D} = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}} \quad (2)$$

Where Δt_c is the critical time step, E is the elasticity modulus, ν the Poisson number and ρ the density of the material.

3. SMOOTH PARTICLE HYDRODYNAMICS

In the SPH method, the state of a system is represented by a set of particles, which possess individual material properties and move according to the governing conservation equations. Since its invention to solve astrophysical problems in three-dimensional open space by Lucy, Gingold and Monaghan [4], SPH has been extensively studied and extended to dynamic response with material strength as well as dynamic fluid flows with large deformations. Smoothed particle hydrodynamics, as a meshfree, Lagrangian, particle method, has its particular characteristics. It has some special advantages over the traditional grid-based numerical methods, the most significant one being the adaptive nature of the SPH method.[5]

The formulation of SPH is often divided into two key steps. The first step is the integral representation or the so-called *kernel approximation* of field functions. The concept of integral representation of a function $f(x)$ used in the SPH method starts from the following identity, which is derived from the Dirac function:

$$f(x) = \int_{\Omega} f(x')W(x-x',h)dx' \quad (3)$$

where $W(x-x',h)$ is the so-called *smoothing kernel function*, f is a function of the three-dimensional position vector x and h is the smoothing length defining the influence area of the smoothing function W.

The second key step is the *particle approximation*. The continuous integral representations concerning the SPH kernel approximation can be converted to discretized forms of summation over all the particles in the support domain shown in figure 2.

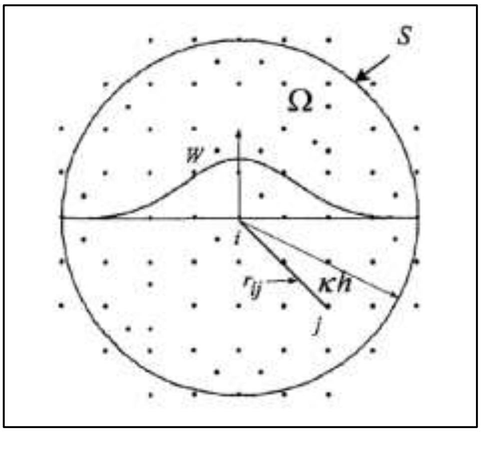

Figure 2. Particle approximation using particles in the support domain S [5]

The support domain Ω has a radius of kh, where k is chosen by the user, usually it has a value of 2; in figure 2 we can also see a representation of the smoothing function W and how it shows the influence of random particles j, from the support domain, on particle i. Let us consider an infinitesimal volume dx' in the position of particle j and replace it with a finite volume ΔV_j which depends on the mass of the particle as follows:

$$m_j = \Delta V_j \rho_j \tag{4}$$

where m_j and ρ_j are the mass and density of the particle $j = (1,2,\dots,N)$ and N is the number of particles j inside the influence domain Ω of the particle i; in the end the integral representation can be approximated with the following formula

$$\begin{aligned} f(x) &= \int f(x')W(x-x',h)dx' \\ &= \sum_{j=1}^{N} f(x_j)\, W(x_i - x_j, h)\Delta V_j \\ &= \sum_{j=1}^{N} f(x_j)\, W(x_i - x_j, h)\frac{1}{\rho_j}(\rho_j \Delta V_j) \\ &= \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) W(x_i - x_j, h) \end{aligned} \tag{5}$$

Using the particle approximation we can derive the equations for the mass, momentum and energy conservations.

In our impact problem, the smoothing function W has the following definition [4]:

$$W = \begin{cases} 1 - \frac{3}{2}R^2 + \frac{3}{4}R^3, & \text{for } 0 \le R < 1 \\ \frac{1}{4}(2-R)^3, & \text{for } 1 \le R < 2 \\ 0, & \text{for } R \ge 2 \end{cases} \tag{6}$$

where we consider $R = \frac{|x_i - x_j|}{h}$, and where W must respect a unity condition $\int W(x - x', h)dx' = 1$, and a compact condition $W(x-x',h) = 0\,, |x-x'| > kh$.

Several other operations must be performed so that the SPH method can be used; an important step is the neighbor search operation that offers the number of influence particles and must be performed at every time step, that is why this method is very time consuming. In our application the sphere of influence of each particle is a finite domain of radius 2h. In a direct search for N particles, the required number of distance comparisons is $N-1$; since the comparison must be performed for every particle, the total number of comparisons is $N \cdot (N-1)$.

The idea of the search for neighbors is to use the same algorithm as the one used for the contact search and that is the “Bucket Sort”; the domain is split into multiple boxes of a given size. Then for each particle we search for neighbors inside the main box and also neighbor boxes contained in the domain of influence of the given particle [6].

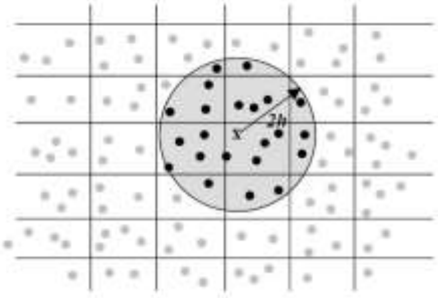

Figure 3. Neighbor search [6]

Recent developments have also included a variable smoothing length to avoid problems that appear on the compression or expansion of the material; the idea is that it is always desirable to have a certain number of particles in the vicinity of the main particle to validate the approximation of the continuum variables. For computational reasons the smoothing length can't vary more than a maximum and a minimum value set by the user.

$$HMIN * h_0 < h < HMAX * h_0 \tag{7}$$

where h_0 is the initial smoothing length and in our application we select $HMAX = 1.2$ and $HMIN = 0.2$, values are in meters.

The pressure on the solid boundary is calculated by using the real particles from the neighbourhood of the solid wall, by extrapolation in its previously specified points. Extrapolation may be done using the method of the diffuse approximation. [7] Also the critical time step of the problem will be defined with the following formulation

$$\Delta t = C_{CFL} \min\left(\frac{h_i}{c_i + v_i}\right) \tag{8}$$

where C_{CFL} is the Courant-Friedrichs-Lewy condition for numerical stability and v_i is the speed of the particle.

4. SIMULATION MODELS

To generate the hollow ball, we used HEXAEDRICAL finite elements. The sphere has a diameter of 0.2 m, an inner thickness of 0.004 m and a total number of 9600 elements.

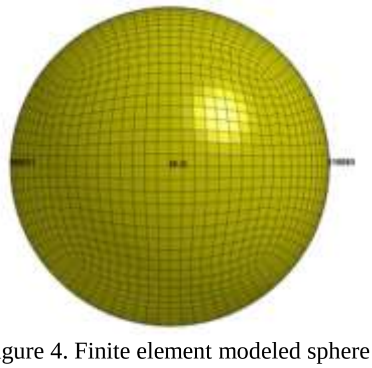

Figure 4. Finite element modeled sphere

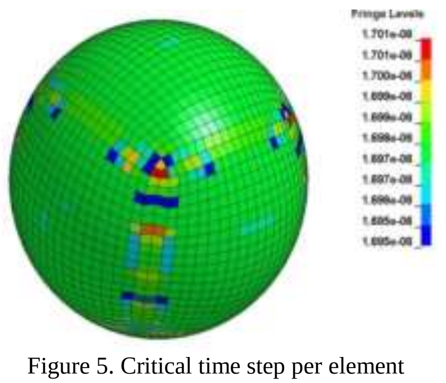

Figure 5. Critical time step per element

In figure 4 we can see the finite element mesh of the sphere and figure 5 shows the critical time step calculated per element; the values are shown in the legend on the right of the figure. The material of the sphere is of elastic-plastic isotropic type, having the following mechanical properties:

Table 1 – Material properties

Property	Units	Value
Density	$\frac{Kg}{m^3}$	1240
Melting temperature	$°C$	160-210
Young elastic modulus	GPa	3.5
Shear modulus	GPa	1.287
Tensile strength	MPa	50

In some profile literature it is recommended to take a minimum of 9 SPH particles for every solid element, and at least 4 particles for a shell element. In our case, we have 9600 solid elements and at a simple calculation we can find that we need at least 38400 particles. Taking these things in consideration we generated a number of 47833 particles; on each X, Y, Z axis there are 45 particles, as shown in figure 6.

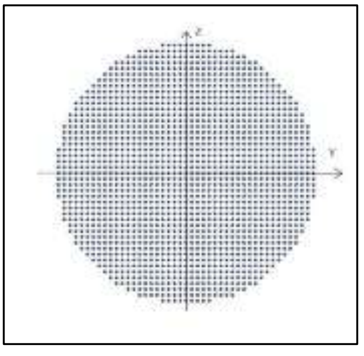

Figure 6. SPH particle generation

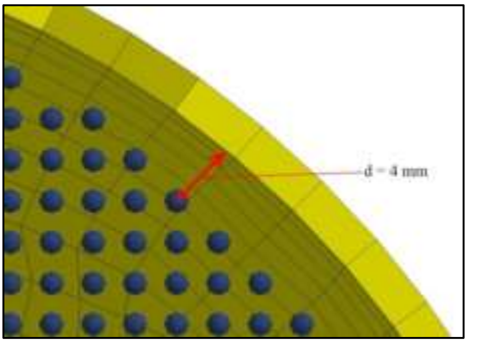

Figure 7. Distance outer particle, inner sphere

The sphere radius of the SPH generated particles is $R = 0.091\, m$, because we don't want initial penetration to occur between the particles and the finite elements and we also don't want to give a lot of space between them; thus we have chosen a distance of 0.004 m, see figure 7. For modelling the SPH particles material we consider the following parameters: $= 1000\frac{kg}{m^3}$, $\mu = 10^{-3}\frac{Kg}{ms}$,$PC = -100\, Pa$ (PC is the cavitation pressure), $c = 1500\frac{m}{s}$ (speed of sound through the material). To generate the impact plate, we used shell elements; 3808 elements were disposed on a length of 3m and a width of 2.5m to better capture the spill of the fluid after the impact. The plate is treated as a rigid wall, it cannot move in any direction. For the material of the plate we used a type of concrete with the following properties: $E = 14000\, MPa$, $\rho = 2240\frac{kg}{m^3}$, $\nu = 0.2$.

5. RESULTS

Impact simulations where performed with the modification of some parameters, although the ball will hit the wall at a speed of $25\frac{m}{s}$, we also performed a simulation at a speed of $100\frac{m}{s}$ just to compare the pressure at the impact and the Von Mises stress distribution in the sphere. The simulation was performed for a ball that hits the rigid-wall at a 45° angle with and without a 5 rot/min. The results have been posted in the table below.

Table 2 - Results

	Max Pressure [Pa]	Max Von Mises stress [MPa]
Sphere without rotation 100 m/s	$1.24 \cdot 10^8$	246
Sphere with rotation 25 m/s	$1.725 \cdot 10^7$	50.2
Sphere without rotation 25 m/s	$1.96 \cdot 10^7$	40.57

In the figures below we can observe the moment at 0.1 s after impact, considering a time step of $10^{-5}s$. The time step cannot take a value bigger than $10^{-5}s$ because of the solid element dimensions.

Table 3 – Graphical results

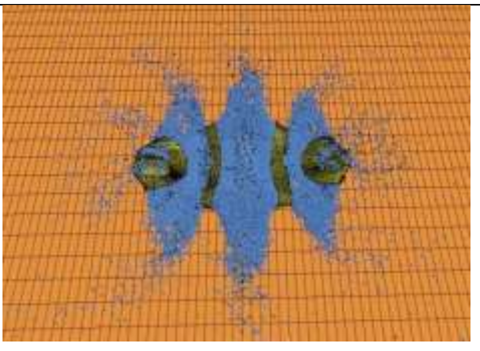
Figure 8. 100 m/s Impact, top view

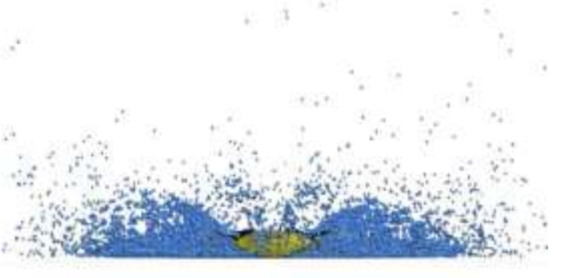
Figure 9. 100 m/s Impact, side view

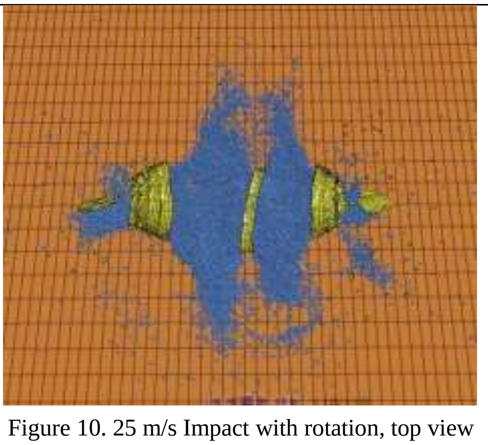
Figure 10. 25 m/s Impact with rotation, top view


Figure 11. 25 m/s Impact with rotation, side view

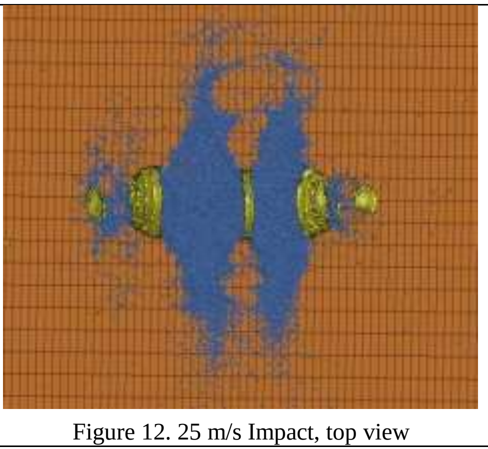
Figure 12. 25 m/s Impact, top view

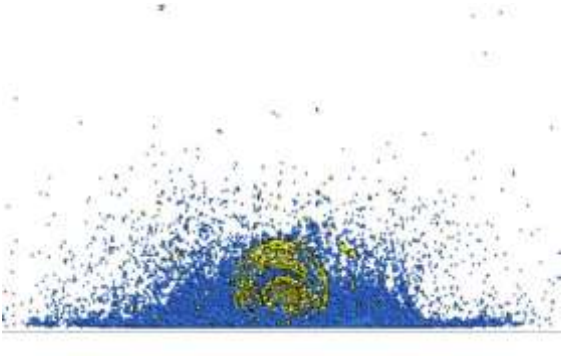
Figure 13. 25 m/s Impact, side view

6. CONCLUSIONS

The impact analysis highlighted the way the sphere breaks when it is modeled using an isotropic material. We also obtained the maximum value for pressure and Von Mises stress on impact, and in conclusion we demonstrated that 5 rot/s don't have a great influence on these parameters. But when increasing the speed 4 times we also increased the maximum stress and pressure, although it is improbable that the sphere will reach a speed of 100 m/s.

Another important thing that we observed, was how the fluid flows after the impact. Apparently at this configuration, a hollow sphere with a smooth exterior surface, the fluid is dispersed in the direction of the movement and very little on the lateral direction; we can improve this thing by adding breaking primers on longitudinal and transversal directions similar to those of a grenade.

REFERENCES

[1] * * * https://en.wikipedia.org/wiki/Fused_deposition_modeling.

[2] A. M. Cismilianu, I. C. Oncescu, *Simulating material behavior of 3D Printed ABS* Parts*, 3rd International Workshop on Numerical Modelling in Aerospace Sciences, INCAS – National Institute for Aerospace Research "Elie Carafoli", 06-07 May 2015, Bucharest, Romania.

[3] J. O. Hallquist, *LS-Dyna Theory Manual*, Livemore Software Technology Corporation, March 2006, ISBN 0-9778540-0-0.

[4] R. A. Gingold, J. J. Monaghan, Smoothed particle hydrodynamics: theory and application to non – spherical stars, *Monthly Notices of the Royal Astronomical Society*, vol. 1**81**, Nov. 1977, p. 375-389, September, 1977, ISBN 981-238-456-1.

[5] G. R. Liu, M. B. Liu, *Smoothed Particle Hydrodynamics a meshfree particle method*, World Scientific Publishing Co., 2003, ISBN 981-238-456-1.

[6] Dr.Jean Luc Lacome, *Smoothed Particle Hydrodynamics*, FEA Information International News For The World-Wide Engineering Community, November 27, 2001.

[7] F. Frunzulica, A. Dumitrache, M. Stoia-Djeska, A Numerical Simulation Of Fluid-Structure Interaction Problems by A Mesh-Free Method, *Rev. Roumaine des Sciences Techniques/Serie de Mecanique Applique*, Tome **55**/ No. 2, Mai-Aout 2010, pp.135-144. ISSN 0035-4074.