RIGID BODIES IMPACTS ON WATER SURFACE. NUMERICAL AND EXPERIMENTAL ACTIVITY

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Abstract

The study of hydrodynamic impacts between a body in motion and a free water surface finds applications, in aeronautical fields, in splashdown and ditching problems. The effect of these impacts is often prominent in the design phase of the project and, for this reason, the importance of studying the event with more accuracy than in the past is imperative.

Usually the study of the phenomenon is dealt with experiments, empirical laws, and, lately, with finite elements simulations. These simulations are performed by means of special codes that allows the fluid-structure coupling, codes that have their origin in Lagrangian finite element programs developed for crash analysis which were improved with the possibility of interfacing continuos with Eulerian spatial description, typical of fluids. Critical points in this kind of modelling are the fluid-structure interaction algorithm, constitutive modeling of the fluid and time efficiency of the computation.

In this work an experimental and numerical activity has been faced to deeply study the behaviour of simple bodies during the impact against water. The study started with simple perpendicular impacts of a rigid sphere, passing then to impacts with semi-cylindrical and semi-pyramidal shapes with also horizontal component of the velocity. All the specimens have been designed to be considered fundamentally rigid during the impact. This choice has been done in order to focus the attention on the event interesting feature, the water impact, leaving out the problems of structure deformations during impacts, faced in other works.

During the tests of the rigid sphere the acceleration time histories of the center of gravity were recorded, while the other two shapes have been covered with piezoresistive pressure transducers to obtain pressure contour fields during the impact.

The numerical study has been supported by the experimental activity carried out also with the aim of comparing and completing bibliographic results.

During the numerical model evaluation a special attention has been given to the study of fluid-structure coupling algorithms and their effects on final results. In addition the influence of mesh, boundary condition and material constitutive laws on simulation process have been evaluated. The codes adopted for finite element simulations have been Msc Dytran and Ls-dyna.

1 Test Facilities

1.1 The drop tower

Typical equipment, characteristic of this kind of impact, require the realization of particular test facilities, the so-called drop-tower, dedicated to exclusive performing of drop-tests, since other facilities like horizontal sled were shown not to be proper to this scope. On the other side, these tests are very important since they are required for the certification of aeronautical structures like tank and sub-floor of the helicopters.

At the Dipartimento di Ingegneria Aerospaziale of the Politecnico di Milano a new drop-tower for the realization of vertical impact of structure against the ground or against the water has been recently build.

The tower is able to lift the structure to be tested, weighting up to 2000kG, up to about twenty meters from ground. The basis of the tower are placed in a pool: the impact is against the ground when the pool is left empty, the impact is on water when the pool is filled with water, as well.

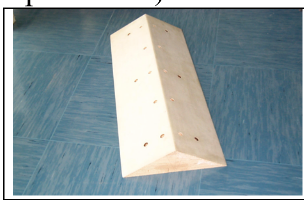
Drop Tower

During the fall two guide – steel cable diameter 8.mm – prevent oscillation of the structure to test.

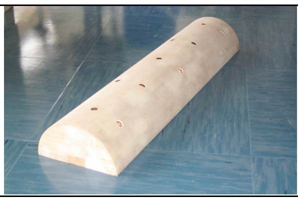
1.2 The specimens

The specimens were realized from plies of evaporated beech-wood properly shaped and covered with glycol reinforced fiber-glass fabric on the surface that impact the water.

On the surface that first impact the water, in addiction, the housings for the transducers of pressure were realized starting from a spot-facing hole. (In the figures below are shown the specimens.)



Wedge-Shaped Specimen



Semicircular Specimen

1.3 Data acquisition system

Data were acquired using two different acquiring system: Pacific Instrumentation 5400 transient recorder and an Intelligent Instrumentation PCI-428 data acquisition board. The sampling frequency used was 12500Hz and a standard CFC1000 filtering technique has been applied.

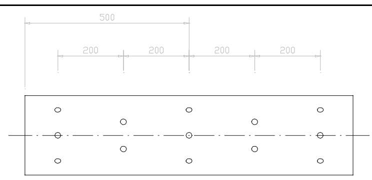
For each test, were measured the vertical acceleration (the acceleration normal to the surface of the water) of the specimen using accelerometers placed at the opposite ends of the specimen itself and the pressure on the surface of the specimen using thirteen piezo-resistive pressure transducer. Tests have been conducted also with horizontal component of the velocity measuring three components of acceleration at the opposite ends of the specimens.

1.4 Accelerometers and pressure transducers

The accelerometer used are Endevco EGCS-D0 ± 250 g and on the surface of the specimen thirteen piezo-resistive pressure transducer Metallux ME 505 have been placed.

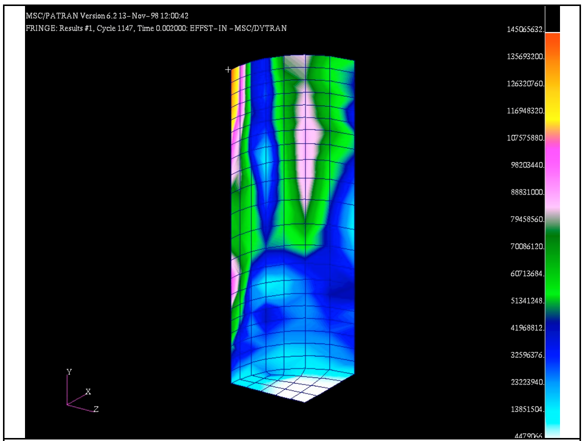
The criteria followed to position the pressure transducers on the surface of the specimen was not to introduce peak of stress in the structure and, as well, to obtain a complete view of the temporal evolution of the pressure on the whole surface of the specimen.

Eventually the transducer were placed as shown in the scheme below.

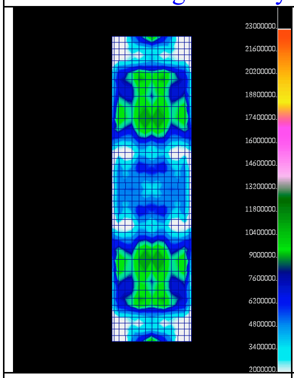


Location of the pressure transducers.

In order to evaluate the range of the pressure transducers several numerical simulations were performed using the Finite Method code MSC/Dytran. This code allows the users to study the interaction fluid-structure trough ALE Coupling Algorithm which, in the past, was shown to be able to model properly the main features of the phenomenon: providing results close to experimental evidences.



Stress on the surface of the specimen – calculated using MSC/Dytran.



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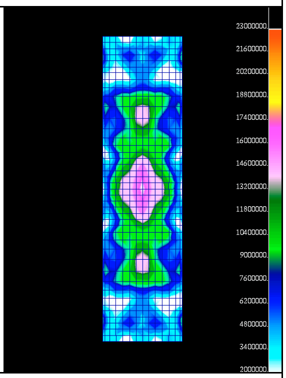

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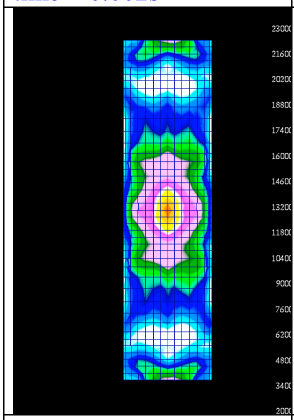

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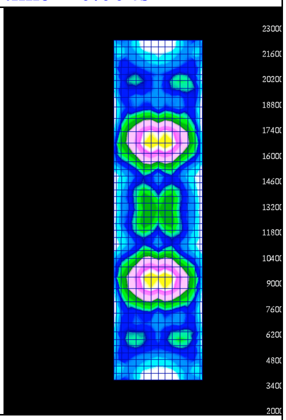

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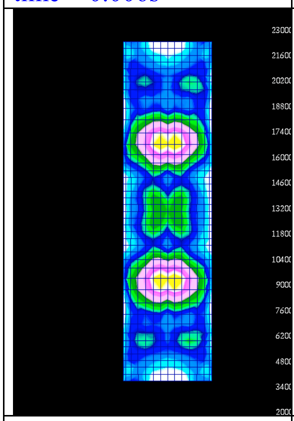
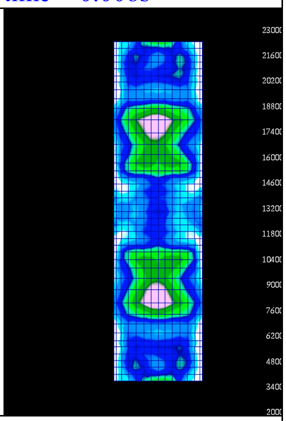


time = 0.010s



time = 0.012s

1.5 High speed video

In each drop-test an high velocity movie trough a Redlake MotionScope camera placed in the control room has been acquired.

2 Description of the tests

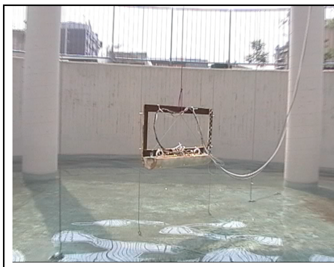
In order to realize the planned drop-test a wooden-made light truss-beam with a pulley was hoisted within the drop-tower at about ten meters over the ground.

During the drop-tests, one of the most frequent and adverse phenomenon is the uncontrolled change in the trim of the structure to test during the fall which eventually causes an incidence in the impact.

In order to avoid discomposing and loose the alignment with the surface of the water during the fall, the specimen, properly instrumented, was fastened to a wooden-made square-shaped frame constrained through four metal eyelet to the guides (two stainless strands with diameter ∅ 4.mm).

In this way, the impact angle of the specimen was order of one degree – well above the maximum degree accomplished. (The estimates were based both on the difference in the time the acceleration measured by the

two accelerometer reach the maximum and on the evidence of the high velocity movie.)



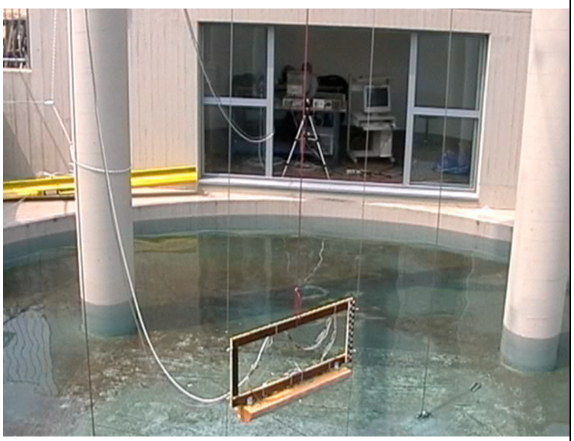
The specimen just before a drop-test.

The wooden frame and guides.

The signals from the instruments were acquired directly through a umbilical cable fastened to the specimen and then, only partly, to the rope. The sampling frequency adopted for all the channel was 12500.Hz. Then the acquired signals were filtered with the typical CFC 1000 filter.

Since the signals from the transducers were acquired through an umbilical cable, the wooden frame was also used to fastened its end in order to avoid variation in the trim of the specimen due to the presence of the umbilical cable itself

In the figure below the specimen just before the test, the location of the high velocity camera and of the data acquiring system in the control room, and the umbilical cable are shown.



The control room and the specimen just before a drop-test.

3 Performed tests.

The total number of performed tests was much higher than the planned because of the difficulties we met. And own to these difficulties, only a small number of the performed tests can be considered representative from the point of view of the data obtained.

4 Experimental results.

Performed the tests and acquired the data, the results considered most representative were represented graphically for each configuration as:

- vertical acceleration [g] as a function of the time;
- pressure [N/mm2] on the surface of the specimen as a function of the time.

In particular, were chosen two among the tests with the same drop height, the most representative, where the effects of the inclination of the specimen were absent or negligible.

4.1 Vertical accelerations

The most representative datum for the impact of a rigid body is surely its vertical acceleration or better its vertical deceleration.

In particular, the data we acquired dial with the measures of two accelerometers placed at the opposite end of the specimen. Rather than present an average value of the acceleration of the specimen we preferred to present separately the value measured by the two accelerometers. In this way it is possible to evaluate (also graphically) the influence of the inclination of the specimen on the value of the acceleration.

V_{imp} [m/s]	a_{MAX} #13 [g]	a_{MAX} #14 [g]	Δt	α_{incl} [deg]
10.5	52.2	81.9	0.002	0.9
10.6	81.0	82.9	0.001	0.8
7.2	48.6	42.9	0.002	0.7
7.8	41.5	41.1	0.006	2.8
3.3	20.2	20.8	0.003	0.6
3.7	24.1	20.2	0.005	1.1

4.2 Pressures

During the tests performed the measure of pressure on the surface of the specimen using proper transducer of pressure has been conducted. But, since the beginning, the pressure acquisition on the surface of the specimen presented repeatability problems. Actually one of the most important result obtained is that pressure-time histories are probably not suited for comparison with numerical analysis. This is due to the big influence on the time-histories of local phenomenon that can change drastically the results from one test to the other. The problem is similar to the attempt of comparing numerical and experimental strain time histories for transducers placed near the impacting point in a deformable structure. Also in this case the signal is strongly influenced by local imperfections.

The pressure measured are presented below. The value of the pressure is expressed in [kPa].

Maximum pressures measured

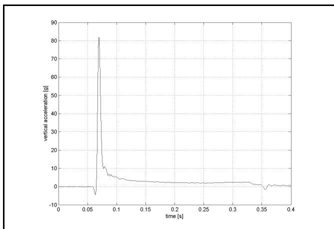
V_{imp} [m/s]	p_{MAX} #02 [kPa]	p_{MAX} #07 [kPa]	p_{MAX} #08 [kPa]
10.5	6.9867	2.9777	2.4647
10.6	2.3992	2.6676	4.5539
7.2	3.1957	3.0990	2.1270
7.8	4.2984	2.6325	2.1933
3.3	2.4051	2.9612	1.9542
3.7	2.4168	2.3382	5.7414

Minimum pressures measured

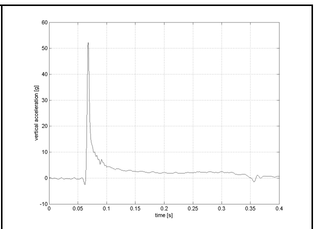
V_{imp} [m/s]	p_{min} #02 [kPa]	p_{min} #07 [kPa]	p_{min} #08 [kPa]
10.5	-2.9643	-5.8706	-2.0408
10.6	0.1624	-0.2463	-0.9675
7.2	-0.0650	-0.0328	-0.4636
7.8	-2.5321	0.0087	-1.9789
3.3	-1.0758	-0.7541	-1.0485
3.7	0.4253	-0.1046	-0.3878

In the following pages are presented the results obtained for two of the representative drop-tests.

Drop height 7.40 m - test #1
Drop height 7.40 m
Impact velocity 10.5 m/s

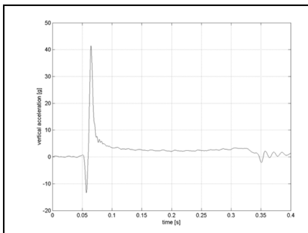


a_{MAX}=81.9g.

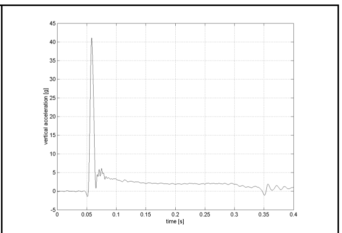


a_{MAX}=52.2g.

Drop height 3.30 m - test #2
Drop height 3.30 m
Impact velocity 7.8 m/s



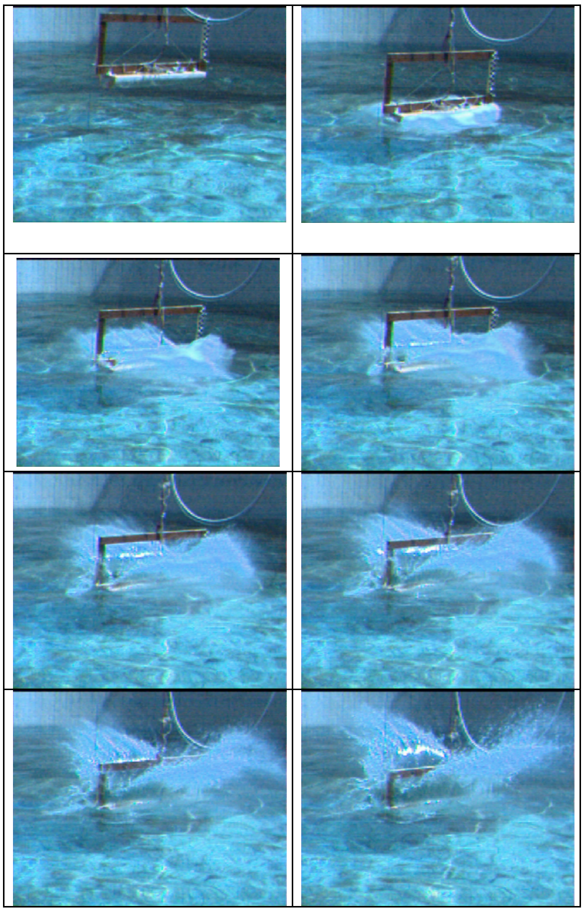
a_{MAX}=41.5g.



a_{MAX}=41.1g.

4.3 High velocity video

In the figures below, some frames from the high velocity movie of a drop test are shown.



5 Numerical activity.

A quite recent technique to analyze fluid-structure interaction based on Smooth Particle Hydrodynamic Method (SPHM) has been applied to this problem.

As known, the main problem in modeling fluid-structure interaction following a Lagrangian approach, is the extreme distortion of the elements. SPHM, adopt a Lagrangian point of view, but since it does not need the definition of a mesh, it does not suffer the extreme distortion of the elements used to model the fluid. In fact, the Conservation Laws are applied to a set of nodes with mass, called particles, that flows following the flow of the fluid.

In order to evaluate the SPH method to model the behaviour of the water some simple cases were considered.

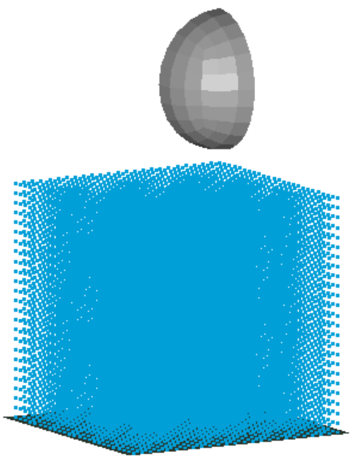
As reported by several authors, SPH Method born as Monte-Carlo Algorithm for the integration of the Euler Equation written following a Lagrangian approach and then were applied to the analysis of high velocity impact – after being properly modified.

In spite of the goodness of the idea at the basis of the method, many questions about the goodness of the results remain without an answer. Our aim was to apply SPH Method to the analysis of simple cases of fluid-structure interaction – as we are interested in understand if it were possible to use this method to evaluate the crashworthy of the structure of an aircraft in event such the ditching. (In particular, in the within of the present work, we use the SPH Solver implemented by LS-Dyna.)

The cases considered were: the impact of a rigid sphere onto water – a classical test for any hydro-code, and the impact onto water of the two rigid specimens used in the previous activity.

As said, to acquire the necessary confidence with the SPH Method, at the beginning, we start considering a classical test-case: the impact of a rigid sphere onto water.

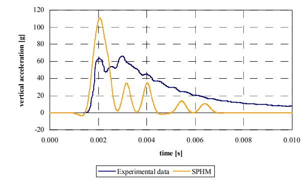
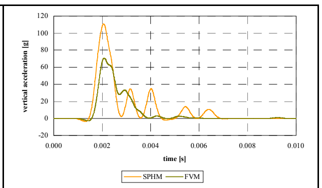
In order to simplify the analysis of the problem only a quarter of the sphere were modeled and the region used to modeled the pool was a cube with edge-length equal to twice the ray of the sphere.



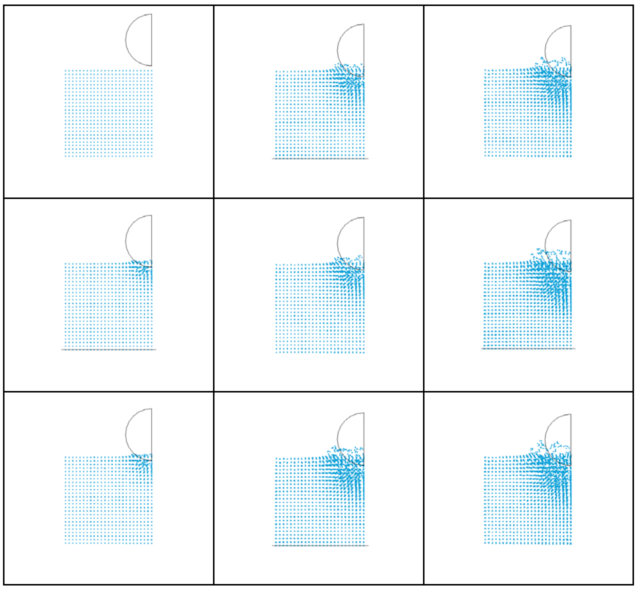
FE model of the sphere and SPH model of the water.

5.1 Evaluating the results obtained with the SPH Method.

The results of the simulation performed seemed to suggest that the SPH Method has an actual advantage in modeling the sloshing than the flow of the water. In the following figure a comparison between different solvers and experimental results are reported as well as the time history of the problem.

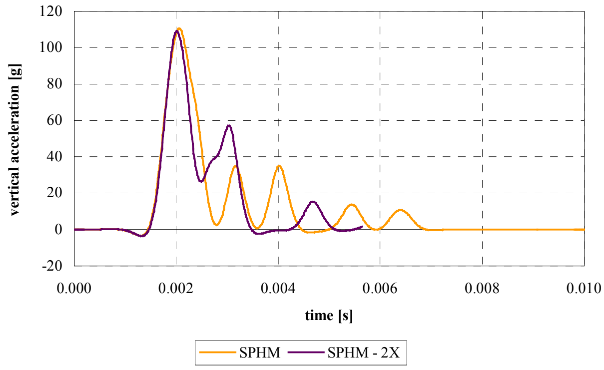
	
Comparison between SPHM and FVM (Eulerian Solver)	Comparison between SPHM and experimental data.

Several simulations have been performed to evaluate the influence of boundary conditions as well as fluid constitutive law and formulation.



5.2 Influence of the discretization.

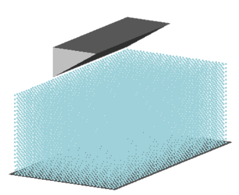
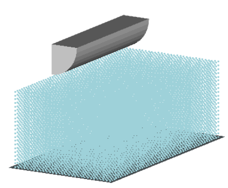
One of the most important parameter in obtaining results close to experimental data is the dimension of the fluid region and, obviously, the number of particles used to discretize it.



SPHM: influence of the number of the particle.

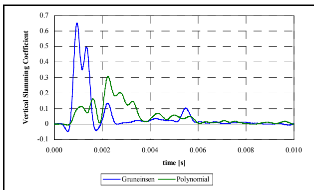
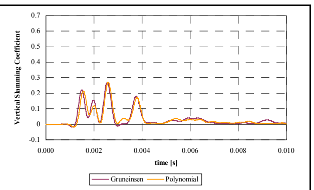
5.4 Drop-test: rigid specimens onto water

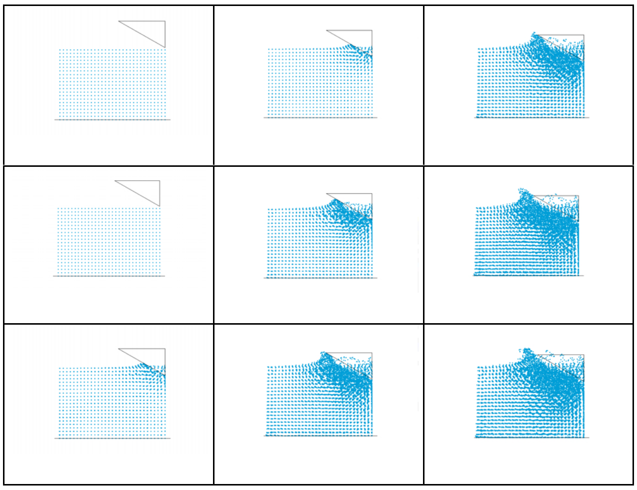
Using the data collected during the drop-test performed we tried and applied SPH Method to the analysis of the impact of a shaped rigid specimen onto water.

	
Triangular-shaped section specimen.	Semi-circular shaped section specimen.

5.4 Fluid characterization: the equation of state.

Central in the analysis of the interaction between fluid and water is the **constitutive law** used to characterize the behaviour of the water. In particular, the influence of the choice of the equation of state was investigated. Two equations of state were considered: polynomial and Gruninsen's. The results obtained are presented below together.

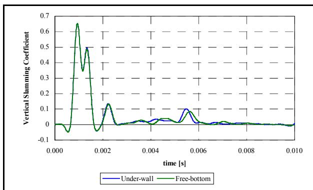
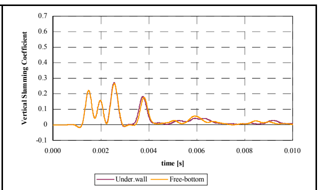
	
Semicircular-section specimen	Wedge-shaped-section specimen.



5.5 Boundary condition

In the within of the simulation performed it was possible to realize that the influence of the boundary is weak on the solution if the boundary are sufficiently far from the region where the specimen impact the water.

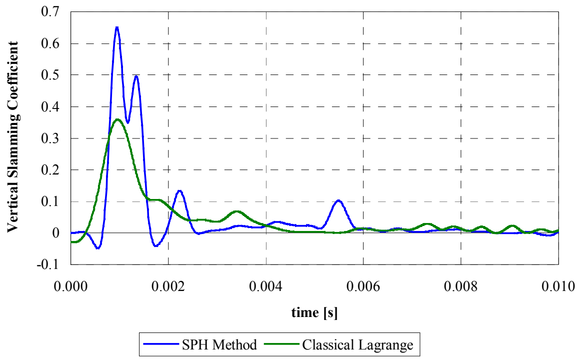
In particular, it was shown that the presence of a fixed boundary does not influence the maximum value of the VSC (and hence of the vertical acceleration), but the decay of it.

	
Semicircular-section specimen.	Wedge-shaped-section specimen.

5.6 SPH Method and classical Lagrangian approach

The SPH Method is quite different from the classical Lagrangian approach followed by the most explicit FE codes. In fact, the idea at the basis of the SPH Method consist in to apply the Lagrangian stand-point to solution of the Euler's Equations that is Conservation Laws. It does not surprise then that the results obtained are rather different.

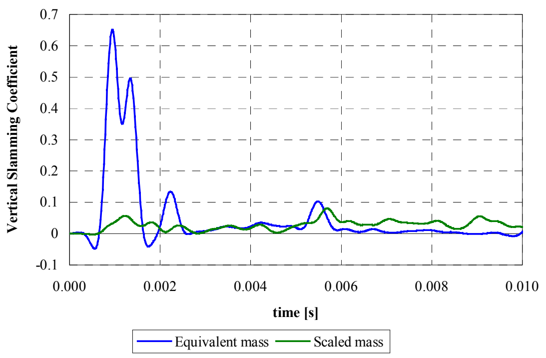
The main difference between the two methods cited above is in the qualitative representation of the event. The SPH Method allows to follows the flow of the fluid without suffering the troubles deriving from the distortion of the mesh used to discretize the body of the fluid. And this with a time-step larger than the largest time-step permitted by the classical Lagrange approach.

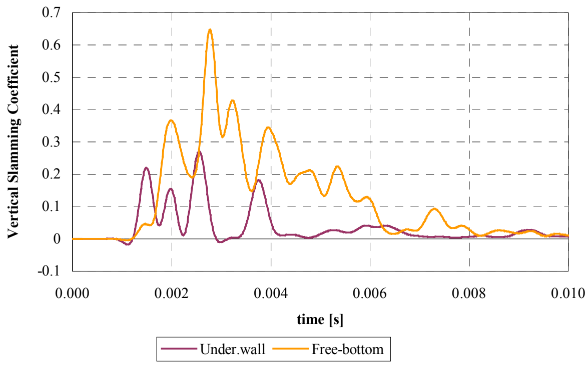


5.7 Scaling the masses

To improve the results obtained we tried and scaled the masses associated with each particle. The results got numerically better, but qualitatively worse.

The particle with a smaller mass, because of the contact with the rigid body gained an acceleration such that they were bring away from the impact region without the possibility of interact with the other particles. This circumstance cause a strange behaviour in the results obtained as shown in the figure below.



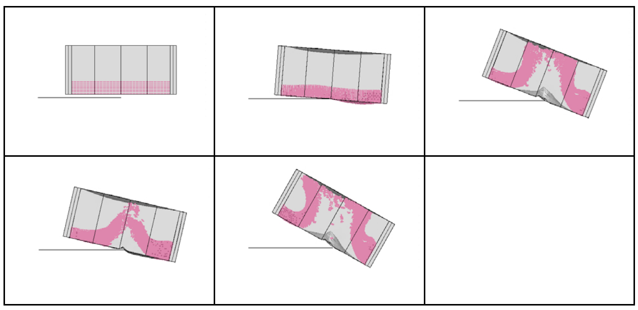


6 Other cases analyzed

In the within of fluid-structure interaction there are several other case to which could be successfully applied the SPH approach. We considered two event of particular interest: the impact with the soil of a filled tank, and the impact of a bird against the structure of an aircraft.

6.1 Impact with the soil of a filled tank

The impact with the soil of a filled tank is very difficult to analyse following classical Lagrangian approach because of the sloshing of the fluid in the tank. Adopting SPH approach it were possible to overcame this difficulties.

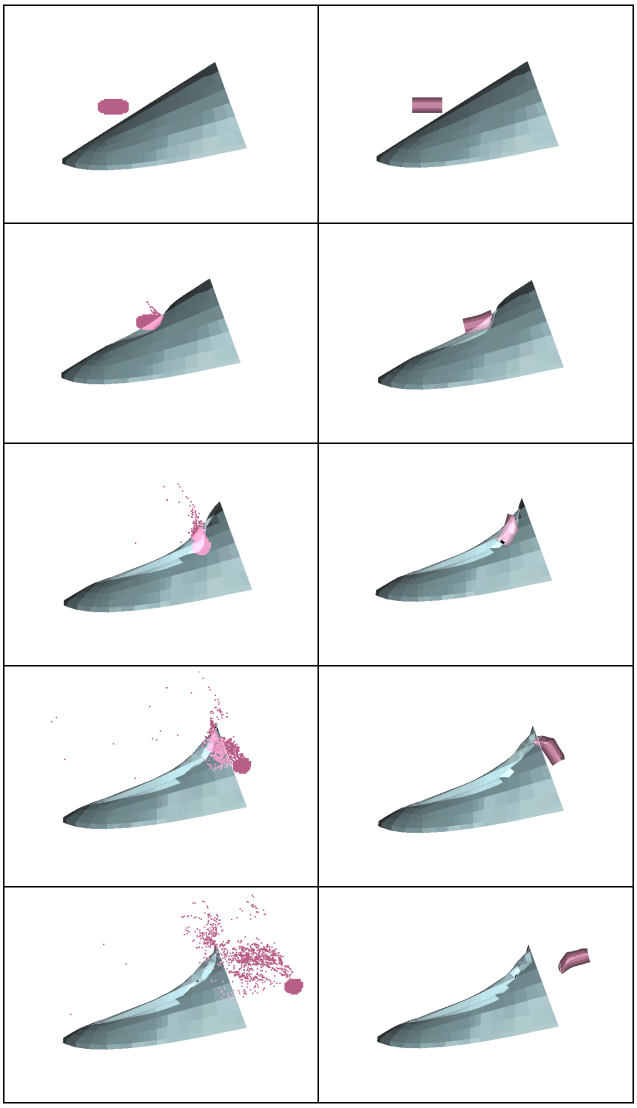


Simulation of a drop-test on soil of a filled tank.

6.2 Bird impact onto aircraft structure

As underlined previously, SPH Method allows to describe event characterized by large deformation and displacement which eventually implies huge distortion in the mesh. This circumstance is evident in bird impact analysis as shown by the figure below.

A very interesting phenomenon that SPH Method allows to analyze is the second impact of a bird onto the bulkhead behind the nose-lip typical of modern aircraft structure design to be as light as possible.



Bird impact: a comparison between SPHM and classical Lagrangian approach.

Conclusions

In the within of the study of the interaction between fluid and structure during the impact of a structure with the water, experimental evidences represent the natural begin for the developing of new numerical model.

In order to acquire new data about the impact of a (rigid) body against the water, at the Dipartimento di Ingegneria Aerospaziale of the Politecnico di Milano, it was carried on an intense program of drop tests using a semicircular-section specimen and wedge-shaped section specimen.

It was tried to measure not only the vertical acceleration of the body, but also the pressure on the surface of the specimen.

Unfortunately, the data acquired during the tests performed were representative only for those about the acceleration of the specimen whilst for those about the pressure it was possible estimate grossly the magnitude and vaguely the temporal development. These problems are related to the strong influenced of local phenomenon on resultant time-histories.

In spite of this circumstances, the substantial uniformity in the data acquired e the congruency with the data acquired by other during similar tests (but) using more sophisticated instruments, confirm the goodness of the approach and encourage to continue on this way.

In the within of the fluid-structure interaction, a new method for the description of the flow of the fluid-material was considered: the SPH Method.

Two cases were considered to acquire the necessary confidence with this new method: the impact with water of a rigid sphere, and of shaped specimens. Then two other classical example of fluid-structure interaction were investigated *only* qualitatively: the impact with the soil of a filled tank, and the bird impact onto a nose-lip.

The representation of the events above was qualitatively close with the actual dynamic of the phenomenon investigated – also if the results obtained were numerically far from the experimental data. This circumstance was manly due to the model used to characterize the behaviour of the water. Hence, further development of the method have to be in the direction of a better characterization of the behaviour of the fluid.

An other important feature of the method, we could observe, was the importance of the number of grid point required to improve the results: SPH Method require a enormous number of particle to furnish results quite close to experimental data.

Concluding, SPH Method, at the moment, seems to be more proper for the qualitative than quantitative representation of the event.

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