Experimental and Numerical Activity on Impacts on Water Surface.

Marco ANGHILERI – Luigi CASTELLETTI
Politecnico di Milano – Dipartimento di Ingegneria Aerospaziale

Abstract
The consequences of a ditching in emergency of an aircraft could be tragic for the occupants and for the aircraft itself. In fact, in spite of a deeper understanding in the within of crashworthiness, remarkable loss not only economical but also in human lives seem to justify a new interest in the study of the phenomenon.
The structure during the impact against the water undergoes to a complex system of forces which, because of their nature itself, are not easy to be modelled and then require the use of sophisticated numerical codes able to model the mutual influence between hydrodynamic loads and response of the structure.
Historically, the first attempts to model the interaction fluid-structure were based on the use of two different home-built codes – one for the hydrodynamic loads and the other for the response of the structure – which operate at iced time.
Since the beginning of eighteens new explicit analysis codes based on Finite Element Method took the place of this rudimental attempts. Codes, like ESI/Pam-Crash and LS/Dyna3D, initially developed for the analysis of automotive crash showed to work properly also in most of the cases of water impact.
Next to the main feature in the research based on (purely) Lagrangian analysis, several authors tried and model the phenomenon using codes able to couple a Lagrangian approach, for the study of the response of the structure, and an Eulerian or an Arbitrary Lagrangian-Eulerian approach, for the hydrodynamic loads, obtaining remarkable results.
Anyway, the new frontier of the study in matter of water impact is called Smooth Particle Hydrodynamic. A method of analysis based on classical Lagrangian approach, characterized by grid-less meshes.
Independently on the approach or on the code used, since it is a standard practice to calibrate the numerical model on experimental evidence, the data acquired through proper drop tests are at the base of the study of the interaction fluid-structure during the impact of an aeronautical structure against the water.
In particular, to obtain the necessary experimental data which eventually enlarge the horizon of the research, at the Dipartimento di Ingegneria Aerospaziale of the Politecnico di Milano, it was be performed an intense program of drop tests using a slender specimen with a semicircular section – a shape considered proper for the develop new mathematical models to use for the study of the phenomenon.
A detailed description of the of the tests performed and the data acquired are presented in this work.

Test Facilities

<u>The drop tower</u>

The study of the impact on the ground or on the water of structure after a free fall is one of the most interesting fields of the research in the within of crashworthiness.
Typical features, 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, this 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 structure to test, weight 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. During the fall two guide – steel cable diameter 8.mm – prevent oscillation of the structure to test. In the lower part of the tower is located the control room: from the control room it is possible to make an high speed movie of the impact from an optimal point of view.

Drop Tower

Semicircular Section Specimen

Wedge-Shaped Section Specimen

Figure 1 The specimens: the photos.

The specimens

The specimens ware realized using a technique typical in the realization of gliders which eventually made of the specimens structures light and at the same time little deformable (rigid). In particular, 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.)

Data acquisition system

Data were acquired using two different acquiring system: the Pacific Instrumentation 5400 transient recorder and an acquisition card Intelligent Instrumentation PCI-428. 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, for the first time, 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.

Accelerometers and pressure transducers

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

Technical characteristic of interest regarding EGCS-D0 accelerometer:

Range	± 250	g
Over-range	± 10000	g
Frequency	0 to 1750	Hz
Natural Frequency	2600	Hz
Sensivity	0.8	mV/g nom.
Output	± 200	MV

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.

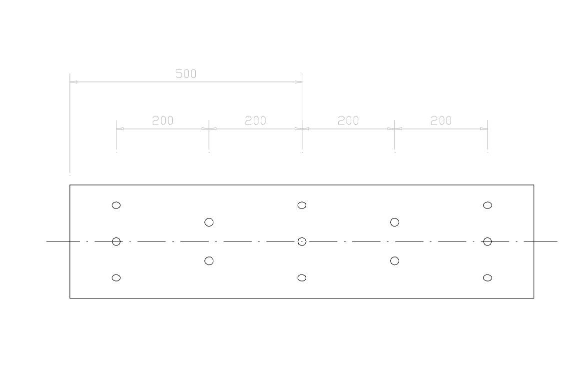
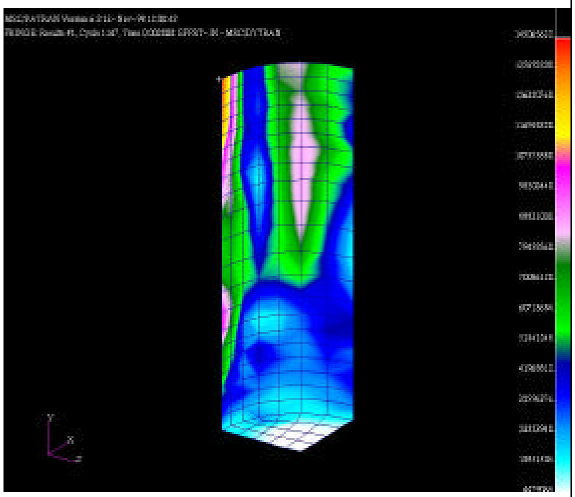


Figure 2 Location of the pressure transducers.

The pressure transducers chosen to measure the field of pressure on the surface of the specimen during the water impact were provided by Metallux SA. The measuring bridge is printed directly on one side of the ceramic diaphragm by means of thick film technology. The rear part of the diaphragm can be exposed directly to the medium to be measured. Because of the excellent chemical resistance no additional protection is normal required.
Technical characteristic of interest regarding ME505 transducer of pressure:

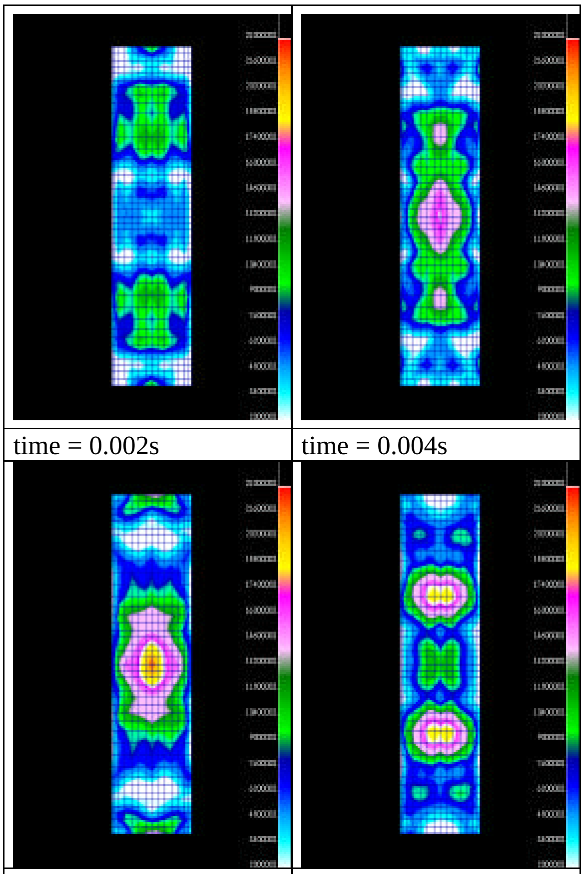
Range	400	bar
Overloading	600	bar
Dimensions	∅ 10.0 x	mm
Supply voltage	5-30	VCD
Bridge resistance	11 ± 20%	kΩ
Output signal	1.5-6.0	mV/V @ 25°C
Linearity	≤ ± 0.4	%FS
Stability	≤ ± 0.4	%FS
Thermal zero	≤ ± 0.04	%FS/K

In order to evaluate the range of the pressure transducers several numerical simulations were performed using a Finite Method code, the 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.

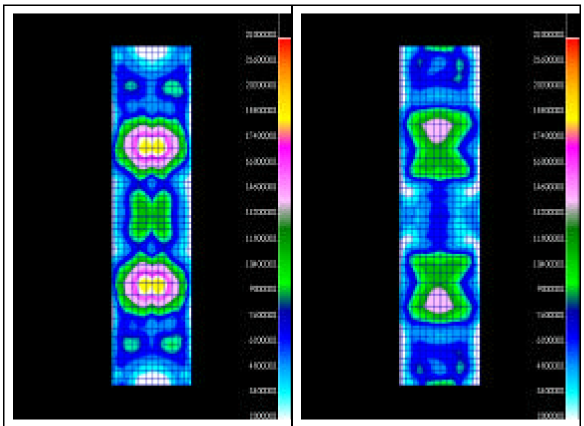


Stress on the surface of the specimen – calculated using MSC/Dytran.

Figure 3Stress on the surface of the specimen.



time = 0.002s	time = 0.004s
time = 0.006s	time = 0.008s



time = 0.010s	time = 0.012s

Figure 4 Stress on the specimen during the water impact.

High speed video

High-speed video is one of the easiest and most cost-effective ways to study fluid-structure interaction during the impact of a body against the water.

For this reason, for each drop-test was made a high velocity movie trough a Redlake MotionScope camera placed in the control room – the best place for the wide view of the event.

Description of the tests

In order to realize the planned drop-test it was hoisted within the drop-tower at about ten meters over the ground a wooden-made light truss-beam – on which it was previously mounted a steel pulley. Over the steel pulley runs a rope and at the end of this rope is fastened off the specimen.

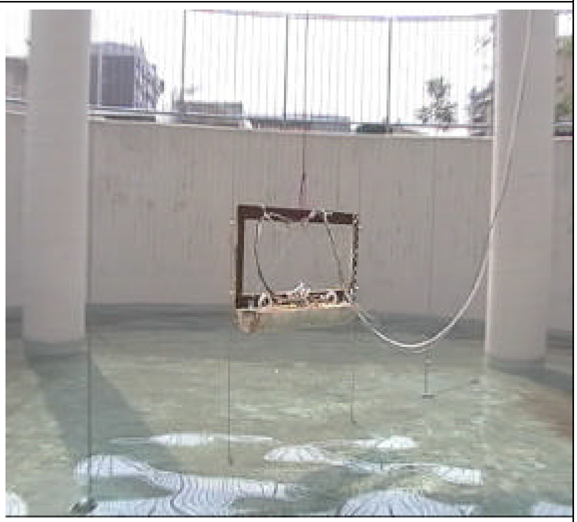
Chosen the impact velocity, the drop height were evaluated: in the formula the acceleration due to gravity was approximated for defect to compensate the influence on the motion of the specimen of both the drag of the air and the friction on the guide. Then, for the tests considered representative, the actual impact velocity was calculated using high-velocity movies of the event.

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 wooden frame and guides.



The specimen just before a drop-test.

Figure 5 Features of the drop-tests.

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.

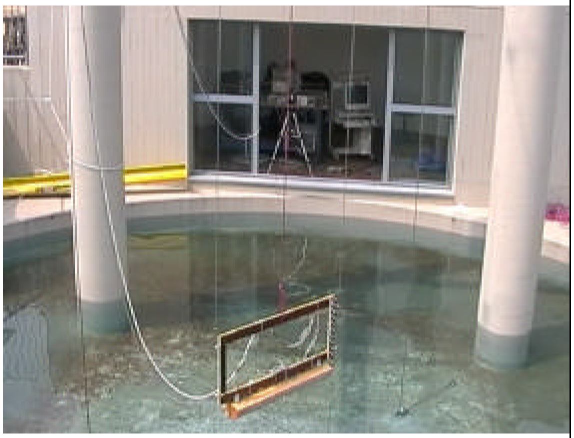


Figure 6 The control room and the specimen just before a drop-test.

V_{imp} [m/s]	a_{MAX} #13 [g]	a_{MAX} #14 [g]	Dt	a_{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

Performed tests

The total number of performed tests was much higher than the planned because of the difficulties we met with in the practical realization of the tests. 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.

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.

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.

Pressures

During the tests performed we tried to measure the pressure on the surface of the specimen using proper transducer of pressure. But, since the beginning, acquiring the pressure on the surface of the specimen presented a lot of problems. In particular, central was the remarkable decay in the quality of the datum measured: of the thirteen transducers mounted on the surface of the specimen only three of these gave measure considered representative.

The most part of the problems was mainly due to the failure of the system of protection against the water infiltration and consequently to the failure of the insulation of the cables – as shown by the progressive decay in the quality of the datum measured. The cause of the failure was the high impact velocity and deceleration rather than a lack of care in the realization of insulation.

For this reason it was possible only estimate grossly the magnitude and vaguely the temporal development.

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

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.

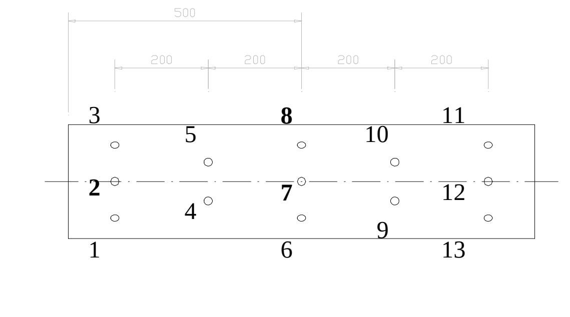


Figure 7 Pressure transducers: identification number and location.

The pressure measured, important even if little accurate are presented below. The value of the pressure is expressed in [kPa] – since 1.0kPa is about 1.0atm.

<u>Maximum pressures measured</u>

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

<u>Minimum pressures measured</u>

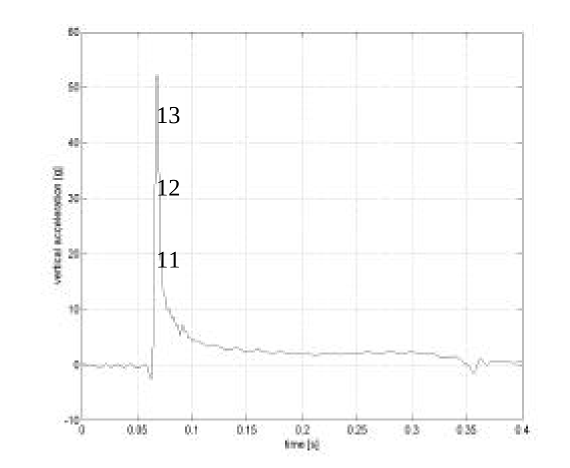
V_{imp} [m/s]	p_{min} #02 [kPa]	p_{min} #07 [kPa]	p_{min} #08 [kPa]
10.5	[-2.9643	[-5.8706	[-2.0408]
10.6	0.1624	[-0.2463	[-0.9675]
7.2	[-0.0650	[-0.0328	[-0.4636]
7.8	[-2.5321	0.0087	[-1.9789]
3.3	[-1.0758	[-0.7541	[-1.0485]
3.7	0.4253	[-0.1046	[-0.3878]

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

Drop height 7.40 m - test #1

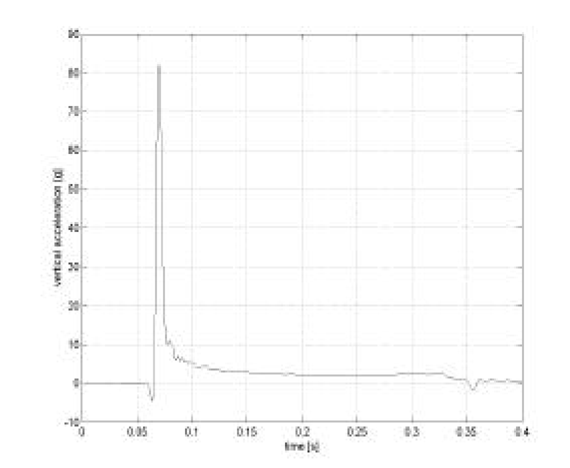
Drop height 7.40 m

Impact velocity 10.5 m/s



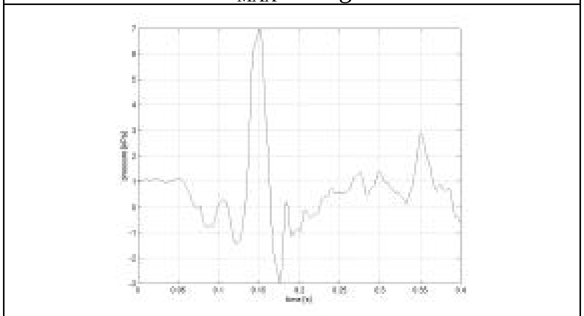
Accelerometer #14

a_{MAX}=52.2g.



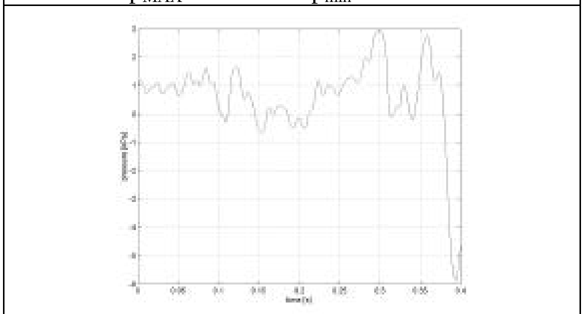
Accelerometer #14

a_{MAX}=81.9g.



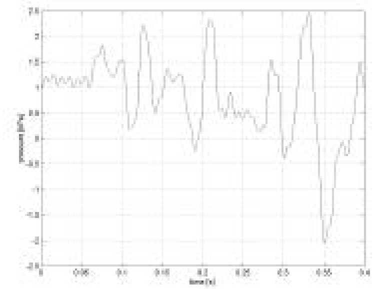
Pressure transducer ch. #2

p_{MAX}=7.0kPa – p_{min}=-3.0kPa.



Pressure transducer ch. #7

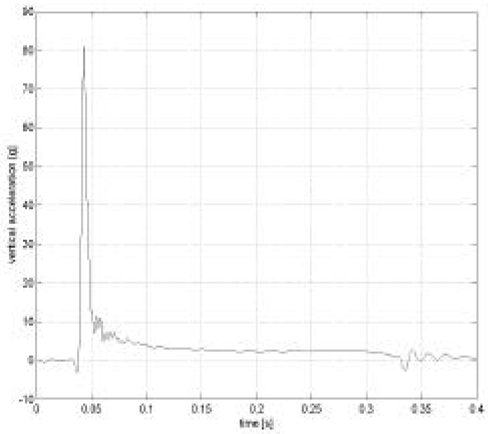
p_{MAX}=3.0kPa – p_{min}=-5.9kPa.



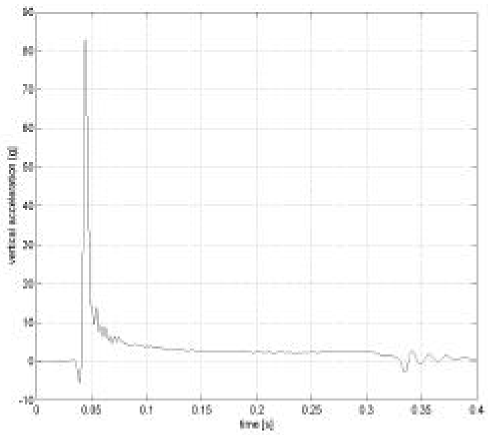
Pressure transducer ch. #8
p_{MAX}=2.5kPa – p_{min}=-2.0kPa.

Drop height 7.40 m - test #2

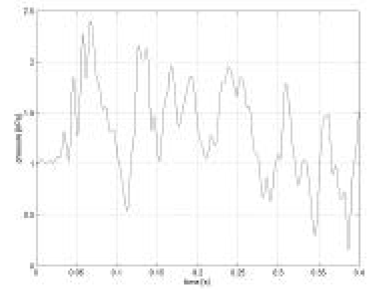
Drop height	7.40 m
Impact velocity	10.6 m/s



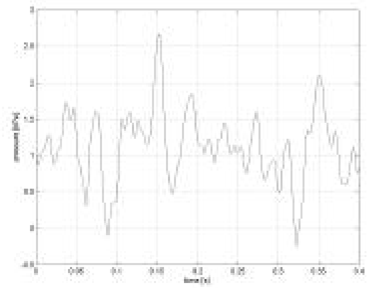
Accelerometer #14
a_{MAX}=81.0g.



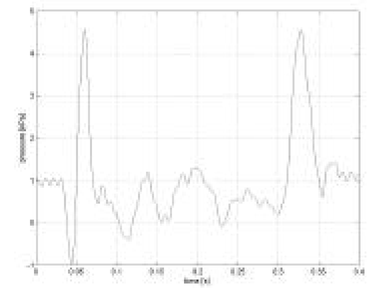
Accelerometer #15
a_{MAX}=82.9g.



Pressure transducer ch. #2
p_{MAX}=2.3kPa – p_{min}=0.1kPa.



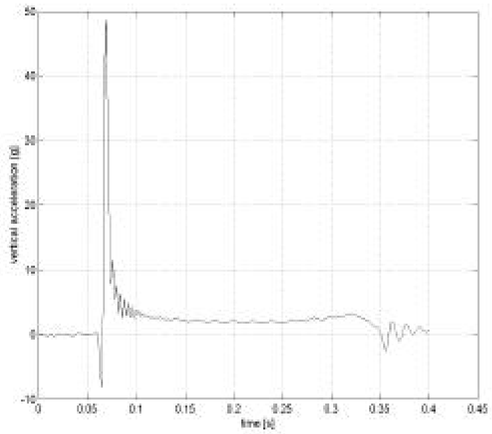
Pressure transducer ch. #7
p_{MAX}=2.7kPa – p_{min}=-0.2kPa.



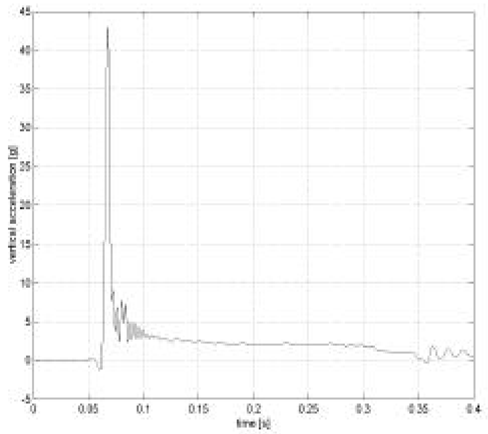
Pressure transducer ch. #8
p_{MAX}=4.5kPa – p_{min}=-1.0kPa.

Drop height 3.30 m - test #1

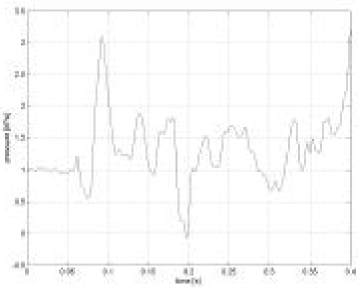
Drop height	3.30 m
Impact velocity	7.2 m/s



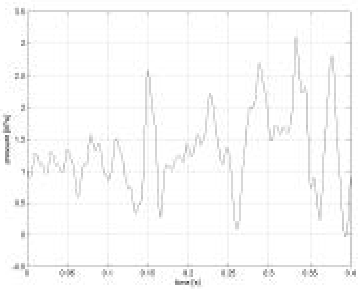
Accelerometer #14
a_{MAX}=48.6g.



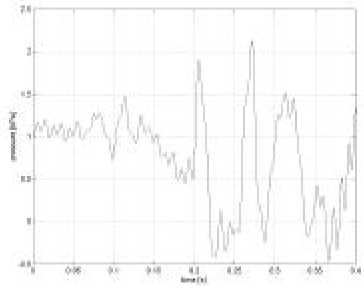
Accelerometer #15
a_{MAX}=42.9g.



Pressure transducer ch. #2
p_{MAX}=3.2kPa – p_{min}=-0.1kPa.



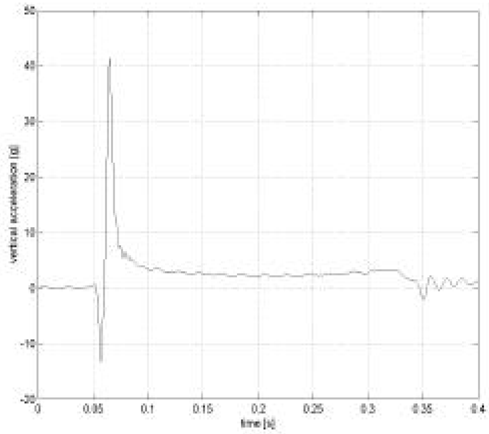
Pressure transducer ch. #7
p_{MAX}=3.1kPa – p_{min}=-0.0kPa.



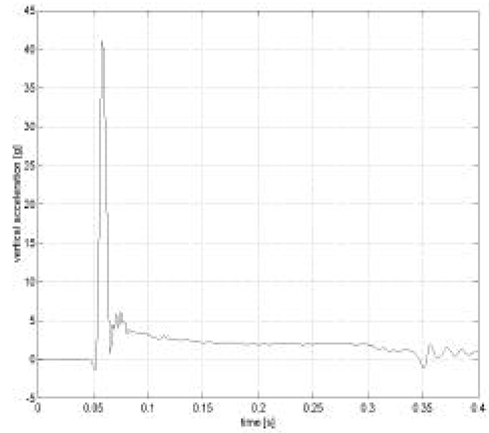
Pressure transducer ch. #8
p_{MAX}=2.1kPa – p_{min}=-0.5kPa.

Drop height 3.30 m - test #2

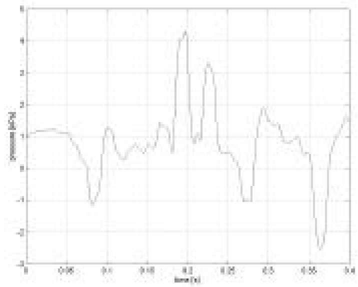
Drop height	3.30 m
Impact velocity	7.8 m/s



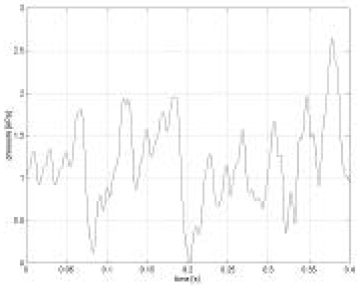
Accelerometer #14
a_{MAX}=41.5g.



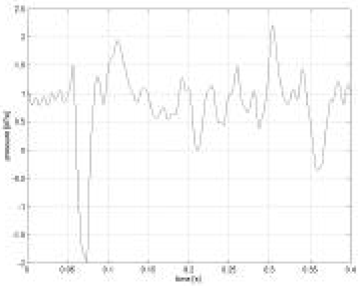
Accelerometer #15
a_{MAX}=41.1g.



Pressure transducer ch. #2
p_{MAX}=4.3kPa – p_{min}=-2.5kPa.



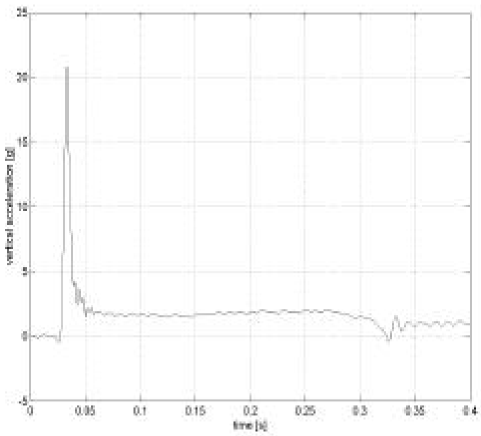
Pressure transducer ch. #7
p_{MAX}=2.6kPa – p_{min}=0.0kPa.



Pressure transducer ch. #8
p_{MAX}=2.2kPa – p_{min}=-2.0kPa.

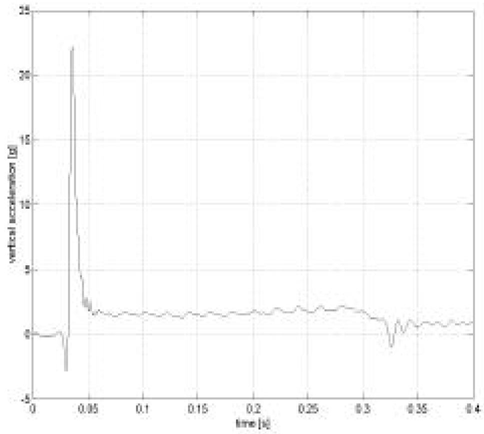
Drop height 0.80 m - test #1

Drop height	0.80 m
Impact velocity	3.3 m/s

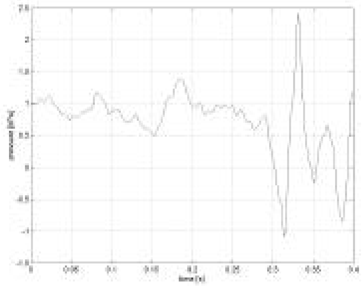


Accelerometer #14

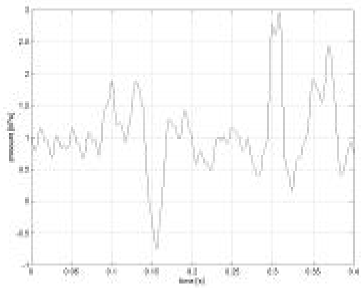
a_{MAX}=20.2g.



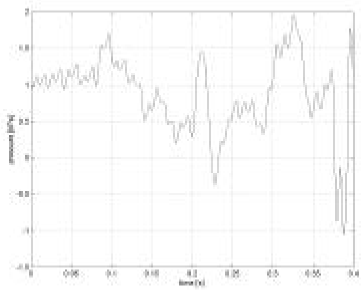
Accelerometer #15
a_{MAX}=20.8g.



Pressure transducer ch. #2
p_{MAX}=2.4kPa – p_{min}=-1.1kPa.



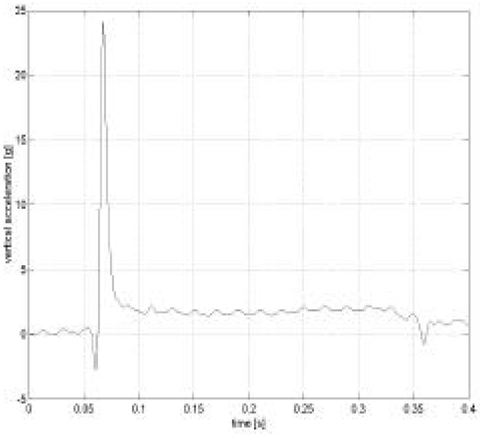
Pressure transducer ch. #7
p_{MAX}=3.0kPa – p_{min}=-0.8kPa.



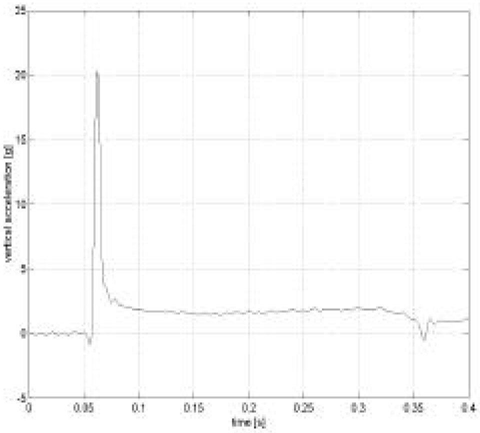
Pressure transducer ch. #8
p_{MAX}=2.0kPa – p_{min}=-1.0kPa.

Drop height 0.80 m - test #2

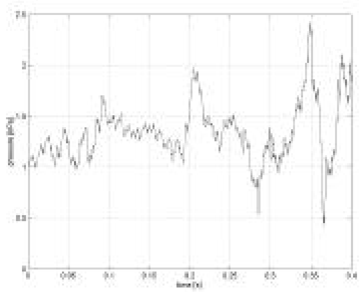
Drop height	0.80 m
Impact velocity	3.7 m/s



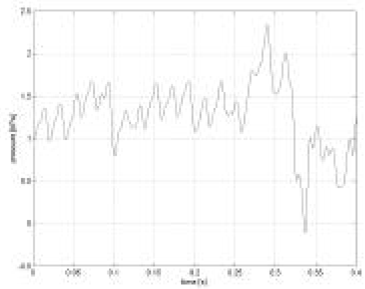
Accelerometer #14
a_{MAX}=24.1g.



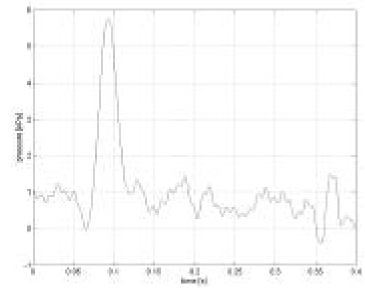
Accelerometer #14
a_{MAX}=20.2g.



Pressure transducer ch. #2
p_{MAX}=2.4kPa – p_{min}=-0.4kPa.



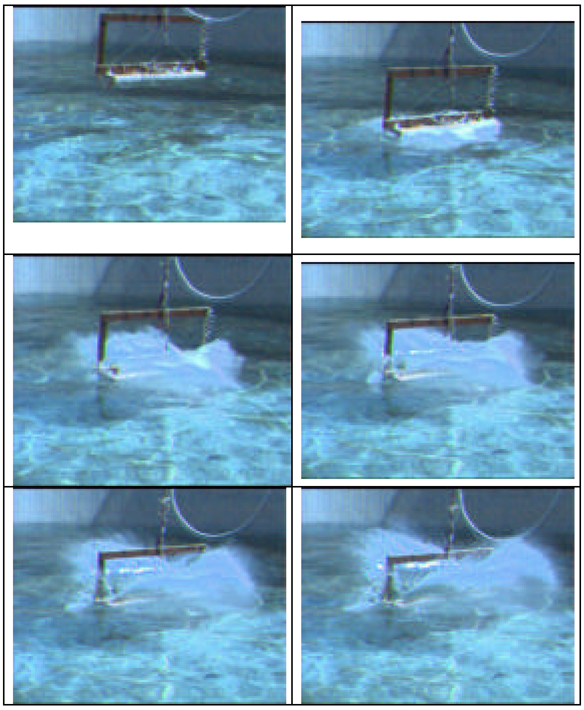
Pressure transducer ch. #7
p_{MAX}=2.3kPa – p_{min}=-0.1kPa.



Pressure transducer ch. #8
p_{MAX}=5.7kPa – p_{min}=-0.4kPa.

High velocity movie

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



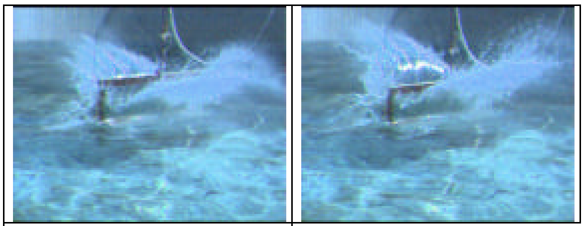


Figure 8 Frames from a high velocity movie of a drop test (drop high 7.40m).

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.

1. V.G. Szebehely, “Hydrodynamic Impact”, *Applied Mechanics Reviews*, Vol.12, N. 5, pp. 297-300, 1959.
2. J.L. Baldwin, “Vertical Water Entry of Cones”, *Naval Ordinance Lab*., White Oak, Maryland, 1971.
3. S.M. Stubbs, “Water Landing Characteristics of a Model of a Winged Re-entry Vehicle”, Nasa Langley Research Center, Hampton, Virginia, 1972.
4. “The NASTRAN SRB Slapdown Water Impact Analysis: Final Report”, Universal Analytics, Inc., Los Angeles, 1975.
5. J.L. Baldwin and H.K. Steves, “Vertical Water Entry of Spheres”, Naval Surface Weapons Center, White Oak, Maryland, 1975.
6. W.L. Thomas, “Ditching Investigation of a 1/20-scale Model of the Space Shuttle Orbiter”, Grumman Aerospace Corporation.
7. Y.W. Chang, H.Y. Chu, J. Gvildys and C.Y. Wang, “Evaluation of Lagrangian, Eulerian, arbitrary Lagrangian-Eulerian Methods for Fluid-Structure Interaction Problems in HCDA (Hypothetical Core Disruptive Accident) Analysis”, Argonne National Laboratory, Argonne, Illinois, 1979.
8. R.L. Mullen, “Numerical Methods for the Analysis of Fluid-Structure Interaction Problems”, Thesis, Northwestern University, Evanston, Illinois, 1981.
9. A.W. Troesch and C.G. Kang, “Hydrodynamic Impact Loads on three Dimensional Bodies”, University of Michigan, 1986.
10. M.Anghileri, A.Spizzica, “Experimental Validation of Finite Element Models for Water Impacts”; Proceedings of Second International Krash users’s Seminar Cranfield June 1995
11. M.Anghileri, L. Notarnicola, “Experimental Testing and Numerical Simulations of a Helicopter Fuel Tank Crash”, Proceeding 22 nd European Rotorcraft Forum, Brigthon (UK) sept. 1996.