LS-DYNA Applications in Shipbuilding

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ABSTRACT

Ship and submarine structures have long been studied thanks to finite element methods. Their large dimension and complexity, the coupling with heavy fluid and the presence of a free surface raise numerical problems on the field of dynamic analysis. This is particularly true for extreme or accidental situations such as collision and grounding, underwater explosion and severe fluid impact.

This paper describes first numerical methods and tools developed in LS-DYNA and used in the simulation of ship-submarine collisions, with a focus on the outer collision dynamics, i.e. global motion of the impacted structure. Using a new version of the rigid body dynamic program MCOL included in LS-DYNA, the influence of hydrodynamic effects is highlighted in ship-submarine collisions and in military surface ship collisions.

The second part of this paper is dedicated to dynamic response analysis of surface ship or submarines submitted to underwater explosions (UNDEX). Coupled with the Underwater Shock Analysis (USA) code, LS-DYNA is a powerful tool used to simulate the response of ships or submarines to both the shock wave induced by the detonation and the bubble gas effects. Through some examples of 3D numerical models of military vessels, the paper presents the capabilities of the LS-DYNA/USA tool and some difficulties encountered in such an analysis.

Impulse loads with high pressure peaks may occur when a ship bottom hits the water with a high velocity. This is often called "slamming". Sometimes ships suffer from local damage from the impact load or large buckling on the deck. In the last part of this paper, LS-DYNA is used to simulate such water-entries. Interaction between lagrangian bodies and multi-materials eulerian fluids (air and water) is taken into account thanks to a penalty coupling method.

SHIP-SUBMARINE AND SHIP-SHIP COLLISIONS

Introduction

The continuous increase of maritime traffic makes the risk of collisions greater and several incidents have been reported during the last few years. Extensive research has been done about prediction of structural damage and increased crashworthiness of ships, especially tankers. A seven-year research project on tanker structural failure and crashworthiness was carried out by Japan, Holland and Germany as described in (Kitamura, 1998). A numerical simulation system based on the explicit finite element code LS-DYNA was developed and verified by large-scale tanker collision and grounding experiments.

Some cases of ship-submarine collisions near the sea-surface and head-on collisions of submarines with rocks have occurred during the last few years. A head-on collision is analysed in (Monfort, 1996). A research program on submarine behaviour in ship-submarine collisions was initiated by the French Navy in 1995. The numerical simulation system with LS-DYNA described in (Kuroiwa, 1995) and in (Kitamura, 1998) has been used and improved in this research program (Donner, 2001).

LS-DYNA/MCOL tool

The ship-ship collision mechanics, described in (Pedersen, 1995) and (Petersen, 1982) can be subdivided into inner collision mechanics and outer collision dynamics :

- The inner collision mechanics is a crash problem governed by buckling, yielding and rupture of materials and assemblies. It is investigated using the explicit finite element code LS-DYNA. Collision forces are computed at this step.

- The outer collision dynamics, i.e. global motions of the two ships considered as rigid bodies under collision forces and hydrodynamic pressure forces, are computed with the program MCOL, coupled with LS-DYNA. Hydrodynamic loads are calculated with the hydrostatic restoring matrix, the added mass matrix and the frequency dependant added damping matrices computed for each ship by the 3D sea-keeping code AQUA+.

A model of the collision analysis is shown on figure 1. Only the collision areas of both ships are meshed, the remaining structure being modeled by a rigid body described by its inertia matrix and the position of its centre of mass.
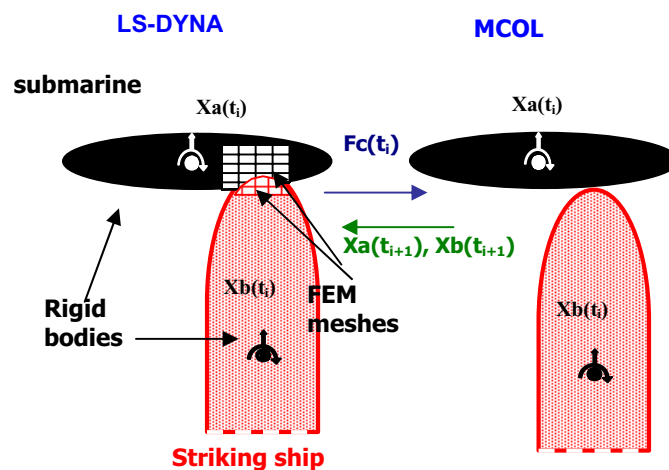

Figure 1 LS-DYNA/MCOL collision simulation system

So far only hydrostatic restoring forces, added inertia and wave effects have been considered in the MCOL program. Moreover, the rigid body mechanics implemented in MCOL was limited to small rotational movements. In order to treat correctly the outer collision dynamics of a submarine impacted by a ship, viscous damping and large rotation mechanics including gyroscopic effects have been introduced in the completely re-written MCOL program (Le Sourne, 2001). The resulting equation of ship motion can be written in the body-fixed reference frame with the following general form :

$$[M + M_\infty]\ddot{x} + G\,\dot{x} = F_W(x) + F_H(x) + F_V(x) + F_C \qquad (1)$$

where *x* denotes the earth-fixed position of the centre of mass of the ship, M and M_∞ are the structural mass and added mass matrices, G is the gyroscopic matrix, F_W, F_H, F_V and F_c are respectively the wave damping force, restoring force, viscous force and contact force vectors.

Equation (1) is integrated using a Newmark implicit scheme and the new position x, the velocity $\dot{x}$ and the acceleration $\ddot{x}$ are transmitted from MCOL to LS-DYNA for the next integration time step. Furthermore, decoupling MCOL from LS-DYNA at a given time is possible in the new version. After this time, the contact force resultant is supposed to remain unchanged and MCOL continues the calculation alone.

Ship-submarine collision

A collision scenario between a bulk carrier of 93 000-ton displacement with 10.6 m draught and 12-knot forward speed and a submarine of 3 000-ton DWT resting at periscopic immersion is investigated. A view of the scenario is shown in figure 2.
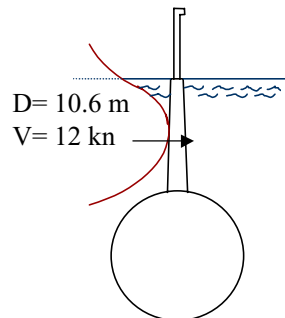

D= 10.6 m
V= 12 kn

Figure 2 Impact on submarine superstructure

The deformations of the structures at the end of two numerical simulations using LS-DYNA and LS-DYNA + MCOL with simplified bi-dimensional models are shown on figure 3. In both analyses the submarine superstructure exhibit significant bending. The global motion of the submarine is <u>purely translational</u> in the first simulation and contains a <u>large rolling component</u> in the second one, as can be expected from the displacement differences between the two ships. Thus the importance of hydrodynamic effects in ship-submarine collisions is demonstrated along with the necessity of taking into account large rotations into MCOL not accounted for in the original program.
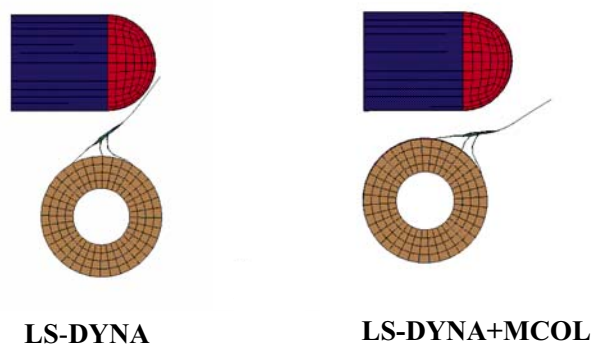

LS-DYNA   **LS-DYNA+MCOL**

Figure 3 Simulation of the bulb/superstructure collision

In this scenario, LS-DYNA was run with MCOL for 2 seconds. At this time, the superstructure separated from the bulb and MCOL continued alone during more time (here, 58 seconds). Three calculations were performed. The first without any

damping, the second with only wave effects and the last with wave effects and viscous damping. The influence of each kind of damping on the normalized roll angle is shown in figure 4. It appears that the viscous damping forces have a great influence on the rolling movement of the submarine.
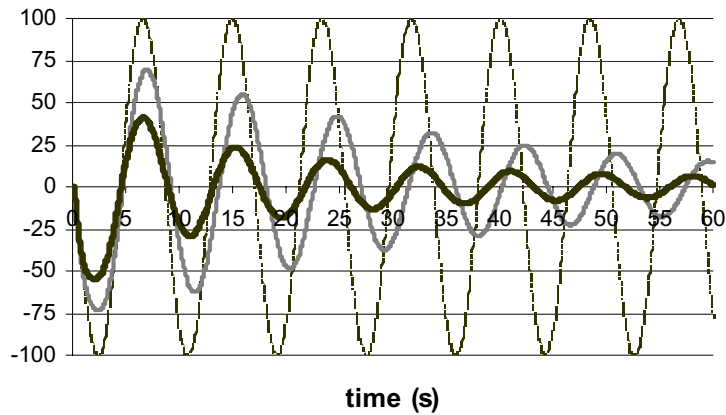

time (s)

Figure 4 Submarine normalized roll angle : ---- without damping
with wave damping
with wave and viscous damping

Ship-Ship collision

The LS-DYNA/MCOL tool presented above has been used to study the crashworthiness of real submarines impacted by different ships, at different velocities and with different impact angles. In order to validate the tool for surface ship collisions, a collision accident between two military surface ships was simulated and the numerical results were compared with the post-accident observations. The following figure shows the surface ships collision at the end of the simulation.
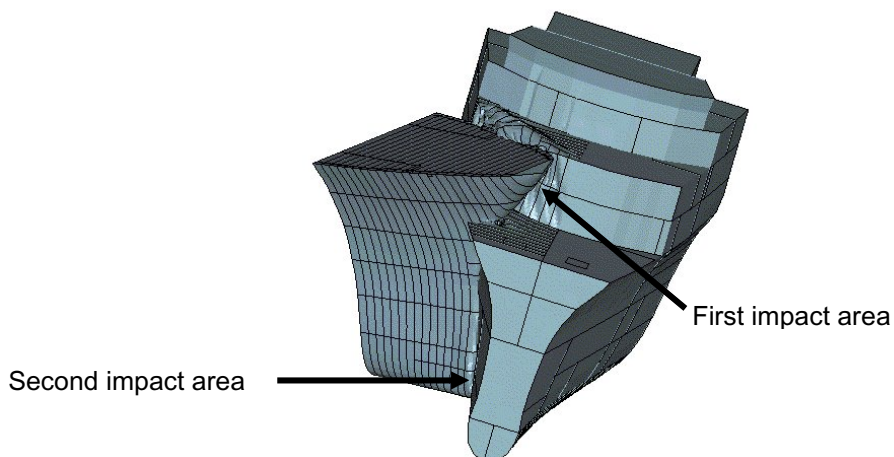

First impact area

Second impact area

Figure 5 Simulation of military surface ships collision

As shown in figure 5, the second impact was due to the strong rolling movement of the collided ship. Using LS-DYNA without MCOL, only a translational movement of the collided ship would have been obtained.

In the following pictures, the deformations calculated by LS-DYNA/MCOL are superposed and compared to the pictures taken after the collision.
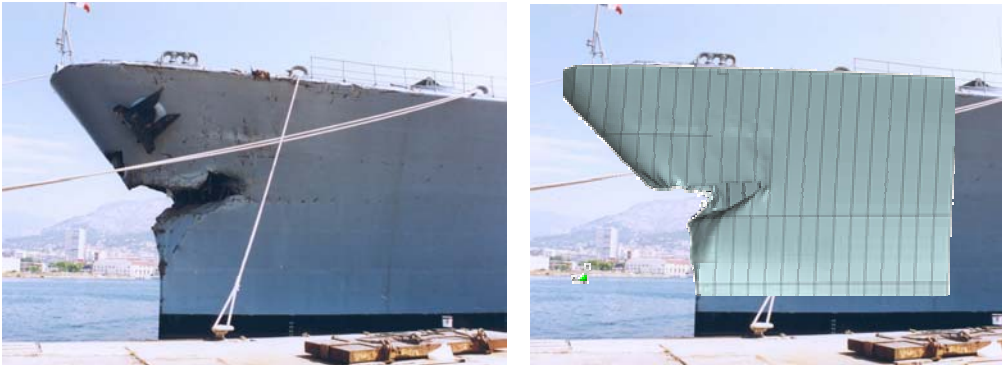

Figure 6 Indentation of the colliding ship hull

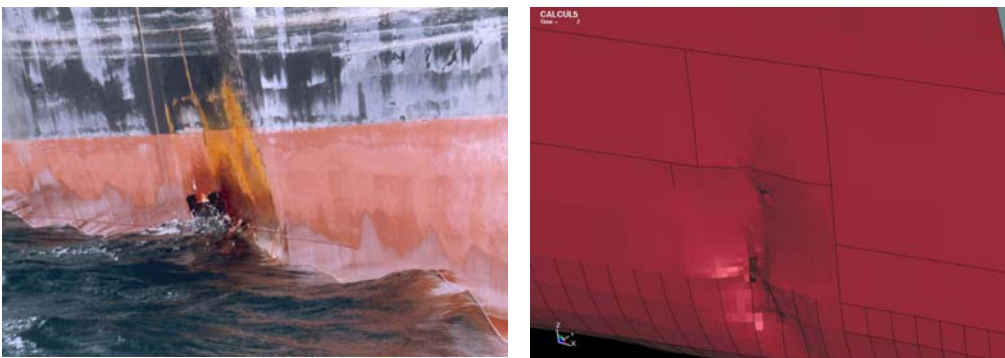**Figure 7** Rupture observed in the colliding bow

Figure 8 Indentation of the collided ship hull near the second impact area

UNDERWATER EXPLOSIONS

Introduction

Underwater explosions and their effects on floating and submerged structures represent a matter of considerable interest for designers and researchers. The most important applications of these studies are concentrated in military fields, but other important applications could be possible, for example, in offshore technology. The sequence of events associated to an underwater explosion of a typical military explosive, such as TNT, in their order of occurrence can be summarized as (Cole, 1948) :

1. Detonation
2. Shock wave propagation
3. Motion of the gas bubble

As regard the first phenomenon (generally referred to as explosion process), it involves chemical reaction of the mass of explosive which is converted into very high temperature and pressure gas. Results of this process are a perturbation of the surrounding water (shock wave) and the creation of a gas bubble first expanding against the ambient pressure and then pulsating and migrating upwards.

Shock wave and bubble pulsation induce different effects on ship structures. Bubble pulsation load has mainly low frequency components, close to first natural frequencies of the ship and involves the whole ship girder response. In this case the occurrence of a resonant condition may lead to global high amplitude response of the hull girder with severe structural damages. Moreover, the response of inboard suspended materials in term of displacement or acceleration can be affected by the ship whipping. On the other side, high frequencies dominate the shock pulse spectrum: it loads the ship structure locally, acting mainly on bottom plating and stiffening system.

LS-DYNA/USA tool

The Underwater Shock Analysis (USA) code (DeRuntz, 1989) is a boundary element code for the underwater shock fluid-structure interaction problem based on doubly asymptotic approximation (DAA) (Geers, 1978). The principal advantage of the DAA approach is that it models the interaction of the structure with the surrounding acoustic medium in terms of wet-surface response variables only, eliminating the need for fluid volume elements around the outside of the structure.

Free field shock wave input to USA is in the form of a pressure-time history associated with a spherical wave and the explosive source associated with the wave can be arbitrarily located. USA also has the capability to treat the fluid flow associated with the pulsation and migration of a spherical gas bubble due to a nearby explosion.

Coupled with USA, LS-DYNA is a powerful tool used to simulate the response of ships or submarines to both the shock wave induced by the detonation and the bubble gas effects.

Surface ship test section response to shock waves

The aim of this first UNDEX example was to simulate three underwater explosion tests carried out on a test section representative of structural members of a frigate and to compare the numerical results with the post mortem observations, i.e. local deformations like :

- the indentation of the hull measured in the bottom of the section,
- the deformations (or the lack of deformation) observed in the main stiffeners and in the bulkheads.

A non-linear calculation using LS-DYNA/USA was carried out for the three successive underwater explosions, considering only the shock wave phase of each explosion. The pressure-time history is presented in the figure 9.
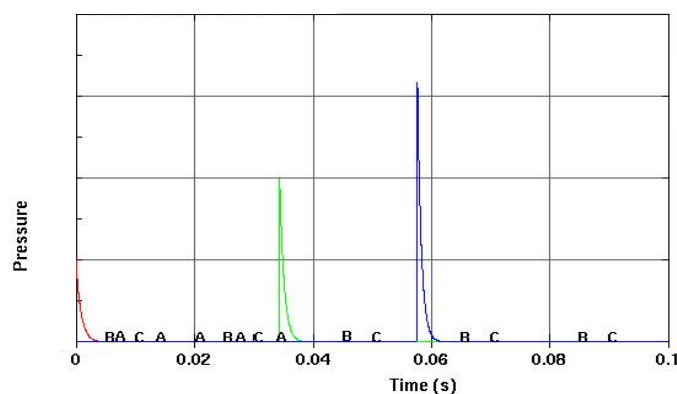

Figure 9 Shock wave pressure-time history of the three successive UNDEX

The test section hull was meshed with under integrated Belytchko-Lin-Tsai shell elements with 5 Gauss integration points through the thickness. The medium size of a shell element was about 5 cm in the half part of the section which receives the shock wave. All the girders and stiffeners pertaining to it were modeled using shell elements. In the opposite side, the medium size was about 20 cm and the longitudinal stiffeners were modeled using Hugues-Liu beam elements.

The simulation showed that the calculated hull deflections between the longitudinals correlate well with the measured one's (figure 10).
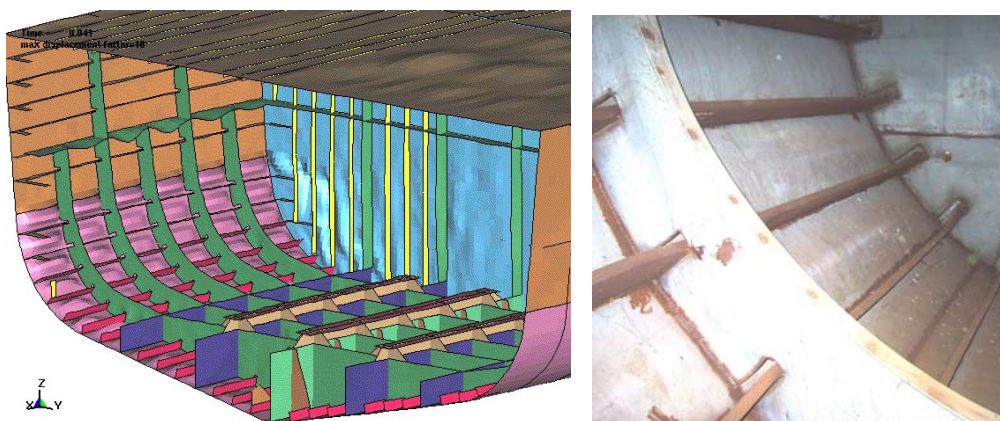

Figure 10 : Hull deflection between longitudinals

On the other hand, the transverse floor buckling observed in the structure was more pronounced in the reality than in the simulation (figure 11). This difference is probably due to the presence of initial geometric flaws and stresses in the floor, not modeled in the simulation.
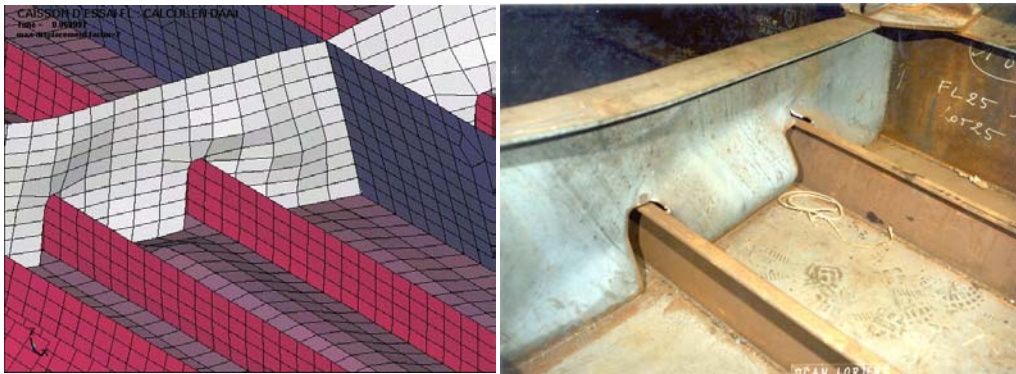

Figure 11 : Transverse floor buckling

Submarine response to UNDEX (shock wave and bubble)

The second example concerns the UNDEX response analysis of a small submarine. Contrary to the test section example, the aim of the study was to assess the elastic response of inboard suspended masses, essentially governed by the gas bubble pulses, and to compare the calculated accelerations, velocities and displacements of these masses to the experimental one's.

The model of the submarine, presented in figure 12, includes the ballast water, the suspended masses, the stiffened inside hull and the immersed outside hull with its stiffening system.
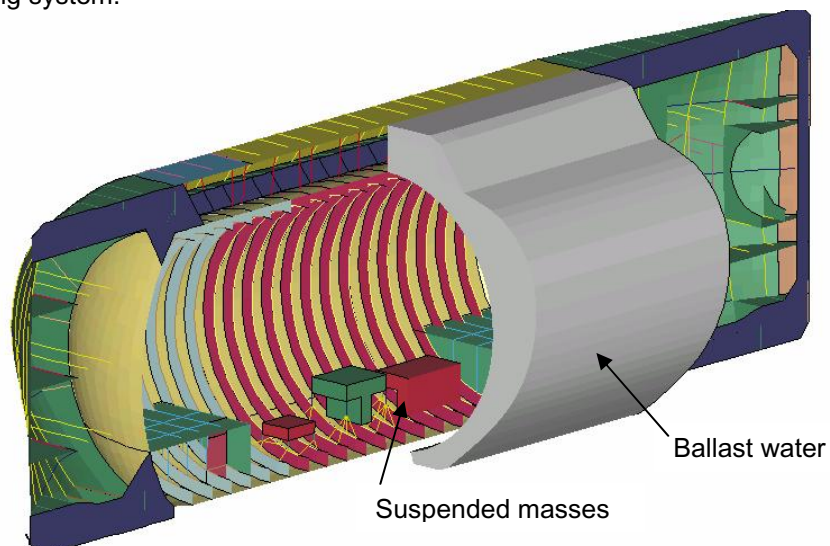

Ballast water

Suspended masses

Figure 12 : Submarine model

In USA, the bubble effects are described by the velocity-time history of a fluid particle located in the vicinity of the *standoff point* (the nearest structural node of the charge).
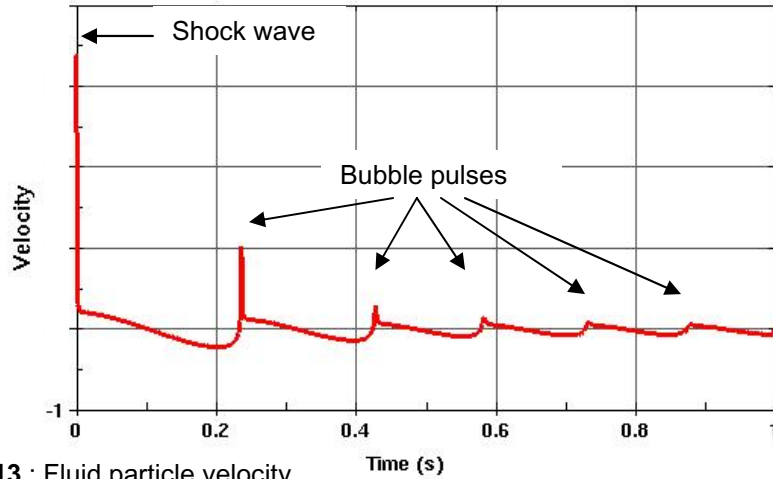

Figure 13 : Fluid particle velocity

At early time, the acoustic shock wave propagates through the outside submarine hull and then through the ballast water, as shown in figure 14. At late time, the bubble effects are predominant and the inboard suspended materials respond to the bubble pulses (figure 15).
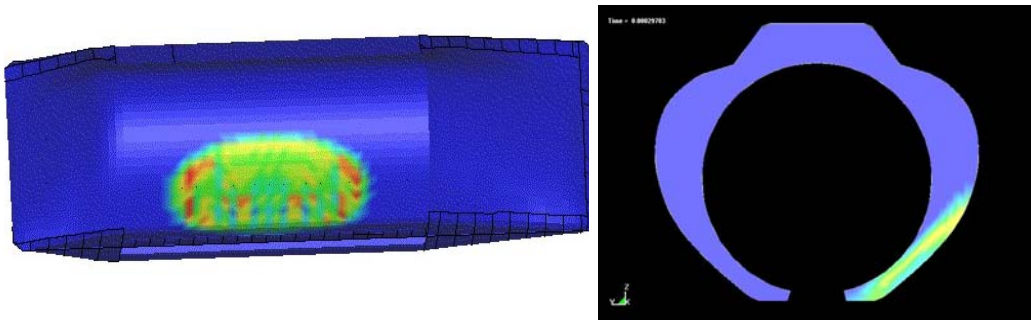

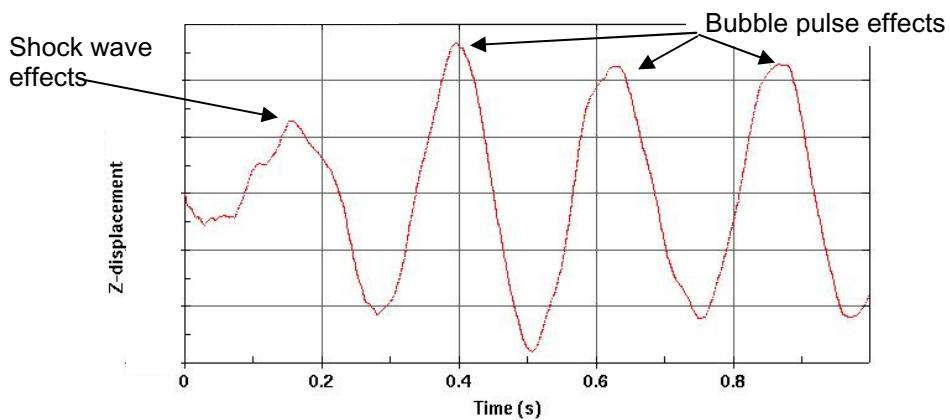**Figure 14** : Shock wave propagation in the outside hull and in the ballast water

Figure 15 : Typical displacement response of an inboard suspended material

THREE DIMENSIONAL MODELIZATION OF SLAMING IMPACTS APPLICATION TO FAST SHIPS

The dynamic structural response of a fast ship excited by slamming impacts may bring an important contribution to its damaging process. The work presented here focused on the numerical simulation of slamming. It was a part of a larger work aiming at simulating the whole response of the ship, from its seakeeping to its fatigue response, under both low frequency and such impulsive loads.

The approach to study slamming impacts was based on the use of the LS-DYNA multi-materials eulerian fluids / lagrangian solid coupling capabilities.

In a validation step, the drop-test of a V-shaped cylinder has been simulated in two and then three dimensions. In an application step, the water-entry of the bow of a fast monohull was studied in 3D.

Modelization of the fluid and solid domains

Fluids (here air and water) were modelized as multi-materials eulerian (composite stress tensor calculated thanks to the Volume Of Fluid method). The interaction between eulerian fluids and lagrangian solids was taken into account thanks to a penalty coupling method. The developments on both last points have been strongly reinforced in recent years by Olovsson and Souli (Olovson, Souli, 2000) (Olovsson, Souli, 2001). In particular, an interface reconstruction method has been implemented (version 960) leading to improved transition zones between gas and liquid. The behaviours were modelized with a polynomial equation of state.

The solids were modelized as rigid lagrangian. All the calculations were performed with a penalty coupling method limited to the normal direction of the solid surface (so the sliding was allowed in the tangent direction) and with the material of largest density only (namely with water). Sizes of fluid and solid elements of volume were taken similar, as advised to get the best coupling quality.

Validation

Some comparisons have been made with the experimental results from Zhao and al. (Zhao and al., 1997). Their experiments consisted in free-falling drop-tests of cylinders. A V-shaped section with 30 degrees deadrise angle was tested in particular, what has been studied here. It is worth noticing that the flow of liquid was not prevented at the longitudinal extremities of the test sections.

First, calculations were performed in two dimensions (only one layer of elements of volume in the longitudinal direction). A finite element model is shown in figure 16. The dimensions of the fluid domain have been chosen by studying the convergence of the results according to the distance between the frontiers and the solid. Only the frontier located at the top of the model was let free in order to avoid effects of eventual local overpressures of the gas on the liquid spray. The initial state coincided with the instant of contact. Only the initial velocity was imposed and gravity was taken into account for both the fluids and the solid.

The figure 17 shows the free-surface of liquid after the spray has reached the knuckles. The detachment of liquid at the spray head was due to both an imposed cutting pressure and inertial effects.

The filtered time history of the hydrodynamic force acting on the solid is presented in figure 20. When unfiltered, it is affected by numerical noise although the interface reconstruction method contributes to reduce this (has been noted by comparing the 950 and 960 versions). A thesis (by N. Aquelet, with M. Souli for advisor) has begun in October 2002 at the Mechanical Laboratory of Lille (France) to globally improve this kind of results. It has been shown that the largest part of numerical noise is due to the coupling method. To make it decrease, a damped penalty coupling method has been developed (Aquelet and Souli, 2003).

The figure 20 shows that the 2D numerical results overestimate the experimental results, what is not surprising as the flow of liquid is allowed at the extremities of the test section in the experiment. So, this difference is explained by 3D effects.
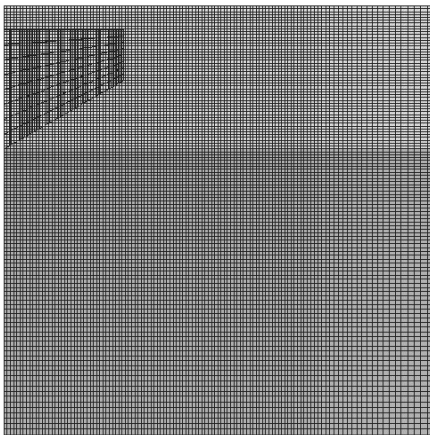

Figure 17 Shape of the jet 15 ms after impact.

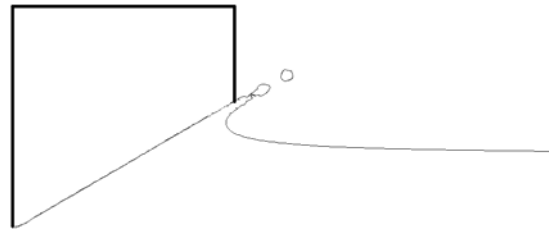**Figure 16** 2D model of a V-shaped section.

Consequently, so as to make a more pertinent comparison, a 3D modelization of the test section has been investigated. In order to reduce the cost of the simulation, the convergence of the results regarding the elements size has been studied in 2D. The reference size of the elements in the cross-section of the 3D model was deduced from this parametric study.

In the longitudinal direction, the fluid mesh was refined near the extremities of the cylinder test section (see fig. 18) in order to get the simulation of the fluid flow more precise in this zone, which is responsible for the 3D effects. The tridimensional flow can be observed in figure 19, near the extremities of the test section in particular.

The 3D numerical results have been added in figure 20. The following conclusions can be derived :
- It was verified that simulations with initial velocity only and velocity history imposed (both given by the experiment) give similar results.
- Numerical and experimental histories have similar shapes. The difference at the maximum force is lower than 5 % (for velocity history imposed). The influence of the longitudinal mesh density on the force history will have to be studied.
- As foreseen, the 2D numerical force overestimates the 3D one of about 20 % at the maximum. The same gap was reported in (Zhao and al., 1997).

These results confirm that the modelization used is suitable for the simulation of water entries.
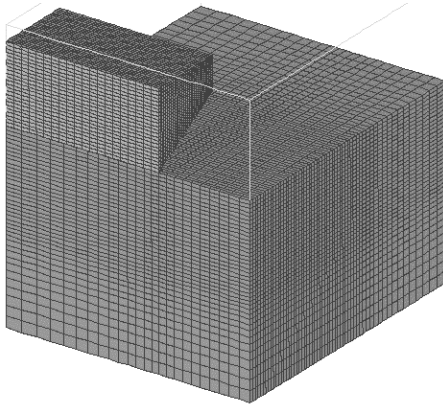

Figure 18 3D model for the drop-test of a cylinder with V-shaped section (gas domain represented by its contour).

Figure 19 Free surface 25 ms after impact (the model has been deliberately completed by its symmetries to improve the display).
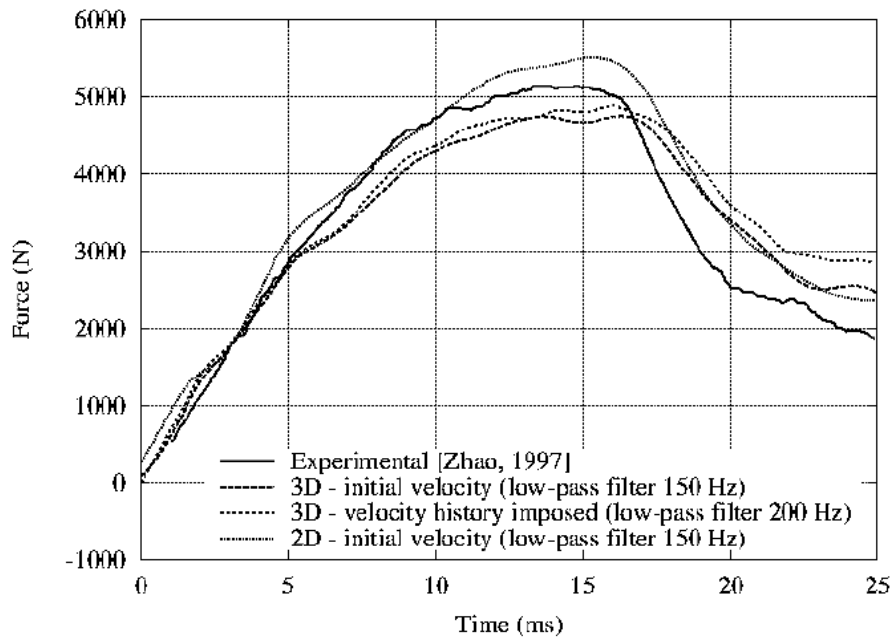

Figure 20 : Force history for 200 mm length. Comparison between experimental and 2D, 3D numerical results.

Application to a fast monohull

For the time being, the sea is considered at rest in the initial state, the whole keel of the ship being just in contact with the free surface of water, the FE model is limited to the part of the ship subject to the impact (the fore part) and the kinematics is imposed (time history of six degrees of freedom).

The figure 21 shows the model of fast monohull used (front quarter) and the associated liquid domain ; figure 22 is a picture of the simulation.
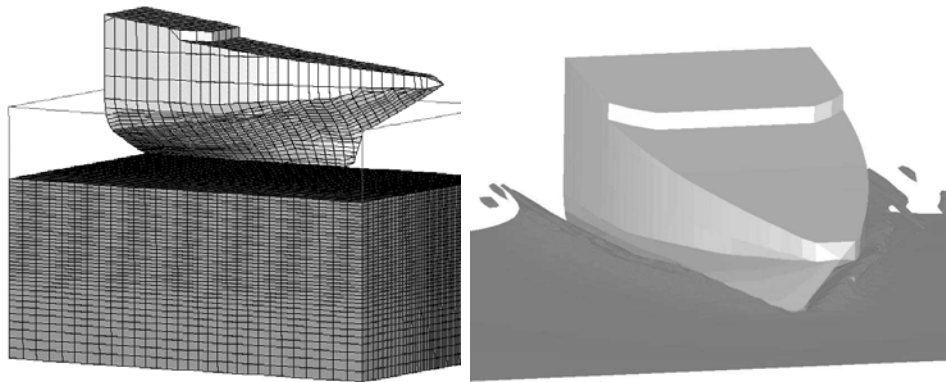

Figure 21 Finite element model of the fore part of a fast ship and liquid domain.

Figure 22 Deformed free surface.

Some recordings of vertical acceleration were available for the fore part of the ship (by courtesy of Bureau Veritas). A particular peak of acceleration corresponding to a slamming impact has been detected and a vertical velocity history has been obtained by time integration.

Firstly, calculations have been performed with vertical kinematics only. The resulting vertical force history is presented in figure 23. This history looks like a peak with a strong rise. Its duration corresponds to the duration of the contact between the solid and the liquid.

Secondly, forward speeds (21 and 33 knots) have been added to the previous vertical kinematics. The force history is compared to the result with vertical velocity only in figure 23. The following differences can be noticed :
- The maximum force is higher with forward speed. This is certainly due to the lift phenomenon produced by the longitudinal flow.
- The duration of the peak is larger with forward speed. The forward speed makes the contact last a longer time since the solid continuously meets water at rest.
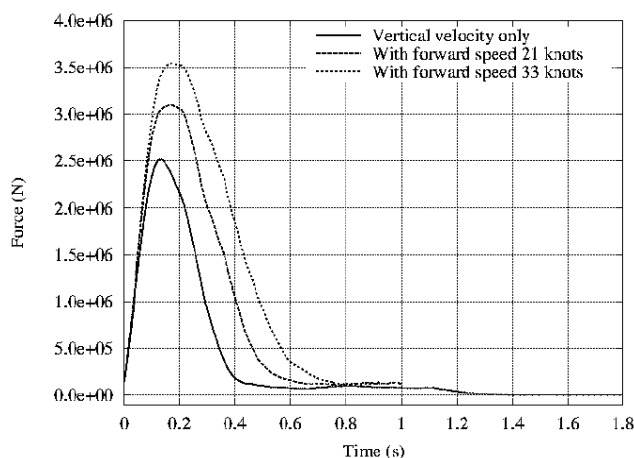
Figure 23 : Influence of the forward speed on the vertical force history (filtered).

CONCLUSIONS

Collisions

The improved MCOL program, included in LS-DYNA v960, takes into account the hydrodynamic viscous forces and large rotational movements. The LS-DYNA/MCOL models for ship-submarine and ship-ship collisions have been validated by comparison with experiments and accident observations. The difficulty of such a study is to determine the fracture strain input to LS-DYNA. The next step will be to develop more realistic fracture models, independent of the mesh size and able to take into account the bi-axiality or tri-axiality of the stress state near the fracture areas.

Underwater explosions

LS-DYNA is an efficient tool to analyze the response of a submarine or a surface ship to UNDEX. In order to take into account the hull cavitation effects due to the reflection of the incident pressure on the ship hull or on the free surface, finite volume of the surrounding fluid have to be modeled, using an appropriate material law in LS-DYNA. The remaining work is first to find the best way to model the cavitation and then to validate the developed fluid-structure models by comparison with experimental explosions located near the free surface. Using multi-scale models may be also interesting in order to treat both whipping and local damages in the same model.

Slamming

A LS-DYNA 3D modelization of water entry has been applied to the slamming of a fast monohull fore part. Such impulsive pressure fields can be used to simulate the response of the ship (during loading and then free vibrations).The next step would be to improve the representation of the initial liquid state (any initial free surface with associated velocity and pressure fields). Another important research topic would aim at performing calculations with only initial kinematic conditions for the ship fore part model. In order to describe the interaction with the rest of the ship, the LS-DYNA model would be coupled with a rigid body modelizing the rest of the ship and submitted to hydrostatic and hydrodynamic forces, in a similar approach than for ship collisions.

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