

Evaluation of a Euler/Lagrange coupling method for the ditching simulation of helicopter structures

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Abstract

This paper deals with the evaluation of a Euler/Lagrange coupling interface implemented in the RADIOSS code, to cope with the modelling of fluid/structure interaction. In the first step, a parametric study on the structure/fluid mesh sizes ratio and the contact gap is performed, through the simulation of a rigid flat plate impact on water. In the second step, the method is evaluated by simulating water impact tests performed at CEAT (French aeronautical test centre) on rigid flat and triangular shapes. The numerical results are compared to the experimental data and allow one to conclude that such a Euler/Lagrange coupling interface constitutes a convenient solution for modelling fluid/structure interaction, in terms of physical phenomenon modelling, as well as simulation of high penetration inside water. In the final step, works are applied to the simulation of the ditching of a full-scale helicopter structure and confirm the relevance of the method for such a problem. The results are additionally compared with those generated within the research GARTEUR group AG15, which addresses the same topic with the SPH (Smooth Particle Hydrodynamics) method.

Keywords: helicopter, ditching, interface, Euler, Lagrange.

1 Introduction

Standard solutions for fluid/structure interaction modelling, based on Finite Element Lagrange or even ALE (Arbitrary Lagrange Euler) formulations, face well-known limitations [1] – mesh distortions leading to numerical instabilities



(negative volumes) and high CPU consumption (time step decrease) – resulting from the direct coupling between the soft and solid media meshing. More recent formulations using SPH (Smooth Particles Hydrodynamics) formulations permit one to get rid of most numerical issues but are usually too CPU consuming for industrial applications. The present work investigates a new methodology involving a Euler/Lagrange coupling interface recently implemented in the Radioss code, in which the fluid and structure meshes are fully independent. In the first step, a parametric study on the structure/fluid mesh sizes ratio and the contact gap is performed, through the simulation of a rigid flat plate impact on water. In the second step, the method is evaluated by simulating water impact tests performed at CEAT (French aeronautical test centre) on rigid flat and triangular shapes. In the final step, works are applied to the simulation of the ditching of a full-scale helicopter structure. The results are compared with those generated within the research GARTEUR group AG15, which addresses the same problem with the SPH (Smooth Particle Hydrodynamics) method.

2 Fluid/structure interaction modelling methodology

The modelling methodology relies on a contact interface – Radioss code – which permits one to couple soft and solid media and controls the contact between slave nodes (material grid) belonging to the Euler fluid medium and the master surface of the Lagrange solid medium. Two parameters are mesh dependent – the gap and the stiffness – defined by relations (1) and (2) respectively, where l_f is the fluid finite element size (Euler or ALE), ρ is the highest fluid density, V is the phenomenon relevant velocity and S_{EF} is the area of the solid elements media.

$$\text{Gap} = 1.5 \times l_f \quad (1)$$

$$St_{fac} = \frac{\rho V^2}{\text{Gap}} S_{EF} \quad (2)$$

The fluid media (air and water) is modelled using 3D finite elements associated to a bi-phase liquid/gas constitutive EOS (3)–(7), where ρ is the current density, ν is the kinematic viscosity, s_{ij} and e_{ij} are the stress and strain deviators, ϵ_{ij} is the strain tensor, γ is the perfect gas constant and relation (7) gives the balance between water and air.

$$s_{ij} = 2\rho\nu e_{ij} \quad (3)$$

$$\sigma_{kk} = \lambda \epsilon_{kk} \quad (4)$$

$$\Delta P_l = C_l \mu \quad (5)$$

$$\Delta P_g = P_0 \frac{\rho^\gamma}{\rho_0^\gamma} - P_0 \quad (6)$$

$$P_l = P_g \quad (7)$$

In a preliminary step, impacts on water of two-dimensional cylinders and wedges were simulated and confronted to analytical data available in the literature [2]–[7]; the results proved that the method was in good agreement with theoretical models.



3 Evaluation of the methodology – parametric study

In the following paragraph, a parametric study on the fluid/structure mesh size ratio and the gap influence is performed. The selected simulation case is the impact of a flat plate.

3.1 Mesh size dependency

The mesh of the plate is whatever fixed to 10mm, while the fluid (air and water) mesh varies from 2mm to 20mm, leading to fluid/structure mesh sizes ratios from 1/5 to 2. The gap and the stiffness of the F/S interface are computed using relations (1) and (2). Two series of simulations are performed considering 2 plate initial velocities, 10m/s and 1m/s. As previously recalled, the stiffness being calculated according to the velocity, one set of parameters is therefore defined for each velocity. Numerical results are presented in Figure 1 for both plate initial velocities, in terms of peak force in the interface. One can observe that the peak force is very influenced by the fluid mesh (i.e. the smaller the fluid mesh is, the higher the peak is), this tendency being similar whatever the initial velocity of the plate. Moreover, as shown in the following table, one also observes that the effect of the fluid/structure mesh size ratio, in terms of variation of the peak force with respect to the ratio 1, is higher for the lowest impact velocity.

Table 1: Results of the parametric study on the mesh size dependency.

Mesh size ratio	10 m/s		1 m/s	
	Max force (N)	Deviation (wrt ratio=1)	Max force (N)	Deviation (wrt ratio=1)
1/5	2450	133%	61	190%
1/2	1600	52%	30	43%
1	1050	0%	21	0%
2	820	-22%	10	-52%

The CPU cost widely increases from the smaller fluid mesh size to the higher one (x220), which results from the time-step decrease (from 0.15E^{-2} to $0.11\text{E}^{-2}\text{ms}$, noting that the time-step switches from the solid elements to the fluid elements for the higher fluid mesh size case), the increase of fluid elements number in the simulation and the increase of slaves nodes taken into account in the interface.

3.2 Gap dependency

The influence of the contact gap is studied without changing the theoretical contact stiffness given for the theoretical gap. Computations are performed considering a F/S mesh ratio equal to 1/2 and an initial velocity of the plate equal to 10m/s. Two simulations are performed, with a twice bigger or twice smaller theoretical gap, for comparison with the theoretical gap case. Numerical results are presented in Figure 1 and show that the contact peak force is largely influenced by the interface gap i.e. the higher the gap is, the higher the peak

force is. The CPU cost is very similar for the two lowest gaps, and only increases for the one that is twice as big (x1.2), which involves the highest number of slave nodes taken into account in the interface.

3.3 Synthesis of the parametric study

As shown in Figure 1, the fluid/structure mesh size ratio and the contact gap highly influence the contact peak forces. When analysing results with respect to the peak force obtained for the recommended configuration (mesh ratio equal to 1 and theoretical gap), one can also notice that no convergence seems to establish for the range of parameters investigated in this study (variation of the F/S mesh ratio from 1/5 to 2 and variation of the gap for twice or half of the theoretical value), as well in terms of mesh ratio as of gap.

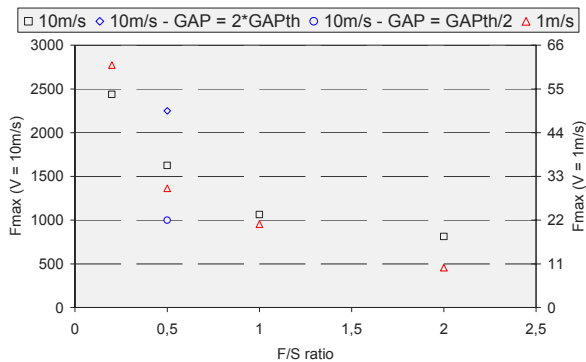


Figure 1: Results of the parametric study.

4 Simulations of water impact tests

In the following paragraphs, water impact tests of quasi-square and triangular shapes performed at CEAT (Centre d'Essais Aéronautiques de Toulouse) are simulated in order to evaluate the prediction capacity of the method. Numerical/experimental comparisons are performed in terms of force supported by the specimen (similar filtering sequence applied for the tests and simulations).

- In the tests, this force is measured by 2 load beams – referenced EFCDR and EFCGA in the following figures – connecting the sample to the upper rig,
- In the simulation, this force is post-treated from the interface force – referenced EFC (interface) in the figures – or from section forces in the load beams – referenced EFC (fem) in the figures.

The simulated configurations are shown in Figure 2, for the quasi-square and triangular shapes. Only a quarter of the physical problem is modelled, with appropriate symmetry boundary conditions. The fluid area is modelled in 2 areas, with a finely meshed area in the impact zone, including the impacting structure and extra space around it (from a 10mm size under the structure – i.e.

fluid/structure mesh ratio of 0.4 to 50mm) and a coarse meshed area for the rest of the water volume. The connection between both water volumes is done with a Fluid/Fluid interface. External nodes of the fluid domain are given fixed boundary conditions. The structure is made of the quasi-square or triangular target, the metallic beams and a plate that models the test rigs.

4.1 Analysis of the water impact tests of a quasi-square shape

Two impact velocities are modelled (10 m/s and 2 m/s). Numerical results are compared to experiments in Figure 3 for both velocities, with the model evolution shown for the 10m/s impact velocity only.

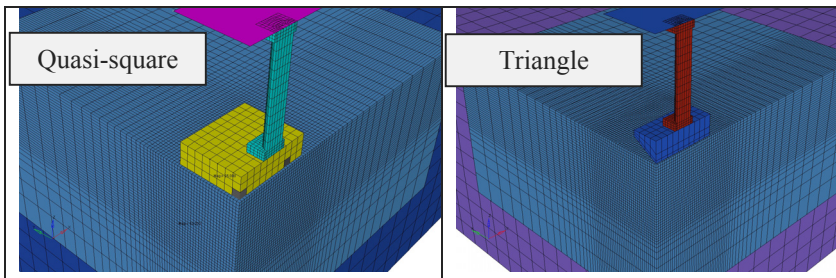


Figure 2: FE model of the simulation of water impact tests.

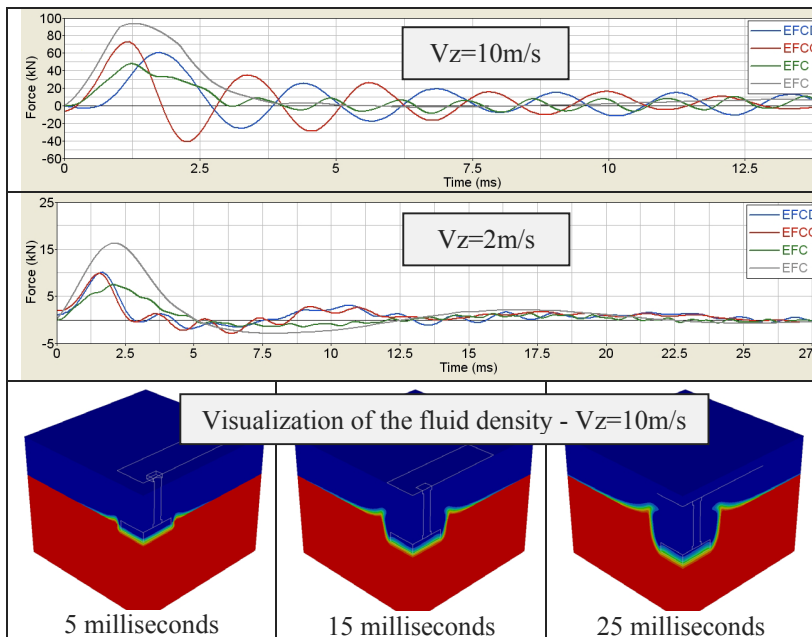


Figure 3: Simulation results of the water impact tests of the quasi-square shape.

In a general way, the force measured in the section force through the beam underestimates the experimental data, whatever the impact velocity. Such a tendency has already been observed in previous researches, which showed that the ALE formulation seems to filter high frequency phenomena [1]. Despite this general underestimation, the general trend of the time histories correctly correlate with the test data, noting that the time rise of the maximum force is systematically delayed compared to the test data (effect of the interface gap). One finally notices that the numerical force measured by the interface is almost twice higher than that measured in the section force and consequently higher than the experimental data, whatever the impact velocity. For this impact configuration, this shows that the comparison with the test data, in terms of force, must be performed with the section force in the load beam.

4.2 Analysis of the water impact tests of a triangular shape

One impact velocity is modelled (10 m/s). Numerical results are compared to experiments in Figure 4. Numerical data exhibit a 2 peaks response (contrary to experimental data); the first one occurs at around 1 ms and results from a phenomenon of water penetration inside the shape (observable in Figure 4 at 5ms). Indeed, as no air nodes are actually interfaced with the wedge, the water jet produced by the impact inside the air domain, at the first moments of contact, can potentially penetrate inside the shape. The second peak occurs at around 7 ms, once the target has fully immersed. This second peak force, measured in the section of the beam, is in quite good agreement with the experimental result. As for the quasi-square case, this maximum amplitude is reached with a delay compared to the experimental signals (effect of the interface gap). Finally, contrary to the quasi-square case, the numerical force measured by the interface is quite close to that measured in the section force. This shows the influence of the impact severity on the interface signal.

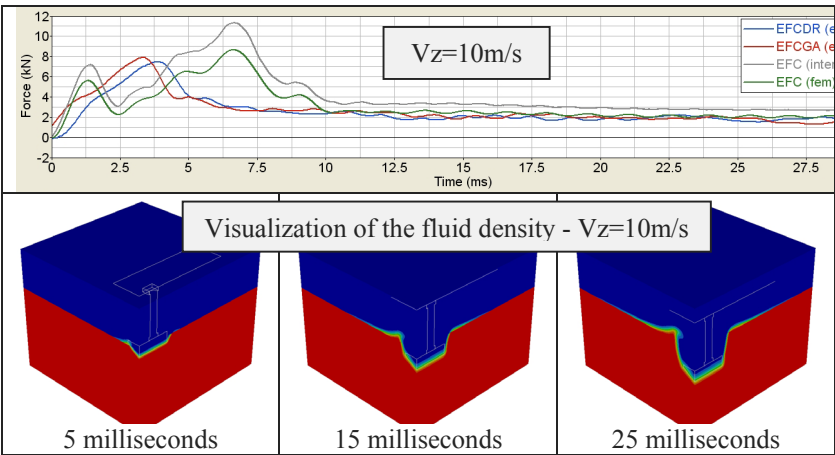


Figure 4: Simulation results of the water impact tests of the triangular shape.



5 Application to the simulation of a full-scale helicopter impact on water

5.1 Model description

The methodology is applied to the simulation of a full-scale helicopter ditching. The selected helicopter structure is shown in Figure 5 and is representative in external shape and mass distribution of a generic helicopter. The dimensions of the fluid media (air + water) are 18 m long, 3.5 m high (2m for the water and 1.5m for the air) and 5 m wide, which fully covers the helicopter dimensions (12m long and 2m wide for the central fuselage). The portion of the fluid domain in first contact with the rotorcraft is meshed with a regular size of 50 mm (similar to the helicopter mesh size), over a 600mm depth for the water and 250mm height for the air. Outside this region, the fluid mesh is progressively increased up to the boundaries of the model, leading to 715000 3D elements for the fluid media. Two impact configurations are considered: Vertical impact at $V_z=8\text{m.s}^{-1}$ and vertical impact with forward velocity at $V_z=8\text{m.s}^{-1}$ and $V_x=5.8\text{m.s}^{-1}$.

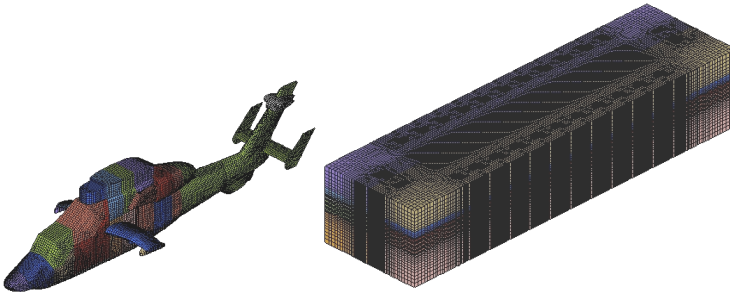


Figure 5: Full-scale helicopter and fluid media model.

5.2 Vertical impact simulation: $V_z=8\text{m.s}^{-1}$

Simulations are performed on a Unix Cluster of PC platform, with 4 processors. The model at the final stage is shown in Figure 6 (visualisation of the fluid density), with the plot of the vertical velocity versus time. The energy balance and time step evolution show a stable simulation, without any numerical instability. The vertical acceleration of the structure reaches a maximum of 20g, at a time around $t=25\text{ms}$. At the end of the simulation, the residual vertical velocity of the fuselage is 1,1m/s i.e. 14% of the initial velocity and the penetration of the helicopter inside the water reaches 900mm. Finally, the CPU cost is 131 hours, on 4 processors.

5.3 Vertical impact simulation: $V_z=8\text{m.s}^{-1}$ / $V_x=5.8\text{m.s}^{-1}$

The model at the final stage is shown in Figure 7, with the evolution of the horizontal and vertical velocities. As for the vertical impact, the simulation does

not exhibit any numerical instability. The vertical acceleration of the structure reaches a maximum 18g value, at the same time as for the vertical impact. At the end of the simulation, the residual vertical velocity of the fuselage is about 0,9m/s i.e. 11% of the initial velocity and the residual horizontal velocity is 5m/s i.e. 86% of the initial velocity, which shows that the helicopter does not undergo significant horizontal deceleration. The penetration of the helicopter inside the water reaches 875mm. Finally, the CPU cost is 131 hours.

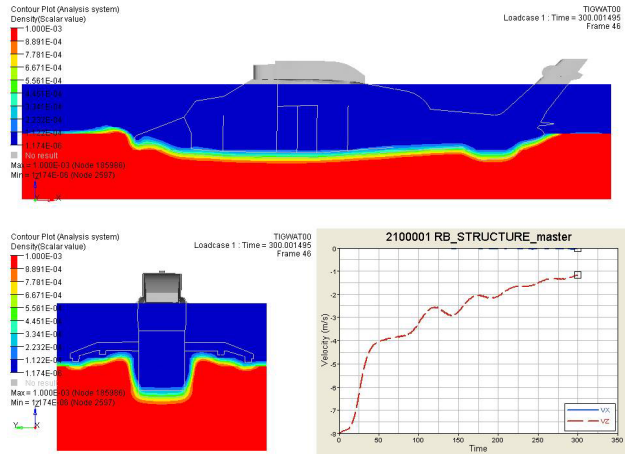


Figure 6: Vertical impact simulation – final stage: 300ms.

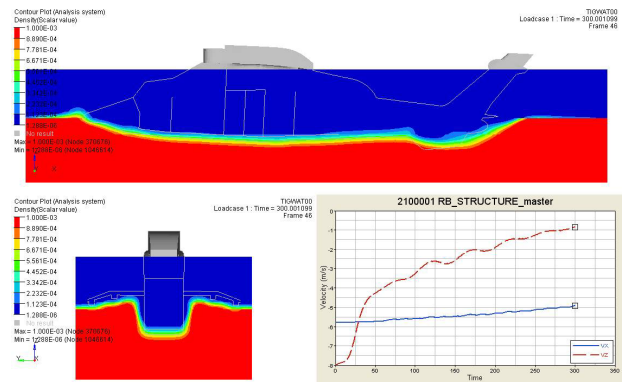


Figure 7: Vertical + horizontal impact simulation – final stage: 300ms.

5.4 Comparison with the smooth particles hydrodynamics modelling – action group AG15

The Garteur Action Group AG15 (“Improvement of SPH methods for application to helicopter ditching”) aims at assessing numerical tools for modelling helicopter impacts on water, and more especially focuses on the

Smooth Particle Hydrodynamics formulation. This method is also investigated at ONERA for various applications [8]–[10]. As part of the AG15 objectives, works concerned the modelling of a generic helicopter structure (different from the previous one, but involving similar mesh size and elements number), for different impact configurations including vertical impacts at $V_z=4\text{m.s}^{-1}$. In one model configuration in which only half of the physical problem was considered (Figure 8), the fluid media (only water) was modelled with 200000 Particles representing a 30m^3 water volume (Length=12m, Width=2.5m and Height=1m), surrounded by a margin of 3D Finite Elements, to limit the number of particles, and leading to a global 98m^3 water volume (L=14m, W=3.5m, H=2m) i.e. similar to the $2\times 90\text{m}^3$ water volume of the full model with the interface method. Each particle occupied a 150mm^3 volume i.e. in the same range as the 125mm^3 volume of the fluid Finite Elements located in the impact area of the model with the interface method. For a 100ms run time, the simulation required a CPU cost of 37 hours; reported to a full model and a 300ms run time (assuming a proportional evolution of the CPU with respect to these 2 parameters), this means a $2\times 3\times 37=222$ hours i.e. +69% compared to the interface method.

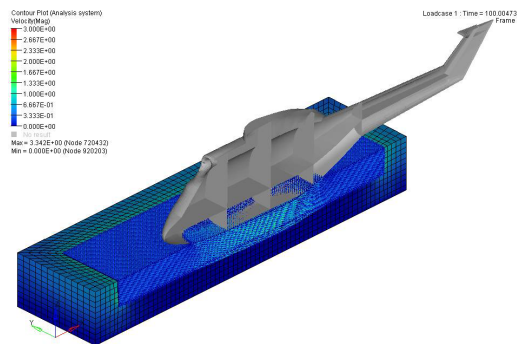


Figure 8: Vertical impact simulation – SPH method – AG15 – final stage: 100ms.

6 Conclusion

Though results highlight the strong influence of mesh dependant parameters (gap and stiffness), they also demonstrate that the application of the Euler/Lagrange coupling method to the simulation of a full-scale helicopter impact on water is suitable, as all simulations could be performed up to their end without generating any instability (usually encountered with Lagrange or even ALE formulation) and in reasonable CPU costs (main drawback of the SPH formulation). As it permits the interacting between 2 independently meshed domains, the method is therefore appropriate to model problems involving 2 physical media (soft and solid), in which the soft media undergoes large deformations/displacements compared to the solid one. Finally, it permits to model large fluid domains – without strongly penalizing calculation costs – which therefore prevents from

potential effects at the boundaries (compared to the SPH formulation which usually involves a reduced SPH meshing around the impacted area and a coupling with surrounding Finite Elements).

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