Numerical Simulation of a Helicopter Ditching with Emergency Flotation Devices.

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***Abstract*— Smoothed Particle Hydrodynamics (SPH) is used to model the ditching of a helicopter. Helicopters have a high centre of gravity, are not integrally watertight so tend to roll over and sink within seconds of landing on the water surface. Modern helicopters employ Emergency Flotation Systems (EFS) that are essentially large air-bags to provide increased buoyancy and stability to the helicopter, thereby enhancing occupant survival rates. A hybridised finite element code that includes SPH elements, rigid finite elements, flexible finite elements, sliding contact interface algorithms and air-bag simulation tools from the automotive industry is used to demonstrate the behaviour of the complex fluid-structure interaction scenario of a helicopter landing on water with and without inflating air-bags.**

I. INTRODUCTION

When a helicopter ditches into the sea, the high centre of gravity, narrow base and lack of watertight integrity cause it to overturn and sink rapidly. An Emergency Flotation System (EFS) such as inflatable pontoons that can be deployed prior to, or upon, contact with the water, can keep the helicopter afloat, and prevent it from overturning. This greatly improves the survival chance of the occupants.

The behaviour of an airframe with flexible pontoons in impacting and floating on water is a complex phenomenon. The explicit finite element code PAM-CRASH with its SPH solver has already been shown [1,2] to successfully simulate various scenarios involving fluid-structure interaction (FSI). The dynamics of a helicopter ditching with a rigid EFS has previously been demonstrated [3]. The development in this paper exploits the (automotive) occupant safety airbag model within the aforementioned code to approximate the inflation of large flexible pontoons, facilitating the simulation of ditching of helicopters fitted with an EFS.

II. NUMERICAL APPROACH

A. *Overview*

The PAM-CRASH general purpose FE code used is built around an explicit solver optimized for the analysis of highly non-linear structural dynamical behavior. It contains element formulations for thin shells, solid elements, membranes and beams with material models for plasticity and failure for metals, plastics, rubbers, foams and composites. The code contains robust contact algorithms, including sliding interface algorithms, to model the dynamic contact between various parts within a model. The solver allows both finite elements and smoothed particles to be used simultaneously within the same model, with optimal performance achieved by using either the Distributed Memory Parallel (DMP) or the Shared Memory Parallel (SMP) version.

Interaction between particles representing a fluid and moving or deformable structures may be modelled by one of the contact algorithms. Such algorithms, while allowing sliding at the interface, prevent penetration between selected structures. Their implementations are based on the well known penalty formulation, where geometrical interpenetrations between so-called slave nodes and adjacent master faces are penalized by counteracting forces that are essentially proportional to the penetration depth. The contact algorithm will automatically detect when a particle (slave) penetrates any segments (master) of the outer surface of the finite element model of the structure. The contact thickness indicates the distance away from a contact face where physical contact is established. For SPH particles as slaves, the contact thickness should be representative of the particle spacing. This type of contact has been validated by the vertical motion of floating bodies. It has been found that the correct position is reached when the thickness defined for the contact is in the vicinity of half the particle spacing and the artificial viscosity coefficients are significantly smaller than the values normally applied for shocks. In that case the upward force is also correct. The use of coupled SPH-FE has been used for many applications such as sloshing [4], the opening of a heart valve [5], the impact of birds onto aeronautical structures [6], and lifeboat drop [7] onto water.

In addition, it is possible to define a tied contact in which virtual spring elements are automatically defined between particles that are sufficiently close to segments in the initial configuration. Such a contact acts as a rigid connection between the two parts.

B. *Hydrostatic Pressure Initialisation*

For many hydrodynamic simulations involving a free surface, a significant amount of computer time may be expended to reach hydrostatic equilibrium under gravity in the water before the event of interest can start. An option has been implemented that allows initializing the hydrostatic pressure at the start of the simulation. This may be done for an assembly of particles representing a single density liquid in which case the position of the free surface is evaluated automatically, or for finite volume elements in which the free surface location has to be provided by the user. For each particle, or the centre of gravity of each solid element, the distance to the free surface in the direction of the gravity as specified by the user is evaluated and the initial density is multiplied by an exponential function of this distance. It must be assumed that the reference density is the same along the line in this direction and that there exists a unique location of the free surface. Although the hydrostatic pressure is likely to change when the water is settling into a container acting as a boundary for a finite volume of water, these changes are small with respect to the changes required without this option. Hence, computer time may be reduced when this option is exploited.

C. Gauges for Pressure and Free Surface Level

For hydrodynamic simulations with SPH, it is convenient to define the concept of gauge nodes. These gauges may be defined as moving along with the structure (as FE nodes), given a fixed motion (as free nodes), or as particles. Their use enables information about the pressure to be obtained at any desired location. Note that since the pressure will be averaged over a number of nearby particles, it will not suffer from the strong spatial fluctuations typical for the pressure for individual particles. For many hydrodynamics applications it is interesting, and even critical, to know the current free surface location. Gauges are defined as a special type of particles for which no force calculation is made and which also do not contribute to the evaluation of SPH properties of regular particles. This is accomplished by the definition of a flag for the particles. The pressure at the gauges is located by taking the average using the smoothing kernel over the current neighbouring particles within a smoothing length defined by the user. Tests have indicated both that the pressures evaluated by gauge points have the same smoothed appearance as the particle pressures and that they correspond to the hydrostatic values in the case of equilibrium. The free surface level is evaluated by an iterative procedure that searches for the coordinate in a given direction where the SPH particle density equals one half. This definition is the most appropriate one to determine the location of singly-defined free surface for a given direction, although in the case of over-turning waves or splashing, this definition may not be unique.

D. Periodic Boundary Conditions

For studies involving undisturbed flow or free-surface wave propagation in extended domains, the option of periodic boundary conditions significantly reduces the number of particles required. For SPH, a rectangular box is defined where, as soon as a particle crosses a boundary face, it is injected at the opposite face with the same velocity and material properties. When due care is taken such that the neighbour search of all particles extends over the faces of the domain, the flow remains undisturbed.

III. Water Entry of a Flexible Cylinder

To demonstrate that the coupled SPH-FE approach is able to simulate fluid-structure effects relevant for hydro-elasticity as may occur during water entry and ship slamming, the results from a simulation of an aluminium cylinder falling from 1m onto calm water are presented. Experimental results for this case and its numerical simulation including the effects of hydro-elasticity have been reported by Arai [8]. Numerical simulations by a coupled Euler-Lagrange approach, including the effects of water compressibility and entrapped air, have been reported by Bereznitski using a coupled Euler-Lagrange code [9]. A comparison is made here between a fully FE solution and a combined FE and SPH solution. The combined solution employed SPH in the inner fluid region where splash is anticipated, and FE elements in the regions further from the impact site. The tied contact between the SPH and FE elements noted in Section 2 maintains continuity throughout the domain. The simulation was done in 2D, did not include air and used elastic shell elements for the cylinder with a material modulus of 75GPa and a Poisson's ratio of 0.34. The 3mm thick aluminium cylinder had an outer diameter of 306mm.

Initial simulations revealed a relatively small nominal size of 4.1mm for the particles and finite elements was required in the impact region to maintain stability and capture transient events. It was also found that a first-order polynomial equation of state (EOS) for the water gave better results than the frequently used Murnaghan equation of state. Using the actual compressibility of water, the polynomial EOS revealed propagation of compression waves following the impact. The same EOS material model has been used for particles and elements representing water. Artificial viscosity parameters for α and β of 0.005 and 0.0 respectively were found to produce proper splashing. The fluid viscosity corresponding to these values is higher than that of water, but viscosity is believed to be a less important effect during slamming [10]. Simulation results showing the location of the cylinder and the outline of the free surface, as well as contours of the velocity magnitude in the upper part of the computational domain, for the mixed, as well as the pure FE computations, are shown in Figure 1. The equivalent stresses at the bottom element of the cylinder for the pure FE model and the combined SPH-FE model were found to be in good agreement with each other. For the cylinder deformation of Figure 2, the agreement in amplitude with that of Arai and that of Bereznitski is quite good, although the period of vibration is different.

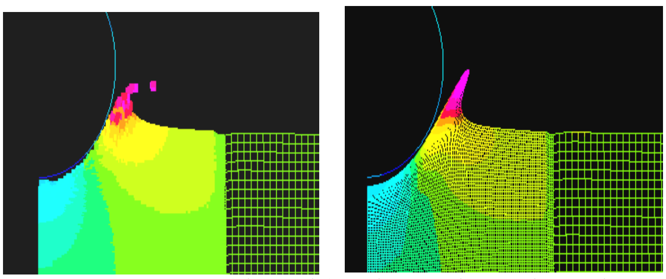

Figure 1: A segment of the FE (left) and SPH and FE (right) simulations in PAM-CRASH. Contours indicate velocity magnitudes, showing good correlation with each other.

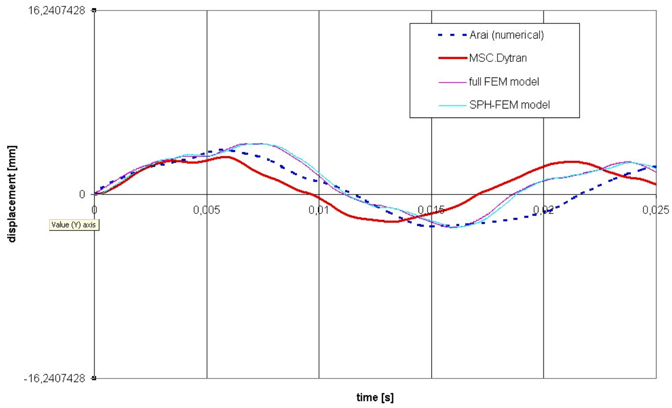

Figure 2: Time history of the deformation of the cylinder bottom for the FE simulation (purple) and SPH model (light blue) vs. the numerical results from Arai and Bereznitski (MSC-Dytran) for a drop height of 0.75 m.

A suggested reason for this difference is the possible sliding and separation of the water along the cylinder which is treated differently by the various numerical approaches [9].

It may be concluded from these results that the mixed SPH-FE approach enables the interaction between water and deformable, thin-walled structures to be modelled accurately, as long as the particle distribution is reasonably fine and some parameter recommendations are followed. In this particular case, there is no specific preference for either model, but for cases with more complex (3D) geometry or more violent interaction, the finite element model will definitely break down due to element tangling, whereas SPH would have no problems continuing.

IV. Inflating Air-Bags

Air-bags are a significant safety feature in modern cars. Their use is stipulated by regulation in most countries. To address the demand from automotive designers, the numerical simulation of air-bags in crash scenarios is well developed in commercial automotive software codes such as PAM-CRASH.

In car-crash scenarios, occupant protection is provided by an air-bag inflating in about 60-80 milliseconds. The bag then deflates through vents or leakage within the bag construction so as not to suffocate the occupants.

The above-mentioned software contains numerous methods for simulating air-bag deployment. The most common approach is to use an empirical adiabatic ideal gas relationship with uniform gas temperature and pressure. A Finite Point Method Mesh-Free implementation has recently been added to the above-mentioned software although this is mainly used for curtain airbags and out-of-position studies.

The pressure developed by the gas acts on the surface of finite elements that represent the fabric of the air-bag. The fabric is represented by membrane finite elements with orthotropic material properties. Simulation of the air-bag accounts for construction features such as outlet vents, leakage through the fabric seams, and inflow and outflow characteristics.

Prior to use, the air-bags are folded compactly for stowage. The air-bag must unfold in an orderly manner to ensure successful operation. A high-end commercial pre-processor, such as Visual [11], includes algorithms for modifying a flat air-bag finite element mesh into a folded arrangement according to interactive user-specified fold-lines.

The application of the existing automotive air-bag technology to the helicopter Emergency Flotation System (EFS) is primarily one of scale. The volume of the air-bag in an EFS is much larger than that required for occupant safety in a car. The flow-rates are consequently much larger, and ultimately the air-bag must retain pressure and not leak.

V. Helicopter Ditching

Helicopters have unique operational envelope characteristics that make them indispensible to specific civilian and defence applications. Inevitably some of these applications will require flying over water, and inevitably also, reliability mishaps may occur over water which will result in a controlled or uncontrolled crashing onto the water surface.

Statistics from helicopter accidents occurring into water [12] indicate that most fatalities occur from drowning, not injury attributable to the structural failure of the helicopter. Following drowning, the next most likely cause of death in accidents over water is by hypothermia. It is also noted from the number of accidents that in nearly 60% of the accidents, the helicopter inverted and sank “almost immediately”. Such a response by the helicopter in water provides very little opportunity for egress of the crew and is a contributor to the high rate of drowning fatalities.

A conclusion from the helicopter ditching statistics was that occupant safety could be greatly increased if the helicopter was both prevented from sinking and provided with sufficient stability such that the floating helicopter remained upright.

External Flotation Systems (EFS) for helicopters were developed to achieve this goal, and have been used operationally since the mid 1990’s [13]. In practice, EFS spend most of their life stowed, and are not needed except in that rare event of an emergency - much like air-bags in cars. Recent accidents indicate that when the EFS are called upon in an emergency, they do not always deploy as intended and consequently do not offer the occupants the protection anticipated.

VI. Simulation of the Emergency Flotation Systems (EFS) for Helicopters

Four independent flotation devices comprise the helicopter EFS modelled here, each folded into a compact format for stowage during flight. Two small flotation devices are located on either side of the cockpit, and two large devices are attached to the aft sponsons.

The EFS are modelled by flexible orthotropic finite element membrane elements. The properties of the membrane elements are similar to the rubberised fibre-reinforced materials that are commonly used for the construction of such flotation devices. The finite stiffness of the membranes results in a small increase of volume at the design pressure. The flotation devices used for helicopters may be required to provide buoyancy for many hours, and so, unlike the automotive air-bags that must deflate to avoid suffocating the occupants after restraint, the implementation here does not contain vents or leakage.

The inflation of the EFS devices is achieved by defining a flow-rate such that the chambers fully inflate in about 6 seconds from being triggered. The respective time histories of the pressure in the airbags and the volume of the chambers are shown in Figures 3 and 4 respectively. Chamber 1 is an aft flotation device, and Chamber 4 is a forward flotation device. The x-axis is the time from the start of the simulation.

In practice, inflation of the chambers is triggered prior to, or on contact with, the water surface. The sliding interface mentioned previously acts between the flexible airbags and the particles to ensure the particles remain on the outside of the airbag, thus providing buoyancy. A similar interface is defined between the SPH and the body of the helicopter.

The airbags were constructed from a simple flat shape envelope of the air-bag shape that was folded into a compact stowed configuration using the previously mentioned folding algorithms. This algorithm produces a complex folded finite element model of the airbag that will unfold in the correct manner to produce the original air-bag shape. This process allows the simulation of the complete unfolding process that the real EFS would experience. When combined with the helicopter structure this unfolding process allows confirmation that the EFS will not tangle or be punctured by the helicopter airframe, or get caught on local features such as landing skids, antennae, or pitot tubes on the outside of the helicopter.

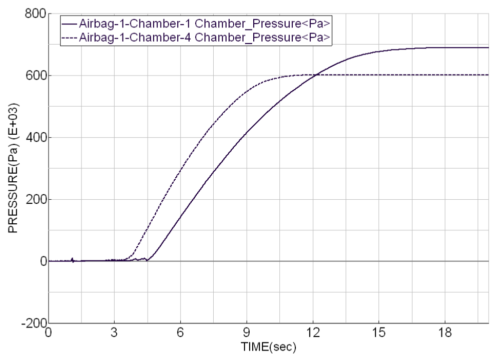

Figure 3: Chamber pressure for the front and rear EFS

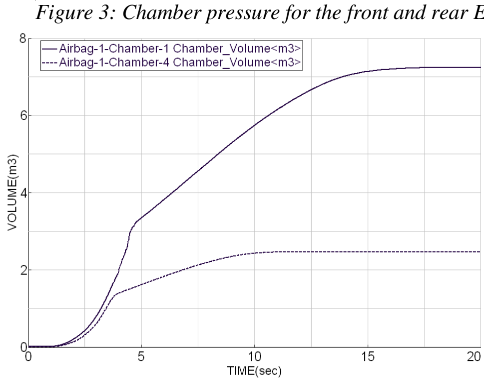

Figure 4: Chamber volume for the front and rear EFS.

A few stages of the EFS unfolding are shown in Figure 5.

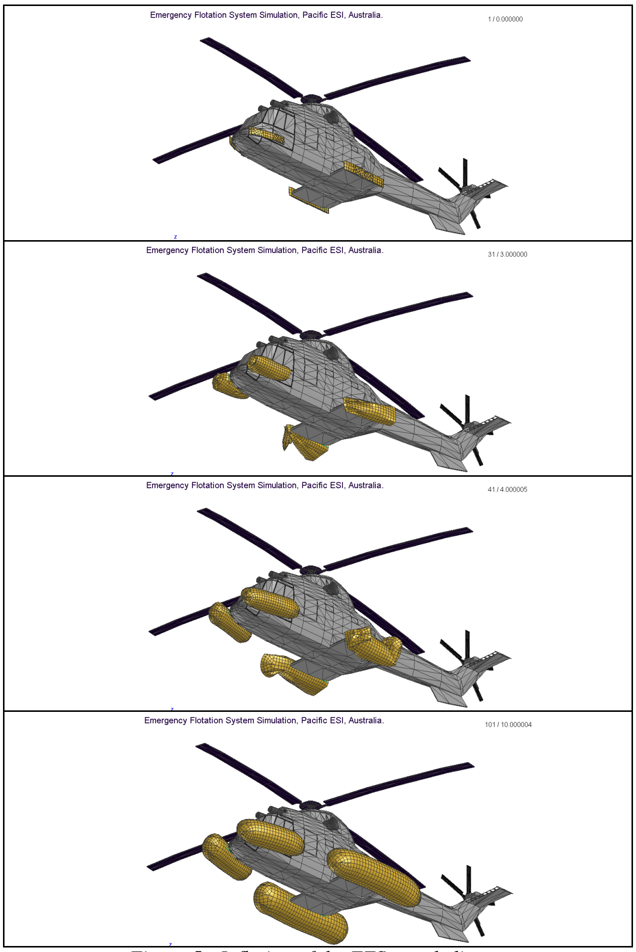

Figure 5: Inflation of the EFS on a helicopter.

VII. Simulation of Ditching

A generic implementation of the technology is shown in Figure 6. The simulation consists of a generic helicopter that is falling under gravity, a body of water, a tank for containment of the water, and the airbags fitted to the helicopter. The simulation is conducted at full size and in real time.

The helicopter was modelled as a rigid body of finite elements with six degrees of freedom, a mass of 8800 kg and representative inertias.

The water was represented by approximately 100,000 SPH elements of increasing size with depth. This varying of the SPH size had two primary benefits. The first was that smaller SPH elements on the water surface provided more accurate fluid-structure interaction in the areas of water ingress into the helicopter, interaction with the lightweight flexible EFS membrane elements, and splash development. The second benefit was that fewer SPH were required if larger SPH elements were used at depths where less fluid motion was anticipated, resulting in less computational effort being required compared to a full tank of the surface-sized smaller SPH elements. The bulk modulus of the SPH elements was adjusted such that the deeper elements retained the same time-step as the surface elements, even though their dimension was increasing. This also reduced compressibility effects at depth.

Figure 6: Generic Helicopter with inflating flotation devices.

Figure 6 is from the final stages of the simulation where the buoyancy of the helicopter has been established and the motions reduced to near steady-state. It is evident that the helicopter is floating and will not topple over, offering an extended period for the occupants to egress safely.

Not shown here is the simulation of the helicopter without airbags. This simulation was presented previously [3] and displays the reported characteristics of initially floating whilst upright, subsequently rolling over, and finally sinking. The loss of watertight integrity by the helicopter through doors and windows results in a rapid ingress of water, a loss of buoyancy and the sinking of the helicopter within 10 seconds of impact.

The ingress of water into the helicopter through the doors and windows is achieved by excluding these specific finite elements from the contact interface that controls the interaction of SPH and the helicopter and flotation devices.

VIII. Stability in Waves

The stability of a helicopter with EFD deployed in waves by numerical simulation can be evaluated by numerical simulation to establish confidence that a particular EFS system will provide the level of safety required in the intended environment which the helicopter will operate.

The response of a helicopter to waves may be evaluated using the techniques previously developed by the authors to study the response of naval craft in non-dissipating regular waves in the SPH domain [1,2,7].

This work is continuing, at an advanced level in both 2D and 3D, as shown in Figure 7.

IX. Conclusions

Recent developments in the numerical simulation of airbag systems for automotive applications and the use of SPH technology for maritime studies has enabled a marriage of the two technologies to simulate the impact of a helicopter on a water surface, complete with the inflation of the EFS device. This provides a capability to simulate EFS systems for new helicopters, and the virtual try-out of newly developed EFS systems that may be lighter and/or more effective than current designs.

Figure 7: Helicopter with EFS in wavess.

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