FE-MODELLING OF HYDRODYNAMIC HULL-WATER IMPACT LOADS

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ABSTRACT

This paper considers finite element modelling of the hydrodynamic loads in hull-water impacts. The commercial FE-code LS-DYNA is used with a multi-material arbitrary Lagrangian-Eulerian formulation and a penalty contact algorithm. The great advantage of this modelling technique is that it enables the modelling of the instantaneous fluid-structure interaction. A difficulty is however the selection of appropriate modelling parameters. A method to rationally select appropriate modelling parameters is discussed and briefly described. Convergence of the pressure distribution is presented and discussed. Pressure distributions and loads are favourably compared with other theoretical methods and with experiments.

KEYWORDS:

Fluid-structure interaction, hydroelasticity, hull-water impact, high-speed craft, slamming, explicit finite element methods

INTRODUCTION

The complex environment a high-speed craft encounters during operation in rough seas implies complex loading situations, which may result in very violent motions. The wave-induced hydrodynamic loads are transient loads characterised by short rise and fall times and high peak pressures of very short duration. These loads may dominate in the design of bottom hull-panels and are in the design process commonly treated as quasi-static and uniformly distributed. This simplified modelling of the actual conditions might lead to restrictions when optimizing the structure.

The objective of this work is to investigate the modelling of hydrodynamic impact loads by use of the explicit FE-code LS-DYNA (2003). The great advantage of this modelling technique is that it enables the modelling of the instantaneous fluid-structure interaction. An application is for example to study the hydroelastic effects of hull-water impacts. FE-modelling of hull-water impacts has for instance been presented in Olovsson&Souli (1999, 2000 and 2001), Bereznitski (2001), Aquelet&Souli (2003), Le Sourne et al. (2003) and Stenius et al. (2006 and 2007).

HYDRODYNAMIC IMPACT LOADS

The loading situation a high-speed craft encounters in rough seas is commonly idealized as a two-dimensional transverse section of a ship-hull vertically impacting an initially calm water surface. This is illustrated for a v-shaped section in Figure 1. The pressure distribution on the hull is critically dependent of the local relative angle between hull and water surface, and the incident impact velocity. The pressures on the bottom-hull panels increase for increased incident impact velocity and decreased relative angle between hull and water. At small hull-water angles ($< 5°$) an air-cushioning effect however results in decreasing pressures.

During the impact, the water surface piles up close to the hull and forms a jet in the intersection between hull and water surface. The hydrodynamic pressure acting on the bottom-hull and the water surface pile-up close to the hull is schematically pictured in Figure 1. The characteristics of the pressure distribution on the bottom-hull may be distinguished by a *chines-dry* stage and a *chines-wet* stage. In the *chines-dry* stage, the pressure distribution is characterised by a quite localized pressure-peak at the intersection between hull and water and a distinctly lower fairly constant pressure over the remaining part of the bottom-hull. In the *chines-wet* stage the pressure distribution loses its peaked characteristics and may be described as a fairly uniform pressure distribution, which gradually approaches atmospheric pressure near the chine.

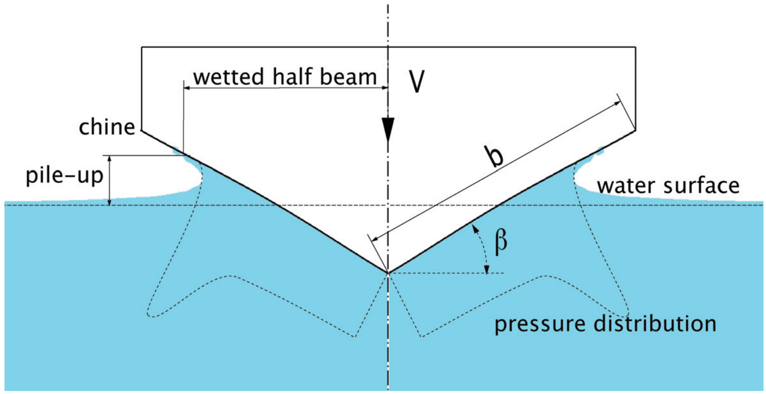

Figure 1: Schematic illustration of idealized hull-water impact illustrating pile-up, hydrodynamic pressure distribution (dashed), impact velocity V, ship-hull deadrise β and width of panel b.

FE-MODELLING

The impact situation considered in these FE-simulations corresponds to the idealised two-dimensional problem schematically pictured in Figure 1. Figure 2 illustrates the modelling setup. The FE-model has an extension in the x-direction of one element. Two-dimensionality and plane strain is provided by constraining all nodes in the x-direction. The fluids (water and air) are divided into two domains: A and B. Domain A is uniformly meshed. In B the mesh is moderately expanded towards the boundaries. Water and air, are modelled with solid ALE elements. The fluid boundaries are fixed. Gravity and viscosity are neglected. In the water domain the Gruneisen equation of state formulation is used, where the water density is 1000 kg/m^3 and the acoustic wave speed is 1500 m/s. The air domain is modelled as void allowing the water to redistribute. The structure is modelled with Lagrangian shell elements, which in the simulations presented here are kept rigid.

The contact between water and structure is provided by a penalty contact formulation. The penalty contact formulation may be described as a numerical spring-damper system. Traction constraints are set upon the interacting parts proportional to the penetration and a contact stiffness parameter. An additional damping parameter may also be used which adds traction constraints proportional to the penetration velocity and a contact damping parameter. The penalty contact parameters may be set as fractions of system stiffness or as user defined (LS-DYNA 2003). For hull-water impact problems the most appropriate contact formulation is the penalty-based formulation with user defined contact parameters (Olovsson 2003). The problem here is however the selection of the contact stiffness. Too low contact stiffness results in too large non-physical penetrations, which disturbs the flow field and might even lead to leakage. An excessively large contact stiffness on the other hand can cause numerical noise in the solution (Aquelet&Souli 2003, Le Sourne et al. 2003, Stenius et al. 2006).

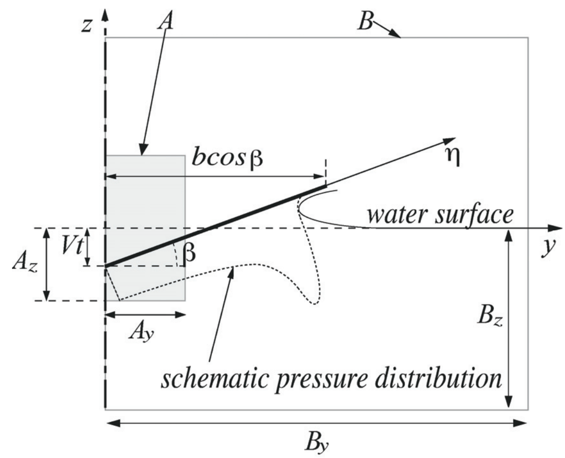

Figure 2: Model setup with pressure distribution (dashed) schematically pictured. Domain A is uniformly meshed while the mesh in domain B is moderately expanded towards the boundaries. Note, figure is not drawn to scale.

A critical parameter in finite element modelling is the mesh density. The mesh needs to be fine enough to capture the highest gradients in the stress fields, within for the problem at hand appropriate limits, yet a coarser mesh is favourable in terms of computational cost. As described in the introduction, large pressure gradients are inherent in hull-water impacts, and need consequently to be considered in the selection of the mesh density. Furthermore, for the selection of the contact stiffness in the penalty based contact algorithm it is required that the maximum pressures are approximately known ahead, so that the non-physical contact penetration can be controlled. Apart from the mesh density and the contact-stiffness, contact damping, time-step scaling, and number of contact points per element can be assumed important modelling parameters as well.

In this work the importance of these modelling parameters have been studied. The results of the parametrical study show that; the solution stability is highly dependent of a mesh-density/contact-stiffness relation; very fine meshes are required for complete convergence of the pressure peak; contact-damping, time-step scaling and number of contact points per element are of less importance.

In a second step, Wagner (1932) theory is synthesized with the results of the parametric study in order to estimate the required mesh-density and corresponding contact stiffness for arbitrary impact situations. The idea is to select the mesh in relation to a representative value of the pressure peak width, here estimated by Wagner theory. Thus, in order to satisfactorily capture the high gradients associated with the peak pressure a certain number of elements (denoted α_s) within this width are required. An estimation of the required number of elements (α_s) for one specific impact situation is obtained from the parametric study. Wagner theory is then used to enable extrapolation of these results to arbitrary impact situations. The corresponding contact stiffness is estimated based on the peak pressure value estimated according to Wagner theory. The idea here is to control the relation between the contact penetration and the actual fluid boundary displacement during a small time increment. Estimations of the appropriate contact penetration are also obtained from the parametric study. Similarly as for the mesh density, Wagner theory is then used to enable extrapolation of these results to arbitrary impact situations

A more detailed description of the parametric study and the synthesis with the Wagner (1932) theory can be found in Stenius et al. (2006).

RESULTS

Figure 3 and Figure 4 shows the convergence of the pressure distribution for different mesh densities in terms of number of elements (α_s) within the reference peak width. It can be seen that, except for the very pressure peak, the pressure distribution seems to have converged at the lower mesh densities. The convergence of the absolute pressure peak is on the other hand quite slow and very fine meshes are required to obtain a final convergence. Even the highest mesh density (corresponding to approximately 2 weeks of computer time on a standard 2.6GHz PC) does not result in a complete convergence as seen in Figure 4. However, it can be seen that the peak value approaches, and seems to level off close to the peak pressure according to Wagner (1932).

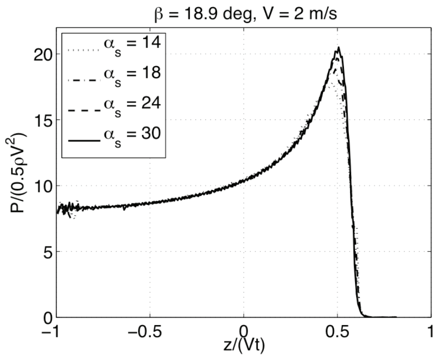

Figure 3: Convergence of pressure distribution.

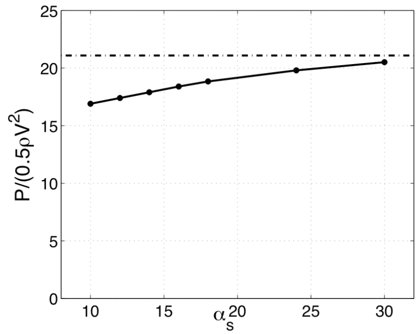

Figure 4: Convergence of peak pressure values.

In Figure 5, pressure distributions based on FE-simulations, Wagner theory (1932) and a similarity solution presented in Zhao&Faltinsen (1993) are shown. Data according to Zhao&Faltinsen (1993) is digitized from paper. The pressure distributions are presented for an impact situation with a deadrise of 10 degrees. As discussed above, the absolute peak pressures are very costly to capture. By allowing a slightly decreased mesh density a considerable amount of computational cost can be saved (see Stenius et al. 2006) and still capture the major part of the pressure distribution. Hence, a lower mesh resolution (α_s = 8) is chosen here to minimize the computational cost. The result is that the very pressure peak is not captured. It can however be seen that Wagner theory predicts slightly higher pressures than predicted by both the FE-simulation and the similarity solution. Further, it can be seen that the FE-simulation and the similarity solution shows similar results except at the very pressure peak. It can be expected that an increase in mesh density results in a more accurately captured peak pressure similarly as in Figure 3.

Figure 6 presents the vertical hydrodynamic load of a drop-test with an initial impact velocity of 6.15 m/s, a deadrise of 30 degrees and a total panel weight of 442 kg/m^2. Hydrodynamic loads based on finite element simulations with different mesh densities are compared with experiments presented in Zhao et al. (1996). Data according to Zhao et al. (1996) is digitized from paper. As seen, the hydrodynamic load from a simulation with the lower mesh density, α_s = 10, is almost identical to the one with the higher mesh density, i.e. α_s = 20. The FE-simulations also correlate well with the experimental results.

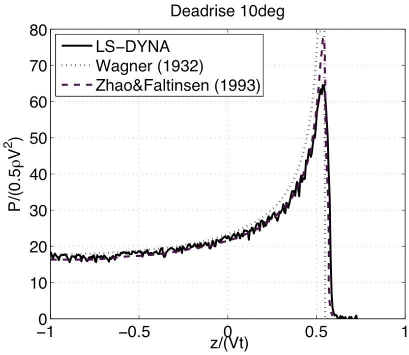

Figure 5: Comparison of normalized pressure distributions for a deadrise of 10 degrees.

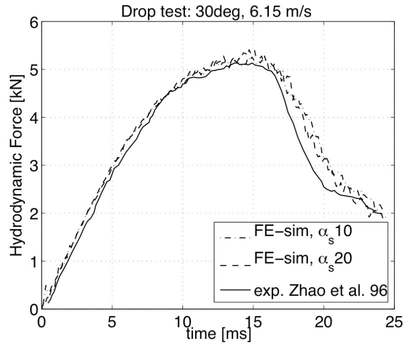

Figure 6: Comparison of vertical hydrodynamic load from FE-simulations and experimental results.

CONCLUSIONS

The paper presents FE-simulations of idealised hull-water impacts based on the modelling setup proposed in Stenius et al. (2006). Comparisons are made with other theoretical methods (Wagner 1932 and Zhao&Faltinsen 1993) and with experiments (Zhao et al. 1996). The main conclusions are:

- The solution stability is highly dependent of the mesh-density/contact-stiffness relation.

- A relative mesh density $\alpha_S > 30$ is required for complete convergence of the very pressure peak. The relative mesh density formulation implies that different mesh densities are required for different deadrise of the bottom panel. Hence, higher resolutions may be affordable at larger deadrise angles since the pressure gradients decrease for an increased deadrise angle.

- It is computationally very expensive to resolve the absolute pressure peak. However, lower mesh densities may be used if the very pressure peak is of less importance, for example when studying the structural response and the fluid-structure interaction.

- Similar pressure distributions are predicted by the FE-simulation and the similarity solution presented in Zhao&Faltinsen (1993). Wagner (1932) predicts slightly higher pressures.

- Good correlation in hydrodynamic load can be seen between the FE-simulations and the experimental results presented by Zhao et al. (1996).

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