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Hydroelasticity in Marine Hull Bottom Panels - Modeling and Characterization

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Preface

The work in this thesis was carried out at the KTH Centre for Naval Architecture, Royal Institute of Technology (KTH), Stockholm, Sweden. The work was supervised and initiated by Dr. Anders Rosén and Dr. Jakob Kuttenkeuler, and financially supported by the Swedish Defense Materiel Administration (FMV) and the USA Office of Naval Research (ONR 332-Rajapakse).

There are a number of individuals that have contributed to this work and to whom I am very grateful. In particular Dr. Anders Rosén without whom I would never have reached this far. I would also like to address a special thanks to Dr. Jakob Kuttenkeuler for always believing in me and supporting me in work and life.

Dr. Mark Battley is acknowledged for support during this work and for making the experimental work possible. Johan Breder and Petter Pehrson are acknowledged for experimental work at Industrial Research Ltd. (IRL), New Zealand, during their master thesis projects. Dr. Lars Olovsson is acknowledged for comments and rewarding discussions. Dr. Karl Garme is acknowledged for valuable support during this work and always interesting discussions. I would also like to thank my office college Anders Lindström for inspiring discussions and a nice working atmosphere.

Finally, I would like to thank my family Therese, Noel and Moa for support and encouragement, with a special thanks to my wife Therese, without whom this work would have been impossible.

Stockholm, June 2009

Ivan Stenius

Abstract

The work in this thesis is concerned with the localized problem of hydroelasticity in marine panel-water impacts with an overall aim to increase the efficiency of high-speed craft by application of more refined methods in the structural design. The work mainly focuses on numerical modeling of the hydroelastic problem and therewith related aspects in the modeling and characterization of hydroelasticity. In addition, the work also addresses aspects regarding design methods of high-speed craft and experimental analysis of hydroelasticity.

Two-dimensional panel-water impacts are simulated by using the commercial finite element code LS-DYNA. For the modeling of the panel-water impact situations a generalized approach for determination of fluid discretization and contact parameters is derived and extensively used throughout this work. The hydroelastic problem is studied through systematic series of numerical simulations regarding different impact situations. The work advances the understanding of the hydroelastic problem and introduces concepts such as kinematic and inertia related hydroelastic effects. The work further presents hydroelastic effects in contrast to previously published results, in the sense that it may not be conservative to ignore hydroelasticity in the structural design. This increase in the structural response when accounting for hydroelasticity can partly be related to kinematic effects, and partly to inertia related added mass effects. The results further show that, the effects of hydroelasticity increase with increased impact velocity, increased panel width, decreased deadrise angle, decreased panel flexural and in-plane stiffness, and decreased rotational and in-plane fixation at the boundaries.

A tentative method is derived to characterize the hydroelastic problem, which, despite its simplicity and limitations, is found to successfully capture the complexity of the hydroelastic interaction in the design of the experimental setup. The experimental water slam testing of composite hull panels are conducted to study the effect of hydroelasticity for panels with different stiffnesses. The observed hydroelastic effects included changes in panel geometry, local velocity and hydrodynamic pressures. These effects also correlate with the observed hydroelastic effects from the numerical simulations.

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

Dissertation

This doctoral thesis consists of an introduction to the area of research and the following appended papers:

Paper A

Stenius I., Rosén A., Kuttenkeuler J., *On Structural Design of Energy Efficient Small High-Speed Craft*, submitted for publication, 2009.

Paper B

Stenius I., Rosén A., Kuttenkeuler J., *Explicit FE-Modelling of Fluid-Structure Interaction in Hull-Water Impacts*, International Shipbuilding Progress, vol. 53, issue no. 2, 2006.

Paper C

Stenius I., Rosén A., Kuttenkeuler J., *Explicit FE-Modelling of Hydroelasticity in Panel-Water Impacts*, International Shipbuilding Progress, volume 54(No. 2,3), 2007.

Paper D

Stenius I., Rosén A., Kuttenkeuler J., *Hydroelasticity in Marine Hull Bottom Panels*, submitted for publication, 2009.

Paper E

Battley M., Allen T., Pehrson P., Stenius I., and Rosén A., *Effects of Panel Stiffness on Slamming Responses of Composite Hull Panels*, 17th International Conference on Composite Materials, ICCM17, Edinburgh International Convention Centre (EICC), Edinburgh, UK, 2009.

Division of Work Between Authors

Paper A

Stenius developed the design tool and procedure, and performed the material concept study guided by Rosén and Kuttenkeuler. Rosén performed the evaluation of the results. The paper is written jointly by Stenius, Rosén and Kuttenkeuler.

Paper B

Stenius performed the finite element simulations and developed the method for preselection of modeling parameters guided by Rosén and Kuttenkeuler. The paper is written jointly by Stenius and Rosén.

Paper C

Stenius performed the finite element simulations and developed the tentative method for dynamic characterization guided by Rosén and Kuttenkeuler. The paper is written by Stenius. Rosén and Kuttenkeuler contributed to the paper with valuable comments and revisions.

Paper D

Stenius performed the finite element simulations and analyzed the results. Stenius developed the simplified hydroelastic modeling technique. The paper is written by Stenius. Rosén and Kuttenkeuler contributed to the paper with valuable comments and revisions.

Paper E

Stenius contributed to the work in the design of the experimental methodology and in the analysis of the results. The experimental work is performed by Pehrson with assistance from Allen. The paper is written jointly by Battley, Allen, Stenius and Rosén.

Contents

1 Introduction

Picture yourself standing on the top of the cliff in figure 1, about to make a 10 m plunge into the water beneath. The result of an unsuccessful landing, such as for example a belly flop, is easily imagined. A high-speed craft operating in rough seas can actually be compared with a continuous belly flopping, where each wave encounter results in large transient hydrodynamic impact loads on the hull. The loading is dependent on sea-state, direction and speed of the craft in relation to sea, as well as on the size and geometry of the craft. The hydrodynamic loads, which may result in very violent motions, affect passengers, crew, equipment and not least the craft itself, which has to be designed to withstand the pounding of these wave-induced hydrodynamic loads.

Figure 1: *Backflip by Petter Ekman (a former KTH-student) in the archipelago of Åland (Foto: Sebastian Englund).*

Hence, designing a high-speed craft is a challenging task, not least with respect to the rough conditions in which the craft may be intended to operate. The designer has to consider extreme loads, fatigue, operability etc, and at the same time minimize structural weigh since this is a critical parameter in terms of operational cost and performance. Designers today rely to a large extent upon semi-empirical design methods e.g. design rules by DNV and other classification societies. The principle of these design methods is to calculate design loads on the hull bottom panels by using a design-acceleration. The design-acceleration may be chosen based on design criteria, simulations, model tests, experience etc. The design loads are then determined by calculating the loads on the hull bottom panels that reproduce this design acceleration. The benefit of these methods is that they are simple and easy to use, which however is to the cost of accuracy (e.g. Rosén 2004 and Koelbel 2000 & 2001). An alternative approach is direct calculations based on first principles of loads and strength, which implies direct assessment of loads and structure load carrying capacity. Direct calculation methods have for instance been proven necessary in the design of the Visby Class Corvette (figure 2). The Visby Class Corvette was difficult to strictly fit within the DNV rules due to low weight of the craft in combination with extreme operational conditions (e.g. Lönnö 1998 & 2000, and Hellbratt and Vallbo 1998). By direct calculations the accuracy of the design methods can be significantly increased, which also results in the ability to achieve more optimized structures (Rosén 2004). The potential gain in terms of structural weight savings and thereby related improvements in the craft efficiency by application of more rational design procedures is for instance demonstrated in Stenius et al. (2009b)/paper A.

Figure 2: *The Visby Class Corvette (courtesy of Kockums, Photo: Peter Nilsson).*

A key component in applying more refined design methods is the ability to accurately predict the hydrodynamic loading situation, including identifying the range of validity of quasi-static load assumptions and establishing the significance of hydroelasticitiy on the problem. This thesis addresses these aspects by studying the influence of bottom-panel elastic effects on the loading and the structural responses. The objectives are to identify the range of applicability of the quasi-static design methods, and also to quantify and characterize the hydroelastic effects in panel-water impacts. The hydroelastic problem is mainly studied by the explicit finite element code LS-DYNA, by which the instantaneous fluid structure interaction can be modeled. Promising results of using this FEA-technique in the modeling of fluid-structure interaction in hull-water impacts has been shown in for instance Souli and Olovsson (1999), Olovsson and Souli (2000 & 2001), Bereznitski (2001) and le Sourne et al. (2003). The methodology however needs further evaluation in the modeling of hull-water impacts, for example in the selection of appropriate modeling parameters (e.g. Aquelet and Souli 2003). One objective with this thesis is hence also to further evaluate the explicit FEA-technique in the modeling of hull-water impacts.

Within the framework of the present thesis, experimental work has also been performed using a novel Servo-Hydraulic Slam Testing System (SSTS) developed at Industrial Research Ltd. (IRL) in Auckland, New Zealand. The work has for instance been presented in Battley and Stenius (2003), Battley et al. (2005), Breder (2005), Battley et al. (2008), Pehrson (2009), and Battley et al. (2009)/paper E.

In the following, the hydroelastic mechanisms in panel-water impacts are first discussed with reference to concepts used in this work. In section 3 the finite element modeling technique is described, including arbitrary Lagrangian Eulerian (ALE) formulations, multi-material formulations, and penalty based contact formulations. Section 4 gives an overview of the experimental facility and experimental investigations of hydroelasticity are discussed with the focus on the experiments undertaken during this project. Section 5 gives an example of the numerical and experimental results of panel-water impacts highlighting the effects of hydroelasticity. The research results are finally in section 6 discussed and summarized, and topics for future work are given in section 7.

2 Hydroelasticity in Panel-Water Impacts

Since the late 1920s hull-water impacts have been investigated by analyzing the idealized problem of a two-dimensional wedge impacting a calm water surface. Pioneering work was made by von Karman (1929) and Wagner (1932) on sea-plane floats. Recently presented modeling techniques in the analysis of hull-water impacts involve non-linear boundary element methods (e.g. Zhao and Faltinsen (1993)), computational fluid dynamics (e.g. Tveitnes 2001) and explicit finite element analysis (e.g. Souli and Olovsson 1999, Olovsson and Souli 2000 & 2001, le Sourne et al. 2003, and Stenius et al. 2006/paper B). A comprehensive introduction to the field of high-speed craft in waves can be found in Rosén (2004). Early work on hydroelasticity in marine applications can for instance be found in Bishop and Price (1979). Following the work by Bishop and Price (1979), the effects of hydroealsticity have been investigated in a variety of marine related fields such as, ships, off-shore platforms, very large floating structures, and aqua-culture structures (Temarel 2008). Not until the early 1990s however more extensive research were reported in the literature on high-speed craft related localized hydroelastic effects such as the influence of panel elasticity on the slamming loads and structural responses (e.g. Aarsnes 1994 and Kvålsvold 1994). In the last decades localized hydroelastic effects have become more of an issue with increasing speed, ship size, and increased focus on achieving more optimized structures.

Hydroelasticity in general terms may be regarded as a sub-category to fluid-structure interaction describing a class of problems related to the interaction between a flexible structure and a liquid. One type of such problems are hull-water impacts of high-speed craft. Consider for example the high-speed craft in figure 3. As the craft re-enters the water, the hull-bottom structure will be subjected to large transient hydrodynamic impact loads. The loads are critically dependent of the relative angle between hull and water surface and the impact velocity. The pressure magnitudes increase for increased incident impact velocity and decreased relative angle. At small hull-water angles ($< 5^\circ$) an air-cushioning effect however contributes to decreasing the pressures. The pressure distribution is characterized by a very 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, as schematically illustrated in figure 4. In response to the hydrodynamic loading the hull structure deforms, which affects the flow-field and thereby the pressure distribution, etc. The significance of this interaction on the particular problem of interest may of course vary from negligible to significant depending on the details of the structure and loading. Some of the terminology used in this work regarding the study of this problem are given in figure 4, and some main concepts used are described below, including kinematic and inertia related hydroelastic effects and *rigid/quasi-static* solutions.

Figure 3: *High-speed craft Storebro 90E, used for instance by the Swedish navy and operates in speed regimes up to and above 40 knots (photo: Anders Rosén).*

Kinematic and Inertia Effects During the impact event, two types of hydroelastic effects may in a tentative manner be identified. These are kinematic effects and inertia effects. Kinematic effects are associated with the structural deformation which changes the geometry, velocity and acceleration conditions at the fluid-structure boundary, while inertia effects are associated with loading rates of the structure in relationship with the ability of the structure to respond. Essentially these are combined and interrelated, which certainly does not simplify things, however a distinction between these two mechanisms is useful in the study of the problem, as will be discussed later.

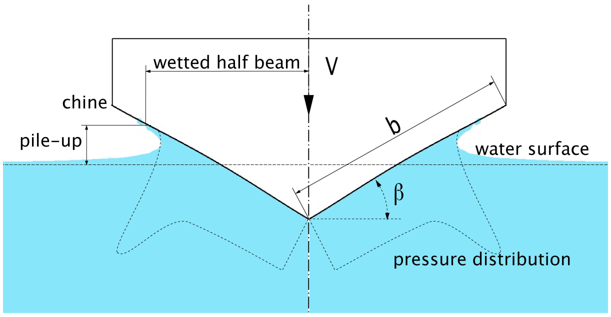


Figure 4: *Schematic illustration of an idealized hull-water impact illustrating pile-up, hydrodynamic pressure distribution (dashed), impact velocity V, ship-hull deadrise β and width of panel b.*

Rigid/Quasi-Static Solution In practice, hydroelasticity is just one part of the physics involved during the entire impact event. Extracting the explicit dependence of hydroelasticity from full-scale experiments or laboratory tests is not a straightforward or easy task (e.g. Battley et al. 2009/paper E). When studying the problem by means of analytical methods or numerical simulations on the other hand, the different interacting mechanisms may be included or excluded from the analysis and thereby when comparing the different solutions the explicit dependence of certain mechanisms can be assessed. For the purpose of quantifying the influence hydroelasticity has on the structural response, the solutions from fully coupled simulations are in this work compared with that of *rigid/quasi-static* simulations. The term *rigid/quasi-static* is used for completely separated and quasi-static solutions, which means that the hydrodynamic load is unaffected by the deformation (i.e. *rigid*), and the structural response is unaffected by structural inertia (i.e. *quasi-static*). This also relates back to the above description of kinematic and inertia related effects, i.e. rigid implies no kinematic effects and quasi-static implies no structural deflection related inertia effects.

3 Numerical Methodology

The full governing equations of fluid-structure interaction problems are generally too complex to be solved analytically, hence numerical methods are employed to analyze these problems. This involves the modeling of structures and fluids and the coupling between the interacting parts. Some of the early work on numerical modeling of fluid-structure interaction was made on nuclear power plant simulations and can for instance be found in Belytschko (1977) and Zienkiewicz and Bettess (1978).

Recently developed techniques for numerical modeling of fluid-structure interaction in hull-water impact problems are for example coupled plate/beam theory and Wagner (1932) theory techniques (e.g. Faltinsen 1999, Hua et al. 2000, and Stenius et al. 2009a/paper D), coupled boundary element methods and finite element methods BEM-FEM (e.g. Lu et al. 2000 and Qin and Batra 2009), coupled fluid dynamics codes with finite element methods CFD-FEM (Hudson et al. 2007), smoothed particle hydrodynamics codes SPH (e.g. Cartwright et al. 2006 and Brizzolara et al. 2008), and explicit finite element methods FEM (e.g. Olovsson and Souli 2000 & 2001, Aquelet and Souli 2003, Stenius et al. 2006/paper B, Stenius et al. 2007/paper C, and Stenius et al. 2009a/paper D).

Coupled beam/plate theory and potential theory techniques offer computationally efficient solutions to the problem. In the most simplified form the coupling formulation of the fluid-structure interaction is however limited to only include mean deflection velocity terms. The more advanced methods such as CFD-FEM, SPH, and FEM, offer a more detailed fluid-structure interaction coupling and modeling of the flow field, which typically also requires large computational efforts (e.g., Engle and Lewis 2003, Stenius et al. 2006/paper B, Brizzolara et al. 2008). Comparisons between different methods can for instance be found in Engle and Lewis (2003) and Alexandru et al. (2007).

For the work in the present thesis the commercial explicit finite element code LS-DYNA was considered suitable in the modeling of the hydroelastic problem. The fluid-structure interaction capabilities in LS-DYNA are briefly described below. This includes the explicit time-integration scheme, the arbitrary Lagrangian Eulerian (ALE) formulations, multi-material formulations, penalty based contact formulations, and mesh density selection.

Explicit Time Integration Scheme Explicit FEA referrers to the time integration schemes in the finite element code. The predominant explicit time integration scheme is the central difference method (Belytschko et al. 2000). In explicit time integration the first approximation of the next time step is accepted, as opposed to in implicit time integration schemes, which iterate at each time step in order to minimize the error. Explicit time integration is conditionally stable, meaning that the solution is stable for sufficiently small time steps. In LS-DYNA the critical time step is approximated by not permitting an acoustic wave to cross the smallest element of the model during one time step. Generally, explicit time integration schemes are appropriate for short duration dynamic/non-linear problems with large gradients in the history variables while implicit time integration is more applicable in smoother problems where longer durations of the physical problem are of interest. This has to do with the maximum time step size that can be used. In explicit schemes very small time steps are required, however each time step is fast. In implicit schemes larger time steps can be taken under the condition that the solution is smooth making this method faster.

Multi-Material Arbitrary Lagrangian Eulerian Formulation (MMALE) In Eulerian and ALE formulations there is material flow through the elements, as opposed to in Lagrangian formulations where the material and mesh deformations follow each other. This material flow complicates the governing equations. The multi-material ALE formulation implies interface reconstruction between the materials and a composite stress tensor formulation. In LS-DYNA the ALE formulation is effectively Lagrangian, but with a remapping step at a user defined rate. In the remapping step the nodes are moved to new positions and the solution is mapped onto the new mesh configuration. In this re-meshing step the nodes may be redistributed to their original positions (Eulerian mesh), according to mesh smoothing algorithms, or according to a user defined mesh-motion. Hence the name, arbitrary Eulerian Lagrangian formulation. In this thesis the nodes are redistributed to their original positions, which gives an Eulerian mesh and thereby enables large fluid deformations without element distortion problems. The multi-material formulation enables both air and water to be present in one single element.

Fluid-Structure Coupling In FE modeling where different parts interact, the contact between the parts has to be formulated explicitly, e.g. through constraint based and penalty based formulations. In a constraint based contact formulation the fluid and structure nodes in contact are instantly forced to follow each other. In the penalty-based formulation on the other hand a non-physical penetration of the parts is allowed. The penalty contact formulations 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 and Souli 2003, le Sourne et al. 2003, Stenius et al. 2006/paper B).

Selection of Mesh Density and Contact Stiffness A critical parameter in finite element modeling 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 favorable regarding computational cost. As described in the above, large pressure gradients are inherent with 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. As shown in Stenius et al. (2006)/paper B, the solution stability is highly dependent on the mesh-density/contact-stiffness relation. In Stenius et al. (2006)/paper B, a method for the selection of mesh-density and the corresponding contact stiffness for arbitrary impact situations is presented. The method is based on a parameter study and Wagner (1932) theory. By the Wagner (1932) theory an estimate of the peak pressures and the pressure gradients is obtained.

Modeling Idealizations Regardless of modeling technique, some idealizations of the problem are inevitable in order to limit modeling efforts and computational cost. To what extent idealizations are done depends on the problem at hand and the needs and resources available to solve it. For panel-water impact problems such as those investigated in this thesis a common approach is to study the idealized situation of 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 4. In comparison to experiments (Zhao et al. 1996) the 3D effects on the problem when comparing hydrodynamic loads from drop tests of wedge sections with that of numerical simulations may be in the order of 20%. Some additional common idealizations used when modeling the impact problem are to ignore viscosity and gravity. The reason is that viscous forces and gravitational forces are small in comparison to the hydrodynamic pressure forces. For the impact situations studied in this thesis, the viscous forces are in the order of less than 1% of the hydrodynamic pressure forces and the hydrostatic forces are typically less than 10% of the hydrodynamic pressure forces. The influence of non-linear material models has not been considered in this study. Studies by Faltinsen (1999) indicate that structural damping effects should have a minor effect on the maximum structural responses. For sandwich panels however, worth considering in future work is strain rate effects, which can affect the results of slamming loaded panels (Battley and Lake 2006).

4 Experimental Methodology

Experimental analysis of hull-water impacts have for many years been performed both in laboratories and by dropping actual vessels. In many tests rigid models have been used to investigate the resulting pressure distributions, such as those by Chuang (1967), Wraith (1998), and Breder (2005). Tests using non-rigid panels include those by Hayman et al. (1992), Aarsnes (1994), Kvålsvold (1994), Samuelides and Katsaounis (1997), and Battley and Lake (2006). The main focus when studying non-rigid panels has been on wet-deck slamming, with very small or zero deadrise angles. For larger deadrise angles there seems to be a lack of experimental work on hydroelasticity. Typically also the considered impact situations provide a limited dynamic span in terms of the relation, R, between loading periods and first wet natural periods of vibration, as illustrated in table 1. Compare for example with Battley et al. (2009)/paper E bottom row in the table, in which the experimental setup is designed to study stiffness effects on the loads and responses. From basic mechanics, impact situations for which $R >> 1$ can be considered as quasi-static, while dynamic effects can be expected for impact situations for which $R \lesssim 1$. To be able to identify trends it is essential that the test range includes situations with clearly identifiable differences regarding hydroelastic effects.

Table 1: *The dynamic span for experiments conducted with non-rigid panels. In accordance with figure 4 the table presents range of impact velocities (*V*), deadrise angles (*β*), flexural stiffness (*D*), panel span (*b*), boundary conditions (*BC*), and relation* R *between loading periods and first wet natural periods of vibration calculated according to Stenius et al. (2007)/paper C. The notation for the boundary conditions correspond to, pp - partial at both ends and ss - simply supported at both ends.*

Reference	V (m/s)	β (deg)	D (kNm)	b (m)	BC -	R -
Hayman et al. (1992)	5.5-9.1[a]	30	49.9	1.15	pp	1.29-2.13
Battley and Lake (2006)	3.5-5.5[b]	10	9.9	0.5	ss	0.64-1.01
Faltinsen (1999)	2.6[c]	5-15	7[d]	0.95	pp	0.34-1.04
Battley et al. (2009)	0.5-6[b]	10	1.5,6.7,274	0.5	ss	0.46-6.2[e]

[a] mean impact velocity in drop test

[b] forced constant impact velocity

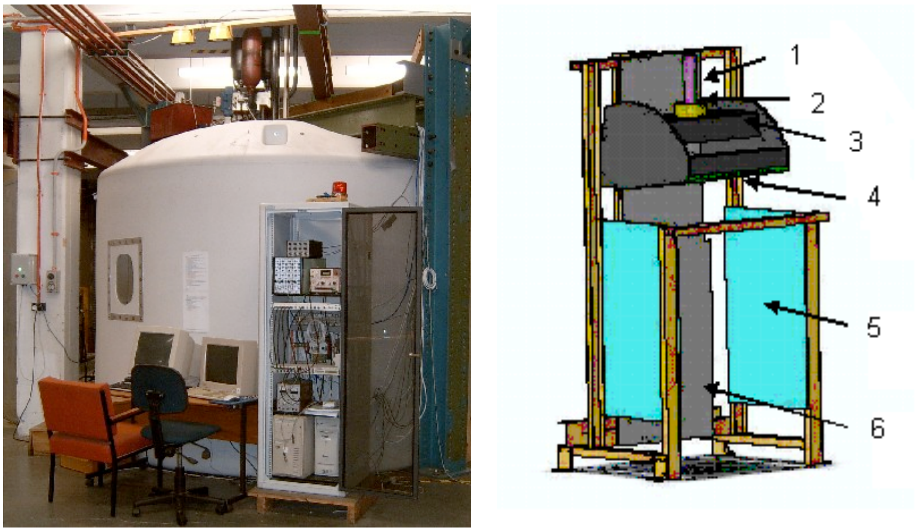
[c] estimated impact velocity from full-scale trials

[d] calculated as stiffness equivalent isotropic panel from orthotropic panel properties

[e] the full range of velocities were not run for all stiffnesses

The experiments conducted within the framework of this thesis were performed using a Servo-Hydraulic Slam Testing System (SSTS) developed at Industrial Research Ltd. (IRL) in Auckland, New Zealand (figure 5a). The system uses a computer controlled servo-hydraulic actuator enabling controlled velocity impacts, e.g. constant velocities or velocity profiles. For example reproducing velocity profiles from full scale trials. The impact events are reproduced in a cylindrical tank with a diameter of 3.5 m and a water depth of about 1.3 m. Hull bottom panels of about 0.5 x 1 m can be tested with deadrise angles from 0° to 40° in 10° increments.

The experimental setup is idealized to a two-dimensional flow situation by fixed end-plates at the sides of the specimen (figure 5b). To enable larger panels to be tested within the limits of the test facility non-symmetrical impact conditions are considered, where symmetry conditions at the centre plane (apex of the wedge) are provided by a back-plate. The system has proved to provide good repeatability.



(a) (b)

Figure 5: a: *Servohydraulic Slam Testing System (SSTS).* b: *Sketch showing the ram (1), load cell (2), specimen fixture (3), panel (4), side plate (5) and back plate (6).*

5 Results

The detailed results of this work are presented in the appended papers. This section discusses some typical results from simulations and experiments. In particular kinematic effects are here illustrated with reference to local variations in deadrise angle and impact velocity.

Numerical Results

An example of how the flexibility of the panel may affect the pressure distribution is here given for the impact situation considered in figure 6. The figure shows one half of the symmetric two-dimensional impact situation throughout three instances of the impact (t = 19, 52 & 69 ms). During the impact event, the panel deformation leads to a local variation in panel deadrise and a local variation in incident impact velocity as illustrated at three points along the panel in figure 7. The corresponding pressure distribution on the flexible panel is shown in figure 8 (a), while the pressure distribution based on the same impact conditions except that the panel is rigid is presented in figure 8 (b). As seen for the rigid panel-water impact the pressure magnitudes are fairly constant up to the separation point (chines-wet). For the flexible panel on the other hand, as the pressure pulse propagates from keel to chine the magnitude first decreases and reaches a minimum at t = 20 ms, where after the magnitude increases and reaches a maximum at t = 52 ms. The magnitude of the entire pressure distribution changes, not only the peak pressure. Studying figure 7 and figure 8 (a) it can be seen that the minimum pressure level occurs when the local velocity reaches its minimum, and the maximum pressure occurs near the chine where the local panel deadrise reaches a minimum and the relative local impact velocity is zero.

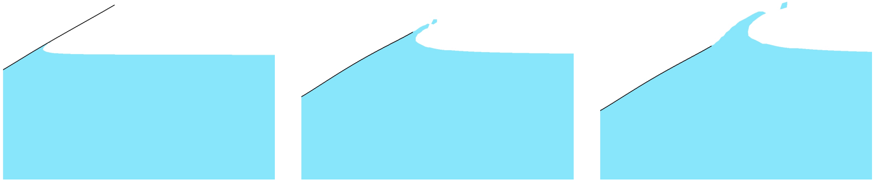


Figure 6: *FE-simulation of a 30° elastic panel-water impact with 6 m/s constant impact velocity and clamped boundaries at keel and chine. The impact is illustrated at t = 19, 52 and 69 ms, where 52 ms corresponds to maximum panel deflection.*

The deflection fields corresponding to the three instances of the impact (figure 6) from fully coupled hydroelastic simulations and *rigid/quasi-static* simulations are presented in figure 9. The *rigid/quasi-static* solutions presented here are obtained by, first running finite element simulations with a rigid-panel from which the time history pressure signals are stored for each element, and subsequently applied on the elastic panel quasi-statically in new finite element simulations. In figure 9 the hydroelastic solution in the initial stages yields a lower structural deflection than the *rigid/quasi-static* solution, while in the later stages of the impact the hydroelastic solution gradually approaches the *rigid/quasi-static* solution and ultimately results in the largest deflections. Returning to figure 8, it can be seen that both the relatively smaller and larger structural responses when accounting for hydroelasticity partly can be explained by a decrease and increase in the pressure magnitudes.

Naturally inertia is also an integrated part here, however the explicit dependence is more difficult to extract. An interesting result regarding the inertia effects can however be identified by examining figure 7a and figure 9a&b. This follows from the

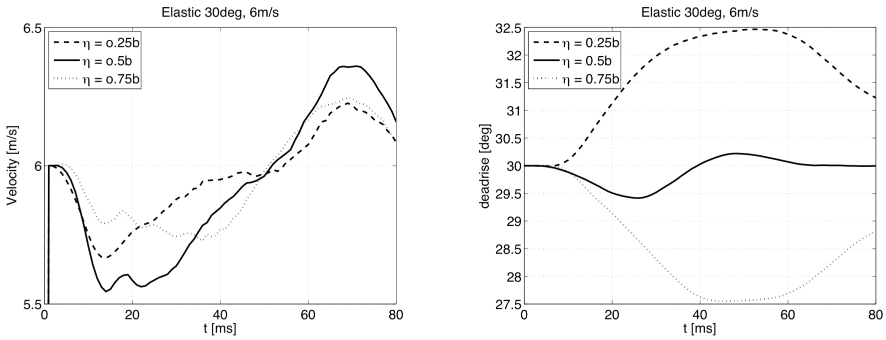


Figure 7: (a): *Time history variation of local nodal impact velocity.* (b): *Time history variation of local deadrise. (η = 0.25b, 0.5b and 0.75b is a local coordinate on the panel, where η = 0 at the keel and η = b at the chine).*

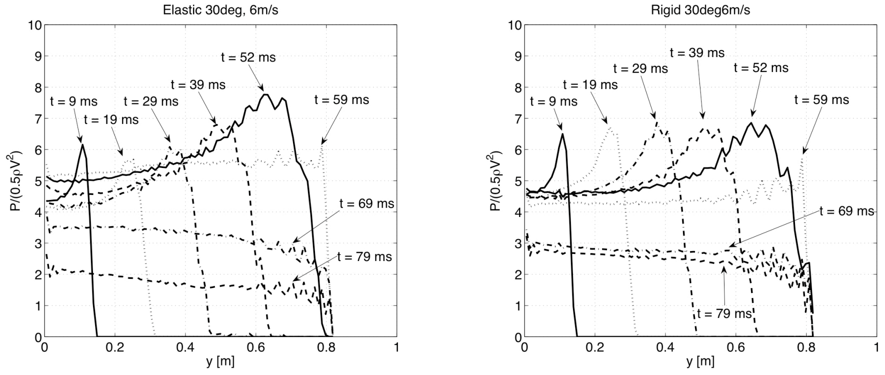
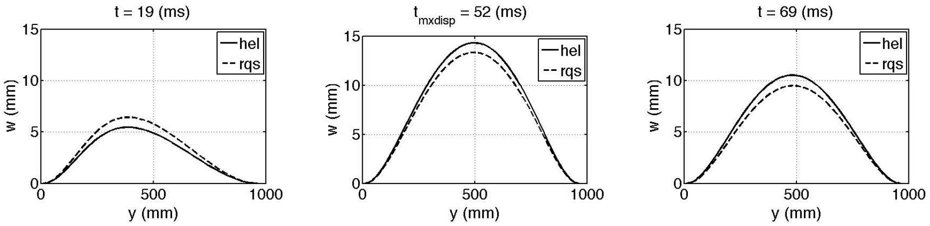


Figure 8: (a): *Normalized pressure distribution at t = 0.9, 19, 29, 39, 52, 59, 69 and 79 ms on an elastic panel.* (b): *The corresponding normalized pressure distributions on a rigid panel.*

gradual wetting of the panel, which changes the inertia of the system from being purely structural inertia at the moment of impact to a combination of structural inertia and added mass inertia at the end of the impact event. Figure 7a, in addition to giving information about the local panel deflection velocity, also gives information about the panel deflection acceleration and deceleration phases. As seen the relative impact velocity reduces within the first 20 ms, implying that the panel deflection velocity increases within this time span. Similarly, the relative impact



(a) (b) (c)

Figure 9: *Deflection fields from finite element simulation of a 30° elastic panel-water impact with 6 m/s constant impact velocity and clamped boundaries at keel and chine. The impact is illustrated at t = 19, 52 and 69 ms, where 52 ms corresponds to maximum panel deflection (hel - hydroelastic, rqs - rigid/quasi-static).*

velocity increases again from 20 ms up to 70 ms, which consequently corresponds to a decrease in the panel deflection velocity. Hence, within the fist 20 ms the panel deflection acceleration occurs, while during the remaining 20 to 70 ms of the impact event the panel deflection deceleration occurs. Following the fundamental principles of classical physics, during the acceleration phase of the panel deflection, inertia acts in an opposite direction contributing to decreased deflections (figure 9a). In the deceleration phase of the panel deflection, inertia by acting in the opposite direction contributes to increased panel deflections (figure 9b). Thus, inertia effects also contribute to the trend seen in figure 9a&b, i.e. structural inertia initially contributes to reducing the structural responses, while during the later phases of the impact event structural and added mass inertia contributes to increasing structural responses.

Experimental Results

Figure 10 shows time-history pressure signals from an impact event with a 3 m/s impact velocity and a deadrise angle of 10°. Pressure signals are shown for three different positions along the panel, starting at the lower end which impacts the water first (keel), the middle of the panel (centre), and the upper end (chine). The results are shown for three different panels, one very flexible (SS), one medium flexible (FC) and one very stiff (R). As can be seen, the measured pressure magnitudes increase in the centre and at the chine with increased flexibility. At the keel however the trend is not as clear and there are some larger oscillations going on for the flexible panel, but here the pressures seem to decrease with increased flexibility. By comparing with the numerical simulations in figure 8 it can be seen that the trend is similar with increasing pressures at the centre and chine when studying the flexible panel.

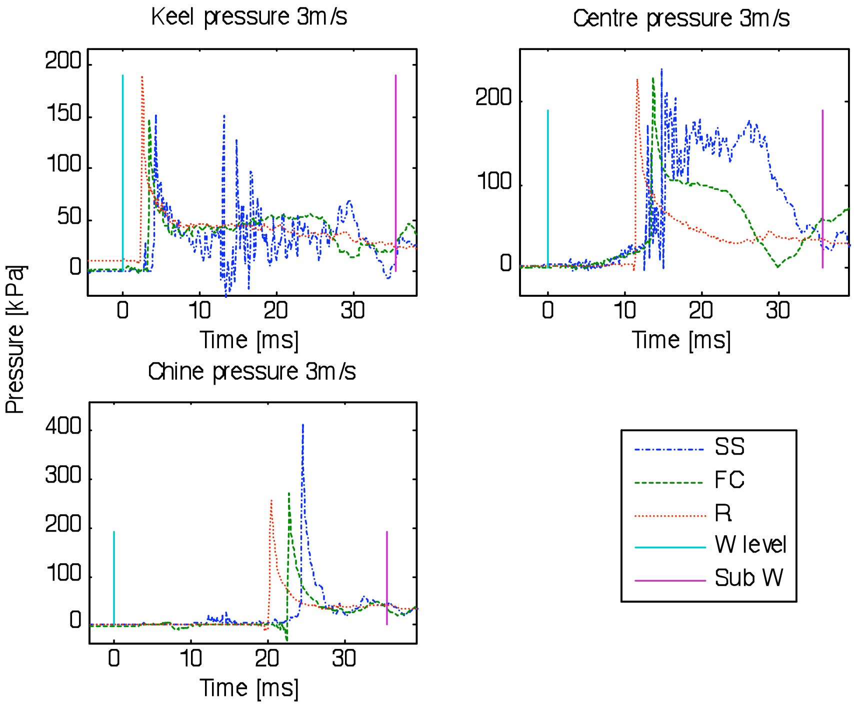


Figure 10: *Pressure signals from experiments for 3 m/s slamming impacts of three different panels, one very flexible (SS), one medium flexible (FC) and one very stiff (R). Vertical lines indicate the keel water entry and the chine passage of the idle water surface.*

As also mentioned above, extracting the explicit effects of hydroelasticity from experiments is difficult and associated with challenges in the design of the experiment, measurement of the considered parameters, and last but not least analysis of the results. In particular it is difficult to analyze the effects of hydroelasticity on the structural responses, as there is no obvious reference solution to compare with. This is in a tentative way addressed in Battley et al. (2009)/paper E by scaling the structural responses with the flexural stiffness. However, more work related to this topic is important in order to experimentally quantify the effects of hydroelasticity on the structural responses.

6 Summary and Discussion of Research Results

This thesis is concerned with the localized problem of hydroelasticity in marine panel-water impacts with an overall aim to increase the efficiency of high-speed craft by application of more refined methods in the structural design. The work mainly focuses on numerical modeling of the hydroelastic problem and therewith related aspects in the modeling and characterization of hydroelasticity. In addition, aspects regarding the design procedures for high-speed craft and experimental analysis of hydroelasticity are also addressed. The following discusses the main contributions from the present work.

In **paper A** aspects regarding the design and development of weight efficient high-speed craft structures are addressed. In the paper this is approached by an integrated design procedure for determination of structural arrangement and scantlings for the complete structure of small high-speed craft. The purpose of the procedure is to serve as a tool in the preliminary design stage where it enables generation of weight minimized designs with very limited efforts. The results are assessed with respect to reductions in the overall displacement of the craft, and thereby related fuel consumption and emissions. The paper illustrates the potentials of applying rational design procedures and selections of efficient material concepts.

In **paper B** an explicit FE-technique is evaluated in the modeling of hull-water impact problems. This involves the selection of appropriate finite element modeling parameters in terms of mesh resolution and parameters describing the fluid-structure coupling. The paper suggest a modeling methodology for arbitrary v-shaped rigid hull-water impacts. The suggested methodology has been extensively used with good results throughout the finite-element simulations in paper C&D.

In **paper C** the finite element modeling methodology suggested in paper B is first evaluated for elastic structures. The methodology is subsequently applied in the analysis of the structural response through a number of systematically varied impact conditions. Different impact situations are studied concerning panel deadrise, impact velocity, boundary conditions and structural mass. A tentative method for dynamic characterization of the hydroelastic problem is presented based on the relation between loading periods and wet first natural periods of vibration. The results indicate that accounting for hydroelasticity results in reduced structural responses and that the effects of hydroelasticity increase with increased impact velocity, increased panel width, decreased deadrise, decreased panel stiffness, and decreased fixation of the boundaries.

In **paper D** the results presented in paper C are evaluated by studying the significance of hydroelasticity on the problem by comparing with the corresponding completely separable and quasi-static solution (*rigid/quasi-static*). The paper shows that, in contrast to what was shown in paper C and in the literature, accounting for hydroelasticity may imply larger structural responses than what is obtained from the corresponding *rigid/quasi-static* solutions. The reason for the difference in the results presented in paper C and D, can be related to the quantification of the hydroelastic effects. In paper C the results are compared with a corresponding *rigid/quasi-static* solution based on engineering beam theory, where in-plane forces are neglected. However, in paper D in-plane forces are found to have a significant influence on the hydroelastic effects. The results motivated further examination of the hydroelastic mechanisms and the development of a complementary method for studying the hydroelastic problem. This in-house developed simplified method is useful in studying the different force components throughout the impact event. It is shown that the increase in the structural response when accounting for hydroelasticity can partly be explained by kinematic effects, and partly by inertia related added mass effects.

In **paper E** controlled water slam testing of composite hull panels were conducted in order to study the effect of hydroelasticity for three panels with different stiffnesses. The method for dynamic characterization of the hydroelastic problem presented in paper C is, despite its limitations as discussed in paper D, successfully used in the design of the experimental setup. The observed hydroelastic effects include changes in panel geometry, local velocity and hydrodynamic pressures. These effects also correlate with the observed kinematic effects from the numerical simulations in paper D. A tentative approach is presented to extract inertia effects from panel structural responses.

7 Future Work

Some of the most important aspects regarding future work are summarized in the points below:

- In this thesis numerical and experimental results are mainly compared regarding the trends in hydroelastic effects, more extensive comparisons should however be a high priority in future work. An important aspect regarding experimental work is also related to experimental quantification of hydroelastic effects on the structural responses.
- Depending on the particular structure and loading the hydroelastic effects are in the present work ranging from negligible to significant. Evaluating the importance of hydroelasticity in impact conditions corresponding to the design conditions for high-speed craft is also an important part of future work.
- Strain rate effects is another aspect worth considering in future work, in particular for sandwich panels.
- A limitation with this work is that the problem is studied in two dimensions. Studying the tree-dimensional situation is also an aspect that should be considered in future work.

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