Spyros Hirdaris - Hydroelasticity of Ships

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As a generic definition, hydroelasticity is the branch of science concerned with the interactions of deformable bodies with the water environment in which they operate. Hydroelasticity as the naval counterpart to aeroelasticity recognizes that at fluid structure interaction level significant differences may exist between the hydrodynamic, inertia, and elastic forces experienced by a floating marine structure. In other words, the fluid pressure acting on the structure modifies its dynamic state and, in return, the motion and distortion of the structure disturb the pressure field around it.

Keywords: Hydroelasticity of Ships ; Flexible Fluid Structure Interactions ; Wave Loads

1. Introduction

This entry gives a brief introduction to "Hydroelasticity of Ships". Emphasis is attributed to the description of past and recent state of the art theoretical developments, validation methods and emerging strongly coupled Flexible Fluid Structure Interaction (FFSI) modelling approaches for strength assessment of marine structures.

2. History

Hydroelasticity of Ships was brought to the attention of the Naval Architecture community in the 1970s through the work of Bishop and Price, culminating with the publication of the synonymous book [[1]]. The overriding aim of the concept was to improve the accuracy of fluid–structure interaction modelling by describing more accurately the physics of the engineering system, namely allowing the flexible structural characteristics of the ship influence and the corresponding interactions with the fluid forces. The new theory, within the assumptions of twodimensional (2D) potential flow analysis and linear beam structural dynamics, offered the possibility of assessing the influence of symmetric (i.e. vertical bending), antisymmetric (i.e. coupled horizontal bending and twisting), and unsymmetric (coupled vertical and horizontal bending and twisting) distortions on wave-induced loads in regular and irregular waves [[2][3]].

The potential use of 2D hydroelasticity theory was illustrated through applications to naval vessels and a wide range of merchant ships, such as tankers, bulk carriers, and container ships, together with comparisons against available full-scale measurements [[4][5][6][7][8]]. A fundamental aspect of this theory was the use of the ‘in vacuo’ or ‘dry hull’ analysis to determine the principal mode shapes of the flexible structure. Earlier work was based on the ‘wet modes’, accounting not only for the mechanical properties of the hull structure but also for the influence of the fluid [[9]]. In recent years the application of the 2D form of theory for the service factor assessment of a Great Lakes bulk carrier highlighted the potential usefulness of validated hydroelasticity theory predictions for ship operation assessment procedures [[10]].

The three-dimensional (3D) form of unified hydroelasticity theory was developed in the late 1980s to include applications to non-beamlike marine structures, such as multihulled vessels, and to assess the effects of more detailed local structural configuration on the global dynamic response [[11]]. This theory employs either 2D beam or 3D structural idealizations, through finite element (FE) modelling, together with 3D potential flow analysis using pulsating source distribution over the vessel’s mean wetted surface.

Over the last fifteen years, large-scale applications and, wherever applicable, comparisons between 2D and 3D hydroelasticity analyses, for a mine hunter, a bulk carrier, and a container ship have been carried out. These have indicated the importance of assessing the influence of structural modelling on dynamic response, from the viewpoint of application at different stages of the design process, as illustrated with examples in section 3 [[12][13]]. These applications and the increasing market demand for standardized computer aided design assessment solutions provided the momentum to develop a concept design assessment philosophy on the usefulness of hydroelasticity for design, as well as the prototype of a web-enabled software that allows users to solve fluid–flexible structure interaction (FFSI) problems by utilizing grid-based computer resources [[14]]. More recently applications utilizing weakly non-linear hydroelastic methods became increasingly evident [[15]].

The incorporation of the combined effects of springing and whipping induced loads in the design
process in a sensible and quantifiable manner are technical challenges that will definitely impact applied research and development studies over the short to medium term. However, as ships change in terms of scale and type, and operational, economic, and environmental requirements become more stringent, it is possible that the use of a more realistic ‘first principles’ approach for the assessment of wave-induced loads, either on its own or in combination with the latest generation of prescriptive Classification Rules and procedures, could become more prevalent [[16][17]]. In the future, 3D non-linear theories based on traditional or CFD/RANS solvers and hydroelasticity applications could become more prevalent for the solution of local or global problems [[18][19][20]].

3. Theory Basics

The mathematical background of the two- and three-dimensional hydroelasticity theories has been well established in literature and not repeated here [[1][7][8][11]]. The theories are based on employing the “dry hull” and “wet hull” approach. The former, assuming the hull in vacuo, i.e. the free-free hull structure in the absence of any external actions or internal damping, is used to obtain natural frequencies and corresponding principal mode shapes. Both theories perform the fluid-flexible structure interaction (FFSI), i.e. the “wet hull” stage, using potential flow theory. Accordingly, the fluid domain, extending to infinite depth, is treated as homogeneous, inviscid and incompressible, and the fluid motion is irrotational. A unique solution for the velocity potential is obtained via the application of the linearised boundary conditions on the mean free surface and the body, as well as a radiation condition at infinity. In 2D hydroelasticity this is achieved through the use of strip theory. In 3D hydroelasticity the boundary conditions are applied by implementation of the generalised Timman-Newman formulation [[21]]. It is worth noting that in the classic form of the theory linearised boundary conditions imply that :(a) wave amplitudes remain small, (b) the unsteady oscillations of the body and the surrounding flow are of small amplitude and (c) the perturbation of the steady flow due to the steady forward motion of the body is assumed negligible.

4. The future

Coupling of linear structural dynamics with weakly or fully non-linear three-dimensional hydrodynamic methods (e.g. Rankine sources or Time domain Green’s function) can only be viewed as a first step in the way forward. From a hydrodynamics perspective longer term research efforts should focus on coupling linear finite element analysis with a Mixed Eulerian-Lagrangian scheme or RANS methods based on commercial software or other RANS methods such as Smoothed Particle Hydrodynamics (SPH) and Moving Particle Semi-implicit Scheme (MPS). From a structural mechanics perspective one may need to consider geometric nonlinearities, i.e. large deformations, as well as material nonlinearities, i.e. plastic range. Development of the ‘*hydroplasticity*’ analysis may be required in order to assess ship hull structural collapse, plastic buckling of plates, crack development due to fatigue, as well as predict damaged ship structural responses in plastic stage. A hydroplasticity theory can be based on the same basic principles of the linear hydroelasticity theory, in terms of the concept of principal modes. However, the extraction of eigenvalues and eigenvectors will probably have to be based on a complex asymmetric matrix incorporating the effects of stiffness. The use of direct calculation methods that account simultaneously for the effects of dynamic wave environment using fully nonlinear hydrodynamics / FEA will evolve further by:

- 3D full-ship detailed linear and, wherever applicable, non linear FEA to support coupling with hydroelasticity analyses;
- 3D fully non linear springing and whipping analysis. The 3D bow flare and stern slamming analysis should incorporate the effects of hull flexibility, green water and wherever applicable air trapping, jet flow formation etc.;
- 3D spectral fatigue analysis accounting for the effects of hydroelasticity, e.g. springing and whipping;
- Vibration analysis incorporating the effects of machinery or propeller excitation on FFSI RANS CFD approaches, such as the finite volume method and the particle based methods (SPH, MPS etc.) are expected to become increasingly useful in the future. The use of RANS/CFD methods as part of or coupled to hydroelastic solutions are the ultimate goal. However, due to lack of computational efficiency in the short to medium term our understanding of time domain potential flow hydrodynamics needs to be improved beyond the exact evaluation of the Froude-Krylov and hydrostatic actions, towards a more comprehensive understanding and solution of the fully non linear aspects of fluid-structure interaction.

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