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Predicting the natural frequency of submerged structures using coupled solid-acoustic finite element simulations

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ABSTRACT

This study concerns fluid-structure interaction analysis by using a solid-acoustic finite element model, letting an acoustic medium represent the fluid. This is a promising methodology to obtain computationally affordable advanced models of fluid structure interaction problems were the deformations can be assumed relatively small and the added mass effects dominate the dynamic characteristics. The work presents an extensive study of 19 plate specimens with material properties corresponding to carbon-fibre reinforced plastics, glass-fibre reinforced plastics, as well as steel and aluminium, and a range of different panel aspect ratios. In particular the effects of added mass on fibre-reinforced plastic materials are highlighted in comparison to how these typically are treated in the industry today. Based on a systematic isolation of the added mass effects, this paper enables a precise evaluation of the solid-acoustic FSI modelling approach. The modelling technique is also compared with previously published experiments. The results show good agreement (less than $\sim \pm 3\%$ difference) between numerical and experimental results for the first natural frequency. The results indicate that this is a very promising modelling technique that can serve as a refined analysis method for design work performed within the maritime industry.

1. Introduction

Polymer composite materials play a crucial role in designing optimised structures for the maritime environment. Composite materials have a wide range of applicability as they have high stiffness to weight ratio, are corrosion resistant and can be taylor designed for very attuned purposes and needs, may it be lighter over all weight and thereby increased speed and/or range, which typically is the case, or some very specific capabilities, such as bend-twist coupling or taylor designed acoustic impedance, or simply aesthetics with complex shapes and high requirements on surface finish.

As the tension on the worlds resources grows and the need for environmentally sound solutions increases there is also an ever increasing need for more energy efficient and optimised structures. This concerns both military and civilian applications ranging from entire hull structures to cantilevered structural components such as hydrofoils, fins, keels, turbines, and propeller blades (e.g. Lönnö, 2003; Marsh, 2006; Young et al., 2016; Mouritz et al., 2001). Regardless of part however, to design an optimised component, it is essential that the dynamic loading situation is understood properly and that the dynamic characteristics of the part can be predicted with enough accuracy for the situation at hand.

For structures submerged in water a complicating factor is the accentuated effect of added mass from the surrounding water that lowers the natural frequencies and thereby changes the dynamic characteristics of the component. The dynamics of submerged cantilevered beams and plates has indeed been studied extensively within the research community since the mid-1960s (e.g. Lindholm et al., 1965; Muthuveerappan et al., 1979; Zheng-ming 1992; Liang et al., 2001; Fluid et al., 2003; Kramer et al., 2013; Sedlar et al., 2011). However, the main focus has been on metallic structures, and hence the knowledge about the behaviour of composite materials in sub-sea applications is more limited.

The focus on steel structures by the research community naturally also influences the typical design methods, or "rule of thumb", used in the industry today. Typically, steel or brass weight is simply doubled and no concern is taken for geometrical aspects when estimating the "added mass" effect on the natural frequencies. There is hence a lack of knowledge and design methods for complex composite structures, which is limiting the designers from utilising the full potential of composite materials and developing optimised structures.

In previous studies it is also shown that lighter composite materials with high specific stiffness are more susceptible to the influence of the surrounding water. Hence, the "added mass" effect can have an even

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greater influence on the natural frequencies of composite materials than for the heavier steel or aluminium structures (e.g. Kramer et al., 2013; Stenius et al., 2016).

Kwon et al. (2013) presents an experimental study on the effect of water on vibrating cantilever beams. The tested beams are slender plates with a narrow width and the results are in line with those presented in (Stenius et al., 2016) with the dry to wet eigenfrequency ratio of 70% for aluminium, 60% for CFRP and 50% for GFRP. Kwon et al. (2013) used two test setups one where the beam was clamped in one end and another test where it was free-free. In the first test the displacement was monitored using digital image correlation (DIC) techniques and in the latter ten accelerometers where assembled along the length of the beam. In both test set-ups the beams where initially disturbed, either released from a pre-stressed state or impinged by an impact hammer, and the response was thereafter monitored. Further, resent research on the fluid-structure interaction also demonstrates the effect of the fluid compressibility e.g. Canales and Mantari (2018) and how to account for these effects in the design by analytical expressions.

Traditional approaches of addressing fluid-structure interaction problems can for instance be found in the review by Young et al. (2016) describing the current state of the art in modelling adaptive composites propellers. Young et al. (2016) describes the progress and challenges of the simulation topic very well. The review includes composite propellers but is equally applicable to all submerged and flexible bodies. Young et al. (2016) describes different simulation techniques for both inviscid and viscous fluid-structure interaction modelling and also includes a comprehensive reference list to the research field.

To fully resolve the flow around a vehicle (in air or water) using viscous flow computational fluid dynamics (CFD) with large-eddy simulations (LES) the grid must be highly resolved around the boundaries of the structures, and this in turn also requires a very fine mesh and time step. Spalart (2000) predicts that a fully resolved LES modelled flow around an airliner or car will include 10^{11} grid points and be possible to perform in 2045. The model discussed in Spalart (2000) is intended to resolve the flow around the object and not only the pressure acoustics, but still the size of the model and computational power needed is overwhelming.

The topic of this paper concerns development and evaluation of more computationally efficient methods (but still precise enough) to predict the dynamic characteristics of submerged structural components. The focus is to study more complex geometries than simple cylinders or rectangular plates with an interior consisting of internal stiffening with varying non-isotropic material properties (with for example local modes or bend-twisting coupling), which often is the case in real engineering problems, the added mass then no longer depends only on a rigid outer geometry (e.g. cylinder) and the fluid properties. A very promising approach is to utilise acoustic fluid-structure interaction modelling techniques, which are simple and straightforward with modern modelling techniques eliminating the need for deriving separate added mass properties, yet fast enough for optimisation considerations. Large finite element models of the design can hereby be analysed and solved within fractions of the computational cost of fully coupled CFD-FEM, or similar (e.g. Kwon and Plessas, 2014; Motley et al., 2013).

The acoustic fluid-structure modelling technique is not new in it self. The finite element approach has been used in the car industry when predicting internal noise since the 1970's (Hambric et al. (2016), Kim et al. (1999)). It is also possible to include the effect of a surrounding acoustic domain using a wave formulations (Hambric et al. (2016), Zhang (2002)). Normally when airborne sound is predicted a one-sided coupling is sufficient, coupling the movements of the structure to the pressure sound-waves in the air. In the application with slender structures submerged in water a two-way coupling is necessary since the surrounding acoustic domain affects the eigenfrequencies of the submerged structure. However, there is a lack of well described and rigorous acoustic fluid-structure finite element simulations in the literature which are compared to physical experiments. Therefore the accuracy of the modelling technique, depending on the inherent simplification of modelling water as an acoustic medium, is difficult to assess.

Kwon and Plessas (2014) introduces a technique for modelling the fluid domain in one far-field and one close-field sub-domain in order to further reduce the computational cost. Although, this seems to be a reasonable approach, it is not clear from Kwon and Plessas (2014) whether the authors have studied mesh convergence and the sensitivity of the location of the boundary between the far-field and the close-field fluid domains, and to what extent this might affect the results and conclusions drawn in the paper.

Motley et al. (2013) also use a similar modelling technique, i.e coupling rectangular cantilevered plates (using shell elements) with a fluid represented by an acoustic medium to simulate the boundary effect in the proximity of a rigid wall or free surface to the natural frequencies of the plates. Motley et al. (2013) compare their simulations with experiments by Lindholm et al. (1965) showing good agreement. Further, their results give wet/dry frequency ratio of 40%–60% for studied steel plates and 20%–30% for the CFRP plates which is also in line with the experimental results presented in (Stenius et al., 2016).

In this study the hypothesis is that fluid-structure interaction problems, where added-mass effects dominate, can be very efficiently simulated by using an acoustic medium for the fluid and studying the problem in the frequency domain instead of running full time-domain simulations. This reduces the problem to 1 degree of freedom for each grid point in the fluid domain and hence simplifies the calculations.

This paper presents an extensive parameter study on simulating the dry and wet natural frequencies for a large number of rectangular test specimens with different materials and dimensions. The simulations are compared with experimental results presented in a previous study by the authors (Stenius et al., 2016). The FSI simulations are systematically isolated with respect to material properties, dry eigenfrequncies and boundary conditions in order to be able to single out the effect of using an acoustic medium as fluid and assess how well the problem can be modelled with this assumption.

2. Acoustic finite element FSI model

All simulations presented in this paper are based on the commercial finite element modelling package COMSOL Multiphysics® 4.4. All parts (both solid and acoustic) are discretized using elements with second order shape functions and a Lagrangian formulation. Each solid mechanics node has three translational degrees of freedom, while there is only one degree of freedom, pressure (p), in the acoustic domain. A continuous mesh is used, where the solid mechanics and acoustic domains share nodes at the interface boundaries, thereby forcing a constant contact between the fluid and the solid. This results in four degrees of freedom for the nodes on the interface surfaces, separating the acoustic and solid mechanics domains. The eigenfrequency problem is then solved using a full two-way coupling between the solid and the acoustic nodes.

The modelling approach in this paper is similar to Kwon and Plessas (2014) but differs in how the solid mechanics domain is discretized; in this paper all solid elements are second order and full 3D elements while Kwon and Plessas (2014) use an eight node solid shell approach with reduced integration. The approach in Kwon and Plessas (2014) is typically limited to shell like structures, as in their paper, however, the aim in this paper is to evaluate a modelling technique for more general submerged bodies and hence a slightly more computationally costly modelling of the solid elements is motivated.

Further, in Kwon and Plessas (2014) a Cellular Automata (CA) is used to reduce the size of the acoustic domain that needs to be solved using finite elements. In this study the complete tank is modelled. The computational cost is naturally increased with a larger acoustic domain but as long as the studied frequencies are of reasonable magnitude, the size of the acoustic mesh elements can be increased and still solve the problem with acceptable accuracy.