Structural and acoustic responses of a fluid loaded shell due to propeller forces

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Abstract The low frequency structural and acoustic responses of a fluid loaded shell to propeller induced fluid pressures are investigated. The propeller operates in the non-uniform wake field and produces fluctuating pressures on the blades of the propeller. This in turn generates acoustic waves and a near field that excites the surface of the shell. The resulting incident pressure is scattered and diffracted by the shell surface, and also excites structural vibration. A potential flow panel code is coupled with the Ffowcs-Williams and Hawkings acoustic analogy to predict the fluctuating propeller forces, blade pressures and the resulting incident field on the surface of the fluid loaded shell due to operation of the propeller in a non-uniform inflow. The propeller induced incident pressure field is then combined with a coupled three-dimensional finite element/boundary element model of the submerged shell to predict the vibro-acoustic and scattered field responses.

1 Introduction

Kinns et al. (2007) investigated the fluid path excitation on a submerged shell caused by a propeller rotating through a non-uniform inflow. The propeller was represented by axial and radial dipoles located at the propeller hub and the submerged shell was considered to be rigid. They demonstrated that propeller forces transmitted through

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the fluid can be significant for realistic geometries. Merz et al. (2009) considered the vibro-acoustic response of a submerged shell due to propeller thrust forces using an axisymmetric, fully coupled finite element (FE)/boundary element (BE) model. The fluid path excitation was achieved using an acoustic dipole. Peters et al. (2014) developed a three-dimensional fully coupled FE/BE model of a submerged shell and investigated the fluid loaded radiation modes of the structure. The hydrodynamic panel code of Brandner (1998), modified by Mulcahy et al. (2014) for hydroacoustic applications, is used in the present work to calculate the incident pressure field on a submerged shell caused by the propeller rotating through a spatially non-uniform inflow. The vibro-acoustic response of the shell is then predicted using the three-dimensional FE/BE technique of Peters et al. (2014). Three acoustic dipoles derived from the propeller forces are also applied to the model for comparison purposes. Only the sound scattered and radiated by the shell is considered in the present work. Direct radiation of the propeller noise sources to the far-field is not considered.

2 Numerical Procedure

2.1 Coupled FE/BE model of the submerged shell

The FE method is used to represent the structural shell and the BE method is used to represent the unbounded fluid domain. The fully coupled three-dimensional FE/BE model is used to predict the structural and acoustic responses of the fluid-loaded shell. The structural model consists of a cylindrical shell of 45 m length and 6.5 m diameter and is closed by flat end plates. A truncated cone of 9.079 m length and a small base diameter of 0.6 m (18°cone angle) is attached to one end of the cylindrical shell. Internally, there are two bulkheads spaced 15 m apart and 87 ring stiffeners spaced 0.5 m apart. A cut view of the model is shown in Fig. 1. The thickness of the cylindrical shell, conical shell, flat end plates and bulkheads is 40 mm. The ring stiffeners are 150 mm deep and 80 mm thick. Additional mass is distributed evenly over the entire structure to achieve neutral buoyancy. This results in an effective material density of $23,879\,\mathrm{kg/m^3}$, approximately three times the density of steel. The structural Young's modulus is 210 GPa and the Poisson's ratio is 0.3.

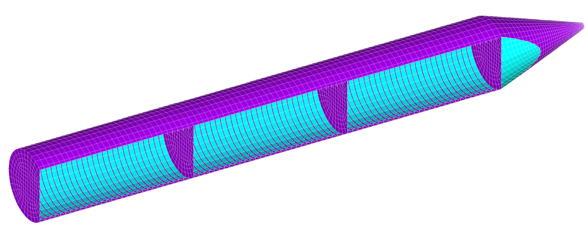


Fig. 1: Cut view of the submerged shell structural model

2.2 Hydrodynamic panel code for propeller forces and pressures

The hydrodynamic panel code is a modification of the panel code by Brandner (1998). The flow field around the propeller is assumed to be inviscid, irrotational and incompressible. The coordinate axes translate and rotate with the propeller, so that the solution can be found for a flow problem in which the propeller is at rest in a moving fluid. To demonstrate the proposed technique, a simplified situation has been considered. A five bladed propeller with zero skew and zero rake (propeller 4381 from Boswell (1971)) is used with the non-uniform inflow represented by a four-cycle wake characterised in water tunnel tests by Boswell and Miller (1968). This four-cycle wake inflow field consists of eight sectors with higher than average velocities on four alternate sectors and lower on the others with approximately $+/-$ 25% maximum variation.

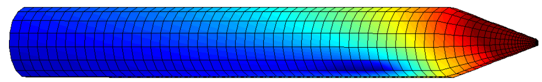
A propeller diameter of 3.5 m, rotation rate of 2.0 revolutions per second and average inflow velocity of 8.9 m/s was used for the present work. This produced an average thrust of 114 kN. The fluctuating propeller forces are used to define the strength of the dipole sound sources located at the propeller hub. Also, propeller blade pressure variations occur as the propeller rotates through the spatially non-uniform inflow. This pressure variation produces acoustic waves and a near-field that excite the surface of the submerged shell. A Hann window is used to enforce periodicity of the propeller forces and FW-H incident pressure time histories created by the panel code. A fast Fourier transform algorithm is used to convert these time histories to frequency spectra, which are applied to the FE/BE model of the shell.

2.3 Incident pressure field on the submerged shell

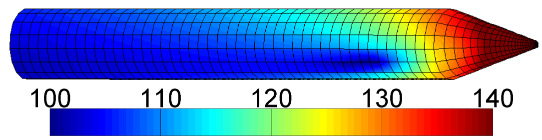
The fluctuating blade pressures predicted with the hydrodynamic panel code generate acoustic waves and a near field that excites the surface of the submerged shell. The incident pressure field is calculated at the collocation points of the FE/BE model of the submerged shell. Two approaches are used to predict the incident field:

1. Three idealised dipoles at the centre of the propeller hub with the propeller force variations in the x, y and z directions used as the dipole source strengths. This is a similar approach to that used by Kinns et al. (2007) and Merz et al. (2009).
2. The convective Ffowcs Williams-Hawkings (FW-H) equations for moving sources in a uniformly moving medium (Najafi-Yazdi et al., 2011).

Figure 2 shows the pressure incident on the submerged shell at the blade passing frequency due to the combined idealised dipoles (Fig. 2(a)) and from the FW-H acoustic analogy (Fig. 2(b)). The incident pressure due to the idealised dipoles closely matches the incident pressure field produced by the FW-H acoustic analogy. The asymmetries in the incident fields arise due to the transverse forces acting on the propeller and rotation of the propeller through the spatially non-uniform wake field.



(a) Idealised dipoles from propeller forces



(b) FW-H acoustic analogy

Fig. 2: Incident pressure on the submerged shell. Pressures in dB (ref. 1×10^{-6} Pa)

3 Acoustic Results

The radiated sound power from the submerged shell is presented in Fig. 3 for the idealised dipoles and FW-H incident fields. While the blade passing frequency and its harmonics do not coincide with those of the shell modes, the axisymmetric component of the incident fields predominantly excite the cylinder's breathing modes and the asymmetric component of the incident fields excite the cylinder bending modes. Fig. 3 indicates clear tonal peaks at the harmonics of the blade passing frequency. Very similar radiated sound power levels are predicted using both incident field techniques at the blade passing frequency and its first two harmonics. At higher harmonics of the blade passing frequency the sound power level predicted from the idealised dipole incident field is significantly lower than the sound power level predicted from the FW-H incident field. This suggests that at higher frequencies the idealised dipoles are an inadequate representation of the near-field and acoustic pressures produced by a propeller rotating through a non-uniform inflow. Figure 3 shows a significant background level of radiated sound power at all frequencies. This is a numerical artifact resulting from signal processing spectral leakage combining with the radiation modes of the coupled FE/BE model. Peters et al. (2014) have shown that similar submerged shells have over 700 radiation modes up to 140 Hz.

4 Conclusions

The vibro-acoustic response of a submerged shell to propeller fluid loading caused by rotation of the propeller through a non-uniform inflow was presented. A three-dimensional FE/BE model of the submerged shell was combined with the incident pressure field produced by the propeller. The FW-H acoustic analogy and idealised dipoles derived from the fluctuating propeller forces were used to predict the incident pressure on the submerged shell. Although the incident field tends to be underestimated using the simplified dipole model, the radiated sound power predicted with both incident fields are in close agreement at the blade passing frequency and its first two harmonics.

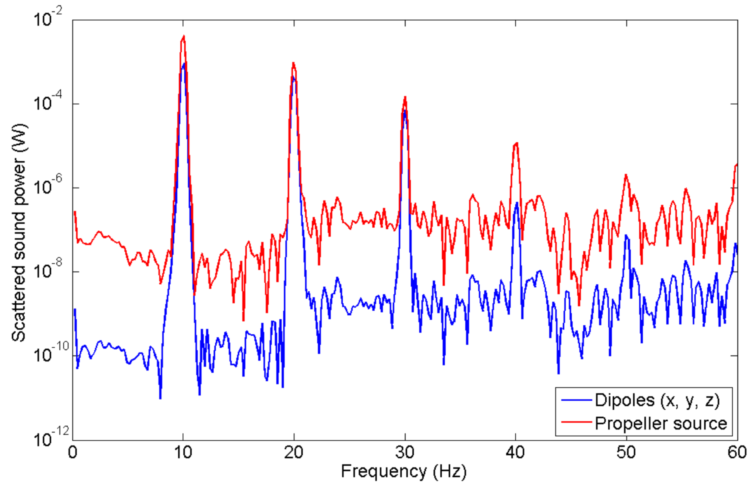


Fig. 3: Comparison of the radiated sound power produced by the dipoles and the FW-H generated incident pressure field

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