BRIDGING THE FREQUENCY GAP FOR VIBRO-ACOUSTIC PREDICTION OF A SUBMERGED SHELL

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Modelling the vibro-acoustic behaviour of an underwater vehicle is important to predict the impact on the marine environment, to ensure that the noise and vibration levels do not pose discomfort for crew, and to assist in identifying mitigation strategies to reduce underwater radiated noise. The motivation of this paper is to examine the vibro-acoustic responses of a simplified physical model of an underwater vehicle corresponding to a finite cylindrical shell submerged in a heavy fluid of infinite extent, representing a classic fluid-structure interaction problem. The cylindrical shell is excited by a point force in the radial direction. The structural and acoustic responses of the submerged hull in the low to medium frequencies are predicted using a range of techniques to cover and bridge the frequency ranges. The advantages and limitations of each technique are discussed.

1. Introduction

Predicting the radiated noise from a submerged vessel is important to implement mitigation strategies to reduce underwater radiated noise. The aim of this work is to predict the vibro-acoustic responses of a simplified model of a submerged vessel using a range of techniques to cover the low to medium frequency ranges. At low frequencies, the behaviour of a structure is dominated by a few modes and the response depends on the geometry and boundary conditions. Due to structural complexity, theoretical models are prohibitively challenging and numerical methods are widely used. Discretization techniques such as the finite element method (FEM) and the boundary element method (BEM) are generally employed [1]. At high frequencies, discretization methods become impractical due to the requirement of small mesh sizes leading to high computational cost. Further, the system response becomes very sensitive to the input parameters. A high frequency prediction method that uses a reduced number of degrees of freedom is Statistical Energy Analysis (SEA) [2,3]. To address the mid-frequency range, a hybrid FEM/SEA method has been developed in which rigid components with low modal density are modelled as deterministic subsystems and flexible components with high modal density are modelled as statistical subsystems [4,5]. An alternative predictive technique that can bridge the low to medium frequency ranges is the Condensed Transfer Function (CTF) method [6,7]. This semi-analytical sub-structuring approach couples analytical and finite element models of subsystems at their junctions using mechanical admittances. In this work, three techniques are employed to predict the vibro-acoustic responses of the submerged cylindrical shell, corresponding to a fully coupled FEM/BEM model, the CTF technique and a SEA model. Results presented here show that the semi-analytical CTF technique can be used to bridge the frequency gap between the low frequency deterministic FEM/BEM approach and the high frequency SEA approach.

2. Model

A simplified physical model of a submerged vessel is a fluid-loaded cylindrical shell [8]. Figure 1 shows a cylindrical shell of R=3.25 m radius, L=45 m length and h=0.04 m thickness. The cylindrical shell is closed by two hemispherical end caps of thickness 0.04 m. The system has free boundary conditions. The water surrounding the cylindrical shell has density of 1000 kg/m^3 and sound speed of 1500 m/s. The structure is made of steel with Young's modulus of 210 GPa, Poisson's ratio of 0.3, density of 7860 kg/m^3 and a structural damping coefficient of 0.02. No fluid is considered inside the shell. The cylindrical shell is excited by a point force of unity amplitude in the radial direction at x=12 m, as shown in Figure 1.

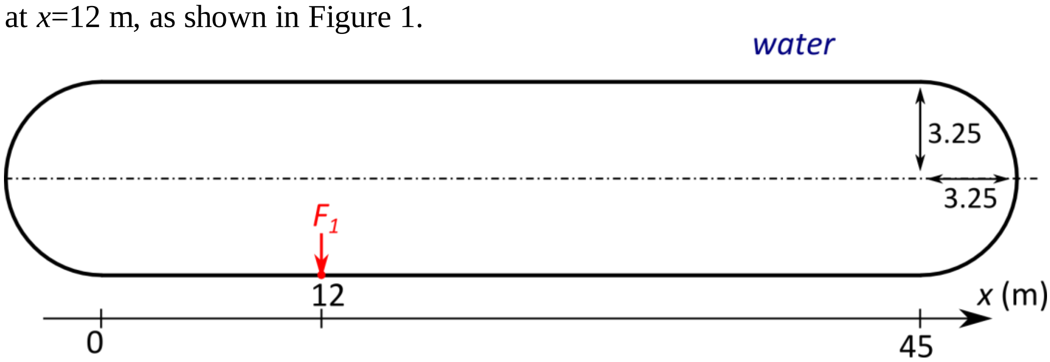

Figure 1: Cross section of the cylindrical shell.

3. Modelling approaches

3.1 FEM/BEM

A fully coupled FEM/BEM model previously developed by Peters et al. [9,10] was employed to examine the vibro-acoustic behaviour of a submerged cylindrical shell closed by hemispherical end caps. To extend the frequency range of the model as well as for computational efficiency, a model order reduction technique and non-conforming meshes between the FEM and BEM were used. The cylindrical shell with hemispherical end caps was modelled in ANSYS using 3264 8-node quadratic shell elements. The fluid domain was modelled using 2880 4-node discontinuous linear boundary elements in AKUSTA [11]. The FEM and BEM meshes are shown in Figure 2.

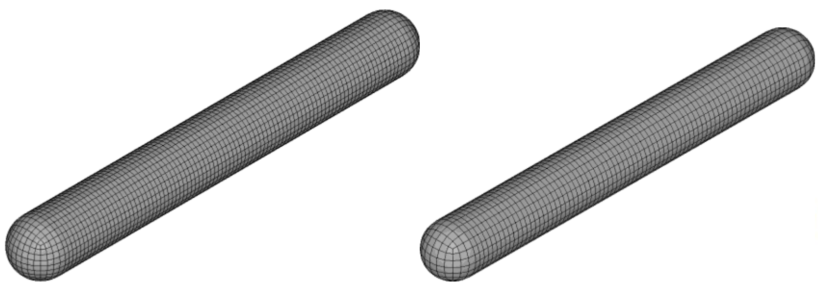

Figure 2: FEM mesh (left) and BEM mesh (right).

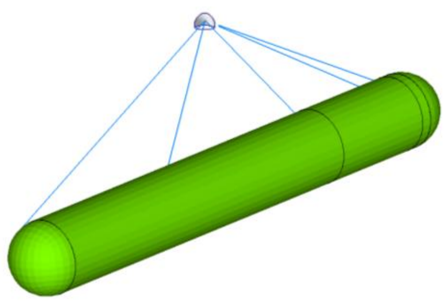

Figure 3: SEA model.

3.2 SEA

In an SEA model, the structure is modelled as an assembly of subsystems. A power balance equation for each subsystem is developed by considering the input power to each subsystem due to external excitation, the power dissipated via damping in each subsystem, and the power transmitted between subsystems. Results from an SEA model are usually limited to high frequencies because of the underlying assumptions of high modal density and weak coupling between subsystems. The cylindrical shell was modelled using the SEA module in the VA-One software as shown in Figure 3. The external water was modelled as a semi-infinite-fluid subsystem connected to the SEA subsystem of the cylindrical shell. Vibrational energy was injected into the structure by a point force as shown in Figure 1.

3.3 CTF method

In the CTF method, a set of orthogonal functions called condensation functions are used to approximate mechanical admittances at line junctions between coupled subsystems [6]. In this case, the junctions correspond to circumferential rings where the cylindrical shell is coupled to the hemispherical end caps. The displacements of the shell are calculated using Flügge equations of motion. The coupling with the surrounding fluid is described by the Euler equation at the shell/fluid interface and by considering the Helmholtz equation in the fluid with the Sommerfeld radiation condition.. The displacements and acoustic pressures are converted from the spatial domain to the wavenumber domain by Fourier transform. The wavenumber domain is discretized and the equations of motion are solved for couples of axial and circumferential wavenumbers. The admittance of the hemispherical end caps are calculated using FEM, without taking fluid loading into account. The coupling forces exerted by the hemispherical end caps on the cylindrical shell at x=0 and x=L are calculated using the admittances of the uncoupled subsystems [12]. The equations of motion of the shell under the coupling forces are also calculated in the wavenumber domain. The total response of the cylindrical shell due to the point force and the coupling forces yields the radial acceleration of the infinite cylindrical shell coupled to the hemispherical end caps. The far-field radiated pressure is obtained using the stationary phase theorem whereby only the radial displacement of the shell between x=0 and x=L is considered [13]. The radiated power is then obtained by integrating the acoustic pressure over a spherical surface enclosing the finite cylindrical shell.

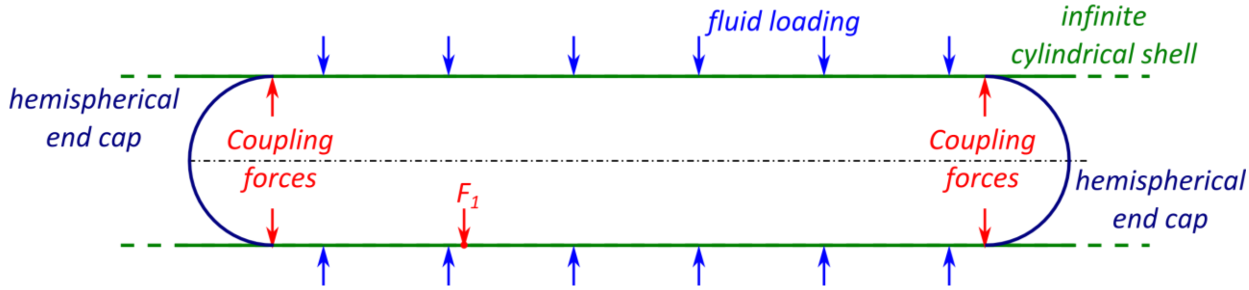

Figure 4: Schematic view of the CTF model.

4. Results and discussion

Results using the three prediction techniques are presented for the mean quadratic acceleration associated with the spatially averaged radial acceleration of the shell. Figure 5 shows the mean quadratic acceleration obtained using the FEM/BEM for a frequency range up to 200 Hz, SEA for a frequency range from 200 Hz to 2 kHz, and the CTF method for the entire frequency range up to 2 kHz. The FEM/BEM and CTF methods show good agreement above 10 Hz. At higher frequencies, it is harder to distinguish individual resonance peaks and the use of SEA is more appropriate. The SEA results are given in one-third octave frequency bands. As such the mean quadratic acceleration does not fluctuate with frequency. The shell exhibits modal behaviour at low frequencies. Figure 6 presents the radial acceleration on the surface of the shell at the first peak corresponding to 1.6 Hz using FEM/BEM and 2.1 Hz using the CTF method. For both techniques, the first resonance corresponds to mode $(m,n)=(1,2)$ where m is the axial mode number and n is the circumferential mode number. Similarly, the second and third peaks obtained using the two methods are shown in Figures 7 and 8, and correspond to modes $(m,n)=(1,3)$ and $(m,n)=(2,3)$, respectively. Good agreement in the results for the radial acceleration at the respective resonant peaks obtained using the two techniques is observed.

In the FEM/BEM and CTF models, only acoustic radiation from the cylindrical shell was studied, that is, no radiation from the end caps was considered. In the FEM/BEM model, this was achieved by only coupling the FEM model of the cylindrical shell with the BEM model of the cylindrical shell. Similarly in the CTF method, the far-field radiated pressure was calculated using stationary phase theory for the spectral radial acceleration of the cylindrical shell. Figure 9 compares the radiated sound power predicted using the three techniques for a frequency range up to 2 kHz. Results show that the radiated sound power gradually increases with increasing frequency. Results predicted using FEM/BEM technique show that the structure does not radiate efficiently compared to the mean quadratic acceleration result shown in Figure 5. In the low frequency range, the radiation characteristics of a submerged cylindrical shell were shown to be those of a dipole [14]. The radiated sound power by an ideal acoustic dipole, corresponding to the radiation from an acoustically compact, neutrally buoyant, rigid sphere excited by a point force, is also shown in Figure 8. The radiated sound power from the cylindrical shell is higher than that of a dipole for a frequency range up to 500 Hz. This is due to the fact that cylindrical shell is very buoyant whereby the mass of the cylindrical shell (330 tonnes) is approximately 20% of the mass of the displaced water (1637 tonnes). For frequencies between 500 Hz and 2 kHz, the product of the acoustic wavenumber and cylindrical shell radius is large ($k_fR>4$). Hence the cylindrical shell radiates approximately similar to that of a plate with fluid loading on one side only [13]. The coincidence frequency for an equivalent plate in water is around 5.7 kHz. Below the coincidence frequency, the radiated sound power of the plate is similar to dipole radiation. Thus, the radiated sound power from the cylindrical shell predicted using the three techniques is similar to that due to a simple dipole over the entire frequency range considered here.

One of the main advantages of the FEM/BEM approach is the ability to model geometric complexity. Further, it can identify structural modes. However, the approach is limited to the low frequency range as the discretization mesh needs to be refined when solving the model at higher frequencies, leading to prohibitive calculation costs. The CTF method can also identify structural modes. A limitation in the CTF method lies in the definition of the boundary conditions. Another limitation occurs at higher frequencies due to the computational cost of the calculation of the response of the cylindrical shell with the discretized equations of motion [12]. SEA is characterised by a large number of modes. One of the main advantages of SEA is that it is not dependent on boundary condition effects. However, the approach is restricted to weakly coupled systems and modes are statistically independent within subsystems so that all modes are equally excited by the driving forces.

5. Summary

Using three prediction approaches, the vibro-acoustic responses of the simple fluid-loaded cylindrical shell are presented. At low frequencies, the system was characterised by low modal density and sensitive to boundary condition effects, and represented by a fully coupled FEM/BEM model. At higher frequencies the system was characterised by a large number of modes and represented using an SEA model. To bridge the low and mid frequency ranges, a semi-analytical sub-structuring method called the condensed transfer function (CTF) method was employed. Results for the radiated sound power predicted using three approaches were found to be in close agreement and were similar to that of a simple acoustic dipole source. The results are part of a wider project aiming at bridging the frequency gap between different numerical methods for submerged cylindrical shell with various internal structures and under different mechanical and acoustical excitations.

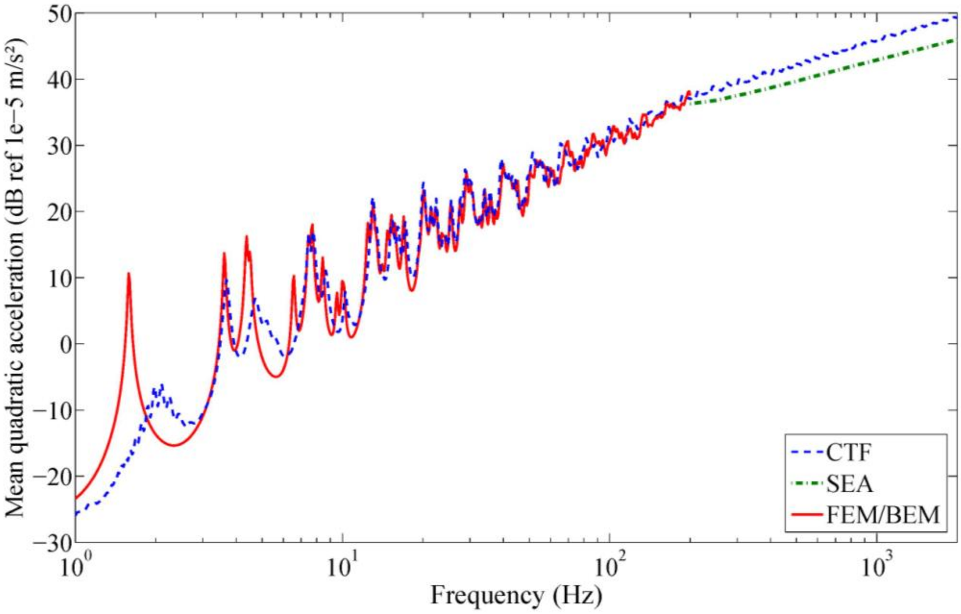

Figure 5: Mean quadratic acceleration of the fluid-loaded cylinder.

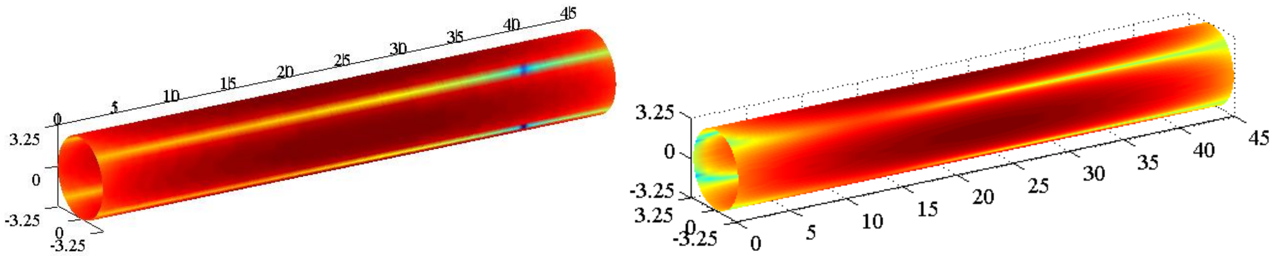

Figure 6: Radial acceleration (dB ref 1e-5 m/s²) on the surface of the fluid-loaded cylindrical shell at the first resonance peak corresponding to 1.6 Hz using FEM/BEM (left) and 2.1 Hz using CTF (right).

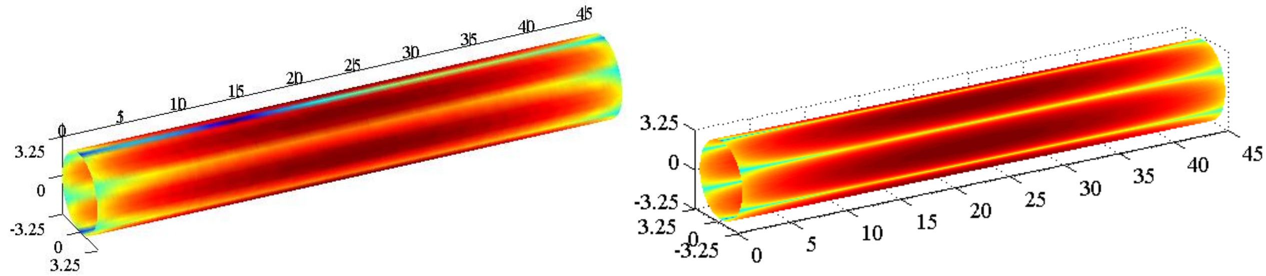

Figure 7: Radial acceleration (dB ref 1e-5 m/s²) on the surface of the fluid-loaded cylindrical shell at the second resonance peak corresponding to 3.6 Hz using FEM/BEM (left) and 3.7 Hz using CTF (right).

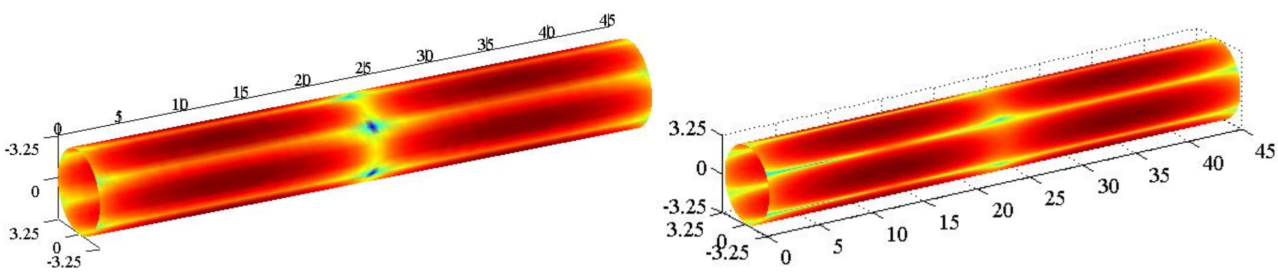

Figure 8: Radial acceleration (dB ref 1e-5 m/s²) on the surface of the fluid-loaded cylindrical shell at the third resonance peak corresponding to 4.4 Hz using FEM/BEM (left) and 4.7 Hz using CTF (right).

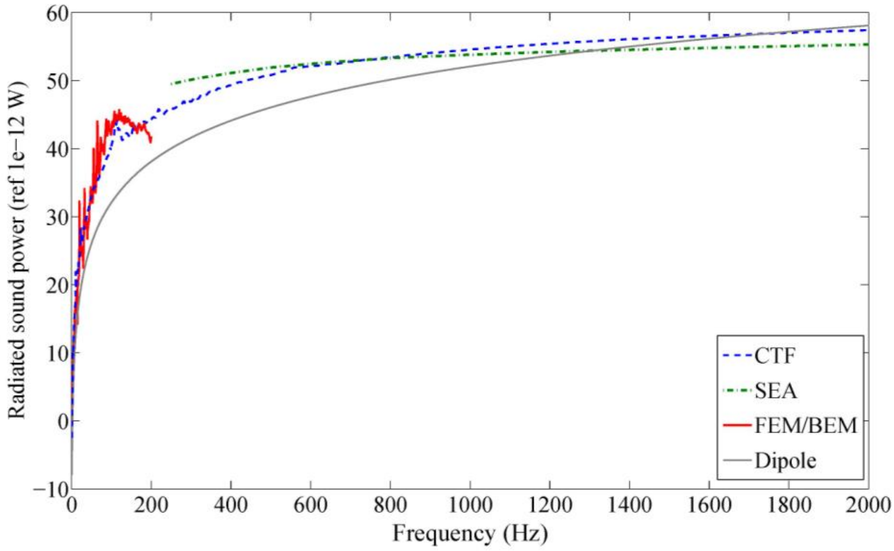

Figure 9: Radiated sound power of the fluid-loaded cylinder.

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