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Effects of apparent mass on the radiated sound power from fluid-loaded structures

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ABSTRACT

Prediction of radiated noise from underwater vehicles due to propeller excitation is of significant interest to maritime defence industries. In mathematical and numerical modelling, the pressure hull of an underwater vehicle is usually modelled with additional mass to achieve neutral buoyancy in water. However, the hull can also be regarded as a buoyant structure surrounded by free-flood spaces whose boundaries are acoustically transparent when flooded. In this work, apparent relative mass describes the ratio of the apparent mass of a longitudinal cylinder section to the mass of the water displaced by that section, where apparent indicates the fact that the effective structural mass is a function of frequency. The overall apparent mass and the apparent sectional mass distribution have an important effect on sound radiation. A rigid cylindrical hull with hemispherical ends is initially examined. Departures from dipole behaviour for a rigid body are shown to depend on apparent relative mass, cylinder length and direction of excitation. The analysis is then extended to higher frequencies and to a representative submarine pressure hull with stiffeners, bulkheads and added mass. The contributions of the rigid body and flexible modes to the radiated sound power for axial and transverse excitation cases are presented.

1. Introduction

The prediction of sound radiation from submerged bodies has been the subject of extensive previous research, for which the underlying principles and equations are described by Junger and Feit (1986) and Skelton and James (1997), while physical phenomena and the characteristics of real ships and submarines are described in general terms by Ross (1987). Increasing computer power has allowed development of more complex numerical models. This increased complexity of the numerical models presents a challenge to ensure that predicted results are accurate. One aim of this work is to demonstrate characteristics that should be observed in predictions from any submarine or underwater vehicle model at very low frequencies, where the structure behaves as a rigid body. For very low frequencies corresponding to frequencies less than approximately one third of the lowest resonant frequency of the structure and wavelengths longer than approximately three times the length of the structure, the radiation characteristics of a structure under translational force excitation are shown to be those of a simple dipole, with a constant of proportionality that depends on the apparent mass, the direction of excitation and the shape of the structure. These dipole characteristics define the asymptotic limit at very low frequencies for any structure. Building on the analysis of the radiated sound from fluid-loaded rigid cylinders, a fluid-loaded elastic cylindrical shell is then considered. Results presented here show that rigid body modes can also play an important role in determining radiation at higher frequencies, where the wavelength of underwater sound is no longer very large in relation to the cylinder dimensions and resonant characteristics also occur.

Although numerical models of a submarine pressure hull and its internal systems are generally developed to have neutral buoyancy, this constraint is not necessarily appropriate when the pressure hull is surrounded by free-flood spaces. The pressure hull of a submarine is often surrounded by relatively light tank structures that are filled with air when the submarine floats on the surface. These structures are flooded when the submarine dives by opening vents. Typically, the external free-flood structures have plating thicknesses that are several times smaller than that of the pressure hull. Hence, the ballast tank structures may be considered as acoustically transparent, so that the water surrounding the submerged hull behaves as though the light structures were absent altogether. Usually, a submarine is between 10% and 20% buoyant on the surface. Although a submerged submarine is neutrally buoyant statically, the assumed acoustic transparency results in an apparent mass mismatch for frequencies other than zero, as the water in the ballast tanks is part of the ocean rather than of the submarine. The

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appropriate apparent mass for frequencies greater than zero is then the mass of a surfaced submarine. Another important consideration in the study of a submarine pressure hull is that a significant proportion of the internal mass is on soft resilient mounts. This internally isolated mass "disappears" at more than about twice the resonant frequency of a passive isolation system, so the hull behaves as though it effectively has a reduced apparent mass over a wide frequency range (Peters et al., 2014). The reduction of internal mass changes the radiation characteristics of the hull in frequency ranges where both rigid body and flexible hull modes govern radiated sound.

In this work, apparent relative mass describes the ratio of the apparent mass of a longitudinal cylinder section to the mass of the water displaced by that section. Although the actual mass of the structure remains unchanged when the structure is vibrating, the effective or apparent mass of the structure changes. For example, in the case of an underwater vehicle, ballast tanks become acoustically transparent at low frequencies when free flooded; resilient mounts isolate mass and internal structures decouple from the pressure hull. Hence, the apparent mass in the acoustic domain is different from the actual mass in the static domain. The apparent relative mass of an oscillating object in the acoustic domain is a valuable quantity as it reduces the information of the apparent mass of the object and the mass of the displaced fluid to a single number.

In this work, the effect of the apparent relative mass on the radiated sound power from a simplified model of a submarine pressure hull is investigated. The change in radiation characteristics of a rigid hull with increasing frequency are initially explored. It is shown how the radiation depends on apparent relative mass, the direction and location of applied forces, and on the ratio of cylinder dimensions to the wavelength of underwater sound. A fully coupled 3D finite element/boundary element model for a more complex hull structure comprising a fluid-loaded cylindrical shell with hemispherical end closures and with stiffeners, bulkheads and added mass is then developed. The effect of apparent relative mass on the resonant frequencies and radiation characteristics of hull vibrational modes is examined. The focus is on the low frequency range, where the wavelength of underwater sound is more than one third of the hull length. The significance of the contributions from rigid body and flexible hull modes on the radiated sound power is observed. A reduction of apparent mass due to vibrational isolation is shown to increase radiated sound power from fluid-loaded structures. A mismatch of structural and displaced fluid mass distributions is also shown to increase radiated sound power.

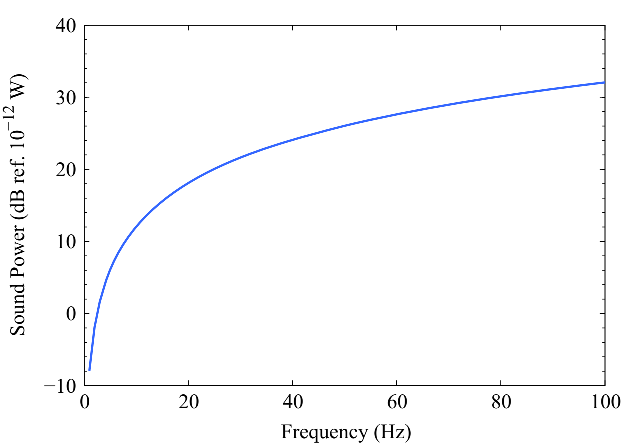

Fig. 1. Radiated sound power from a dipole with 1 N amplitude.

2. Low frequency sound radiation from rigid bodies

2.1. Submerged sphere

An analysis of radiation from a fluid-loaded rigid sphere excited by a point force is given by Ross (1987). When the mass of the sphere equals the mass of the corresponding displaced fluid and the acoustic wavelength is very large relative to the diameter of the sphere, the free-field radiated sound power from a point-excited sphere is exactly that due to a dipole and is given by

$$P_d = \frac{\omega^2 F^2}{24\pi \varrho_0 c_0^3} \tag{1}$$

where ω is the radian frequency, F is the excitation force amplitude, ϱ_0 is the density of fluid and c_0 is the speed of sound in fluid. For the case where the mass of the sphere m_s does not equal the displaced mass of the fluid m_f, the radiated sound power increases as follows:

$$P_s = P_d \left(\frac{3m_f}{2m_s + m_f} \right)^2. \tag{2}$$

The sound power is amplified by 9.5 dB if the sphere has no mass at all (0% apparent relative mass) and by 3.5 dB if the mass is half that of the displaced fluid (50% apparent relative mass). If the mass of the sphere is 80% of the displaced fluid the increase is 1.2 dB.

Throughout this paper, the acoustic dipole is used as a reference source. This source defines the underwater sound radiation that would be observed for a force applied to an acoustically compact, neutrally buoyant sphere in water. The amplification or reduction in radiated sound power as well as the changes in directivity pattern that occur when a load is applied to a flexible structure at different frequencies and locations can then be easily observed. The sound power radiated by a dipole source is shown in Fig. 1, due to a sinusoidal force of 1 N amplitude. The sound power increases at a rate of 6 dB per doubling of frequency.

2.2. Submerged cylinder

The model of the pressure hull used here has the external shape of a submerged circular cylinder with hemispherical ends, as shown in Fig. 2. The acoustic responses for the rigid hull are obtained from a fully coupled finite element/boundary element model. A rigid hull was approximated by artificially increasing the Young's modulus of the cylindrical shell so that the lowest resonant frequency only

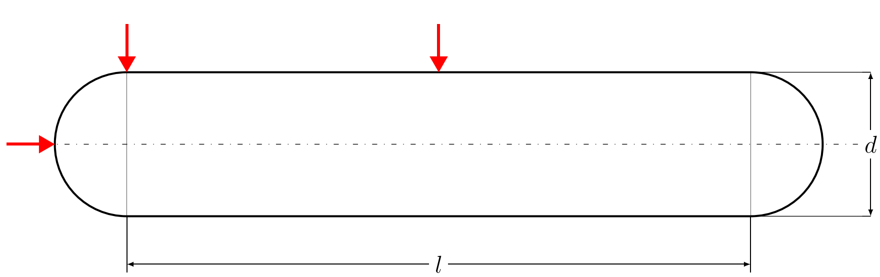

Fig. 2. Cylindrical hull with hemispherical end closures showing axial, end transverse and centre transverse excitation of the cylinder.