CHALLENGES IN THE PREDICTION OF UNDERWATER NOISE DUE TO PROPELLERS

Roger Kinns[1], Nigel Peake[2], Nicole Kessissoglou[3]

[1]School of Mechanical and Manufacturing Engineering
UNSW Australia, Sydney NSW 2052, Australia and RKAcoustics, Clynder, Helensburgh G84 0QQ, UK
Email: rogerkinns17@gmail.com

[2] Department of Applied Mathematics and Theoretical Physics,
University of Cambridge, Cambridge CB3 0WA, UK
Email: np100@cam.ac.uk

[3] School of Mechanical and Manufacturing Engineering
UNSW Australia, Sydney NSW 2052, Australia
Email: n.kessissoglou@unsw.edu.au

Abstract

The aim of this paper is to explore techniques that are being developed by the authors and their colleagues to estimate underwater noise radiated by marine propellers. Some fundamental aspects of propeller noise prediction are considered, including the nature of broadband noise due to flow over propeller blades and the effects of rotating and fluctuating forces that lead to tonal components in the underwater noise spectrum. It is shown how research in aeroacoustics can be applied at the much lower Mach numbers associated with marine propellers. A major challenge in surface ship design is prediction of the onset of cavitation, occurring when the pressure in the flow over the rotating propeller drops below the vapour pressure of water, and of its effect on the spectrum of underwater noise as ship speed increases. Acoustic sources change from higher order sources such as dipoles and quadrupoles, to monopole sources that have much greater acoustic efficiency. Furthermore, these cavitation sources are sensitive to the properties of water, including temperature and air content, as well as sea state and ship heading. Overall propeller noise increases progressively with speed, with changes in the spectral shape that bias the content to lower frequencies. The nature of the spectral changes, and the combination of experimental and numerical methods that can be used to estimate cavitation noise are discussed.

1. Introduction

The problems associated with prediction of underwater noise due to propellers are well-described by Ross [1], with reference to full-scale data, fundamental acoustic sources and experimental investigations. Increasing computer power and advances in numerical methods have allowed more detailed predictions, but it remains important to retain physical insight and to check that numerical models give correct results in limiting conditions where analytical results are available. Junger and Feit provided a sound foundation for later work, so far as analysis of submerged structures is concerned [2]. The aim of this paper is to review techniques for prediction of propeller noise that are being developed by the authors and their colleagues for prediction of underwater noise due to propellers.

1.1 Cavitation sources

A challenge in the design of a surface ship is prediction of the onset of cavitation and of its effect on the spectrum of underwater noise as ship speed increases. Cavitation occurs when the pressure in the flow over the rotating propeller drops below the vapour pressure of water. The propeller operates in the turbulent ship wake, so each blade experiences changes in angle of attack as it rotates and regions of cavitation wax and wane. The tip vortex usually cavitates first, because it develops in the region of highest flow speed, causing a rapid increase in noise for a small change in speed. Overall propeller noise then increases progressively, with changes in the spectral shape that bias the content to lower frequencies. Often, a ship can only conduct search operations or survey work at speeds below cavitation inception. In the case of passenger ships, propeller noise may limit the use of stern compartments to restricted speed ranges.

1.2 Noise sources below cavitation inception

When a submarine is operating at depth, cavitation can be suppressed by static water pressure, but the sound power radiated by its propeller still increases rapidly with speed. The precise rate of change depends on the combination of noise generation mechanisms. Many sources are dipole-like, with frequencies and fluctuating forces proportional to speed and speed squared respectively, so the sound power increases as the sixth power of speed. Other sources, such as those associated with the flow of turbulence over propeller blade trailing edges, increase at the fifth power of speed. Submarine hulls and propellers have to be designed to ensure that the intensity of those sources is controlled to match underwater noise requirements. Factors such as the propeller diameter, the number of propeller blades, the shaft speed and the radial distribution of load are all important. Delayed cavitation inception speeds for surface ship propellers have placed further emphasis on sources that arise below cavitation inception.

1.3 Applications of aeroacoustics research

Some fundamental aspects of propeller noise prediction are considered in this paper, including the nature of broadband noise due to flow over propeller blades, the effects of rotating and fluctuating forces that lead to tonal components in the underwater noise spectrum, and the interpretation of noise data from model-scale experiments. In what follows it is discussed how research in aeroacoustics can be applied at the much lower Mach numbers associated with marine propellers.

2. Noise Sources at Low Frequencies

The frequency range up to about 100 Hz at full scale contains tonal components at multiples of blade passing frequency, as well as broadband random components that arise from turbulent flow over the hull and propeller. A typical large passenger ship may have twin 5-bladed propellers and a shaft speed range up to 150 rpm. At maximum speed, the blade passing frequency (*bpf*) is then 12.5 Hz. Tonals at various multiples of *bpf* may be observable, depending on the quality of the ship's wake and the propeller design. The wavelength of underwater sound at 50 Hz is 30m, much larger than the typical propeller diameter of 6m. This allows the propeller to be regarded as an acoustically compact source in the low frequency range. An important difference between a submarine and a surface ship, so far as noise prediction is concerned, is the presence of the sea surface near to a ship propeller. This acts as a pressure release boundary, which has a large effect on the radiated sound field at low frequencies [1, pp 78-81].

2.1 Radiation due to rotating blade forces and volumes

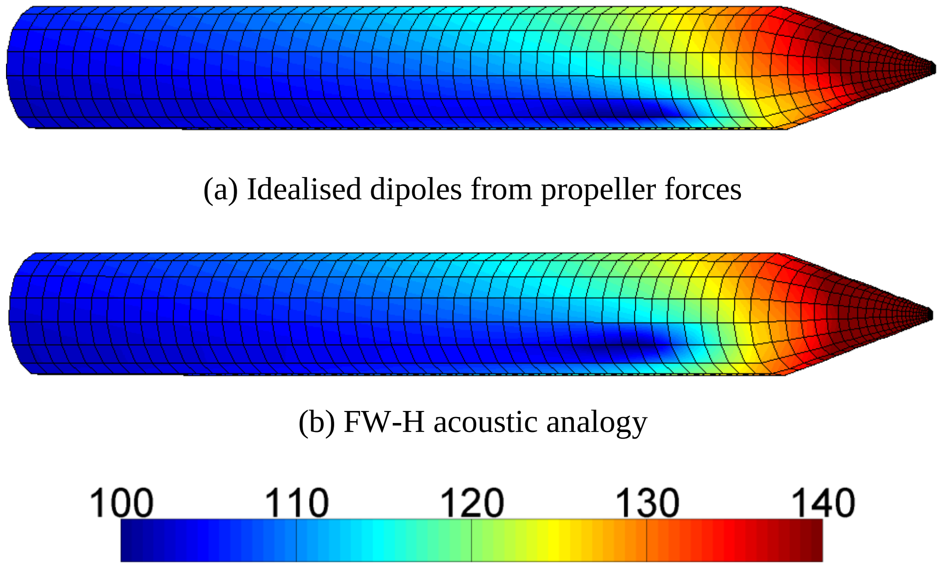
In the case of aircraft propellers, rotating blade forces and volumes are significant sources of radiated noise at multiples of *bpf*. At the low Mach numbers associated with marine propellers, far-field radiation from these sources is usually negligible, but this is not so for the pressure field in the vicinity of the propeller. This field can excite the hull of a ship or submarine, whose vibration can cause significant radiation in the far field.

2.2 Radiation due to fluctuating forces

Fluctuating forces due to a propeller at low frequencies are a combination of almost periodic and broadband components.

2.2.1 Radiation at multiples of blade passing frequency

The main source of radiation at multiples of *bpf* is the fluctuating forces and moments that arise from rotation in a non-uniform wake. These cause radiation from the propeller itself, but they also excite the hull via the propeller shaft and pressure fluctuations on the hull surface [3]. The nature of the pressure field due to a rotating propeller in a steady, but spatially varying, wake field can be seen in Figure 1 (from [4]). In this case, the cylindrical hull has a conical end termination and the propeller is located at its vertex. Figure 1 shows two predictions of the incident pressure field on the hull due to flow over a nominated propeller in a prescribed wake [4]. The first prediction is calculated from the pressure field due solely to triaxial dipoles, whose amplitude and phase correspond to fluctuating forces acting at the propeller hub. The second prediction shows the pressure field calculated from flow over the propeller blades using the Ffowcs Williams-Hawkings (FW-H) analogy [5]. Both fields are dominated by components at 1, 2 and 3 times *bpf*. Analysis using the FW-H analogy introduces additional components and a stronger near field in the immediate vicinity of the propeller, but the pressure field further away is governed by the dipoles. In a complete model, both the external pressure field and the forces transmitted to the hull via shaft bearings and the thrust block are taken into account in the prediction of underwater radiated noise.



(a) Idealised dipoles from propeller forces

(b) FW-H acoustic analogy

Figure 1. Incident pressure on a submerged shell (pressures in dB ref 1μPa)

2.2.2 Radiation due to hull boundary layer turbulence

The boundary layer on the hull introduces fluctuating velocity components in the wake field at entry to the propeller that are superimposed on the mean flow. This causes time-dependent variation in the amplitudes of radiated pressure levels at multiples of *bpf*, so that tonal components have finite bandwidths at steady speed. At low frequencies, the scale of the turbulent fluctuations is large relative to the propeller diameter, so their principal effect is to cause additional fluctuating forces at the propeller hub. These forces cause radiation that it is governed by the dynamic properties of the hull. The propeller blades experience changes in angle of attack due to turbulence as the propeller rotates, but the variations can be regarded as quasi-steady, so far as the blade boundary layers are concerned. Estimation of the spectra of broadband random forces at low frequencies requires knowledge of the flow over the hull from calculations using computational fluid dynamics or model-scale experiments. Alternatively, the spectral shapes can be estimated from empirical observations. The force spectra can then be used to determine broadband sound radiation using knowledge of hull dynamic characteristics.

3. Hull Dynamic Characteristics

Fluctuating forces and the external pressure field cause a ship or submarine hull to vibrate and radiate sound. The radiated sound tends to be of reduced importance for a surface ship, because of the free surface of the sea, but the vibration can have a large effect on the internal environment and therefore passenger comfort. At low frequencies, the radiation from a submarine hull can exceed the direct radiation from the propeller, sometimes by a large margin. The potential significance of zero order, or accordion modes, of a submerged hull has been widely recognised [1, pp 98-101] and explored using numerical models of varying complexity. First order bending, or whipping, modes of a submerged hull also enhance low frequency vibration, to an extent that varies greatly with the shape and mass distributions of the hull, as well as with structural damping. They can even dominate accordion modes [6]. These accordion and whipping modes have different directivity patterns, but their overall significance can be demonstrated by comparing the radiated sound power due to an applied force with the radiation due to a simple dipole, where the same force is applied to an acoustically compact body with neutral buoyancy. The dipole is an important reference source, because it is found that hull dynamic properties cause variations about a dipole characteristic that are often much weaker than the change in absolute sound power with frequency, given by equation (1).

$$P_d = \frac{\pi f^2 F_{\mathrm{rms}}^2}{6\rho_f c_f^3} \tag{1}$$

where P_d is the radiated sound power, F_{rms} is the root-mean-square applied force, ρ_f is the density of water and c_f is the speed of sound in water. Thus, P_d increases by 20 dB for a ten-fold increase in frequency. The low frequency dipole limit is also an important test of any numerical model of a neutrally-buoyant hull.

Peters et al. [7] demonstrated the extent to which rigid body modes determine radiation, not just at very low frequencies where the hull behaves as a rigid body, but over a wider frequency range that includes hull resonances. Figure 2 shows a simplified model of a submarine pressure hull, having a cylindrical section 45m long with 6.5m diameter, closed by hemispherical ends to give an overall length of 51.5m. The external shape of a pressure hull includes buoyancy tanks and free-flood regions at the bow and stern that are often of relatively light construction, which are ignored in the simplified model. The pressure hull is modelled as an axisymmetric shell with internal frames and bulkheads and has distributed mass loading to give neutral buoyancy. In this model, the loss factor associated with structural damping is 0.02 at all frequencies. A combined finite element and boundary element model is used to explore its radiation characteristics. Complete details are given in [7].

Figures 3 and 4 show the radiated sound power relative to a dipole, due to unit forces applied axially and transversely at the interface between a hemispherical shell and the straight cylinder at one end. This is approximately the location at which propeller shaft forces might be transmitted to the thrust block in a real hull, as well as the principal point of action of the external pressure field due to a rotating propeller. Contributions from flexible hull modes to overall radiation at a given frequency have been separated from those due to rigid body motions. In the case of transverse excitation, both rotational and translational rigid body motions are excited. At very low frequencies, where the hull is acoustically compact in all dimensions, the radiation is exactly that due to a dipole. The dominant peak for axial excitation is due to the first accordion mode which is resonant at about 22 Hz. The rigid body motions have a weak effect at frequencies above a few Hz. Peaks at higher frequencies are associated with a combination of other accordion modes as well as bulkhead resonances. When the excitation is transverse, the rigid body motions have a significant influence on overall radiated sound power over a frequency range that extends to more than 50 Hz, despite the low structural damping. Successive bending modes cause narrow peaks in radiated sound from about 5 Hz upwards, but these do not become prominent until the frequency exceeds 30 Hz for the current specified hull parameters. More complex modes have an increasing effect as the frequency approaches 100 Hz.

Detailed responses vary with hull dimensions and a real design will not be axisymmetric, but it can be seen that hull dynamic response can be a major factor in determining radiation due to propeller excitation. This has led to consideration of active and passive devices that reduce axial forces transmitted to the thrust block, limiting hull radiation to the effects of the external pressure field and forces in other directions [8].

At higher frequencies, the forces transmitted by the propeller shaft tend to have reduced significance and the hull scatters sound radiated directly by the propeller. Also, the propeller is no longer acoustically compact at high frequencies and the dynamic properties of propeller blades may have an important effect. Other simplifications then become possible, including a focus on direct radiation from the propeller and the effects of turbulent flow over the blades.

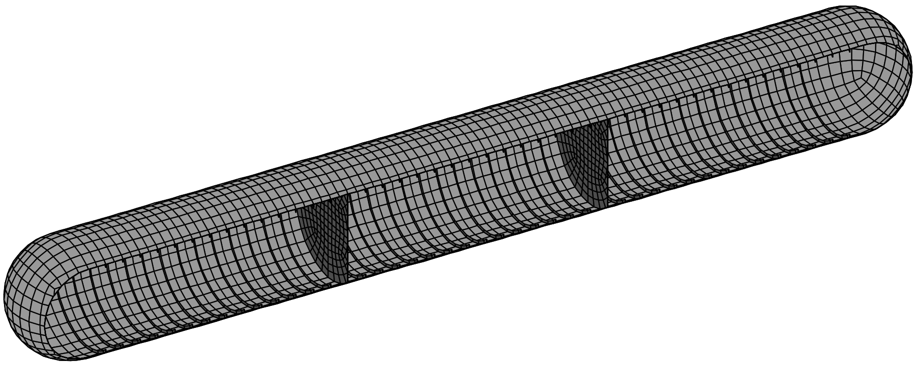


Figure 2. Simplified model of a submerged pressure hull

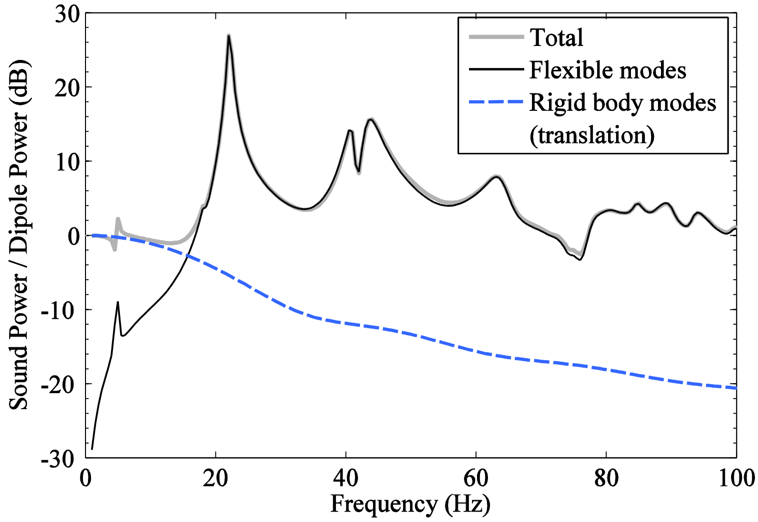


Figure 3. Radiated sound power relative to a dipole for axial excitation

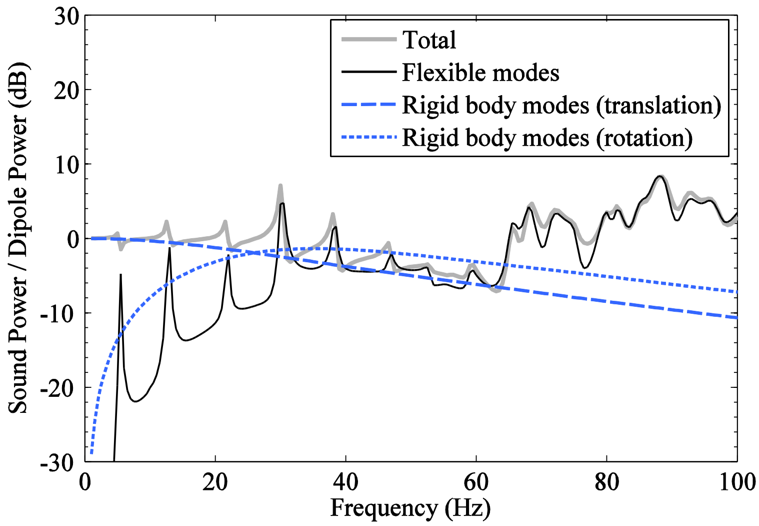


Figure 4. Radiated sound power relative to a dipole for transverse excitation

4. Noise at Higher Frequencies due to Turbulent Flow over Propeller Blades

At higher frequencies it is well-known that the flow of the turbulent boundary layer over the trailing edge is a key source of noise, not only underwater but also in a wide range of aeronautical applications, for example, aircraft approach noise due to boundary-layer flow over deployed flaps and wind-turbine noise. The fully turbulent nature of the boundary layer at the high Reynolds numbers found in typical applications makes this a very difficult problem to tackle in a fully computational sense, but it is possible to make progress using scaling arguments and extrapolation from experimental data.

Definitive and seminal work on noise due to uniform flow over aerofoils was undertaken by Brooks et al. [9]. They conducted an exhaustive set of experiments on the noise from a NACA0012 aerofoil section in a wind tunnel, varying a range of key parameters including Reynolds number and angle of attack. They then developed a set of formulae for predicting the far-field noise, by using a combination of known scaling laws together with empirical functions which were chosen to fit their extensive data set. Those scaling laws are applied here, but considerable care is needed to convert their results for air into results that are relevant to marine propellers.

In Ref. [9] five different mechanisms for blade broadband self-noise are identified. Of these, turbulent boundary layer trailing-edge noise and tip vortex formation noise are particularly significant in the marine context. Trailing-edge noise is usually the more important of the two. Boundary layer trailing-edge noise is the noise associated with a fully turbulent, attached, boundary layer passing over the trailing edge, but ignoring any effects of the blade tip. The associated noise spectrum is fully broadband without any tones. Tip vortex formation noise arises from the turbulence in the core of the tip vortex passing over the trailing edge, and is therefore additional to the noise generated by the attached boundary layer passing over the trailing edge.

4.1 Application of results from aeroacoustics

Several simplifications and approximations are required in order to allow application of the methodology developed by Brooks et al. [9]. One key point is that their experiment was conducted on a straight aerofoil section of given span placed in a wind tunnel, so that each point on the span experienced the same oncoming flow speed and was set at the same angle of attack. Of course, for a rotor this is not correct. As a first approximation, flow parameters are derived for the radial location of maximum load on the blade: the absolute Mach number at that section is used as the effective flow speed. The angle of attack is that required from a straight aerofoil to produce the same mean thrust as the rotor blade. A more sophisticated approach is instead to divide each blade into several radial sections, use the local flow properties at that section and then ‘integrate’ along the blade span by adding up acoustic contributions from each of these sections. Also, the variation in angle of attack with blade position can be taken into account, using wake field data. The authors are presently extending calculations to include these features. Once the local mean flow and angle of attack, together with certain geometrical parameters such as the blade chord have been specified then the methodology of [9] can be applied. The basic procedure is outlined below.

1. The boundary layer thicknesses on the blade pressure and suction sides are determined as functions of the Reynolds number based on blade chord, using empirical fits to experimental data given in [9].
2. At each given frequency, Strouhal numbers relating to the pressure-side and suction-side boundary layers are defined.
3. The spectral shape for the far-field noise from each of the two surfaces, in terms of the relevant Strouhal number, is given in [9] again as an empirical fit to experimental data.
4. The Sound Pressure Level in the far field is then determined using a combination of the spectral shape in Point 3 above together with the known scaling for trailing edge noise - specifically, the noise scales with the fifth power of Mach number, and decays with distance due to spherical spreading.
5. The sound directivity, if required, is assumed to follow the directivity of trailing-edge noise [9].
6. Noise from individual blades is added together, as incoherent sources.

The procedure described above applies to the turbulent boundary layer trailing-edge noise. To account for tip vortex formation noise, certain additional corrections are required, as described in Ref. [9]. Two points seem crucial here; first, the span-wise extent of the tip flow must be included; and second, the effective angle of attack at the tip is highly dependent on the detailed blade design. One approach is to consider a range of possible values and investigate the sensitivity of the noise results.

Figure 5 shows illustrative results for a 5-bladed propeller at two speeds. This figure does not take account of turbulence in the entry flow or of variations in angle of attack as a propeller rotates though a region of wake deficit. These variations are typically encountered behind A-brackets and propellers in a surface ship, and behind control surfaces in a submarine configuration. Both cause an increase in noise, particularly at low frequencies.

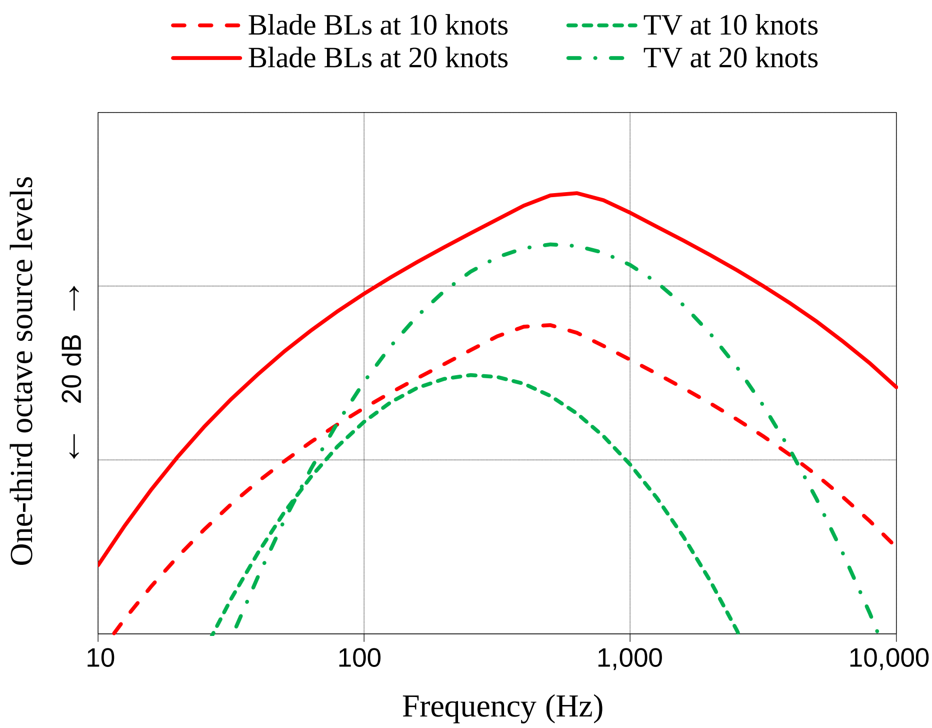


Figure 5. Broadband noise due to flow over propeller blades at 10 and 20 knots

5. Noise due to Cavitation Sources

Prediction of noise due to a cavitating propeller brings challenges that require a mixture of model-scale experiments, full-scale experience and theoretical insight. One major problem is that the properties of seawater are not invariant: temperature, nucleate and air content all vary with time and location, so that cavitation will tend to occur at lower speeds in tropical waters than in the North Atlantic, for example. Propeller load is affected by wave drag, hull fouling and deployment of towed bodies. The sea is rarely calm, so that small ships in particular will be subject to seaway motions that cause the depth of propeller immersion and therefore the static water pressure at the propeller location, to vary with time. These motions include heave, pitch and roll. All these factors add to the complexity of flow over rotating propellers in a turbulent wake field. The design of propellers that give desired cavitation characteristics, noise performance, thrust and efficiency in such variable conditions has a large influence on the commercial viability of cargo and passenger ships and the operational effectiveness of naval vessels. The general characteristics of noise due to cavitation are described by Ross [1, pp 202 *et seq*.]. Some of the principal design approaches are described by Breslin and Anderson [10]. The design of appendages, which can have a large influence on the flow field at the propeller and the consequent cavitation behaviour, have also received considerable attention [11].

5.1 Tonal noise due to cavitation

Despite the overall difficulties, simplifications still allow cavitation noise to be estimated. When cavitation appears, the dominant acoustic sources change from higher order sources, including dipoles and quadrupoles, to monopoles that are much more efficient radiators of sound. Tonal sources at multiples of blade passing frequency appear as a result of cyclic changes in cavitation volume. The maximum cavitation volume tends to occur near the top of the propeller, where the static pressure is lowest and the flow speed over the propeller blades is highest. Each blade in turn will cavitate in almost the same location, so the main effect corresponds to a monopole at a fixed location with spectral properties at multiples of *bpf* that reflect the growth and collapse of the main cavitation region on each blade surface. This monopole source is close to the hull and to the surface of the sea, so its far-field radiation properties are similar to those of a vertical dipole at the surface. It can be evaluated at model scale, because Reynolds number has a weak influence on blade sheet cavitation, in contrast to broadband sources like the tip vortex. It is not unknown for the cyclic cavitation sources to interfere with the dipole sources due to fluctuating forces, so that far-field tonal levels at *bpf*, for example, fall when cavitation first appears. It is also possible to phase-lock propellers in a twin-screw ship so that the sources associated with one propeller interfere with those from the other and reduce the overall tonal noise.

5.2 Broadband cavitation noise

Prediction of broadband noise due to cavitating propellers represents the greatest challenge. Model-scale test facilities allow blade sheet cavitation characteristics to be modelled with high fidelity, provided that the nucleation properties of water and the wake flow can be represented accurately. Particular difficulties arise with the tip vortex. At model scale, the Reynolds number is at least a factor of 10 lower than at full scale, so the effects of viscosity are much larger. This delays the onset of tip vortex cavitation to scaled speeds that can be a factor of 2 too high relative to blade sheet cavitation. Full-scale cavitation inception speeds can still be determined using empirical factors based on the McCormick index [12], but the model-scale tip vortex noise, which is likely to be dominant at full scale, is often swamped by noise due to blade sheet cavitation. Other potential noise sources, including bubble cavitation, root cavitation at the interface between propeller blades and the hub, and the hub vortex which is also subject to large Reynolds number effects, further complicate noise prediction.

One of the most important features of broadband noise due to cavitation is the initially rapid increase in propeller noise with speed above cavitation inception. The noise is intermittent when the first blade shows incipient tip vortex cavitation, becoming more continuous as cavitation develops on all blades and extends in angular range and depth. Semi-empirical methods are often used for estimation of noise due to cavitation, based on propeller properties such as the number of blades, diameter and shaft speed, together with inception speeds for different types of cavitation that can be estimated from model-scale tests [13]. Figure 6 shows the changes in spectral shape and intensity that can be expected as ship speed increases above tip vortex cavitation inception. Figure 7 shows the combined effect when blade sheet cavitation is taken into account. The frequency scale is appropriate to a 6m diameter propeller. The cavitation inception speeds of 12 knots for the tip vortex and 15 knots for blade sheet are typical of a large commercial vessel with twin screws: real inception speeds may be considerably higher for a refined propeller at its design condition and much lower in rough seas when a ship is heading into waves. It is assumed here that the ship speed increases linearly with shaft speed. Levels at low frequencies can be reduced markedly by the free surface of the sea, depending on propeller immersion. This effect is not included in Figures 6 and 7. The 6 dB/octave decline in one-third octave level with frequency in Figures 6 and 7 is often lower in practice, but the general shift to lower frequencies with increasing speed is commonly observed. It is clear from these results why an increase in cavitation inception speeds can have a marked effect on underwater radiated noise and why cavitation inception speeds are often key design requirements.

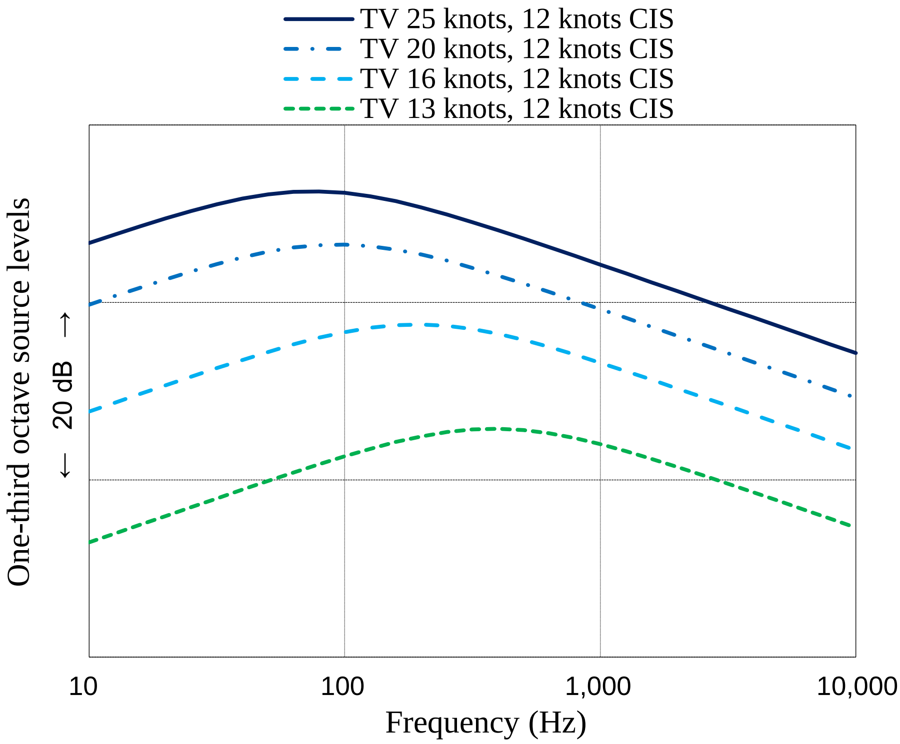


Figure 6. Broadband propeller noise due to cavitation showing dependence of tip vortex cavitation noise on speed: Tip vortex inception at 12 knots

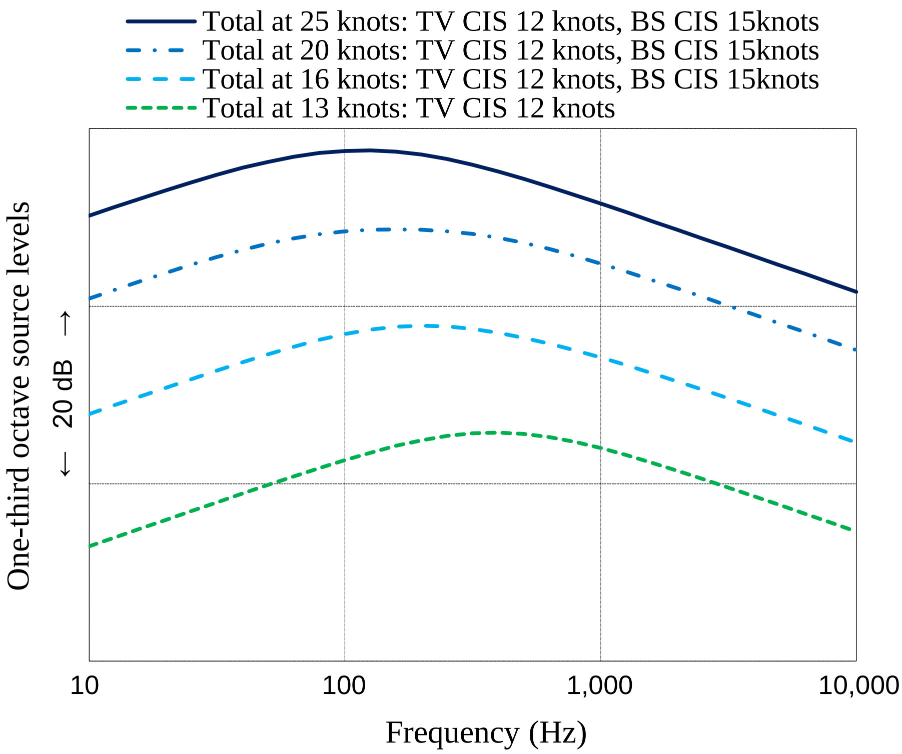


Figure 7. Broadband propeller noise due to cavitation showing dependence of overall cavitation noise on speed: Tip vortex inception at 12 knots, blade sheet inception at 15 knots

6. Conclusions

The prediction of underwater noise due to propellers will remain one of the greatest challenges in acoustics. The problem is simpler for a submerged vessel where the surface of the sea is remote from the propeller, but the range of physical phenomena that have to be addressed is still extraordinarily wide. The flow into the propeller contains turbulence of different length scales from the hull and from nearby control surfaces. These cause propeller blades to experience changes in angle of attack as the propeller rotates. Continuing development of numerical methods will allow the effects of turbulence, propeller design and hull design to be evaluated with increasing fidelity. Simplifications remain crucial in allowing first estimates and also in checking complex numerical models. For example, representation of a propeller by a set of fluctuating forces at the hub, which excite the hull via both the propeller shaft and an external fluctuating pressure field, allows prediction of underwater noise in the frequency range up to about 100 Hz at full scale. It also allows specification of maximum fluctuating forces that can be accepted in an emergent design. This force set can include both tonal and broadband random excitation. Recognition that a fluctuating force applied to a neutrally buoyant hull at very low frequency causes dipole radiation provides both a check on complex numerical models and a reference for variations at higher frequencies. The characteristics of noise at frequencies in the kHz range due to turbulent flow over marine propeller blades can be explored using experimental and theoretical results in aeroacoustics. As a first approximation, the flow conditions at the radial location of maximum thrust, together with specific consideration of the propeller tip, can be used to estimate broadband noise. Refinements include the use of strip theory to explore the contributions from different radial positions for a specific propeller design and inclusion of the variations in angle of attack that arise from rotation in a non-uniform wake. Cavitation introduces monopole sources which tend to overwhelm the effects of higher order sources due to turbulent boundary layer flow, causing a marked change in radiated noise levels for a small change in speed. Tip vortex cavitation in particular depends strongly on Reynolds number, so that model scale tests have to be interpreted with considerable skill in order to estimate inception speed at full-scale. It is doubly difficult to predict the strengths and spectral distribution of cavitation sources. Development of accurate prediction techniques is one of the principal challenges in underwater acoustics.

References

[1] Ross, D. *Mechanics of underwater noise*, Peninsula Publishing, Los Altos, California, USA, 1987.

[2] Junger M.C. and Feit, D. *Sound, structures and their interaction*, MIT Press, 1985.

[3] Kinns, R., Thompson, I.R.M., Kessissoglou, N.J. and Tso, Y. “Hull vibratory forces transmitted via the fluid and the shaft from a submarine propeller”, *Ships and Offshore Structures,* **2**, 183-189, (2007).

[4] Croaker, P., Peters, H., Mulcahy, L., Kinns, R., Brandner, P.A. and Kessissoglou, N.J. “Structural and acoustic responses of a fluid loaded shell due to propeller forces”, *Proceedings of the 3rd Symposium on Fluid-Structure-Sound Interactions and Control (FSSIC)*, Perth, Western Australia, 5-9 July 2015.

[5] Najafi-Yazdi, A., Bres, G.A. and Mongeau, L. “An acoustic analogy formulation for moving sources in uniformly moving media, *Proceedings of the Royal Society A*, **467**, 144-165, (2011).

[6] Caresta, M. and Kessissoglou, N.J. “Structural and acoustic responses of a fluid-loaded cylindrical hull with structural discontinuities”, *Applied Acoustics*, **70**, 954-963, (2009).

[7] Peters, H., Kinns, R. and Kessissoglou, N.J. “Effects of apparent mass on the radiated sound power from fluid-loaded structures”, *Ocean Engineering*, **105**, 83-91, (2015).

[8] Merz, S., Kessissoglou, N.J., Kinns, R. and Marburg, S. “Passive and active control of the radiated sound power from a submarine excited by propeller forces”, *Journal of Ship Research*, **57**, 59-71, (2013).

[9] Brooks, T.F., Pope, D.S. and Marcolini, M.A. *Airfoil self-noise and prediction*, NASA Reference Publication 1218, 1989.

[10] Breslin, P.B. and Anderson, P. *Hydrodynamics of ship propellers*, Cambridge University Press, 1994.

[11] Hämäläinen, R., “The high comfort class appendage design for cruise liners, ferries and Ropax vessels”, *Proceedings of the First International Symposium on Marine Propulsors*, Trondheim, Norway, 22-24 June 2009.

[12] McCormick, B.W. “On cavitation produced by a vortex trailing from a lifting surface”, *ASME Journal of Basic Engineering*, **84**, 369-379, (1962).

[13] Fischer, R.W. and Boroditsky, L. Supplement to the design guide for shipboard airborne noise control, *SNAME Technical Bulletin* 3-37, pp. 15-19, 2001.