Using computers for achieving quiet oceans

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Water is very effective at propagating sound waves and as a result there is significant concern that as ships increase in terms of size and effective power their impact on the underwater sound scape is causing real environmental harm (Tasker *et al.*, 2010). While of course there are multiple sources of noise in the Oceans, natural and anthropogenic alike, shipping as a whole contributes to a large proportion of the total ambient sound level. Although certain aspects of this problem are understood it is, in general, an open field with multiple questions as yet unanswered.

As a consequence of realising the negative effects of shipping noise, concerns have been raised over whether regulation should be put in place in order to limit these emissions. Indeed, there are already some aspects of marine operations, mainly related to the oil & gas industry, which have specific environmental noise controls in place. A loose parallel may be seen between the maritime and the aerospace industries, with the latter having been driven primarily by fuel efficiency in its early days, much as shipping is now. As the time progressed, efforts put into minimising noise from aircraft have grown greatly and it is not unimaginable for a similar scenario to unfold for ships in the near future.

Why are ships noisy?

The wake flow developed along the ship, in which the propeller must operate at all times, produces a large boundary layer region which contains unsteady turbulent flow. This is further affected by ship motions caused by waves or manoeuvres. As a result, propeller blades experience constant load fluctuations, primarily at the blade rate but also over a broadband range, which manifests itself in a complex noise signature.

Furthermore, propulsion of large merchant ships requires a significant amount of power to pass through the relatively confined region of a propeller disc. The resulting high power density associated with operating the propeller close to its optimum efficiency induces a local pressure drop and causes an enhanced risk of cavitation. Load variations due to non-uniform and turbulent inflow act to make cavitation less stable and potentially more prone to generating noise.

Out of the multiple noise sources present in the ship-propeller system, the low-frequency noise due to cavitation and non-uniform wake are of primary concern from an environmental impact point of view. That is because the sound they generate is likely to propagate at large distances due to high power and low attenuation, thus affecting the largest area, and is typically in the frequency band many organisms are capable of hearing.

Due to the presence of such a variety of complex, non-linear phenomena, marine propeller flows are very interesting, but also difficult to deal with, both numerically and experimentally. An example of a model-scale propeller operating in a non-uniform wake is shown in Figure 1. One may note prominent cavitation close to the tip which then becomes trapped in the tip vortex further downstream.

How to measure noise?

One of the primary means of assessing the radiated noise of a ship is full-scale testing at sea. This involves placing an array of hydrophones at a remote location with low ambient noise and favourable noise propagation conditions, such as apt water depth and seabed type, and recording the noise from a passing ship. This, while shown to be feasible, for instance during EU-funded projects such as AQUO and SONIC (Brooker & Humphrey, 2014, 2015, Audoly *et al.*, 2014), is currently far too expensive and would present a real challenge if, for instance, regulation requiring the noise from each newly built ship to be assessed were introduced.

An alternative to this approach is the use of model-scale testing in facilities like cavitation tunnels or de-pressurised towing tanks. This method is significantly cheaper and more available than full scale testing, but still only affordable in a limited number of cases. Due to physical limitations of the experimental facilities, most model measurements are to some degree compromised by phenomena such as reverbration, background noise due to machinery like impellers or carriages, and near-field fluctuations being included in the data. The difficulty here is also finding an appropriate method of scaling the near-field measurements to full scale and deducing the correct far-field noise level from them.

Due to the limitations of the experimental methods, making trade-offs, performing optimisation, or sensitivity studies of the radiated noise against propulsive performance is an expensive and challenging endeavour. These limitations also pose a major obstacle to truly understanding the commercial shipping noise effects and being able to conclude whether an action is required by the maritime community in order to reduce the environmental impact. Fortunately this gap in our understanding of the problem may be overcome using numerical analysis tools.

Computational solutions

High-fidelity turbulent flow modelling has become increasingly accessible with the steady rise of computational resources available. These allow for unsteady flow features, vital from noise prediction point of view, to be predicted much better using methods like Large Eddy Simulation (LES) or Detached Eddy Simulation (DES) as opposed to the results offered by the URANS "workhorse" omnipresent in marine Computational Fluid Dynamics (CFD). In the marine context, however, the inherently high Reynolds numbers make it challenging to use such methods on a regular basis, particularly when predicting full scale values.

A significant difficulty in computing marine flows is also associated with the relatively high speed of sound in water compared to air. This implies that the speed of the wavefronts that need to be captured for a hydroacoustic simulation is greater, which limits the maximum time steps possible. Furthermore, the higher density and speed of sound in water imply it has a much higher acoustic impedance. This means that for a pressure source of the same amplitude the induced particle velocity will be much smaller for water. From a numerical standpoint, the associated computational effort required to achieve full convergence using high order schemes, and mesh density necessary to keep the dissipation and dispersion errors low may thus be expected to be higher for a computation in water than in air. It also follows that the amount of acoustic energy in the flow, compared with that contained in the other range of wave numbers, will be relatively low.

As a result, approaches alternative to solving the full compressible Navier-Stokes equations into the point of interest, typically in the far-field, are often sought for. One of these are the acoustic analogies, arguably the most popular being the one by Ffowcs Williams & Hawkings (FW-H) (1969). This method involves solving flow around a moving object in the near-field and then solving surface and volume integrals, obtained by virtue of the Gauss theorem applied to rearranged Navier-Stokes equations, in order to deduce the radiated pressure signals at an arbitrary location away from the body. In a traditional sense, the surface integrals would be solved on the body surface. An alternative variant, termed the porous method, assumes that the control surface is not coincident with the body surface, but instead encloses a volume of fluid surrounding the object, as depicted in Figure 2.

The latter approach removes the need for the volume integral to contain fluids of different properties and instead only requires flow field data to be known on the FW-H surface. This makes said method applicable in cases where there are two or more fluids present in direct proximity of the body and where main noise generation mechanisms may be present further away in the fluid. One of such cases is a cavitating marine propeller, which may yield significant pressure oscillations in the near-field, as well as induce significant amounts of turbulence, as seen in Figure 3 the example of a hydrofoil.

There has been a growing interest in numerical prediction of marine propeller noise in the recent years with a large proportion of studies utilising acoustic analogies in one form or another. Ianniello *et al.* (2013), for example, applied several of the FW-H methods to study non-cavitating noise radiated from model-scale propellers and full scale ships using CFD. Their study showed how promising the approach is to predicting radiated pressure induced in the marine environment. An important point is that this type of a calculation could be used at final vessel design stages to verify whether it meets given noise criteria.

The on-going work undertaken at the University of Southampton is aimed to extend the acoustic analogy approach and use it in conjunction with high-fidelity CFD methods in order to study the multi-scale nature of marine propeller noise. It is viewed as the next step in accurately tackling this problem, as methods for predicting large-scale cavitation phenomena do exist but often fail to account for the more intricate flow features. To date, research has been focused on establishing the baseline simulation frameworks, predicting non-cavitating noise of propellers (Lloyd *et al.*, 2015, Lidtke *et al.*, 2015) and characterising noise due to hydrofoil sheet cavitation.

At present, the in-house acoustic analysis code is being extended in order to more accurately account for high- and broadband-frequency noise components. Building from the research to date, a postgraduate research project is planned with the aim of studying noise radiated by ships fitted with energy saving devices (ESD's), such as accelerating ducts. Another related project, undertaken in collaboration with Lloyd's Register (LR), has set out to further develop numerical methods for assessment of erosive cavitation.

Prospects

It is hoped that in the future the investigated numerical methods will become widespread in the maritime community, providing reliable tools for assessing novel ship designs based on their noise pollution potential. Irrespective of whether regulation is introduced in order to govern this side of marine vessel construction, dissemination of such evaluation techniques will lead to minimising the impact of shipping on the oceans. In the short term, numerical noise prediction techniques present a unique opportunity to support full- and model-scale experimental studies. Given the large number of free parameters involved, correlating the two has always been challenging and it is believed that providing a third, independent method of assessment may accelerate progress in devising unified and widely accepted testing and scaling procedures.

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Figures

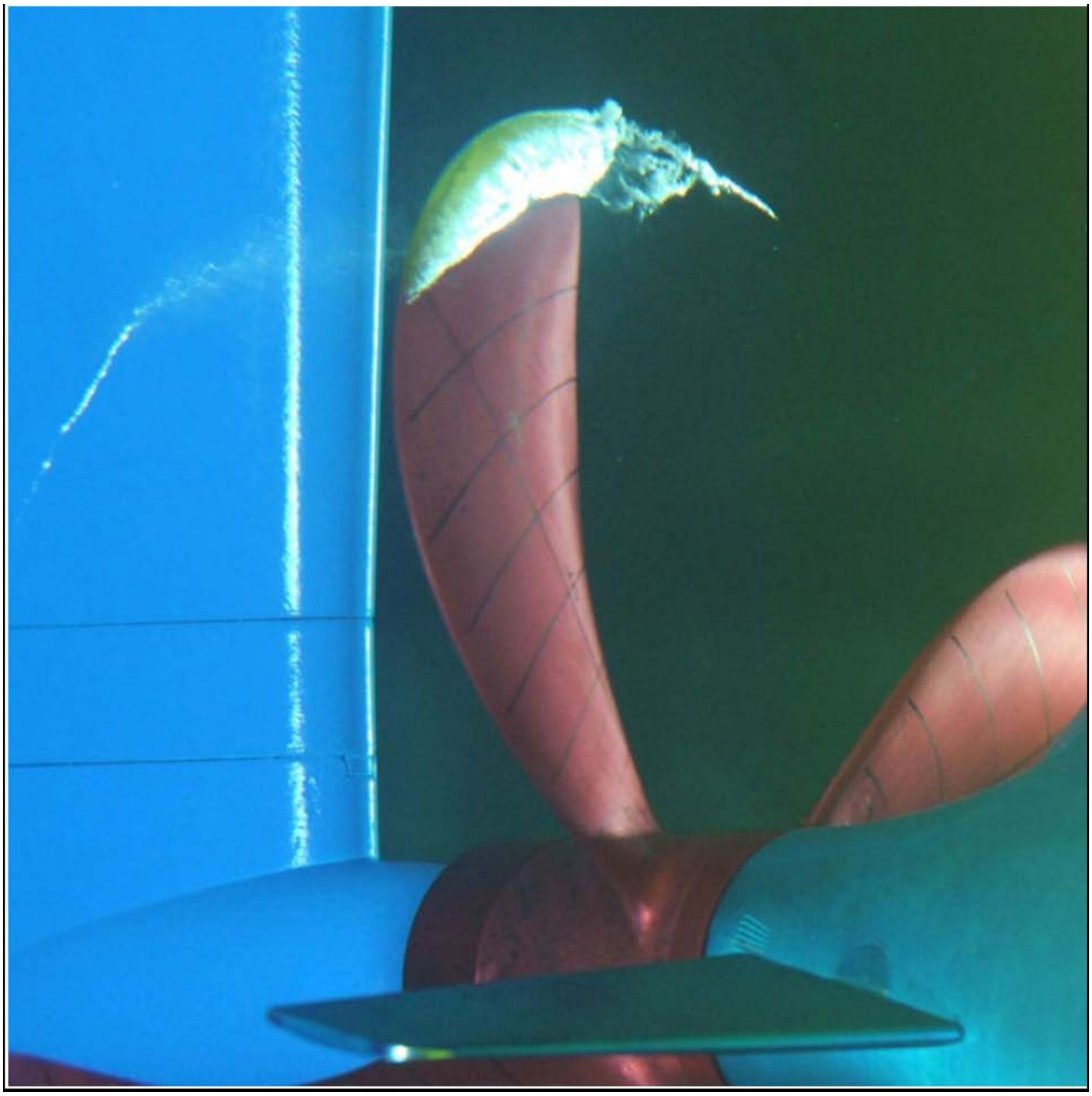

Figure 1: Example of experimental cavitation observations on a fully appended ship model placed in a cavitation tunnel. Credit: Daewoo Shipbuilding & Marine Engineering Co., Ltd.

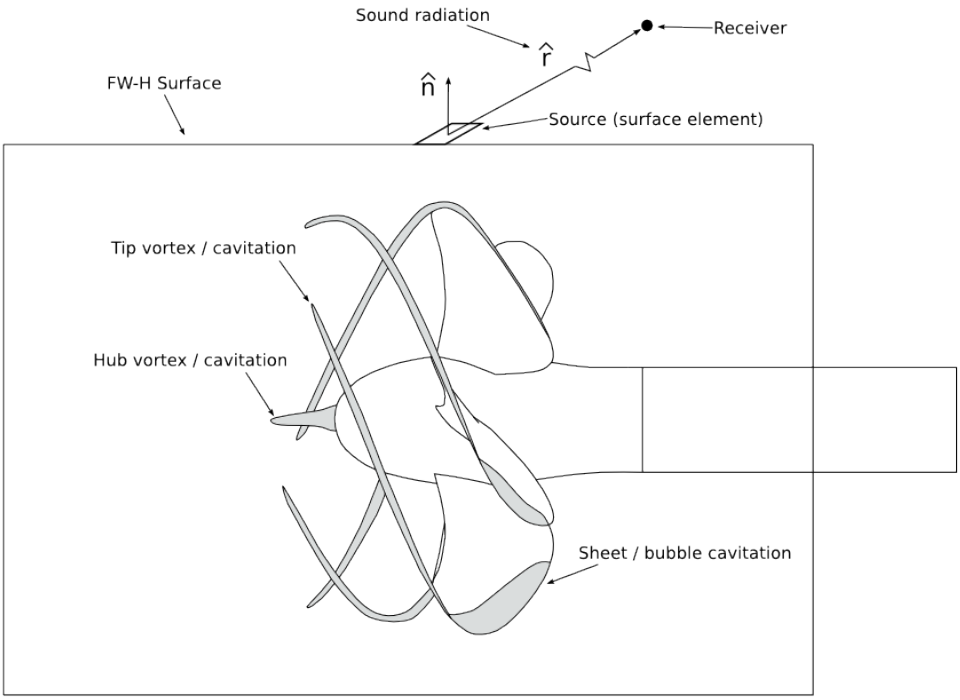

Figure 2: Illustration of the porous Ffowcs Williams - Hawkings acoustic analogy: flow around a body is solved as in regular CFD, data is sampled on a control surface surrounding the problem, and radiation equation is then solved from the interpolation surface into the far-field.

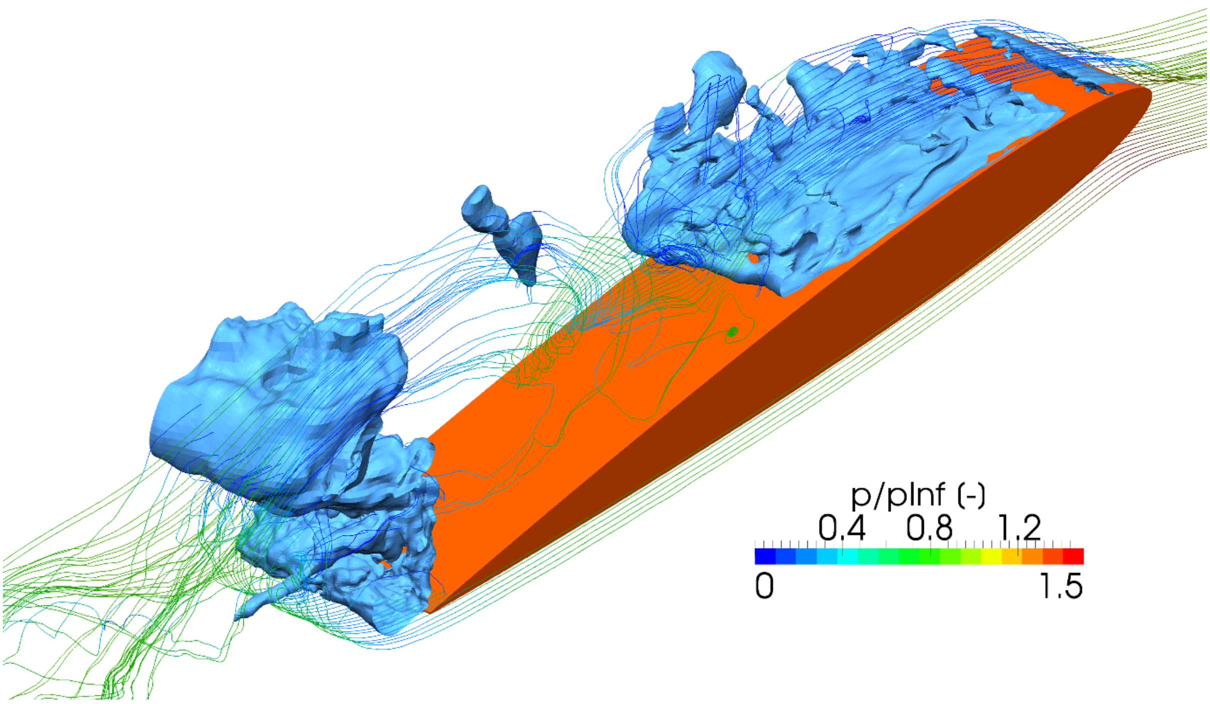

Figure 3: Sheet cavitation on a hydrofoil visualised as an iso-contour of the volume fraction field ($\alpha = 0.5$), also showing complex flow pattern around the cavities using instantaneously computed streamlines.