Sailing to the beat of a different drummer

Propeller noise is a rapidly expanding area of research, but what are the underlying principles? HydroComp's Don MacPherson gives a primer

Late November is a cold time in Halifax, Nova Scotia, but for two days last year it was the hotspot for a gathering of marine professionals, ship operators, academics, and representatives from government and other regulatory agencies to discuss ship noise mitigation. Hosted by CISMaRT (www.cismart.ca) and supported by Transport Canada, the workshop provided a setting for training, discussion, and collaboration. As a participant at the event, I found it to be an outstanding overview of the state-of-the-art in many aspects of Underwater Radiated Noise (URN), yet there were also a few things that surprised me.

While all seemed to appreciate and accept that propellers are the dominant source of detrimental ship-generated radiated noise, it became clear that the mechanism of propeller-driven noise is not well understood at all. I hope to use this article to offer a 'practical primer' on this topic. (I also am intentionally avoiding any discussion about the social and environmental impact of noise. There are others much more qualified to speak about this). Let me acknowledge that I am not an acoustic expert, just a practitioner (albeit one with a special interest in the topic and experience in hydrodynamic systems) that is driven to peak behind the curtain.

Three-part harmony

SLAM! Now it's your turn. Take your hand and slap your desk. Why you hear any noise at all is the result of a three-part system of Excitation, Transmission, and Response.

- Excitation is the source of the noise. It is your hand slapping the desk.
- Transmission is the highway for the energy that propagates from the source. In this case, air provides the fluid pathway, but the medium for transmission could be gas, liquid, or solid as long as it has some elasticity.
- Response is how your body accepts and responds to the energy from the transmission fluid. The eardrum picks up the fluid motions and converts it into signals that your brain processes.

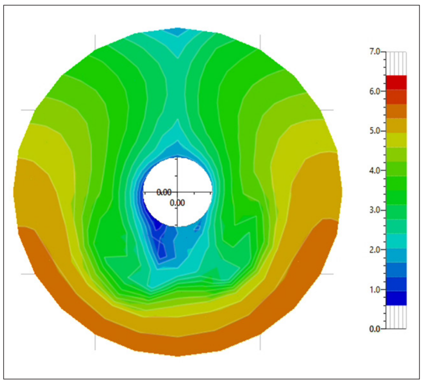

Figure 1: Propeller wake field. Boundary layer thickness will increase with distance from the bow

Every such system is unique, but they all more-or-less follow a similar framework. Let's first distinguish between sound and noise. Sound is the term for the physical process, the conversion of source energy into a response. Noise is simply disruptive or unwanted sound, and admittedly, this can be a very subjective term (as a bagpiper, I am frequently reminded of the distinction...).

Now in professor-speak: *Sound is a vibratory mass fluctuation that travels through an elastic medium.*

But wait, I just slapped my desk once? How is this vibratory? Even though the sound is processed as a single "burst" it is in fact made up of a spectrum of vibratory subsets at very tiny time scale. The energy from your single impact caused the spring-damper system that is your desk to vibrate and reflect the fluid back to you. The nature of this sound depends not just on the impact energy, but on the physical characteristics of the impact site. Not quite sure? Slap a pillow... While there is indeed a whisper of noise from the mass being moved by your hand, it is a fraction of the sound energy that was reflected by the desk – and at a differing frequency as well.

OK, now set off a firecracker on your desk. Just kidding! Don't try this at home. But it does provide an illustration of a different kind of sound generation – the direct mass fluctuation of the fluid via an explosive expansion or contraction within a very, very small time frame. The thunder created by a lightning's instantaneous heating of air is another such example.

Propeller-driven noise

This sets the stage for a deeper understanding of propeller-driven noise. There are two noise sources in play here – non-cavitating and cavitating – and they are similar to the two described above.

Frequency of noise

Propeller-driven noise sources most significantly occur at each blade's passing though a region of slower water – hence the name 'blade rate' or 'blade pass' frequency (BPF). The BPF is the principal frequency of noise generation, with its first two or three multiples as additional significant frequencies.

As a propeller blade rotates through its circumferential path, it passes incoming water which are at different velocities – its 'wake field'. Figures 1 and 2 show examples of differing water velocities and how boundary layers on hull and appendages can create this non-uniform inflow. Oblique flow due to shaft angle can also be a major contributor to variation in the wake field.

Frequency is an important consideration in the 'radiated' part of URN, as lower frequency pressure wave systems can travel much farther than those at higher frequencies. This means that the region of potential acoustic 'damage' is much farther away from the source. There is also some speculation that a perceived regular sound is more psychologically harmful than a collection of higher-frequency 'white noise'. Consider rain. I find it soothing – but a continuous single... regular... drip... on a metal lid can drive you crazy.

Non-cavitating noise

This temporary passing from higher velocity to lower and back again is akin to a wing traveling with a fluctuating angle of attack. This brief increase in lift and thrust (also called a 'gust') imparts a periodic load on the blade and is often referred to as a 'pressure pulse'. Just for reference, the time of a blade passing a slower region on a merchant ship (e.g., the sweep through the darker green region in the wake field plot above) is just a few hundredths of a second.

While the pulse itself can alter flow enough to cause direct noise, it is the vibratory noise that is the principal source. Like your desk top, the propeller blade is a spring-damper system that is responsible for reflecting imparted energy. The shape and typical metallic material properties of commercial propellers cause them to be effective vibratory reflectors.

Non-cavitating noise is one of a soup of noises generated at lower ship speeds. Machinery and hull noise actually can be the principal sources of ship noise at these lower speeds, with non-cavitating propeller noise as a lesser contributor. Once a propeller cavitates, however, everything changes.

Cavitating noise

Cavitation is the dominant noise source associated with harmful URN, as mass fluctuation is caused directly by the instantaneous expansion and collapse of what can be sizeable cavitation volumes. Cavitation comes in different types, and not all types are important noise producers. For example, cavitation that remains as individual bubbles will collapse in a chaotic fashion, resulting in a band of noise often sounding like a can of pebbles (typically between 1,000 and 2,500 Hz).

Sheet and tip vortex cavitation, on the other hand, produce strong singular cavities of substantial volume. These are created and destroyed during each blade pass, and are the source of high energy spikes in the noise spectrum at BPF (and multiple) frequencies.

Tip vortex cavitation has the distinction of typically being the first cavitation encountered as loading is increased on a propeller (by an increase in speed or towpull). It therefore can be a useful metric for defining the critical point of cavitation inception. (You may see this referred to as a Cavitation Inception Speed, or CIS.)

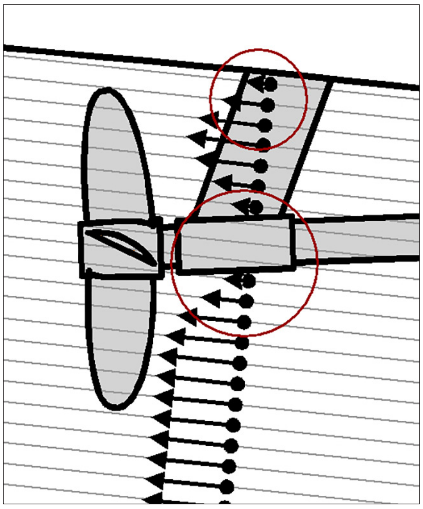

Figure 2: The propeller shaft angle creates oblique flow, which influences the wake field

In simple terms, a tip vortex is created by fluid movement across the blade tip due to the differential between the pressure and suction sides of the propeller. (We have all seen the tip vortex from an airplane wing – same phenomenon.) When the vortex is strong enough, its internal pressures drop and a cavitation tube is formed. It is a significant explosive fluctuation noise-producer when the cavitation tube collapses in the trailing wake. For ships with a mission requirement for low-noise operation, such as a research vessel, it is important for designers to avoid or delay tip vortex cavitation.

Noise mitigation

There are a variety of design strategies for the mitigation of propeller-driven noise, and they generally focus on two objectives – improving the inflow uniformity and reducing blade pressures.

Inflow uniformity

To improve noise, think like the water. Reducing the variation in the wake field velocities will reduce the strength of the periodic loading and unloading pulses on the blade. And remember, the big noise problems come from the rapid and strong generation and collapse of the cavities – also due to variation of the inflow.

Improving the inflow is always justified. Noise is not just about the propeller, but about its interaction with the environment in which the propeller works. It is important to remember that uniformity is critical around the rotational circumference, but not so much in the radial direction. In other words, any particular radius on the blade should "fly" thought water with as little variation as possible, but it is OK to have different velocities at different radii. The characteristics of each radial blade sections (e.g., chord, pitch, and camber) can be adapted to its axial and tangential inflow (hence the term "wake-adapted" design).

Reducing blade pressure

The propeller thrust needed for a particular speed is constant, so mitigation of noise requires compromise via altering or shifting thrust development on the blade. These include the following:

- Unloading the blade tip via reduction in blade pitch or camber. This will shift the loading lower in the span of the blade to reduce the pressure differential near the tip. Of course a strong differential is necessary for thrust-making, so carrying parts of a blade that are not fully developing thrust comes at the cost of lost propeller efficiency. It is important, however, to be careful about increasing the loading too much at lower radii, as this can create a strengthening of a leading-edge vortex that rolls up into the tip. This is particularly important for highly-skewed propellers, and it suggests incorporating the next item in our list.
- Reduce the pressure differential with a wider blade – even at the tip. Pressures are reduced as the required thrust is distributed over a wider area. Again, the added drag of a wider blade surface for the same thrust contribution reduces efficiency.
- Increase blade count. For propellers where complete unloading is not possible (which would be most propellers for commercial applications), it can be beneficial to distribute the thrust over a greater number of blades. This will generally not eliminate the tip vortex, but will reduce the strength of each individual vortex. Similarly, other cavity volumes can be smaller per blade. Less amplitude at higher frequencies.
- A larger or smaller diameter – which is best? Well, it depends. While you can reduce blade pressures with the

greater area of a larger diameter, this will reduce the transmission distance (the tip clearance). That being said, it is important to appreciate that the useful rules-of-thumb for tip clearance generally do not consider the other measures that might have been taken. So, if you are unloading the tip, you might be able to increase diameter.

Why are propellers still producing noise?

Great question... This was the other thing that struck me at the meeting – how the analytical predictions for propeller noise sources are offloaded to propeller specialists. Let me note two particular items raised during the meeting:

- System noise models are generally of a type called "Statistical Energy Analysis" (SEA), but for these codes, the propeller excitations are not calculated but added as a separate external noise source. Where these sources are supposed to come from is uncertain.
- URN mitigation is still a selective task, not yet mandated or a company priority (for most). I am not being critical, just realistic. The cost of fuel and impending emissions regulations are going to be at the top of the list.

Of course, this means that comprehensive noise mitigation will also require simultaneous evaluation of the cost of doing so – in terms both of capital cost as well as operational cost. Short of model testing (with uncertain expansion to full scale) or complex numerical codes, there is currently no practical way for the assessment of propeller-driven noise production without the consultation of a subject matter expert. Ship designers need the ability to evaluate fundamental URN metrics early and in a way that is also integrated with hull form and propulsion system design decisions.

So what is HydroComp doing about it? I am pleased to be a contributor to HydroComp's maritime sustainability initiative (http://hydrocompinc.com/blog/sustainability). Every new product development decision includes a check of what it can contribute to noise mitigation, fuel conservation, or the reduction of GHGs. Propeller blade design for noise reduction is currently part of the work of many in our PropElements software user community.

Closer to home, work is being undertaken in-house to develop parametric prediction models for the influence of blade tip parameters on radial loading for the NavCad hydrodynamic and propulsion system simulation tool. Couple these with new models for noise source prediction and propagation, and we are encouraged that meaningful noise mitigation for practicing naval architects is quietly approaching. *NA*