Beating the Drum

In recent times requirements regarding noise and vibration onboard mega yachts have got more demanding. One major source of noise and vibration are the propellers. This article deals with procedures to control and reduce propeller induced noise and vibration.

Noise that is unwanted sound is generally understood to relate to acoustic, airborne, disturbance. The distinction from vibrations is such that the latter are structure borne. Vibrations will excite the bodies of those onboard who get in direct contact with a piece of structure. As far as the "total annoyance level" is considered, the effects of noise and vibration in concert, cause mutual aggravation.

Noise and vibration are closely related, either phenomenon will cause discomfort, fatigue and increased stress levels. In the context of megayachts, owners will invariably demand the highest possible comfort levels. Exceeding specified noise and vibration parameters may result in disappointed clients, loss of yard reputation and severe pecuniary losses. Therefore, it is an obvious risk reduction exercise, to control, manage noise and vibration as much as possible from the very early stages.

Generally, it is the best idea to "design it out", by reducing the excitation of the yacht's structures and tuning the structure to frequencies that are different from those of the actuator. In this way, the application of sound damping material can be minimised, improving the overall performance and cost of the yacht. While the focus has traditionally been with the machinery, today noise and vibration experts also target the major hydrodynamic source of noise and vibrations, the propeller.

The path of noise and vibration

The operating propeller will cause general flow noise and varying levels of pressure pulses. The latter may quite possibly excite

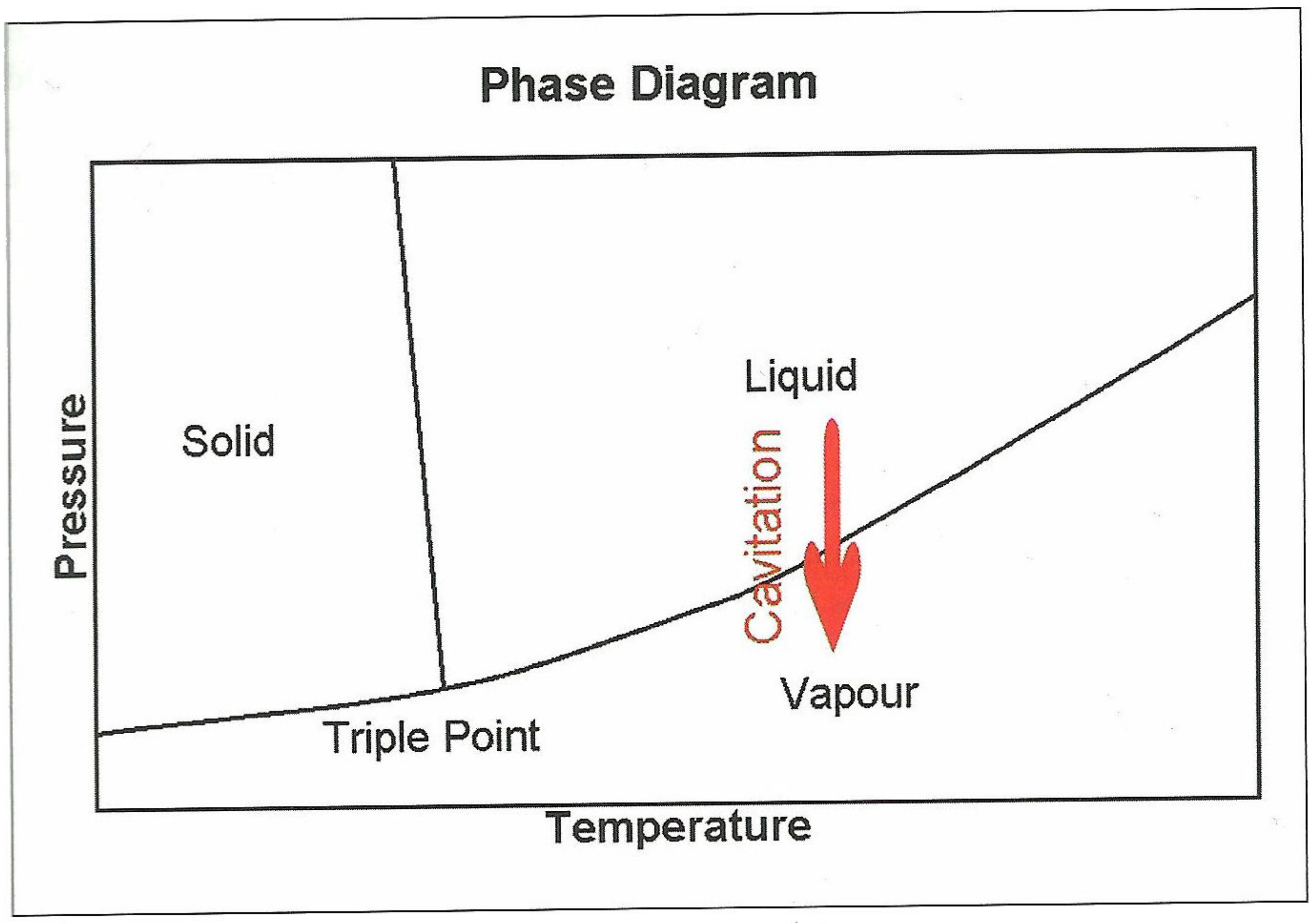

Figure 1: Phase Diagram.

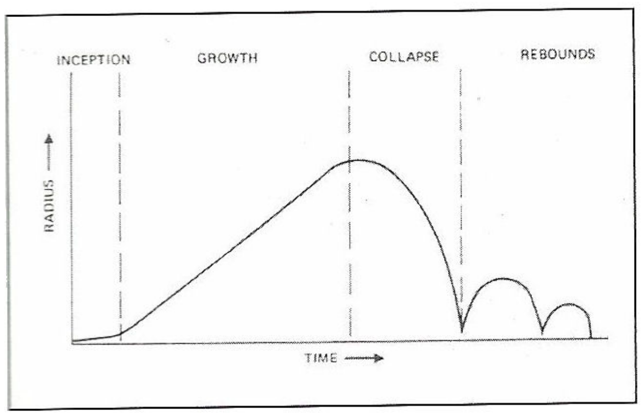

Figure 2a: Radius of a cavity over its lifecycle.

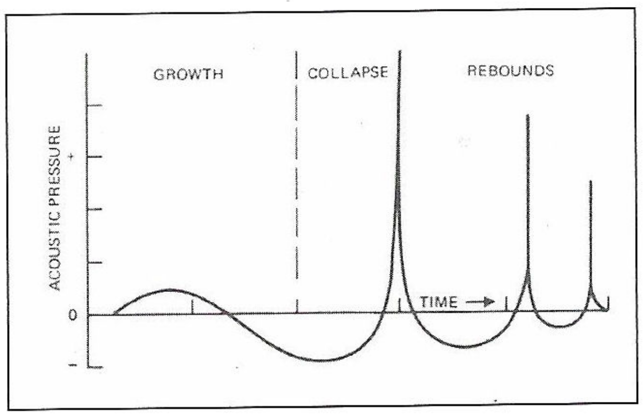

Figure 2b: Modulation over the lifecycle of a cavitation bubble.

Source (2): Ross

the hull structure. In fact, in this way, the prop may cause all sorts of parts of the vessel to vibrate quite badly, causing rattling and discomfort.

The most basic consideration is that structures should be tuned in a way that their respective Eigen frequencies are different from that of the most common blade passing frequencies. The blade passing frequency (or blade rate) being the number of times a propeller blade passes the top dead centre per second. It is, of course, nearly impossibly to tune every constituent of the vessel's structure so that it will not resonate at any conceivable frequency. This in fact obviates the importance of low propeller related pressure pulses. Luckily, pressure pulses tend to be less at lower speeds and the vessel's top speed is normally taken as the design case.

Pressure fields

Generally, pressure fields surrounding the propellers of the yacht will result in some sort of excitation on the side of the hull because the pressure differential is what produces the propulsive force. Unfortunately, these pressure fields are located on a rotating body. Further, they are ultimately not constant, but tend to fluctuate since the wake of the yacht in which the propeller operates is inhomogeneous. Since these pressure fields rotate in the vicinity of a rigid body, the latter is prone to being exited. Whilst there is no way to completely avoid this problem, there are ways to cope with the propeller's pressure pulses.

Cavitation: microscopic level

If the pressure in a fluid is lowered as indicated by the red arrow in the Phase Diagram (Figure 1), the fluid will vaporise, even though temperature remains unchanged.

If the resulting vapour bubbles are carried to a region with increased pressure, they will suddenly collapse. The surrounding fluid will very suddenly rush into the previously void region. However, the bubbles may not entirely collapse, but their remains may in fact rebound. It is obvious that this sudden and repeated change of volume (see Figure 2a) will result in an energy rich modulation of the surrounding medium (see Figure 2b).

Cavitation may not only be present on the propeller itself, but also in the propeller wake (see Figure 3). The helix, or tip vortex, is due to the highly loaded propeller tips. At the blade tips, a rotational motion is initiated within the fluid, which remains intact, even though being swept downstream, as the vessel advances. Tip vortex cavitation occurs, because the local pressure within a rotating fluid is lower than that of a fluid at rest (Bernoulli's Law).

These vortices may twist, bend or neck. Recent research indicates that this could be the reason, why a vortex is prone to cause a stronger modulation of its environment, than one would expect. The resulting so-called "broadband excitation" is so difficult to handle because an enormous amount of energy is being transferred into the environment, covering a large frequency range (see Plate 7). Therefore, it is very difficult to avoid a response from the yacht's structure and constituents.

Cavitation: macroscopic level

On most modern propellers, there will be stationary clusters of cavities (see Plate 3), which are typically situated on the low pressure side of the prop. Since the wake is not homogeneous, the inflow velocity into the propeller plane (or velocity of advance, see Plate 4) will alternate through the course of the revolution of the prop. As the rotational velocity stays constant, the resulting velocity, and therefore the angle of attack at each blade, will change during the course of each revolution (see Figure 3).

The higher the angle of attack, the lower the pressures on the lifting surface. As a result, a propeller blade is likely to experience more cavitation when entering the hull boundary layer, the shadow of shaft struts or a skeg, where the velocity of advance is comparatively low. The presence of the resulting cavities increases the amount of water that will be displaced by the blade itself, thereby increasing or even being more dominant than the pressure pulse caused by pure displacement action of the blade alone. As a consequence of this gradual growth and decay, there will be a modulation of the surrounding medium. This pressure alternation will be experienced by the hull (see Plate 5), which could subsequently lead to vibration onboard.

Propeller selection

The blade rate will have to be out of tune with the vessel's structure. First of all, it is important to select the right gear box ratio. The faster the propeller rotates the more likely the occurrence of cavitation will be. Therefore, lower rates of propeller revolutions, n, are recommended.

Further Z, the number of blades per Propeller, will have to be decided upon. Z, in combination with n determines the frequency at which the yacht will be excited. The number of blades are not only important for propeller - structure tuning, but the strength of the individual pressure field surrounding each blade will reduce with the increase in Z, which literally helps to reduce the impact of the passing blades on the hull. This is the primary reason why there has been a trend to higher blade numbers in recent years. This trend persists, even though each additional blade will slightly reduce the propeller's propulsive efficiency through tip losses and blade interference effects.

Finally, the propeller diameter and propeller clearance (closest approach of the blades to the hull, expressed in percent of propeller diameter) will have to be determined. The impact of pressure pulses reduces exponentially with distance. Thus, it may be possible to increase propeller clearance by tunnelling the hull for the obvious cost in displacement. Though this may help, tunnelled propellers suffer from high wake due to the thick boundary layer inside.

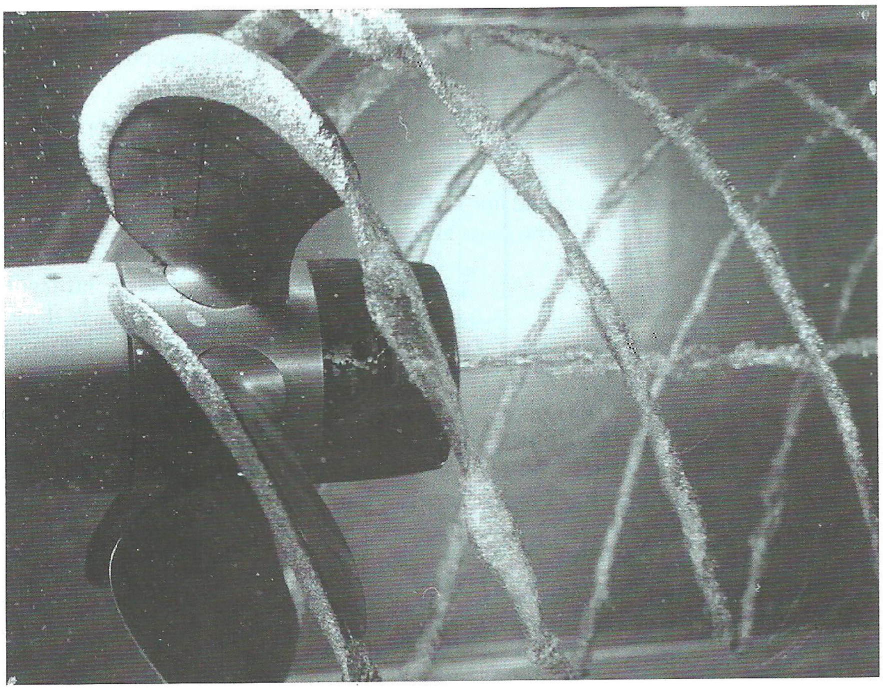

Figure 3: A propeller in a cavitation tunnel displaying the back skew and the three distinct types of cavitation present: On the back of the blade surfaces, the helical tip vortex and the central hub vortex.

Courtesy: HSVA

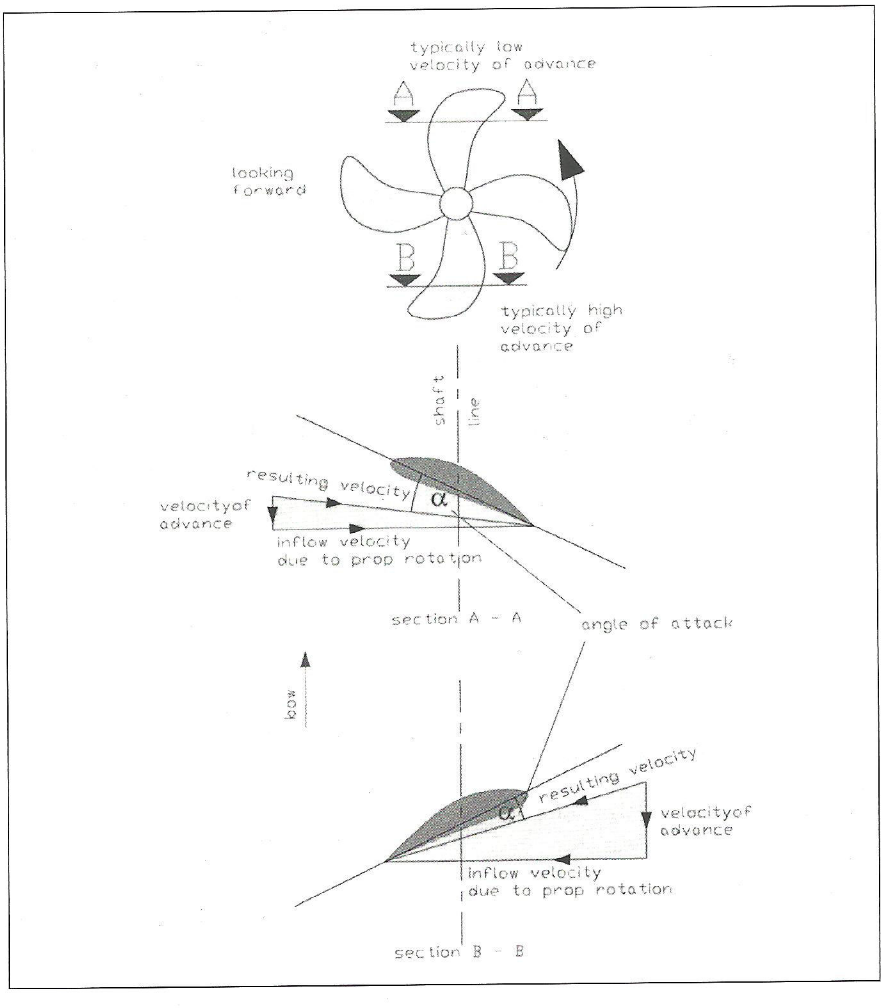

Figure 4: The Effect of changing Inflow Velocity into the propeller plane on Angle of Attack α at constant rate of rotation. The marked increase of α at lower velocity of advance will notably increase the risk of cavitation.

Note that the inflow into the prop in fact occurs from abaft. The vessel's bow would be at the top, the stern at the bottom.

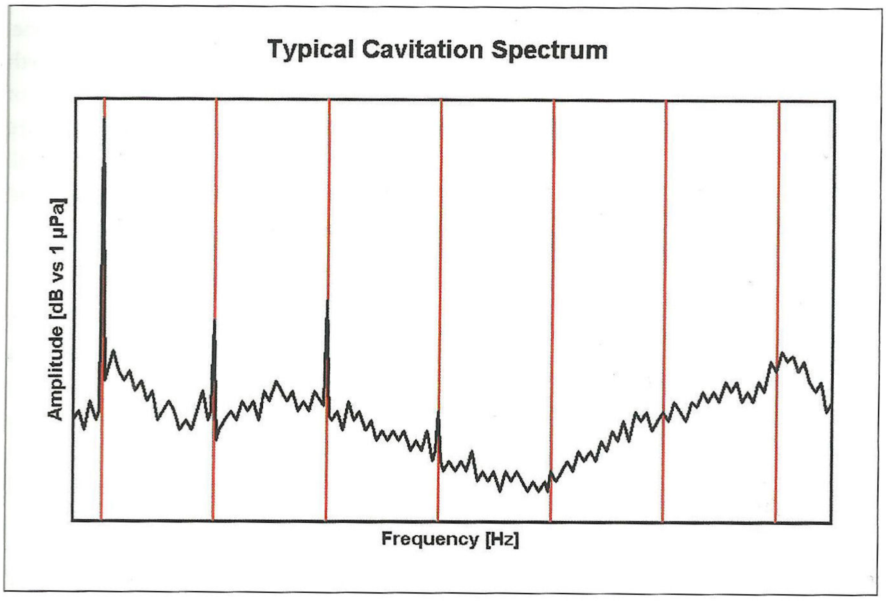

Figure 5: Typical Cavitation Spectrum.
Red bar (far left): Blade Rate. Other bars: Blade rate multiples.

This would imply a small propeller diameter. However, the smaller the propeller, the higher the pressure differential per unit area on the prop will have to be, to achieve the thrust necessary to reach contract speed. Lowering pressure may in fact lead to an increase in cavitation. This classic "catch 22" situation requires careful balancing of design variables. One may be tempted to increase propeller shaft inclination to increase propeller clearance. Note however, that this will reduce overall propulsive efficiency of the vessel.

Cavitation Control

- **Wake**: Keep as low as possible, i.e. the inflow velocity into the propeller plane should be as uniform as possible, thus reducing the tendency of alternating cavity volumes. A low and homogeneous wake will be achieved by means of fair buttock lines. This includes shaft struts which are carefully aligned with the flow, avoiding local disturbances to the propeller inflow. Those shaft struts in Plate 5 should in fact be re-aligned to better cavitation performance.
- **Blade Loading**: Reduce propeller loading per unit area by means of appropriately large propeller diameter and blade area ratio (BAR, the area that is covered by the developed blades as compared with the area swept by the prop during one revolution). Increasing BAR will spread the hydrodynamic load carried by the prop over a larger area, thereby helping to alleviate the overall pressure levels on the propeller blades. Note that maximum BAR will of course be limited if CPPs are to be fitted as it must be possible to reverse pitch. Increasing blade area will also reduce the propeller's propulsive efficiency.
- **Skew** (*e.g. tangential sweep of blades*): As the propeller rotates, each consecutive blade excites the hull through its displacement action as it travels past the top dead centre. This excitation will occur more gradually, if the blade tip pressure field is spread out circumferentially and therefore the gradient of excitation force vs. time is smaller. This is achieved through the application of skew.
- **Tip Rake**: Cupping propeller tips to the high pressure side will reduce propeller tip vortices, as well as it slightly increasing propeller efficiency through reduced tip losses.
- **Blade Sections**: Employing a blade section featuring an evenly distributed lifting line along the chord of the blade as well as carefully rounding the leading edge will avoid local pressure drops which might cause cavitation.
- **Radial Load distribution**: Unloading the blade tips helps to avoid tip cavitation (see helix, Figure 4). This will however, increase the load on the central radii and therefore needs careful balancing against possible cavitation inception there.

The naval architect should be aware, that if a propulsion test has been performed at a ship model basin, the results should be treated very conservatively since the design propellers may as a result of the above considerations be less efficient than the stock propellers (such as those of the Wageningen Series), used for the propulsion experiment. Further more, when evaluating high performance craft in the tank, the results of the propulsion test will usually be without consideration to possible cavitation related thrust reduction.

Design evaluation

At the time of writing, model tests are still considered the most reliable source for hard numeric results in a commercial environment. As a pre-requisite for the cavitation experiment, resistance and propulsion experiments will have to be done. Further, an open water experiment needs to be carried out, to determine the characteristics of the designed propeller. These experiments serve to generate the input into the cavitation experiment: Thrust, RPM and stern wave height as a function of velocity.

The result of the cavitation test will be the pressure pulses, frequency spectrum (see Figure 5), a check for erosive effects and possibly loss of thrust owing to cavitation as well as the margin against tip vortex cavitation. Pressures are recorded at several locations at about the propeller's top dead center. The described experiment is generally gifted with good reliability if an experienced model basin has been chosen.

The ultimate evaluation will of course be that at sea. The hydro-acoustic performance will frequently be done indirectly through noise and vibration measurements in the accommodation areas. However, further insight into the cavitation performance may be gained by means of pressure pulse measurements and boroscope high speed optic and acoustic recording technology that allows to observations and records of in-service cavitation patterns. *NA*