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DESIGN

Bow Thruster Induced Noise And Vibration

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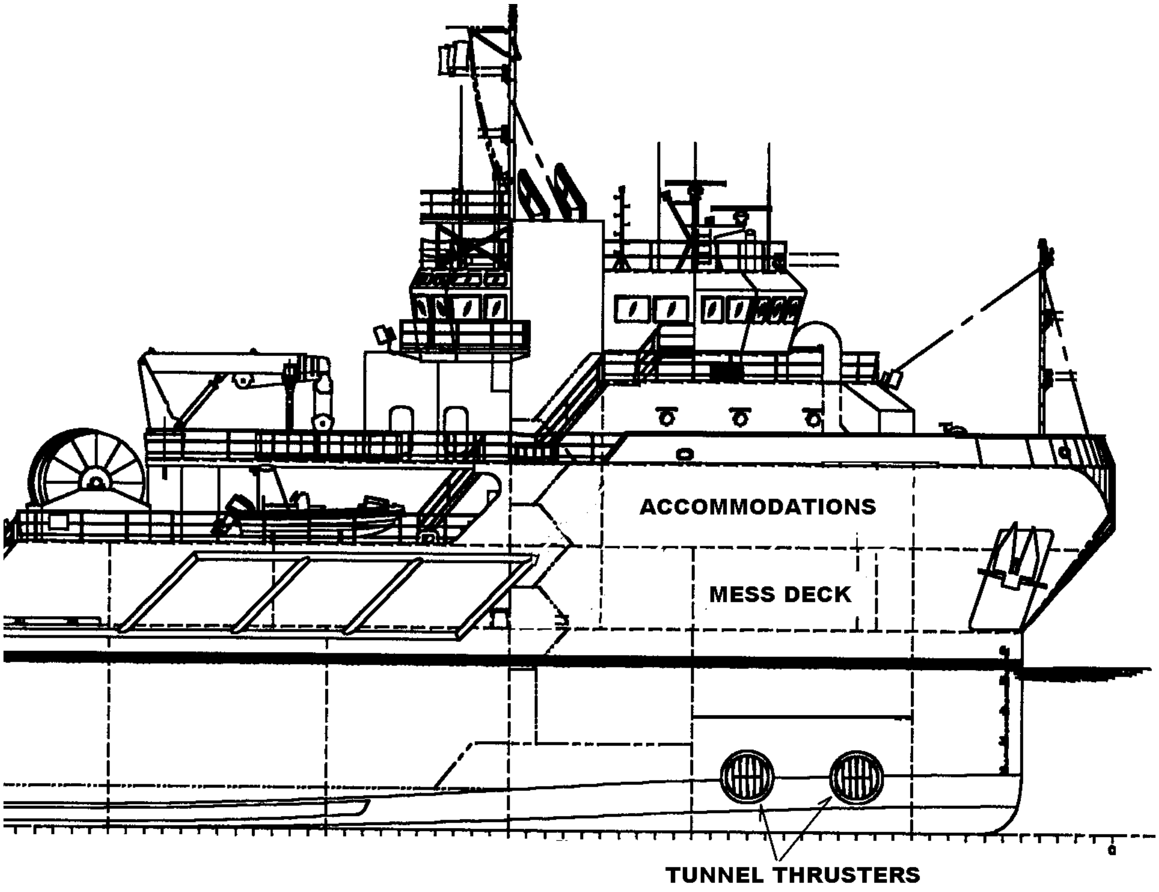
ABSTRACT:

Bow thrusters can induce high noise and vibrations onboard a vessel as well as high underwater-radiated noise. If these units are only used intermittently for docking or maneuvering, their operation may not prove annoying to the crew or passengers. However, most research vessels or offshore support vessels have extensive dynamic positioning requirements. In this case, thruster operations can cause significant acoustic problems. This paper addresses noise goals, methods to assess the acoustic characteristics of thrusters and potential noise and vibration abatement methods. Design guidance is provided to improve the acoustic environment onboard all vessels. Measured habitability and radiated noise and vibration data are provided for several case histories.

Figure 1: Typical Offshore Work Boat Profile with Twin Tunnel Bow Thrusters



INTRODUCTION

Bow thrusters are standard on most research and work vessels. Transverse tunnel thrusters are the most common type (see Figure 1), though retractable thrusters are also utilized. Other hybrids include steerable thrusters or pump jets that take suction from below or from the side. On some vessels different types of thrusters are installed in tandem in the bow, e.g., retractable aft and tunnel forward. Furthermore, both bow and stern thrusters on the same vessel are not uncommon.

Unfortunately, most of these thrusters, particularly tunnel thrusters, cavitate at relatively low operational speed. Cavitation is the creation of air bubbles in the water by the high impeller load and high tip speed. These bubbles violently "implode" causing high acoustic energy in the water. If the cavitation is heavy enough, it can erode or destroy the impeller and tunnel material. This cavitation is primarily due to the poor inflow conditions associated with the thruster's location in the bow[1] where the hull lines are rapidly changing. It may also be controlled by other factors such as improper loading on the blade or other hydro-acoustic parameters. These include poor inlet conditions, vortices and turbulence created by the inlet grating or motor support structure, too shallow an immersion depth for the tunnel, or flow interaction between adjacent tunnels or hull openings.

A cavitating impeller will induce high vibrations in the surrounding tunnel wall and hull plating. This noise is transmitted along structural paths to adjacent manned compartments where it generally dominates the overall received noise level[2]. In some cases, this received noise is at a level considered by OSHA and the US Coast Guard [1] to be hazardous, that is above 90 dB(A) for 8-hours of exposure or 82 dB(A) for 24 hours of exposure, respectively. Even if the received noise is not hazardous, intermittent operation of the thruster is considered to be annoying by the crew, which will contribute to crew fatigue and loss of sleep. For dynamic position operations, particularly over long periods of time, thruster-induced noise can become a severe problem. In addition to causing high compartment noise levels, thrusters can also induce unacceptable noise levels at on-deck stations, which can adversely impact effective communications. Often, the thruster can also induce a high vibration level in the low frequency range, below 100 Hz, that exceeds typical habitability vibration criterion [2]. There have been cases where this vibration level is high enough to cause structural damage. This is particularly true if the ship has a resonance that is excited by the thruster. An example is a fore mast that has a natural frequency that coincides with the impeller blade rotation rate.

For vessels that need to follow an acoustic baseline, operation of the thruster can interfere with these acoustic systems. The noise radiated by the thruster depends on the amount of cavitation and the directivity associated with the tunnel opening. Cavitating impellers typically induce high noise levels over the mid- to high-frequency range, above 1,000 Hz; thus, they can interfere with high frequency baseline acoustic positioning systems.

The acoustic characteristics of the thruster and its interaction with its operating environment are explored in this paper. Good acoustic design practices are also provided. Potential noise and vibration abatement techniques are discussed along with their expected noise reduction. Finally, measured data for habitability noise, radiated noise, and vibration are provided.

THRUSTER ACOUSTIC CHARACTERISTICS

The real noise problems are associated with a cavitating impeller. Non-cavitating impellers are not of interest unless they excite a ship resonant response. The hydro-acoustic energy produced by the impeller excites surrounding ship structure, including the tunnel wall and ship's hull plating. The cavitating source level and expected vibration caused by this source level are addressed in the following sections.

Blade passage rate (rpm x number of blades) and cavitation induced noise depend to a large extent on the hydrodynamic and hydroacoustic design of the impeller. Impellers induce pressure fluctuations, thereby exciting the tunnel, which in turn can cause high airborne and structureborne[3] levels in the vessel. These pressures are affected by 1) impeller-tunnel clearance, 2) blade loading, 3) changes in local pressure fields around the blade, and 4) tunnel configuration. Unsteady forces acting through the shaft and shaft bearings are not expected to be a significant noise source. Thruster electric motors are not an important source relative to a cavitating impeller. Hydraulic and diesel drives can be significant sources, particularly at low impeller power settings.

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[1] While this paper concentrates on bow thrusters, the same principles apply to stern thrusters. Z-drives are not considered as stern thrusters in this sense.

[2] Other inherent noise sources are propulsion machinery induced noise and ventilation induced noise.

[3] Structureborne noise is that noise transmitted over the structural path from the vibrating source to the receiver space, where it radiates from the compartment's finish surfaces to produce the received noise.

Cavitation noise consists of a broadband noise component and tonal or discrete components. Cavitation has a continuous spectrum due to the large number of random bursts caused by various sized bubbles collapsing. The discrete spectral "blade rate" component occurs at multiples of the rate at which any irregularity in the flow pattern or in the impeller itself is intercepted by the impeller blades.

Generally, a large slower turning impeller will have lower acoustic source levels. Second, for conventional designs, there is little difference in the source level of conventional fixed pitch impellers (FP) and controllable reversible pitch impellers (CRP) at full power [3]. Basically the noise of any cavitating impeller is independent of type. For any impeller the acoustic source level varies as the diameter to fourth power and the rotation rate to the third power [5].

As noted above, the flow uniformity in an impeller disk is a significant factor influencing noise generation. It has been found that noise and vibration levels are different depending on starboard or port trust, which is related to which side contains the impeller drive mechanism and the fact that nearly equal thrust must be developed no matter which direction the impeller turns. The difference is significant (5-10 dB) in the low frequency range, especially for frequencies coinciding with blade rate multiplies. The noise is higher if struts and the drive mechanism are located upstream of the flow. This points out the need to have thin and streamlined struts and hubs. It has been found helpful to reduce the non-uniformity of the inflow velocity, including rounding of the tunnel inlet edges. A rule of thumb is that the radius of rounding should be not less than 0.05 *D*, where *D* is the tunnel diameter.

AIRBORNE NOISE

As with most machinery spaces, the noise level in the thruster room is generally considered hazardous. OSHA defines hazardous levels as those higher than 90 dB(A) for over eight hours of exposure. The US Navy considers a compartment level above 84 dB(A) to be hazardous. The US Coast Guard considers hazardous noise level at an Leq(24)[4] of 82 dB(A) [1]. Typical bow thruster room noise levels can easily exceed 100 dB(A) with the thruster cavitating. The noise level for diesel or hydraulic driven thrusters is on the order of 100 dB(A) even without the thruster cavitating. Hearing Protection Devices (HPD) should be worn upon entering any bow thruster compartment.

The noise level is typically very high in any adjacent compartment to the thruster room. A survey of 50 offshore support boats determined that the **mean** level in the compartment above the thruster room was 80 dB(A) with the thruster operating at 80% to 100% of rated load[6]. Hazardous noise levels have also been measured in compartment above the thruster compartment. In a study on offshore support vessels, compartments two decks above the thruster room have a mean level of 77 dB(A). On the third deck above the thruster room, mean levels amounted to 70 dB(A). All these levels are in excess of IMO's Code for Noise Levels On Board Ships [7] suggested level of 60 dB(A)[5] for berths and 65 dB(A) for mess or recreation rooms. For thruster operations, a time weighted average noise criterion, Leq, is often imposed rather than a compartment criterion. This approach considers hearing conservation but not crew comfort. For instance, the underway requirement for IMO [7] ship-wide is a 24-hour equivalent or Leq(24) limit of 80 dB(A). Thus, the noise induced by operation of the bow thruster would be averaged by the time it operates in a 24-hour period.

Not only is the noise level high in berths around the thruster room, but by the nature of its operation, the noise is intermittent. This recurrent operation of the thruster can interfere with rest and adversely impact crew performance by increasing fatigue rates. According to reference [8], the level of sound required for sleep awakening for 40% of the population[6] is 60 dB(A).

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[4] Leq(24) is the time weighted average noise over a 24-hour period.
[5] IMO suggests testing the noise in berths with the bow thruster operating.
[6] 60% of people would require a higher sound level to be awoken.

Even for typical conditions where full thrust is not required over long periods of time, the thruster induced noise can still be significant. Generally, operation at 40% to 50% of load is 5 to 7 dB quieter than operation at full load. Operating in a non-cavitation condition, typically below 40% of load, the noise can be 8 to 12 dB below that induced by full load. Even for these lower load cases, the thruster induced noise is generally above IMO's noise goals.

The above factors imply either significant noise control treatments would be needed to meet these goals or thrusters with lower source levels would need to be designed and installed. Figures 2 and 3 provide typical noise levels measured in a bow thruster room and in a cabin over the thruster room for various operating speeds. Table 1 provides a survey of noise levels in various compartments for several operating speed and when thrusting to either port or starboard. In this case the directional differences are not too significant.

Table 1: Noise Survey CPP Bow Thruster

Deck	***Pitch =*** ***Direction =*** ***Condition =*** **Compartment**	**0%** **None** **Non-Cav.**	**30%** **Stbd** **Non-Cav.**	**30%** **Port** **Non-Cav.**	**70%** **Stbd** **Cav.**	**70%** **Port** **Cav.**
Hold	Bow Thruster Room	98	97	97	104	102
Main	Mess	83	78	81	90	89
	Lounge	79	79	78	87	86
	Galley	81				
01 Level	Forepeak	85	85	87	95	95
	Laundry Room		72	74	84	82
	Fwd Stbd Inboard Berth	67	62	65	n/a	80
02 Level	Fwd Stbd Berth	66				
	Fwd Port Berth	63				

Two 600 kW bow thrusters operating. Note that at 0% pitch, the noise in the mess exceeds that when the thruster operates at 30% load. This is caused by an unloaded gearbox rattle at no load.

STRUCTUREBORNE NOISE

The noise in non-adjacent compartments to the thruster room is generally controlled by structureborne transmitted noise from the thruster itself. Structureborne noise in this paper refers to vibrations transmitted from the thruster machinery and from the hydrodynamic excitation of the tunnel wall due to operation of the impeller. These vibrations are transmitted to the adjacent spaces where they radiate from the structural and finish surfaces. In most cases, the structureborne-transmitted noise is more important than noise transmitted over the airborne path[7]. The amount of structureborne noise depends on the source vibration level of the machinery and the excitation of the tunnel wall. These vibration levels are attenuated by losses at intersections and by inherent damping losses for the ship's structure. The inherent damping losses for typical ship constructions are very low. The coupling from vibration level of the radiating surfaces in the receiver compartment to the received noise level is controlled by the structure's radiation efficiency[8]. If the compartment has joiner panels on its bulkheads, the received noise is typically controlled by the vibration and radiation from the deck plate. This is not always the case - there may also be significant vibration and radiation from the joiner panels themselves.

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[7] The transmission loss of the common interface and interface area control the amount of airborne transmitted noise from the machinery space into an adjacent compartment.

[8] Radiation efficiency is controlled by the plate thickness, panel perimeter, panel area, and frame properties.

Figure 2: Noise in Thruster Room versus Thruster Operating Speed

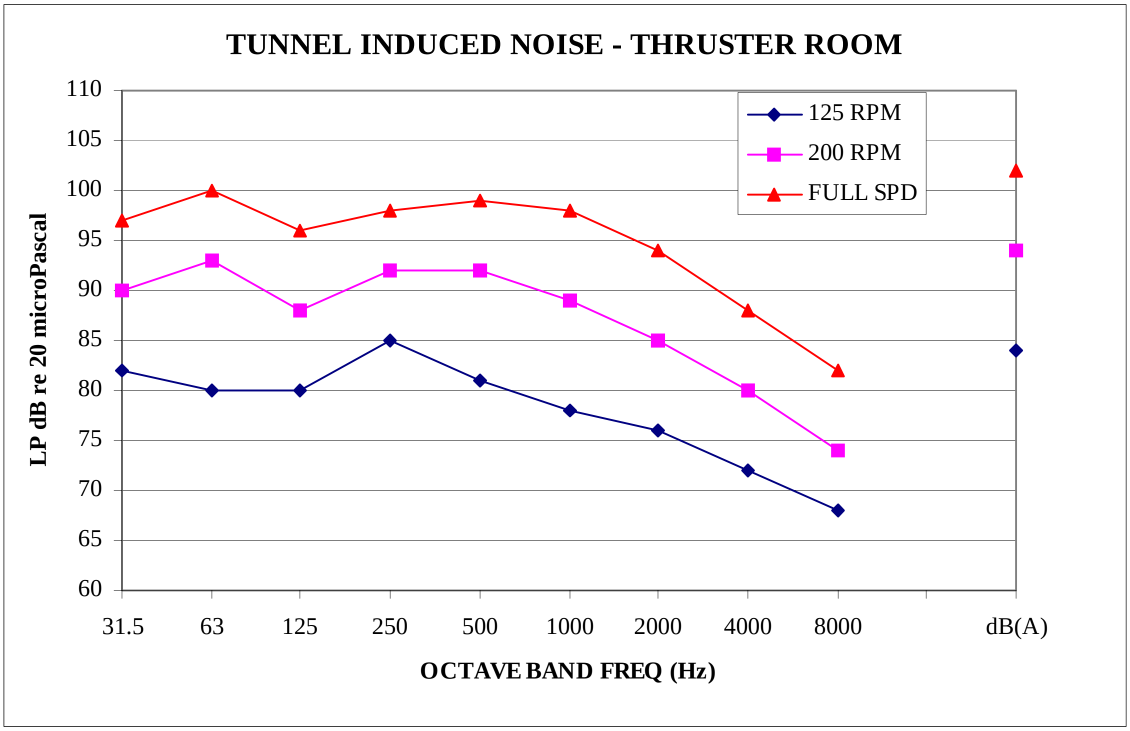
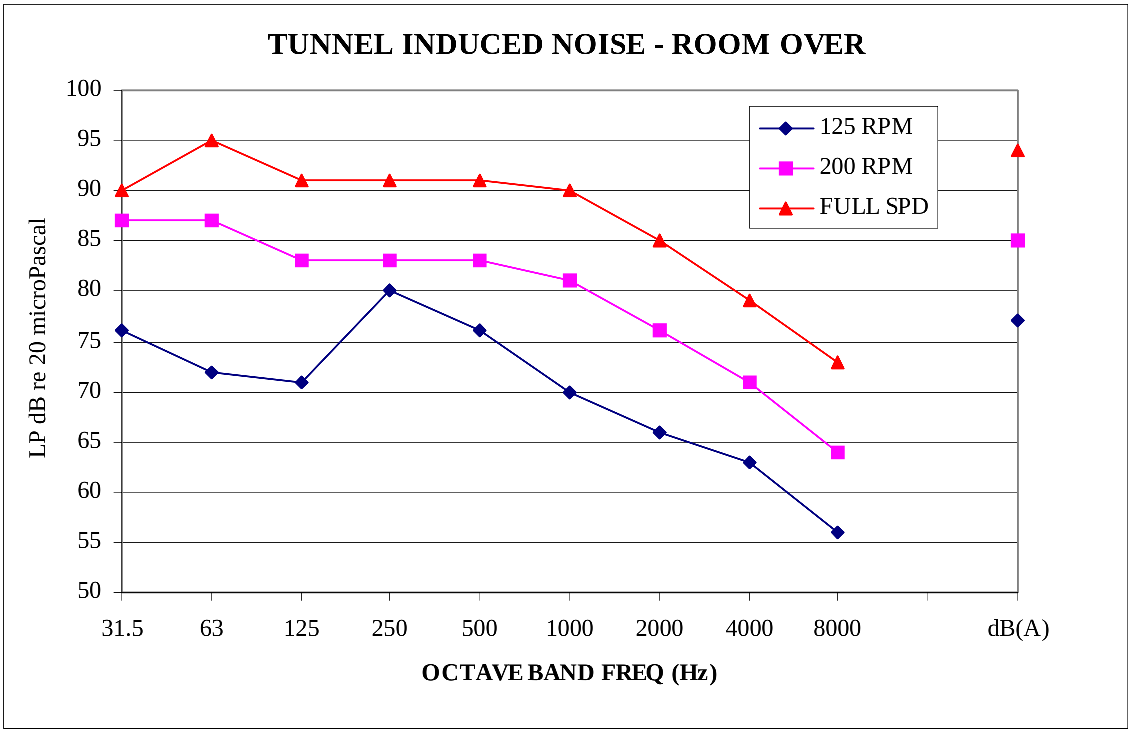


Figure 3: Thruster Induced Noise in Compartment Above Thruster Room versus Operating Speed



Measured tunnel wall vibration for several different size thrusters is presented in Figure 4 Figure 5 presents data for various surfaces onboard the vessel.

A bow thruster can induced high vibration as well as high structureborne noise levels. This is especially true if a ship resonance is excited. Figure 6 shows the measured structural vibrations induced in plating on the bow side hull above the Main Deck. This vibration exceeds the recommended limits for structural integrity [11]. The structural resonance was confirmed by conducting impact hammer tests on the ship's structure.

UNDERWATER RADIATED NOISE

The underwater noise induced by cavitating impellers can interfere with the operation of acoustic positioning systems or navigation systems employed on drill ships or scientific research vessels, especially during dynamic positioning. Due to draft constraints, this problem is more severe on scientific vessels than on drilling or mining platforms. However, when drilling or dynamically positioned vessels require high thrust to remain on station, the likelihood of cavitation and loss of signal for positioning is highest. Other factors such as air ingestion in high sea states can also lead to increased radiated noise.

Typical acoustic positioning systems utilize high frequencies. As shown in Figure 7, cavitating impellers produce significant high frequency noise. Thus, any reduction in the cavitating noise signature will improve the performance of any positioning system. Steps can also be taken to shield the positioning hydrophones from the noise generated by the thruster itself. The tunnel itself provides a baffle that reduces noise radiated at 90 degrees to the thruster axis. For a retractable ducted thruster, it may be necessary to use a decoupling material on the upper half of the exterior of the tunnel wall to prevent structureborne excitation of the wall from interfering with the baffle effectiveness described above.

Figure 8 illustrates the predicted advantage of delaying cavitation inception. If the cavitation inception speed can be moved from 300 rpm to 600 rpm for a system that operates at 800 rpm the peak radiated noise level can be reduced by approximately 10 dB and the peak frequency shifted to a higher frequency. This change in the radiated signature is illustrated in Figure 8 for various inception speeds [12].

CASE HISTORIES - INTERIOR NOISE AND VIBRATION

Case A: Noise and vibration data were collected on a pump jet thruster to determine the physical reasons of extremely high noise levels in the forward berths during bow thruster operation. Noise excesses at full power operation in the berths near the bow thruster were 85 dB(A), some 15 dB above the noise goal. Harmonics of blade rate are prevalent in the low frequency part of the noise and vibration spectrum. In the middle and high frequency range there were no strong peaks in the spectrum. Cavitation wide band excitation dominates in this range. The thruster cavitates heavily at relatively low operating speed. This cavitation generated a high-level acoustic field in water and in the bow thruster compartment itself. This high intensity field acts directly on ship structure forming the inlet water chamber: bulkheads, shells and overhead, inducing vibration on these structures. The vibration is transmitted along the bulkhead and shell plating to the accommodations. The structureborne sound induced by cavitation excitation dominates the airborne transmitted sound from the adjacent bow thruster room. Structural resonances were investigated and it was found out some of these are close to excitation frequencies. The measured decay rate corresponds to typical undamped ship structure.

The electric motor and bow thruster auxiliary equipment do not themselves contribute in the overall level in the berths. On the basis of this information, three main paths for bow thruster noise control were suggested:

Figure 4: Tunnel Wall Vibration

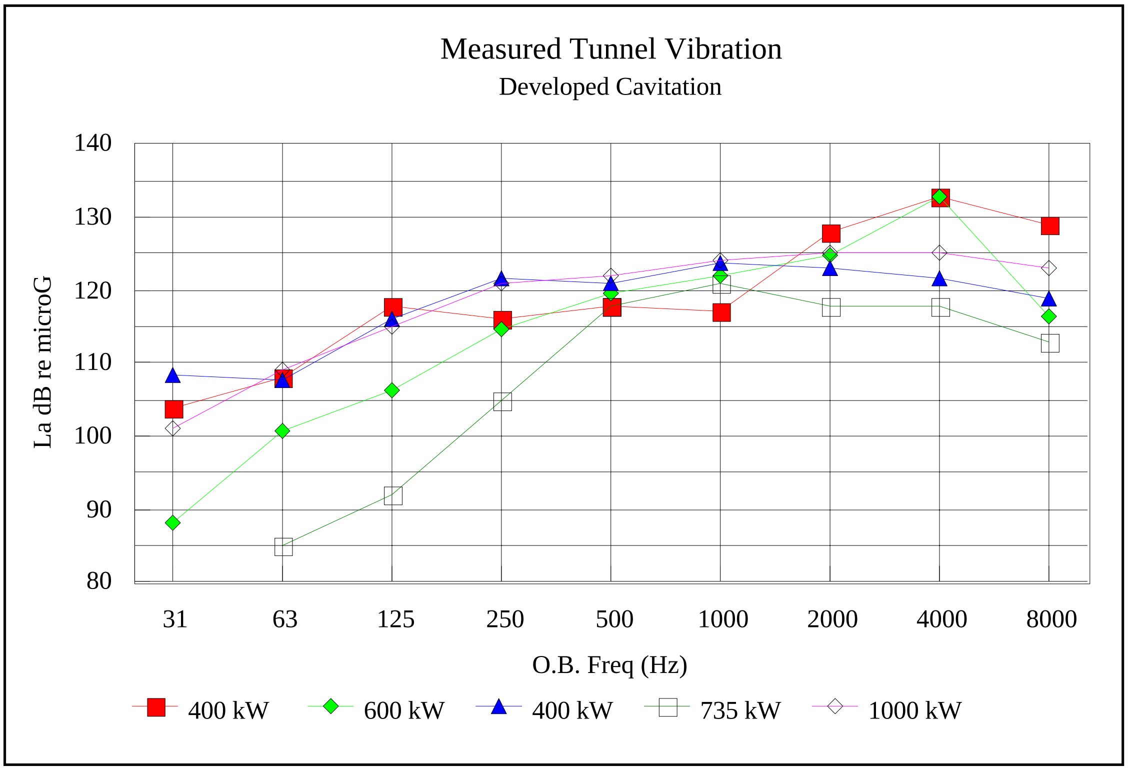


Figure 5: Measured Vibration Levels on Various Ship Surfaces

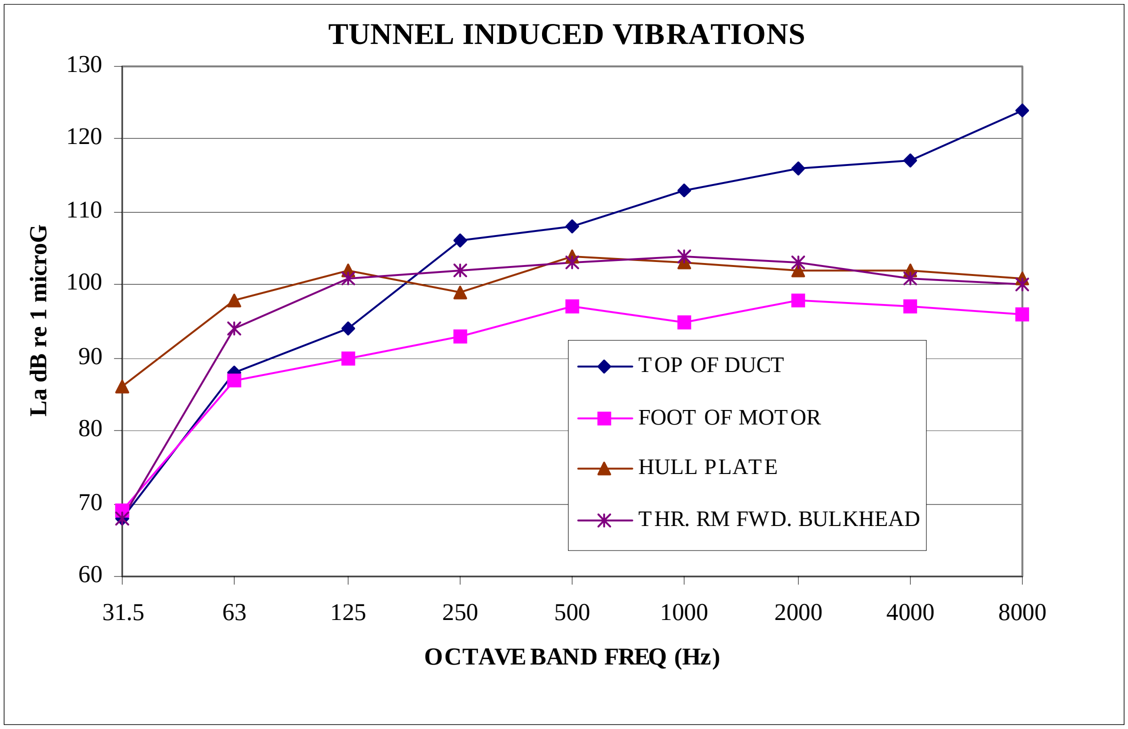


Figure 6: Bow Thruster Induced Vibration at Structural Resonance.

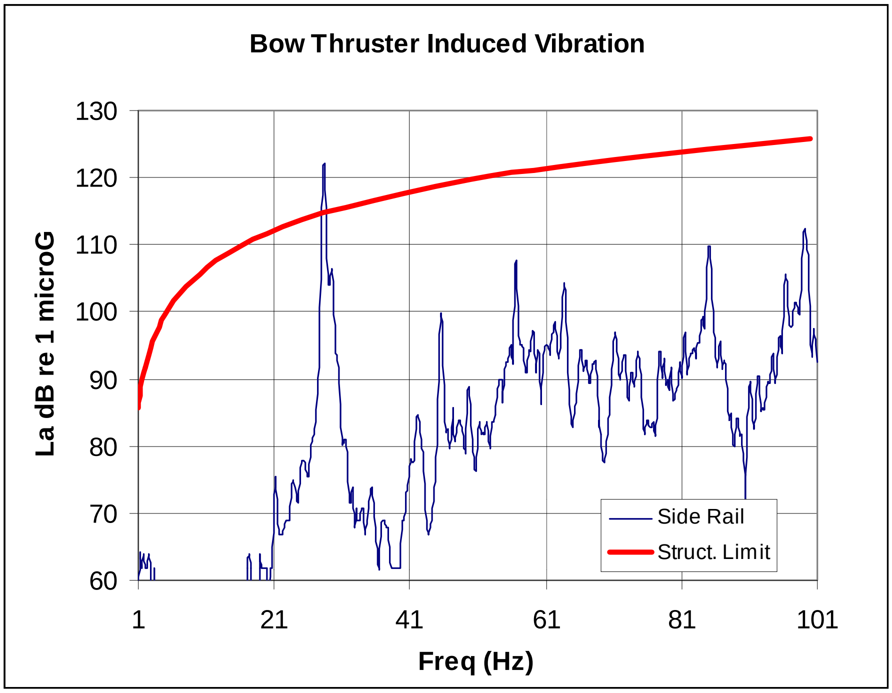


Figure 7: Bow Thruster Underwater Radiated Noise

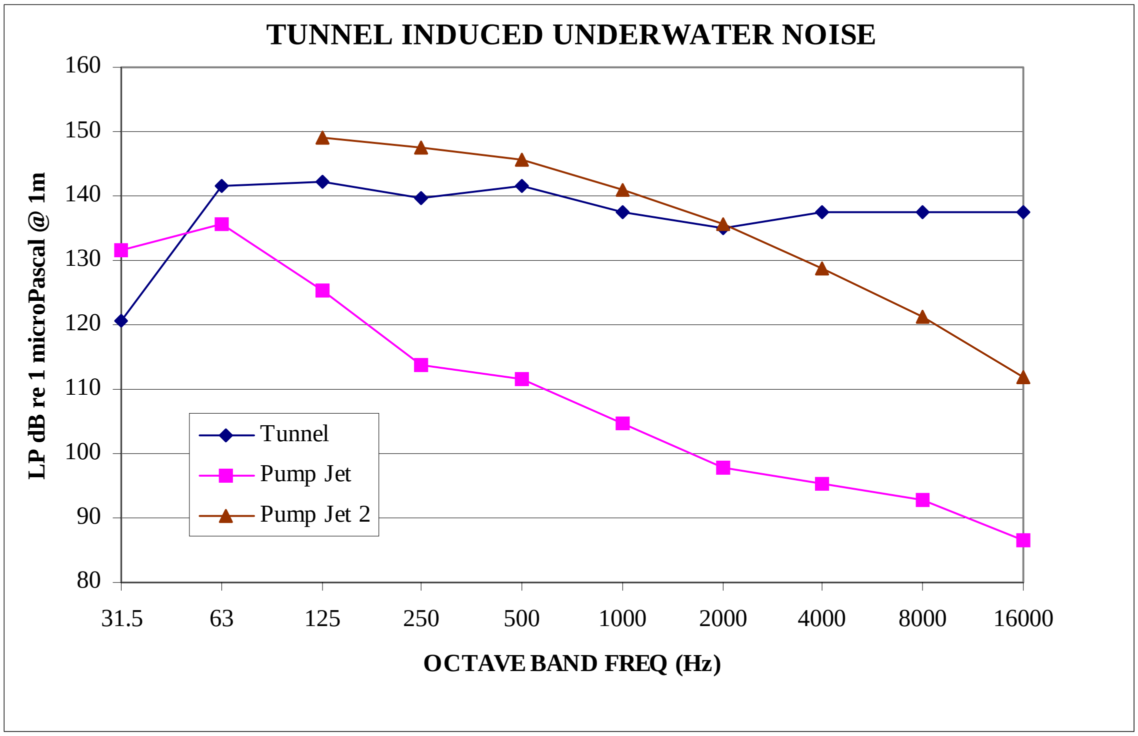


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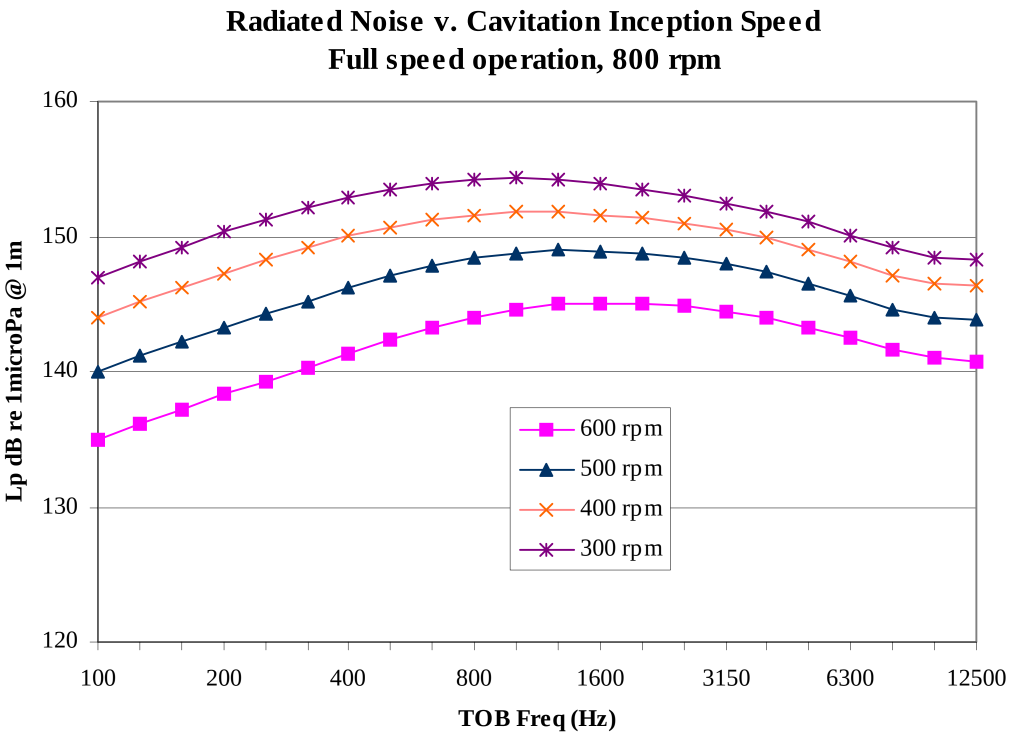
Figure 8: Underwater Radiated Noise versus Cavitation Inception Speed



1. Change the geometry of system to reduce cavitation noise via hydrodynamic methods.
2. Install a rubber absorption coating inside of all hull structures forming the inlet water chamber.
3. Install damping tiles on the common bulkhead, on the hull shell plating in bow thruster room and berths, and also on the deck of the berths.
4. Install floating joiners in berths adjacent to bow thruster room or a cladding treatment on the bulkhead and on the deckhead.

Installation of items 2, 3, and 4 (cladding) resulted in a 15 dB noise reduction.

Case B: Table 3 shows the predicted and measured noise onboard a supply boat with two bow thrusters operating. A hybrid Statistical Energy Analysis (SEA) method was used to carry out these predictions [13, 14]. This program accurately accounts for the path losses and acoustic characteristics of the ship's structure and compartments. These results show that thruster induced noise can be accurately predicted. Knowledge of the primary source and critical path allows one to select the proper and optimal noise control treatments.

Table 3: Noise levels in the compartments – 2 cavitating bow thrusters in operation

Compartment	Calculated, dB(A)	Measured, dB(A)
Engine Room	108	109
Mess/Galley	87	87
Berth on the Main Deck	83	82
Berth on the 01 Level	75	75

DESIGN GUIDANCE

The following rules of thumb should be followed with respect to the location and design of tunnel thrusters.

- The centerline of the tunnel should be a minimum of one duct diameter above the baseline
- The centerline of the tunnel should be a minimum of one duct diameter below the lightest water line
- The minimum axial distance from the lower opening edge to the impeller is one duct diameter
- The minimum length of the tunnel at centerline is two duct diameters or there is potential for turbulent flow, which also reduces thrust
- The hull should be dished downstream of the tunnel opening. The major axis of the dish should be approximately 15 degrees below the horizontal (or follow flow lines) and the angle from the tunnel opening to the edge of the undished hull should not exceed 15 degrees (see Figure 9).
- The radius of the inlet along the hull interface should be 0.05 times the duct diameter
- The grill should follow the water streamlines, typically 15 to 20 degrees off the horizontal.
- The grills themselves should not be flat bar but aerodynamically shaped with rounded leading edges. Grills should take up as little free area as possible. Maximum opening blockage should be 10% to 15%.
- The axial spacing between the grill and impeller edge should be a minimum of 0.3 times the duct diameter from the impeller.
- Struts holding the impeller should be faired as much as possible to reduce turbulence, especially when thrusting in a direct where the flow hits the struts before the impeller
- Reduce strut cross sectional area as much as possible.
- Place generous fillets between strut and tunnel wall to reduce voritces.
- For twin tunnel thrusters, distance between centerlines should be 1.5 duct diameters to 2 diameters for Fixed Pitch Impellers (FP); distance should be a small as possible for Controllable Pitch Impellers (CP)

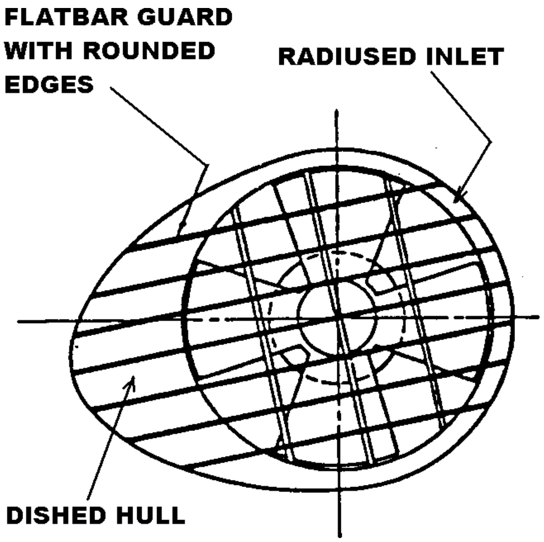
Impeller

- Increased impeller pitch may produce the same thrust but at a lower rotation rate, which is equivalent to a lower tip speed.
- Impeller tip speed should be less than 100 fps.
- A skewed impeller shape has significantly better low frequency performance than one with a radial trailing edge. Skew for "reverse" thrust since this should not harm "ahead" thrust; requires careful hydroacoustic design. For side-by-side tunnels, the skew could be in opposite directions.
- Consider trade-off between increased tip clearance, which reduces unsteady load at tips that operate in the strut wake, and affect on tip vortex cavitation and thrust performance.
- Adjust blade pitch distribution to unload tip.
- Consider odd number of blades, which are susceptible to lower amplitude wake harmonics, therefore generate lower forces.
- Impeller should have symmetrical blade sections and well rounded edges for equal performance in either direction.

ABATEMENT TECHNIQUES

The best noise control approach is to attack the noise at the source. The source in this case is the impeller. Obviously the best condition is a non-cavitating impeller over the entire operating range. This is seldom achieved. The next best approach is to delay cavitation inception to as high an operating power as possible. Since thrusters are not often operated at full power, but rather at partial power, this approach can definitely improve the acoustic conditions onboard. Often, improvements that delay cavitation inception also improve the thrust developed by the system. The best method to delay cavitation inception is to improve the inflow conditions to provide a uniform inflow into the impeller disc. These methods

Figure 9: Grill Alignment [15]



were described in the preceding section. As discussed previously, once the impeller cavitates, its noise level is proportional to the ratio of cavitating area to the impeller disc area. In this sense all bow thrusters are equally bad actors.

Low noise impeller designs exist. These typically make use of skewed blades. In some cases, skewing the blade forward may relieve the tip overloading and provide a more uniform loading over the entire blade. The next best non-engineering approach is not to place berths or noise sensitive compartment within one deck or two compartment longitudinally of the thruster room. Place storage or refrigeration lockers in this area.

SOURCE TREATMENTS

Some thruster vendors are aware of the adverse impact of their system on the vessel and crew. These vendors have carefully considered the hydro-acoustic design or provided built-in acoustic controls. One example is a tunnel thruster that is installed as a double skin tunnel with resilient attachment between the two skins. Studies done by Andresen and Nilsson [6] show that an isolation-mounted tunnel with air in the cavity between the two shells can reduce the vibration onboard the vessel. The percentage of air in the cavity is a controlling factor in the performance of this type of treatment. Furthermore, to achieve a high level of vibration reduction, the entire tunnel over its entire length must be resiliently supported. Other vendors claim only an 8 dB reduction in the A-weighted noise for a double wall tunnel with isolators. The cost of these special units needs to be considered against the cost and risk associated with the design and installation of the treatments described in the following sections. Vendors should be able to justify their noise reduction claim with measured noise and vibration data.

Other vendors will supply air injection systems with their thruster. These Prairie type masker systems decouple the wall from the high hydro-dynamic noise induced by the impeller. The air can be injected near the tunnel inlet or near the impeller. This generally takes the form of perforated air emitter pipes located on the perimeter of the duct. This air would be pulled into the thruster, mix with the cavitation, resulting in a gaseous cavitation-ventilation mixture. This mixture would cushion the bubble collapse and thereby reduce the induced vibration and structureborne noise. The additional air would also provide some absorption in the tunnel.

These air systems have provided significant interior noise and underwater noise reductions. Measured noise reduction on one system is 10 dB in the frequency range above 500 Hz. However, these systems also tend to increase the low frequency noise in the range below 100 Hz. This is generally acceptable since the ear is less sensitive at these low frequencies. For instance, a person's perception of a noise level of 92 dB at 80 Hz is the same as a level of 70 dB at 1000 Hz. The amount of reduction achieved by air injection is limited by the potential for other flanking paths for the hydro-acoustic induced noise.

Passive treatments can be employed to reduce the thruster induced noise and vibration. Selection of the optimum approach depends on many non-acoustic factors such as available space, weight constraints, cost and impact on the ship operation. In addition to “source” treatments, two other types are generally classified as treatment of the acoustic path and treatment of the receiver space. Source treatments are those directed at the hydro-acoustic environment. Active noise or vibration cancellation treatments are not yet a proven abatement approach.

PATH TREATMENTS

Only one type of path treatment is generally considered - damping. Noise is carried to adjacent compartments primarily over the structureborne path. Though the airborne noise level in the bow thruster compartment itself is usually on the order of 100 dB(A) or greater, receiver spaces are rarely adjacent to the thruster compartment. Thus, airborne transmitted noise is usually not a concern. However, if there is a receiver space with a common interface to the thruster room, this interface should be treated with a high transmission loss material, e.g., a limp mass-loaded material sandwiched between compliant layers such as fiberglass.

Damping treatments generally consist of visco-elastic tile material attached to hull plating between the frames. These tiles convert the structureborne energy to heat via a shearing process thereby attenuating the propagation of structureborne energy to the receiver. The effectiveness of this type of treatment depends on the total path length. Damping treatments are typically most effective over the mid- to high-frequencies, the same range over which the source levels are highest. Given the proper amount of damping treatment - that is sufficient path length to the receiver and treatment of all potential structureborne paths by a well designed damping treatment - the received A-weighted noise level may be reduced by 5 to 7 dB, at best. Constrained[9] damping has the potential of reducing noise by 8 to 12 dB, but at a significant weight penalty. Damping on the tunnel wall itself is usually ineffective. This is due to the high inherent impedance of the curved tunnel and its high inherent damping through water loading and the multiple hull connections.

RECEIVER TREATMENTS

"Floating" cabins can be used to mitigate noise in compartments located near a bow or stern thruster. A floating room has finish surfaces connected to the hull though resilient mounts. The gap or void between false deck and structural bulkheads is partly filled with thermal and/or acoustical insulation. This type of treatment attenuates both high structureborne sound and airborne sound. Properly designed and installed, this type of treatment should provide a minimum of 7 dB reduction in the A-weighted noise to a maximum of 20 dB. The most critical parameter in this system is the height of the gap between this deck and the structural deck. The void or gap between the structural and false deck should be between 50 and 100 mm depending on the desired noise reduction. A 100mm gap provides an effective treatment for low frequency noise (which is not usually a problem for bow-thruster induced noise) [17,18].

Damping in the form of special tiles or a resilient underlayment covered by a poured floor can reduce the noise in the receiver compartment by 3 to at most 5 dB. If the deck is not the primary noise radiator, "cladding" treatments can be added to the interior of the bulkheads that control the received noise level.

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[9] Constrained layer damping has a cover plate, nominally the thickness of the bottom plate, on top of the damping material to provide additional shearing.

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These cladding treatments consist of two layers of a compliant material, typically 50 mm thick 50 kg/m^3 density fiberglass, with an intermediate limp mass layer with a surface density of 5 kg/m^2.

CONCLUSION

Habitability noise, radiated noise, and vibrations induced by thrusters can be controlled to acceptable levels. This requires careful consideration of the thruster type and design, thruster location, and location of sensitive receivers - either internal compartments or external sensors. These factors should be considered early in the vessel design to minimize the need for add-on treatments. Initial noise estimates can be made and effective treatments exist to abate thruster induced noise. These typically will adversely impact space, weight and cost. Reservations should be made for these impacts should the thruster induced noise be excessive. Otherwise the crew may be subject to excessive noise and annoyance, the ship subject to excessive and potentially destructive vibration, and dynamic positioning systems subject to dropped signals.

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