The Increasing Noise Level in the Sea – a Challenge for Ship Technology?

Paper presented at the 104th Congress of the German Society for Maritime Technology, 2009

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Summary. The low frequencies of background noise in the sea which are also used by large whales for communication are completely dominated by sea-borne traffic. The number, size and speed of ships increase continuously and lead to ever increasing noise levels. Most important noise sources are cavitating propellers and medium speed diesel engines. Medium speed propulsion engines with controllable pitch propellers present particularly complex conditions. First descriptions of underwater radiated noise of merchant ships already helped to understand some of the basic parameters but there is considerably need for research on how to effectively silence ships without too many negative consequences for economic ship operation. Underwater noise due to shipping became an issue in the IMO in October 2008.

1 Introduction

The underwater noise spectrum in the oceans of the northern hemisphere is dominated by shipping noise in important frequency ranges. In the frequency range from 10 to 300 Hz the natural background noise level is raised by 20 to 30 dB due to shipping. In the last 30 years alone the increase amounts to 10 dB. This particular frequency range is used by baleen whales, mainly for communication. With the increase of shipping noise the communication ranges of these animals quickly becomes shorter. Marine biologists claim that this possibly reduces their ability to survive.

Baleen whales are a suborder of the order whales with about 11 species. Their original numbers are reduced to 1 to 10% particularly by commercial whaling in the 1920s to 1960s.

Since banning of whaling the various species and populations have recovered more or less, but in some cases not at all.

There are indications that acoustics represent one of the environmental hazards for marine mammals. Relevance for survival of the animals is difficult to predict.

In the meeting of MEPC 58 of the IMO a Correspondence Group „Noise from Commercial Shipping and its Adverse Impacts on Marine Life“ has been established. Germany is one of its contributors.

In the following results from own investigations into radiated noise of ships will be reported. Emphasis is on low frequencies above 10 Hz.

The investigations dealt with the following questions:

1. What is the influence of sound propagation in radiated noise?
2. How does the type of ship and her operational condition influence absolute levels?
3. Which noise source onboard a ship dominates which frequency range?
4. What could be done to find first indications how to reduce global shipping noise?

2 What causes the noise level in the sea?

Noise propagation in water is much more effective than in gases, particularly because damping is lower. At low frequencies noise can be received over thousands of kilometers. As light only propagates over short ranges marine animals use acoustic signals to interact with their environment. In this way they communicate and detect obstacles and prey.

Without the presence of biological or manmade noise, continuous noise in the sea is dominated by wind and waves. Short time noise results from precipitation and seismic events like earthquakes. In arctic regions there are contributions from ice movement.

Natural background noise has a characteristic spectral shape denoted by severeness of sea states. Figure 1 shows minimum, maximum and average background noise levels, the frequency band in which baleen whales communicate and the spectral contribution of shipping noise which came about during the last 150 years.

It appears that level bandwidth is small with just 50 dB between the quietest and the noisiest condition. For comparison: human hearing ranges from hearing threshold to damage threshold which is 120 dB. In the average, natural noise in the sea is just below seastate 4, and the highest level are less likely to occur.

Since the appearance of the mechanically propelled ships noise from propulsion and machinery adds to ocean noise. Because of the good propagation conditions especially at low frequencies this leads to domination of shipping noise below 300 Hz for most of the time. The level maximum lies around 50 Hz. Shipping noise as natural noise is categorized by standard spectra which describe light, medium and heavy shipping. These spectra are to be understood as the sum of noise from all distant ships (beyond the horizon).

According to measurements in the US [1], [2] shipping noise levels have increased by 10 dB from the 1960s to 1990s, i.e. an increase of 3 dB per decade.

Damaging effects on marine mammals could be shown in connection with employment of naval active sonar. Airguns for seismic exploration are under suspicion to also have damaging effects. The use of both sources can be controlled and occasionally has been limited by legal means.

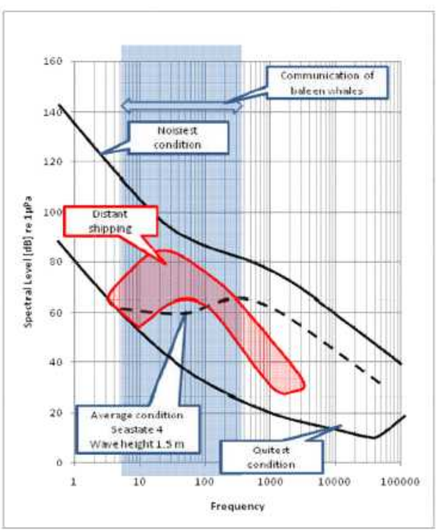

Fig. 1. Background noise in the sea with contribution from distant shipping

3 What is the cause of shipping noise?

Ship acoustics mainly deals with ships with already have particular requirements in this field. Every ship must meet certain requirements to ensure safety, health and comfort at sea. For cruise liners, yachts and naval and research vessels these requirements are particularly high. For naval ships and research vessel there are additional requirements for underwater radiated noise. This should ensure small detection ranges and minimum interference with acoustic sensors.

Unfortunately, experience from e.g. naval ship building can hardly be transferred to normal commercial ships. The reason is that naval ships and also research vessels have to meet acoustic goals at small speed and have different propulsion systems. A large containership at 25 knots, a tanker at 16 knots or a RoRo vessel at 20 knots with a single propeller cannot be compared to a frigate at 16 knots.

Qualitatively, noise sources can be identified by measurements on board and by the very few measurements at sea. These are:

Propeller:

1. The propeller can easily be identified in onobard and radiated noise measurements by its harmonics of blade rate (revolutions times number of blades). They are caused by pressure pulses due to each blade passing to an inhomogeneous wake field. Physics are described in some detail, therefore predictions are relatively precise.
2. In many (but not all) measurements a broad band level maximum at around 40 to 60 Hz is observed. The reason is also cavitation but the exact mechanism is not known. A prediction of levels may be possible. Mitigation measures are not described. Investigations on single ships, also in cavitation tunnels sometimes reveal a level maximum at around 50 Hz.
3. Controllable pitch propellers which do not operate at design pitch show a very complex acoustic behavior. In particular, ships with a power take-off (shaft speed is independent from ship speed, speed control is only by pitch adjustment) tend to increasing noise levels with decreasing speed.
4. At service speed, the propeller dominates the frequency range up to 100 Hz and sometimes also at high frequencies depending on the severeness of cavitation. At unfavorable conditions, cavitation can dominate the whole spectrum as for example for a ship in ballast at high speed.

Machinery:

1. In modern ships the contribution from medium speed diesel engines are apparent. Such an engine for propulsion can dominate the spectrum from 100 Hz on depending on the contribution of the propeller.
2. Also in ships which are propelled by a low speed engine auxiliary diesels may be dominant. They are identifiable by their characteristic narrow band frequency pattern typical for 4-stroke diesels at 600, 720 and 900 rpm.

Additional information on the state of knowledge is:

Underwater radiated noise of merchant ships is not considered during design. Criteria for on board vibration concentrate on contribution at propeller blade rate harmonics.

There are only a few publications on noise contributions of propellers, which cover the whole frequency spectrum. In many cases the low frequency end is not part of considerations.

The few remaining publications in almost all cases lack information on the operating states of the ship or ships in question. More exact indications for classifying noise sources like source levels, structure-borne noise levels at the hull, quality of the wake field, propeller design, are completely missing. Considerations are made almost exclusively for older ships.

Two publications [3], [4] compare measurements in a cavitation tunnel with measurements in full scale for the pressure at the hull above the propeller.

Another complexity is the difficulty in measuring merchant ships at sea under varying distances and environmental conditions. Special considerations have to be taken into account at frequencies below about 100 Hz, as a consequence of the short distance between the source and the hydrophone to the water surface. There is no standard for this kind of measurement.

[5] is an example for modern measurements of passing ships which cover the full frequency range.

The only comprehensive measurement of a single ship is described in [6], figure 2.

The reason for the level below 300 Hz and the maximum at around 50 Hz are broad band contributions from propeller cavitation. They are considered as a consequence for stochastic parts of otherwise periodic cavitation [7] or in the behavior of the cavitating tip vortices [8]. Opinions vary, and there is no relation shown to the geometry of the propeller.

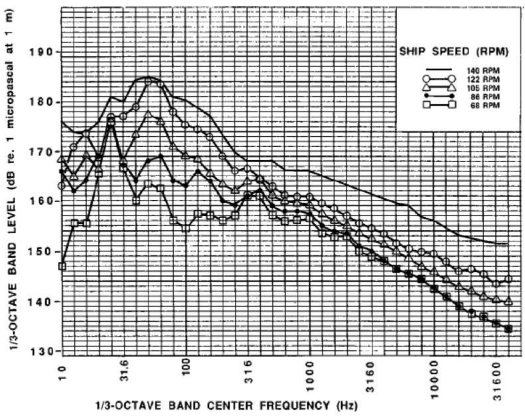

Fig. 2. Measurement of underwater radiated noise for a small bulkcarrier in ballast from [6]. With increasing speed a maximum at around 50 Hz develops.

4 Influence of range

Traditionally, naval and research vessels undergo radiated noise measurements in specially designed acoustic ranges under uniform conditions. Measuring range and hydrophone depth are always the same. Results are then converted to a standard distance of 1 m by assuming spherical spreading, which is

$$L_{1m}[dB] = L_{received} + 20 \cdot \log\left(\frac{Measuring\,range[m]}{1[m]}\right)$$

For a typical measuring range of 100 m, 40 dB have to be added to measured level. By definition this calculations yields the source level at the reference distance of 1 m.

This is justified, if conditions are always the same and comparability is ensured.

If measurements are made at variable distances, the true source level must be found to compare measurements made at the respective distances. For this, it must be taken into considerations that there is not only a propagation path from the source to the hydrophone but also one which is reflected at the surface. As air is “soft” compared to water, this reflection goes along with a phase shift of 180°. The superposition of the two propagations paths lead to a noise radiating behavior which is best described by a dipole radiator for low frequencies. At higher frequencies an interference pattern is observed. For details see [9] or other textbooks. For a typical geometry the propagation loss is described in figure 3.

For this particular geometry the actual propagation loss increases with decreasing frequency below 300 Hz. It is 30 dB higher at 10 Hz compared to spherical spreading. Above 300 Hz the said interference pattern is observed where values fluctuate around constant spherical spreading (54 dB).

In waves the surface of the sea does not represent a flat mirror. Following the relationship of acoustic wave lengths and surface wave lengths the reflected part of radiated noise may be scattered or undergo reflection in different directions. It has to be expected that propagation loss may deviated from what is shown in figure 3.

If measuring distance is even larger so that reflections at the bottom have to be taken into account the received level may also be dependent on the acoustic properties of the bottom. E.g. for reflective bottoms, like rock, at long distances cylindrical spreading would be observed.

For very large distances, sound waves propagate in channels as a result of layers in the sea. Propagation would also follow cylindrical spreading resulting in a level reduction of 3 dB per doubling of distance.

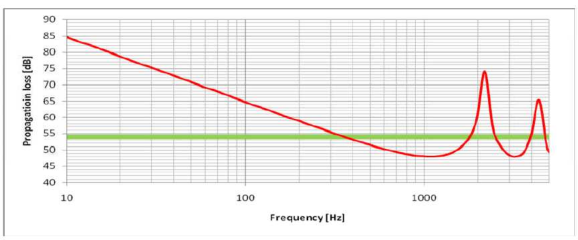

Fig. 3. Propagation loss for a point source 5 m below surface, calculated for a receiver 35 m below surface at 500 m distance (red) compared to spherical propagation (blue)

5 Noise measurements in the English Channel

To gain a first impression of underwater radiated noise of merchant ships, passing ships have been measured in the English Channel in 2007. Frequency range was 10 to 2,500 Hz, frequency bandwidth was about 1 Hz. The hydrophone was deployed from a small boat and was suspended at a depth of 15 to 20 m. Water depth was 70 to 80 m. Bottom was rock with a layer of gravel with several meters thickness.

The characteristics of a high pass filter was removed from the recorded levels in post processing. During the pass the respective vessel was hailed and speed and shaft rate be enquired. With an assumed blade number of the propeller and the blade rate harmonics in the spectrum it was verified that the passing ships was recorded and not a noisier, more distant one. Distance was estimated by using the navigation radar.

Results were recalculated to unit distance. For up to 25 Hz cylindrical spreading and above 250 Hz spherical spreading was assumed taking account of the increasing absortiveness of the bottom with frequency. Between 25 and 250 Hz an empirical transition was estimated.

A typical example for the noise level of a containership is shown in figure 4. The high levels at low frequencies are understood as a consequence of the propagation characteristics described above. Blade rate harmonics can easily be identified. Above about 100 Hz the characteristic signature of a 4-stroke diesel engine with 600 rpm, the auxiliary diesels, can be seen. There is a gap where levels cannot easily be attributed to a source due to lack of identifying features. They could be broad band contributions from cavitation or the main engine.

In figure 5, 4 different types of ships in their actual operating conditions are displayed, in third octaves for simplicity. Levels are converted to 1 m distance. Characteristics of the ships are:

- A 5000 TEU containership built in 2004 at full speed (24 knots) and close to design draft. Measuring range was 0.4 nm. The ship is only noisy at blade rate frequencies.
- A bulkcarrier of 1984 with 18,300 GT at full speed (14 knots) in ballast. Measuring range was 0.2 nm. The ship is quiet in the frequency range of blade rate harmonics but very noisy above this range. Narrow band analysis did not yield a characteristic signature. There is a pronounced maximum at 50 Hz.
- A multipurpose vessel of 1995 with 4,000 GT at full speed (abt. 13 knots) at a measuring distance of 0.5 nm. The ship is very noisy at blade rate harmonics but partly quiet in higher frequencies. Narrow band analysis revealed a frequency pattern associated with a 4-stroke diesel engine of around 550 rpm, i.e. the main engine of the vessel.
- A tanker of 1993, fully laden, at 1.5 knots and measured at a distance of 0.2 nm. Only the lowest 2 blade rate harmonics are identifiable. In all other frequencies there is no particular narrow band signature.

In total, measurements of 18 ships have been evaluated. The following can be summarized for different types of ships:

- All containerships have high levels at blade rate harmonics. Above 100 to 150 Hz auxiliary diesels can be identified. The levels for all ships measured are similar over the whole frequency range.
- Tankers and bulkcarriers in ballast have comparatively low levels at blade rate harmonics, above that they are among the noisiest ships. Only with these ships a strong 50 Hz maximum could be observed.
- Smaller ships propelled by medium speed engines have very different levels. Some are also very noisy.
- Correlation with ship size is low. For a ship with a fixed pitch propeller levels dominated by the propeller reduce with speed. But a small general cargo ship can be noisier than a containership 20 times the size and twice the speed.
- Scatter of levels between different ships at similar measuring ranges is around 20 dB sometimes even 30 dB.
- An influence of the age of a ship could not be determined.

To demonstrate the influence of the measuring geometry and the boundaries, received levels of a containership in the channel are converted to open water. The result is shown in figure 6. At low frequencies in shallow water with a reflecting bottom much higher levels are measured than could be expected in deep water. The difference increases with increasing distance.

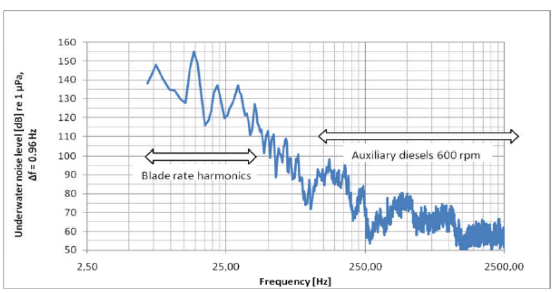

Fig. 4: 7500 TEU Containership at 75 rpm measured at a range of 0.6 nautical miles

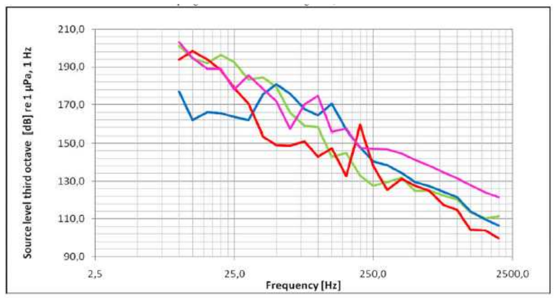

Fig. 5. Source levels for four ships measured at short distance:

Red: Multipurpose cargo ship, built 1995, 3,999 GT, 13.4 kts, 130 rpm

Blue: Bulk Carrier, built 1984, 18,259 GT, 14 kts, 110 rpm, Ballast

Green: Containership built 2003, 5,048 TEU, 24 kts, 100 rpm

Magenta: Tanker, built 1993, 93,891 dwt, 12.5 kts, 71 rpm, full draught

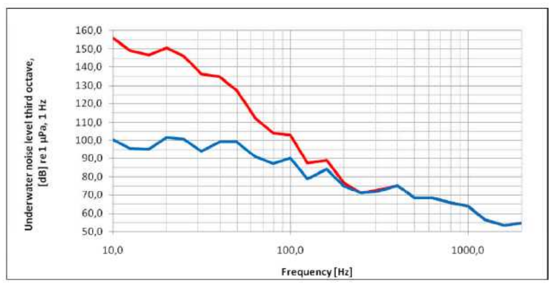

Fig. 6. Received level of a containerships at a distance of 950 m and 70 m water depth (red line). The same ship, how it would be measured in deep water at the same distance (blue line). It was assumed that noise sources are at 5 m depth and the receiving hydrophone at 20 m depth.

6 Measurements on a containership

During sea trials of a 3400 TEU containership building number 558 of Blohm + Voss Nordseewerke (BVN) structure-borne noise measurements were performed in the vicinity of propeller, main engine and auxiliary diesels. Measurements should allow estimation of relative contributions to under water radiated noise.

On behalf of BVN, Germanischer Lloyd had pressure pickups installed in the hull above the propeller in the first of class ship. Results from these measurements could be included in consideration of structure-borne noise.

Figure 7 show pressure levels above the propeller measured at two different shaft speeds but very similar power. During operation close to design draft levels are up to 12 dB lower (equivalent to one quarter in absolute pressure amplitude) at blade rate harmonics. The broad band contribution observed between the harmonics shows a flat maximum at 40 to 50 Hz.

Figure 8 depicts the structure-borne noise level above the propeller. Figure 9 is the level in vicinity of the main engine and the auxiliary diesels expressed in third octaves.

These diagrams and the narrow band results not displayed here show the following:

- In the pressure spectrum at the hull blade rate can be identified up to the 8th harmonic.
- The spectra develop a wide maximum centered at around 50 Hz, which is not obvious in the structure-borne noise readings. In general, structure-borne noise on the hull does not allow inference on noise in the water.
- Lower blade rate harmonics dominate the structure-borne noise spectrum also in the vicinity of machinery
- The main engine has no characteristic spectrum like a 4-stroke engine has. Even the ignition frequency (number of revolution times number of cylinders, 8 for this engine) does not leave a clear mark.
- Main engine has significantly higher levels than the auxiliary diesels below 150 Hz, above that it slightly less nosy
- Main engine becomes less noisy by about the expected 6 dB only below 150 Hz when reducing speed from 108 rpm to 70 rpm. It is not clear why levels do not reduce at higher frequencies but instead remain constant.

The main engine excites a larger area of the hull than the auxiliary diesels due to its size and weight. Therefore it could be expected that its contribution to radiated noise is larger. This is, however, in contradiction to the observations in the English Channel, where only auxiliary diesels could be identified in the spectrum of containerships. In any case, auxiliary diesels could be integrated acoustically in a better way than done today without problems. Improvements for the then dominant main engine are, on the other side, very difficult. There is no practical solution today to acoustically isolate a noise source of 945 tons, which is the mass of the engine of this ship.

For a big block ship with the same type of propulsion system it can be expected that machinery noise does not contribute more significantly than in a containership. Rather, the less optimal working conditions of the propeller lead to higher contributions, particularly when looking at operation in ballast.

Figure 10 tries to compare results from containership trials with observations of containerships at sea.

To do this, certain assumptions have to be made. It is assumed that the noise level of the propeller measured at the hulls represents free field noise levels. This is certainly not too accurate, but if the source can be considered a point source, the level cannot be significantly overestimated. For machinery radiation efficiency and radiating area must be assumed, both carry uncertainties. Comparison with measurement results form a containership still leads to plausible results. Even accounting for all uncertainties it can be safely inferred that in this operating condition the noise level from the propeller far outweighs the contribution from machinery. Above this range, machinery contributions become more and more important. The practical consequence is that reduction of propeller noise will render the ship quieter to the amount propeller noise is reduced until machinery noise prevails. However, propeller noise will dominate also if speed is considerably reduced.

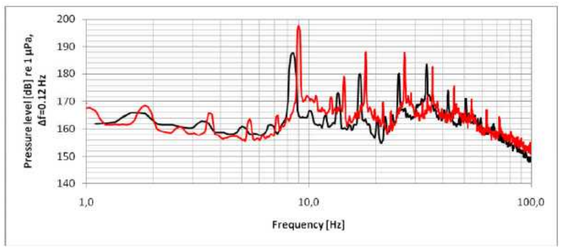

Fig. 7. Pressure level at hull above propeller at 108 rpm at trial draft (red) and 101 rpm close to design draft (black)

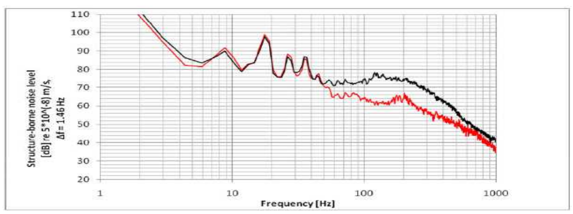

Fig. 8. Structure-borne noise above propeller at 108 rpm. Black: Level in the bay between frames. Red: Levels at stiff girders

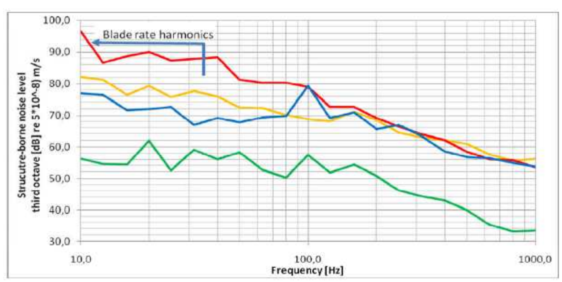

Fig. 9. Average structure-borne noise level at the hull close to engine:

Red	Main engine at 108 rpm
Orange	Main engine at 70 rpm
Green	Main engine stop, background noise
Blue	Two auxiliary diesels at 720 rpm, 20% full power

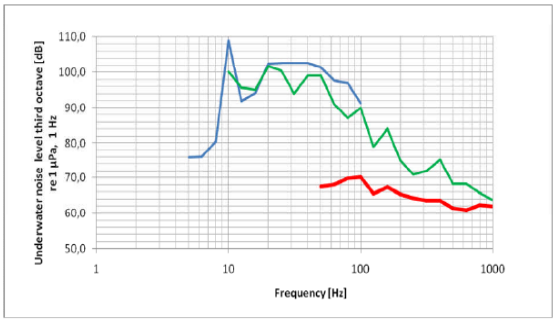

Fig. 10. Predicted level of BVN containerschip at 108 rpm at 1000, distance. Source depth assumed 2.5 m, hydrophone depth 35 m. Contribution of propeller (blue), contribution of main engine (red), measured level of containership as in figure 6 (green)

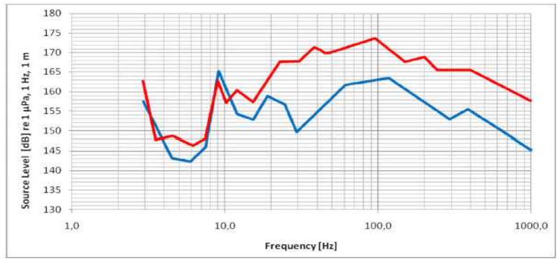

Fig 11. Research vessel Polarstern: Source level at 12 knots (blue) and 6 knots (red)

7 Ships with controllable pitch propellers

There is a special situation with ships with a controllable pitch propeller, particularly if they use a shaft generator. In this case shaft speed has to remain constant. Speed is adjusted only with propeller pitch. This leads to unfavorable hydrodynamic conditions at the blades with increasing deviation from design pitch leading to extended cavitation. Because of this, these ships could become noisier with decreasing speed.

With the German research vessel Polarstern test have been performed with respect to this question [10]. Polarstern has two controllable pitch propellers with adjustable shaft speed. They operate on a so-called combinator curve which relates shaft speed and propeller pitch to speed. This curve is determined such as to give most economical operation of the ship. Figure 11 shows the source level of Polarstern at two different speeds. At half the speed the ship is in parts more than 10 dB noisier.

In connection with other trials an acoustically optimum relation of shaft speed and pitch setting was tested. The result is shown in figure 12 for a different measuring geometry as in figure 11. Emphasis is on the level difference between the two conditions.

The level could be lowered by 10 dB with this measure. However, this is not to the advantage of the engine which now has to deliver a higher torque at lower speed.

For a propulsion system with constant shaft speed there are fewer options. Systematic investigations on speed dependence of underwater radiated noise of these ships with varying speed are not available

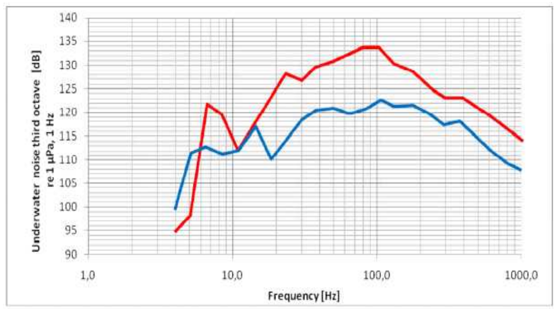

Fig. 12. Research vessel Polarstern: Difference in underwater radiated noise at 5 knots at the same range: Shaft speed 182 rpm, pitch 27% (red). Shaft speed 152 rpm, pitch 28% (blue). Diagram based on data of WTD 71 provided by Alfred Wegener Institut

8 Summary and Outlook

The following crucial investigations have to be performed to find a starting point for lowering global shipping noise levels, where emphasis is placed on the propeller.

- The basic physics of low frequency, broad band cavitation noise and the operation conditions of the propeller have to be clarified. Model testing technologies in cavitation tunnels and in full scale are available in general.
- Results must be supported by systematic measurements on ships in all operating conditions.
- Noisiest ships and their operating conditions should be identified as quickly as possible and the cause of their high noise levels be identified. This can be done by measurements on board, in the water with the ship passing and supported by model tests.

- The relative importance of other noise sources, namely diesel engines should further be investigated.
- A new standard for measurements of ships in the open sea must be created. It must reflect typical measurement geometries at least in deep water. Source levels of ships must be described in a way that they can serve as an input for all noise propagation calculations and as a base for comparison of underwater radiated noise spectra measured under different conditions.

There is still no scientific or technical basis for regulations or recommendations of mitigation measures for underwater noise radiation of merchant ships. All prerequisites for dedicated investigations of the matter are present in Germany.

9 Acknowledgements

The studies described here have been financed by okeanos foundation namely Dieter Paulmann, to whom I am particularly grateful. Participation in sea trials of building number 558 has been made possible by the building yard Blohm + Voss Nordseewerke, Emden. Germanischer Lloyd provided data for post processing in cooperation with BVN.

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