MEASUREMENTS OF NOISE FROM CAVITATING PROPELLERS

by

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Introduction.

Cavitation on marine propellers may be a considerable source of noise. Todays recommended standard on maximum allowable noise onboard ships and the more wide spread use of hydroacoustic navigation-, search- and positioning-systems, has initiated civil research on cavitation noise from propellers. The Ship Research Institute of Norway has a division engaged in cavitation testing of model propellers in order to predict and optimize the behaviour of the full scale propellers. A natural extent of this work is to measure and describe model cavitation noise in order to predict full scale noise. As a typical example of the problems involved, the noise measured on a scientific echosounder onboard a research vessel is shown in figure 1.

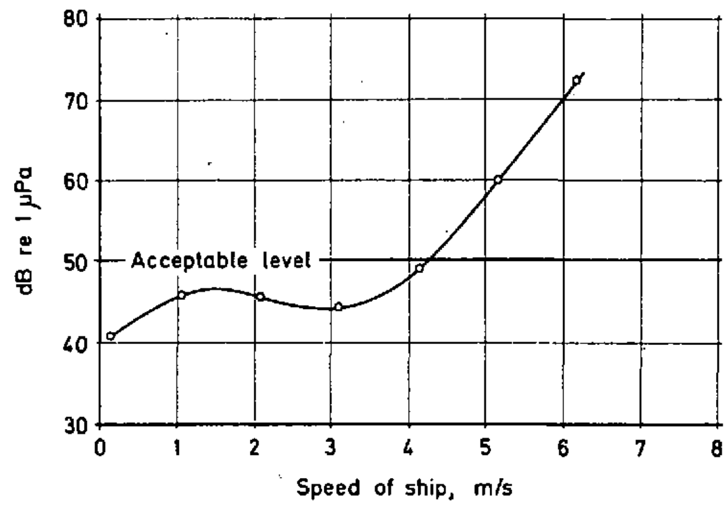

Figure 1 - High frequency noise measured on an echosounder.

The use of the echosounder is of prime importance to the operation of the ship, and we can see that the operation speed of the ship is limited to about 4 m/s, while the design speed was 6 m/s.
It was found by measurements that propeller cavitation was the dominating noise source at higher speeds of the ship.

Description of the noise spectrum.

At low Mach number, the acoustic monopole is the most efficient acoustic sound source. It is thus the changes in volume of the individual cavitation bubbles that accounts for the major part of the cavitation noise. For propellers operating behind a vessel, the bubbles generally pass through a pressure well where the pressure may drop below the vapour pressure. This gives a bubble growth to some maximum and then a rapid reduction of the volume. The pressure well generally has its minimum when a propeller blade passes through its top point.
The emitted noise from a bubble passing through this pressure well may be divided into two parts; figure 2 (ref. 1, 2, 3).

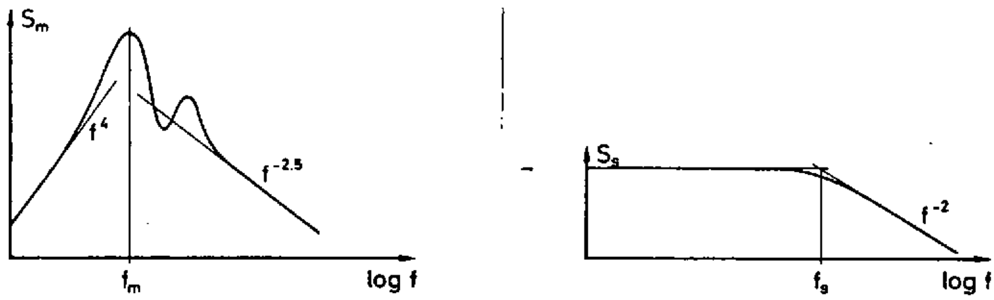

Figure 2 - Energy spectrum

a - Spectrum of monopole b - Spectrum of shock wave

The first part is given by the slow volume changes of the bubble (figure 2 a), described by linear acoustic theory, and called the monopole spectrum. The second part is given by the collapse of the bubble (figure 2 b), described by non-linear acoustic theory, and called the shock wave spectrum. This part of the spectrum may also be generated by finite amplitude wave propagation.

Measurements on marine propeller indicate that the monopole part will dominate the spectrum of low frequency.

Generally the cavitation zone appears as a cloud of bubbles of different size, collapsing at different times. Treating the cavitation as a random process, it can be argued that the resulting spectrum from a cavitation zone will resemble that of a single bubble (ref. 4, 5, 6).

If the cavitation is generated by a harmonic time varying pressure, the resulting spectrum may show peaks at frequencies equal to the driving frequency and its harmonics. A general noise spectrum from a wake operated propeller is then shown in figure 3.

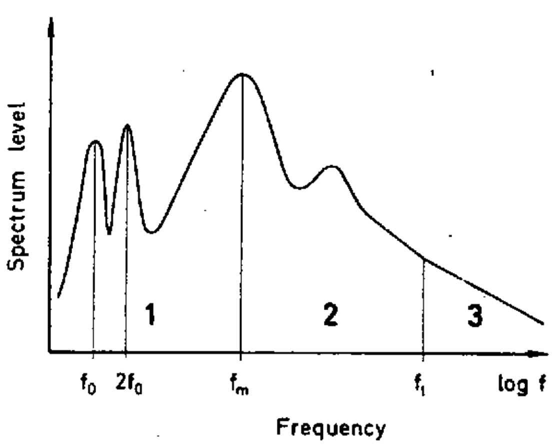

Figure 3 - General noise spectrum from a propeller f_0 is blade frequency = number of blades x revolution per sec.

The spectrum is divided into three parts:

Part one: Covering the lowest frequencies showing peaks at the blade frequency and its harmonics. The spectrum level raises as much as 40 dB per decade up to the fundamental frequency f_m which is equal to the resiprocal of bubble life time.

Part two: Starting from the fundamental frequency, has a level dropping in mean with approximately 25 dB per decade.

Part three: Starting from the transition frequency, f_t, is given by the shock wave and falling with 20 dB per decade.

The division of the spectrum into these three parts is interesting not only because they reflect different properties of the cavitation zone, but also because they can be related to different problems caused by cavitation. At the low frequencies of part 1, the pressure fluctuations on the steel-plating of the ship will be the dominant problem. The noise of part 2 covering the audible range of frequencies will certainly effect the comfort onboard, and part 3 is of main importance in the problem of cavitation erosion and acoustic interference with hydroacoustic instruments.

Cavitation testing and scaling.

The cavitation testing of the model propellers are performed in the largest of the cavitation tunnels at the Ship Research Institute of Norway.
In general, the testing is done so as the model and full scale propeller are operated at the same cavitation number:

$$\sigma \quad = \Delta p/\tfrac{1}{2}\rho V_A^{\,2} \qquad (1)$$

and the same advance number:

$$J \quad = V_A/nD \qquad (2)$$

where

V_A : speed of advance of the propeller
D : diameter of propeller
n : rate of revolution
Δp : ambient pressure minus vapour pressure
ρ : density of water

The propellers should further be of geometric identical shapes and operate in similar flows.
Within these constrains, the general cavitation spectrum may be scaled as follows:

The power spectrum G is scaled by (ref. 7):

$$\frac{G_F}{G_M} = \left(\frac{r_M}{r_F}\right)^2 \lambda^3 \frac{\Delta p_F}{\Delta p_M} \tag{3}$$

where:

- r : measuring distance
- λ : model scale, Full scale/Model
- F : index, Full scale
- M : index, Model

Eq (3) should be applied to shock waves when frequency tends to zero, and to the maximum point for the linear term of the noise spectrum.
The frequency can be scaled to a Strouhal number:

$$s = \frac{f}{nz} \tag{4}$$

where:

- z : number of blades
- f : frequency

which by the use of (1) and (2) gives:

$$\frac{f_m}{f_F} = \lambda \sqrt{\frac{\Delta p_M}{\Delta p_F}}$$

In general we measure a model or a full scale noise spectrum and want to convert it into the other one. This situation is indicated in figure 4.

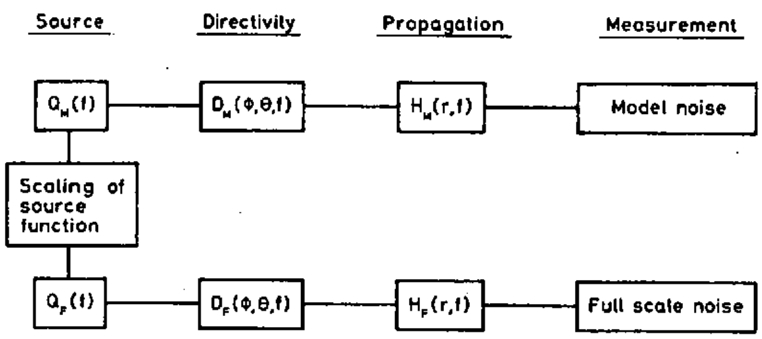

Figure 4 - Block diagram of the noise scaling.

We see that the source function is modified by the directivity of the source and by the propagation function describing the acoustic propagation from source to the measuring position. In order to apply eq (3) and (5) to the source function, we must in general know both the directivity and propagation function.
Scaling of cavitation noise measured in a cavitation tunnel to a full scale cavitation noise generated by a ship, involves besides the parameters menti-

oned several other factors as cavitation type, characteristics of the flow and qualities of the fluid. One parameter of prime interest is the content and size distribution of cavitation nuclei. Measurements of the nuclei distribution is done by measuring the acoustic attenuation as function of frequency. The set-up transmits acoustic CW pulses in the frequency range from 20 kHz to 250 kHz.

Experimental work.

The experimental work in model scale is done in the before mentioned cavitation tunnel.

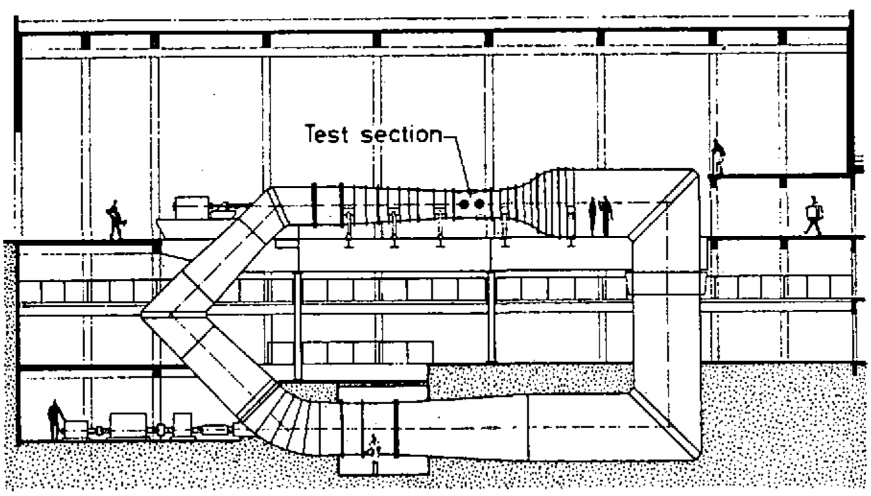

Figure 5 - General view of the cavitation tunnel.

Full scale measurements are performed at sea. The model is placed in the test section where the diameter of the tunnel is 1.2 meter.

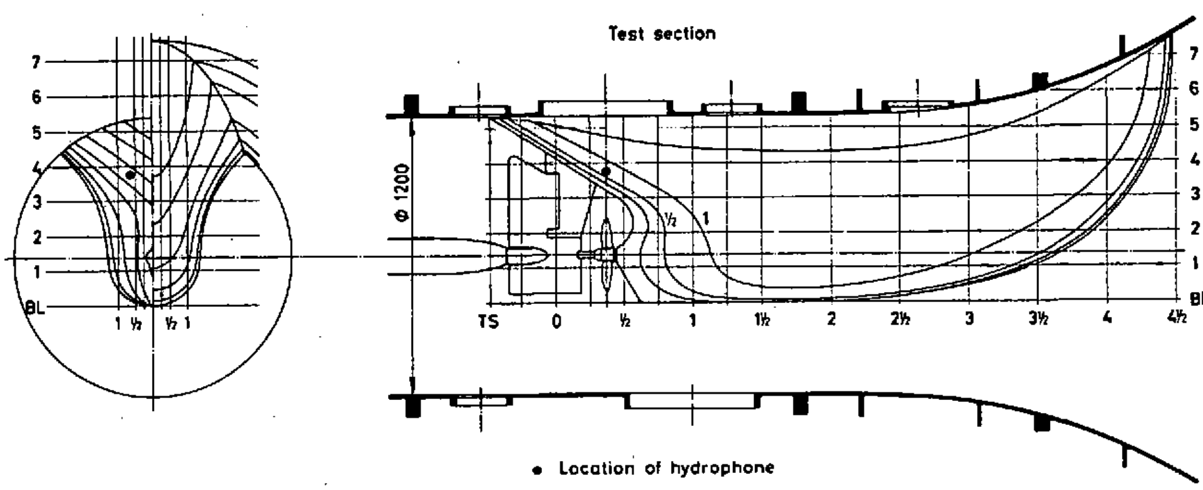

Figure 6 - Typical model arrangement in cavitation tunnel.

The propeller shaft is coming up from aft, and thus preventing mechanical vibrations to be excited. The hydrophone is mounted in the after ship model which is made of glassfibre reinforced polyester. The signal received by the hydrophone is analyzed in 1/3 octave band filters ranging from 20 Hz to 200 kHz.

Results.

Experiments are done to study the variation of the fundamental and transition frequency with ambient static pressure. Figure 7 shows typical curves.

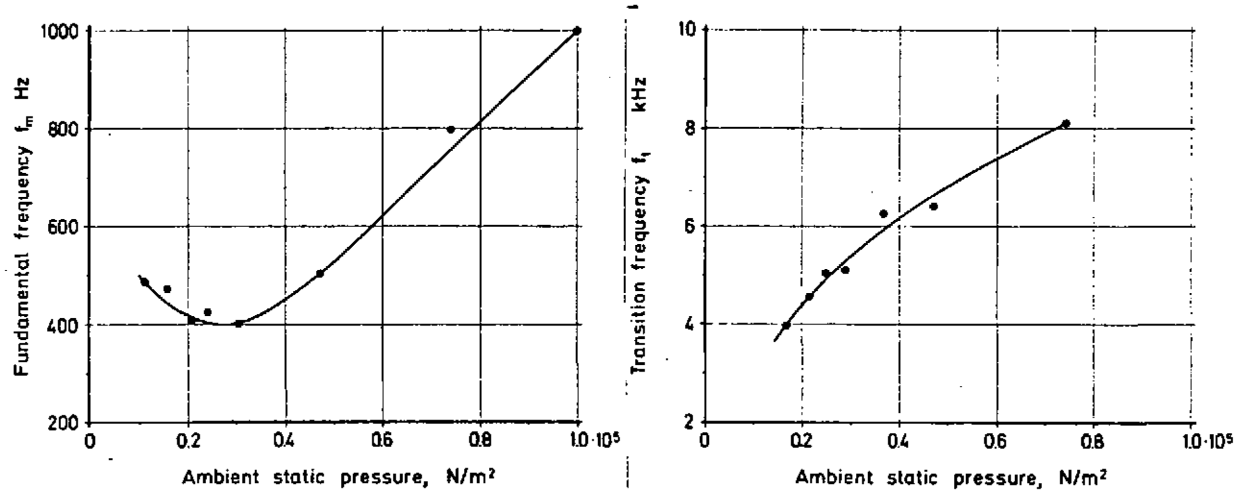

Figure 7 - a) Variation of fundamental frequency with ambient static pressure.

b) Variation of transition frequency with ambient static pressure.

The propeller of figure 7 is running with constant revolution per sec. As the pressure is lowered, both the fundamental and the transition frequency tends against lower frequencies. A drop in the ambient pressure gives bubbles growing to a larger radius which again gives a longer lifetime, or a lower fundamental frequency. The increase in fundamental frequency at very low static pressures is accompanied by an increase in bandwith. This may indicate that bubbles with different initial radius reach nearly the same maximum radius.

The sensitivity of the noise spectrum to changes in total gas content in the water is scarcely discussed. Much attention has been devoted to the influence of gas content on cavitation inception. We are, however, interested in fully developed cavitation. In figure 8 the spectrum level for three frequencies is shown as function of total gas content in water. The total free content was varying less than the total gas content.

From figure 8 we can see that the spectrum level in region 1 and 2 are rather insensitive to variations in total gas content. The spectrum level in region 3, however, changes drastically. The drop in pressure at low gas content may be related to the fewer number of free bubbles, while the drop at higher gas content may be a consequence of the bubbles containing more gas. This will reduce the maximum collapse pressure of the bubble, reducing the spectrum level in region 3 which is dominated by the shock wave.

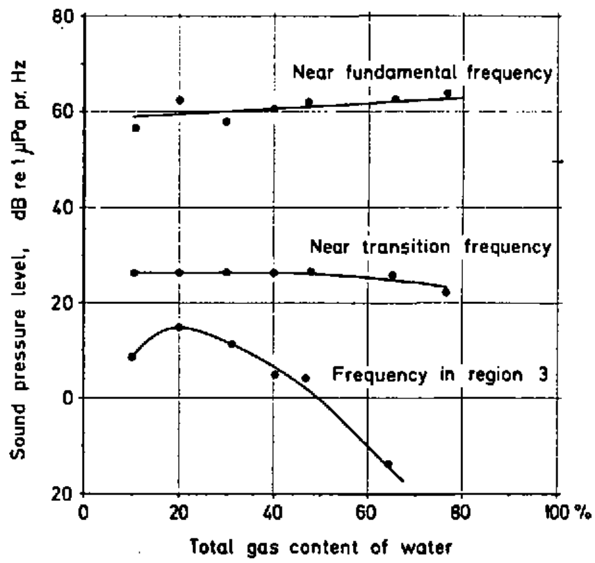

Figure 8 - Sound pressure as function of total gas content in the water.

Looking at the scaling laws eq. (3) and (5) we can see that running a propeller at one cavitation and advance number with varying waterspeeds gives:

$$\frac{G_1}{G_2} = \left(\frac{V_1}{V_2}\right)^2 \tag{6}$$

$$\frac{f_1}{f_2} = \frac{V_1}{V_2} \tag{7}$$

From eq. (6) and (7) we see that the frequency scaled spectrum level will be proportional to square of the water speed or the Reynolds number. In figure 9 the solid line gives a linear relationship between sound pressure and water speed. The mean measured pressure levels seem to fit this line very well. The mean is raken over frequencies from the blade frequency and up to transition frequency.

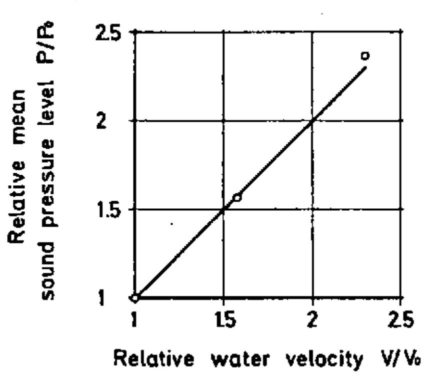

Figure 9 - Sound pressure as function of water velocity.

Returning to the noise measured on board the research vessel, shown in figure 1, work was undertaken to increase the usable crusing speed of the vessel. A model of the original propeller was tested in the cavitation tunnel, and on this basis a model redesigned propeller was made and tested. Later a similar vessel was built with the redesigned propeller. In figure 10 the model spectrum level in part three is plotted as function of relative advance coefficient for the original and redesigned propeller. The original propeller is working with heavy back side cavitation at its relative design advance number 1.

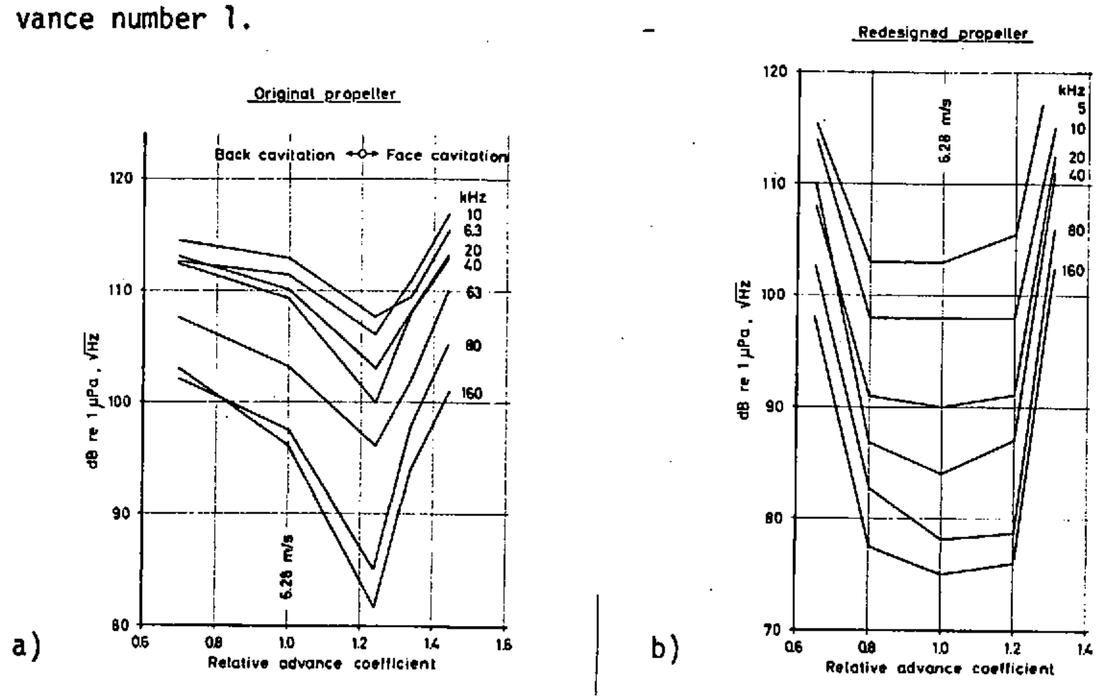

Figure 10 - Model spectrum level in part three as function of relative advance number. a) Original propeller. b) Redesigned propeller.

The minimum in spectrum level is sharp, so the propeller is very sensitive to variation in advance number. For the redesigned propeller, the cavitation has been moved closer to face side cavitation. The minimum noise level is reduced and the propeller is less sensitive to variations in advance number. This last feature is especially important for propellers with variable pitch.

Results from the model and full scale measurements are shown in figure 11, which shows the spectra of the original and redesigned propeller scaled to full size (ref. 1).

The model and full scale spectra agre within ± 3 - 5 dB except at frequencies around s = 20 - 30 and 80. The discrepancy at s = 20 - 30 is due to vortex induced sound by the wire screen used for the wake simulation in the cavitation tunnel.

In the high frequency range the obtained reduction in noise level is at least 20 dB.

Looking at the spectrum at 6.28 m/s, we can find the three parts of the spectrum to be

Part 1: s < 10 Part 2: 10 < s < 100 Part 3: s > 100

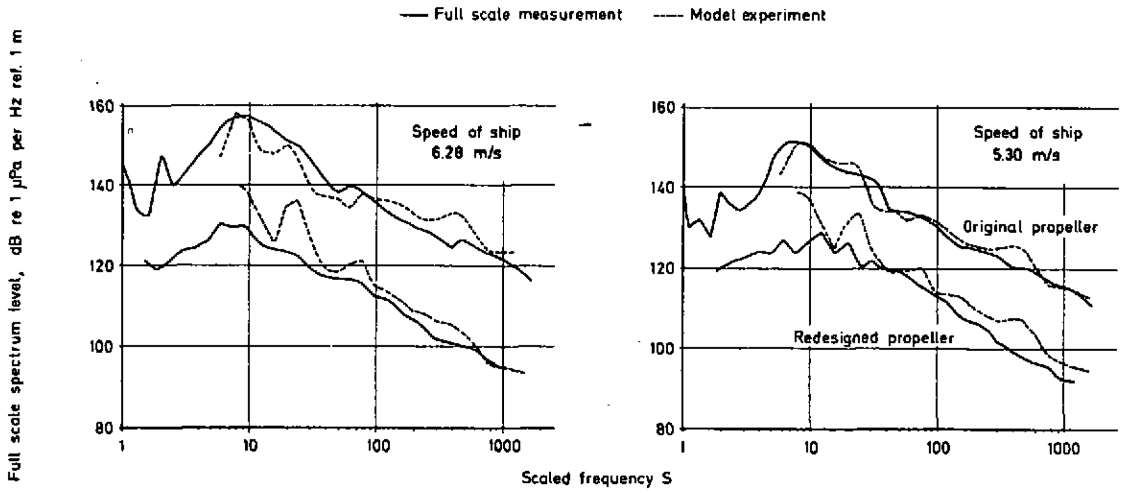

Figure 11 - Spectrum scaled to full size

The predicted and measured reduction in noise level was also confirmed by measurement of noise on the echosounder as shown in figure 12.

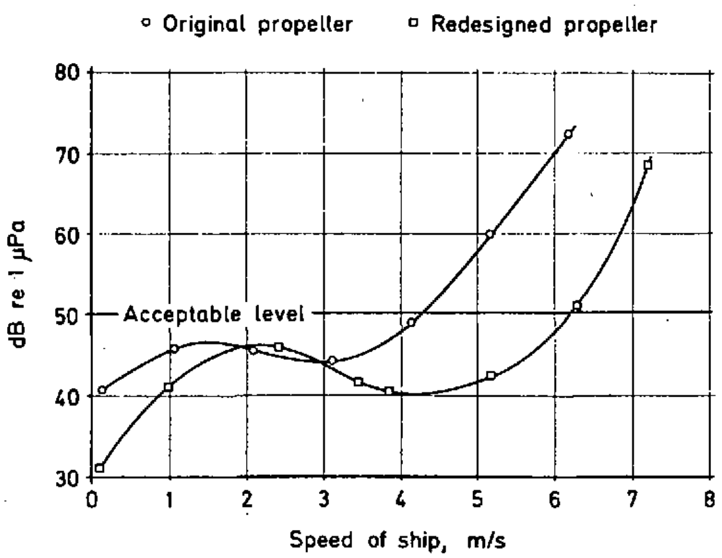

Figure 12 - Noise measured on an echosounder for vessels with the original and redesigned propeller, frequency in part 3.

Concluding remarks.

From the results of these experiments, we find that the model measurements of noise from cavitating propellers may be a useful tool in predicting full scale noise. The measured noise spectra for cavitating propellers has shown to agree with the general noise spectrum resulting from the basic sources of noise in the cavitation process.

We do also feel that the noise emitted from the cavitation zone, is valuable source of information on the cavitation process itself.

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