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Non-linear effects in a 200-kHz sound beam and the consequences for target-strength measurement

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When estimating target strength (TS), sound pressure in the beam where the target is located has to be measured accurately. Sound pressure is normally calculated from the source level, and transmission loss is based on geometric spreading and absorption loss. Additional losses caused by non-linear acoustic propagation may be important, especially in the case of high-power, high-frequency, and highly directive sources. 'Non-linear loss' from the fundamental frequency is due to energy from the fundamental harmonic being transferred into higher harmonics. This loss affects the beam pattern in ways that will depend on both power and range, since the non-linear loss depends, in turn, on sound pressure. We present the results of sound-pressure measurements and simulations from a 200-kHz transducer with a beam width of 7°. Sound pressure was measured at different ranges and power levels using a broadband hydrophone to detect some of the higher harmonic frequencies that occur in non-linear acoustic propagation. The TS of a solid copper sphere was measured using a standard echosounder with no correction for non-linear loss. Our study illustrates that this can be significant and that a corresponding correction needs to be considered when estimating TS.

Keywords: beam pattern, non-linear effects, sound beam, target strength.

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Introduction

Target-strength (TS) measurements are often performed to estimate fish abundance and size in acoustic surveys. The precision of TS measurements depends on several important parameters, one of which is the sound pressure in the beam where the target is located.

Traditional algorithms for calculating the sound-pressure level at different depths do not take account of 'non-linear losses'. These are caused by the non-linear propagation process, and can be important, especially for high-power, high-frequency, and highly directive sources. Losses from the fundamental frequency occur through energy being transferred into higher harmonics. These losses have been both measured and simulated for plane-circular pistons (Ryan *et al.*, 1962; Lockwood *et al.*, 1973; Shooter *et al.*, 1974; Baker and Humphrey, 1989, 1992). Additionally, the beam pattern of a conventional echosounder may be affected depending on the power setting and the range. However, prior to this study, non-linear effects have not been taken into account in traditional TS measurements, presumably because the magnitude of such effects has been assumed to be negligible.

In this article we present actual TS and sound-pressure field measurements as well as simulations for a 200-kHz transducer with a beam width of 7°. The results indicate that non-linear losses can be significant, and that to make accurate estimations of fish and plankton abundance and sizes, these losses must be taken into consideration.

Materials and methods

The measurements were performed in the freshwater test tank at SIMRAD A/S in Horten, Norway. Water temperature was around 18 °C in a tank measuring $6 \times 6 \times 15\,\mathrm{m}^3$ (breadth by depth by length). The experimental set-up for sound-pressure level measurements is shown in Figure 1. The measurements were performed using a SIMRAD scientific echosounder EK 60 with an ES 200-7C transducer as the source. The transducer has an effective radius $a = 34.5$ mm, a centre frequency $f_0 = 200$ kHz, and a wide

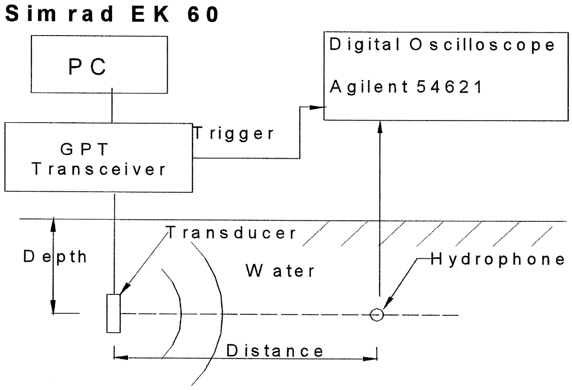


Figure 1. The experimental set-up.

bandwidth of almost 100 kHz. The transducer signals are weighted to reduce the side lobes. The near-field distance of this transducer is around 65 cm. The transducer was at 3-m depth during the measurements, so that echoes from the walls and surface would arrive much later than the direct echo, thus avoiding interference. A broadband 6128 ITC hydrophone was used to receive several of the higher harmonics generated in the water when transmitting a 200-kHz pulse. The hydrophone signal was sampled using an Agilent 54621A oscilloscope with a bandwidth of 60 MHz. This oscilloscope also directly provided the Fast Fourier Transform (FFT) of the measured signal.

For TS measurements, a standard copper sphere with diameter d = 13.7 mm and a TS of −45.0 dB was installed at the place where the hydrophone had been, and TS measurements were performed. The copper sphere was centred using the split-beam principle and by finding the maximum echo at the specific distance. The experiments were done with a horizontally-directed beam. In both the sound-pressure level and TS measurements, the power applied to the transducer and the distance from the transducer were varied.

The simulated results presented in this article were performed at Christian Michelsen Research (CMR) in Bergen, Norway, where the Khokhlov–Zabolotskaya–Kuznetsov (KZK) equation (Zabolotskaya and Khokhlov, 1969; Kuznetsov, 1970) was solved numerically with the Bergen code (Aanonsen *et al.*, 1984; Hamilton *et al.*, 1985; Berntsen, 1990). The KZK equation is a propagation model for sound waves in fluids, and includes effects such as diffraction and non-linearity. The propagation medium was assumed to be freshwater with density $\rho = 1027$ kg m^3; sound speed $c = 1500$ m s^{-1}; absorption loss $\alpha_0 = 25 \times 10^{-15}$ Np m^{-1} Hz^2 and non-linearity parameter B/A = 5.0 (relevant to pure water).

Results and discussion

The results from direct TS and sound-pressure level measurements for several power levels and range settings are presented. For the sound-pressure level measurements we also present comparison of the experimental and the simulated results.

TS measurements

Measurements of TS showed that the results obtained with the 200-kHz transducer were not constant. The TS depended on both the transmitted power and the target range (Figure 2). The transmitted-power levels were calculated from electrical measurements at the transducer terminals.

A possible explanation for these results is that non-linear losses can sometimes be of such magnitude that they should be corrected for. For the low sound pressure (56 W) we can see that TS decays only slightly with distance. However, for increasing sound pressures, the decay in TS increases to about 3 dB at 10 m for 560 W. TS will therefore be underestimated for targets beyond the range where the echosounder was calibrated and overestimated inside this range. For TS measurements, the discrepancies shown by these results are substantial.

Sound-pressure level measurements and simulations

Measurements of the 200-kHz pulse emitted by the transducer are presented in Figure 3. The acoustic power on the transducer was around 1000 W. The pulse waveforms at different ranges are presented at the left-hand side, while the right-hand side shows the corresponding FFTs. Here we can see that the waveform changes as the pulse propagates in the water. The FFTs indicate that the energy in the higher harmonics relative to the fundamental (200 kHz) increases with range, which means that energy from the fundamental frequency is transferred into higher harmonics in the water, representing a non-linear loss from the 200-kHz pulse.

The non-linear loss is compared with the simulated data in Figure 4. Agreement between the experimental and the simulated data is reasonably good and the losses are comparable with the drop in TS measurements, suggesting that the non-linear loss has caused the apparent TS reduction with range.

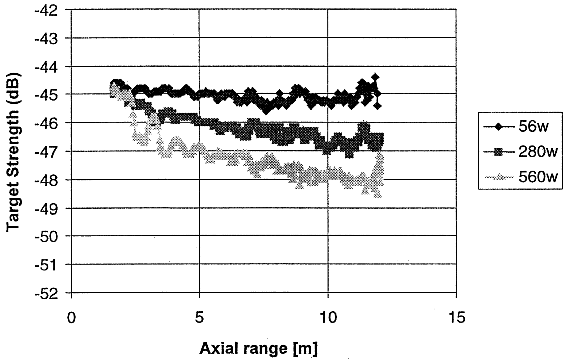
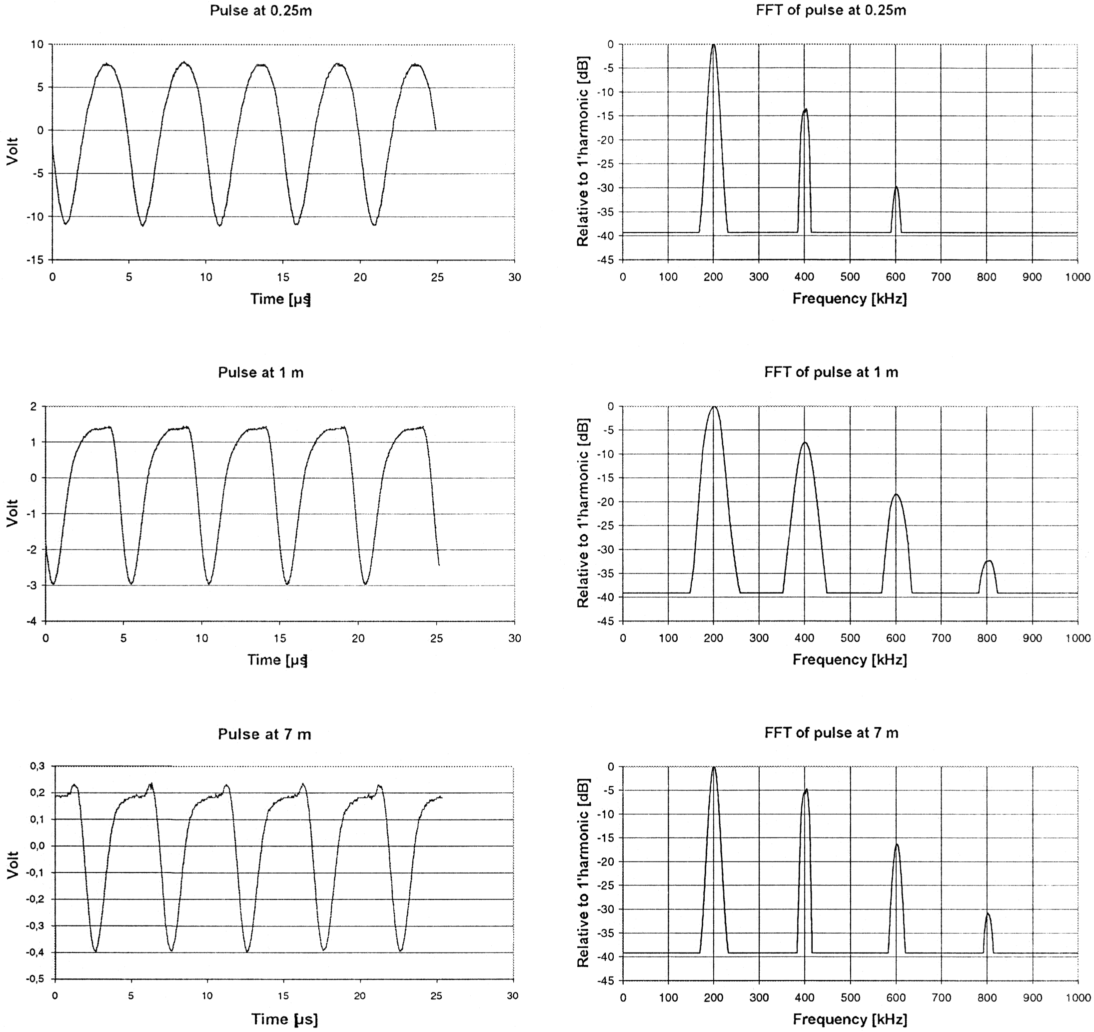


Figure 2. The measured TS along the transducer axis for different power levels.


Pulse at 0.25m

FFT of pulse at 0.25m

Pulse at 1 m

FFT of pulse at 1 m

Pulse at 7 m

FFT of pulse at 7 m

Figure 3. The waveforms and FFT of the transmitted pulse for three distances along the transducer axis.

Because of the good agreement between the short-range measured and simulated data, a further simulation out to 260 m was performed for a transmission power of 330 W at the transducer. The results are shown in Figure 5, where it can be seen that the simulation indicates a further loss of about 2 dB from 10 m, where we also have measurements, out to 260 m range. This suggests that non-linear losses probably occur beyond 10 m range, and that they should be compensated for if the TS is to be estimated correctly. The losses will be even higher for power settings above 330 W.

Another consideration is the non-linearity parameter (B/A) of the medium. This is proportional to the change of sound speed with sound pressure and depends on the condition of the water. Bubbly water will have a large B/A value, and consequently more non-linear loss (Wu and Zhu, 1991).

In certain circumstances the losses can be so high that at a certain distance it is not possible to increase the sound pressure by increasing the transmitted power. At this point acoustic saturation has been reached, and increasing the power will only increase the higher harmonics (Shooter *et al.*, 1974).

Summary

It is important to note that our results relate to the transducer axis. At off-axis positions, the non-linear losses are smaller because of the lower sound pressures, which means that the beam pattern will depend on both the power and the distance. To summarize, since the non-linear losses are dependent on frequency, a transducer with the same beam pattern, but operated at a higher frequency, will have greater losses for the same power settings. Conversely, a transducer with a lower frequency will have fewer non-linear losses for the same power settings, which means that in estimating the 'linear' losses the beam pattern has to be mapped and the condition of the water determined.

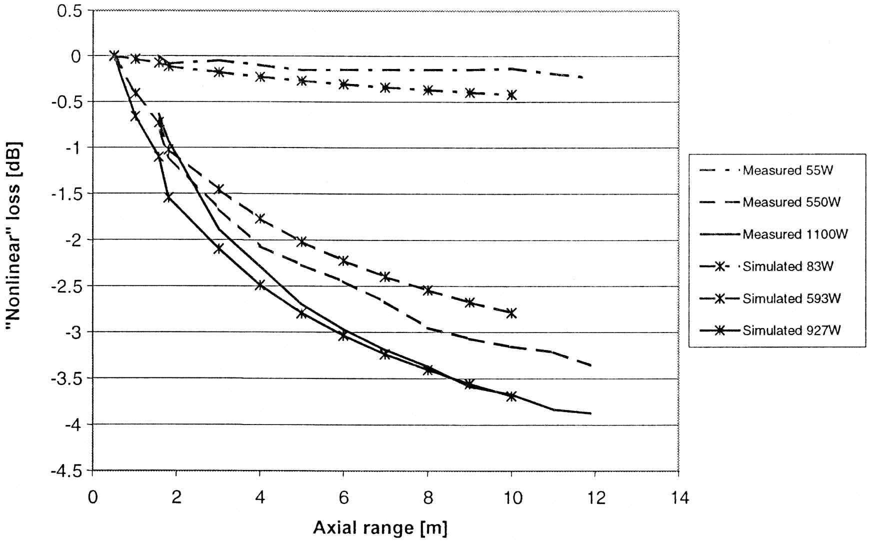


Figure 4. The measured and simulated non-linear loss along the transducer axis for different power levels.

The results of this study indicate that a non-linear loss adjustment should be included in TS measurements made with a given transducer so that the targets are estimated correctly. It is further suggested that the transmitted power should be set at the lowest practical level so that the non-linear losses are minimized.

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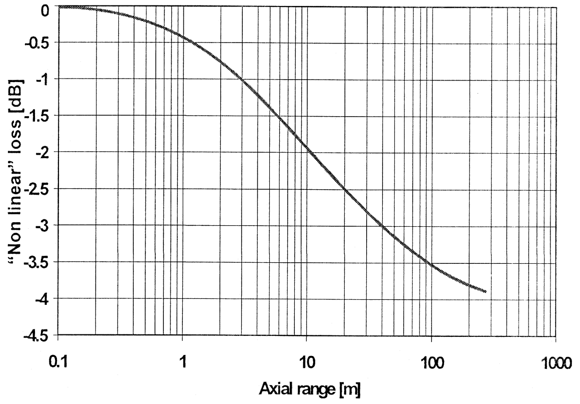

Figure 5. The simulated non-linear loss along the transducer axis out to 260-m range for 330-W transmitted power.

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