Influence of Acoustic Intensity on the Second-harmonic Beam-profile

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Abstract

A method for 3D simulation of wave propagation based on a quasilinear approximation has previously been presented [1].
Current aim:

- compare quasilinear simulation to a conventional nonlinear simulation model
- verify simulation using hydrophone measurements

Background

The introduction of harmonic imaging in medical ultrasound applications has led to major improvement in image quality. In order to take full advantage of this in ultrasound transducer design, the ability to predict the beam-profile of a particular transducer geometry/frequency is necessary. At present, the easiest way to do this is by way of computer simulations; most commonly solving the full nonlinear wave equation [2], or by using a parabolic approximation which leads to the KZK-equation [3].
For an accurate computation of the beam-profile, the three dimensional effects of the transducer and sound propagation need to be taken into account. For an annular probe, the circular symmetry may be exploited to view the problem in cylindrical coordinates, thus reducing the problem size to two dimensions [4]. In general, this is not possible. However, for ultrasound applications with low intensity or a sufficient degree of attenuation, the generation of higher harmonics is weak. This may be exploited in a quasilinear approximation to the wave equation [1].

Theory

A nonlinear equation which describes the propagation of sound in soft tissue is

$$\nabla^2 p - \frac{1}{c^2}(p)_{tt} + L(p) = \epsilon \left(p^2\right)_{tt}, \qquad (1)$$

where $L(p)$ accounts for loss.
The quasilinear simulation method is based on a perturbation solution to (1)

$$p(r,t) = p_1(r,t) + \epsilon p_2(r,t) + O(\epsilon^2).$$

Fundamental field:

$$\nabla^2 p_1 - \frac{1}{c^2}(p_1)_{tt} + L(p_1) = 0$$

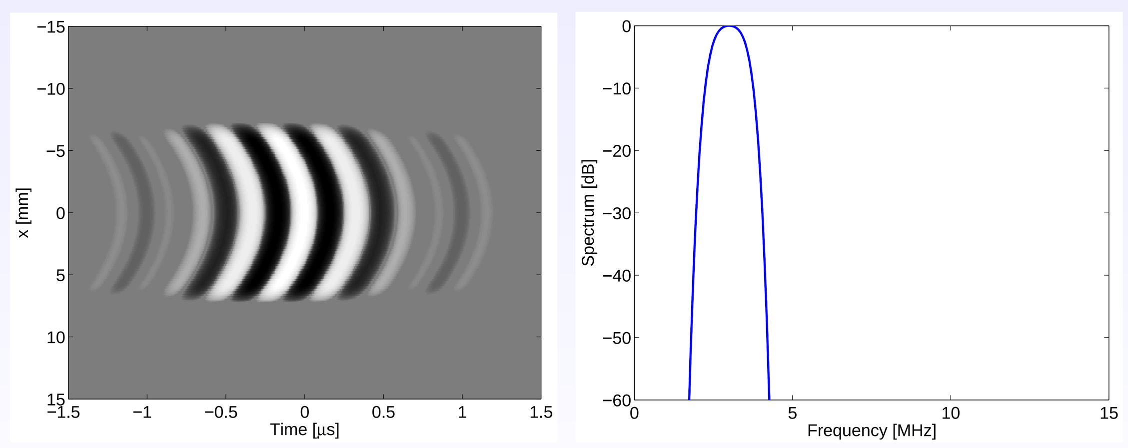
Second-harmonic field:

$$\nabla^2 p_2 - \frac{1}{c^2}(p_2)_{tt} + L(p_2) = \epsilon \left(p_1^2\right)_{tt}.$$

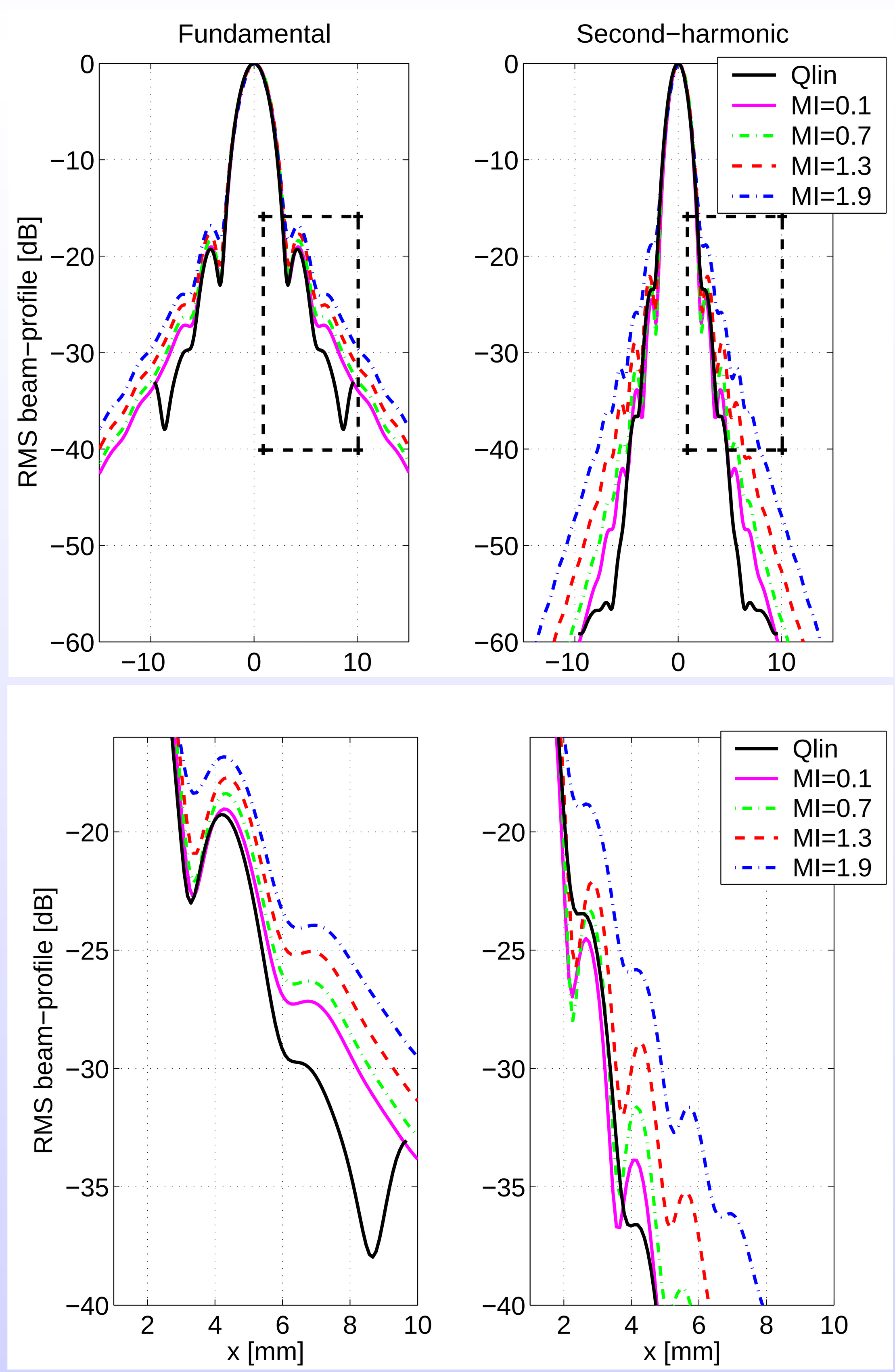
The underlying assumption for perturbation is that $|\epsilon^2 p_1(r,t)| = O(\epsilon^2)$, *i.e.* $|p_1(r,t)|$ should be small.

Quasilinear vs. KZK

A planar annular array probe was simulated using the quasilinear method and a KZK-based method. Focusing was obtained by delays.



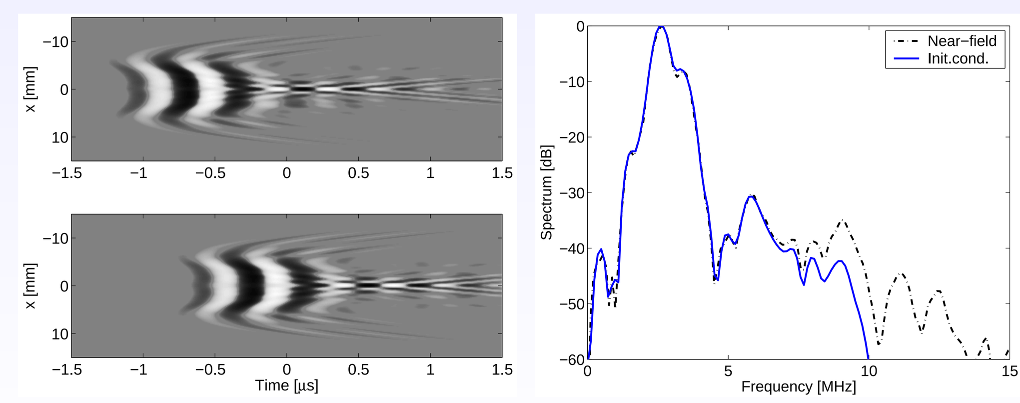
Transmit pulse at the simulated transducer.



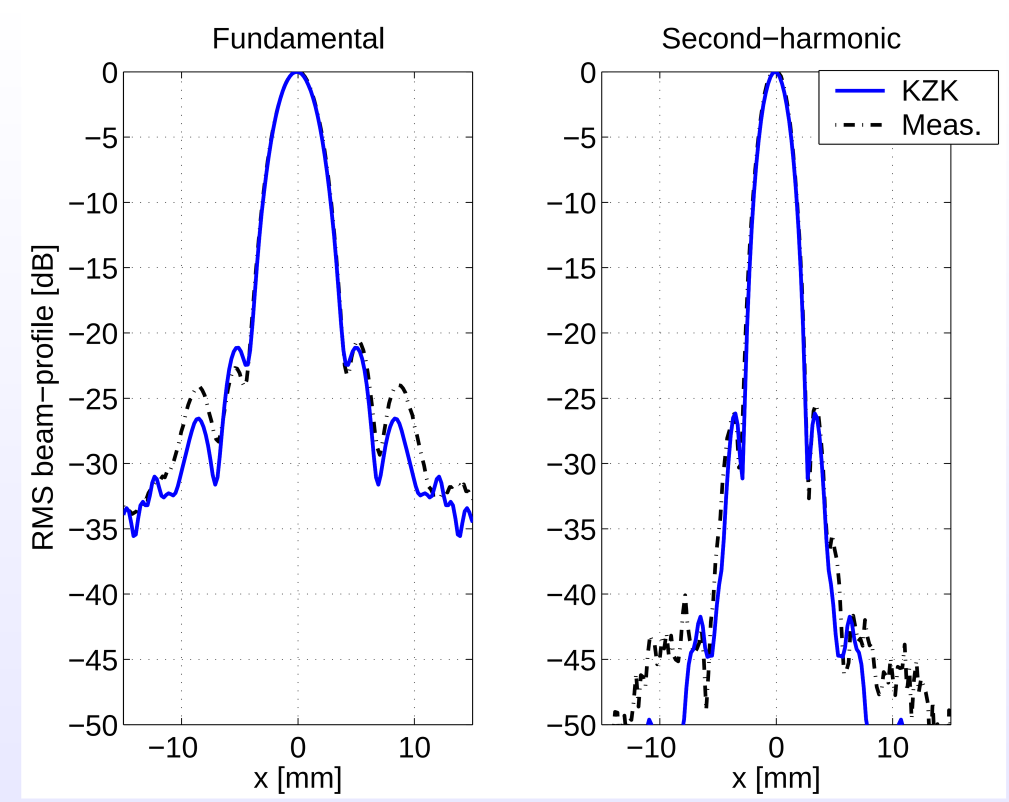
Comparison at focal depth using quasilinear simulation (Qlin) and KZK-based simulation for various values of the MI.

Measurements vs. KZK

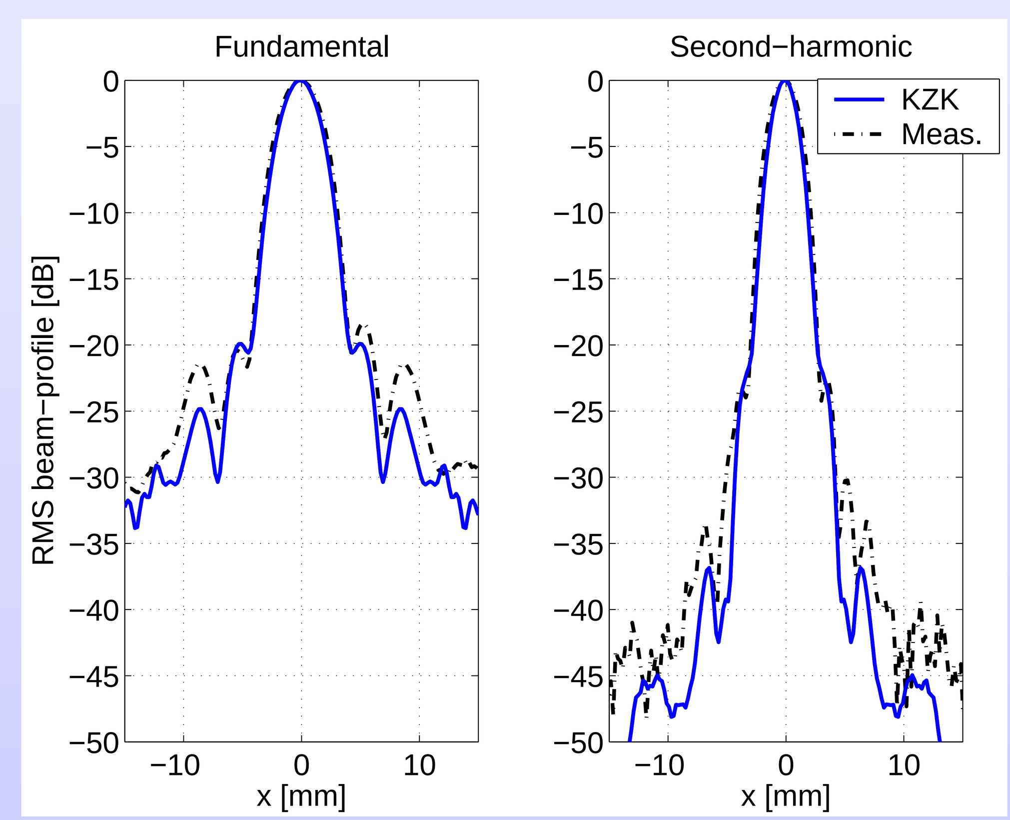
The near-field of an annular array probe was recorded. It was adjusted to be axis symmetric, and used as an initial condition for the KZK-based simulation. A simulated field was compared to recorded measurements. Measurements were conducted in a water tank using a hydrophone.



Recorded near-field (top left) and initial condition for simulation (bottom left).



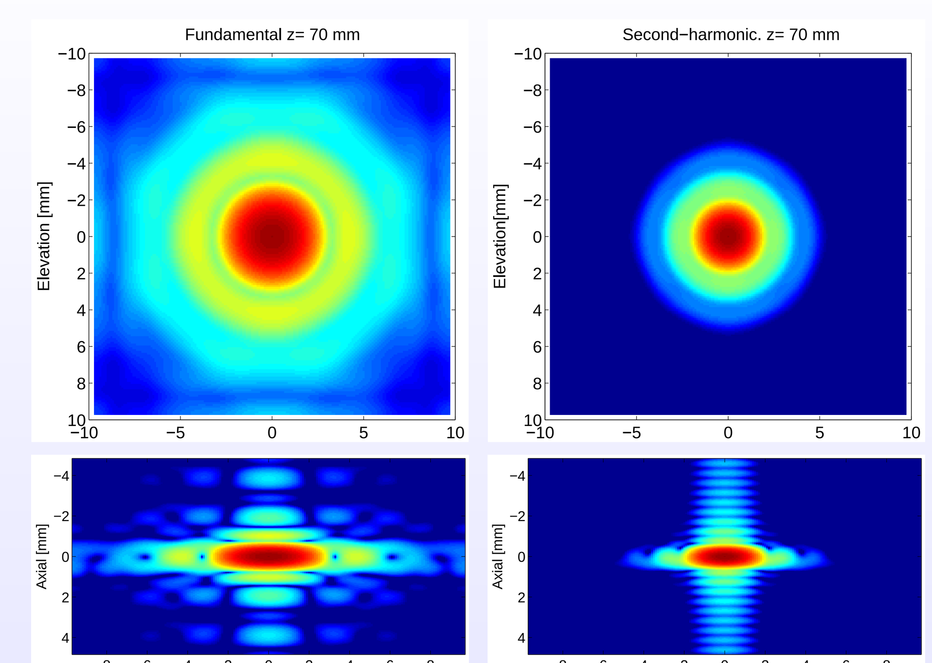
Comparison at the focal depth for MI = 0.3.



Comparison at the focal depth for MI = 0.9.

Conclusion

- Results from the quasilinear simulation and the KZK-based simulation are virtually the same when the MI is below 0.5.
- The quasilinear simulation predicts side-lobe levels which are too low for the beam-profiles when the MI increases.
- The KZK-based simulation concurs with the measurements.
- The 3D quasilinear simulation took approximately 5 minutes on a standard workstation. (The KZK-based simulation used 10 minutes for completing a 2D computation).



Quasilinear simulation of the fundamental and second-harmonic field for an annular array probe. The colour scale shows a 50 dB dynamic range.

References

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