Aberration and harmonic imaging

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Motivation

- Good understanding of wavefront aberration and linear wave propagation.
- time-delays and amplitude filter / generalised screen
- time-reversal / DORT
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- "... but harmonic imaging works so well ... why bother ... "

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"... but harmonic imaging works so well ... why bother ... "

"... harmonic imaging has solved the problem of aberration ... "

Aberration and harmonic imaging
Theory

Westervelt equation

\[ \nabla^2 p - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = \frac{1}{c^2} \frac{\partial^2 \mathcal{L} p}{\partial t^2} - \epsilon_n \frac{\partial^2 p^2}{\partial t^2} \]
Theory

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Define linear and nonlinear parts

\[ p = p_l + p_{nl} \]

\[ \nabla^2 p_l - \frac{1}{c^2} \frac{\partial^2 p_l}{\partial t^2} = \frac{1}{c^2} \frac{\partial^2 \mathcal{L}p_l}{\partial t^2} \]

\[ \nabla^2 p_{nl} - \frac{1}{c^2} \frac{\partial^2 p_{nl}}{\partial t^2} = \frac{1}{c^2} \frac{\partial^2 \mathcal{L}p_{nl}}{\partial t^2} - \epsilon_n \frac{\partial^2 p^2}{\partial t^2} \]
Theory

Westervelt equation

\[ \nabla^2 p - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = \frac{1}{c^2} \frac{\partial^2 L p}{\partial t^2} - \varepsilon_n \frac{\partial^2 p^2}{\partial t^2} \]

Define linear and nonlinear parts in frequency domain

\[ p = p_l + p_{nl} \]

\[ \nabla^2 \hat{p}_l + \frac{\omega^2}{c^2} \hat{p}_l = -\frac{\omega^2}{c^2} L \hat{p}_l \]

\[ \nabla^2 \hat{p}_{nl} + \frac{\omega^2}{c^2} \hat{p}_{nl} = -\frac{\omega^2}{c^2} L \hat{p}_{nl} + \varepsilon_n \omega^2 \hat{p}^* \hat{p}. \]
Theory

Westervelt equation

$$\nabla^2 p - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = \frac{1}{c^2} \frac{\partial^2 Lp}{\partial t^2} - \epsilon_n \frac{\partial^2 p^2}{\partial t^2}$$

Define linear and nonlinear parts in frequency domain for $|p_{nl}| \ll |p_l|$

$$p = p_l + p_{nl}$$

$$\nabla^2 \hat{p}_l + \frac{\omega^2}{c^2} \hat{p}_l = -\frac{\omega^2}{c^2} L \hat{p}_l$$

$$\nabla^2 \hat{p}_{nl} + \frac{\omega^2}{c^2} \hat{p}_{nl} = -\frac{\omega^2}{c^2} L \hat{p}_{nl} + \epsilon_n \omega^2 \hat{p}_l \ast \hat{p}_l.$$
Observations

- Aberration of linear part is well understood
- Nonlinear part is governed by the same equation with additional source term
- Source for the nonlinear part is an aberrated linear part
- Expect the nonlinear part to be as aberrated as the linear part.
Simulations

TX frequency : 2.5 MHz
Focal depth : 6.0 cm
XD : 2.0 × 2.0 cm
Wall model : abdominal
2.0 cm
Tissue : muscle
Simulation : 3D
Energy distr. fundamental
Energy distr. fundamental
Energy distr. harmonic
Energy distr. harmonic
Energy distr.

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Peak pressure

[Graph showing peak pressure in decibels (dB) vs. distance in millimeters (mm).]
\[ E(z) = \int_{-\infty}^{\infty} \int_{T_z} |p(r, t)|^2 dt dr. \]
Energy

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Beam profiles

[Graph showing beam profiles with dB values on the y-axis and mm values on the x-axis.]
Beam profiles

Aberration and harmonic imaging
Beam profiles
Summary

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- Reduced aberration for fundamental at lower frequency.
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- Source for the second harmonic is aberrated fundamental.
- Aberration of second harmonic is similar to that of fundamental.
- Reduced aberration for fundamental at lower frequency.
- Other sources for improved image quality in harmonic imaging.