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To cite this version:
Sébastien Ménigot, Jean-Marc Girault. Harmonic Magnification by Time Reversal based on a Hammerstein Decomposition. IEEE International Ultrasonic Symposium 2016, Sep 2016, Tours, France. <hal-01371266>

HAL Id: hal-01371266
https://hal.archives-ouvertes.fr/hal-01371266
Submitted on 25 Sep 2016

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Harmonic Magnification by Time Reversal based on a Hammerstein Decomposition

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Introduction

The medical ultrasound imaging systems have been improved by taking into account the nonlinear wave propagation. These improvements lead to increases in the signal-to-noise ratio and the focusing in tissue harmonic imaging (THI). Since the backscattered nonlinearities are a function of the transmitted signal, enhancing these nonlinearities means to design the best wave [1]. Time reversal process is well-known to optimize the SNR and free itself to phase aberration, by combining a waveform design in space and in time thanks a physical matched filter [2]. However, it is not well-adjusted for THI, because the propagation of the time reversed signal destroys the harmonics.

How can we optimize the SNR in tissue harmonic imaging?

As we want to guarantee a SNR optimization with a good focusing, the method has to include time reversal. The solution firstly consists in extracting the harmonic component at $2f_0$ by a Hammerstein filter. Then this time reversed harmonic component at $2f_0$ is frequency shifted to the fundamental component at $f_0$ and retropropagated in the medium.

Methods

1. Sending a first standard excitation $x_{\text{standard}}(n)$
2. Harmonic extraction based on a Hammerstein model where the nonlinear function is a frequency shifting by modulation (since it is a bijective function on $R$):

$$ y(n) = \sum_{j=1}^{M} h_j(n)x_{\text{standard}}(n-m)\cdot C_j(n), $$

$n$ the discrete time, $M$ the memory of the Hammerstein model and $C_j(n) = \cos\left(\frac{2\pi f_0 M n}{F_s}\right)$ with $F_s$ the sample frequency.

The model can be solved by a pseudo-inversion:

$$ \mathbf{h} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{y}. $$

$$ \mathbf{h} = [h_1(1), ..., h_1(M), h_2(1), ..., h_2(M)], \mathbf{y} = [y(M+1), ..., y(N)]' $$

with $N$ the sample quantity, the matrix of input signals $\mathbf{X} = [x_1 x_2]$ with

$$ x_p = \begin{pmatrix} v_p(M) & v_p(M+1) & \cdots & v_p(N) \\ v_p(M+1) & v_p(M+2) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ v_p(N) & 0 & \cdots & 0 \end{pmatrix} $$

and $v_p(n) = x(n)C_p(n)$. Finally, the second harmonic signal is: $y_{\text{NL}} = x_2 = [h_1(1), ..., h_2(M)]'$.  
3. Time reversing $y_{\text{NL}}$
4. Annihilation of the second harmonic effects of the second harmonics:

$$ x_{\text{out}}(n) = A \cdot y_{\text{NL}}(n) \cdot \cos\left(2\pi f_0 n + \phi \right), $$

$A$ preserve the transmit power to $x_{\text{standard}}(n)$ and $\phi = \arctan\left(\frac{\dot{v}_{y_{\text{NL}}}}{v_{y_{\text{NL}}}}\right)$ with $\dot{v}(y_{\text{NL}})$ the phase of the the second harmonic signal $y_{\text{NL}}$ and $v(y_{\text{NL}})$ the phase of a cosine at the frequency $f_0$.

Simulation

• 2D nonlinear wave propagation in a cavity [3]
• 8-element probe centred at $f_s = 4$ MHz
• Initial Gaussian pulse $x_{\text{standard}}(n)$ centred at $f_0 = 22$ MHz and with a bandwidth of 50%

Results

Discussions and Conclusion

• Magnify the second harmonics and improve the SNR
• Hammerstein model using frequency shifting with the good phase
  → Annihilation of the harmonic effects before sending the time-reversed signal
• Matched filter for harmonic components
  → Extension of the time reversal principle to second harmonics