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Complexity Reduction of Ultrasound Sub-Ultra-Harmonic Modeling by an Input Modified Volterra Approach

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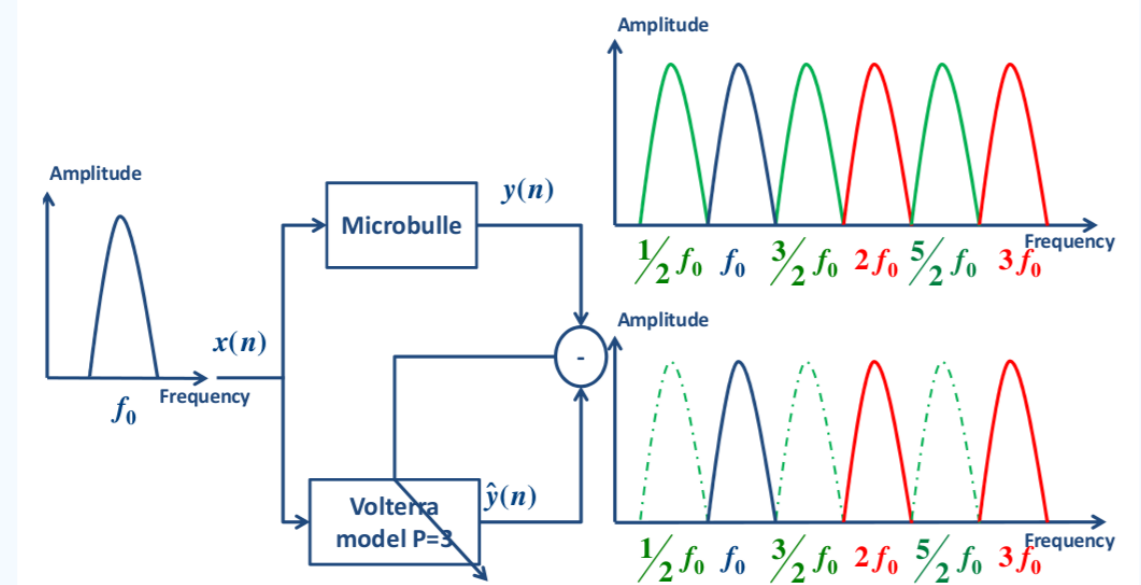
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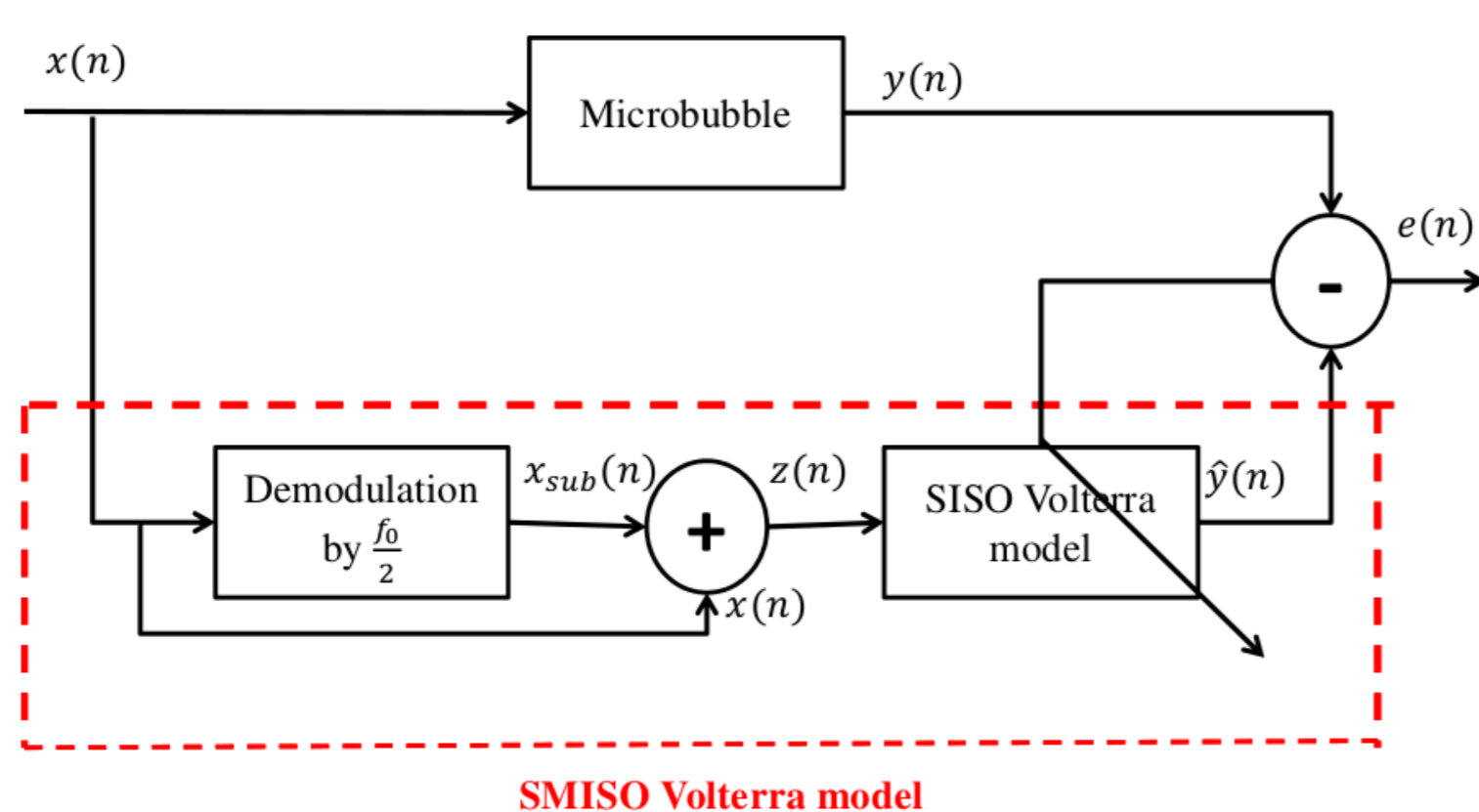
Introduction

- Contrast of echographic images has been highly improved by the injection of microbubbles. However, this contrast enhancement is limited by the nonlinear acoustic propagation in tissue. To overcome this drawback, sub and ultra-harmonic contrast imaging can be used, since only microbubbles can generate these components.
- Nonlinear models like Volterra model has been applied in harmonic imaging to model harmonics optimally. However, it can model harmonics only.



- Nonlinear models as Hammerstein [1] and Volterra can be modified for sub and ultra-harmonic modeling. However, only multiple input single output (MISO) keeps intermodulation in the model to minimize the error.
- **Problematic:** MISO Volterra model is time and memory consuming model.
- **Proposed solution:** We propose a modified single input single output (SMISO) Volterra model based on input demodulation to reduce the computation cost of sub and ultra-harmonics modeling.

Methods



1. The input signal is demodulated by $\frac{f_0}{N_{sub}}$, to include the subharmonic frequency.
2. The new modified input $z(n)$ of the SMISO Volterra model is obtained by adding the demodulated input $x_{mod}(n)$ of frequency $\frac{f_0}{2}$ and the input $x(n)$ of frequency f_0 :

$$z(n) = x(n) + x_{mod}(n) = x(n)(1 + \cos(2\pi n \frac{f_0}{2} T_s)) + \tilde{x}(n) \sin(2\pi n \frac{f_0}{2} T_s).$$

where \Re represents the real part, $\tilde{x}(n) = \mathcal{H}(x(n))$ is the Hilbert transform of $x(n)$, and T_s is the sampling frequency.

3. The modeled output $\hat{y}(n)$ is calculated following Volterra equation with input $z(n)$:

$$\begin{aligned} \hat{y}(n) = & h_0 + \sum_{k_1=0}^{M-1} h_1(k_1)z(n-k_1) \\ & + \sum_{k_1=0}^{M-1} \sum_{k_2=0}^{M-1} h_2(k_1, k_2)z(n-k_1)z(n-k_2) \\ & + \dots \\ & + \sum_{k_1=0}^{M-1} \dots \sum_{k_p=0}^{M-1} h_p(k_1, \dots, k_p)z(n-k_1) \dots z(n-k_p), \end{aligned}$$

where $h_p(k_1, k_2, \dots, k_p)$ is the kernel of order p with $p \in \{1, 2, \dots, P\}$.

4. The modeling process is resumed to finding the kernels $h_p(k_1, k_2, \dots, k_p)$ of the SMISO Volterra with input $z(n)$. The number of kernels is given by:

$$N_{p_{sym}} = \sum_{p=1}^P C_p^{M+p-1} = \sum_{p=1}^P \frac{(M+p-1)!}{(M-1)!p!}.$$

The vector of kernels \mathbf{h} is calculated by a pseudo-inversion solution:

$$H = (Z^T Z)^{-1} Z^T Y.$$

where Y is the output signal: $Y = [y(M+1), y(M+2), \dots, y(L)]^T$,

with L is the length of the signal, M is the memory of Volterra model. H is the vector of kernels:

$$H = [h_1(0), \dots, h_1(M-1), h_2(0,0), \dots, h_2(M-1, M-1), \dots, h_p(0,0, \dots, 0), \dots, h_p(M-1, M-1, \dots, M-1)]^T,$$

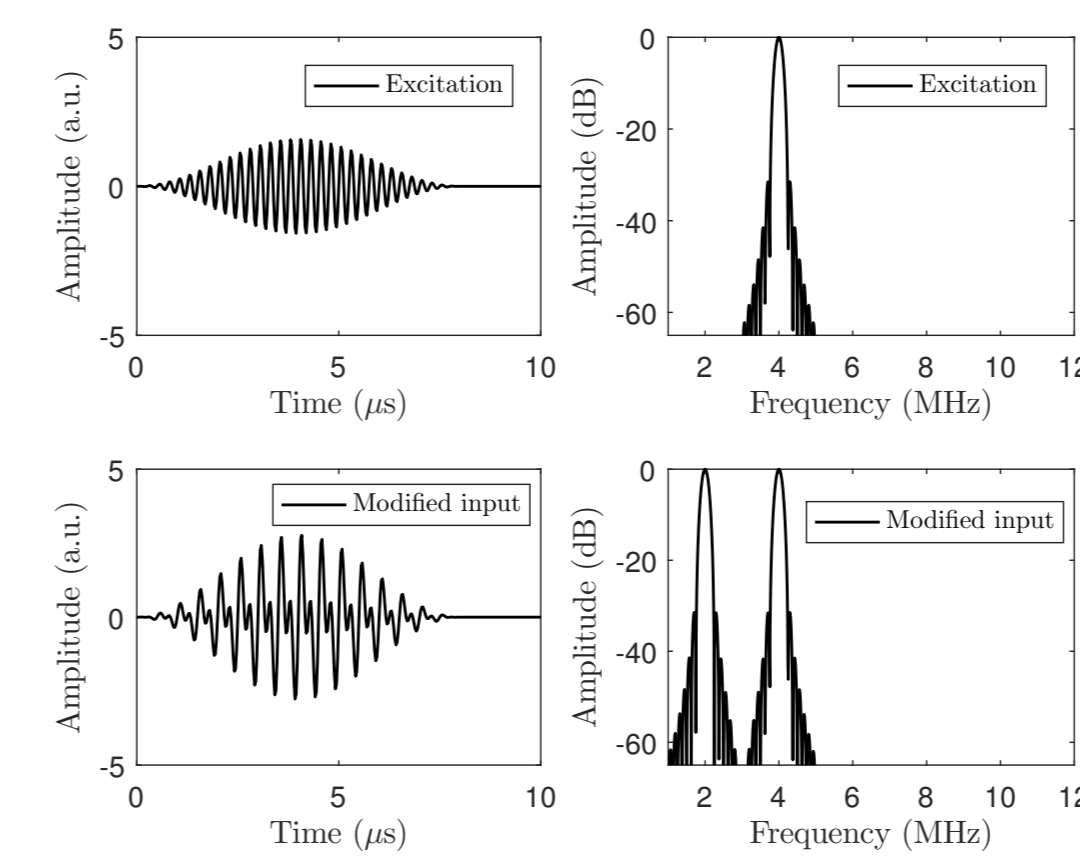
and where Z is the input matrix: $Z = [z_{M+1}, z_{M+2}, \dots, z_L]^T$, with the vector:

$$z_n = [z(n), \dots, z(n-M+1), z^2(n), z(n)z(n-1), \dots, z^2(n-M+1), z^3(n), z(n)z(n)z(n-1), \dots, z^3(n-M+1)]^T,$$

with $l \in \{M-1, M, \dots, L\}$.

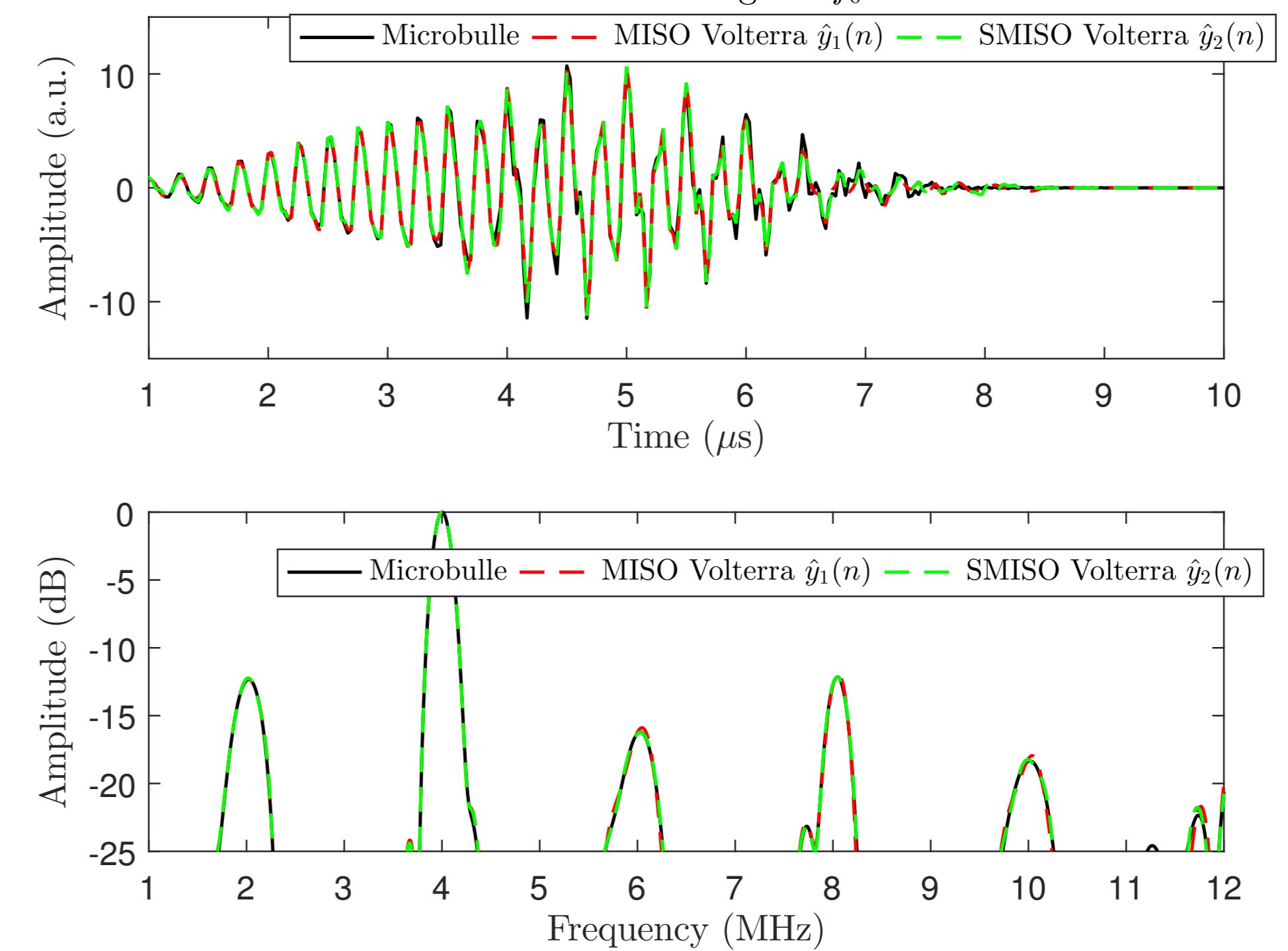
Simulation and Results

- Free simulation software Bubblesim [2].
- The incident burst to the microbubble is a sinusoidal wave of frequency $f_0 = 4$ MHz, at 1.6 MPa pressure, and consists of 32 cycles.



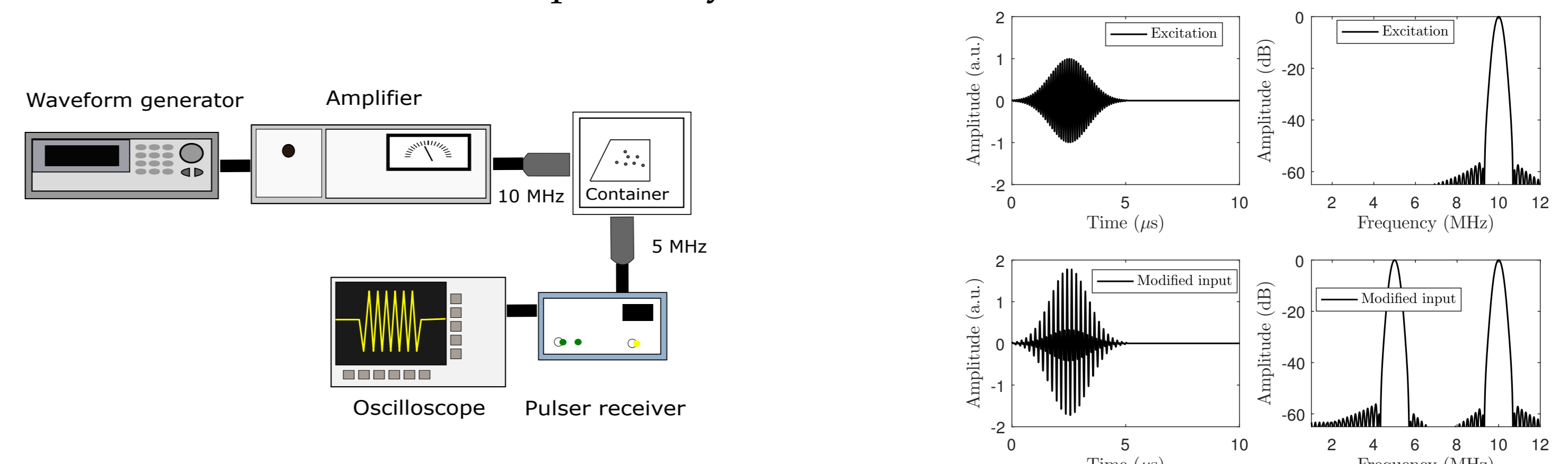
Model	MISO	SMISO	ratio
rMSE (dB)	-15.5	-15.8	1.02
Computation time (s)	960.14	236.5	4
Number of kernels	16870	8435	2

Results from simulated signals $f_0 = 10$ MHz

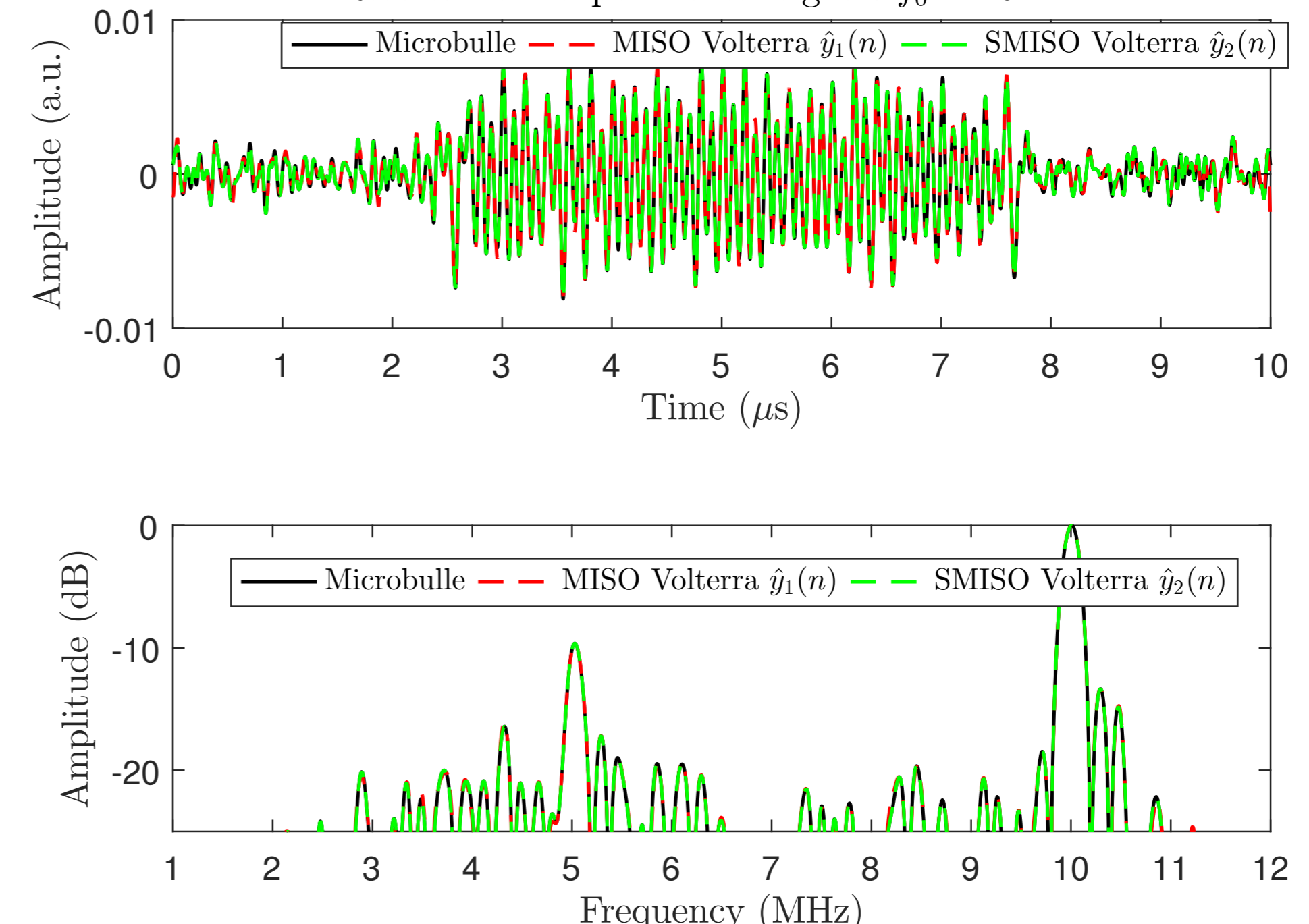


Experimentation Setup and Results

- Signal transmitted at 10 MHz
- Responses of a diluted solution of Sonovue™ microbubbles were measured by a 5 MHz PZT single element transducer
- Measured echoes were amplified by 30 dB [1]



Results from experimental signals $f_0 = 10$ MHz



Model	MISO	SMISO	ratio
rMSE (dB)	-17.5	-63.7	8.5
Computation time (s)	236.5	48.5	5
Number of kernels	10000	5000	2

Discussions and Conclusion

- SMISO Volterra model is a simple, quick and efficient method to model sub and ultra-harmonics
- Significant reduction of the computation cost: time and number of kernels
- Significant gain in the terms of rMSE
- It can be used in sub and ultra-harmonic ultrasound contrast imaging

[1] Ménigot S. & Girault, J.-M. SNR improvement by subharmonic extraction with Hammerstein models for microbubble signals. IEEE International Ultrasonics Symposium (IUS). 2016.

[2] L. Hoff, Acoustic Characterization of Contrast Agents for Medical Ultrasound Imaging. Boston, USA: Kluwer Academic, 2001.