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Sharp and nonlinear cavitation mapping using synchronized sine-sweep imaging

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Abstract

Cavitation mapping is a reliable tool to monitor therapeutic ultrasound applications based in microbubbles. However, when the temporal duration of the transmitted pulses is long, the acoustic emission of the bubbles extends in time, and it becomes difficult to generate sharp acoustic cavitation images. In this work, we present a method based on long synchronized sine-sweep pulses that enable the separation of individual impulse responses to produce sharp cavitation images and increases the signal-to-noise ratio. By uncoupling nonlinear signatures, the method allows the separation of pulse-compressed impulse responses for the linear response and for each harmonic component. In this way, using synchronized sine-sweep, the cavitation of microbubbles under the action of a therapeutic transducer can be mapped with accuracy and with a robust signal-to-noise ratio. This pulse compression method enables the harmonic localization for nonlinear cavitation mapping, enabling the individual imaging of nonlinear signatures of cavitating bubbles. The cavitation images allow to identify the real focal spot of a therapeutic transducer, and the nonlinear signatures offers quantitative information about the stable or inertial regime of the cavitating bubble.

Keywords: Ultrasound, Imaging Ultrasound, Cavitation, Pulse-compressed

1 Introduction

The applications of pulse compression and coded excitation in ultrasonic imaging have been explored in many investigations [1]-[2]. The interest in this type of long duration and broadband signals has increased due to their advantages over short narrowband sinusoidal signals such as, for example, better signal to noise ratio (SNR), better depth resolution. In addition, these signals allow increasing the pulse power, in order to improve the SNR, without increasing the pulse amplitude, thus avoiding the possibility of excitation of nonlinearities. This can be very useful in cavitation detection applications, where harmonic signals are produced due to the excitation of nonlinearities.

Ultrasound cavitation has an infinite number of therapeutic applications and a great potential, but for safety reasons it is very important to be able to effectively evaluate the state and level of cavitation. The information provided by the cavitation effect in radio frequency (RF) signals will be in the upper harmonics since the behaviour of cavitation corresponds to a nonlinear regime.

In this paper, we present a method based on the deconvolution of long synchronized sinusoidal sweep pulses that allows the separation of the individual impulse responses for the harmonic components produced by cavitation nonlinearities and offers an increase in the signal-to-noise ratio.

2 Methods

A focused therapeutic transducer (64-mm OD, 31.7-mm ID, 64-mm ROC) transmitting a plane wave signal is simulated. Then, using a simulated 5 MHz, 64-element transducer, the signals received after transmission are detected using a synchronized sine-sweep coded excitation (2.1 to 4.5 MHz, 0.5-MPa PNP) with the following expression [3],

$$x(t) = \sin\left[2\pi f_1 L \exp\left(\frac{t}{L}\right)\right] \tag{1}$$

where L is the frequency increase factor,

$$L = \frac{T}{\ln\left(\frac{f_2}{f_1}\right)} \tag{2}$$

and where f_1 and f_2 are the initial and final frequencies of the sinusoidal sweep and T is the pulse duration.

On the other hand, the scattering of a bubble oscillating in water is simulated using the Rayleigh-Plesset model [4]. The bubble is placed in the focal zone of the therapeutic transducer.

After receiving the scatter signal, the frequency deconvolution of the synchronized sine-sweep is performed to calculate the impulse response, knowing that the spectrum of the transmitted signal is given by [3],

$$\tilde{X}(f) = 2\sqrt{\frac{f}{L}} \exp\left[-j2\pi fL\left(1-\ln\left(\frac{f}{f_1}\right)\right)+j\frac{\pi}{4}\right] \tag{3}$$

After deconvolution it is possible to separate the impulse response from the received harmonics by means of a time shift $\Delta t_n = L\ln(n)$, where it corresponds to the harmonic number. This gives us the possibility to focus on higher harmonics as well as sub-harmonics (see Figure 1).

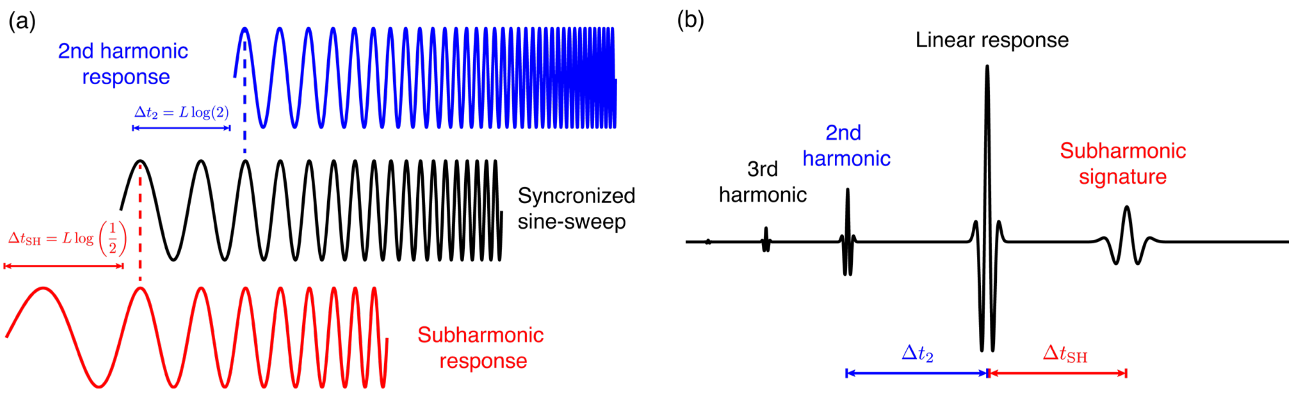

Figure 1 – Emission of a synchronized sine-sweep pulse, second harmonic response and subharmonic response. (b) Deconvolved signal where due to the synchronization integer and subharmonic components are separated.

After deconvolution, a B-mode image is performed by applying delay-and-sum beamforming [5] to the impulse response of the harmonics.

Finally, an experimental setup is proposed to experimentally evaluate the signal-to-noise ratio of the proposed method. The experiment consists of imaging a point scatter while it is excited focally with a high-power transducer in the scatter region. The 256-Vantage system (Verasonics), consisting of the H-101 focused therapeutic transducer (64-mm OD, 31.7-mm ID, 64-mm ROC) and the IP-105 phased array (5 MHz and 64 elements), is used for this purpose.

3 Results

In this section we present the results of simulated scattering measurements of a bubble oscillating in water. Figure 2a shows the B-mode image of the fundamental component of the impulse response produced by the scatter, while Figure 2b shows the impulse response of the second harmonic component. The location of the scatter in the second harmonic image is very similar to that of the fundamental component, with the advantage of better resolution, as the sidelobes are narrower in the harmonic component.

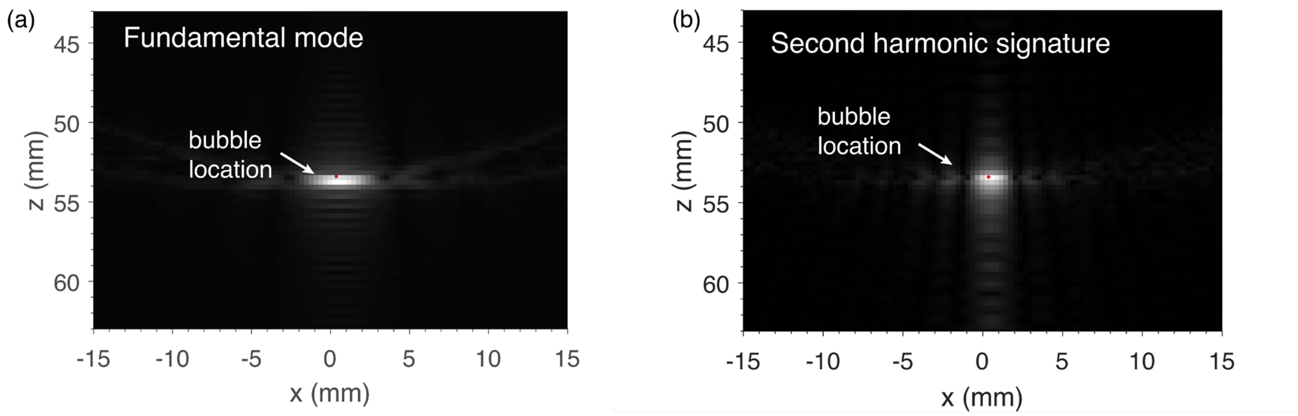

Figure 2 - Cavitation imaging (simulated) using the deconvolved signals where the 2nd harmonic signature results in a localized nonlinear signature.

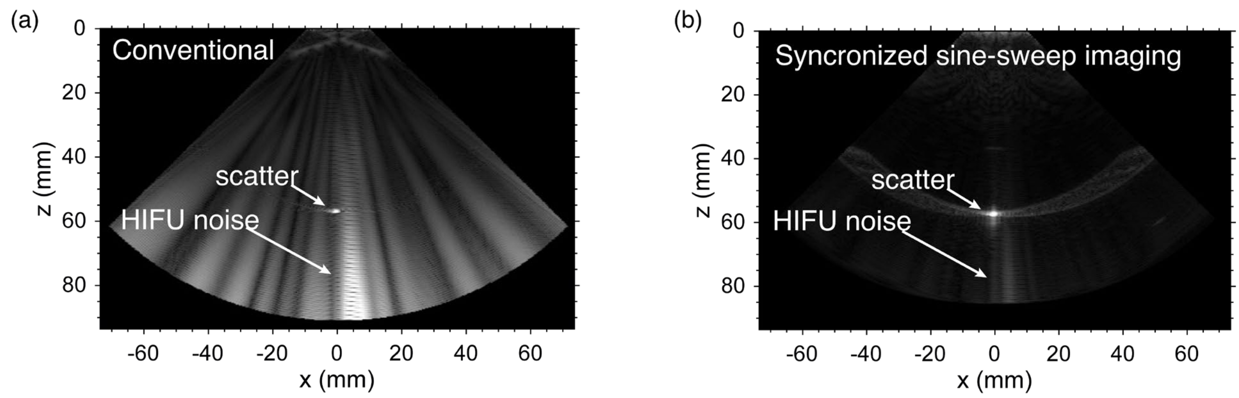

Figure 3 - Experimental demonstration of the SNR enhancement.

Secondly, the results of experimental measurements are presented to evaluate the signal-to-noise ratio of synchronized sine-sweep coded excitation signals compared to conventional short pulses. Figure 3a depicts a B-mode image where the pulse emitted by the receiving transducer consists of a short duration plane wave, while Figure 3b shows the reconstructed image using the impulse response of the fundamental component of the scatter after emitting with a long duration synchronized sine-sweep signal.

4 Conclusions

By uncoupling nonlinear signatures, the method allows the separated pulse-compression of fundamental and harmonic components. Applying the harmonic pulse compression, the simulated images of fundamental and second harmonic responses show a sharp resolution (fundamental, 3.4 mm by 0.75 mm; 2^{nd} harmonic 1.8 mm by 0.75 mm) at a depth of 54 mm. Experimental results show a signal-to-noise ratio enhancement of 50.8 dB when comparing with conventional pulsed imaging when the therapeutic transducer was driven at 168.7 V. By using a synchronized sine-sweep we have been able to map the cavitation of a microbubble located at the focal zone. In addition, this pulse compression method enables the individual localization for cavitation mapping, enabling the imaging of nonlinear signatures of cavitating bubbles.

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