Synchronized sine-sweep imaging for uncoupling nonlinear signatures during pulse compression

Nathalie Lamothe, Enrique González-Mateo, Noé Jiménez and Francisco Camarena
Instituto de Instrumentación para Imagen Molecular, Universitat Politècnica de València, Spain
e-mail: nlamothe@upv.es

***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.**

***Index Terms*—ultrasound, imaging ultrasound, cavitation, pulse-compressed**

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I. 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, e.g., better signal-to-noise ratio (SNR) or better depth resolution. Using long coded excitations, the total pulse power can be controlled without varying the pulse amplitude. In this way, the SNR of the resulting images can be increased under the same level of nonlinearity in the tissue. This can be very useful in cavitation detection applications, where harmonic signals are produced due to the excitation of nonlinearities. Ultrasound cavitation is at the basis of a high number of imaging and therapeutic applications and the magnitude of this effect strongly depends on the amplitude of the ultrasonic pulse, and for safety reasons it is very important to be able to effectively evaluate the state and level of cavitation.

Cavitation activity can be captured by ultrasound probes, and as microbubbles are strongly efficient nonlinear oscillators, usually the recorded radio frequency (RF) signals present harmonic, sub-harmonic, and ultra-harmonic, and even broadband components. The activity of cavitating microbubbles, i.e., the amplitude of their oscillations, is linked to the magnitude of the spectral components of the recorded signals. Therefore, it is common in therapeutic applications to excite the bubbles with a long pulse to produce a bio-effect, record the cavitation activity of the emission and, then, use that data to monitor the treatment. However, as usually the temporal duration of the therapeutic pulse is long, it becomes difficult to conform a sharp cavitation images to spatially localize the cavitation activity.

In this paper, we present a pulse compression method to monitor and map the cavitation activity for therapeutical ultrasound applications. It is based on the deconvolution of a particular broadband signal, a synchronized sinusoidal sweep pulse, that allows the separation of the impulse responses for the individual harmonic components produced by cavitating microbubbles. On the one hand, by compressing the temporal signals the technique can conform images of the cavitating activity for each harmonic component and, on the other hand, it offers a high signal-to-noise ratio due to the long temporal emitted signals, i.e., it can be used to real-time monitor therapeutic ultrasound applications. The technique is validated numerically and experimentally.

II. Methods

A synchronized sine-sweep [3] is a broadband chirp-type signal, defined as

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

where

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

is the rate of frequency increase, f_1 is the initial frequency, f_2 is the final frequency and T is the total duration of the signal. When microbubbles oscillate under a synchronized sine-sweep pulse, $x(t)$, they produce an acoustic emission, $y(t)$, that is recorded by a probe. The deconvolution of these signals can be computed directly in the frequency domain as

$$h(t) = \mathcal{F}^{-1}\left[\mathcal{F}\left[y(t)\right]\tilde{X}(f)\right], \tag{3}$$

where $\tilde{X}(f)$ is the inverse Fourier transform of the input signal, given by

$$\tilde{X}(f) = 2\sqrt{\frac{f}{L}}\exp\left[-i2\pi f L \exp\left(1 - \log\left(\frac{f}{f_1}\right)\right) + i\frac{\pi}{4}\right]. \tag{4}$$

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A property of interest here is that a time delay Δt_n of the synchronized sine-sweep is equivalent to a copy of the signal itself at the n-th higher harmonic. The time shift is defined as

$$\Delta t_n = L \ln(n). \tag{5}$$

This property is depicted in Fig. 1 (a), where the second harmonic of the signal is obtained delaying the sine-sweep a time Δt_2, for $n = 2$, and a delay of $\Delta t_{1/2}$ results in a sub-harmonic response. The impulse response $h(t)$ of the system corresponds to the sum of the time-shifted impulse responses $h_n(t)$ of all harmonics, as shown in Fig. 1 (b). Then, using the deconvolved pulses detected by a phased-array and a proper temporal windowing, sharp cavitation mapping images can be conformed.

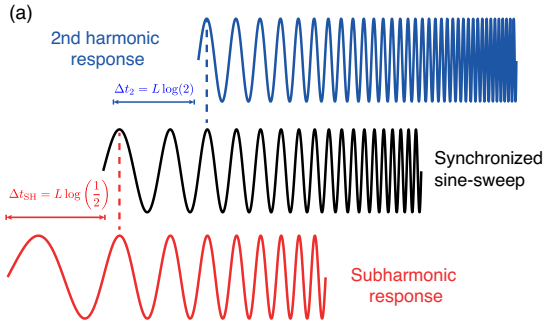


Fig. 1. (a) Emission of a synchronized sine-sweep pulse, and the second harmonic response and subharmonic response by time delaying the signal. (b) Time-shifted impulse responses of the higher harmonics and sub-harmonic after deconvolution process.

To validate the technique, a therapeutic synchronized sine-sweep pulse is generated by a therapeutic focused ultrasound (FUS) transducer, 64-mm OD, 31.7-mm ID, 64-mm ROC, (H-101, Sonic Concepts, USA), and the cavitation signals were acquired by a 5-MHz, 64-elements imaging probe (IP-105, Sonic Concepts, USA). The generated sine-sweep was defined at the third harmonic of the therapeutic source, i.e., $f_1 = 2.1$ MHz, $f_2 = 4.5$ MHz, and the amplitude was selected to produce 0.5-MPa peak-negative-pressure at the focal spot. The technique is validated numerically and experimentally.

First, a numerical model based on a dual transducer setup describes the cavitation imaging of an individual microbubble located at the focal zone of the therapeutic beam. Fig. 2, illustrates the setup, showing the microbubble oscillating in water when excited by the incident acoustic beam. The behaviour of the microbubble in response to the ultrasound excitation is described by a Rayleigh-Plesset model [4].

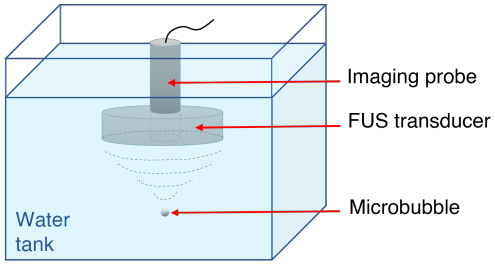


Fig. 2. Schematic of the simulated setup.

Second, an experimental setup is proposed to evaluate the signal-to-noise ratio of the described method. The experiment consists of imaging a point scatterer while it is excited with the focused ultrasound transducer. A 256-Vantage system (Verasonics) was used here. After deconvolution, a B-mode image is conformed by applying delay-and-sum beamforming [5] to the impulse response of the harmonics.

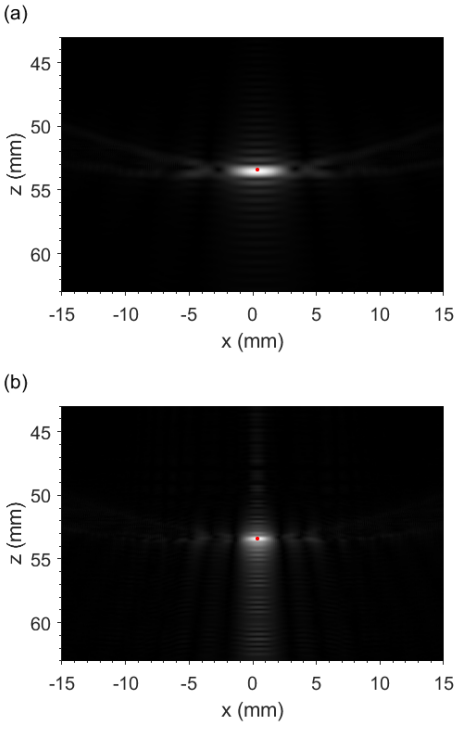


Fig. 3. (a) Simulated Synchronized sine-sweep cavitation imaging using the deconvolved signals for the fundamental component. (b) Simulated Synchronized sine-sweep cavitation imaging using the deconvolved signal for the 2nd harmonic.

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III. Results

In this section we present the results of simulated cavitation mapping of a microbubble in water by using pulse compression method. Fig. 3(a) shows the B-mode image of the fundamental component of the impulse response, and Fig. 3(b) shows the impulse response of the second harmonic component. The theoretical position of the microbubble is marked by a red dot. Both simulated images show a sharp resolution (fundamental, 3.4 mm by 0.75 mm; 2nd harmonic 1.8 mm by 0.75 mm) at a depth of 54 mm.

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. Fig. 4(a) depicts a B-mode image where the pulse emitted by the receiving transducer consists of a short duration plane wave, while Fig. 4(b) shows the reconstructed image using the impulse response of the fundamental component of the scatterer after emitting with a long duration synchronized sine-sweep signal.

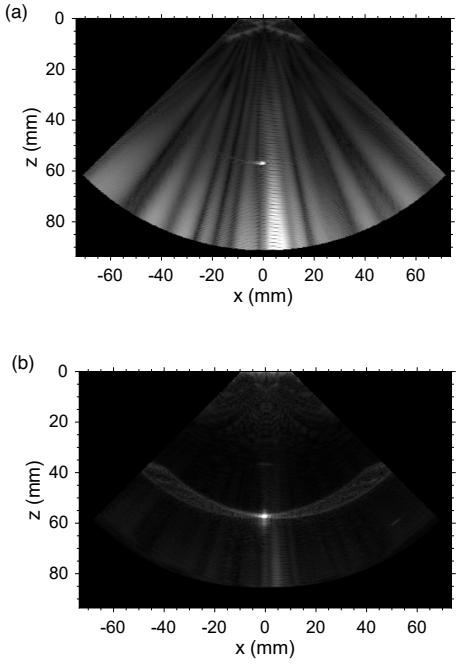


Fig. 4. (a) Conformed image of a single scatterer by using short pulse emission (conventional). (b) Synchronized sine-sweep imaging of single scatterer.

IV. Conclusion

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. 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 in 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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