Experimental Investigation of Chirp Coded Excitation in Ultrasound Superharmonic Imaging

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***Abstract*—Superharmonic imaging (SHI) provides improved spatial resolution and contrast detection with low reverberation artifacts by combining the third, fourth and fifth harmonics of the nonlinear received signal. The aim of this study is to increase the signal-to-noise ratio (SNR) with improved axial resolution and reduced ripple artifacts in the SHI using chirp coded excitation. Experiments are performed using a 2.25 MHz transducer mounted coaxially at a distance of 1-10 cm with a 0.2 mm hydrophone in a tank containing deionised, degassed water. The applied linear chirp signals have 10 μsec duration, and fractional bandwidths (FBW) of 20% and 40%. In the experiments, the 2.25 MHz tone-burst signal of same duration is used for comparison. The pressure level of each waveform is calibrated and the mechanical index of 0.75 is set at the focus of the transducer. The harmonic matched filtering is applied to the received signal to perform pulse compression of the individual harmonic chirp components to recover axial resolution. To get the superharmonic chirp, the third to fifth harmonic components are combined after pulse compression. To avoid ripple artifacts in the superharmonic component of the tone-burst, the envelopes of the individually filtered third, fourth and fifth harmonic signals are combined in the time domain. The results indicate that the compressed superharmonic chirp, under a 20% FBW chirp excitation, show a 35% reduction in the axial pulse width at -20 dB when compared with the superharmonic of a tone-burst. Similarly using a 40% FBW chirp excitation, 65% reduction in the pulse width of the compressed superharmonic chirp has been found when compared with the superharmonic of a tone-burst.**

***Index Terms*—ultrasound imaging, superharmonic, linear frequency modulation, harmonic pulse compression.**

I. Introduction

Ultrasound diagnostic imaging based on the nonlinear second harmonic component is now the *de-facto* standard in clinical practice. A new ultrasound imaging technique called "superharmonic imaging" (SHI) was proposed in the recent years [1]. SHI relies on the third, fourth and fifth harmonic components of the nonlinear received signal. These higher order harmonic components are produced either due to the nonlinear propagation of ultrasound waves through biological tissue at high acoustic pressure [2] or by the nonlinear backscattering from ultrasound contrast agents insonated at their resonance frequency [3]. SHI provides improved axial and lateral resolution with reduced near-field and reverberation artifacts. Also by the incorporation of ultrasound contrast agents, it provides better contrast-to-tissue ratio (CTR) than the second harmonic imaging [4]–[6].

The main issues in the SHI are: low signal-to-noise ratio (SNR) of the higher order nonlinear harmonic components; spectral ripple artifacts in the superharmonic component; and the requirement of large transducer bandwidth and sensitivity to accommodate fundamental to fifth order harmonics of the nonlinear received signal. An interleaved phased array transducer having a -6 dB bandwidth of 144% was recently developed for SHI with improved transmission efficiency and better reception sensitivity [7]. A multi-pulse excitation scheme based on the frequency compound method was proposed in the area of SHI [8], [9]. This technique showed improved image resolution with suppressed ripple artifacts however it is susceptible to motion artifacts and reduced system frame-rate.

Coded excitation with linear frequency modulated (or chirp) signals offer the potential to improve the SNR of the higher order harmonics. Long duration chirp signals are able to carry more energy without increasing the peak excitation pressure and without reducing the system frame-rate. A matched filter, whose impulse response is the time reversed complex conjugate of the excitation signal, is typically applied on the received signal to perform pulse compression to achieve high axial resolution [10], [11].

In this paper, linear frequency modulated (LFM) signals are proposed as an excitation method to improve the SNR and axial resolution of the SHI. The rest of the paper is divided as follows: Section-II describes the excitation signals, experimental setup and the evaluation procedure of the received signals, the experimental results are presented in Section-III, and finally the achieved SHI performance using the proposed technique is discussed in Section-IV.

II. Experimental Investigation

A. Excitation Signals

The LFM chirp signal, $x(t)$, can be expressed as [12],

$$x(t) = W(t) \cdot \left\{ P \cdot \exp\left[j2\pi \left(\frac{B}{2T} t^2 + (f_c - \frac{B}{2}) t \right) \right] \right\}, \ 0 \leq t \leq T \tag{1}$$

where $W(t)$ is the windowing function, P is the peak excitation pressure, B is the bandwidth, T is the duration, and f_c is the centre frequency of the chirp signal.

In the experiments, chirp and tone-burst are used as an excitation signals. Chirp signals have a centre frequency of 2.25 MHz, duration of 10 μsec, and a -6 dB fractional bandwidths (FBW) of 20% and 40%. For comparison, a 2.25 MHz tone-burst signal of same duration is used as an

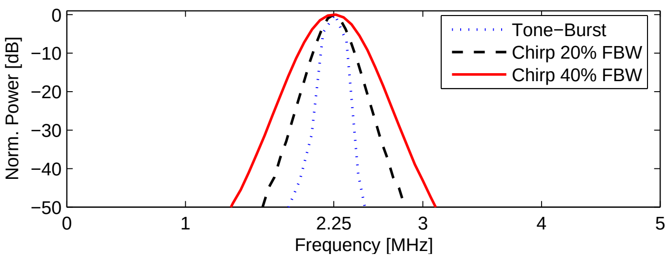

Fig. 1. Illustration of the power spectra of 20% FBW chirp, 40% FBW chirp and 2.25 MHz tone-burst excitation signals.

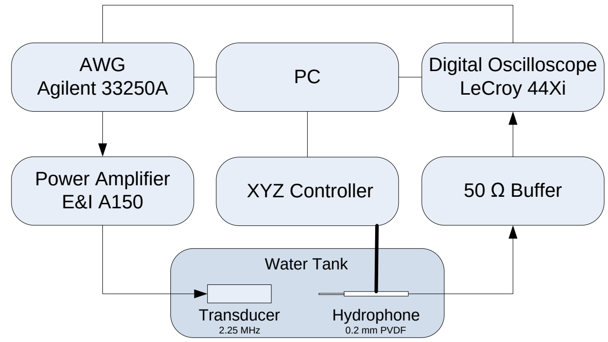

Fig. 2. Schematic diagram of the experimental setup.

excitation. The ripple artifacts in the signals' power spectra are reduced using a Hann window. The excitation signals and their power spectra are shown in Fig. 1.

B. Experimental Setup and Procedure

In order to validate the proposed method, experiments are performed to measure the harmonic components generated due to the nonlinear propagation of ultrasound waves through water. The experimental setup is shown in Fig. 2. The experiments are performed in a tank containing deionised, degassed water. The transducer and hydrophone are mounted coaxially in a pitch-catch configuration. An axial scan is performed between the depths of 1-10 cm using a custom built motion control system. A programmable function generator (33250A Agilent, 80 MHz, Santa Clara, CA, USA) is set to generate excitation signals. The signals are amplified by an RF power amplifier (A150 E&I, 55 dB, Rochester, NY, USA). The amplified chirp signals are transmitted by a 56% fractional bandwidth 2.25 MHz single element immersion transducer (V323-SM, Panametrics, Waltham, MA, USA). The nonlinear signals are detected using a needle-type Polyvinylidene Fluoride (PVDF) hydrophone with an active element diameter of 0.2 mm (calibrated from 1 to 20 MHz, Precision Acoustics Ltd., Dorchester, UK). The pressure level of each waveform is calibrated and the mechanical index (MI) of 0.75 (peak negative pressure of 1.125 MPa at 2.25 MHz) is set at the focus of the transducer. The pulse repetition frequency of the excitation is 100 Hz. The received signals are acquired at 1 GHz sampling rate using a digital oscilloscope (44Xi LeCroy, 400 MHz, Chestnut Ridge, NY, USA) with 32-times averaging. The captured data is stored in a computer and processed offline using MATLAB software (The MathWorks Inc., Natick, MA, USA). All received signals are corrected using an inverse filter designed in Matlab according to the frequency response of the hydrophone.

C. Design of Harmonic Matched Filters

The harmonic matched filter is used on the received signal to perform pulse compression of the individual harmonic chirp components. In this paper, the centre frequency and bandwidth of the desired harmonic matched filter is set by multiplying the centre frequency and bandwidth of the excitation signal with that harmonic number. Also the same windowing function is applied in the design of the harmonic matched filter as used in the excitation signal. Table I shows the centre frequencies and −6 dB bandwidths of the designed harmonic matched filters.

TABLE I
DESIGNED PARAMETERS OF HARMONIC MATCHED FILTERS

		Chirp 20%	Chirp 40%
	Centre Frequency [MHz]	Bandwidth [MHz]	
Fundamental	2.25	0.45	0.90
Second	4.50	0.90	1.80
Third	6.75	1.35	2.70
Fourth	9.00	1.80	3.60
Fifth	11.25	2.25	4.50

D. Processing and Performance Evaluation of the Superharmonic Component

In order to get the superharmonic chirp, the third to fifth harmonic components of the chirp signal are summed after pulse compression. To avoid ripple artifacts in the superharmonic component of the tone-burst, the envelopes of the individually filtered third, fourth and fifth harmonic signals are first calculated using a Hilbert transform and then summed in the time domain. For performance evaluation, the axial pulse width (axial resolution) of the time domain signal is measured at −20 dB and is expressed in microseconds. Also the peak sidelobe level (PSL) of the compressed chirp signal is measured by taking the ratio of the highest sidelobe level to the mainlobe level and is expressed in decibels.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The nonlinear signals received at a depth of 8 cm and their associated power spectra obtained using the Fourier transform are shown in Fig. 3. The nonlinear propagation at high acoustic pressure yields the distortion in the signal symmetry. This can be seen by comparing the positive and negative pressure peaks of the received signals. It is found that the compression pressure level is greater than the rarefaction pressure level of the signals. The figure shows that the generation of the higher harmonic components up to the order five in all the nonlinear

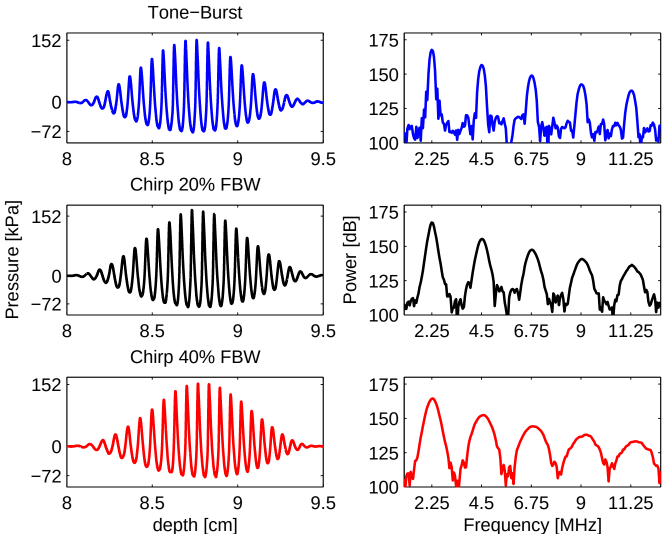

Fig. 3. The nonlinear signals received at a depth of 8 cm (left) and the associated power spectra (right).

received signals. The harmonics in the tone-burst spectrum are narrow-band and contain more ripples in their spectral gaps. However in the case of chirp signals, the peak harmonic amplitude and spectral ripples are reduced as a function of excitation bandwidth. Also increasing the bandwidth of the excitation will increase the bandwidth of the harmonics and will result in the overlapping between the higher orders harmonic components.

A comparison of the bandpass filtered harmonic signal envelopes obtained with a tone-burst excitation is shown in Fig. 4 where the signals are normalised with the fundamental frequency component. A comparison of the axial pulse width of the harmonic signals is shown in Table II. The results indicate that the superharmonic of a tone-burst provides a 31.6% reduction in the pulse width (improved axial resolution) when compared with the fundamental component. Similarly, a 15.6% reduction in the pulse width has been found in the superharmonic of a tone-burst when compared with the second harmonic component. Combining the third to fifth order harmonics not only will improve the axial resolution but also will improve the SNR. After this improvement in the SNR, the superharmonic component becomes comparable to the second harmonic component. A comparison of the PSL in the harmonic signals is shown in Table III. It is found that the PSL increases for the higher order harmonics. The PSL of the superharmonic tone is comparable to the third harmonic component.

A comparison of the chirp harmonics obtained after pulse compression with a 20% FBW chirp (chirp20) excitation is shown in Fig. 5. It is found that the superharmonic chirp20 provides a 57.6% reduction in the axial pulse width when compared with the fundamental component. Also a 30.3% reduction has been found in the axial pulse width of superharmonic chirp20 when compared with the second harmonic component. The PSL of the superharmonic chirp20 is comparable to the second harmonic component.

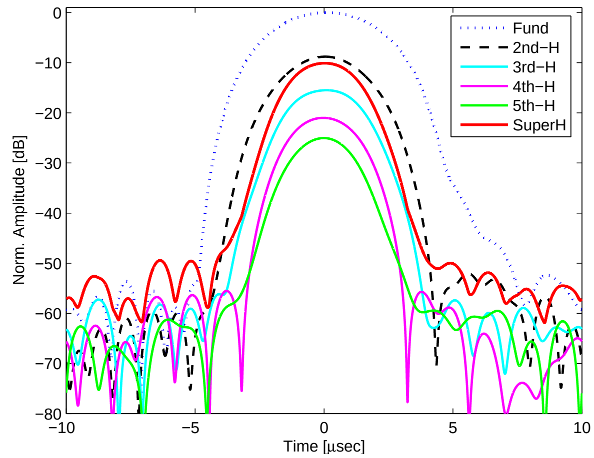

Fig. 4. Comparison of the filtered harmonic signal envelops obtained with a tone-burst excitation.

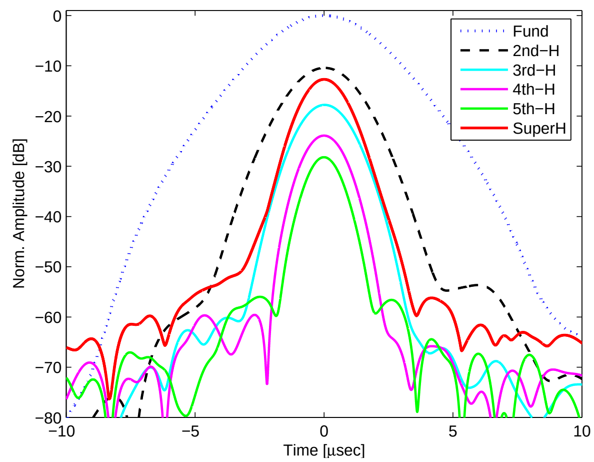

Fig. 5. Pulse compression comparison of the chirp harmonic signals obtained with a 20% FBW chirp excitation.

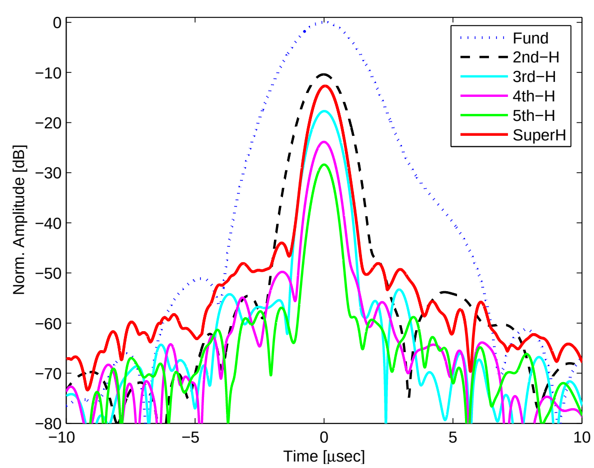

Fig. 6. Pulse compression comparison of the chirp harmonic signals obtained with a 40% FBW chirp excitation.

A pulse compression comparison of the chirp harmonics

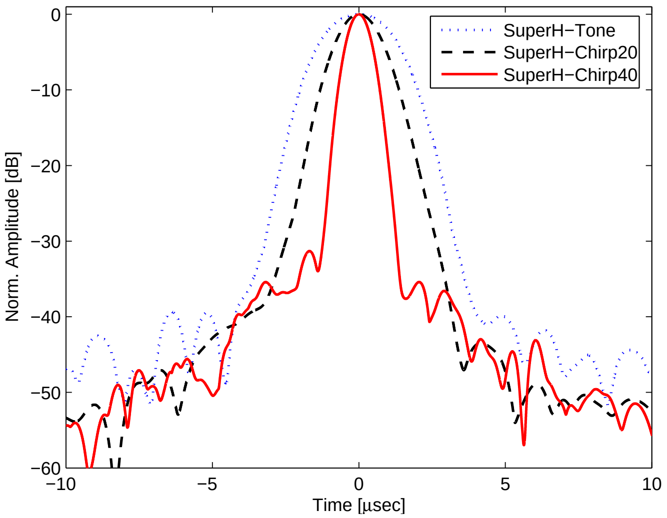

Fig. 7. Comparison of normalised superharmonic tone-burst and compressed chirp signals.

TABLE II
AXIAL PULSE WIDTH OF HARMONIC SIGNALS

	Pulse Width [μsec]		
	Chirp 20%	Chirp 40%	Tone-burst
Fundamental	9.2	5.1	7.9
Second Harmonic	5.6	2.9	6.4
Third Harmonic	4.3	2.1	5.7
Fourth Harmonic	3.3	1.7	5.1
Fifth Harmonic	2.9	1.5	5.0
Super Harmonic	3.9	2.0	5.4

TABLE III
PEAK SIDELOBE LEVEL OF HARMONIC SIGNALS

	Peak Sidelobe Level [dB]		
	Chirp 20%	Chirp 40%	Tone-burst
Fundamental	-64.7	-50.3	-52.3
Second Harmonic	-43.2	-43.3	-43.2
Third Harmonic	-42.3	-35.1	-40.6
Fourth Harmonic	-35.6	-26.4	-34.7
Fifth Harmonic	-27.2	-27.8	-34.4
Super Harmonic	-43.5	-31.5	-39.4

with a 40% FBW chirp (chirp40) excitation are shown in Fig. 6. The results indicate that the superharmonic chirp40 provides a reduction in the axial pulse width of 60.7% and 31% when compared with the fundamental and second harmonic components respectively.

A comparison of normalised superharmonic signals is shown in Fig. 7. The results indicate that the compressed superharmonic chirp20 shows a 35% reduction in the axial pulse width when compared with the superharmonic of a tone-burst. Similarly a 65% reduction in the pulse width of the compressed superharmonic chirp40 has been found when compared with the superharmonic of a tone-burst. It is found that the superharmonic chirp40 provides reduced pulse width due to the higher bandwidth excitation. However it contains higher PSL due to overlapping between the higher orders harmonic components.

IV. CONCLUSION

In this paper, linear chirp signals are proposed as an excitation method in the area of SHI. Chirp coded excitation can potentially enhance the SNR and axial resolution with reduced ripple artifacts in the SHI when compared with conventional tone-burst excitation.

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