Sources of 2nd harmonic generation in a medical ultrasound probe

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Abstract— **Tissue harmonic imaging is often the preferred ultrasound imaging modality due to its ability to suppress reverberations. The method requires good control on the transmit stage of the ultrasound scanner, as harmonics in the transmitted ultrasound pulses will interfere with the harmonics generated in the tissue during nonlinear propagation, degrading the image quality. In this study, a medical ultrasound probe used in tissue harmonic imaging was experimentally characterized for transmitted 2nd harmonic distortion. To investigate the phenomenon and push the system to the limit, transmit powers well above conventional operation level were tested. We observed transmit levels at the 2nd harmonic frequency up to -20 dB relative to the fundamental frequency. The transmit stage consists of high-voltage output electronics, cable, tuning network, and the acoustic transducer stack. By separating and measuring at different stages in the ultrasound transmit chain, the main source of 2nd harmonics in transmitted ultrasound pulses was identified as nonlinearities in the acoustic stack.**

I. INTRODUCTION

The principle of tissue harmonic imaging is transmitting an ultrasound pulse at one frequency and receiving echoes at the harmonics of this frequency, usually the second harmonic, generated from nonlinear propagation of wave in tissue. The method is vulnerable to undesired 2nd harmonics generated in the transmit stage of the ultrasound scanner, as this will interfere with the harmonics from the tissue. In practice, the transmitted level at the 2nd harmonic should be at least 25 dB lower than the level at the fundamental frequency. Transmitted 2nd harmonics are generated by nonlinear distortion, which normally increases with increasing transmit power. This distortion may originate from one dominant subsystem in the transmit chain, or it may be coupled from several parts in the system. The aim of this study was to carefully investigate the distortion in each part in the transmit chain of a clinical ultrasound probe, to identify sources of transmitted 2nd harmonics. This was done by separating and measuring electrical and acoustic signals at different stages in the transmit chain.

The transmit stage can be divided into two main parts, the driving electronics, and the electro-acoustic transducer. Nonlinearities in the driving electronics are purely electrical. Transducers in clinical ultrasound are usually arrays, where each element is an acoustic stack consisting of an active piezoelectric layer, backing, and acoustic matching layers. The piezoelectric material in the active layer can behave nonlinearly at high voltage excitation, and may introduce both dielectric, mechanical and piezoelectric non-linear effects. One manifestation of nonlinearity was demonstrated by Perez and Albareda[1], showing how the impedance in the piezoelectric material varied under high mechanical strain. Second harmonic generation was observed in displacement and particle velocity measurements, for both soft and hard type piezoelectric materials, working in both 31 and 33 mode at resonant frequency [2], [3]. For the passive materials used in the backing and matching layers, a nonlinear stress-strain relationship can become apparent at large strains, generating second harmonics in these layers as well.

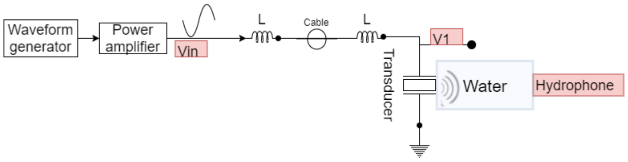

Fig. 1. Schematic of the ultrasound probe and measurement set up

The aim of this paper is to quantify and identify the sources of 2nd harmonic generation in a medical ultrasound system. First, the level of 2nd harmonics in pulses from a medical probe was measured using a hydrophone in a water tank. Then, the sources of the 2nd harmonic generation were sought by measuring electrical signals at various positions in the transmit chain, in a variety of experimental conditions.

II. METHODS

A. *Measurement of 2nd harmonic in transmitted ultrasound pulses*

Transmitted pulses from a medical ultrasound probe were measured by a hydrophone in a water tank. The probe consists of a cardiac phased array transducer with cable assembly containing an electrical tuning network for each element. In this study, only one element in the probe was used, this is referred to as the acoustic stack. The schematic can be found in Fig. 1. The transducer stack consists of an active layer of single crystal PMN-PT piezoelectric working in 3-3 mode, backing, matching layers, and an outer acoustic lens. The stack is connected to the excitation source by a shielded 2 m long coaxial cable. Each end of the cable contains a tuning inductor to optimize the electric energy transfer to the transducer.

One channel in the probe was driven by an arbitrary waveform generator (PicoScope 5244B, Pico Technology) connected to a power amplifier (E&I 2100L, Electronics

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& Innovation, Ltd). The excitation pulse was a Gaussian waveform with center frequency at the chosen transmit frequency. Acoustic pulses were measured using a calibrated hydrophone (HGL-0200, Onda Corporation) with an AG-2010 preamplifier connected to a digital oscilloscope (PicoScope 5244B). The aim of the study was to identify nonlinearities in the transmit chain, hence, nonlinear distortion from propagation in water had to be minimized. This was done by placing the hydrophone as close as possible the probe surface, at 4 mm. In addition, by using only one element in the probe, the acoustic pressure was kept below 0.5 MPa even at the maximum driving voltage level. The input excitation was scaled in the waveform generator to change the driving voltage. The actual voltage over the transducer stack was measured using the Pico oscilloscope with an x10 probe (TA386).

B. Search for sources of 2nd harmonic distortion

The following candidates were investigated with the aim of identifying the main source of the observed 2nd harmonic in the acoustic pulses:

1) Waveform generator and power amplifier
2) Inductors in the tuning network
3) Acoustic stack
4) Propagation of the ultrasound pulse in water
5) Hydrophone with preamplifier

1) Waveform generator and power amplifier: The function generator and power amplifier were selected to have low distortion, stated to -40 dB in the relevant frequency range. The 2nd harmonic level was measured to below -50 dB, into a 50 Ohm terminator, at the highest voltage level. Hence, the output of the power amplifier can be considered linear.

2) Tuning inductors: Inductors with core material other than air are known to be nonlinear at high currents, due to saturation of the magnetic flux density in the inductor core. This saturation is independent of current direction. Hence, this distortion is symmetric, creating mainly odd harmonics. However, asymmetric saturation may occur at very high current levels, creating also 2nd harmonics. Nonlinear distortion from the inductors was tested by replacing each of the two tuning inductors in Fig. 1 with four inductors of identical type, connected as shown in Fig. 2). This gives the same inductance while reducing the current through and voltage over each inductor by a factor 2. If the 2nd harmonics observed in transmitted pulses are caused by the inductors, the level should be reduced in this arrangement.

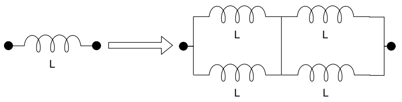

Fig. 2. Replacement of 1 inductor by a constellation of 4 inductors. The inductance value is the same but the voltage and current decrease by half.

3) Acoustic stack: Nonlinearity in the acoustic stack was checked by replacing the stack with a passive electric load having similar electrical impedance. If the voltage V1 measured over this dummy load, see Fig. 1, contains no 2nd harmonic, the electric transmit chain, i.e. generator, amplifier, tuning and cable assembly, cannot be the source of the observed 2nd harmonic. In other words, the 2nd harmonic in transmitted pulses must come from the acoustic stack, propagation in water, or the hydrophone.

4) Simulation of propagation in water: Ultrasound pulse propagation through water is nonlinear, this is actually the basis for doing harmonic imaging. Sufficiently accurate measurements of 2nd harmonics generated when ultrasound pulses propagate in water would require a source known to be linear. Such a source is not easy to obtain. Instead, the generation of 2nd harmonics by propagation through water was simulated using the nonlinear ultrasound model in the Matlab toolbox *k-Wave*[4], using the k-space pseudo spectral method [5]. The accuracy of k-wave for estimating 2nd harmonics through nonlinear propagation in water has been confirmed in [6].

A 5-cycle sine wave enclosed in a Gaussian envelope was used as the input pressure at the source in the k-wave simulation. The pressure amplitude at the source was selected so that the simulated pressure at 4 mm has the same positive peak pressure, 0.5 MPa, as the measured pressure at this position.

5) Hydrophone and preamplifier: A hydrophone should be linear, and no information of nonlinearity was provided by the manufacturer. If present, hydrophone nonlinearity might occur at very high received pressure, hence, it is important to investigate the 2nd harmonic level at the highest pressure used in this study. As a linear reference source was not available, the probe under test was used to generate a reference pressure pulse. Instead of using only one element in the array, several elements were excited, and the beam was focused at the hydrophone. By this method, it was possible to create pulses having the same pressure amplitude at the hydrophone, while driving the elements with much a much lower excitation voltage.

III. RESULTS

A. Second harmonic in the transmitted pulses

The transmit pulse, measured by the hydrophone, is shown in Fig. 3. A 5-cycle sine wave enclosed in a Gaussian envelope was used to drive the transducer element. The pulse length of 5-cycle is longer than typical imaging pulses, and was chosen to create a narrow bandwidth, making it easier quantify the 2nd harmonic level. The received pulses and spectra for three input voltage amplitudes are shown, 5 V, 40 V, and 80 V, The spectra in Fig. 3 show a distinct peak at the 2nd harmonic frequency for the two highest driving voltages. For the highest voltage, 80 V, this peak is 20 dB below peak at the fundamental.

B. Second harmonic from different components in the transmit chain

Replacing each inductor in the tuning circuit by the group of 4 inductors shown in Fig. 2 caused no measurable difference in the received pulses for any driving voltage.This rules out the inductors as source of the observed 2nd harmonic.

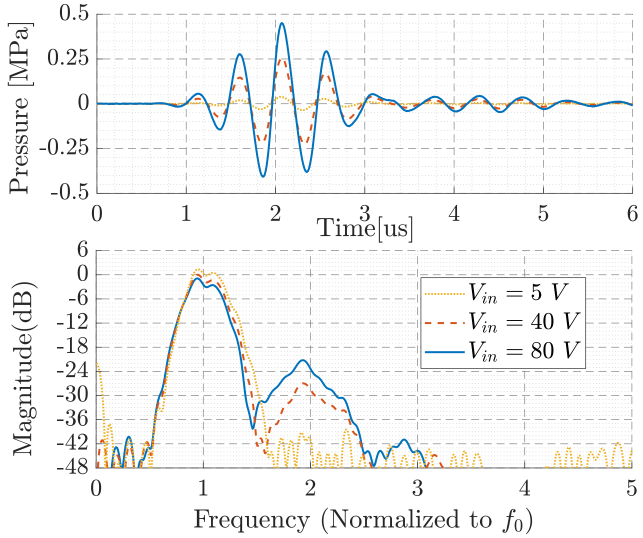

Fig. 3. Acoustic pressure measured 4 mm from the transducer surface, for different excitation voltages. Distinct peaks are seen at the 2nd harmonic frequency for the two highest driving voltages. The spectrum were normalized to the input voltage amplitude.

TABLE I

ACOUSTIC PARAMETERS OF WATER USED IN THE K-WAVE SIMULATION.

c_0 $[m/s]$	ρ $[kg/m^3]$	B/A	α_0 $[dB/(MHz^y cm)]$	y
1496	997	5.2	0.0019	2

The voltage V1 measured over the acoustic stack (Fig. 1) is shown in Fig. 4. For high transmit voltages, a strong 2nd harmonic peak (-25 dB) is seen (dashed lines in Fig. 4). When the acoustic stack was replaced by a passive load with similar impedance, no peak at the 2nd harmonic could be seen, for any driving voltage. The level at the 2nd harmonic is at the noise floor, 45 dB below the level at fundamental the frequency (solid lines in Fig. 4). This dummy load was selected to give similar electrical loading, i.e. current and voltage, as the active transducer element. From this result, it is concluded that the electrical transmit circuits, consisting of the generator, power amplifier, and tuning network, behave linearly at even the highest driving voltages, and do not contribute to the 2nd harmonic in the transmitted pulse.

The 2nd harmonic from propagation through the water was estimated from simulations in k-wave, run over a region measuring 3.2×12.8× 6.4 mm (x×y×z, where z is the beam axis), terminated by a perfectly matched layer with thickness 0.5 mm. The grid point spacing was 25 um and the aperture equal to the transducer size. The acoustic lens focusing at 86 mm in elevation in the actual probe was also included in the simulation. Typical acoustic parameters for water were used, these are listed in (Table. I). The simulation results are presented in Fig. 5. After 4 mm of propagation, the simulated second harmonic level was at -35 dB relative to the fundamental frequency, i.e. far below the measured value.

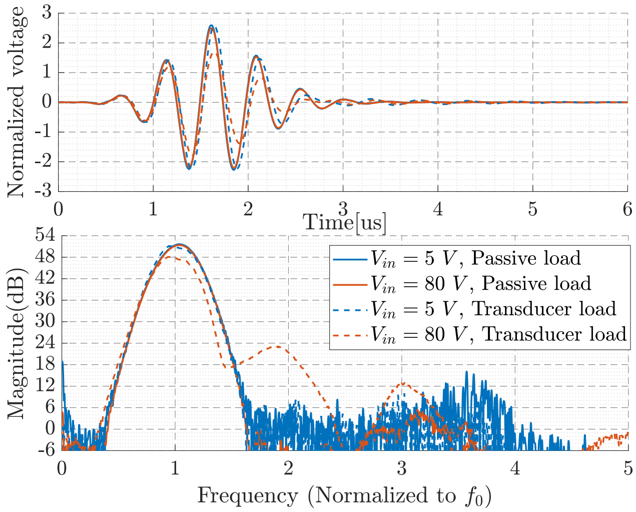

Fig. 4. Voltage measured over the acoustic stack, and after replacing the stack with a passive load of similar impedance. No 2nd harmonic peak can be seen when using the passive load (solid curves). For the transducer load (dashed curves), peaks are seen both at the 2nd and 3rd harmonics. The voltages in the time domain were normalized to the input voltage amplitude.

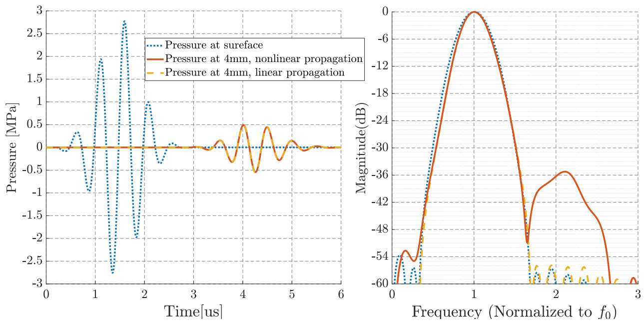

Fig. 5. K-wave simulation of 2nd harmonic from propagation acoustic axis at 4 mm. The maximum pressure at 4 mm (solid-red) is 0.5 MPa, as in the measurement. This result predicts a 2nd harmonic level from nonlinear propagation 35 dB below the level at the fundamental frequency.

Finally, the nonlinearity in the data acquisition system, including the hydrophone, amplifier, and oscilloscope was examined. An ultrasound scanner with a 3-level pulser (Vivid E95, GE Healthcare) which can give control on the active aperture and focusing of the probe was used the excite the probe. The excitation waveform was a 5-cycle square wave. Low excitation voltage was used to avoid nonlinearity in the probe. The driving voltage was much lower than in single-element experiments, but adjusted to give the same pressure level. This was achieved by exciting 16 elements and focusing the beam at the hydrophone. Two transmitted pulses, created by exciting either 1 or 16 elements in the probe, were measured, the results are shown in Fig. 6. This shows that the acquisition system can record a pulse 2nd harmonic level -33 dB. This includes all possible sources of 2nd harmonics in the measurement chain. Therefore, the distortion at the 2nd harmonic in the acquisition system must be less than -33 dB.

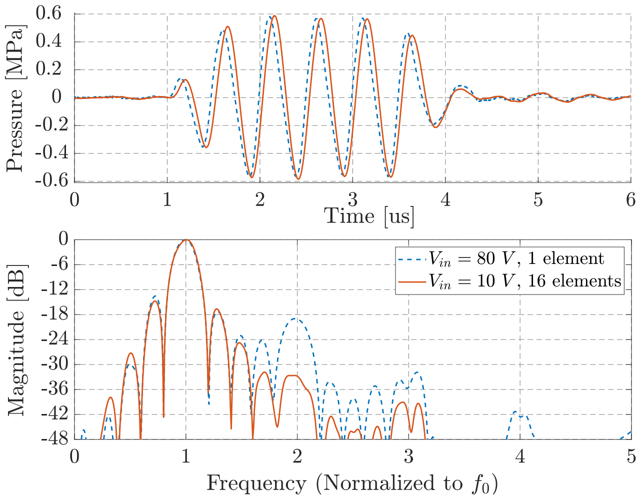

Fig. 6. Pressure measured by the hydrophone, when exciting 1 or 16 elements in the probe, and adjusting the driving voltage to give similar output pressure level.

IV. DISCUSSION

If assuming a worst-case scenario, the maximum 2nd harmonic levels from the electrical circuit, -45 dB, water propagation, -35 dB, and the hydrophone, -33 dB, can add up to -27 dB, if all contributions are in phase. A more realistic scenario is incoherent summing, this would give -31 dB. The measured 2nd harmonic level in the transmitted pulse is -20 dB. This cannot be explained by any combined effect of the three sources above, and it is concluded the main source of 2nd harmonic in the pulse must be nonlinearity in the transducer stack.

The 2nd harmonic level in the acquisition system,-33 dB, may be overestimated because it also includes the SH of the transducer which is considered the dominance.

All measurements were done at room temperature using 5-cycle pulses. These short pulses help the temperature in the transducer element during the measurement does not significantly increase. The pulse repetition frequency was 100 Hz, giving the transducer sufficient time to return the ambient temperature between each pulse. The pulse repetition frequency of 1 Hz was also tested at the highest voltage and indistinguishable results were obtained, meaning 100Hz is efficient. Also, the transducer surface was in water during measurement, further increasing heat dissipation away from the transducer. Hence, temperature effects during the measurements were considered negligible.

The maximum electric field in the active layer, single crystal PMN-PT, was about 5.8 kV/cm. As strong electric field can depole and damage the transducer if higher than coercive field of the material used in the stack. The coercive field in single crystal PMN-PT is not well characterized at the frequency ranges used in medical ultrasound. A coercive field of 3.5 kV/cm for $< 001 >$ oriented 0.67PMN-0.33PT was measured by Wei-Gen [7] using of 2 ms wide triangular pulses, i.e. a much lower frequency than what is used in medical diagnostic imaging. If the transducer is depoled, its electrical impedance curve will permanently change. In this study, the impedance of the transducer was measured before and after the experiment, giving identical results. This verifies that no permanent depoling did occur.

Perez and Albareda [1] reported that mechanical nonlinearity was the dominating nonlinear mechanism in the piezoelectric material, as a low electric field can create high strain at resonance. In this study, the mechanical load consisting of an acoustic lens and water was higher, and a higher electric field was needed to create the high strain and resulting pressure. Hence, the result from [1] may not be transferable, and nonlinearity in both dielectric, piezoelectric and mechanical coefficients should be considered. This study cannot distinguish between effects from these mechanisms. Nonlinear effects in the other layers in the acoustic stack, backing and matching, and in the bonding layers between them, may also be sources of important.

V. CONCLUSIONS

We have measured 2nd harmonic levels in pulses transmitted from a clinical ultrasound probe of up to -20 dB relative to the fundamental frequency, at distance 4 mm and acoustic pressure level 0.5 MPa. Investigation of the possible sources for this nonlinearity ruled out the transmitter electronics, tuning inductors, and propagation through the water, leaving the electro-acoustic transducer stack as the only main source of the nonlinearity. When the acoustic stack was replaced by a passive load of similar electrical impedance, the level of 2nd harmonic dropped down to the noise floor. We conclude that nonlinearity in the acoustic stack is the source of the observed 2nd harmonic, distorting the driving voltage, and causing a peak at the 2nd harmonic in the transmitted pulses.

Note that the driving voltages were well above what is used in a clinical scanner, as they were selected to investigate the phenomenon and push the system to the limit.

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