Bias voltage modulation methods and its optimization for nonlinear contrast imaging

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Abstract* — *The main difficulty in applying ultrasound contrast imaging techniques with cMUT probe comes from the intrinsic nonlinearity of the transducer itself. An approach has been developed in order to adapt the amplitude modulation techniques (AM) to cMUTs. Bias Voltage Modulation (BVM)[1] allows a complete cancellation of the echoes from linear reflectors and thus an enhancement of the contrast agent detection. The main limit is that it can only be applied with low bias voltage, far from the maximum of the probe sensitivity (i.e. at the collapse). Here is proposed an optimization of the BVM sequence allowing a good compensation of cMUT intrinsic nonlinearity even at high bias voltages.

Index terms* - *Biomedical sensors, Contrast agents, Ultrasound.

I. INTRODUCTION

Contrast agents for ultrasound imaging (UCA) is routinely used in many fields of medical diagnosis as for example: tumor detection and echocardiography. In ultrasound imaging, the contrast agents are made of gas-filled microbubbles. These agents are intravenously injected in the patient. Because of their high acoustic impedance compared to the tissue, microbubbles enhance the backscattered signal received from the blood. Moreover, exciting theses microbubbles close to their resonance frequencies induces a strong nonlinear behavior compared to biological tissue. Thus, to detect UCA with a high sensitivity, current detection techniques are based on this nonlinear property, by detecting harmonics scattered by the microbubbles, Second Harmonic, Super Harmonics or Subharmonics. To improve the enhancement of the signal from UCA and suppress tissues' echoes, multi-pulses sequences have been proposed such as Pulse Inversion (PI), Amplitude Modulation (AM) or the combination of the two (PIAM). The purpose is to transmit two consecutive pulses with different phases or amplitudes and use a combination of their echoes to suppress the linear response from the tissue.

Over the past few years, Capacitive Micromachined Ultrasonic Transducers (cMUTs) have emerged as a promising alternative to traditional PZT transducers. For Ultrasound Contrast Imaging, the wide frequency bandwidth of the CMUTs is a valuable advantage. However, these transducers are highly nonlinear and thus, their use in the contrast imaging approaches is compromised. PI method has been adapted for cMUT probe by adding a third pulse or by alternating the bias voltage polarity. Recently, a new method called Bias Voltage Modulation (BVM) has been proposed [1] based on the classical AM method. This method allows a complete cancellation of the response of linear reflectors and an enhancement of microbubble echoes but can only be applied with low bias voltage amplitudes, much below the collapse voltage of the CMUT, where the sensitivity of the emitter in this regime is much higher. We proposed here an adaptation of the BVM method for cMUTs where the method can be fully exploited at bias voltage close to the collapse voltage, allowing hence an increase of the signal to noise ratio (SNR) and of the contrast to tissue ratio (CTR).

II. MATERIALS AND METHODS

II.1. Bias Voltage Modulation

The method used here follows the principle of the BVM sequences [1]. The applied voltage V(t) is expressed as:

$$V(t) = v_{ac}\cos(2\pi f_0 t) + V_{dc}$$

As a result, the electrostatic force on the membrane is proportional to:

$$F\ \alpha\ \frac{{v_{ac}}^2}{2} + {V_{dc}}^2 + 2V_{dc}v_{ac}\cos(2\pi f_0 t) + \frac{{v_{ac}}^2}{2}\cos(4\pi f_0 t)$$

As shown by the theory, a change in the bias voltage does only imply a change in the fundamental component. Three successive pulses are transmitted with different bias voltage amplitudes (A, (λ+1)A and (2λ+1)A with λ a constant). The classical BVM method is obtained with λ=1. The excitation voltage (v_{ac}) remains the same for the three pulses. Theoretically, using the cMUT probe in pulse-echo mode, responses from a linear reflector to the three pulses described above can be written as:

$$E1 = \alpha\cos(2\pi f_0 t) + \beta\cos(4\pi f_0 t)$$
$$E2 = (\lambda+1)\big((\lambda+1)\alpha\cos(2\pi f_0 t) + \beta\cos(4\pi f_0 t)\big)$$
$$E3 = (2\lambda+1)\big((2\lambda+1)\alpha\cos(2\pi f_0 t) + \beta\cos(4\pi f_0 t)\big)$$

Where α and β are constant. Thus, the following operation allows a complete cancelation of the echoes from a linear reflector.

$$E3 + (1+2\lambda) * E1 - 2\frac{1+2\lambda}{1+\lambda} * E2$$

The previous equation became the same as in the classical method in pulse-echo mode for λ=1.

II.2. **Experimental setup**

A 128-element cMUTs linear array (Vermon SA, Tours, France) centered at 4.5 MHz is connected to an open scanner equipped with analog transmitters (M2M, Les Ulis, France). The fractional bandwidth of the probe as measured at -3 dB is 99% and the collapse voltage is estimated at 105 V. Characterization of the ultrasonic beam of the probe is performed with a needle hydrophone (Precision Acoustics, Dorchester Dorset, UK). Flow phantom imaging is carried out using a tissue mimicking Doppler phantom (ATS Laboratories, Bridgeport, CT) with a solution of SonoVue microbubbles (Bracco Research, Geneva, Switzerland). For all pulses, the transmit frequency is set at 3 MHz and the excitation voltage at the maximum value delivered by the open scanner (v_{ac}=40 V_{peak}). The emission is dynamically focused at 20 mm from the probe.

Two different parameters are calculated: the signal to noise ratio (SNR) and the Contrast to tissue ratio (CTR).

III. RESULTS

Ultrasound images are reconstructed from linear scanning of the phantom. Bandpass numerical filters are applied on the RF lines in order to recover the fundamental or the harmonic part of the signal. Figure 1 show four different images from the same section of the flow phantom. The bias voltage is set to 90 V for the images obtained with fundamental approach (Figure 1.a) and with harmonic approach (Figure 1.b). A sequence of three pulses with bias voltage at 30, 60 and 90 V is applied for classical BVM (Figure 1.c). For optimized BVM approach (Figure 1.d) a sequence of pulses with bias at 70, 80 and 90 V is applied.

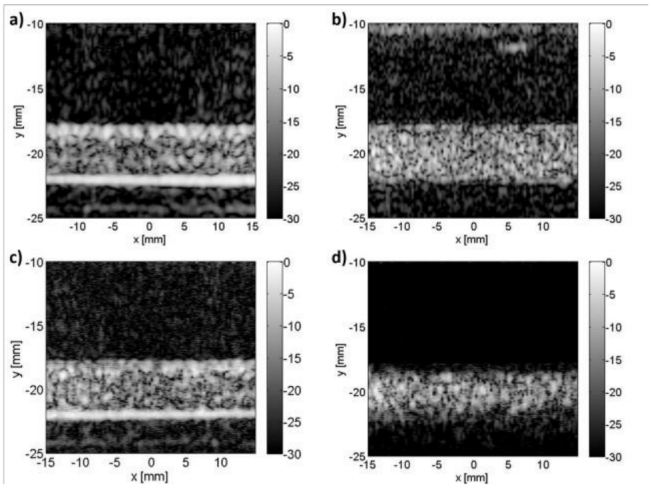

Figure 1: Linear ultrasound images of a flow phantom filled with circulating microbubbles. Images are filtered around fundamental component (a), harmonic component (b), compensated with classical BVM sequences (c) and with optimized BVM sequence (d). In order to compare the results for each method, SNR and CTR are calculated and reported in Table 1.

Method	SNR [dB]	CTR [dB]
Fundamental	12.1	-6.4
Harmonic	17.0	3.6
BVM	15.9	-3.6
Optimized BVM	24.7	16.5

Table 1: SNR and CTR calculated for the different tested methods.

IV. DISCUSSION – CONCLUSION

Improvement of BVM method can be seen both on the CTR and SNR. Because of the high bias voltage used (≈90% of collapse voltage), it is not surprising that BVM method does not suppress the tube membrane considered as a linear reflector (Fig. 1c). SNR and CTR of classical BVM method is simply increased by 3 dB compared to the fundamental image. Harmonic image has a CTR and a SNR higher than in BVM method. This is due to the removal of the fundamental and higher harmonic components. There is not a complete cancelation of the tube membrane echo because of the cMUT non-linearity that is not fully compensated. Finally, a great improvement of both CTR and SNR can be seen for the optimized BVM sequence. Using bias voltage amplitudes close from one pulse to another minimizes the error on the compensation and provides a much higher CTR (22 dB higher than for the fundamental). Moreover, the high sensitivity of the probe at bias voltages equal to 70, 80 and 90 V allows an increase of the SNR by 12 dB.

In this study, an innovative method for the compensation of cMUT nonlinearity is presented. This method allows to use cMUT probe at their maximum of sensitivity. All these results demonstrate that the problem of cMUTs nonlinearity can be addressed without lowering other key parameters of contrast imaging such as temporal resolution or frame rate. Further investigations include the *in-vivo* validation of the BVM sequence.

ACKNOWLEDGMENTS

We would like to acknowledge Bracco Research, Geneva for supplying contrast agent and the Agence Nationale pour la Recherche (ANR-11 TecSan-008–01 BBMUT) for the financial support.

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