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Dynamic nonlinear focal shift in amplitude modulated moderately focused acoustic beams

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ABSTRACT

The phenomenon of the displacement of the position of the pressure, intensity and acoustic radiation force maxima along the axis of focused acoustic beams under increasing driving amplitudes (nonlinear focal shift) is studied for the case of a moderately focused beam excited with continuous and 25 kHz amplitude modulated signals, both in water and tissue. We prove that in amplitude modulated beams the linear and nonlinear propagation effects coexist in a semi-period of modulation, giving place to a complex dynamic behavior, where the singular points of the beam (peak pressure, rarefaction, intensity and acoustic radiation force) locate at different points on axis as a function of time. These entire phenomena are explained in terms of harmonic generation and absorption during the propagation in a lossy nonlinear medium both for a continuous and an amplitude modulated beam. One of the possible applications of the acoustic radiation force displacement is the generation of shear waves at different locations by using a focused mono-element transducer excited by an amplitude modulated signal.

1. Introduction

The study of the acoustic field generated by focusing sources in the nonlinear regime is a continuously developing area of research as finite amplitude sound beams are increasingly used in medicine and industry [1–5]. Nonlinear propagation implies asymmetric wave steepening, progressive harmonic generation, nonlinear absorption, sound saturation, self-refraction and self-demodulation [6]. All these nonlinear effects change the spatial distribution of the acoustic field with respect to the linear case, i.e., among other things, the location of the on-axis peak compression and rarefaction pressure, intensity and acoustic radiation force (ARF), as well as the focal spot dimensions.

The nonlinear focal shift phenomenon, defined as the shift of the maximum pressure (and also intensity and ARF) position along the axis of focused acoustic beams under increasing driving voltages, has been discussed and interpreted in previous works. In 1980 Bakhvalov et al. [7] predicted a shift in the position of the on-axis pressure maximum in unfocused beams where a migration of the location of the maximum was shown, first away from, and then towards the transducer, as the exciting voltage of the source was increased. Duck and Starritt [3] (1986) studied this phenomenon in slightly focused sources, such as those used in commercial medical pulse-echo devices, showing that the nonlinear focal shift exists for on-axis maximum and negative pressure, with different behavior. Averkiou and Hamilton [8] (1997) observed this phenomenon experimentally in a moderately focused piston (linear gain $G = p/p_0 = 10.36$ with p is the value of the pressure at the geometrical focus and p_0 the pressure at the surface of the transducer). The nonlinear focal shift phenomenon was reported by Makov et al. [9] in low gain transducers, and discussed in terms of the harmonics nonlinearly generated during the propagation of a finite amplitude wave. They also provided experimental evidence of the nonlinear shift in slightly focused transducers ($G = 4$). Bessonova et al. [10] reported a numerical study which the nonlinear focal shift is shown for a moderately focused piston ($G = 10$) in a range of intensity covering both the shift of the maximum pressure towards the geometrical focus at first, even passing beyond the focus, and then the shift backwards to the transducer. They also provided an interpretation of the phenomenon based on the self-defocusing effect due to the asymmetrical distortion of the wave

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profile and to the increase in propagation velocity of the compressive phase of the wave close to the beam axis. Recently, Camarena et al. [11] proved experimentally that at high amplitudes and for moderate focusing ($G = 18.8$) the position of the on-axis pressure maximum and radiation force maximum can surpass the geometrical focal length.

The location of the singular points of a focused ultrasonic beam, i.e., the on-axis maximum and negative pressure, maximum intensity and ARF, depends on the nonlinear degree of the propagated waves. This is especially relevant in moderately-focused beams since the focusing is high enough to make the nonlinear effects relevant, but at the same time the transversal area of the focus is not as small as in highly focused devices, making the self-refraction effect to play an important role [6,11]. The singular points of a beam (as for example the location of the maximum ARF) generated by a moderately focused mono-element emitter can be moved just by raising the amplitude of the voltage applied to the source. One of the applications that comes to mind is to generate a supersonic source of shear waves [12] with a focused mono-element transducer for elasticity imaging applications.

The adjustment of the focusing degree of the source and the modulation of the ultrasound amplitude are important tools that enable researchers to plan new treatments and monitoring, and consequently, the nonlinear shift effect must be taken into consideration. This is especially relevant in procedures that seek to reduce the degree of focusing of the ultrasonic source in order to increase the volume of the region treated, as it is in the case of ultrasonic-assisted blood-brain barrier opening techniques [13], which is particularly sensitive, taking into account that the frequencies used are lower than 500 kHz (making diffraction play a more important role) or in hyperthermia [14], if the whole tumor has to be sonicated. Also, monitoring procedures based on the modulation of the excitation amplitude of the emitter, such as HMI [15], should consider the nonlinear shift if at any time they reduce the focusing degree.

The aim of this work is to investigate experimentally and numerically the dynamic behavior of the singular points of a moderately focused beam operating from linear to nonlinear regime, and excited with amplitude modulated (AM) and continuous signals. Both water and soft tissue (human liver) media were considered. The paper is structured as follows: in Section 2 the experimental set-up and methods are described, providing a linear characterization of the beam and adjusting the source parameters to obtain the numerical results. Section 3 gives the experimental and numerical results for the maximum focal displacement in water (Section 3.1) and the dynamical focal shifts for a 25 kHz AM beam (Section 3.2). In Section 3.3 the study is numerically extended to propagation in soft tissue (human liver). Finally, the concluding remarks are given in Section 4.

2. Materials and methods

2.1. Experimental set-up

The experimental set-up for the pressure measurements in water follows the classical scheme of confronted emitting focused source and receiving calibrated membrane hydrophone, located inside a 0.75 × 0.6 × 0.5 m water tank filled with degassed and distilled water at 26°, as shown in Fig. 1. The ultrasound source was formed by a plane single element piezoceramic crystal (PZ 26, Ferroperm Piezoceramics, Denmark) mounted in a custom designed stainless-steel housing and a poly-methyl methacrylate (PMMA) focusing lens with aperture $2a = 50$ mm and radius of curvature $R = 70$ mm. The resonant frequency of the transducer was $f_0 = 1.112$ MHz, and it was driven by a signal generator (14 bits, 100 MS/s, model PXI5412, National Instruments) and amplified by a linear RF amplifier (ENI 1040L, 400 W, +55 dB, ENI, Rochester, NY). The pressure field was measured by a PVDF membrane hydrophone with a 200 μm active diameter (149.6 mV/MPa sensitivity at 1.112 MHz, Model MHB-200, NTR/Onda) calibrated from 1 MHz to 20 MHz). The hydrophone signals were digitized at a sampling rate of 64 MHz by a digitizer (model PXI5620, National Instruments) averaged 500 times to increase the signal to noise ratio. An x-y-z micro-positioning system (OWIS GmbH) was used to move the hydrophone in three orthogonal directions with an accuracy of 10 μm. All the signal generation and acquisition process was based on a NI8176 National Instruments PXI-Technology controller, which also controlled the micro-positioning system. Temperature measurements were performed throughout the whole process to ensure no temperature changes of ±0.6 °C.

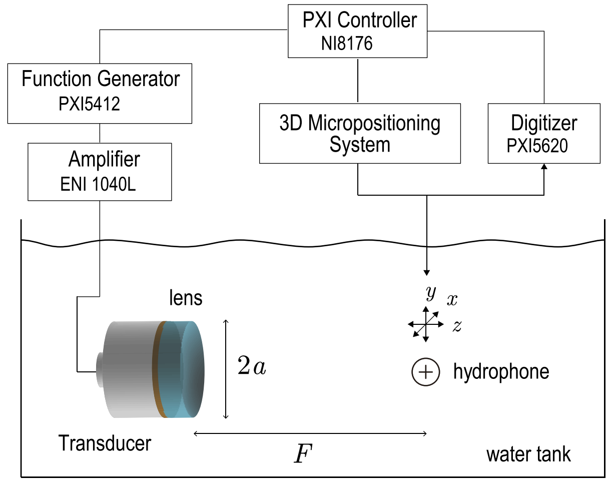

Fig. 1. Scheme of the experimental set-up for the pressure measurement in water.

2.2. Linear characterization of the beam

To accurately determinate the position of the radiator axis, a variant of the procedure described in Cathignol et al. [16] was developed. Firstly, the transducer was oriented along the z-axis of the micro-positioning system. In order to find the focal region of the transducer, the maximum pressure distribution generated by a 20-cycles sinusoidal pulsed burst was measured along the axis of the radiator. These measurements provided a rough estimation of the transducer focal area. Then, the pressure waveforms $p(t, x, y, z)$ were measured at the focal area in five planes along the z axis of the micro-positioning system, separated $\Delta z = 5$ mm. Waveforms were acquired along these planes in planes of 6 mm × 6 mm (x-y directions) at 0.5 mm spatial resolution (144 measurement points per plane). To avoid nonlinear effects in the propagation, low input voltage was employed ($V_0 = 6\,V_p$). Zero-gain band-pass filter was employed using an eight-order bandpass filter with cut-off frequencies $f_{\mathrm{low}} = 0.91$ and $f_{\mathrm{high}} = 1.31$ MHz to increase the signal-to-noise ratio and to avoid introducing any temporal delay in the signals. The maximum of each period of the 20-cycle tone burst was evaluated. The maximum of each waveform was then selected as the mean value of these 20 maxima. The equipressure curves in each plane built with the selected maxima typically had a circular form: This was indicative of the good axial symmetry of the radiator. Finally, the coordinates (x-y) of the maximum and the z position of each transversal plane were used for fitting a 3D line that determines the acoustic axis.

A set of 63 signals was measured on the previously determined radiator axis (dots in Fig. 2) using an input voltage at the trans-