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Parametric array signal in confocal vibro-acoustography

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ABSTRACT

In vibro-acoustography imaging systems, two ultrasound beams of distinct frequencies are employed to form an image of biological tissue at the difference-frequency. Three mechanisms contribute to the difference-frequency pressure, namely induced acoustic emission by a time-modulated radiation force, parametric array signal due to the superposition the beams along the propagation direction, and interaction of sound-with-sound effects. We analyze the strength of parametric array signal generated by a vibro-acoustography system composed of a two-element confocal transducer driven by two sinusoidal signals with center frequency 3.2 MHz. A 1-mm diameter tungsten sphere, placed at the transducer's focus, is used as the target object. We measure the difference-frequency pressure in water at room temperature with a calibrated hydrophone. The measurements are taken along the beam's axis in the farfield. In this configuration, the difference-frequency signal is mostly due to the parametric array phenomenon. Additionally, the acoustic emission and interaction of sound-with-sound signal levels are theoretically estimated. They are, respectively, 33 and 20 dB below the parametric array signal.

1. Introduction

Vibro-acoustography is an imaging method that uses two or more co-focused ultrasound beams at slightly different frequencies in the MHz-range to form an image of biological tissue [1,2]. The ultrasound beams are scanned across a region-of-interest within human or animal body. A difference-frequency pressure in the kilohertz-range arises in the medium due to nonlinear interaction of the ultrasound beams, which comprises parametric array [3–5], interaction of sound-with-sound [6,7], and induced acoustic emission [8] by a time-modulated radiation force [9–13]. The difference-frequency pressure is measured by a sensitive hydrophone. The resulting electric signal is digitally processed to form vibro-acoustography images.

Many studies have shown that vibro-acoustography is a promising method for imaging of pathological abnormalities. Some examples include calcium deposits on heart valve leaflets, liver lesions, characteristics of bone fracture and large peripheral arteries, prostate cryotherapy, kidney stones, microcalcification of the breast, and prostate brachytherapy seeds [14,15], or acting as post-operative image method for assessing metal implants [16]. Moreover, it has been used to analyze vibrations in material structures [17], and map the distribution of ionizing radiation [18].

Vibro-acoustography image formation was analyzed based on the induced acoustic emission by a time-modulated acoustic radiation force exerted on inclusions in the medium [8,19]. However, only a qualitative description of the system point-spread function, which determines the system response to a point source, was provided [20]. The presence of parametric array signal in a vibro-acoustography set-up in a water tank was previously studied in Ref. [21]. Nevertheless, the analysis was limited to the difference-frequency at 10 kHz with 200 ms acquisition time. In this set-up, the detected signal is prone to interference with the difference-frequency standing-waves developed in the water tank. To avoid such interference, vibro-acoustography images are formed with the difference-frequency above 30 kHz. In another study, the influence of interaction of sound-with-sound seems to have a significant role in confocal vibro-acoustography systems [22]. Although, a parametric array analysis was left out in that investigation.

Despite initial efforts in explaining image formation, a deeper comprehension on the parametric array effect in vibro-acoustography is still needed. This will certainly lead to improvements on vibro-acoustography beamforming [19,20,23–27]. Furthermore, the development of image enhancement algorithms [28,29] also depends on understanding parametric effects.

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Here we investigate the parametric array effects in confocal vibro-acoustography from both theoretical and experimental standpoint. We use a system composed of a two-element confocal transducer operating at 3.2 MHz-frequency immersed in a water tank. The difference-frequency ranges from 50 to 100 kHz. A 1 mm-diameter tungsten sphere is used as the target object. A calibrated hydrophone, placed along the beam axis, is used to measured the difference-frequency pressure. The result reveals that the measured parametric array signal is in good agreement with theory. Moreover, the interaction of sound-with-sound and acoustic emission contributions are estimated, respectively, as 20 and 33 dB below the parametric array level.

2. Vibro-acoustography image formation

Consider a fluid of infinite extends with density ρ_0, and adiabatic speed of sound c_0. An acoustic perturbation is described by pressure p as a function of position $\boldsymbol{r}$ and time t. In a confocal vibro-acoustography system, a two-element transducer generates an ultrasound beam with two-frequency components as depicted in Fig. 1. The transducer has a central spherical cap with radius b_1, an external spherical ring with the inner and outer radii denoted by b_2 and b_3. Its geometrical center is located at $\boldsymbol{r}_1$, while its curvature radius is denoted by r_0. The driving frequencies of the central and outer ring are ω_1 and ω_2, respectively, with $\omega_2 > \omega_1$. The generated pressure is regarded as the primary incident beam,

$$p_{\rm in}(\boldsymbol{r},t) = p_{1,\rm in}(\boldsymbol{r})e^{-i\omega_1 t} + p_{2,\rm in}(\boldsymbol{r})e^{-i\omega_2 t}, \tag{1}$$

where $p_{1,\rm in}$ and $p_{2,\rm in}$ are pressure amplitudes and 'i' is the imaginary-unit. We consider a sphere of radius a and density ρ_1 as the target object placed at the transducer focus $\boldsymbol{r}_2$. The primary scattered pressure is given by

$$p_{\rm sc}(\boldsymbol{r},t) = p_{1,\rm sc}(\boldsymbol{r})e^{-i\omega_1 t} + p_{2,\rm sc}(\boldsymbol{r})e^{-i\omega_2 t}, \tag{2}$$

where $p_{1,\rm sc}$ and $p_{2,\rm sc}$ represent the pressure amplitude of the primary scattered waves.

In vibro-acoustography, the difference-frequency wave pressure at $\Delta\omega = \omega_2 - \omega_1$ appears due to the quadratic interaction of all primary waves [7,22]. To better understand this, consider the Fourier transform of a function f of time be $F(\omega) = \mathcal{F}[f(t)] = \int_{-\infty}^{\infty} f(t)e^{-i\,\omega t}dt$. The difference-frequency component of the incident plus scattered pressures squared is

$$\mathcal{F}[(\mathrm{Re}[p_{\rm in}] + \mathrm{Re}[p_{\rm sc}])^2]_{\omega=\Delta\omega} = \pi\delta(\omega-\Delta\omega)\left(p^*_{1,\rm in}p_{2,\rm in} + p^*_{1,\rm in}p_{2,\rm sc} + p^*_{1,\rm sc}p_{2,\rm in} + p^*_{1,\rm sc}p_{2,\rm sc}\right), \tag{3}$$

where 'Re' means the real-part and '$*$' denotes complex conjugation. The amplitude $p^*_{1,\rm in}p_{2,\rm in}$ gives rise to the parametric acoustic array effect [3]. The parametric array pressure is denoted by P_1. An analytical expression for this pressure generated by a confocal transducer is given in Ref. [30]. The other term $p^*_{1,\rm in}p_{2,\rm sc} + p^*_{1,\rm sc}p_{2,\rm in} + p^*_{1,\rm sc}p_{2,\rm sc}$ give rise to the interaction of sound-with-sound pressure [6]. This pressure is represented here by P_2. The sound-with-sound interaction was analyzed in the context of vibro-acoustography for the scattering by a sphere in Refs. [7,22]. Another contribution to the difference-frequency pressure comes from the induced vibration on the object caused by the time-modulated radiation force [20,31]. Consequently, the target further generates a difference-frequency pressure, denoted by P_3, known as the acoustic emission [8]. Finally, the difference-frequency pressure amplitude generated by vibro-acoustography system is given by

$$P_{\Delta\omega} = P_1 + P_2 + P_3. \tag{4}$$

Hence, the difference-frequency signal has three distinct contributions. The pressures P_2 and P_3 carry information of the target object. The parametric array signal P_1 does not have information of the object. Although, when the parametric array signal is scattered, the corresponding scattering pressure will depend on the object's mechanical properties.

The difference-frequency pressure is detected by a hydrophone placed at $\boldsymbol{r}_3$. The hydrophone is considered as a space- and time-invariant linear system described by the impulse function $h(\boldsymbol{r}|\boldsymbol{r}_3;t)$, with $h = 0$ for $t < 0$ due to causality. Let us assume that the difference-frequency wave reaches the hydrophone at $t = t_1$ and vanishes at $t = t_2$, with $t_2 > t_1$. The detected signal is given in terms of the spatial convolution,

$$s(\boldsymbol{r}|\boldsymbol{r}_1,\boldsymbol{r}_2,\boldsymbol{r}_3;t) = \int_S P_{\Delta\omega}(\boldsymbol{r}-\boldsymbol{r}'|\boldsymbol{r}_1,\boldsymbol{r}_2)h_1(\boldsymbol{r}'|\boldsymbol{r}_3;t)d^2\boldsymbol{r}' + n(t), \tag{5}$$

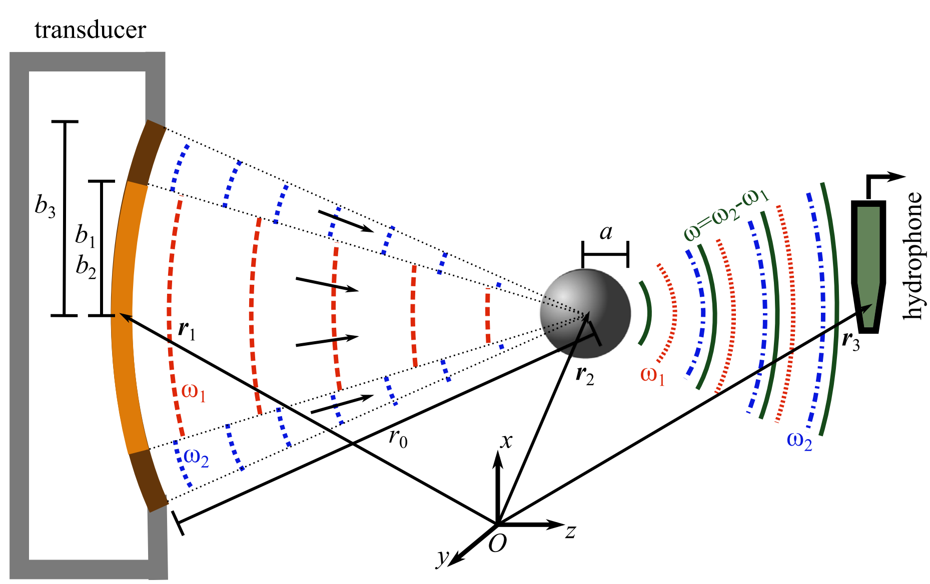

Fig. 1. The confocal vibro-acoustography sketch: a two-element confocal ultrasound transducer with curvature radius r_0, a center disc of radius b_1, and an outer ring with external b_3 radius, produces two focused beams. The beams' angular frequencies are ω_1 and ω_2. A sphere of radius a and located at $\boldsymbol{r}_2$ scatters the ultrasound beams. A difference-frequency wave arises due to nonlinear acoustic effects. A hydrophone placed at $\boldsymbol{r}_3$ detects this wave to form vibro-acoustography images.