Parametric Array Design and Characterisation for Underwater Sonar and Medical Strain Imaging Applications

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Abstract - This paper reports potential contributions of parametric arrays in underwater sonar and biomedical imaging. The parametric array presents the opportunity to use a relatively small device made with high performance, high cost PMN-PT single crystal to produce a low frequency beam in underwater sonar. Additionally, the directional beam has potential applications in medical strain imaging used to detect pathological tissue changes indicative of cancer. The paper also aims to help address the relative lack of published data regarding the technique of parametric generation since its inception in the 1950s. An outline of the design, fabrication and characterisation process required to develop devices for parametric array generation is presented, together with a performance evaluation of two such devices, one with a flat radiating surface and one focused. The ease with which this technique can be employed with modern instrumentation suggests that it is viable for commercial implementation with PMN-PT single crystal material even in the highly cost-competitive underwater sonar market. Our findings also support the proposition that the parametric acoustic field mimics that of an end-fire array providing directional, low frequency excitation desirable in strain imaging.

I. Introduction

Single crystals of lead magnesium niobate-lead titanate (PMN-PT) have previously been reported to produce acoustic transducers with higher sensitivity and broader bandwidth than conventional ceramic transducers [1 - 3]. The major drawback of these materials is their additional cost, presently of the order of eighty times more than PZT ceramic [4]. Preliminary findings, presented in this paper, suggest that parametric array generation with single crystal could be viable for the successful adoption of PMN-PT in underwater sonar as the transducer uses a higher frequency and hence thinner active element to achieve low frequency, requiring a smaller volume of material.

Ultrasound radiation has been widely explored as an excitation source in tissue elasticity estimation [5]. High frequency focused devices are capable of exerting a small volume directional acoustic field over a specific area of interest. By considering the acoustic interaction, mechanical properties of tissue may be estimated. To target specific tissues and avoid measurement complications introduced by tissue boundary interaction, small volume excitation is required, which in turn dictates the use of high frequency focused devices. Tissue is elastically nonlinear meaning that high frequency elasticity information cannot be translated to lower frequency loading conditions. However, with the development of a focused device to generate a parametric array over a predetermined small volume of interest, excitation forces over a range of lower frequencies could be employed. Thus tissue behaviour may be measured over a range of loading frequencies, offering extended tissue elasticity investigation capabilities.

In this paper, the supporting theory of nonlinear acoustics and its exploitation to produce a parametric acoustic array are outlined in Section II, followed by the experimental arrangement used for both applications in Section III. Section IV documents parametric array performance characteristics, specifically the signal amplitudes that may be generated over a range of frequencies. Section V presents findings of a preliminary investigation into the use of PMN-PT single crystal for parametric array generation. Finally, conclusions and future work are presented in Section VI.

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II. Theory

A. Nonlinear Acoustics

The linear approximation of the acoustic wave equation, defined in Eq. 1, is limited to small amplitude acoustic waves:

$$\frac{\partial^2 P}{\partial t^2} = c_0^2 \nabla^2 P \tag{1}$$

where P is the absolute pressure, t is time and c_0 is the acoustic propagation velocity for small amplitude acoustic waves [6].

When considering a lossless plane wave travelling in the positive x-direction with increasing pressure wave amplitude, a more accurate pressure-density relationship is given by [7]:

$$\frac{\partial u}{\partial t} + (c_0 + \beta \hat{u}) \frac{\partial \hat{u}}{\partial x} = 0 \tag{2}$$

where the propagation velocity of the pressure wave is given by ($c_0 + \beta\hat{u}$) and β is the coefficient of nonlinearity of the fluid defined as [8]:

$$\beta = 1 + \frac{B}{2A} \tag{3}$$

where B/A is the parameter which indicates the degree of nonlinearity of the fluid.

Eq. 2 shows that the propagation velocity is dependent on the particle velocity, û, which does not remain constant with respect to x, meaning that the pressure wave will become increasingly distorted with distance. For a sinusoidal pressure wave, the peak of the wave will travel faster than c_0, resulting in its gradual advance toward the trough of the wave, a steepening gradient between the two, and generation of harmonics of the source frequency. When this gradient becomes infinite, an acoustic shock forms as shown in Fig. 1.

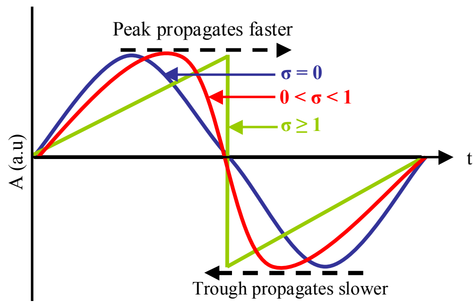

Figure 1. A sine wave (blue) subjected to increasing amplitude (red) which finally results in the formation of a shock wave (green).

In Fig. 1, the shock parameter, σ, identifies the extent of the distortion of the acoustic wavefront [9]:

$$\sigma = \frac{2\pi}{\rho_0 c_0^3}\left[\rho_0 fx\left(1+\frac{B}{2A}\right)\right] = \beta\varepsilon kx \tag{4}$$

B. Parametric Acoustic Array

Fig. 2 shows a schematic of a parametric array, generated using a single acoustic source transmitting two different frequencies, f_1 and f_2.

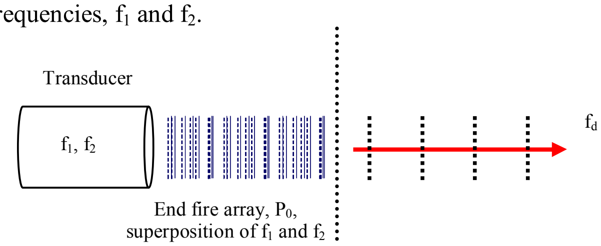

Figure 2. Schematic representation of the generation of a parametric array

The primary field is assumed to consist of two sinusoidal plane waves confined within a very narrow column. The primary pressure field, P_i, is represented by:

$$P_i = P_1 + P_2 \tag{5}$$

where P_1 and P_2 are represented in their complex form as:

$$P_n = P_n \exp\left[-\left(\alpha_n x'\right)\right]\cos\left(\omega_n t - k_n x'\right) \tag{6}$$

where n = 1, 2; P_i is considered to be zero outside the narrow column region; and the average pressure field of the two primary frequencies is defined as P_0 [10]. Under nonlinear acoustic propagation conditions as found in water and tissue, the interaction of the two plane waves produces various harmonics along the length of P_0. The highest frequency of these new harmonics is the sum component of the two primary frequencies, $f_s = f_1 + f_2$, and the lowest frequency is the difference component, $f_d = f_2 - f_1$.

As higher frequencies are attenuated more than lower frequencies, f_d will propagate with less attenuation than both the primary frequencies and f_s. This causes the primary beam to act as an end fire array of sources at f_d, where the effective length of the array will be determined by the attenuation coefficient, α, of the primary beam in a planar radiator. In a focused acoustic device the intensity generated over the focal volume will enhance the nonlinearity of propagation and thus the parametric array will evolve at this point.

III. Experimental Arrangement

Parametric arrays produced by two signals applied simultaneously to a single device were used to generate the high intensity acoustic field. Linear frequency modulated waveforms were generated with a 33250A arbitrary waveform generator (Agilent, South Queensferry, UK), amplified (75A250, Amplifier Research, PA, USA) and then input to the transducers to provided the two high frequency primary beams required for nonlinear parametric generation. System calibration and real-time signal monitoring were conducted via spectrum analysis (ESA-L1500A & 3561A, both Hewlett Packard, CA, USA), and acoustic field characterisation so as to verify parameters for intensity estimation. All experimental work was conducted in out-gassed water at 22°C for ease of acoustic coupling and optimal and repeatable propagation conditions.

IV. Parametric Array Characterisation

The first stage of the present investigation comprised parametric array characterisation. A focused PZT4 piezoceramic acoustic device was fabricated, including a light backing suitable for high power driving conditions. The operational frequency of the device was selected as f_e = 1.09 MHz and the focal length was 75 mm.

Available literature suggests that parametric arrays perform optimally when the drop down between the device primary frequency and the difference frequency, f_e:f_d, is a maximum of 10:1, after which a significant reduction in difference frequency signal amplitude is expected [11]. The nonlinear wave equation indicates that the extent of the nonlinear contribution to wave propagation and hence in this case the harmonic generation which leads to the parametric array will be influenced by the magnitude of the acoustic intensity developed by the transduction device. It is therefore anticipated that a focused device may be used to obtain a greater range of frequency drop down ratios in parametric array generation.

Exploration of array characteristics was conducted in a water tank as described above. Coded waveforms were developed to drive the device over a range of frequencies with drop down ratios of 20:1, 50:1, 100:1, 200:1, 500:1 and 1000:1 corresponding to difference frequencies of 54.4 kHz, 21.8 kHz, 10.9 kHz, 5.45 kHz, 10.9 kHz, 2.18 kHz and 1.09 kHz. A low frequency hydrophone was used to record the difference frequency signals and a high frequency needle hydrophone the primary frequency signals. All signals were measured at the acoustic focus of the device over a range of input drive intensities.

The resulting difference frequency and the primary frequency magnitudes are shown in Fig. 3. It can be seen that the magnitude of the difference frequency increases approximately logarithmically with drive frequency.

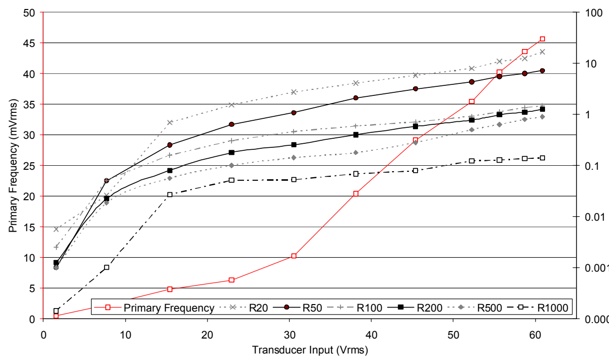

Figure 3. Primary and difference frequency signal amplitudes at the focus

Fig. 4 shows the attenuation of the difference frequency as compared to the primary frequency at a fixed drive voltage. The difference frequency signal drops logarithmically with increasing drop down ratio or decreasing difference frequency. Thus with a drop down ratio of 10:1 the difference frequency (109 kHz) signal attenuation is approximately -4 dB, while at the minimum difference frequency recorded, 1.09 kHz, drop down ratio 1000:1, a signal attenuation of -50 dB was recorded.

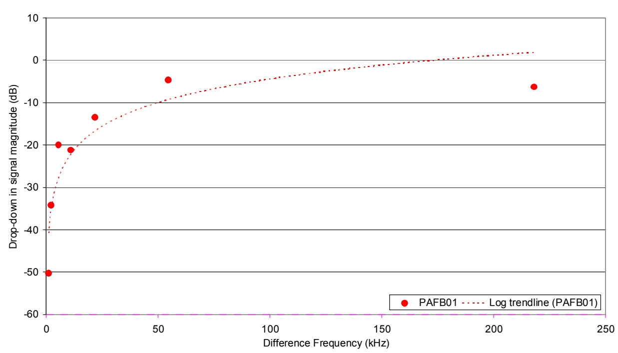

Figure 4. Difference frequency signal magnitude with increasing frequency drop down ratio

Finally, to complete array characterisation, the 10:1 ratio difference frequency field was measured. Fig. 5 shows the extent of the difference frequency field as compared to that of the primary. The evolution of the array ahead of the device acoustic focus can be clearly observed, as can the small volume over which it is exerted, measuring approximately 2.5λ axially and 1.8λ laterally, where λ refers to the difference frequency wavelength.

In summary, parametric arrays have been generated for difference frequencies over a range of 10:1 to 1000:1. With decreasing difference frequency a logarithmic drop in signal magnitude is seen and the strongest difference frequency signals are thus observed for the smallest drop down ratios. Parametric arrays also offer the ability to generate low frequency acoustic fields over small volumes of interest.

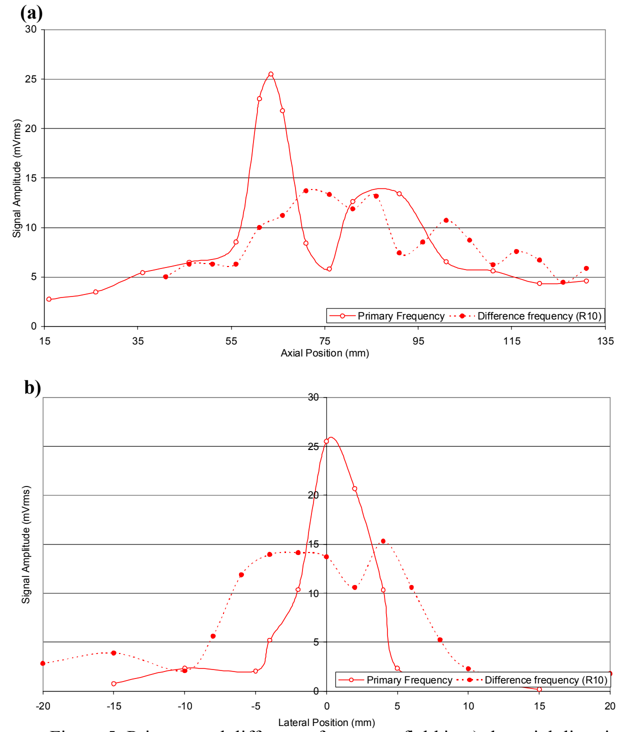

Figure 5. Primary and difference frequency field in a) the axial direction and b) the lateral direction at the focus

V. SINGLE CRYSTAL TRANSDUCER

Following the work described in Section IV, a preliminary investigation was carried out into the suitability of PMN-PT for parametric array generation. First, parametric array generation was investigated with a PZT piezocomposite transducer to establish conventional device behaviour. This transducer had a square aperture 10 mm x 10 mm. Then a PMN-PT piezocomposite was designed for high power and therefore nonlinear projection in water. The transducer was tested to verify a parametric acoustic array could be achieved.

A fundamental electrical resonance frequency, $f_e = 1$ MHz was selected for the transducers. A drop down ratio between the average primary frequency, f_e, and difference frequency, f_d, of 10:1 was used, hence $f_d = 100$ kHz, while primary frequencies of $f_e \pm (f_d/2)$ were used.

The single crystal transducer had a circular PMN-PT element measuring 10 mm in diameter. To prevent the build-up of hot spots during high power drive conditions a light impedance backing comprising an equal volume ratio of Araldite 2020 and microballoons was added, with additional absorbing layers added to the rear face of this backing to prevent unwanted additional resonance behaviour. The transducers were driven in the same way as the one described in Section IV, i.e. with a single signal containing frequency components at both primary frequencies simultaneously.

Fig. 6 shows the acoustic field of both transducers at 100 kHz, clearly indicating that a parametric array has been produced in each case. If the transducers were operating at 100 kHz without nonlinear interaction, then the beam widths would be approximately 141° for the ceramic device and 100° for the single crystal device but much narrower beams are observed. These narrow beams, at f_d, with no side lobes, are strong evidence that a parametric array has been produced. In fact, the beam width of the PMN-PT composite transducer is still narrower that that of the PZT composite transducer.

A full comparison from these preliminary measurements would not be accurate as their apertures are different and other parameters also differ. For example, the electrical impedance magnitudes, $|Z_e|$ at $f_e \pm (f_d/2)$, were different for the two transducers. However, the results that have been obtained do constitute the first demonstration of the generation of a parametric array with a single crystal composite transducer and suggest this may be a cost-effective way to access low frequencies with such materials.

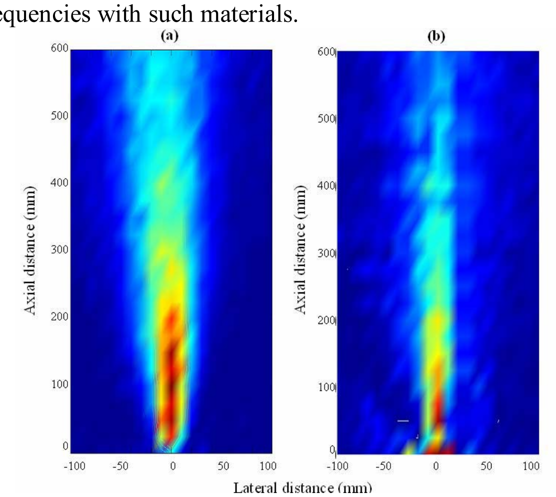

Figure 7. Acoustic field of difference frequency generated by (a) a piezoceramic transducer and (b) a piezocrystal transducer. Note different azimuthal and range axis scales.

VI. Conclusions

Some issues relating to parametric array generation were explored in this paper and key performance parameters were documented. The dependence of the difference frequency signal magnitude on the primary frequency drop down was shown and a maximum difference frequency ratio of 1000:1 was achieved, corresponding to a difference frequency of 1.09 kHz generated from a 1.09 MHz primary frequency. The acoustic field of the difference frequency was measured and the ability to generate small volume, low frequency fields using high frequency devices was demonstrated. This has the potential to extend the capabilities of tissue elasticity investigation where the need to excite small volumes has previously limited investigation to much higher frequencies.

The generation of a parametric array from a high performance PMN-PT single crystal transducer was demonstrated successfully for the first time. Preliminary measurements have shown that the piezocrystal device can produce the characteristically directional and narrow beam associated with the technique. Future work will involve measuring the reduction in source level from the primary frequencies to the difference frequency in these non-focused devices. It is expected that PMN-PT will provide a higher source level at this lower frequency than can be achieved from the equivalent ceramic parametric array. Furthermore, the possibility to increase the bandwidth of devices using PMN-PT may allow a greater range of drop down ratios to be accessed.

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