INTERACTION OF SOUND GENERATED BY A HIGH-FREQUENCY PARAMETRIC ARRAY WITH EXTERNALLY GENERATED LOW-FREQUENCY SOUND

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Abstract: *As a sound transmitting device based on the nonlinear acoustic theory, parametric acoustic array (PAA) can generate low-frequency spatially focused sound beams in wide frequency band using small aperture transducers. Because of this feature, for more than half a century, PAAs have been raising interest in their study and application in various fields both in the air and underwater. In this research, an interaction of the sound field generated by the PAA with a low-frequency external sound source is studied numerically and experimentally. The experimental setup consisted of a hexagonal array of 48 ultrasonic transducers, a low-frequency speaker, and a single channel microphone. Both simple amplitude-modulated tone signals and signals of a more complex form and modulation were used. The real-time modulation was done through a fast digital processor. The simulations were done via k-Wave acoustic toolbox considering nonlinearities and power law absorption. The results of experiments and simulations are discussed.*

Keywords: *parametric acoustic array, nonlinear acoustics, active noise control, interference*

1. INTRODUCTION

Parametric acoustic arrays (PAAs) leverage the nonlinear behavior of sound waves travelling through the nonlinear medium (e.g., air, water, body tissues, etc.) to generate low-frequency broadband sound of high directivity due to the self-demodulation of finite-amplitude modulated ultrasonic waves [1]. Akin to an end-fire array from antenna theory, the PAA is defined as a virtual series of reproduction ends aligned in the medium to produce an approximately cylindrical column of sound (Figure 1). When two sound waves (primary waves) with different frequencies interact with one another in a nonlinear medium, new sound waves (secondary waves) may be produced as the results. The frequencies of the secondary waves correspond to the sum and the difference of the primary waves. This phenomenon was first introduced back in 1963 by Westervelt [2] and is also known as the "scattering of sound by sound" [3]. Later, Berktay studied Westervelt's work and proposed that PAAs may be used for underwater sound transmission [4]. Due to the combination of low-frequency and high directivity with low side lobes, PAA has been widely applied in such underwater fields as sub-bottom profiling, underwater communication, and buried target detection.

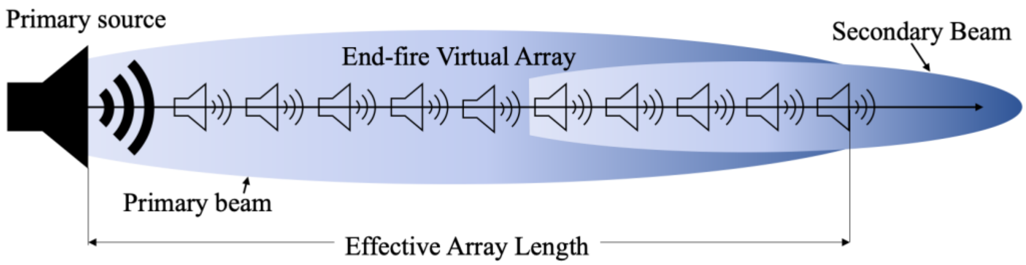

Figure 1. Schematics of the secondary beam generation with a parametric acoustic array.

Despite the aforementioned attractive features, PAAs have some side effects as well. One of those is acoustic saturation of the primary wave, which should be taken into account when analysing the resulting sound field radiated by the PAA. Since the amplitude of the secondary wave is proportional to the amplitude of the primary wave, at first glance it might seem reasonable just to strongly increase the primary wave amplitude in order to enhance the secondary wave. However, due to the finite amplitude effect, the amplitude of the secondary wave cannot increase indefinitely. When the propagation distance of the primary wave reaches a certain value, the sine wave transforms into the saw-tooth wave, and some energy of the primary wave is converted into harmonics. This process is called "excess attenuation" [5].

Various modulation techniques were previously developed and analyzed for harmonic distortion by other authors. Among them are conventional dual-sideband amplitude modulation (DSB-AM), square root amplitude modulation (SQR-AM) and recently suggested modified amplitude modulation methods (e.g., [6]). Also, a simple solution to reduce the second harmonic is to transfer the energy to a single band as in the single sideband amplitude modulation (SSBAM) [7]. Later, improved algorithms for modulation have been proposed to reduce sound distortion and improve conversion efficiency [8].

The purpose of this paper is to present preliminary analysis of interaction of low-frequency sound generated by a conventional low-frequency speaker with a low-frequency secondary wave obtained by radiating a modulated ultrasound with a parametric acoustic array.

2. MATERIALS AND METHODS

2.1. The experimental setup

The experimental setup consisted of i) a single 48-ch PAA (by *JA7TDO*) with a peak frequency of 40 kHz, ii) one 3” 4Ω 60W PC83-4 (*Dayton Audio*) loudspeakers, and iii) a single 1/2" PU REGULAR microphone (*Microflown Technologies*). The distance between each speaker and the microphone was 220 cm, whereas the distance between the speakers’ centers was 55 cm (Figure 2).

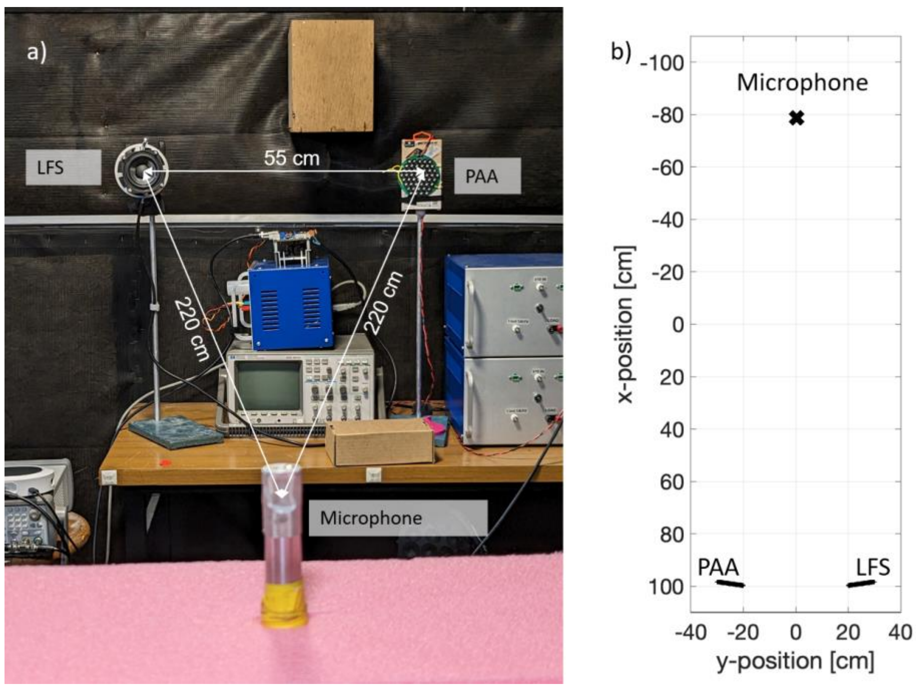

Figure 2. a) The experimental setup consisting of a single low-frequency speaker (LFS), a 48-ch parametric acoustic array (PAA) and single microphone. b) Simulation geometry representing a top view of the experiment.

Low-frequency speaker (LFS) was radiating a single-frequency 2 kHz sine wave generated via the waveform generator at MokuGo portable hardware platform (*Liquid Instruments*). The PAA was radiating an Upper Single Sideband Amplitude Modulated (USSB-AM, Figure 3) signal with a carrier frequency, f_c, of 40 kHz, and the message signal, $g(t)$, being a sine wave with the frequency, f_m, of 2 kHz. The input voltage of both LFS and PAA were preset in such a manner that their spectral competent amplitude at 2-kHz will be the same. The radiated signals were recorded at the sampling frequency of 128 kHz.

2.2. Simulations

Simulations were done using k-Wave, which is an open source, third party, MATLAB toolbox designed for the time-domain simulations of propagating acoustic waves in 1D, 2D, or 3D [9]. k-Wave is capable of accounting for both linear and nonlinear wave propagation, an arbitrary distribution of heterogeneous material parameters, and power law acoustic absorption [10, 11]. The main simulation functions in k-Wave solve the coupled first-order system of equations (momentum conservation, mass conservation, pressure-density relation) rather than the equivalent second-order wave equation.

On this stage, we analyze sound interaction in a more qualitative manner and, for a better visualization, simulations are done for water medium, which has a higher index of nonlinearity than air.

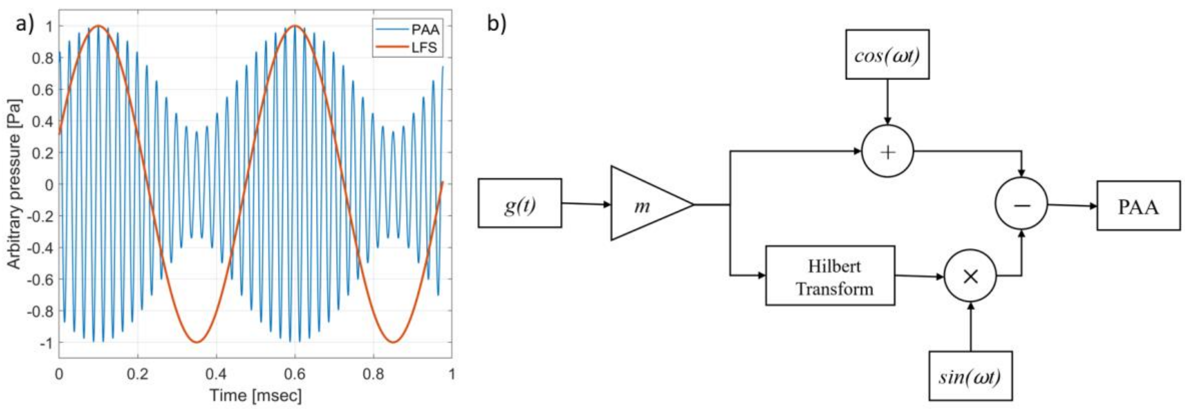

Figure 3.a) Waveforms radiated by the PAA (blue) and LFS (red). b) Block diagram of USSB-AM.

3. RESULTS AND DISCUSSION

Figures 4 and 5 present the results of experiments and simulations, respectively. In the first two scenarios, either the PAA (top row) or the LFS (middle row) was emitting. In the third scenario, both PAA and LFS were emitting synchronously (let us call it "PAA + LFS", bottom row). When only the LFS was emitting, as expected, there was only one spectral component present at 2 kHz, with low-amplitude higher frequency components related to electrical noise.

The spectral picture is more complex when the PAA is involved. Due to nonlinearity, new spectral components are generated while propagating from the PAA to the microphone. Multiples of the sum and difference of the primary and secondary wave frequencies result in new high-frequency waves in the vicinity of the 40 kHz carrier. In addition, simulations show a second harmonic at 4 kHz, which is 24 dB weaker than the first harmonic. In the experiment, multiple harmonics are present, but they are all at least 30 dB below the fundamental one.

In the experiment, the resulting secondary wave at 2 kHz was -63.8 dB, -63.1 dB, and -58.1 dB for PAA, LFS, and PAA + PFS cases, respectively. Converting from dB to Volts, we get 0.645 mV, 0.700 mV, and 1.245 mV, respectively. The voltage on the microphone is almost twice as high when both speakers are working simultaneously, indicating constructive interference between low-frequency sound from the LFS and the secondary wave from the PAA.

Similarly, in the simulation, the resulting secondary wave at 2 kHz was 25.4 dB, 25.8 dB, and 29.7 dB for PAA, LFS, and PAA + LFS cases, respectively. In linear units, that is 18.6 Pa, 19.5 Pa, and 30.5 Pa, respectively. The pressure at the microphone location when both speakers were working is almost identical to the sum of the pressures simulated for separate emissions.

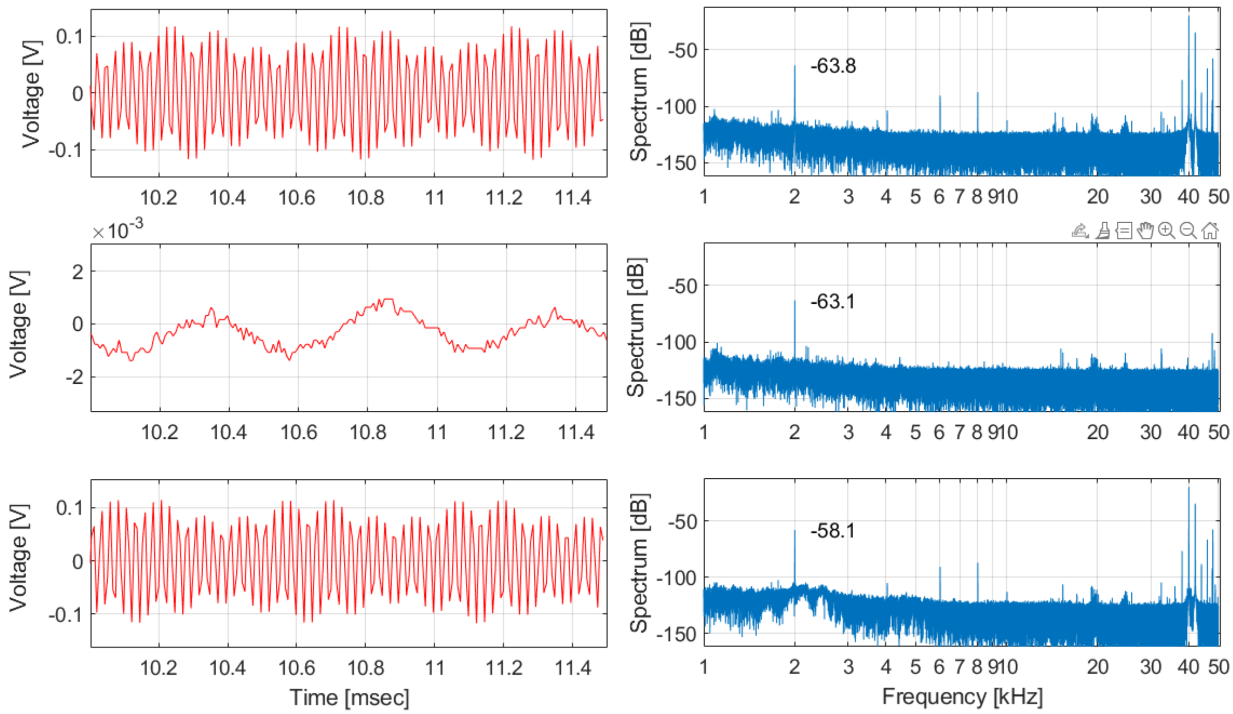

Figure 4. Experimentally recorded waveforms (left) and their spectra (right). Sound field generated by PAA only, LFS only, and PAA + LFS simultaneously are depicted in top, middle and bottom rows, respectively.

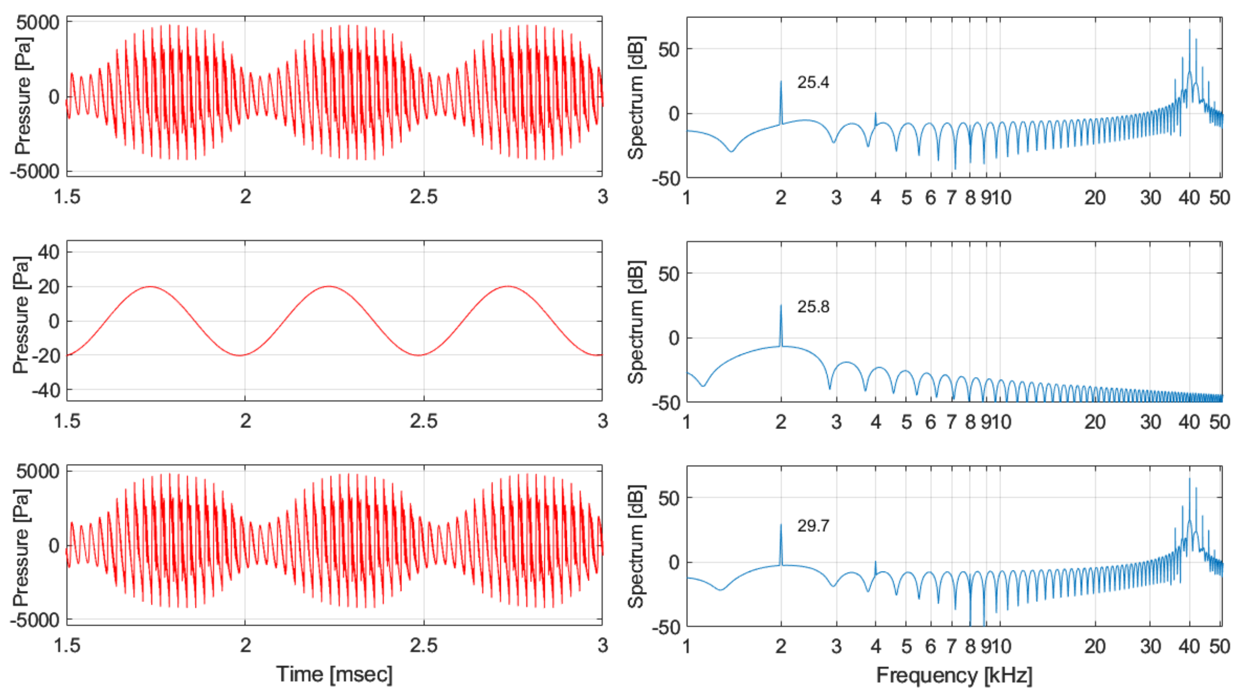

Figure 5. Resulting simulated sound field at the sensor position (left) and their spectra (right). Sound field generated by PAA only, LFS only, and PAA + LFS simultaneously are depicted in top, middle and bottom rows, respectively.

CONCLUSIONS

Constructive interference is observed between the low-frequency field emitted by the conventional LFS and the secondary low-frequency wave obtained as a result of self-demodulation of the amplitude-modulated sound emitted with a PAA. This effect is also confirmed in the framework of a numerical experiment (simulations). As a further development, it is proposed to use close-loop algorithms to control the nature of the interference between the LFS and PAA.

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