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Phase-controlled array of ultrasonic transducers for active focusing of waves in air. Applied to foam abatement

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Abstract: This work presents the development and experimental validation of an annular array of 56 ultrasonic transducers operating at $25\,\mathrm{kHz}$ for contactless industrial foam abatement. Through phase control algorithms, the system achieves acoustic focusing in air, generating pressure levels exceeding $150\,\mathrm{dB}$ SPL at the focal point. Experimental results demonstrate successful foam disruption capabilities, and the scalability was also validated through numerical simulations in COMSOL Multiphysics and laboratory testing.

Keywords: Airborne ultrasound, phased array, acoustic focusing, industrial foam abatement, piezoelectric transducers.

Background, Motivation, and Objective

Industrial foam elimination has been a persistent challenge in numerous sectors, including food processing, pharmaceuticals, petroleum refining, and pulp manufacturing [1, 2]. Foam formation can lead to product losses, reduced equipment efficiency, and operational failures [3]. Traditional defoaming methods are based on chemical additives or mechanical approaches, which can introduce contamination risks or require significant maintenance [4].

Ultrasonic technology offers a promising noninvasive alternative for foam control. Although extensively studied in liquid and solid media for degassing and bubble disruption [5], airborne ultrasound applications face significant challenges due to high acoustic impedance mismatch and transmission losses in air [6]. Recent advances in phased array systems have demonstrated the feasibility of generating high intensity focused ultrasound (HIFU) in air through constructive interference [7].

Annular array configurations are particularly advantageous for acoustic focusing due to their radial symmetry, which enables efficient energy concentration along the central axis [8]. This geometry facilitates the generation of symmetric focal patterns essential for precise targeting applications. In this paper, the development of an active control system using airborne ultrasound specifically designed for contactless industrial foam abatement is presented. The primary objective is to verify whether a low-frequency ultrasonic annular array can generate sufficient acoustic intensities in air to destabilize industrial foam without physical contact or chemical additives.

Prototype Design and Construction

An annular phased array prototype was designed comprising 56 piezoelectric ultrasonic transducers with a nominal frequency of $25\,\mathrm{kHz}$ and a diameter of $16\,\mathrm{mm}$. The transducers were mounted on a rigid $140 \times 140\,\mathrm{mm}$ PCB, arranged in eight concentric rings with radial symmetry to promote acoustic focus along the central axis.

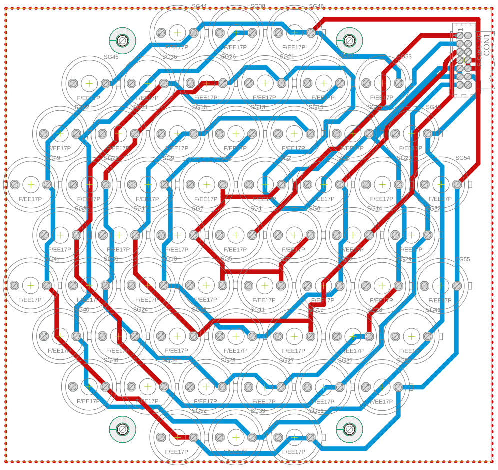

Fig. 1: PCB layout of the ultrasonic transducers developed for this research. Each transducer can be identified, arranged in a hexagonal array, which achieves the highest spatial density.

The geometric configuration formed by eight groups of transducers, each one is separated $18\,\mathrm{mm}$ from its neighbors, following a hexagonal pattern, Fig. 1. Each concentric group was powered by individual electronic stages capable of applying to each group of concentric transducer specific the phase delays. The delays were calculated for each radial group of transducers, considering their position with respect to the desired focal point. In this opportunity, the focal point was located $95\,\mathrm{mm}$ above the array center. Phase delays were determined using spherical wave propagation models in air, considering a propagation velocity of $343\,\mathrm{m/s}$, and rounding the values to integers of microseconds, which is the resolution of the developed electronic system.

Transducer excitation was achieved through H-bridge amplifiers optimized for proper impedance matching between signal sources and transducers. Control and synchronization were implemented using a Teensy 4.0 microcontroller programmed via Arduino IDE with custom libraries for precision timing control.

Numerical Simulation

A three-dimensional numerical model was developed in COMSOL Multiphysics using the Pressure Acoustics Module to predict the acoustic field produced by the device and compare this prediction with the experimental results. The model represents the whole system geometry: an air volume of $150 \times 80 \times 80\,\mathrm{mm}$ above the array plane with transducers arranged in concentric rings, replicating prototype dimensions and pressure scanning zone.

To optimize computational time, quarter of the transducers were included in the simulation. This simplification was justified by the radial symmetry of the array. The air domain was modeled as compressible medium with density $\rho = 1.22\,\mathrm{kg/m^3}$ and sound velocity $c = 343\,\mathrm{m/s}$. Operating frequency was set at $25\,\mathrm{kHz}$, corresponding to the used transducer.

Each transducer was modeled as a normalized pressure source with specific phase delays according to radial position for focusing energy at $95\,\mathrm{mm}$ height above array center. Open radiation boundary conditions were imposed on lateral and upper walls to prevent unwanted reflections.

Experimental Characterization

Because the acoustic field is axially symmetric, two-dimensional acoustic field measurements were enough to its characterization. The measurements were performed using a 1/8" condenser microphone (B&K Type 4138) mounted on a motorized XZ positioning system. The scanning system moved in $2.5\,\mathrm{mm}$ steps along both the X and Z axes over a two-dimensional grid. In the Fig. 2 the transducer array mounted in its scanning system can be appreciated. During the scanning, at each measuring point, acoustic pressure amplitudes were recorded, enabling reconstruction of the spatial pressure field profile generated by the array, assuming rotational symmetry in the acoustic field. In this way, measurements were made to characterize the acoustic pressure in the perpendicular plane centered on the central axis of the array. This allowed quantification of system performance with all transducers emitting waves with phase delays calculated for focus the acoustic field at the desired position.


Fig. 2: Acoustic field characterization setup, showing an array of ultrasonic transducers. On the left edge of the array, the tip of the microphone waveguide can be distinguished, which is arranged horizontally and attached to the two-dimensional scanning system.

Results

COMSOL Multiphysics simulation revealed an acoustic pressure distribution in the XZ plane, clearly showing constructive interference patterns converging at a focal axis approximately $95\,\mathrm{mm}$ from the emitter plane (Fig. 3). The maximum amplitude reached values around 1 normalized unit of pressure, confirming the formation of a high-pressure focused lobe. This behavior validates the design parameters calculations for concentrating acoustic energy at a specific point in airspace for interaction with sensitive materials such as industrial foams.

Measurements

The acoustic field, measured with the two-dimensional scanning system, reveals an acoustic field consistent with the desired characteristics. In fact, the acoustic field reproduced expected behavior with a well-defined focal axis and maximum pressure exceeding $800\,\mathrm{Pa}$ (Fig. 4), corresponding to sound pressure levels above $145\,\mathrm{dB}$ SPL at the focal point. These measurements experimentally validate the constructive interference principle induced by phase control applied to the annular array. The spatial distribution obtained confirms the capability of the system to concentrate acoustic energy at predetermined locations with intensities

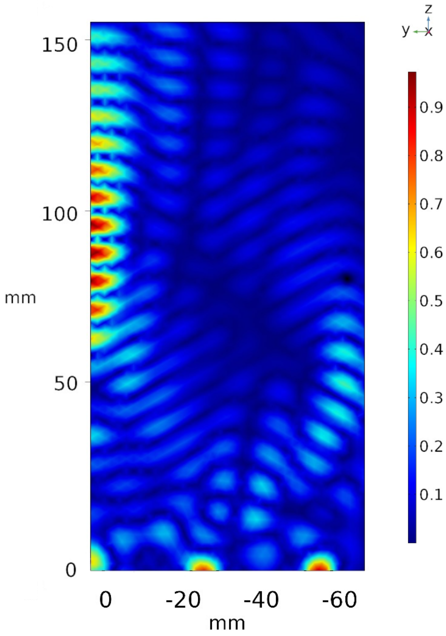

Fig. 3: Result of the acoustic field simulation. In the lower left corner is the central transducer, just above which is the line of maximum expected pressure, the focusing axis. The pressure is normalized, so the scale in the graph is relative as long as the linearity of the medium is maintained.

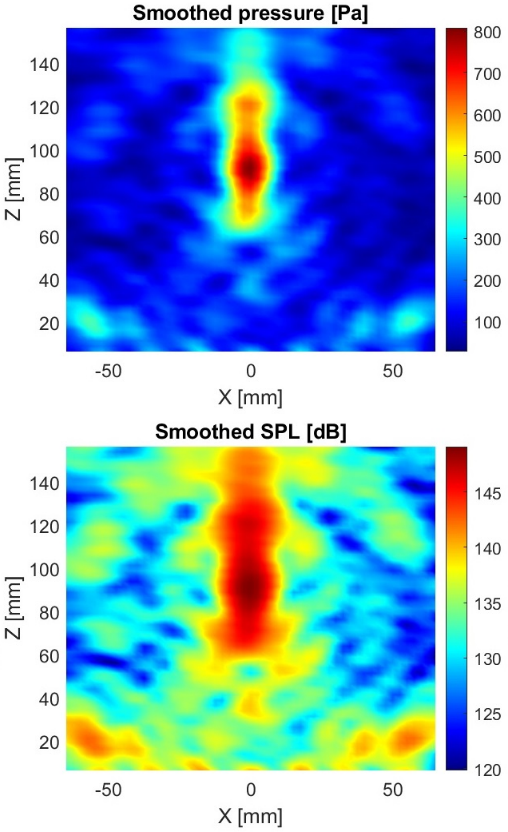

Fig. 4: Result of the acoustic pressure scan based on the X and Z coordinates, in the vertical plane of the array. The maximum pressure obtained under these excitation conditions is over $800\,\mathrm{Pa}$ *and* $145\,\mathrm{dB}$ *SPL.*

high enough for defoaming processes. These results are particularly promising in applications where chemical additives or physical contact are undesirable.

Due to the encouraging results obtained in the first field measurements, we are looking for the limits of the developed system. The power limitation of the generator was established in terms of the maximum feed current allowable without achieving system saturation. This current turned out to be approximately $250\,\mathrm{mA}$. Because the system is operating in its linear regime, the current fits the displacement of the transducers and also the acoustic pressure generated. The maximum acoustic pressure capability performed, based on the excitation current consumed by the array, turned out to be the power limitation of the generator was established in terms of the maximum feed current allowable without achieving system saturation. This current turned out to be approximately $250\,\mathrm{mA}$ of about $1000\,\mathrm{Pa}$ and $150\,\mathrm{dB}$ SPL, as shown in Fig. 5.

Foam Disruption Validation

Practical system effectiveness was evaluated by foam breaking tests in an experimental tank. Results demonstrated a clearly delimited opening in the foam. Because the very poor contrast between the foam and the surrounding space, to facilitate the observation of foam breaking the acoustic field was applied in an edge of a borosilicate container. According to predict results a zone, corresponding to the focal axis shows clearly, a foam disruption process. These findings indicate the system's capability to concentrate acoustic energy at specific points with relevant intensity enough to initiate foam destabilization processes. Fig. 6 shows the foam breakup after $0.6\,\mathrm{s}$ of exposure.

Analysis suggests that scaling up the number of transducers or redesigning electronic stages could substantially increase achievable acoustic intensity, approaching levels required for industrial environments.

Conclusions

Results confirm the hypothesis that an annular array of small ultrasonic transducers with phase control can generate effective airborne wave focusing, producing acoustic pressure levels relevant for foam elimination applications. Simulations and experiments validate system capability to concentrate energy at desired points, opening possibilities for scaling this technology toward industrial applications.

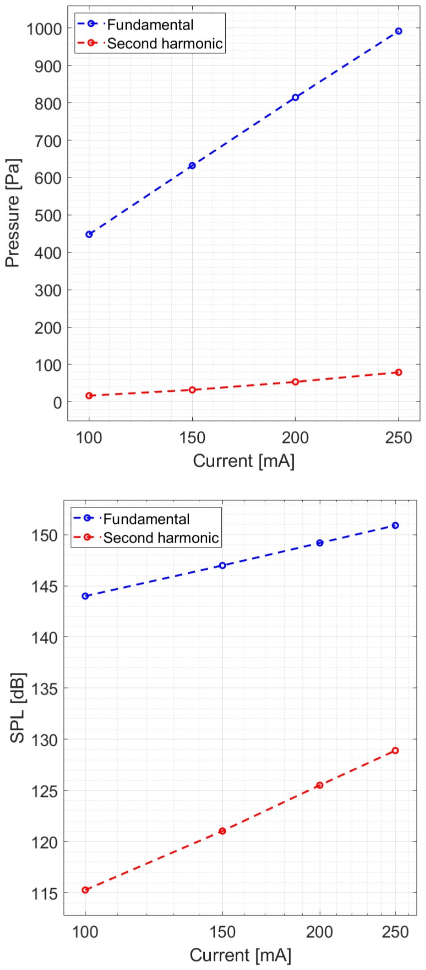

Fig. 5: Acoustic pressure curve as a function of the current consumed by the array, for the fundamental frequency and the second harmonic. It is necessary to remember that the excitation signal is square, so it was necessary to characterize the second harmonic in addition to the fundamental frequency.

Although achieved levels remain below those used in robust industrial systems, the proposed system's simplicity, energy efficiency, and scalability potential make it a viable alternative for environments requiring non-invasive, chemical-free solutions with low maintenance requirements. The natural next step involves scale up and experimental validation with actual foam under applied conditions to directly evaluate effectiveness in real-world scenarios.

References

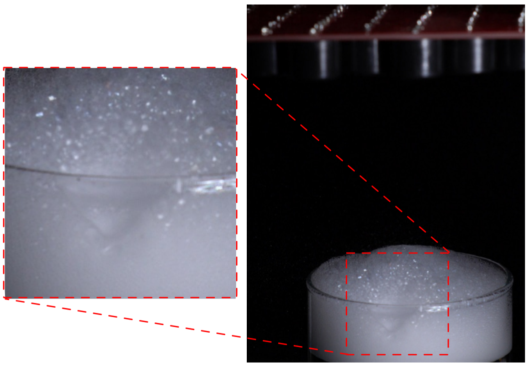

Fig. 6: Photograph of the effects of high-intensity radiation applied to soap foam generated by pressurized air injection. The exposure time required to generate this effect is only $0.6\,\mathrm{s}$*. The developed array of ultrasonic transducers can be seen above.*

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