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A Non-Expensive Massive Transducer Array to Generate Helical Wavefronts in Air

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Abstract

In this work we present experimental characterization results of a non- expensive massive ultrasonic transducer array to generate helical wavefronts in air. The multitransducer is composed by 390 elements operating at a nominal frequency of 40 kHz, precisely located on a helical surface substrate. The same excitation signal is applied to all elements. Due to the “spatial” delay applied to each element, the device is able to generate a helical wavefront of topological charge m =+1. A maximum sound pressure level of 137 dB was measured, on a transverse plane located 1.8 m far from the device, when a 15 Vpp excitation voltage was applied. This work also includes a detailed description of the excitation electronics, the electroacoustic characterization of the array elements (phase, directivity and frequency response) and the inter-element cross-talk quantification. Furthermore, a discussion of the potential of use of this multitransducer device is presented.

Keywords: helical wavefront, acoustic vortex, phased array systems, multitransducer; spatial delays;

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1. Introduction

Ultrasonic Vortices (UV) are acoustic fields in which the geometric locus of the constant phase particles describes a helicoid. In frequency domain a transverse plane of an UV resembles an annular (donut-like) pressure distribution with zero pressure and undetermined phase at its center, which is known as the core of the vortex. In a transverse plane, vortex phase varies from 0 to $2\pi m$ over any closed trajectory that encloses the core, where m represents the topological charge or the number of full turns of the helical wavefront along a wavelength. Other interesting features of acoustic vortices that makes tem appealing for future applications and research are their auto-reconstruction capability after being partially occluded and their capacity to transfer angular momentum to matter [1].

To generate a UV with a phased array system, the delay function applied to the MT must emulate the phase distribution on a transverse plane of the intended acoustic vortex. A slightly different approach is to use an element

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time delay distribution that approximates the geometry of the UV wavefront, that is, a helicoid surface on which are virtually placed the array elements. Generally MT has a flat surface to guarantee that all elements are positioned at the same height. So, if we properly modify the spatial height of each element in order to follow a given surface, i.e., a helicoid, the resultant spatial delay distribution will allow us to generate a particular wavefront, in this case, an acoustic vortex.

Despite phased arrays can be highly manageable for different applications, the more independent each element is the more expensive is the circuitry required. Because of this, the use of non-flat MT opens up to create complex acoustic fields at low cost. Considering the reported high potential of application of UV, i.e. robust transmission of digitalized information [2], rotation control of particles [3], particle manipulation [4], nanotechnology [5], etc., this article shows the design and characterization of a non-expensive massive non-flat ultrasonic array to generate helical wavefronts in air. The UV is created due to the helicoid substrate on which the elements of the MT are located, which allows us to apply a spatial delay distribution that produce an also helicoid constant phase surface. This work is divided into four sections. In Section 2, a detailed description of the MT designed is included along with the instrumentation utilized. Section 3 includes the characterization of the array elements and the quantification of the interelement crosstalk. Also, experimental measurements of the UV generated are shown. Finally conclusions and future research are presented.

2. Materials and Methods

The characterization of the MT designed and implemented was performed by analyzing the pressure of each active element, the possible negative effects of crosstalk and by measuring the acoustic field generated when all transducers are emitting. The helical MT and the instrumentation setup are briefly described below.

2.1. The Helicoid Multitransducer

The MT has 390 commercial ultrasonic transducers, each 9.9 mm in diameter, distributed on a triangular lattice with an inter-element spacing (center to center distance) of 11 mm, which are precisely located inside counterbore holes of different depth fabricated on a helical substrate of 170 mm diameter and a pitch of 1 wavelength at the nominal operation frequency of the transducer elements (40 kHz). The hole depth distribution was calculated so that the resultant radiating surface, composed by the whole set of active areas of the transducer elements, properly emulates a helical wavefront. See figure 1. The resultant holed helicoid substrate was fabricated from a high density polyethylene plate by means of a CNC machine tool. The MT is operated at 40 kHz and excited with a square signal of up to 20 Vpp.

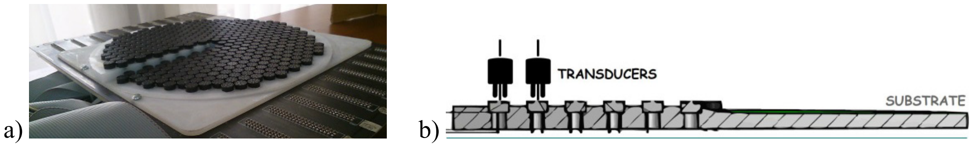

Fig. 1. Different views of the fabricated multitransducer of 390 active elements. (a) isometric view. (b) Section view of the MT showing how the ultrasound transducers are located inside the counterbore holes fabricated on the helicoid substrate.

2.2. Experimental apparatus

The experimental setup implemented in this work basically consists in three parts: the excitation equipment, the measurement devices and the controlled XY linear units. Excitation signals were produced using an arbitrary waveform generator (AWG7000, Tektronix, USA) connected to a high speed voltage amplifier (Model WMA-300, Falco Systems, Netherlands). To measure the acoustic field, a calibrated free field microphone (1/4 in. 40BF, G.R.A.S, Denmark) with a nominal frequency range of operation between 4 Hz and 100 kHz connected to a digital oscilloscope was used. This microphone was located on a XY linear unit in order to sample the instantaneous pressure distribution of the helical wavefront at observation points arranged in a square grid of 120 mm x120 mm. A distance of 5 mm between points was used.

3. Characterization Results

3.1. Single transducer characterization and crosstalk quantification

The characterization results of a representative batch of the commercial transducer used to build the MT include: average sensitivity, resonance frequency distribution, directivity and relative phase response. Transducers exhibit a narrow relative bandwidth (-3 dB) of less than 5%, an average resonant frequency of approximately 39.6 kHz and a -3 dB directivity of around 60 degrees. A maximum average sensitivity of approximately 2.8 Pa/V was measured at 18 cm far from the transducers on principal axis. A relative phase not greater than 25 degrees at 40 kHz was observed, which is low compared to the spatial phase shift provided by the helical substrate. In order to quantify the magnitude of crosstalk two tests were performed. In the first one, a single element is excited and the response of all six adjacent elements is measured with the microphone placed as close as possible to the each emitter. In the second test the same procedure was carried out but the inputs pins of adjacent elements are short-circuited. In both tests, a very low crosstalk level (less than -30 dB) was observed for a representative set of array elements.

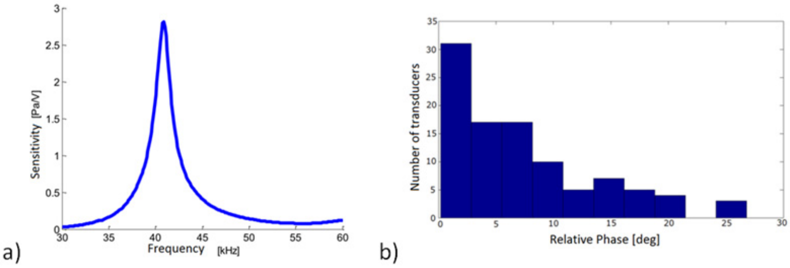

Fig. 2. Acoustic characteristics of a representative batch of the ultrasonic transducers used to build the helical wavefront generator multitransducer (a) Nominal single transducer sensitivity measured at 18 cm far from the emitter on principal axis (b) Relative phase distribution of the transducers.

3.2. Acoustic vortex measurement.

The acoustic pressure was measured over a transversal plane located at approximately 180 cm, perpendicular to principal axis. Figure 8 shows the ultrasonic vortex generated by using only subset of 35 elements surrounding the center of the MT. A good agreement between experimental results and theoretical simulations is observed. Following this, the acoustic vortex generated by the whole set of 390 transducers was characterized. A maximum sound pressure level of 137 dB was measured at 180 cm far when using a 10 V square. See figure 4. A more irregular structure of the vortex is observed. This could be attributable to a lack of homogeneity in the sensitivity distribution of the ultrasonic emitter. Also, it was difficult to guarantee that the observation plane was truly perpendicular to the vortex beam. Also, as the measurements were not conducted in an anechoic chamber, the effect of near reflector may have affected the results.

4. Conclusions

We have shown that is possible to generate helical wavefronts by using the spatial delays provided by a helical substrate. This is a cheaper option when compared to the use of a phased array system. Recent experiments performed in our laboratory have shown that it is possible to transfer the angular momentum to flat objects located in the near field of the multitransducer. Further experimentation is required in order to fully characterize the fabricated multitransducer. Also, the quantification of the potential of this device to manipulate small particles and to exert acoustic torques is a subject of research.

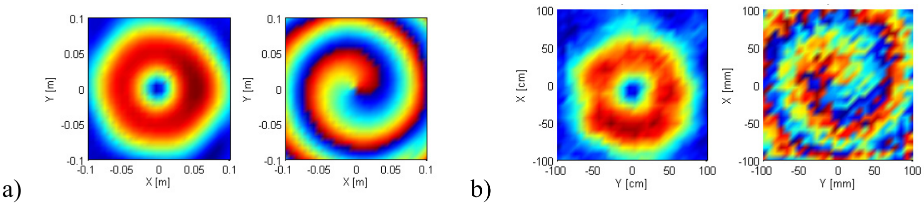

Fig. 3. Magnitude and phase of pressure distribution obtained using 35 active elements surrounding the array center. (a) simulation, (b) measurements

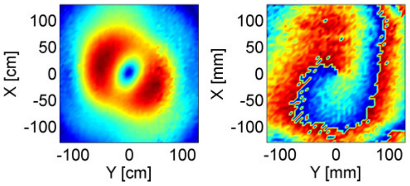

Fig. 4. Pressure and phase distribution of the vortex generated using 390 active elements. Left: Magnitude. Right: Phase

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