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HIGH RESOLUTION MECHANO-OPTICAL METHOD FOR ACOUSTIC FIELD MEASUREMENTS IN AIR (POSTPRINT)

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14. ABSTRACT
Acoustic fields are typically visualized by measuring spatial variation of pressure in a medium, using optical (ie: Schlieren, laser interferometry) and electro-mechanical (ie: transducers, micro-electro-mechanical sensors) methods. These methods have limited ability to visualize acoustic fields in air, especially at high spatial resolution (< 0.5 mm). This paper presents a method to detect and quantify the acoustic fields in air by measuring the displacements of a micro-reflector attached to fiber with a laser interferometer. The potential of the method is demonstrated by measuring acoustic pressure of an air coupled transducer, and the variation of acoustic pressure in the focal region of an air coupled acoustic lens. In the current experimental arrangement an approximate spatial resolution of 250 microns and an approximate acoustic pressure of 7 mPa have been demonstrated. A physics based mathematical model is presented that has been used to analyze the spatial resolution and acoustic pressure. Limitations of the method and possible improvements to achieve higher spatial and temporal resolution are discussed.

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HIGH RESOLUTION MECHANO-OPTICAL METHOD FOR ACOUSTIC FIELD MEASUREMENTS IN AIR

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ABSTRACT. Acoustic fields are typically visualized by measuring spatial variation of pressure in a medium, using optical (ie: Schlieren, laser interferometry) and electro-mechanical (ie: transducers, micro-electro-mechanical sensors) methods. These methods have limited ability to visualize acoustic fields in air, especially at high spatial resolution (< 0.5 mm). This paper presents a method to detect and quantify the acoustic fields in air by measuring the displacements of a micro-reflector attached to fiber with a laser interferometer. The potential of the method is demonstrated by measuring acoustic pressure of an air coupled transducer, and the variation of acoustic pressure in the focal region of an air coupled acoustic lens. In the current experimental arrangement an approximate spatial resolution of 250 microns and an approximate acoustic pressure of 7 mPa have been demonstrated. A physics based mathematical model is presented that has been used to analyze the spatial resolution and acoustic pressure. Limitations of the method and possible improvements to achieve higher spatial and temporal resolution are discussed.

Keywords: Ultrasound, Acoustic Field, Measurement, Laser Vibrometer
PACS: 43.35.Yb, 43.20.Ye

INTRODUCTION

There is interest in developing acoustic lenses in air that focus to less than the incident wavelength through the use of materials with subwavelength structures [1, 2]. Characterizing the acoustic fields of these lenses is necessary to verify the response of the lens, and to validate the accuracy of the models used to design and simulate the lenses. There are several challenges to characterizing lenses of this type: the operating frequency is typically in the tens to hundreds of kilohertz regime, the typical focal spot size is 2 mm or less, and the typical pressures achievable at focus are in the one to tens of mPa range. These unique challenges make it especially difficult to characterize this type of lens with current acoustic field characterization methods.

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STATE OF THE ART

Characterization of acoustic fields is not a new area of research, and the literature is filled with many methods. The major characterization methods include: Schlieren imaging [3], ball reflector [4], cone transducer [5], micro-electromechanical sensors [6], hydrophones, membrane interferometry [7], and capacitive based sensors [8]. Relative to the requirements of 100 kHz, 0.2 mm spatial sensitivity, 1-10 mPa pressure sensitivity, and air coupled ultrasound only capacitive sensors and membrane interferometry were found to be promising candidates. Capacitive sensors have shown suitable capability at higher frequencies [9], but they were not available around 100 kHz. Attempts to use a similar membrane interferometry set up as Royer and Casula [7] described for acoustic field measurements of the aperiodic lens were unsuccessful. Two membrane materials were tested: Mylar and latex. Mylar membranes were prone to wrinkles that affect sensitivity, and measurement with the latex membrane yielded a focal spot diameter 2-3 times the expected value. While there are a number of methods to characterize acoustic fields in the literature, one could not be found that had the frequency range, sensitivity to pressure, spatial resolution, performance in air or ease of use needed to characterize the aperiodic lens.

DESCRIPTION AND SIMULATION OF THE METHOD

The mechano-optical (MO) method presented here leverages the concepts presented in Royer and Casula [7] by replacing the membrane in their method with a fiber. This is expected to increase the pressure sensitivity since less pressure would be required to move a small diameter fiber than a membrane. It is expected that the fiber will be less influenced by the presence of any side lobes present in the acoustic field than a membrane would. A block diagram of the set up is presented in Figure 1. The acoustic wave propagates from left to right starting at the air coupled transducer, being focused by the lens, vibrating the fiber, and it is the vibrations of the fiber that are measured with the laser vibrometer. To improve sensitivity of the laser vibrometer to the motions of the fiber at the expense of spatial resolution a reflector is placed at the midpoint of the fiber.

This set up is constructed by attaching a fiber, hair, at both ends with epoxy to a ring with an inner diameter of 56 mm. The reflector is aluminum coated polymer film 0.01 mm thick and 0.35 mm in diameter attached to the midpoint of the fiber by epoxy. This is illustrated in Figure 2. The length of the fiber is known, the density per unit length of the fiber, the mass of the reflector, and wave speed in the fiber are approximated with average values for hair, and the tension is measured by applying a series of masses to the fiber and measuring the first resonance squared as a function mass. The relationship for tension as a function of first resonance frequency squared and mass is given by:

$$\omega^2 = \frac{4T}{LM} \tag{1}$$

where ω is the angular frequency, T is the tension in the fiber, L is the length of the fiber and M is the mass applied to the fiber.

Assuming the displacements are small and the cross section of the fiber is small effects due to elasticity can be neglected and the wave equation reduced to a 1-dimensional problem given by:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \tag{2}$$

$$c^2 = \frac{T}{\rho} \tag{3}$$

where u is the transverse displacement of the fiber, t is time, x is position, c is the wave speed in the fiber, ρ is the density per unit length of the fiber and T is the tension in the fiber. This can be solved a number of different ways two of which are finite difference time domain and harmonic analysis. Both techniques gave results within 5 Hz of each other and the average values are: 829, 2488, and 4139 Hz which are well below the expected frequency of the lens of 100 kHz. This implies that the fiber will be following the forcing function more than its own resonance behavior.

EXPERIMENTAL RESULTS & DISCUSSION

Preliminary estimates of the sensitivity of this method are made from the response of this method to the acoustic field generated by the lens described in [1, 2]. A step size of 250 microns was determined to be the smallest resolution possible as further decreases in step size did not improve the measurement resolution. Resonances with pressures as low as 0.005 mPa were clearly resolved as shown in [2]. Further characterization of the MO

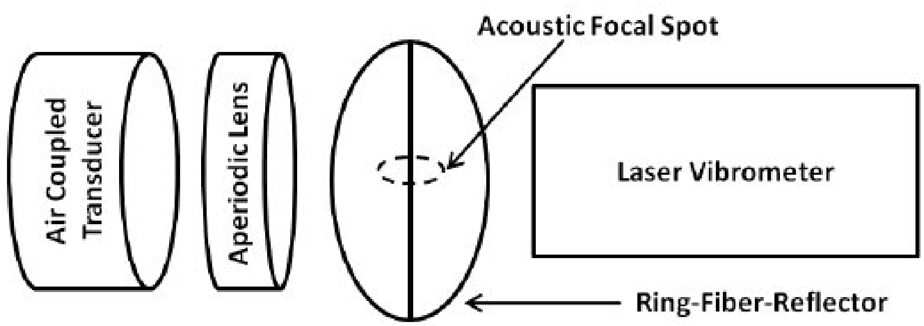

FIGURE 1. Block diagram of the experimental setup.

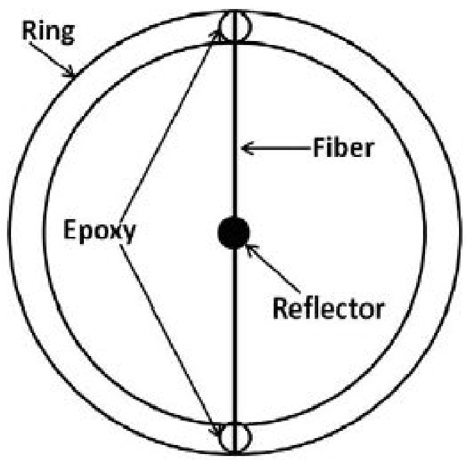

FIGURE 2. Detail diagram of the fiber-ring-reflector.

method is needed to determine the exact spatial and pressure sensitivity. To do this the MO method needs to be tested against a source that is well characterized in terms of pressure, beam or focal spot size and frequency content.

It is recognized that the current embodiment of this detector is not optimized. A number of factors should be investigated to minimize errors and tailor sensitivity to the application. Pressure sensitivity of this method is affected by the tension in the fiber, displacement sensitivity of the laser vibrometer (LV) and operating off resonance. Since the fiber is not operating at resonance the effect of fiber tension on pressure sensitivity is small. Operating off resonance decreases the pressure sensitivity of the MO method versus what is possible. This trade off is made in order to increase spatial resolution by having the fiber follow the excitation function more closely while knowing that the pressure sensitivity is dominated by the displacement sensitivity of the LV. Selection of the proper laser vibrometer for the expected frequency and displacement ranges is critical to achieving high pressure sensitivity while operating off resonance. Spatial resolution of the technique is determined by the detection limit of the reflected laser beam from the reflector on the fiber. This is influenced by the size of reflector, reflector perpendicularity to the laser and the acoustic field, and laser spot size and intensity.

CONCLUSIONS

A method to measure small pressure amplitude acoustic fields in air with high spatial resolution has been demonstrated. Experimentally a pressure resolution of 5 mPa and a lateral spatial resolution of 250 microns in air have been determined. It is expected that a comprehensive characterization of the pressure and spatial resolutions of this method will result in a small improvement of these values. While this method has not been tested on an acoustic in a fluid there is no physical constraint to its use in such an application.

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