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LOW-POWER ACOUSTIC HARVESTING OF AEROSOLS

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Abstract – A new acoustic device for levitation and/or concentration of aerosols and small liquid/solid samples (up to several millimeters in diameter) in air has been developed. The device is inexpensive, low-power, and, in its simplest embodiment, does not require accurate alignment of a resonant cavity. It is constructed from a cylindrical PZT tube of outside diameter $D = 19.0$ mm and thickness-to-radius ratio $h/a \sim 0.03$. The lowest-order breathing mode of the tube is tuned to match a resonant mode of the interior air-filled cylindrical cavity. A high Q cavity results that can be driven efficiently. An acoustic standing wave is created in the interior cavity of the cylindrical shell where particle concentration takes place at the nodal planes of the field. It is shown that drops of water in excess of 1 mm in diameter may be levitated against the force of gravity for approximately 100 mW of input electrical power. The main objective of the research is to implement this low-power device to concentrate and harvest aerosols in a flowing system. Several different cavity geometries are presented for efficient collection of the concentrated aerosols. Concentration factors greater than 40 are demonstrated for particles of size 0.7μ in a flow volume of 50 L/minute.

I. Introduction

Detection and identification of aerosols have application in a wide variety of fields. Particle size, distribution, and composition are quantities that are important to scientists studying the environmental impact of industrial smog to military specialists detecting the presence of chemical or biological agents in the air. One common rule in aerosol classification is that most aerosol detection devices (particle sizers, optical classifiers, etc.) yield higher detection sensitivities if they are given higher aerosol concentrations. The present research investigates a novel aerosol concentrator based on acoustic levitation principles. It is foreseen that this device may be implemented to increase the concentration of aerosol particles at the inlet of in-line aerosol detection or collection instruments.

Acoustic levitation provides a means to isolate small samples without the influence of a containment vessel.¹⁻⁵ It uses acoustic radiation pressure to spatially isolate small samples in a resonant cavity. For an aerosol, a time-averaged force is experienced by the aerosol particles forcing them to a spatial location in the proximity of a pressure node. The geometry of an acoustic cavity may be designed such that the pressure nodes in the field coincide with spatial positions where the collection of the particles will take place. A diagram of such a device is shown in Fig. 1.

Figure 1 -- Concept diagram for low-power acoustic concentration device. Particles enter the acoustic cavity and are forced towards the nodal lines. These are then collected downstream.

In this paper, we describe several embodiments of an extremely simple acoustic levitation device for use as an efficient concentrator of particles in air. This device is constructed from a hollow, cylindrical piezoelectric (PZT) crystal in contrast to the more traditional method of using parallel plate transducer assemblies. This novel cylindrical arrangement allows several important advantages. We show that when the resonance frequency of the interior cylindrical cavity is matched to a structural mode resonance of the cylindrical piezoelectric, the efficiency of the device becomes extremely high.

This results in low-power requirements that make it advantageous for possible use in battery-powered, hand-held instruments. Additionally, the device requires no alignment (in its simplest embodiment) and the hollow PZT cylinders are commercial-off-the-shelf items.

II. Device description

The cylindrical concentrator consists simply of a hollow, cylindrical piezoelectric tube. The fundamental design criterion of this novel design requires that a structural resonance of the tube coincide with a corresponding resonance mode of the air-filled cavity.^{1,6} Moreover, to achieve the necessary efficiency in driving the air-filled cylindrical cavity, it is required that the structural resonance mode of the cylinder be comprised of predominantly radial displacements. Due to mode orthogonality, it is also necessary that the resonance modes of the cylinder and the cavity share the same azimuthal mode number. For simplicity, axisymmetric modes of the cylinder will be assumed throughout the paper.

We present the design of three types of cylindrical-shaped concentration devices in this paper. These fall into two different categories: 1) structurally-tuned devices and 2) cavity-tuned devices.

a. Structurally-tuned devices

A structurally-tuned device is tuned by altering the resonance frequency of the piezoelectric tube by altering the tube itself. This is done to match the frequency of the desired structural resonance with a resonance of the internal cavity. A cross section of a structurally-tuned device is shown in Fig. 2. The cavity mode of interest consists of three concentric pressure nodes ($m = 3$, where m is the radial mode number) as depicted by the dashed lines in the diagram. It is then necessary to tune a predominantly radial mode of the PZT tube to coincide with the desired cavity mode.

In the experiments, a hollow piezoelectric tube with an inner diameter 16.9 mm, outer diameter 19.0 mm, and length 17.0 mm is used. The cylinder is manufactured by Boston Piezo Optics Corporation. The type of piezoelectric material is the manufacturer number VP-A55. It is radially poled with nickel electrodes on the outer and inner surfaces. In its unaltered form, measurements of its radial surface velocity show that the lowest order mode of the tube that exhibits appreciable radial surface displacements

occurs near 61 kHz. This resonance occurs at the manufacturer's predicted value for the frequency of the breathing mode. Unfortunately, the resonance frequency of the desired $m = 3$ cavity mode is 65.7 kHz.

Figure 2 -- Diagram of the interior cavity of the cylindrical levitator. The dotted lines denote the stable equilibrium positions (pressure nodes) where the aerosol congregates. There is a notch cut into the tube that extends along its entire length.

Because of the frequency difference between the resonance frequency for radial vibrations of the PZT tube and the resonance frequency of the $m = 3$ mode of its interior cavity, we must tune the resonance frequency of either the cylinder or the cavity to make the two frequencies match. (It would be preferable if the resonance frequency of the cavity matched the breathing mode frequency of the cylinder in its stock form; however to this point the authors have not found a stock PZT cylinder that has this property.) Finite element modeling of the tube predicts that an axial cut along the outer surface of the tube will result in a radial mode near 66 kHz.⁶ We therefore tune the resonance frequency of the tube by slicing the cylinder axially with a rotary diamond saw along the length of the tube.

The modified PZT tube is mounted with a three-point clamp. The excitation signal is a sinusoid at frequency $f = 66.7$ kHz. Due to the high efficiency of this levitation device, it is driven directly from a function generator eliminating the need for a power amplifier. The ambient temperature for the measurements is $\sim 27^\circ\text{C}$.

A visual inspection of the nodal pattern of the pressure field is obtained by pumping a small amount of water vapor into the cavity. Figure 3 is a Schlieren photograph displaying the results of this type of experiment. Here, a diffuse white light is used to

illuminate the interior cylindrical cavity. The image is dominated by light scattered from the water vapor droplets. In the image, the plane of the paper is perpendicular to the axis of the cylinder. It is easy to discern the two innermost rings where the water vapor has been concentrated into concentric rings. More difficult to determine is the outermost ring which is visible in various locations near the interior wall of the device. The drive voltage necessary to concentrate the aerosol into the observed nodal rings is less than $1.0 V_{pp}$. This equates into an electrical input power of less than 100 milliWatts!

Figure 3 -- Schlieren photograph of water vapor being pumped into the cylindrical cavity. Effective concentration is observed near the stable equilibrium positions of the cavity as shown in Fig. 2. The two innermost rings are easy to discern while the outermost ring near the wall of the tube is somewhat blurred.

b. Cavity-tuned devices

A second embodiment of the cylindrical levitator will now be presented. In the previous device, a structural resonance of the cylindrical PZT was tuned to match a resonance of the air-filled cavity. It is also possible to tune the resonance frequency of the air-filled cavity to match the structural resonance of the cylinder. Figure 4 shows two embodiments of this device where the cavity is tuned. In the first embodiment (a), a circular cross section, metallic rod of diameter a is placed coaxially within the cylindrical cavity as the tuning device. The diameter of the rod is chosen such that one coaxial pressure node exists in the annular cavity. The second embodiment (b) utilizes a metallic rod of elliptical

cross section with major axis diameter b and minor axis diameter c . The elliptical cross section is used to break the axial symmetry of the cavity. In this configuration, two localized pressure nodes are created in the annular cavity in line with the minor axis of the ellipse.

Figure 4 -- Cross sections of acoustic cavities. (a) A circular cross section tuning rod is used to create a single coaxial pressure node. (b) An elliptical cross section tuning rod is used to create two localized pressure nodes.

A cylindrical PZT of inner radius 1.96 cm, length 5.06 cm, and outer radius 2.22 cm is used as the excitation device. It is fitted with an aluminum rod of either circular or elliptical cross sectional geometry. Laser vibrometer measurements demonstrate the breathing mode resonance of the PZT tube occurs at approximately 23.2 kHz. The dimensions of the rods are designed accordingly. For the present application, $a = 24.4$ mm, $b = 25.3$ mm, and $c = 24.0$ mm.

Figure 5(a) shows a Schlieren photograph of the system in Fig. 4(a). Water vapor is injected into the annular region. A single ring of concentrated vapor appears. It should be noted that the radius of the rod may be lessened (to $a \approx 9.4$ mm) to observe an additional concentration ring in the cavity. Likewise, Figure 5(b) shows a Schlieren photograph of the system in Fig. 4(b). Water vapor is injected into the

annular region. Two localized regions of concentrated vapor appear. It is this configuration that will be used in the next section to demonstrate aerosol harvesting.

Figure 5 — Schlieren photograph of water vapor being pumped into two different cylindrical cavities. Effective concentration is observed near the stable equilibrium positions of the cavity as shown in Fig. 4. (a) A single ring of concentrated vapor is observed. (b) The concentrated aerosol can be seen as the two flashes above and below the tuning rod.

III. Aerosol harvesting

The goal of the present research is to obtain high efficiency collection of aerosol particles using acoustic concentration. At present, the cavity configuration shown in Figs. 4(b) and 5(b) is being utilized for collection purposes. A tube is inserted in the cavity of the concentrator in the vicinity of the localized pressure nodes. Concentration factors of

greater than 40 have been observed for 0.7 micron diameter water vapor particles. Current research is addressing the issues associated with cavity perturbations that result from the insertion of collection devices.

IV. Summary

A class of novel low-cost, low-power acoustic levitation devices are presented. They are constructed from hollow, cylindrical PZT tubes. This is in contrast with the traditional design of using a parallel plate configuration. The necessary design criteria requires that a structural mode of the tube correspond to a resonant mode of the interior cavity. This mode matching of the cylinder modes and cavity modes is the basis for the low-power acoustic levitation device. Two different designs are demonstrated: 1) structurally-tuned and 2) cavity-tuned. Experiments described in this paper demonstrate the efficient ability of the devices to concentrate aerosols. Aerosol collection demonstrates concentration factors greater than 40 times.

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