

Airborne particle detection using acoustic transducers

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Abstract

Aerosol particle detection finds important applications in the commercial, military, and aerospace sectors and is of special importance in clean room monitoring. To date, most laboratory-based particle detection devices rely on laser scattering measurements which drive up the cost of these instruments. This experimental study demonstrates a novel and inexpensive particle detection technique which is based on the acoustic signature of airborne particles as they are accelerated through a converging-diverging tube consisting of a capillary (i.e. the acoustic transducer). As a particle-laden flow accelerates through the transducer, the suspended particles cannot follow the rapidly changing flow velocity and vortices are generated which excite the air column inside the transducer tube producing audible noise. Results show how the frequency content of the acoustic signatures relates to the fundamental frequency of the transducer's air column. The acoustic transducer is able to detect micron-sized particles and the sound intensity is a function of flowrate but, unexpectedly, not of particle size. The ability of the transducer to determine particle concentration (as low as a few ppl) is also shown and compared to data obtained from a commercially available aerodynamic particle sizer.

Keywords: acoustic transducer, aerosol/particle detection, concentration, monitoring.



1 Introduction

Airborne particle detection in various environments is highly desirable in many practical applications such as monitoring of clean room facilities used for fabrication and assembly of microelectronic and optical components, detection of breathing hazards (i.e. air quality control), and detection of biological agents and obscitants. Most of the commercially available particle sizing and detection instruments rely on laser based measurements which make these devices costly, hard to maintain, and not mobile. Furthermore, in some low class clean rooms, the relatively unreliable tape-lift surface sampling technique is used [1] where particles deposited on surfaces are lifted using adhesive tape and counted under a microscope. Such technique only provides a measure of surface particulate cleanliness levels and it may be needed when assembling optics or sensors in clean rooms. However, conventional clean rooms (Class 10,000 or better) require the detection of airborne particles 0.5 μm in size or larger; this requires instruments that can continuously sample, count, and size suspended particles.

Acoustic detection of particles received considerable attention in the mid-to-late twentieth century by Langer [2, 3] and Karuhn [4]. They used a glass tube consisting of a capillary (fig. 1) to draw particle-laden air. It was claimed that particles disturbed the boundary layer within the capillary and sound was generated due to a reflected shock wave [2, 3] or as the flow disturbance interacted with a stationary vibrating shock front within the capillary [4]. It was reported that all particles above 40 μm could be detected [3] and hardly any acoustic signals were generated for particle sizes below 10 μm with a cut-off size of 5 μm [2, 3]. The acoustic particle counter developed by Karuhn [4] was shown to detect particles between 4 μm and 100 μm .

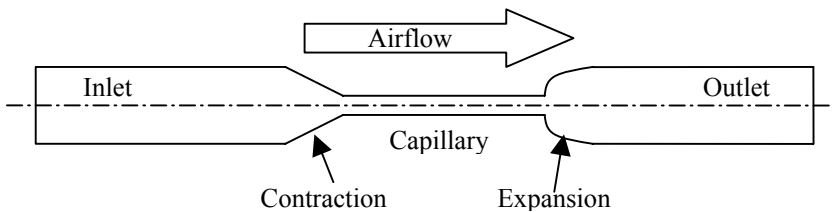


Figure 1: Acoustic transducer.

More recently, a series of articles by these authors [5-8] demonstrated the ability of an acoustic transducer similar to that described in refs. [2-4] to detect particles of different sizes (down to 6 μm) and shapes [5, 6] as well as preliminarily investigating the accuracy of the transducer in measuring particle concentration [7]. It was concluded [5, 8] that the sound generated as particles were accelerated through the transducer was not due to any shock wave phenomena. For a shock to occur the flow at the capillary has to reach sonic

conditions (i.e. choked flow - unity Mach number); further expansion at the outlet section of the transducer may lead to supersonic flow and, consequently, shock waves [9]. In refs. [2-7], the pressure drop between the inlet and outlet sections of the transducer was not sufficient to choke the flow at the capillary. The fact that acoustic signals were detected both upstream and downstream of the capillary [5] lends further support to the invalidity of shock wave phenomena [2-4] as the source of any signals generated in the acoustic transducer. Chen *et al.* [8] determined that acoustic signals were generated as particles were accelerated through the transducer's contraction. Due to their inertia, suspended particles cannot follow the rapidly accelerating flowfield generating a turbulent wake as air rushes past them which disturbs the air column within the inlet and capillary sections of the transducer generating noise.

This paper aims to gain further understanding into the physical processes taking place in the acoustic transducer. Effort is placed in determining the particle detection ability of the transducer as a function of particle size and system flowrate. Since the transducer is very effective in measuring low particle concentrations [7], a correlation is also sought between the concentration measured by the acoustic transducer and that measured by a commercially available aerodynamic sizer [10].

2 Experiment

Experimental procedures are similar to those described in ref. [5]. The acoustic transducer tested (fig. 1) is made of borosilicate glass to ensure smooth internal surfaces; any roughness would lead to early development of turbulence which would interfere with the acoustic signals. The transducer has inlet and outlet diameters of 10 mm and 12.5 mm, respectively. The inlet section has a length of 32 mm and tapers linearly to a diameter of 1.8 mm (i.e. the capillary) over a contraction length of 24 mm. The capillary and outlet sections of the transducer have lengths of 43.4 mm and 46 mm, respectively. As shown in fig.2, the acoustic transducer was placed across two separate but adjoining sealed chambers made of acrylic plastic. The chambers had volumes of 23 L and 4.7 L corresponding to the inlet and outlet sections of the transducer, respectively. The large inlet chamber contained all instrumentation and was open to room air through a quartz microfiber filter capable of filtering naturally occurring particles larger than 1 μm . The outlet chamber was connected to a vacuum pump used to draw air through the system the flow of which was controlled by a rotameter. A maximum flowrate of 55 L/min could be achieved by the current setup. For this flowrate the pressure drop between the inlet and outlet chambers was 0.06 atm which is not sufficient to choke the flow through the capillary [9].

Polystyrene latex (PSL) microspheres with well-controlled sizes were injected into the inlet chamber carried by particle free dry air. A small electret condenser microphone used in hearing aid applications was positioned along the axis of the transducer 5 mm from the inlet and measured any acoustic radiation generated in the transducer. The microphone has high sensitivity and exhibits a flat broadband response over a wide frequency range (0 – 10000 Hz). The



microphone voltage signal was sampled and analyzed by a computer-based data acquisition system. During the experiments, the particle concentration in the inlet chamber was continuously monitored by an aerodynamic particle sizer (APS).

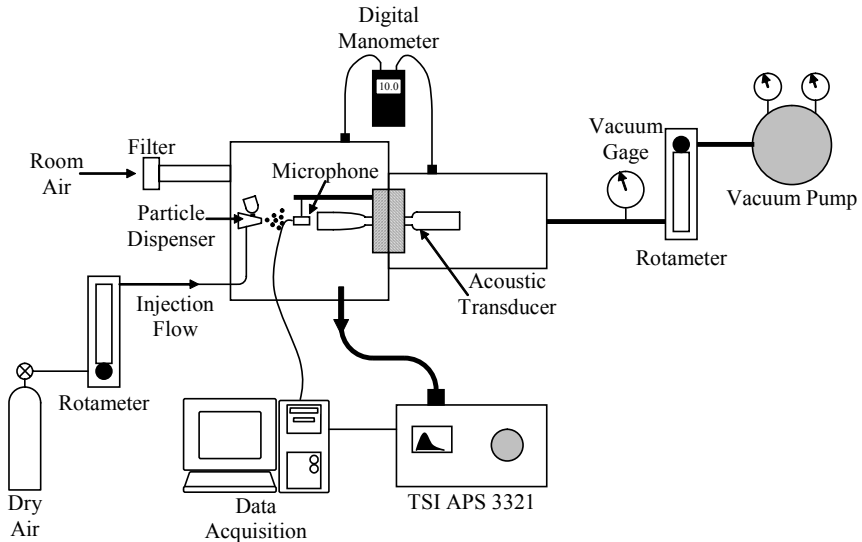


Figure 2: Experimental setup.

3 Results and discussion

3.1 Acoustic signals

When particles were present in the inlet chamber, audible click-type noise signals were generated by the transducer for flowrates above 30 L/min. For such flowrates, flow Reynolds numbers in both the inlet and capillary sections are well above the critical value of 2,100 for turbulent pipe flow [11]. The flow in the transducer, however, has been shown to be laminar [2, 4] since the walls are smooth and the air residence time is short both of which delay the development of turbulence. In addition, the flow acceleration through the contraction combined with a favourable pressure help keep any boundary layer growth to a minimum. Figure 3 shows a typical acoustic signal. The trace starts with a negative voltage, indicating a drop in pressure, followed by a high frequency signal which decays within 3 ms to 10 ms. This leading pressure drop is expected as previous studies [5] have shown that signals collected downstream of the transducer outlet begin as a compression wave (i.e. a pressure rise). The maximum signal-to-noise ratio that could be achieved with the current transducer was on the order of 20/1 for flowrates near 50 L/min. It has previously been

reported that signal strength can be increased by shortening the capillary tube or increasing the capillary diameter [2].

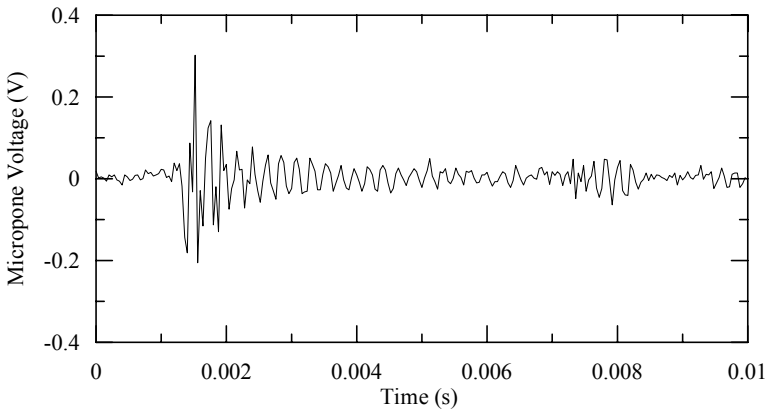


Figure 3: Signal generated by the acoustic transducer when PSL particles are present in the system.

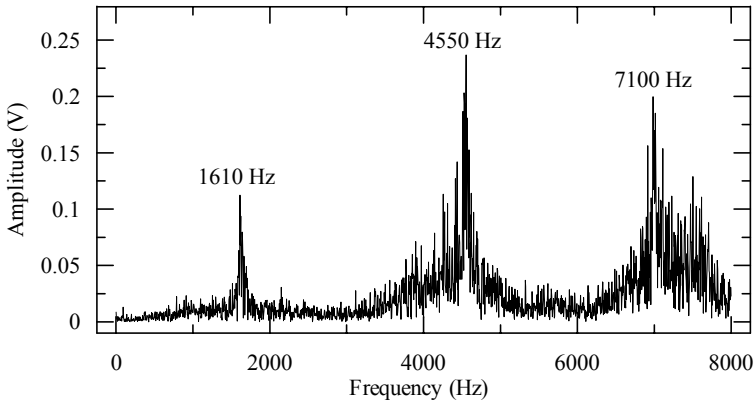


Figure 4: Power spectrum of acoustic signals.

It is of interest to investigate the frequency content of the transducer acoustic radiation. A Fourier analysis of the signal shown in fig. 3 leads to the spectral power distribution shown in fig. 4. The three distinct peaks in fig. 4 can be explained by considering the inlet section of the transducer as a closed cylinder with an open end. A closed cylindrical air column can produce standing resonant waves at a fundamental frequency and at odd harmonics of this frequency [12]. The fundamental frequency is given as $f_0 = c/4L$ where c is the speed of sound and L is the length of the column (i.e. the length of the inlet section up to the capillary, $L = 56$ mm). For the current transducer $f_0 = 1534$ Hz and one can see that the main frequency components in fig. 4 closely correspond to f_0 , $3f_0$, and $5f_0$. This was previously referred to as the “organ pipe”

phenomenon [5]. It is noted that the $3f_0$ peak has the strongest amplitude; such an observation seems to be a characteristic of the sound generated when spherical particles are present in the system [6]. The frequency content of the acoustic signals did not vary from that shown in fig. 4 for different flowrates and particle sizes; therefore the mechanism for acoustic radiation closely depends on the geometry of the transducer used.

3.2 Signal strength

Mills and Chen [5] speculated that the strength of the acoustic signal would increase with particle size by claiming that sound could be generated by the random vibrating motion of the particles as they are accelerated through the contraction; the authors, however, made this claim based on data obtained using just a single particle size (i.e. $50\ \mu\text{m}$). To test this theory, PSL particles of $5\ \mu\text{m}$, $15\ \mu\text{m}$, and $50\ \mu\text{m}$ were introduced in the system and the acoustic signal strength was measured for different flowrates. The size of the particles is strictly controlled with deviations of $\pm 6\%$, $\pm 4\%$, and $\pm 3\%$ for $5\ \mu\text{m}$, $15\ \mu\text{m}$, and $50\ \mu\text{m}$ sizes, respectively [13]. As shown in fig. 5, no apparent variation in signal strength occurred with a change in particle size. For a given flowrate, acoustic signals were similar for all particle sizes tested with signal amplitudes varying considerably by $\pm 20\%$ of the average values shown in fig. 5.

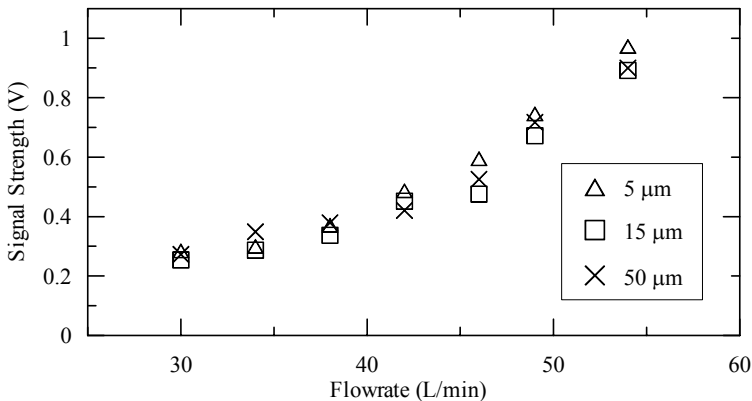


Figure 5: Acoustic signal strength as a function of particle size and system flowrate (error bars not shown for clarity, see text).

As discussed in refs. [2-8], it seems that acoustic radiation generated by the transducer is due the flow disturbance caused by the particles; in refs. [2-4], however, the authors attributed the disturbance to shock wave phenomena which has been shown not to be the case here. Chen *et al.* [8] showed that the maximum Lagrangian acceleration of the flow occurs at the end of the contraction just prior to the capillary. With this result as motivation, the motion of the particles in the contraction and capillary sections of the transducer was

modelled numerically using a Runge-Kutta scheme by considering the acceleration imparted on the particles by the drag force due to the difference between air and particle velocities. Since air velocities can reach near sonic values for the flowrates considered in this study, air compressibility effects were included in the numerical model. Similar models were previously developed [5]; however, these models were based on more crude finite difference methods and compressibility effects were omitted. The computational results are shown in fig. 6. One can see how, for sizes greater than $2\ \mu\text{m}$, the particles never reach the airflow velocity. The maximum velocity difference occurs at the end of the contraction and it is at this location where the source of the acoustic signals is expected to originate [8]. Considering the particle Reynolds number (i.e. based on the particle diameter, d_p , and the air-particle velocity difference at the end of the contraction) yields values from 40 up to 600 for $2\ \mu\text{m} < d_p \leq 50\ \mu\text{m}$. In this regime an unsteady vortical wake is present downstream of the particles [14]. This unsteady disturbance is expected to continue into the capillary altering the flow present in that section. Due to the high flow Reynolds number of the flow in the capillary (in the order of 30,000), any small disturbance can induce the flow to become turbulent, thus generating noise amplified by the inlet section of the transducer. For particles smaller than $2\ \mu\text{m}$, Reynolds numbers are always less than 10 (i.e. near the creeping flow regime) and no wake develops downstream of the particles. Based on these results, the strength of the acoustic signals generated in the transducer is independent of particle size; particles big enough to induce turbulent flow in the capillary will generate signals.

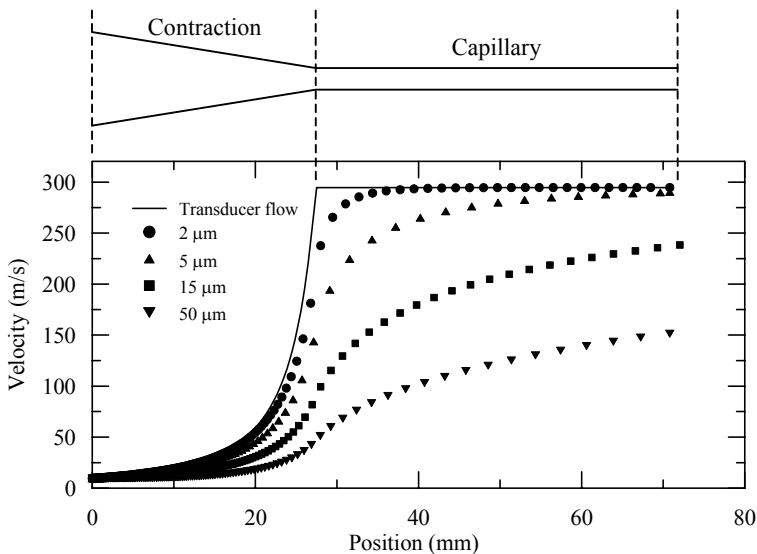


Figure 6: Particle size effect on particle motion through the transducer.

3.3 Concentration

Effort was placed in determining the effectiveness of the transducer's ability to measure particle concentration. Previous studies [7] reported differences of up to 40% between concentration measurements taken by the acoustic transducer and by laser based particle sizers. In the present study, concentration was measured simultaneously by the transducer and by an APS 3321 particle sizer [10]. The inlet chamber was filled with spherical glass particles ranging in size from 1 μm to 20 μm and several measurements were taken as the chamber was emptied by the vacuum pump, results are shown in fig. 7. The APS instrument can measure particles sizes between 0.5 μm and 20 μm with an accuracy of $\pm 10\%$. It can be seen that the correlation between transducer and APS measurements falls around a straight line, however, when considering the entire size range of the APS, the transducer's readings underestimate the concentration measured by the APS by more than 70%. As discussed in the previous section, particles smaller than 2 μm are not expected to generate acoustic signals as they follow the changing air velocity through the contraction faithfully and do not lead to flow disturbances. When taking into consideration the concentration of only those particles larger than 2 μm measured by the APS, the correlation is considerably improved; the transducer readings are always within 15% of the APS readings.

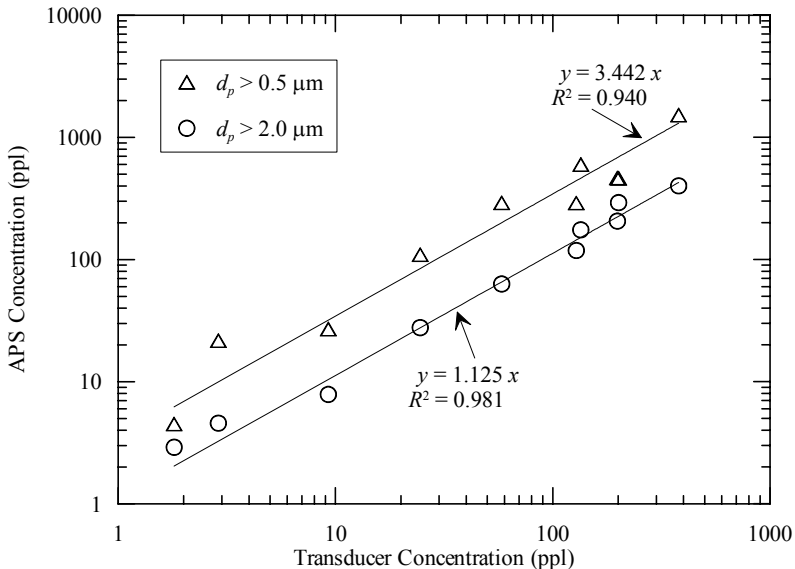


Figure 7: Particle concentration comparison between acoustic and APS measurements. Note the drastically improved correlation when considering particles larger than 2 μm .

4 Conclusion

The concept of an acoustic particle transducer has been discussed and shown to be an effective device in detecting micron sized airborne particles. Results support the fact that acoustic signals are generated in the contraction section of the transducer due to the inability of the particles to follow the unsteady accelerating airflow around them. The difference between particle and air velocities can cause an unsteady wake as the particles enter the transducer capillary disturbing the high Reynolds number flow at this location producing noise which is amplified by the inlet section of the transducer. The acoustic signal is comprised of resonant frequencies of the air column in the inlet section and, thus, is highly dependent on the transducer geometry.

No correlation was found to exist between particle size and the strength of the acoustic signals generated. It is thought that any unsteadiness present in the transducer capillary leads to a transition to turbulence in this section which is responsible for the acoustic radiation generated. Therefore, particles of sizes large enough to produce vortex or unsteady wakes will lead to acoustic signals.

The transducer is very capable of measuring concentration and one of its attractive features is the ability to measure low particle concentrations. However, with the current transducer tested no particles smaller than 2 μm can be detected. With further development, the transducer can be used as a continuous air quality monitoring device in clean room or other applications as it involves no lasers and requires little power and can provide measurements comparable to those of more expensive systems.

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