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Letter to the Editor

Effects of vortex shedding by particles in acoustical transducers

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1. Introduction

A recent series of articles by these authors revealed the capability of an acoustic transducer in detecting several aspects of air-borne spherical particles and fibers [1–3]. The acoustic transducer used is qualitatively similar to that sketched in Fig. 1. Particles and graphite fibers carried by airflow were drawn through the transducer from left to right in Fig. 1, through the inlet tube, the contraction, the capillary tube, and the expansion, followed by the outlet tube. The microphone gathering the signal was placed immediately downstream the entrance of the inlet tube. The existence of polystyrene latex (PSL) spheres with diameters as small as 5.9 μm [1] and concentrations less than 10 parts per liter (ppl) could be detected [3]. The qualitative detection of the aspect ratio of graphite fibers was encouraging [2].

It was reasoned that the acoustic signal was caused by the inability of the particle/fiber to follow the accelerating flow in the contraction [1,4]. As a consequence, flow separation around the particles and fibers led to unsteady or vibrating particle/fiber motion. These events led to acoustic radiation. The acoustic transducer, which acted as an organ pipe, amplified the acoustic radiation. Acoustic signal traces were similar for all particles and graphite fibers investigated in that they began with a drop in the signal voltage (typical signals are as shown in Fig. 2). The frequencies of the detected signals were consistent with the fundamental frequency ($f_o = c/4L$, where c and L ($= L_i + L_c$ as shown in Fig. 1) are the acoustic speed of the air and the length of the inlet tube) and harmonics with odd multiples of f_o, i.e., $3f_o$, $5f_o$, …, etc. These observations were also documented for acoustic transducers of several configurations and dimensions [5]. PSL spheres and fibers with smaller aspect ratios were found to generate dominant spectral peaks at $3f_o$, while fibers with larger aspect ratios generated the largest peak at the fundamental frequency f_o. In earlier development and applications of the acoustic transducer [6–10], the noise/signal generation was

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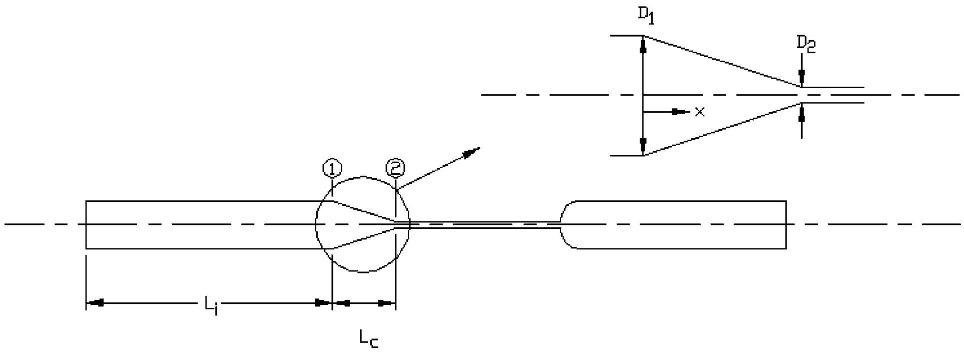

Fig. 1. The acoustic transducer (D_1 and D_2 are inner diameters).

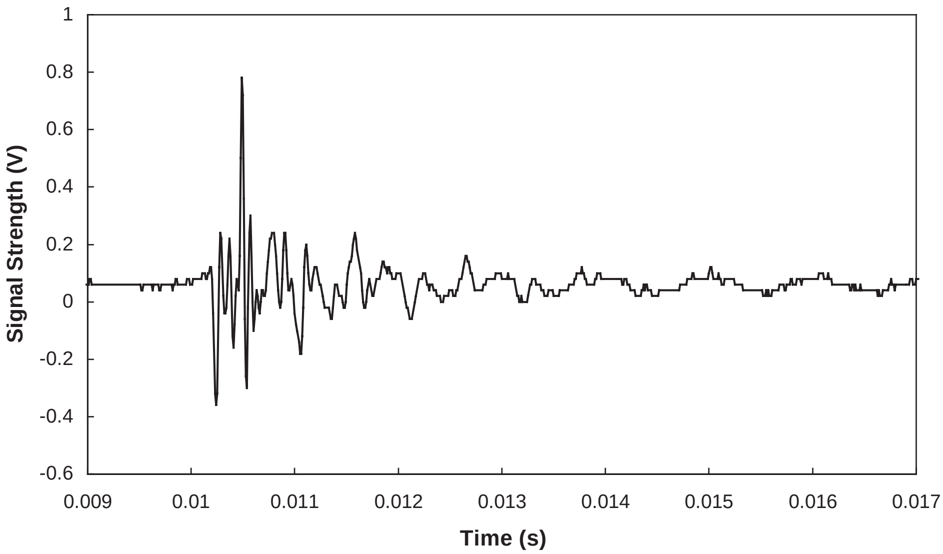

Fig. 2. Typical time trace of an acoustic signal produced by a particle passing through the acoustic transducer shown in Fig. 1. The trace shown is for 50 μm PSL spheres.

attributed to shock waves. However, this is not supported by the results in Refs. [1–3], as the pressure drop across the acoustic transducer was not sufficient to cause supersonic flows and shock waves [11].

In Ref. [1], the peak-to-peak signal amplitude was found to increase and then slightly decrease as the flow rate (i.e., the flow velocity) was increased over the range of investigation. It was thought that the particle motion became unsteady in the contraction area as a result of the difference in velocities of the flow and the particle (e.g., vortex shedding or flow separation from the particle) [1]. The strength of flow separation is expected to increase with the flow velocity. Similarly, the r.m.s. particle velocity would increase with the flow velocity. A moving "compact" sphere was known to radiate a sound power (P) proportional to U^2d^6, where U and d are the r.m.s. particle velocity and the particle diameter, respectively [4]. However, the $P \propto U^2 d^6$ relation suggests that the sound power would increase indefinitely with the flow velocity, which is not in agreement with the result in reference [1].

Only one acoustic transducer was used to obtain the above-mentioned results in Ref. [1]. To further investigate how the flow velocity affects the acoustic signal strength, experiments using several acoustic transducers with different dimensions than those in Ref. [1] were conducted. The focus is on the vortex shedding mechanism on acoustic emission.

2. Experiment

Detailed experimental setup and procedures are similar to those in Ref. [1]. Several acoustic transducers were used in this investigation. They are as sketched in Fig. 1, with their dimensions L_i, L_c, D_1, and D_2 shown in Table 1. A pump was used to draw air laden with aerosol particles through the acoustic transducer; the flow direction was from left to right in Fig. 1. The particles used for this study were PSL spheres with diameters equal to 50 μm. Nearly 100% of these particles can be detected using an acoustic transducer similar to the ones in this study [3]. The microphone for signal detection was placed at several locations upstream and downstream of the inlet of the acoustic transducer. As was also found in Ref. [1], the acoustic transducer behaved in a manner similar to an open-ended organ pipe and the signal strength was found to be relatively independent of the exact location of the microphone. The location chosen for the data reported here was 25 mm inside the inlet. The signal was fed to the storage oscilloscope and an FFT analyzer for data storage and analysis.

3. Results and discussion

The typical acoustic signal is shown in Fig. 2. The difference between the minimum and the maximum of a cycle constituted the peak-to-peak voltage (or the signal strength). The signal strength reported below is the averaged value of 15 signal traces similar to that shown in Fig. 2. For the results shown in Fig. 3, 50 μm PSL particles were used for four acoustic transducers (#1, #2, #3, and #4). It can be seen that the signal strength appears to increase and then decrease with the flow rate for each of the three transducers, although the values of the maximum strength are different and peak at different values of the volume flow rate (Q equal to approximately 25.0 and

Table 1
Parameters of acoustic transducers

Transducer	L_i (mm)	L_c (mm)	D_1 (mm)	D_2 (mm)
#1	32.0	24.0	10.0	1.7
#2	33.0	19.0	7.9	1.7
#3	78.6	20.3	15.4	2.0
#4	40.0	15.0	10.0	1.7

Note: D_1 and D_2 are inner diameters.

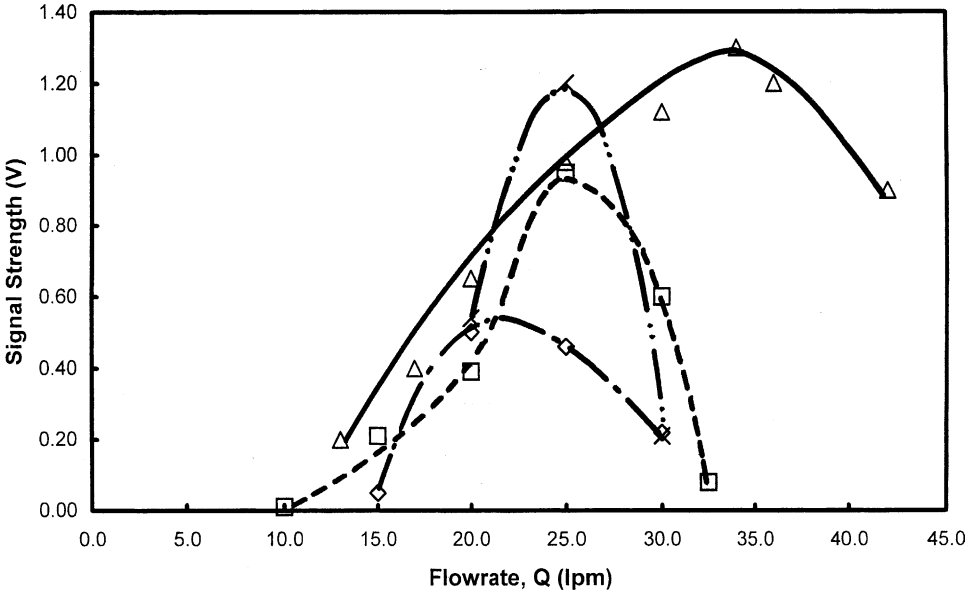

Fig. 3. Peak-to-peak voltage of acoustic signals generated in three acoustic transducers at various flow rates. Particles used are 50 μm PSL spheres. -- □--, Acoustic transducer #1; – · ◇ · –, acoustic transducer #2; –Δ–, acoustic transducer #3; -- × --, acoustic transducer #4.

34.0 lpm). The peak values of the signal strength for transducers #1, #2, #3, and #4 are approximately 0.95, 0.46, 1.30, and 1.20 V, respectively.

The above result suggests that the signal strength does not increase monotonically with the flow rate or the flow velocity for each of the four acoustic transducers. It was decided to examine the effect of the flow acceleration. This is because the flow separation or vortex shedding from the particle discussed in the Introduction above may occur as the flow velocity goes through a step change (i.e., an abrupt acceleration). However, the particle in the contraction region of the acoustic transducer experiences an acceleration that varies in the flow direction for the reasoning developed below. The acceleration as a function of the location within the contraction should therefore be examined.

Assuming a one-dimensional flow, continuity requires that $AV = Q$, where A, V and Q are the cross-sectional area, the flow velocity, and the volume flow rate, respectively. Because the flow is not supersonic (as discussed earlier), Q should remain relatively constant for a given flow rate. For the linearly tapered contraction shown in Fig. 1, the diameter at any location in the contraction region is $D = [D_1 - (D_1 - D_2)(x/L_c)]$, where subscripts 1 and 2 denote the beginning and the end of the contraction and x and L_c are the distance measured from location 1 and the length of the contraction region, respectively. It then follows that $V = V_1/[1-(1-D_2/D_1)(x/L_c)]^2$, where V is the flow velocity within the contraction and subscripts 1 and 2 take up the same meaning as above (see Fig. 1). The Langrangian acceleration (a) can therefore be shown to be, with $D_1/D_2 = R$,

$$a = V\frac{\mathrm{d}V}{\mathrm{d}x} = \frac{2V_1^2}{L_c}\frac{1 - 1/R}{[1 - (1 - 1/R)(x/L_c)]^5}. \tag{1}$$

Expecting that the maximum acceleration must occur either at location 1 ($x = 0$) or at the end of the contraction (location 2, $x = L_c$), the following ratio is of interest:

$$a_2/a_1 = R^5. \tag{2}$$

Since $R > 1$, the maximum fluid acceleration occurs in the narrowest region of the contraction. However, since $a_2 \propto V_1^2$, which is proportional to Q^2, it can be said that the signal does not increase with the flow acceleration either, as can be seen from the results of Fig. 3.

It is well known that vortex shedding from a circular cylinder causes unsteady pressure fluctuation in the wake region with a frequency characterized by a Strouhal number [12,13]. Vortex shedding in a sphere wake is substantially more complex and different from that in the wake of a cylinder. It is known that the strength of the vortex is a function of a Reynolds number (Re) based on the diameter of the sphere and vortex shedding is present in the range of $Re = 350$–3×10^5 [14–16]. The PSL spheres used in this study are also expected to cause vortex shedding as they are accelerated, which as discussed above is responsible for the organ pipe phenomenon previously reported. Since the flow acceleration reaches a maximum in the narrowest region of the acoustic transducer (i.e., the end of the contraction leading to the capillary), it is appropriate to examine the vortex shedding phenomenon there. The values of Reynolds number at both the beginning (Re_1) and the end of the contraction (Re_2) for conditions corresponding to the their acoustic peaks shown in Fig. 3 are listed in Table 2. It can be seen that the values of Re_2 for the acoustic peaks fall around a constant value of 610 (they are 618, 612, 601, and 618 for transducers #1, #2, #3, and #4, respectively). This constant value of Re_2 for maximum acoustic power is worth noting, considering the relatively wide ranges of values of D_1 and L_c. This Re_2 value belongs to a narrow range 400–800 (see Refs. [15,16]) where periodic laminar vortex rings emanate from the sphere. For values of the Reynolds number above 700–800, the vortex rings become turbulent and lose their individual character [15,16]. Therefore it is believed that the Reynolds number value, Re_2, obtained in the present study corresponds to the presence of the strongest vortex rings emanating from the sphere. For comparison, the strength of vortex shedding behind a circular cylinder reaches a maximum for Reynolds numbers approximately equal to 600 [13,14].

It is also noted that corresponding values of Re_1 do not appear to coalesce around a constant value (they are 17.6, 28.3, 10.2, and 17.6, respectively; see Table 2). This lends further support to the reasoning in Ref. [1] that the acoustic source lies in the contraction area of the transducer. In fact, the current results may help pinpoint the location at the narrowest region (i.e., the end of the contraction) immediately upstream of the capillary.

Table 2
Reynolds numbers at maximum acoustic signal strength

Transducer	Re_1	Re_2
#1	17.6	618
#2	28.3	612
#3	10.2	602
#4	17.0	618

4. Summary

The results of the present study of acoustical transducers suggest the following:

1. They suggest that the acoustical signal strength does not monotonically increase with flow rate. It increases and the decreases with flow rate (or the flow velocity).
2. The maximum acoustic signal strength is generated by the particles going through the narrowest region of the contraction, where the flow acceleration reaches its maximum value throughout the flow.
3. It was found that the maximum acoustic signal strength is associated with a particle Reynolds number approximately equal to 610 that corresponds to a transitional value for vortex shedding in the wake of a sphere. It is believed that at this Reynolds number, the strength of vortex shedding from the spherical particle reaches a maximum and the acoustical signal emitted from the acoustic transducer also reaches a maximum. This value of Reynolds number appears to be the same for several acoustic transducers with different dimensions and different flow rates.

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