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13. ABSTRACT *(Maximum 200 words)*

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For the tube with at least two bumps, it was found that the acoustic output peaks when there is an integer number (K) of vortical structures in the "cavities" between two bumps. The highest peak corresponds to K=1.

Some experiments were undertaken to suppress or at least minimize the sound level. One method which significantly reduced the sound intensity consisted of cutting a narrow strip off the tube along the whole length and replacing it with a smooth strip. This is equivalent to cutting a piece off each bump. A more active method of control consisted of forcing the first bump or cavity by using a set of twelve small speakers positioned in a circle around the tube. This technique only allowed the elimination of the lower sound levels (K 1), whereas the K=1 mode was only partially reduced.

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Active Control of Flow Induced Resonance in Continuous Corrugated Tubes

By M. Hammache and J. Rohr

Abstract

Wind tunnel experiments were conducted to study sound generation from corrugated tubes. Hot-wire and microphone measurements were used to determine the response of the following tube geometries to flow excitation: fully corrugated tube, tube with two corrugations, tube with one corrugation only, and tube with no corrugations at all.

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Description of experimets and results

We started our experiments by using a toy tube (a Bloogle™). It is a flexible plastic corrugated pipe 30" long, 1" in diameter with corrugations 3/8". The tube was placed in a PVC pipe to keep it straight and the whole system was then placed in a wind tunnel with the axis of the tube in the direction of the flow. A schematic of the set-up is presented in Figure 1.

Figure 1. Toy tube inserted in a smooth PVC pipe.

We varied the flow speed in order to excite various acoustic tones. A microphone was positioned at the downstream end of the tube to measure the sound frequencies. The various spectra we obtained are displayed in Figure 2. The three frequencies obtained here can be predicted by the simple relationship:

$$F_n = nc/2L$$

with $F_1 \approx 210$ Hz

Where n is an integer, c is the speed of sound and L is the length of the tube.

Figure 2 shows the harmonics F_2, F_3 and F_4 but we could not excite the fundamental tone, F_1. The reasons for this are not clear. We can only conjecture that the tube is too long for F_1 to be excited.

At 7.5 m/s there is a standing pressure wave inside the tube, with the nodes at the ends and the middle of the tube. At the same time there is a velocity standing wave with anti-nodes at the ends and the middle of the tube, as depicted in Figure 3.

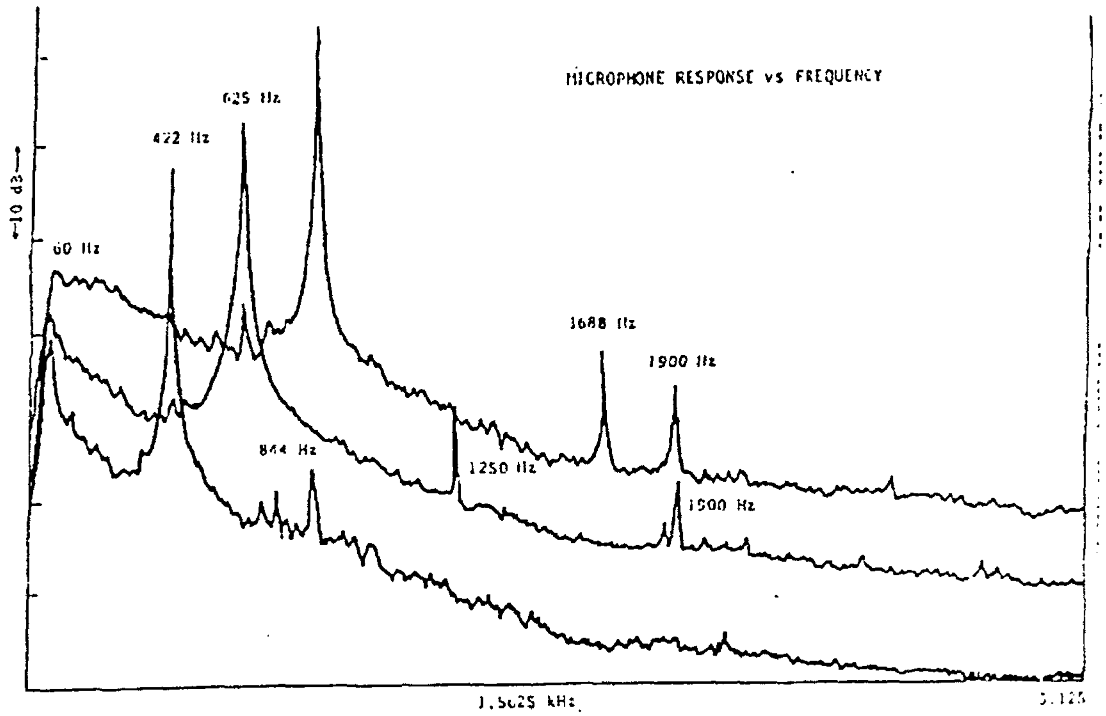

Figure 2. Microphone frequency spectra of toy tube for n=2, 3 and 4.

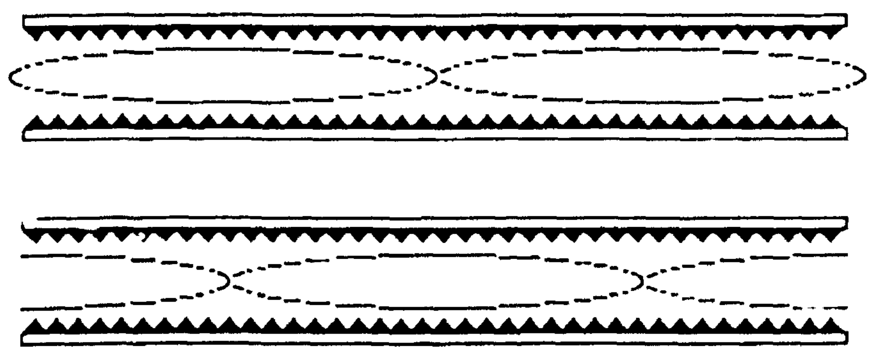

Figure 3. Pressure (top) and velocity (bottom) standing waves inside toy tube at n=2.

The next experiment consisted of cutting equal size pieces of the tube (the equivalent of 4 bumps) and varying the flow velocity in order to determine the maximum sound output of the tube at F_2. The results are in Figure 4. As we remove bumps from the pressure node (velocity anti-node) area the sound drops. Removing bumps from the pressure anti-node (velocity node) has the reverse effect.
Clearly the bumps in the pressure node contribute the most to sound generation. Note that the remaining length of the toy tube is always put back in the PVC pipe so that the total length of tubing is kept constant.

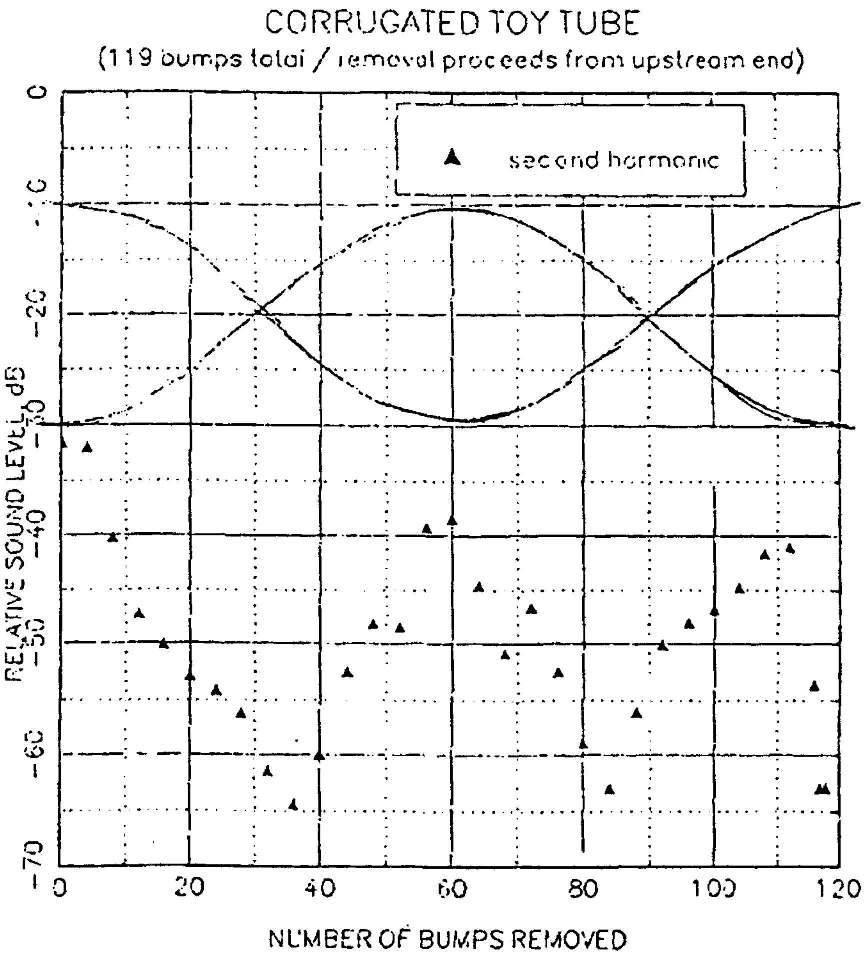

Figure 4. Effect of cutting bumps off downstream end of toy tube on the sound level.

Measurements inside the toy tube were impossible because it got choked when we introduced a hot-wire probe or a microphone inside it. We decided then to build a larger diameter plexiglass tube which would allow to vary the number of rings in the tube and their spacing. The length of the tube is 17.5" and its diameter is 6" and it has square edges. Various sets of rings and spacers, all with square edges, were also constructed out of plexiglass, namely a set 1/2" high by 1/2" wide, 1/2" high by 1/4" wide and 2" high by 1/2" wide. The spacers are 1/8" high by 1/2" wide and 1/8" high by 1/4" wide. A narrow slit was cut in the top of the tube to allow a hot-wire mounted normal to the tube axis to traverse the inside of the tube in the streamwise direction. The slit is always covered to isolate the inside of the tube from the outside. A schematics of the plexiglass tube with the rings is shown in Figure 5.

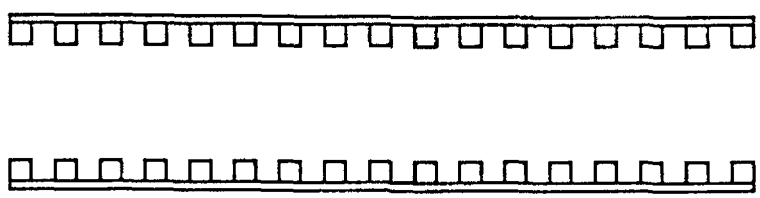

Figure 5. Schematics of plexiglass tube completely corrugated with all 1/2" rings

The inside of the tube can also be traversed by a hot-wire or a 1/2" diameter microphone mounted on a sting. The sting is mounted on a 3D traversing mechanism and is long enough to permit the microphone or hot-wire to traverse the entire length of the tube.
For this tube geometry, we found that we could excite the fundamental tone and its first harmonic in the range of velocities investigated.
It became clear right away that the plexiglass tube could be excited at its fundamental frequency as well as its harmonics.
A centerline traverse of the microphone when the tube is singing at the fundamental frequency revealed a pressure standing half-

wavelength with nodes at the tube ends and an anti-node at the middle. A hot-wire traverse showed a velocity standing half-wavelength with anti-nodes at the tube ends and a node at the middle. Figure 6 shows the streamwise distributions of the microphone and hot-wire levels.

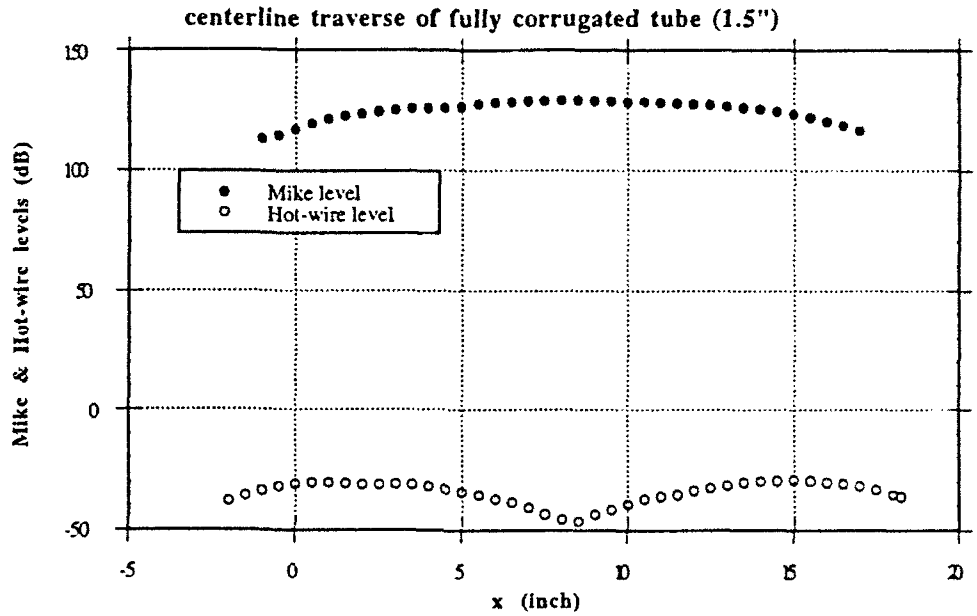

Figure 6. Mikcrophone and hot-wire level as a function of streamwise location at centerline of tube at fundamenntal frequency.

Preliminary studies revealed that the acoustic response of the fully corrugated tube and the tube with two corrugations are very similar. The problem can thus be simplified by studying a tube with two bumps. We then used two bumps only separated by one spacer, thus forming a "cavity" in the tube and measured the output of a microphone kept at a fixed location just downstream of the tube, as a function of the velocity. We did the same thing for various locations of the "cavity" and ploted the maximum sound level versus the "cavity" location. The plot in Figure 7 shows that the tube sings the loudest with the cavity at either end of the tube, i.e. at the pressure nodes (velocity anti-nodes) and sings the least with the cavity at the middle, i.e. at the pressure anti-node (velocity node). This is in agreement with the toy tube data. Note that the maximum sound level obtained with the cavity at the end is higher than the maximum level obtained from a fully corrugated tube.

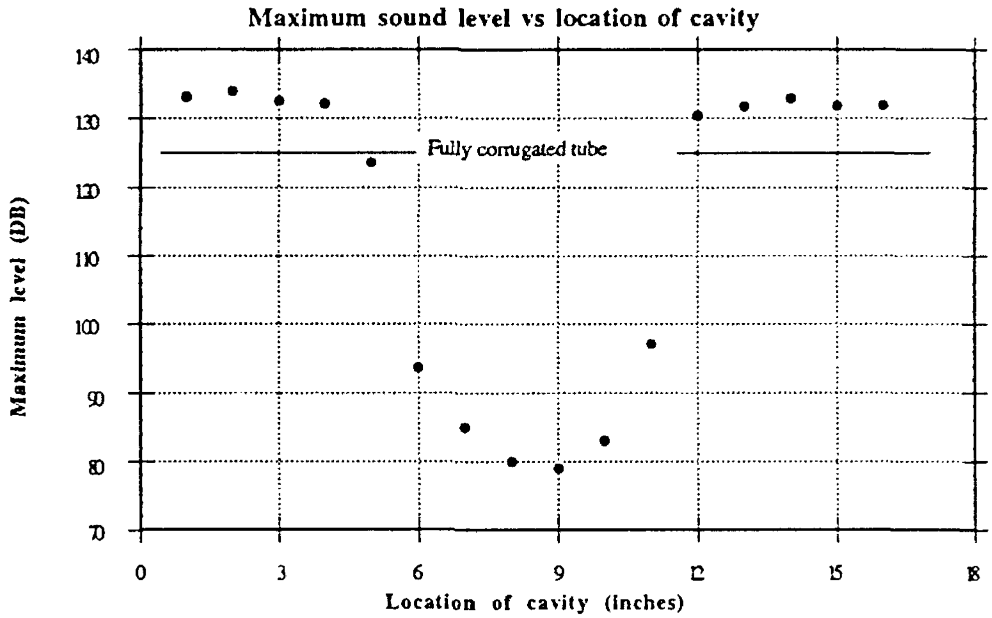

Figure 7. Maximum level output from one "cavity" as a function of location of cavity at fundamental frequency.

In the remaining experiments we focused mainly on the fundamental tone of the tube. For a given number of bumps and a given bump spacing, the response of the tube to flow excitation looks like what is presented in Figure 8. A number of small peaks are present in the data as the velocity is increased, and the peaks get louder for higher velocities.

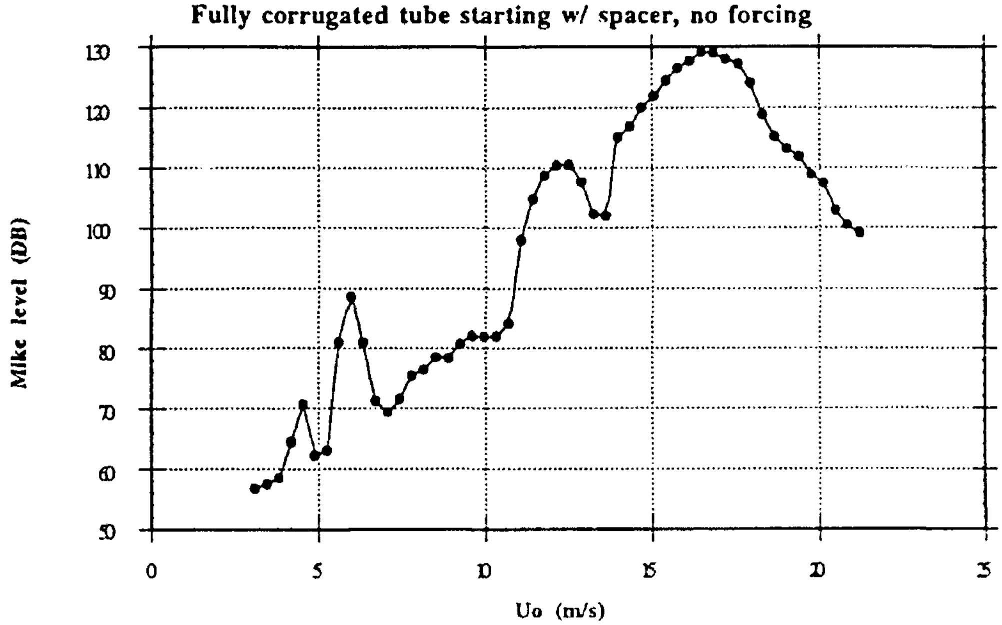

Figure 8. Typical averaged microphone level for the plexiglass tube excited at its fundamental frequency

A look at the frequency response in Figure 9 reveals a basically constant frequency, near the fundamental. There are small "adjustments" the tube makes as the velocity increases but it remains generally constant near the natural fundamental frequency of the tube.

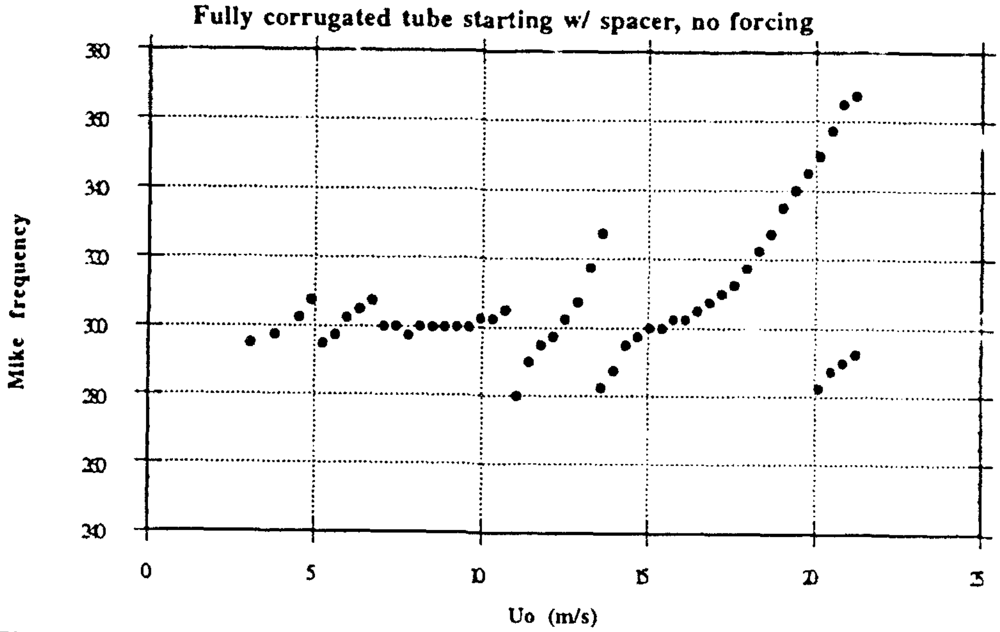

Figure 9. Typical averaged microphone frequency data for the plexiglass tube excited at its fundamental frequency

An attempt was made to monitor the shedding frequency with a hot-wire placed directly behind a bump when the tube is not singing, but for this tube we could not determine the frequency accurately. The idea was to follow the frequency as the velocity is increased and determine whether it is equal to the fundamental frequency when the tube starts to sing.

For this, we decided to use two pieces of the toy tube instead; one 3.25" long and the other 4.75" long. It was expected that there would always be a velocity range for which the longer tube sang and the shorter one did not. We placed the hot-wire behind the second bump of each tube and varied the velocity. The results are presented in Figure 10.

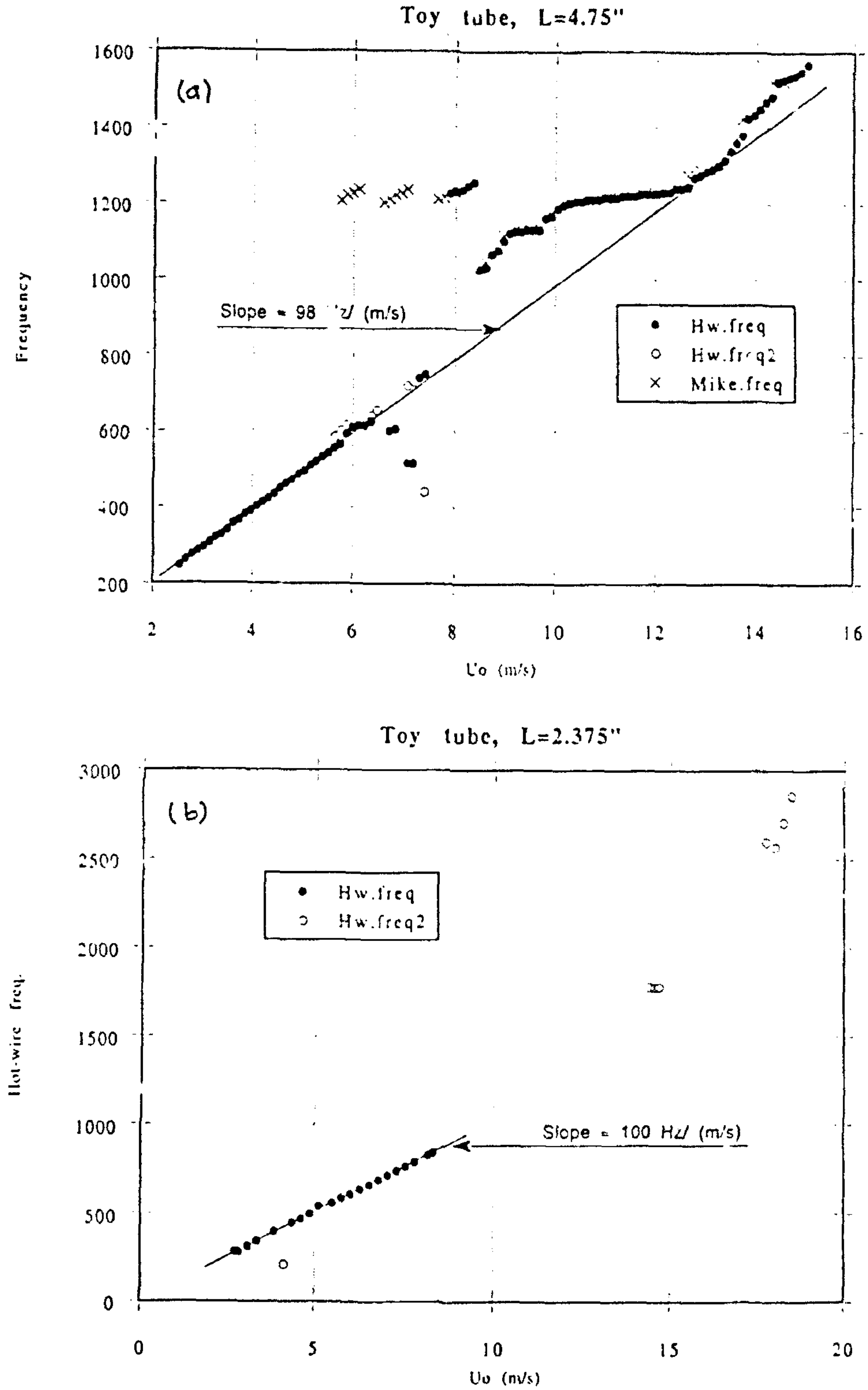

Figure 10. Hot-wire and microphone measurements near the bumps of two toy tubes of different length. (a) L=4.75", (b) L=2.375"

Clearly, the shorter tube exhibits a frequency which grows linearly with the velocity. This is the shedding frequency because the tube does not sing in this range of velocity. The longer tube exhibits the same behavior until the velocity is high enough for the fundamental to be excited, in this case at $F_1 \approx 1200$ Hz. Clearly the shedding frequency grows until it is close to the fundamental, at which point the tube starts to sing. The behavior of the frequency at higher velocities is a puzzle. We do not understand yet why the microphone and the hot-wire measure the same frequency over this range and why this frequency grows linearly with velocity instead of remaining locked at the fundamental.

At this point we can say that the model of bump frequency is verified.

The next step was to go back to the large plexiglass tube and look at the flow inside the "cavity" i.e. between the two bumps.

We essentially studied at the streamwise wavelength of the velocity perturbations. For this, we used two hot-wires which were positioned between the two only bumps in the tube. The first hot-wire was kept stationary just behind the downstream edge of the first bump at 1/4" downstream of and 1/8" below the edge. The second one is mounted on a traverse which allows it to be moved in the downstream direction. A schematic of the set-up is shown in Figure 11. The hot-wires used for cross-correlation measurements are labeled 1 and 2.

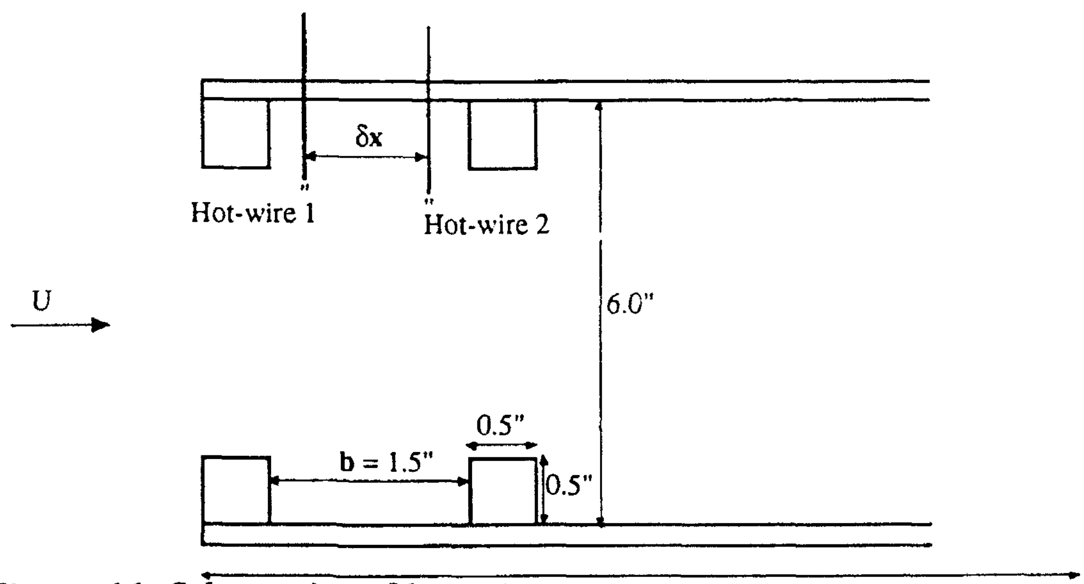

Figure 11. Schematics of hot-wire set-up.

The two hot-wires "see" the same perturbation but the downstream one experiences a delay τ with respect to the first one.
This delay τ can be related to other parameters of the flow, namely the frequency of the perturbations f and the distance between the hot-wires δx by the following relation:

$$\tau f = \delta x/\lambda$$

where λ is the streamwise wavelength of the perturbation.
The quantity λf represents the phase velocity u_c of the perturbations.

The equation above is thus equivalent to:

$$\tau = \delta x/u_c$$

By varying δx we obtain the relation $\tau(\delta x)$ which is a linear curve with a slope of $1/u_c$

These measurements were performed for a variety of geometries and free-stream velocities. Here we present a typical run on a gap b=1.5" at U_1=10.4 m/s and U_2=17.6 m/s. These two free-stream velocities correspond to two distinct regimes of excitation of the tube. Two bumps only were used in this case, at the tube inlet.

We obtained the following slopes:

u_{c1} = 6.18 m/s at U_1=10.417m/s

and u_{c2} = 12.32 m/s at U_2=17.613m/s

These convection velocities are computed by simply inverting the slopes of the two data curves in Figure 12.

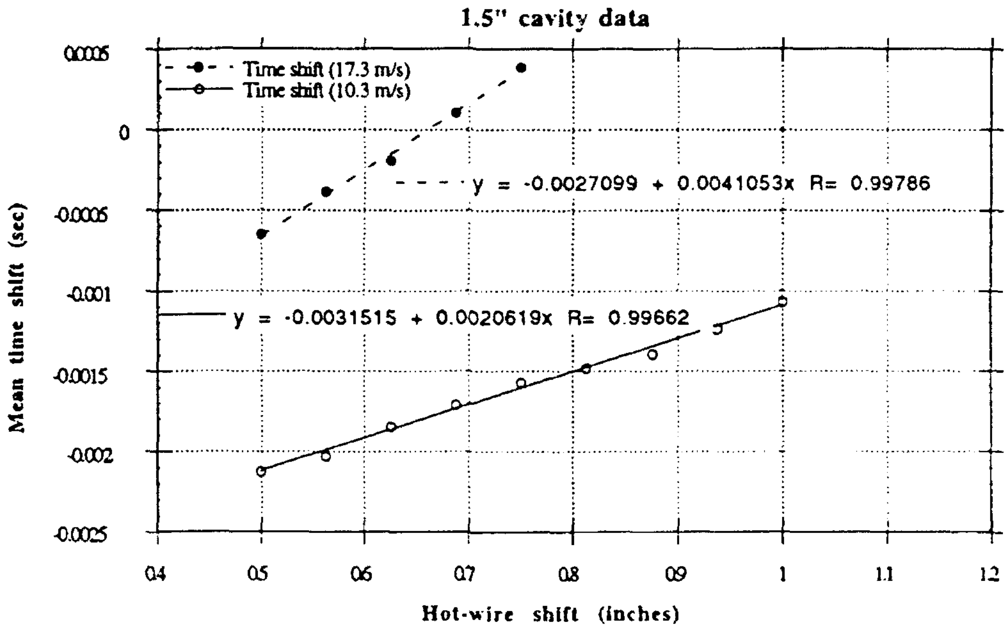

Figure 12. Phase shift data recorded at 17.3and 10.3 m/s

Using $f_1 = f_2 = 327.5$ Hz we obtain the following wavelengths:

$$\lambda_1 = u_{c1}/f_1 = 243.6/327.5 = 0.744'' \approx b/2$$

and

$$\lambda_2 = u_{c2}/f_2 = 485/327.5 = 1.481'' \approx b$$

Therefore there is one vortical structure in the "cavity" at the highest peak of sound, i.e. K=1, and two structures at the lower peak, i.e. K=2. There may be three structures at the next lower one but we did not measure that.

The next step was to study the response of the plexiglass tube with one bump inside it. It turns out that one bump at the downstream end of the tube produces sound levels comparable to a fully corrugated tube. This was observed with the various rings we had at our disposal, although they produced different sound levels as shown in Figure 13.

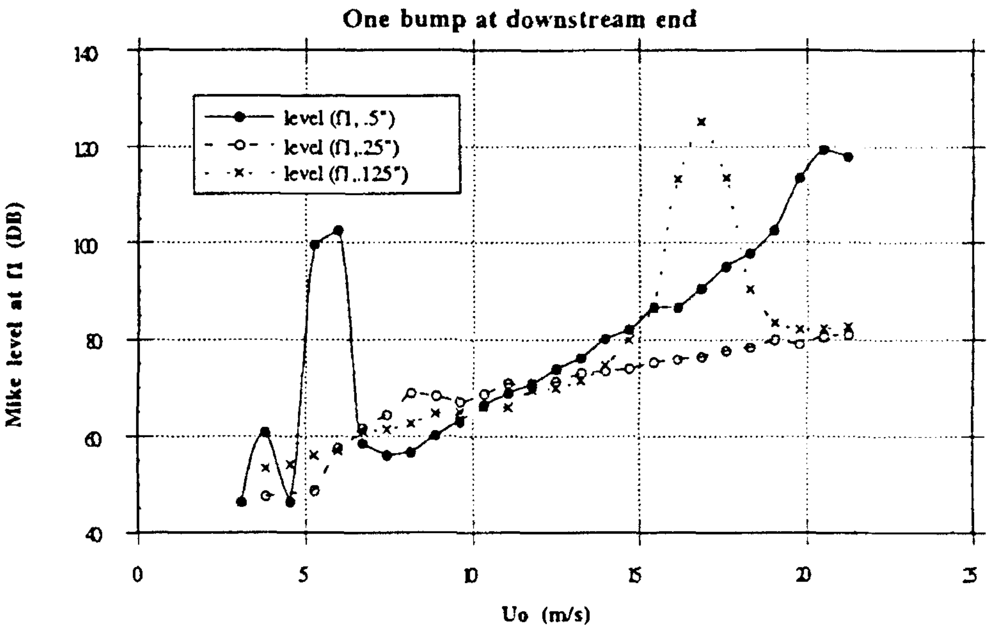

Figure 13. Levels of sound emitted by tube with one bump at downstream end. Data from three bump sizes is displayed.

This indicates that two rings are not necessary for sound generation, but it is difficult at this point to determine whether the mechanism of sound generation is the same for the case of one and two rings. In another set of experiments we removed all rings from the tube and surprisingly we obtained sound for this case as well. Again, the mechanism for sound generation for an empty tube are not clear at this point, but we can conjecture that because the inlet of the tube is square, the flow separates as it enters the tube and the tube sings if the shear layer frequency is close to the tube natural frequency and locks onto it. We also detected a second frequency (noted f2) in this case. This frequency is not a harmonic of the natural frequency of the tube but rather increases linearly with the free-stream velocity. Efforts to identify this second frequency are planned for future work. Figures 14 and 15 show the evolution of the frequency and the sound level for the empty tube, respectively.

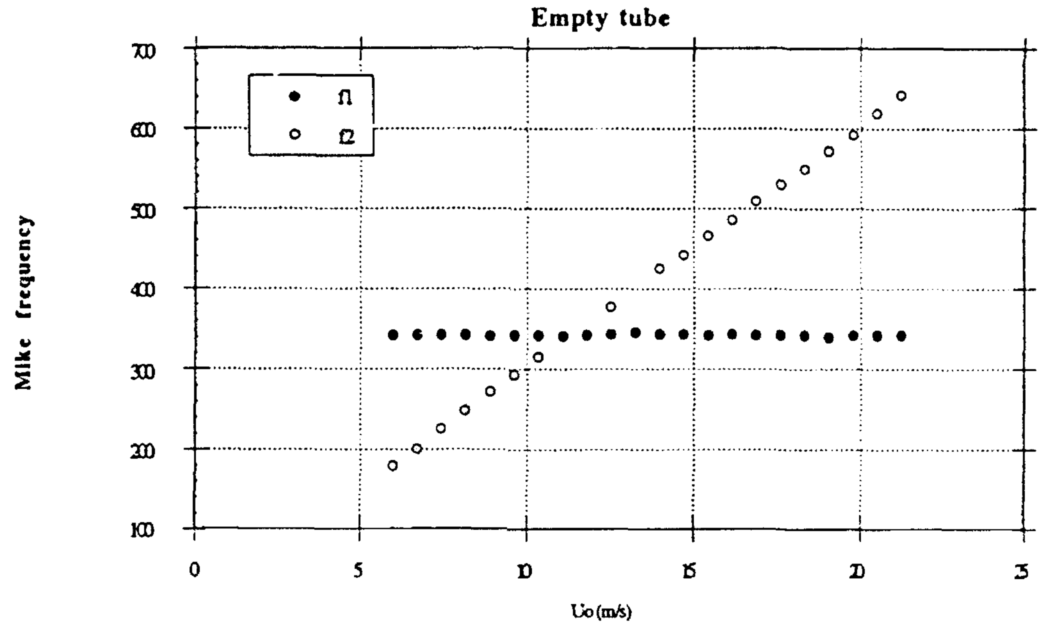

Figure 14. Evolution of frequency with free-stream velocity for empty tube.

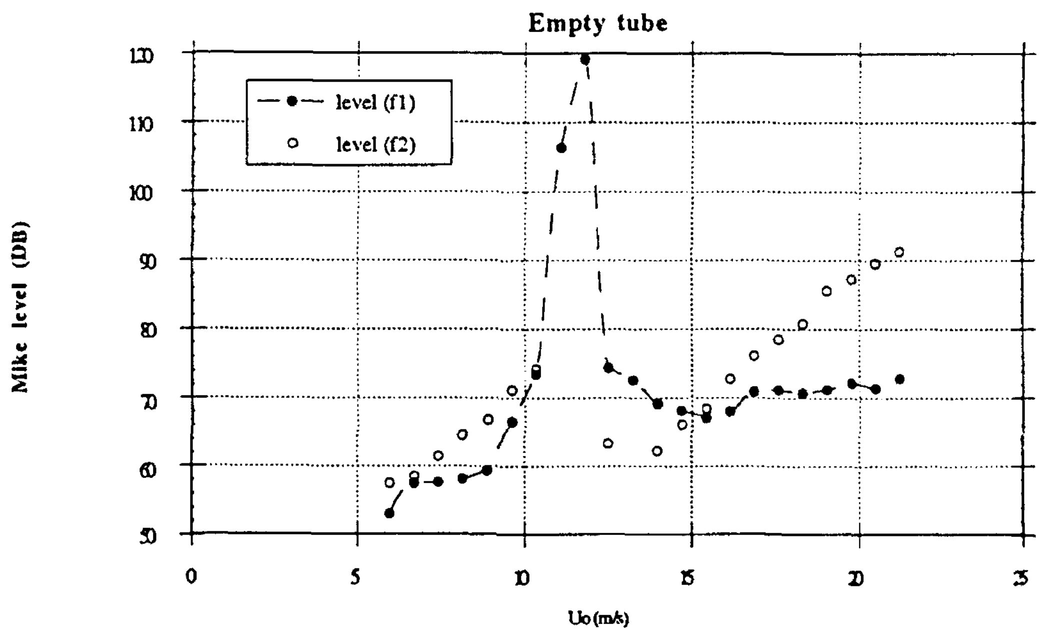

Figure 15. Evolution of sound level with free-stream for empty tube.

On sound suppression

Starting with the toy tube, we found that cutting a narrow band along its length so as to "break" the continuity of the corrugations was effective in suppressing the sound.

For the case of one bump at the downstream end and the empty tube, we found that the sound level could be reduced considerably by affecting the downstream end of the tube instead of the upstream end. This is done by taping a narrow band of the corrugated toy tube on the inside surface of the bump or the tube respectively. The effect of such a "disturbance" of the downstream end of the tube is illustrated in Figures 16 and 17 for the case of one bump and the empty tube, respectively.

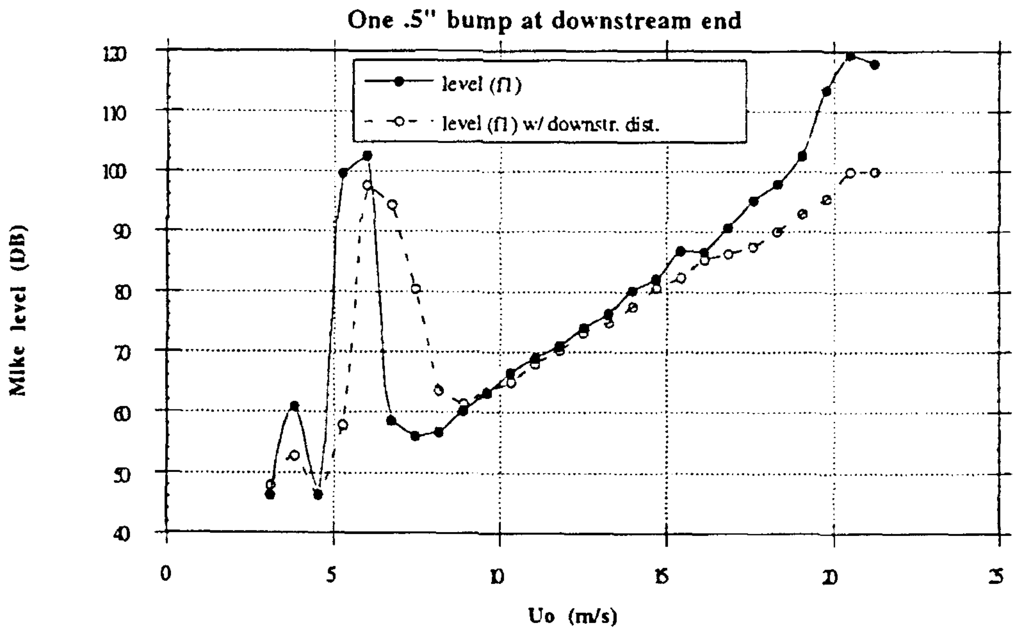

Figure 16. Sound reduction for tube with one bump.

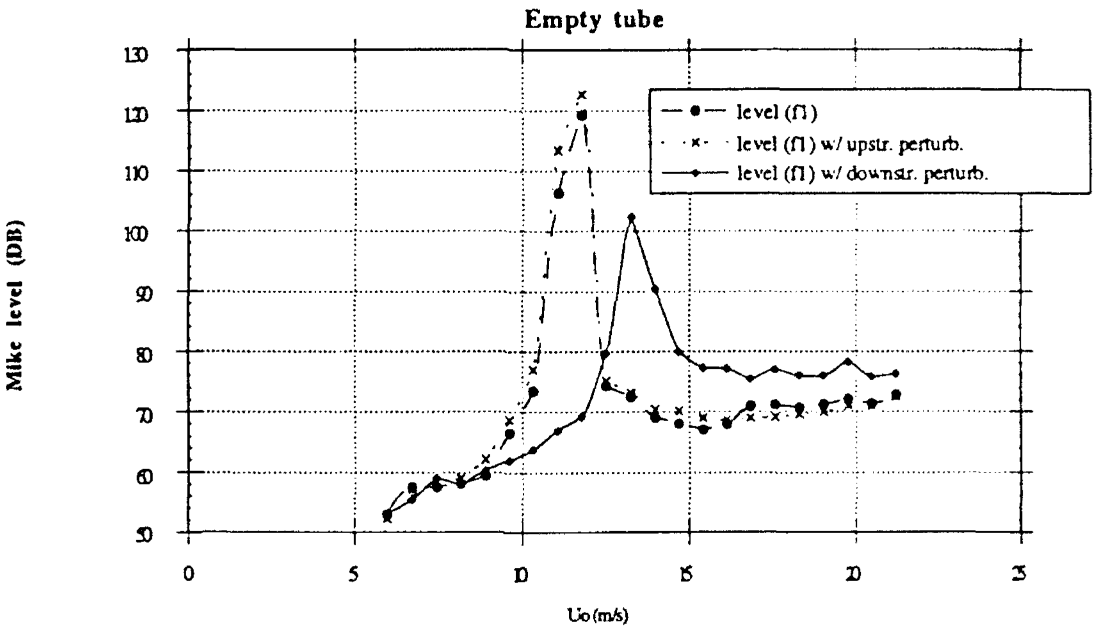

Figure 17. Sound reduction for empty tube.

This suggests that disturbing the separating shear layer does not affect sound generation, whereas disturbing the impingement point does.

A more active control method was also studied. It uses a ring of twelve small speakers positioned in a circonference. The speakers can be used to input sound at the first bump or the first cavity in the tube. The frequency of forcing can be chosen independently of the frequency emmited by the tube or we can use the tube sound signal, invert it and feed it back through the speakers.

This method did not produce results though. It could be due to the low power of the speakers or to the fact that the sound is input at discrete points and not uniformly around the tube. Our best result so far consisted of forcing a cavity at an arbitrary frequency. This resulted in a complete suppression of the lower peak and a reduction of the higher peak over a range of velocities as shown in Figure 18.

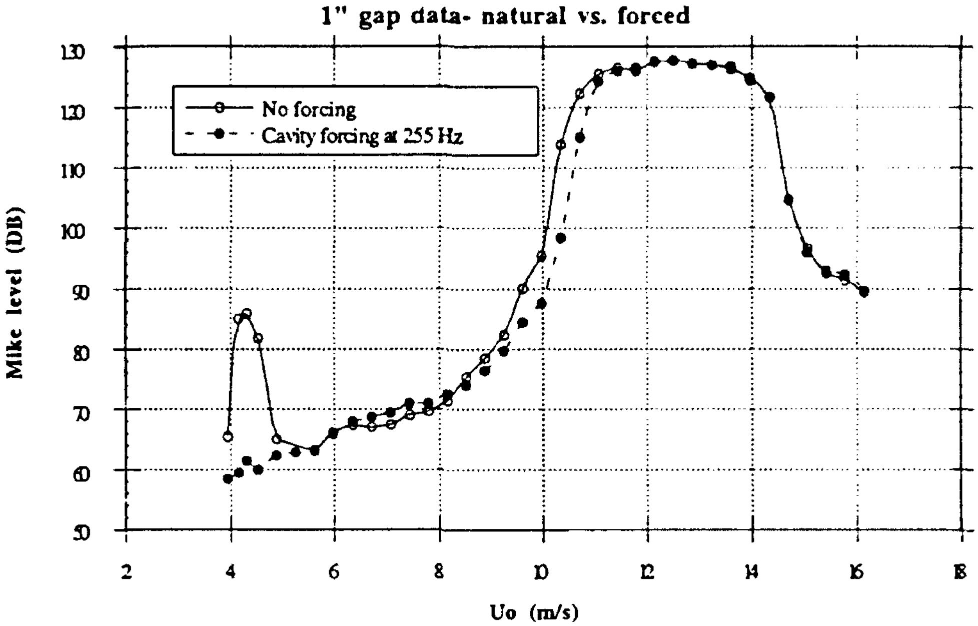

Figure 18. Elimination of lower peak and reduction of higher peak by forcing cavity at 255 Hz.

Future improvements include designing a forcing mechanism which would allow uniform forcing all around the tube as well as a study of other ring geometries.