IYPT2006 #11: Singing Tube:
A tube open at both ends is mounted vertically. Use a flame to generate sound from the tube. Investigate the phenomenon.

References:


   This article lists the following bibliography:


1. This introductory guide to this problem starts by noting that there are two versions of a vertically-oriented singing tube and one extra version based on glass tube (see Sergent-Welch catalog).

The first one is pictured on the website where my student who worked on this problem (Anna Doud, RCDS '07, and now at Yale University) is holding a large mailing tube above a Bunsen burner. This arrangement is far and away the easiest way to hear this weird effect. There are some immediate warnings. The air flow created by the Bunsen burner and the constriction of air at the bottom of the tube is very hot – we measured temperatures above the tube when it was singing of 400 degrees centigrade or more. A "small" thermocouple will not work at these temperatures – check your ranges carefully. And use some gloves. Cardboard mailing tubes will take a fair amount of heat, depending on their wall thickness, but we burned up a couple. This version of the singing tube I am going to call a Tyndall tube after the earliest literature note I have found (see reference 2). Tyndall's book is hard to find and it's filled with those superfluous 19th century descriptive paragraphs, lovely old diagrams, and almost no useful theory whatsoever.

The second one is called a Rijke tube after P. L. Rijke of the University of Leiden who made one (accidentally?) in 1859 and wrote about shortly thereafter (reference 3). In this version of the singing tube one inserts a wire mesh into the tube and heats it with an electric current or an external torch of some sort. When the current is stopped or the torch removes the tube sings. Walker gives a fairly standard introduction. Apparently this became a bit of a sensation in Europe during the mid-19th century as the theory of acoustics was developed by both the English (Rayleigh – reference 1b) and the Germans (Helmholtz – reference 4). You can buy one of these types of tube from Educational Innovations.

I'm going to split this problem into several pieces. Almost ALL real wind-blown musical problems have these pieces. One of these days I'll find a book which adequately treats all of them. Unfortunately after IYPT2004 #5 Sea Shell, IYPT2004 #11 String Telephone, and this one IYPT2006 #11 Singing Tube I haven't found that perfect textbook. So as a NYPT advisor you'll have to assess carefully how far you and your student will pursue each piece. Learning a little about all of the pieces is obviously a good way to prepare to oppose this problem.

2. Problem pieces:

   a. What is the difference between a singing tube and a tube with any old air flow?

   b. What is the resonant structure of the tube and why doesn't a singing tube sing at the tube's unheated resonances?

   c. What is the source of the acoustical fluctuations that excite the resonant structure of the tube?

   d. Where does the sound we hear come from?

   e. One zillion related topics of forced, damped oscillators and mechanical and acoustical low-pass filters, and the precise coupling mechanisms between excitation sources and resonant chambers..
3. What is the difference between a singing tube and a tube with any old air flow?

This question can occupy sometime but most labs will have modern, 21st century microphones and analog-digital converters with software that can perform a FFT on the resulting pressure as a function of time signal (Vernier, PASCO, etc). Here's a singing tube FFT using a Rijke tube and heating the internal mesh with a torch:

![Singing FFT](image)

Here's what I would claim is a "roaring" tube which we produced by using the same tube and exciting it with the torch and no mesh screen:

![Roaring FFT](image)

The recorded tonal qualities of these two "sounding" tubes are noticeably different. Any standard text (see reference 5 for instance) will note that the resultant "time-dependent motion" of a driven multi-mode system can be written as a linear superposition of the absorptive and dispersive amplitudes of each of the resonant modes. The FFT is a plot of the Fourier Transform of that linear superposition. That linear superposition in principle is the convolution of the excitation mechanism and the resonant structure of the tube acting as an acoustical band-pass filter. So one line of "research" could be to work you way back through the Convolution Theorem to that acoustical coupling. This is difficult by the way.

There are many ways of exploring the resonant structure of the tube. We used leaf blowers to just blast air at the tube, frequency synthesizers and loudspeakers to sweep through the tube resonances, and tuning forks. The structure of a resonant tube's mode frequencies is well-known and I won't repeat it here. What is not well-known is how the "ends" of an open tube "reflect" a propagating traveling wave to create the necessary counter-propagating traveling waves that are the basis of the resonant structure. This is a difficult calculation. The best treatment I found was in reference 6. This feature effectively lengthens
the tube by \((8r/3\pi) = 0.85r\). The simplest conceptual picture is that any change in density will cause the propagating sound wave to reflect and transmit as though it had hit a new medium. The speed of sound depends on the density of the medium therefore any change in density results in a media change.

4. What is the resonant structure of the tube and why doesn't a singing tube sing at the tube's unheated resonances?

The shock will come when you calculate the resonant modes and discover that the FFT's observed modes are very far from the tube's modes. Why is this? Basically the speed of sound is also very dependent on temperature and you've got a hot moving column of air rising through that tube. The speed of sound as a function of temperature is well-known (see reference 6) but experimentally measuring the temperature is not. Using a cardboard mailing tube with some small holes and small thermocouples might give a clear picture of the temperature distribution. We found this difficult and never totally solved it.

5. What is the source of the acoustical fluctuations that excite the resonant structure of the tube?

Most folks think there is an obvious answer to this "The flickering flame!" Well certainly not in a Rijke Tube because the tube doesn't sing until you take the flame away. And in a Tyndall Tube you'll quickly discover that the exact relationship of where you put the flame and the air space around the flame makes an enormous difference whether the tube will sing at all. This also happens in a Rijke Tube when you vary the position of the flame. There are places were the heated mesh doesn't excite the tube and it doesn't sing. Hmmmmmm.

So this is not a trivial problem – how does the acoustical structure of the tube get excited and continue to receive energy? In fact how one excites a resonant tube is one of the oldest problems in acoustics and is still not explained well in the texts I found.

The first thing to try is to measure the sound spectrum of the air flowing around heated mesh. This isn't easy as one needs to tube to get the vertical air flow. But you should get something for analysis. It will be a very broad spectrum of Fourier components. The second would be to try and measure the sound spectrum of the Bunsen burner flame you are using.

Then you need to see if those spectra can "convolve" with the resonant structure to produce the final observered FFT. We didn't get agreement with either.

Slowly we became convinced that the source of the acoustical noise was the air flow across the bottom edges of the tube due to the rising air flow. The engineers call these edge vibrations and they are similar to a traffic sign wriggling in a strong breeze. The shedding of vortices on each side of the edge is described by one of those dimensionless numbers in fluid mechanics called the Strouhal Number. It's not hard to calculate and when we did we finally started to get agreement with the excitation spectrum and the relative heights of the peaks in our FFTs.

The definition of the Strouhal number is \(St = (fD/V)\) where \(f\) is the vortex shedding frequency, \(D\) is the diameter of the edge the flow is shedding from, and \(V\) is the flow speed.
(see reference 7). Fortunately if you glance in reference 7 on page 11 you will see that the Strouhal number is approximately 0.2 times the more familiar Reynolds Number which is defined to be $Re \equiv \left( \rho DV / \mu \right)$ which the only new symbols being the density, $\rho$, and the viscosity, $\mu$, of air. This will get you the mid-frequency for the excitation spectrum.

Some of the supporting evidence that the edges at the bottom are important are the following. There is often a delay in a Rijke tube's singing from when you remove the flame of perhaps one of two seconds. The flow across the tube edges will take about that time. The flow across the heated mesh pieces occurs almost instantly. In a Tyndall tube you'll find that the flame must be held at a particular point in the general bottom opening of the tube. Not any place will do. In fact if you put it in a very tightly fitting tube there will not be enough air flow for the tube to sing.

I will let you confirm all of these. Oh, one thing you should try is to excite the tube with a blower hose aimed at the side of the tube. Annie and I did this and it finally convinced us that the edge effects were the source of the acoustical noise.

6. Where does the sound come from?

Well the ends. But both of them or just one? This is hard to tell experimentally and so this is not a trivial question. How could you sort out these differences? We didn't get to this?

7. The entire subject of coupled, forced oscillators is now open for teaching and review. I recommend Crawford's text for beginners although it doesn't address FFTs the way more modern texts do. Someday someone will write a text that unifies all of the modern transform theory, coupled oscillators, linear response models, spectrometers, and driven oscillators.

Enjoy.

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