Aeroacoustic Source Strength Measurement of Helmholtz Resonator

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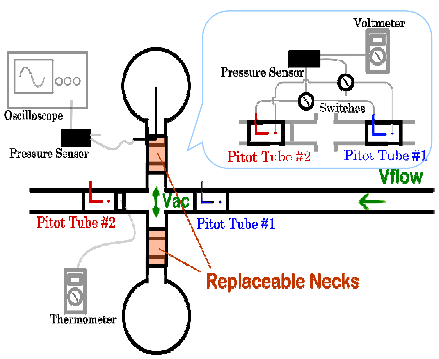
Abstract

The characteristic of the aero-acoustic excitation of Helmholtz resonators with different neck geometries has been determined, and the work done to sustain and excite resonance have been studied. A Helmholtz resonator consists of a volume connected to a duct and has a well defined resonance frequency which depends on the length of the duct, the volume of the resonator and the cross sectional area of the duct. In the system used during the measurement, two Helmholtz resonators have been positioned at opposite sides if a junction in a wind tunnel. The air flowing over the junction openings to the Helmholtz resonators can excite the acoustic resonance of the system. This is similar to blowing over an empty bottle's opening and creating a tone. The effect of the resonator's geometry has been seen in the measured acoustic amplitude and frequency in the resonator. The work done by the aero-acoustic source of sound has been determined through the measurement of the air speed in front of and behind the junction in the wind tunnel; and, the energy stored in the resonator has been determined through the measurement of the acoustic pressure inside the resonator's volume.

Experimental Setup



The system is composed of 2 inch ID glass pipe, a cross junction, various lengths of duct pieces and two 5L flasks. In order to measure the quantities required to see the air flow's behavior, the following are used: a thermometer, an oscilloscope, a voltmeter, two pitot-tubes, and two pressure sensors. The one of the pressure sensors is used as a microphone to measure the amplitude of the pressure change, *Pamp*, and the frequency of oscillation in the flasks. The microphone signal is viewed on the oscilloscope. As the mean flow passes over the junction opening a vortex is created. The creation of the vortex and its behavior influences the acoustic excitation of the flasks. Consequently, the acoustic behavior of the flasks influences the creation of the next vortex. Another pressure sensor is used to measure the mean flow velocities of the air at before and after the junction in the duct, V_1 and V_2, via two pitot-tubes and switches connected to the two pitot-tubes and the sensor; and, it is also can measure the pressure difference between the room and the inside of the duct for another pressure measurement. Each pitot-tube is calibrated to convert from voltage to pressure or velocity directly.

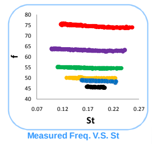
Theory

I. Resonance Frequency
Considering Helmholtz resonators as a mass- spring system, the frequency can be expressed as

$$f = \frac{c}{2\pi}\sqrt{\frac{S_{neck}}{V_0 L'}} \qquad (1)$$

where c is the speed of sound, S_{neck} is the cross sectional area of the neck, V_0 is the volume of the resonator, and L' is the half of the total effective neck length.

II. Strouhal Number
Strouhal Number (St) can be useful to characterize the aero-acoustic excitation of the resonator with different neck geometries. St for this experiment can be expressed as



$$St = \frac{f \cdot D_{neck}}{V_1} \qquad (2)$$

where D_{neck} is the diameter of the neck, and V_1 is the mean velocity inside the duct before the junction.

III. Acoustic Velocity
The acoustic velocity of the air in the neck can be calculated as,

$$V_{ac} = \frac{V_0\,\omega}{\rho_{air}\, S_{neck}\, c^2} \cdot P_{amp} \qquad (3)$$

where $\omega = 2\pi f$ of the resonance, and $Pamp$ is the amplitude of the pressure wave, which can be observed in the oscilloscope's display.

Vac/V1 Range
For ($Vac/V_1 \le 0.001$), the oscillating pressure amplitude of shear layer increases exponentially (Elder and Howe). For ($0.01 \le Vac/V_1 \le 0.1$), the acoustic velocity field helps to form vortices (Bruggeman). For larger Vac/V_1, the shear layer changes into vortices (Nelson).

IV. Energy Dissipation & Quality Factor
Measuring the air flow velocities before and after the junction, V_1 and V_2, the kinetic energy difference (the work done to excite and sustain the resonance) $E_{dissipated}$ is determined. Energy stored in the resonance, E_{stored}, is related to Vac. In order to characterize the resonance in the Helmholtz resonators, the ratio E_{stored} to $E_{dissipated}$, called the quality factor Q, is useful.

$$Q = 2\pi \frac{E_{stored}}{E_{dissipated}} \qquad (4)$$

$$E_{stored} = \frac{1}{2}\left(\rho_{air} L_{total} S_{neck}\right)\cdot V_{ac}^2 \qquad (5)$$

$$E_{dissipated} = \frac{1}{2}\left(\rho_{air} L_d S_{neck}\right)\cdot\left(V_1^2 - V_2^2\right) \qquad (6)$$

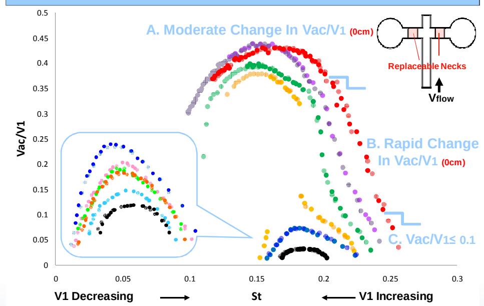
where

$$L_d = V_1 t_{ac} + \frac{V_2^2 - V_1^2}{4 D_{12}} t_{ac}^2 \qquad (7)$$

where t_{ac} is the period of resonance, L_{total} is the total effective neck length and D_{12} is the distance between the two pitot-tubes.
And so,

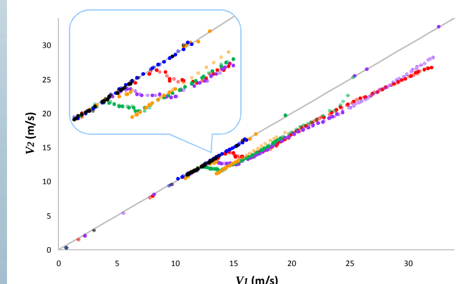
$$Q = 2\pi \frac{L_{total}}{L_d} \cdot \frac{V_{ac}^2}{V_1^2 - V_2^2} \qquad (8)$$

Vac/V1 V.S. St



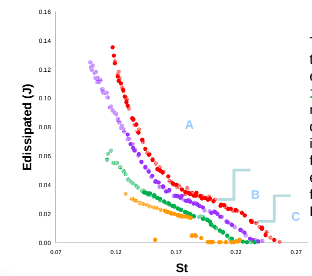
The above graph shows the results with 0, 7, 16, 23, 25, 26, 27, 28, 29 and 30 (cm) straight replaceable necks. Light (Dark) filled data points are for Increasing (decreasing) the flow. The data shows the same general trend for all neck lengths. The acoustic amplitude increases with increased V_1 however, the ratio Vac/V_1 reaches the point where increases in Vac/V_1 *become moderate.* And then, moderately Vac/V_1 reaches to the maximum value depending on V_1 *characterized by each neck length.* At sufficiently high V_1, the resonance is extinguished as illustrated by the abrupt end of the data at low St. Additionally, longer necks and the right tails of shorter necks generally have lower amplitude ($Vac/V_1 \le 0.1$) indicating the importance of damping and the interaction between acoustic velocity and vortices.

Velocities Before and After the Opening

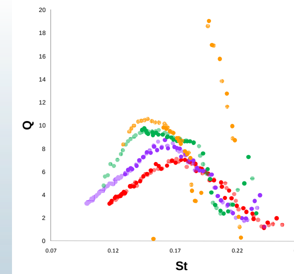


This graph illustrates the relationship between V_2 and V_1 for the 0, 7, 16, 23, 25 and 30 (cm) straight replaceable necks. The grey line has slope 1. Until the point that resonance starts, $V_2 = V_1$, meaning that no work is done. Once resonance starts, V_2 is slightly less than V_1. Though not much, energy starts to be extracted. And then, there is decrease in V_2 for increase in V_1 indicating significant energy extracted from the mean flow going into acoustics. From the characteristic point illustrated as kinks on the above graph, the slope goes back to about 1 though the trend changes based on the velocities. Looking at data taken with longer necks, which has low Vac/V_1, we can notice the small deviation from the line with slope 1 indicating we cannot use them to calculate the energy difference because of the low resolution of our pressure sensor.

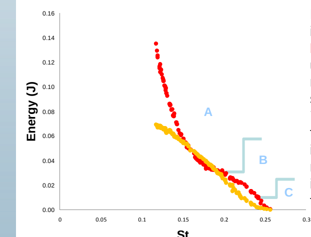
Energy Dissipated & Q Factor



The first graph shows the measured dissipated energy V.S. St using 0, 7, 16 and 23(cm) replaceable necks. Light (Dark) filled data points are for increasing (decreasing) the flow. This is energy extracted from the main flow and calculated using Eq. (6).



The second graph illustrates Q V.S. St with the results using 0, 7, 16 and 23(cm) replaceable neck length. Light (Dark) filled data points are for increasing (decreasing) the flow. The trend corresponds to Vac/V_1. This plot indicates the efficient conversion of flow energy into acoustic energy.



Examining the second graph, it is nice to see the graph of Edissipated and Estored using 0(cm) replaceable neck length representing shorter neck's trend. At lower Vac/V_1, energy is dissipated for driving resonance inefficiently. Around the maximum Vac/V_1, less energy is dissipated from the main flow for driving resonance.

Future Work

We intend to redo this experiment with an improved method to get more accurate flow velocities inside the duct before and after the junction. By this measurement, the quality factors in the low amplitudes' range can be determined. The ratio, Vac to V_1, for each St is a function of quality factor and frequency in the low amplitude range (Mason and Pierce).

Acknowledgement

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