

Application of Helmholtz Resonators in Open Jet Wind Tunnels

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ABSTRACT

Low frequency pressure oscillations in open jet wind tunnels are produced by vortices shed from the nozzle exit coupled with several feedback mechanisms in the circuit. These undesired pressure fluctuations can cause structural vibrations, reduction of flow quality, and delays in delivery of newly-built wind tunnels. One effective method to mitigate this problem is incorporation of Helmholtz resonators in the wind tunnel circuit. In this paper important factors in the design of Helmholtz resonators for open jet wind tunnels are described and a specific design procedure is outlined. Finally, successful design and installation of Helmholtz resonators in several modern open jet wind tunnels is reported.

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INTRODUCTION

Some open jet wind tunnel test sections are subject to low-frequency (<20 Hz) pressure oscillations, or pulsations. These oscillations appear at narrow band or resonant frequencies and significantly exceed the broadband noise levels in the test section. Avoiding these pressure oscillations is a major concern with open jet wind tunnels [1,2,3,4].

Different physical and mathematical models have been proposed over the past 15 years to explain low frequency pressure fluctuations in open jet wind tunnels [5,6,7,8]. The excitation for these frequencies has been hypothesized to be vortex shedding from the nozzle, or an edgetone feedback mechanism. Amplification occurs when a forcing frequency coincides with response modes related to i) wind tunnel circuit geometry, ii) plenum geometry, or iii) plenum Helmholtz response [9]. However, there is still no overall agreement in the literature on what excitation and resonant response modes are responsible for the pressure fluctuations in open jet wind tunnel test sections.

Analysis of low frequency data from several open jet wind tunnels [e.g. 5, 10, 11] supports the hypothesis that the edgetone feedback mode is responsible for generating the low frequency excitations and these are amplified by response modes in the circuit duct. The circuit duct response frequency can be expressed as:

$$f = \frac{n \times (c \pm V_x)}{2L} \quad (1)$$

n = circuit duct mode number (1,2,3...)

L = length around entire circuit duct

c = speed of sound

V_x = mean flow velocity along the wind tunnel duct

In prior versions for the circuit duct response frequency, the V_x term was not included, which is valid only when there is no flow in the duct. However, since these frequencies are excited in the wind tunnel when $V \neq 0$, the flow velocity in the duct needs to be superposed on the speed of sound. Because the sound waves can propagate both with and against the mean flow, the '+/-' term is required. The mean flow velocity varies along the circuit, so this effect must be considered by dividing the circuit duct into several sections and applying a representative V_x for each section. Accounting for sound propagation in both directions results in two velocity-dependent response modes for each value of n . The paired upstream and downstream propagating response modes have the same frequency at $V = 0$ and then diverge as velocity increases, as shown by the sets of dashed (almost vertical) lines in Figure 1. The calculations shown in this plot are for the BMW *Windkanal* geometry and test velocities [10].

The edgetone feedback mode mechanism is based on the physical process of a vortex shedding from the nozzle exit, convecting downstream in the shear layer, impinging on a downstream surface, with the pressure disturbance from the impingement propagating back upstream to the nozzle lip.



where another vortex shedding event is triggered. The mathematical model for the edgetone frequency is expressed as:

$$f_e = \left(\frac{1}{m} * \frac{L_{TS}}{R_{conv} * V_{TS}} + \frac{L_{TS}}{c - V_{TS}} \right)^{-1} \quad (2)$$

m = edgetone mode number (1,2,3...)

L_{TS} = representative axial length along test section

V_{TS} = test section velocity

R_{conv} = convection velocity ratio

c = speed of sound

A convection velocity ratio in the shear layer of 0.65 is suggested in the literature from small-scale laboratory experiments. For the measured data from large-scale wind tunnel projects [10], a value of $R_{conv} = 0.69$ provided a better fit to the data. The difference in Reynolds numbers for these tests compared to the small-scale experiments may explain the difference in the convection ratio. L_{TS} is the distance from the nozzle lip to where the shear layer vortices impinge at the back of the plenum. Practically speaking, this could either be at the back wall of the plenum or at the leading edge of the collector, depending on the specific geometry. The predicted edgetone feedback frequencies, as a function of velocity, are shown as the curved purple lines in [Figure 1](#) for the BMW *Windkanal*.

Comparing the predicted circuit response modes and edgetone feedback modes in [Figure 1](#) with the measured data in [Figure 2a](#) shows reasonably good agreement and supports the hypothesis that these are the dominant mechanisms. The higher pressure fluctuation levels shown in [Figure 2a](#) do not appear along an entire edgetone mode line, but rather only where an edgetone mode coincides with a circuit duct mode. Specifically, the agreement of the following dominant m,n modes in [Figure 1](#) and [Figure 2a](#) are evident: $m,n = (2,3)$, $(2,4)$, and $(3,6)$ at 140 kmh, 180 - 200 kmh, and 230 kmh, respectively. The agreement is within 0.5Hz, due to uncertainty in defining the circuit geometry lengths for calculating the duct modes. There are also other minor modes evident at other speeds.

Analysis of low frequency pressure pulsation data from three open jet wind tunnels [10, 12] indicates that up to 300 km/h, only the $m = 1, 2$, and 3 modes are significant edgetone feedback modes. The edgetone mode number corresponds to the number of vortices in the shear layer. The lowest mode $m = 1$ number is most significant at lower test section velocities. Higher mode numbers ($m = 2, 3$) are significant at higher speeds. [Table 1](#) shows a summary from these wind tunnels, where low frequency pressure fluctuation peaks were measured. The nozzle sizes for these wind tunnels are BMW AVZ = 25 m², *Windkanal*=18 m², BMW AeroLab = 14 m², and Windshear = 16.8 m². Even with the range of nozzle

sizes, there is consistency among the excitation modes and velocity ranges where these pressure peaks appear.

The main problems associated with pulsations in open jet aerodynamic wind tunnels are:

1. Pressure oscillations manifest themselves as low-frequency, high-magnitude periodicity in the wind tunnel's velocity time trace. The periodicity in the velocity field can have a detrimental effect on aerodynamic force measurements. This may cause the aerodynamic coefficients to vary in a non-linear manner with velocity. In particular, the aerodynamic drag can decrease significantly at velocities where the oscillations are highest because the oscillations increase the adverse pressure gradient in the test section and create a horizontal buoyancy effect that artificially increases the vehicle's base pressure [7].

2. When wind noise tests are conducted, it is important that the test section velocity is stable. If the wind velocity varies with time the following negative effects can occur [6, 7]:

- the repeatability of the wind noise data can be impacted.
- a low frequency 'carrier frequency' can be added to the wind noise data, making subjective evaluations difficult or impossible.
- for wind noise tests with open sunroof or open side windows conducted at low speeds for low frequency booming investigations, the low frequency from the wind tunnel could affect the wind noise data measured in the vehicle from the vehicle booming.
- Mechanisms involved in generating low frequency oscillations are highly nonlinear; therefore, they cannot be filtered out from acoustic measurements.

3. The resonance levels can be so high that they may cause structural damage to the facility. This ends up reducing the maximum useable velocity of the facility to some lower level than the initial design target velocity [8].

4. Low-frequency pressure oscillations measured during commissioning of the new wind tunnels, can delay the use of the facility as intended for productive testing while solutions are implemented to reduce the fluctuation levels.

These low frequency pressure oscillations can be quantified by the parameter $C_{p \text{ rms}}$. The calculation of $C_{p \text{ rms}}$ can be done over any frequency range. Because the low frequency pressure oscillation energy may exist at several distinct frequencies, the proper method to quantify the overall pulsation magnitude is to account for all low frequency energy. In the past 10 years, the automotive industry has informally converged to define $C_{p \text{ rms}}$ to include the pressure fluctuation energy between 0.01 Hz and 20 Hz (infrasonic range), measured using a low frequency response microphone. Pressure fluctuation energy can be derived as:

$$C_{p_{rms}} = \frac{p_{ref} 10^{\left[\frac{OASPL}{20}\right]}}{p_{dyn}} \quad (3)$$

$C_{p_{rms}}$ = root-mean-square pressure pulsation coefficient

$OASPL$ = overall sound pressure level over frequency range 0-20 Hz

p_{ref} = sound pressure reference value 20 μ Pa

p_{dyn} = dynamic pressure in Pa

Considering only the highest peak oscillation in the calculation of the $C_{p_{rms}}$ is misleading as 1) there may be multiple pulsation peaks and selecting only the highest peak will give an artificially low estimate of the pulsation levels, and 2) the magnitude of the peak is determined by an arbitrary frequency analysis bandwidth.

Wind tunnel designers try to implement the “known” design strategies to avoid or limit the pressure oscillations. For example, it is known that longer test section jet lengths (distance from nozzle exit plane to the collectors divided by nozzle hydraulic diameter) are more prone to develop undesirable pressure oscillations. Physically, this can be explained by the increase in low frequency energy in the shear layer due to vortex pairing as the jet length increases. This increase in low frequency energy provides stronger excitation for the plenum pressure oscillation phenomena. Due to the complexity of the physics involving such oscillations, the pressure oscillation in open jet wind tunnels cannot be completely avoided; therefore, some mitigation strategies need to be in place. One method of dealing with pressure oscillations is to install vortex breaking plates at the nozzle exit wall [13]. As explained earlier, it is generally understood that the main cause of pressure pulsations is the coupling between the vortices shed off of the nozzle exit and the edge tone-type feedback mechanism in the plenum, and the reinforcing of these frequencies with natural modes in the wind tunnel circuit [14]. By installing tooth like plates at the nozzle exit, the coherent vortices emitting from the nozzle exit are disrupted and the pressure oscillations are attenuated. However, although this method can be effective in some cases, it can also adversely influence important aerodynamic parameters such as longitudinal pressure gradient or flow angularity. Rennie [5] reports considerable improvements in pressure fluctuations by attaching vortex generators to the nozzle lip. However, he warns such vortex generators adversely affect the static pressure gradient as well as the background noise in the test section.

In general, the methods developed so far that focus on the destruction of the vortices in the shear layer are invasive and to some degree adversely influence other important aerodynamic and acoustic performance parameters of the wind tunnel.

One effective method in dealing with the undesired low frequency oscillations is Helmholtz resonators (HR). HRs can effectively attenuate or eliminate single peaks in a spectrum. As applied to wind tunnels, HRs are tuned cavities attached to the plenum or to the airline circuit but are not in the flow and consequently do not disturb it.

The theory of HRs is well understood and its application in many industrial applications is documented. In this paper, we first revisit the theory of HRs applied in the open jet wind tunnels. After describing the important parameters for their design, we outline a procedure for the design of HRs in open jet wind tunnels. Finally, we will provide examples of HRs used in modern wind tunnels and their effectiveness in attenuation of undesired pressure oscillations.

HELMHOLTZ RESONATORS

Helmholtz resonators are acoustic systems consisting of an oscillating air plug connected to an air volume. In one application, a cavity is attached to a long duct through a hollow branch which acts as a band-reject acoustic filter (Figure 3). Fluid inside resembles a damped spring-mass system. Applied force (incident pressure) at the opening causes the fluid within the neck (mass) to oscillate on the fluid inside the cavity (spring).

The oscillation of fluid in the neck converts some of the acoustic energy to heat (viscous losses). However, despite the common understanding, the effectiveness of a HR in this application is mostly due to its ability to reflect the acoustic energy back to the source with a phase difference, and to prevent the energy from propagating downstream. In fact, compared to the energy reflection, thermo-viscous losses are negligible, and therefore, the transmission loss is derived as [15, 16]:

$$TL = 10 \log_{10} \left[1 + \left(\frac{c/2S_d}{\omega L'/A - c^2/\omega V} \right)^2 \right] \quad (4)$$

Here, S_d is the cross-sectional area of the duct in which the HR is being incorporated, A is the cross sectional area of the neck, L' is the effective length of the neck, c is the speed of sound, and V is volume of the cavity. When $TL \rightarrow \infty$, all incoming acoustic energy is reflected back toward the source and no energy is transmitted downstream. Solving Equation (4) for $TL \rightarrow \infty$ yields the resonance frequency of the Helmholtz resonator:

$$f = \frac{c}{2\pi} \sqrt{\frac{A}{L'V}} \quad (5)$$

Therefore, by designing the HR to resonate at the frequency of the tonal noise, the resonator can cause reflection of acoustic waves with frequencies near that of the resonance frequency.

This frequency value has powerful implications. If a system has the majority of noise at one frequency component,

the system can be “tuned” using the above equation, with a HR, to effectively attenuate any transmitted power.

DESIGN OF HELMHOLTZ RESONATORS FOR OPEN JET WIND TUNNELS

Low-frequency oscillations in open jet wind tunnels typically appear at few distinct frequencies which exceed the prevailing broadband noise levels in the test section. Therefore, for each problematic frequency, a separate HR needs to be designed. Some factors that need to be considered in designing a HR used in open jet wind tunnels include:

- The dimensions of a HR must be much less than the target wavelength:

$$V^{1/3} \ll \lambda \quad A^{1/2} \ll \lambda \quad L \ll \lambda \quad (6)$$

- The main resonance parameters are resonance frequency and quality factor. The sharpness of the resonance is measured by quality factor Q [15]:

$$Q = 2\pi \sqrt{V \left(\frac{L'}{A}\right)^3} \quad (7)$$

For optimum design, the resonance frequency of the HR needs to match the target frequency (problematic frequency). Depending on the application, a balance between very sharp resonances (hard to tune) and relatively mild peaks (not so effective) needs to be considered (Figure 4) in specifying the quality factor Q .

- The theoretical resonance parameters are based on an opening at the center of the cavity face. The following correction is suggested when the opening is not at the center face of the volume [17]:

$$f_{corrected} = (k + 1) \times f \quad (8)$$

k is determined based on the location of the opening on the face of the volume (Figure 5). When at the center of one side of the face, $k = 0.02$ and when at a very corner of the face, $k = 0.04$.

- The opening area to the cavity needs to be small compared to the volume. The suggested range for the opening area is:

$$\frac{\sqrt[3]{V}}{3.5} < A < \frac{\sqrt[3]{V}}{2.5} \quad (9)$$

- The volume of the cavity V used in the design of HR is for an empty cavity. For a non-empty room, or if the resonator neck extends into the volume, the effective volume of the cavity is less.

- The number of openings n changes the effective resonance of a HR:

$$f = \sqrt{n} \frac{c}{2\pi} \sqrt{\frac{A}{L'V}} \quad (10)$$

- The shape of the volume (cubical, spherical, etc.) or shape of opening (circular, rectangular, etc.) does not influence the effectiveness of the HR [17, 18].

PROCEDURE TO DESIGN A HR IN AN OPEN JET WIND TUNNEL

- *Specifying HR volume*

Knowing the target frequency f , the location of the cavity opening k , and the number of openings to the cavity n , the volume of the HR can be calculated:

$$V = \frac{1}{Q} \times \frac{c^3}{4\pi^2 \times \left(f \frac{(k+1)}{\sqrt{n}}\right)^3} \quad (11)$$

To balance the sharpness and effectiveness of the HR, an appropriate Q factor range needs to be considered. Based on the Q factor range, a range of possible volumes for the HR can be determined.

- *Specifying HR opening area*

After selecting the HR volume, the opening area to the cavity is selected using Equation (9).

- *Specifying HR neck length*

Finally, the neck length can be calculated:

$$L = \frac{c^2}{4\pi^2} \times \frac{A}{Vn f^2 (1+k)^2} - 1.4 \sqrt{\frac{A}{\pi}} \quad (12)$$

THE BANG TEST

A ‘bang test’ is a quick method for tuning a HR by creating an impulse in the cavity and analyzing the decay of the signal generated. This method is especially suitable for fine tuning of the resonator before final wind-on verification tests. As the neck may reach into the resonator volume and/or the resonator volume may not be distributed homogeneously around the neck entrance, deviations to the optimum volume (difficult to change) or the opening area or the optimum neck length (both easy to change) may occur. Figure 6 depicts an example of such a test. In this example, the impulse noise was generated by slamming the resonator door quickly. The measurement was at 100Hz sampling rate, 2048 samples for 0.05 Hz frequency step, and 20 seconds sampling. From the plot, 16 cycles can be counted during the 3.5 seconds decay, indicating an approximate resonance at 4.6 Hz.