Wind Tunnel Resonances and Helmholtz Resonators

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ABSTRACT

Open jet wind tunnels can be impacted by low-frequency pressure fluctuations due to different feedback mechanisms coupling with vortices shed from the nozzle exit. These fluctuations can reduce the simulation quality of the wind tunnel and/or reduce the effective wind speed range of the facility. Considerable research has been conducted to understand the on-set of these strong pressure fluctuations and different mitigation methods have been attempted to reduce these fluctuations. The idea of using Helmholtz resonators to provide strong absorption in the low frequency regime has been around for a long time in different acoustical applications. It has been applied in aero-acoustic fields also to control cavity resonances. A parametric study of applying Helmholtz resonators to control the pressure fluctuations in open-jet wind tunnels was undertaken. An existing open-jet tunnel was modified to produce strong low-frequency pressure fluctuations. A control volume to represent a Helmholtz resonator was attached to the wind tunnel. The control volume was made adjustable to produce different tuning frequencies to control fluctuations at different wind speeds. The results of the study are presented in this paper.

SOMMAIRE

Les souffleries aérodynamiques à veine ouverte peuvent être affectées par diverses fluctuations de basse fréquence dues à différents mécanismes de rétroaction engendrés par la configuration de la veine. De telles fluctuations peuvent même endommager la structure de la soufflerie si de fortes résonances en résultent. Ces fluctuations, réduiront habituellement la qualité de simulation de la soufflerie et/ou réduiront la gamme efficace de vitesse de vent de l'installation. Des recherches considérables ont été conduites pour comprendre le debut de ces fortes fluctuations de pression, ainsi différentes méthodes de réduction ont été tentés pour réduire ces fluctuations. L'idée d'utiliser des résonateurs de Helmholtz pour fournir une forte absorption dans le régime de basse fréquence a été depuis longtemps employé dans différentes applications acoustiques. Cette approche a également été appliquée dans les domaines aéro-acoustique pour contrôler les résonances de cavité. Une étude paramétrique concernant l'utilisation d'un résonateur de Helmholtz pour contrôler les fluctuations de pression dans des souffleries aérodynamiques à veine ouverte a été entreprise. Une soufflerie aérodynamique à veine ouverte existante a été modifiée pour produire de fortes fluctuations de pression à basse fréquence. Un volume de contrôle, représentant un résonateur de Helmholtz a été fixé à la soufflerie. Le volume de contrôle a été rendu réglable pour produire différentes fréquences de mise au point et ainsi contrôler les fluctuations à différentes vitesses de vent. Cet article présente les résultats de l'étude paramétrique.

1. INTRODUCTION

Pressure fluctuations are an inherent characteristic of open-jet test sections in wind tunnels. The combination of vortices shed from the nozzle trailing edge combined with the development of shear layers between the main flow and relatively quiescent surrounding plenum region provide a source of flow unsteadiness that can couple with various resonant conditions in the wind tunnel. The result is a potential for generating large pressure fluctuations which can interfere and degrade the measurements on a test object in the test section. The various factors that can influence the severity of these fluctuations have been seriously studied for quite some time and are reported in the literature [1-2]. The above two papers by Michel and Froebel discuss the fluctuations as well as the lowest level that is possible by citing actual levels in wind tunnels. The suppression of these jet pulsations has been a key effort during the design and/or commissioning phases of other open-jet wind tunnels.

A brief review of the jet pulsations and their characteristics such as their on-set, amplitudes and dominant frequencies is presented in this paper. Some of the common suppression methods are also highlighted in this paper. A brief review of Helmholtz resonators as acoustic absorbers and their varied applications is also presented in this paper.

Measured data with a Helmholtz resonator assembly added to an existing open-jet wind tunnel at the National Research Council of Canada in the year 2002 are also described. The details of the flexible resonator and its performance in suppressing the open-jet pulsations are the main focus of the current paper. The results of the above study are discussed in this paper.

2. WIND TUNNEL PULSATIONS

2.1 Background

It is not unusual to experience low-frequency pressure and velocity fluctuations at distinct wind speeds in open-jet wind tunnels. These fluctuations have an impact on the aerodynamic quality of the test section flow, resulting in unsteady and inaccurate measurements of pressures and forces. Even the acoustic measurements are compromised as the noise generated by the test model is modulated at the frequency of the fluctuations.

Most open-jet wind tunnels suffer from the low-frequency fluctuations. Rennie et. al performed a detailed investigation into pressure fluctuations measured in the Hyundai Aero-acoustic Wind Tunnel (HAWT) [3]. The main features of the HAWT are: ¾ open-jet test section with 28 m^2 nozzle area; separate turntables for balance and dynamometer testing; and a relatively long, 18 m test section. Sample results, from Reference 3, of the pressure fluctuations measured in the original configuration of the HAWT test section are shown in Figure 1. It is seen that fluctuation pressure levels are 6% of the dynamic pressure at a speed of 80 km/h and 4.5% at a speed of 130 km/h. The main frequency of these fluctuations is a low value of 1.4 to 1.5 Hz. Fluctuations at a higher frequency of 2.6 Hz were also evident from the measurements, albeit, at a reduced amplitude. High amplitude fluctuations, in excess of 1.5%, are seen at a number of wind speeds, thereby reducing the value of the wind tunnel measurements. The different causes for these fluctuations must be properly accounted for before designing suitable control methods and are highlighted in the next section.

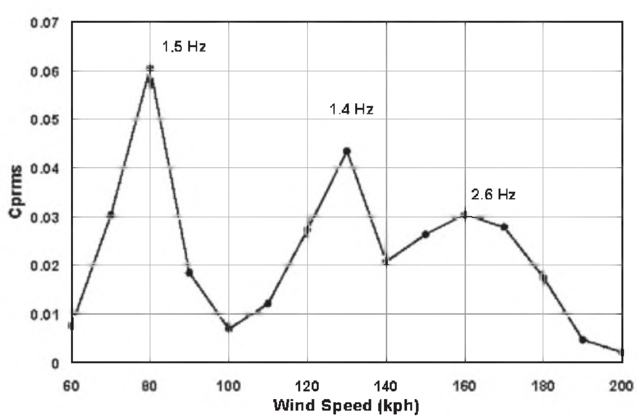

Figure 1. HAWT pressure fluctuations (from Reference 3)

2.2 Physical Mechanisms

Many ideas have been postulated to explain the on-set of the very-low-frequency oscillations in open-jet wind tunnels [4, 5]. Rennie conducted model tests to evaluate the feasibility and performance of different suppression methods to control the pressure fluctuations. The wind tunnel was a 1/7th scale version of the full scale HAWT. This pilot wind tunnel was constructed by modifying an existing tunnel at the Institute of Aerospace Research (IAR) of the National Research Council of Canada (NRC) in Ottawa, Ontario in the year 2000. [For details of the tunnel and its many features please see References 3 and 4]. Even though the main focus was on the development of suppression methods, Rennie conducted detailed analyses of the possible mechanisms for the pressure fluctuations [4]. Descriptions of the resonant frequencies are also given in Wickern et. al. [5].

It is postulated that whenever the large-scale vortices in the open jet mixing layer shed at frequencies that coincide with an acoustic resonant mode of the wind tunnel circuit, high amplitude pressure fluctuations result. There are four possible resonant conditions within the wind tunnel circuit. These conditions are outlined below.

1. Resonance of the complete wind tunnel circuit (organ pipe modes), with resonant frequencies evaluated as

$$f = \frac{n\,c}{2\,L_{circ}} \tag{1}$$

   where c is the speed of sound and L_{circ} is the total length of the circuit.

2. Resonances within the volume of the test section plenum, with frequencies calculated as

$$f = \frac{c}{2\sqrt{\left(\frac{l_x}{n_x}\right)^2 + \left(\frac{l_y}{n_y}\right)^2 + \left(\frac{l_z}{n_z}\right)^2}} \tag{2}$$

   where, lx, ly, and lz are the dimensions of the test section plenum.

3. The nozzle and test-section plenum chamber acting as a Helmholtz resonator. This can be calculated from the suggested equation by Wickern et. al. [5]

$$f = \frac{c\,D_h}{4\pi}\sqrt{\frac{\pi}{V\left(L_{noz} + \pi\frac{D_h}{4}\right)}} \tag{3}$$

   where D_h is the hydraulic diameter of the nozzle, V is the plenum volume, and L_{noz} is the nozzle length.

4. Edgetone feedback mechanism between the collector and the nozzle. A schematic detail of this mechanism is shown in Figure 2. Rennie showed that the feedback is strongly controlled by the jet length between the nozzle and the collector [4].

The measurements were conducted in both the full scale HAWT and the pilot tunnel at IAR of the NRC. The composite results are shown in Figure 3 (with the pilot tunnel frequencies multiplied by the scale ratio of 1/7). The figure also shows the resonance frequencies for the three circuit modes at 0.8 Hz, 1.6 Hz and 2.4 Hz, and the first three edgetone modes, which are a function of wind speed. It can be concluded from the composite data of Figure 3 that at a given wind speed, the pressure fluctuations have high amplitudes if the shedding frequencies are close to the junction of circuit organ pipe modes and the edgetone modes. Another useful conclusion, which has been found by others, is that a geometrically scaled pilot wind tunnel provides representative pressure fluctuation data in magnitude, with the frequencies adjusted by the geometrical scale ratio.

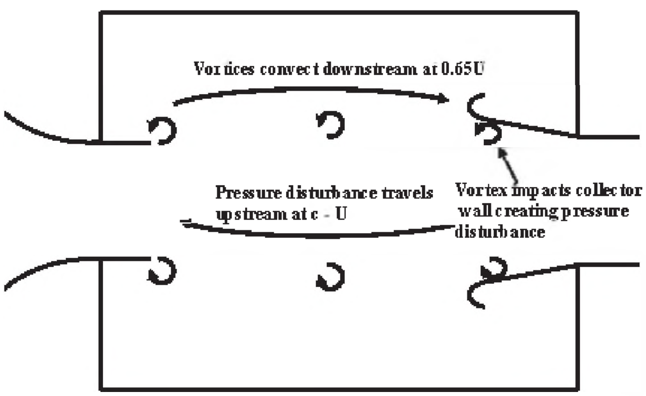

Figure 2. Edgetone feedback loop (from Reference 4)

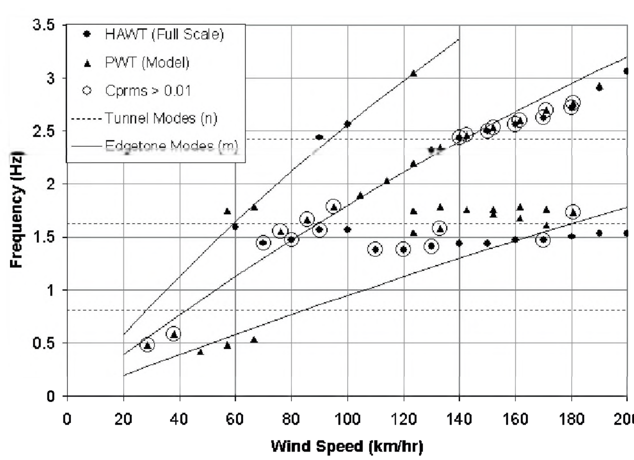

Figure 3. HAWT and 1/7'th scale Pilot Wind Tunnel pressure fluctuations (from Reference 3)

2.3 Suppression Mechanisms

Many different control methods have been attempted to suppress the pressure fluctuations in open jet wind tunnels. A brief review of these techniques will be presented below. Details of one of those techniques will be the main focus of this paper and will be presented in subsequent sections.

The first method applied in general aerodynamic wind tunnels is the installation of vortex generators on the nozzle lip. Vortex generators are a simple way of attenuating the amplitudes of the pressure fluctuations and their success has been proven in many wind tunnel applications. Vortex generators, however, induce a vena contracta type flow at the nozzle exit which results in a negative axial pressure gradient. In addition, they are significant sources of acoustic noise, which is unacceptable for the aero-acoustic demands of most open-jet test sections. As a result, vortex generators are undesirable for most aerodynamic and aeroacoustic open jet wind tunnel applications.

The results of Rennie showed that a properly selected jet length, usually small, can reduce the amplitude of the pressure fluctuations [3, 4]. However, a small jet length limits the size of the models that can be tested in modern automotive

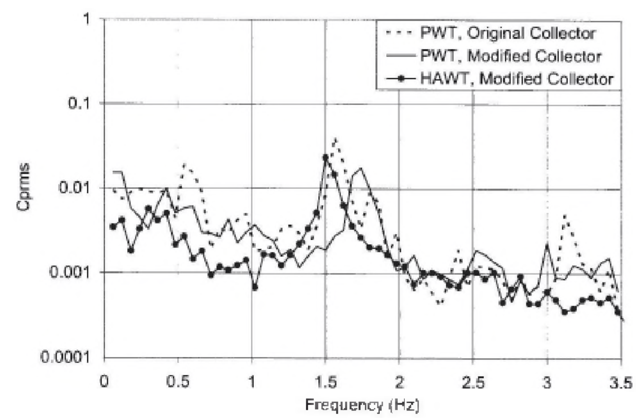

Figure 4a. Measured pressure fluctuation spectra - 80 kmph (from Reference 3)

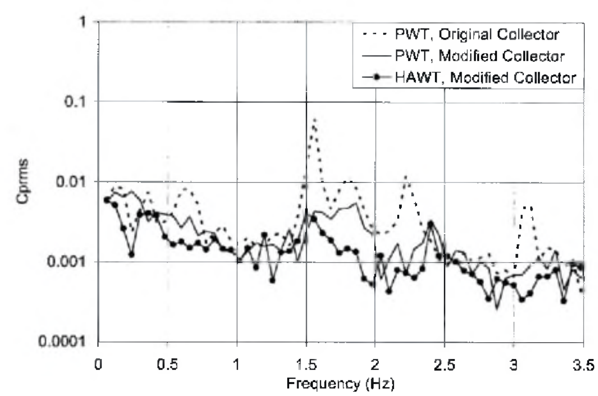

Figure 4b. Measured pressure fluctuation spectra - 130 kmph (from Reference 3)

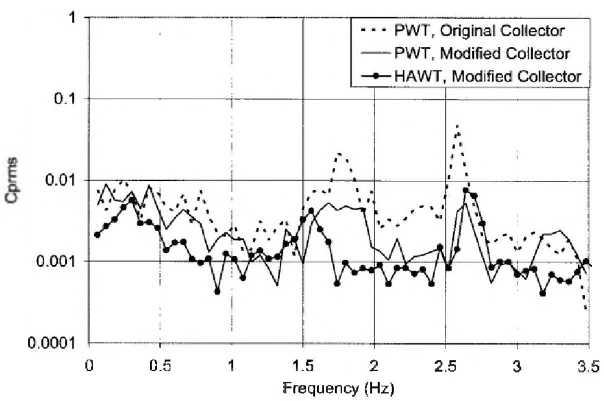

Figure 4c. Measured pressure fluctuation spectra - 160 kmph (from Reference 3)

wind tunnels. Hence, this method of jet length control is not practical in most applications.

Rennie, in the pilot wind tunnel, experimented with collector shapes as well as installing a breather between the trailing edge of the collector and the inlet to the test-section diffuser [3, 4]. The results showed that an optimized collector geometry is one suitable method to reduce the amplitude of the pressure fluctuations (the optimization scheme for the collector is beyond the scope of this paper). The results with the modified collector are shown both for the full scale HAWT and the pilot wind tunnel in Figure 4a to 4c. The results show a large reduction in the amplitude of the resonant peaks (note the logarithmc scale). The pressure fluctuations are seen to be less than 1.5% for the three wind speeds of concern.

Waudby-Smith et.al. reported the results of implementing a similar collector design in the newly constructed GIE S2A aeroacoustic wind tunnel in Paris, a joint project of Renault, PSA Peugeot-Citroën and CNAM [6]. The results, summarized in Figure 5, clearly indicated that with proper design of the collector, the pressure fluctuations can be kept small. The pressure fluctuations at all wind speeds were below 1% except for two low wind speeds. The results were deemed acceptable, since these wind speeds were non-standard test conditions and were at low speed.

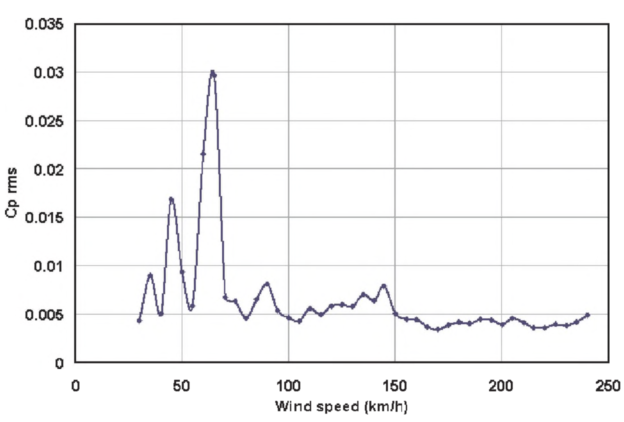

Figure 5. Overall pressure fluctuation amplitudes (from Reference 6)

Attempts were also made to modify the collector configuration by other researchers. Lacey evaluated the impact of an axially slanted collector [7]. Lacey's model tests showed that the slanted collector, with a slant as much as 45° from the vertical, was a promising control method to suppress pressure fluctuations, even for a long test section. According to Lacy the slanted collector does not work by "detuning" the collector feedback frequencies. This conclusion was based on a set of tests with a fixed collector and different test section lengths. In reality the collector size should have increased with increasing test section length. It is difficult to perform a truly parametric investigation into the effects (and optimization) of collector geometry.

Wickern et. al. studied the feasibility of implementing suitable suppression methods when the level of the pressure fluctuations in Audi's new aeroacoustic wind tunnel became a concern during the design stage [5]. It was decided to evaluate the impact of an active resonance control (ANC) system. Pilot wind tunnel studies showed the ANC to be very effective in reducing the wind tunnel fluctuations. The system consisted of a measuring microphone in the test section plenum and a large speaker driver system to generate '180° anti-phase' sound levels at the offending frequencies to cancel the pressure fluctuations. The driver system was located in an adjacent room but communicated with Cross-leg 1 of the airline circuit. The sound level reductions at the full scale tunnel resonances at 2.4 Hz, 3.9 Hz and 6.8 Hz were measured to be 23 dB, 20 dB and 15 dB respectively. Velocity fluctuation measurements showed that the three main resonances were completely eliminated when the ANC system was switched on. The cost of the ANC mitigation method can be hundreds of thousands of dollars due to the cost of generating very low frequency sounds and hence ANC may not be cost effective.

Another active flow control method, this time using oscillating flaps at the nozzle exit, was studied by Heesen and Höpfer [8]. Attenuation up to 29 dB of the pulsation amplitudes was achieved in model-scale tests. The applicability of this system to an aeroacoustic wind tunnel, however, has not been demonstrated.

Finally, a Helmholtz resonator configuration has been developed to remove the pressure fluctuations that occur at distinct frequencies. Since this resonator absorber is the main focus of the current paper, a brief overview is given in Section 3. The application of the resonator absorber in the IAR pilot wind tunnel will be described in Section 4.

3. HELMHOLTZ RESONATORS

Helmholtz resonators have been around as both acoustic absorbers and acoustic amplifiers. They have been applied as side branch absorbers to attenuate noise in many different noise control schemes [9 through 15]. The physical characteristic of a Helmholtz resonator consists of a large volume communicating with the main noisy domain through a short neck (small neck area and neck length). The main acoustic characteristic of a Helmholtz resonator-absorber is the ability to tune the resonator to a single frequency. The tuning frequency of a single resonator is evaluated from:

$$f = \frac{c}{2\pi}\sqrt{\frac{S}{lV}} \tag{4}$$

where, f is the tuning frequency, c is the sound speed, S is the neck area, V is the cavity volume, and l is the effective length. The length l is given by

$$l = t + \delta \tag{5}$$

where, t is the neck length and $\delta = 0.85$ a, where a is the neck diameter.

The acoustic absorptive effect of the Helmholtz resonator operates as follows: The air in the neck of the resonator vibrates back and forth somewhat as a single mass, and the larger volume acts as a spring or restoring force. Frictional resistance is encountered by the alternating flow of air in and around the neck. Hence sound energy is absorbed, mainly in the region of the resonant frequency, 'f'. The larger the mass flow, the larger is the aborptive effect of the resonator.

Davis et. al. tested the use of side branch resonators in muffling systems for helicopter engines and evaluated the transmission characteristics [9]. Soderman used the Helmholtz resonators by creating an absorbing volume behind perforated sheets in silencer baffles for attenuating the fan noise of the wind tunnels [10, 11].

Ackermann et. al. developed a novel membrane absorber for attenuating noise in contaminated flow environments [12]. Multiple resonator volumes were created to broaden the frequency range of the absorbers and were successfully implemented in the turning vane-cross legs junction areas of the IVK wind tunnel in Stuttgart.

Ramakrishnan et. al. created an absorbing volume between the structural wall and facing-brick wall in an underground bus station in Ottawa, Ontario [13]. The facing bricks were mortared only horizontally and a small gap was created vertically, with the bricks set-apart from the structural wall. A Helmholtz absorber was thus created and provided absorption coefficient values between 0.7 and 0.85 in the frequency range of 60 to 300 Hz. The frequency range was also widened by placing fibreglass batts in the cavity.

Helmholtz resonators were used as active control of flow-induced cavity resonances [14, 15]. Hsu and Ahuja used simple pharmaceutical syringes as Helmholtz resonators to attenuate cavity resonances induced by flow in their simulated studies of bomb bays of planes [15]. Their attempts to use different volumes to broaden the frequency ranges were partially successful.

4. EXPERIMENTAL MODEL

4.1 Background

The review presented above shows that Helmholtz resonators have a wide application as acoustic absorbers. The current study was the first investigation that attempted systematically to evaluate the performance of Helmholtz resonators to reduce wind tunnel pressure fluctuations.

The motivation to apply the Helmholtz resonators was also based on a simple observation of a well-behaved wind tunnel designed (by engineers of Aiolos Engineering Company) and built more than 15 years ago. The tunnel under discussion had very low levels of pressure fluctuations and the tunnel had two features: a) a short test section and b) a large side room, built adjacent to the centre of Cross Leg 1 and in acoustic communication with the main wind tunnel circuit, that contained cross leg inserts. It was possible therefore that a Helmholtz resonator volume was serendipitously created thereby absorbing the low-frequency resonances of the tunnel. However, no measurements were undertaken to evaluate the performance of the side room functioning as a Helmholtz resonator absorber.

4.2 Pilot Wind Tunnel

As described in earlier sections, Rennie has outlined the design of a pilot wind tunnel which was used to study wind tunnel pulsations [3, 4]. The pilot wind tunnel (PWT) was designed and built as a (1/7)th scale model of the full scale HAWT.

The PWT was used to conduct the current study. The test section and contraction geometries of the PWT were modified following the HAWT tests. The test section remained representative of an automotive open-jet test section. No plenum walls were used (other tests required improved access to the surrounding flowfield), though this was of no consequence for these tests as the plenum resonance modes had higher frequencies than those of interest for the resonator. Initial "proof-of-concept" tests were performed with the resonator in July of 2002. More detailed tests were performed in December 2002 with the collector geometry "de-optimized" in order to enhance the pressure fluctuations in the baseline condition where no resonator is used.

The PWT had an observation window, just downstream of Corner 1 in Cross Leg 1. The observation window was removed and a Helmholtz resonator volume was created by attaching a room constructed from plywood. The window was replaced with a perforated sheet to provide acoustic communication between the resonator volume and the PWT circuit. The end wall of the room was movable, allowing the resonator volume to be modified to tune to different frequencies. The arrangement of the PWT and the resonator are shown in Figure 6.

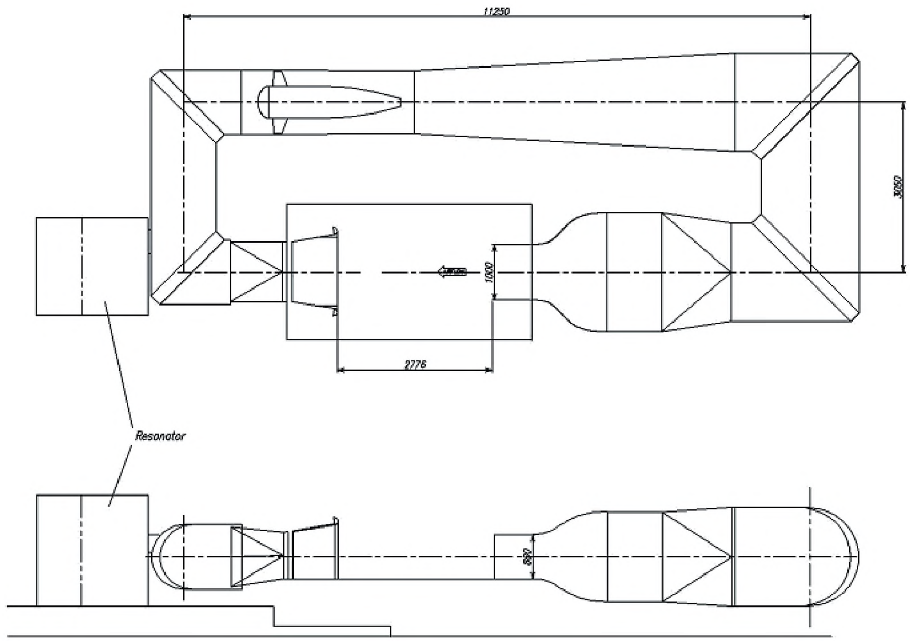

Figure 6. Arrangement of the Pilot Wind Tunnel and Resonator - Top - Plan; and Bottom - Elevation

The resonator used in these tests was located in the first cross-leg of the wind tunnel. This location was chosen because of the existing window, which was converted into the opening for the resonator, and the availability of sufficient space beside the wind tunnel. For other wind tunnels alternative locations are possible including the plenum that surrounds the test section of most wind tunnels.

5. RESULTS AND DISCUSSION

The in-flow static pressure fluctuations measured at the nozzle for the baseline condition (no resonator) are shown in overall Cprms form in Figure 7 and in spectral form in Figure 8. The measurements were made over the frequency range 0.3 Hz to 20 Hz with a 0.0625 Hz interval. The salient observations of these results are: a) Peak fluctuations at 15 m/s and 27 m/s correspond primarily to fluctuations at the first and second organ pipe modes of 6 Hz and 14 Hz respectively; b) Fluctuations can occur for both organ pipe modes at a single wind speed; c) Fluctuations are largest when a nozzle-collector feedback frequency is close to an organ pipe mode; d) Strong resonant frequencies were in the 6 Hz and 14 Hz bands; and e) The data are sufficiently repeatable.

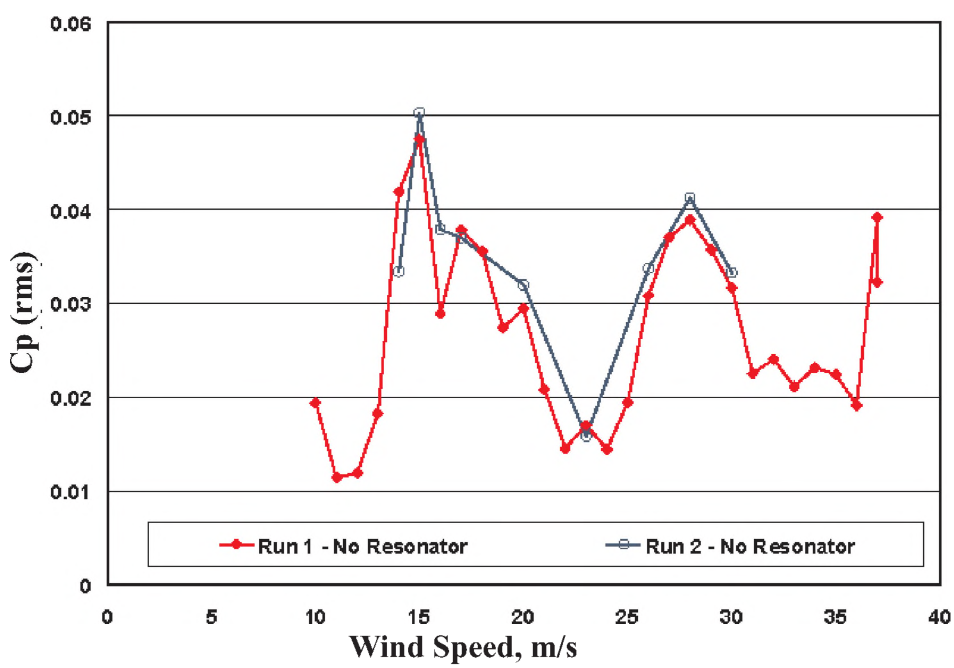

Figure 7. Overall Cp_{rms} values of the baseline conditions of the PWT

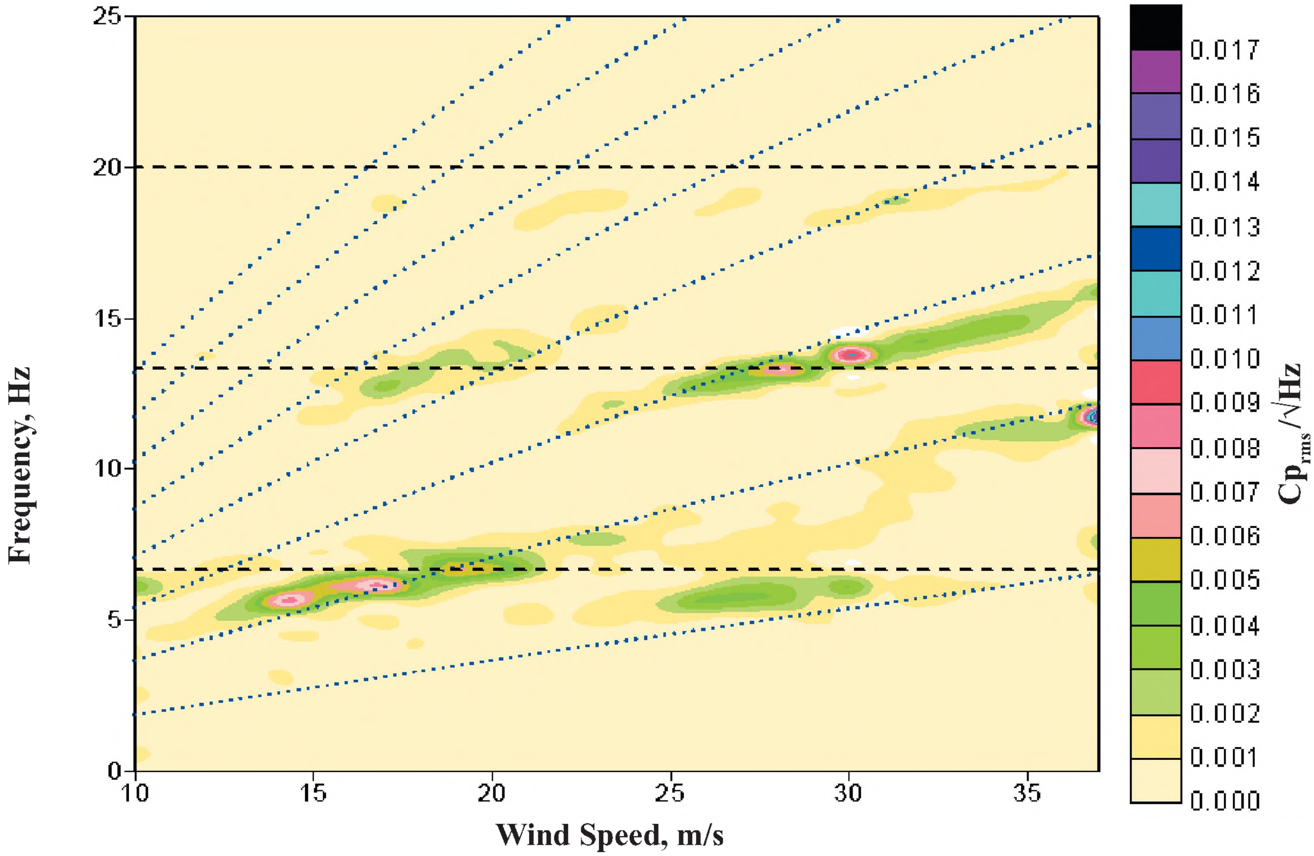

Figure 8. Map of pressure fluctuation spectra with wind speed - No Resonator
Horizontal dashed lines represent the organ-pipe modes and angled dotted lines represent the collector-feedback modes

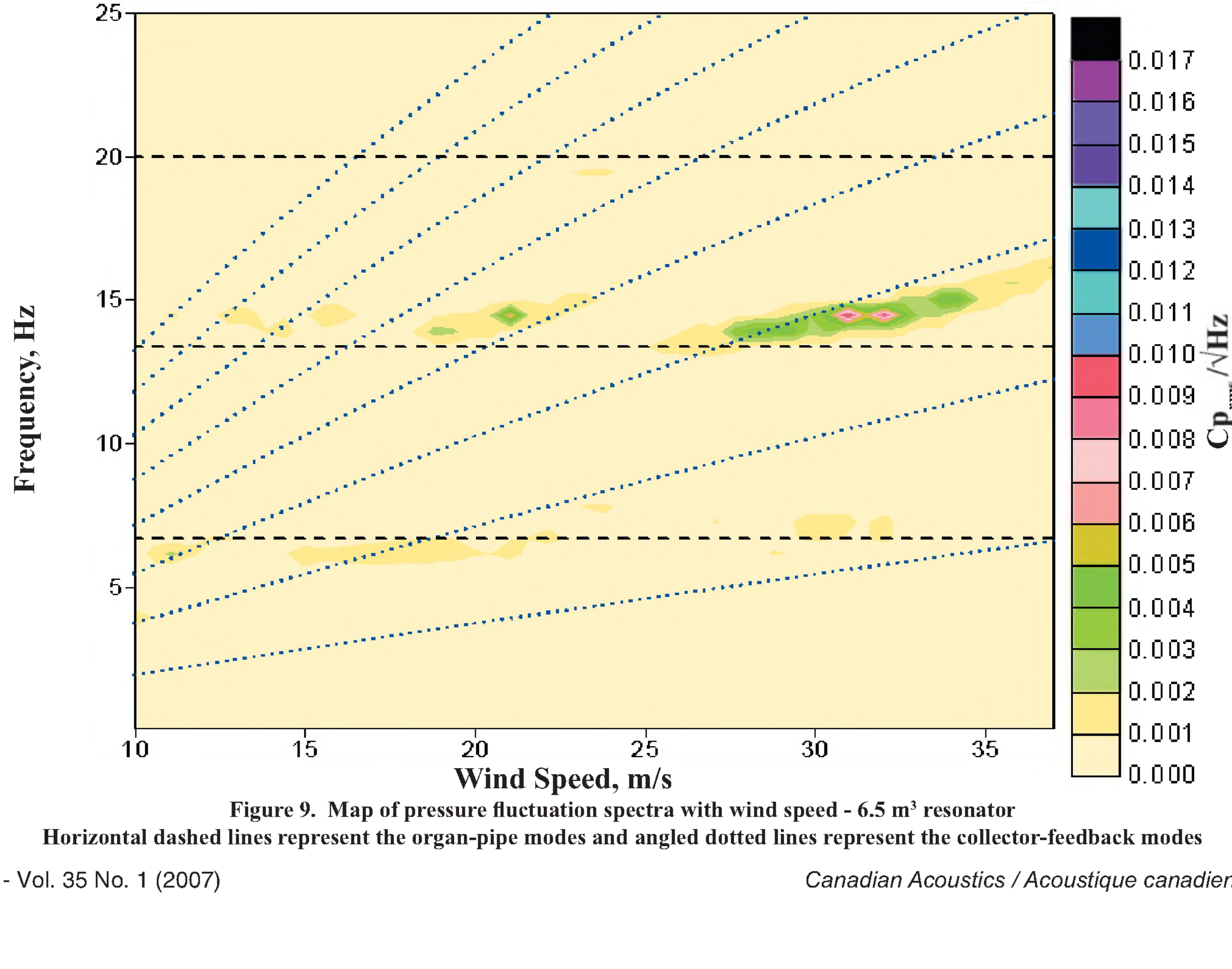

Figure 9. Map of pressure fluctuation spectra with wind speed - 6.5 m³ resonator
Horizontal dashed lines represent the organ-pipe modes and angled dotted lines represent the collector-feedback modes

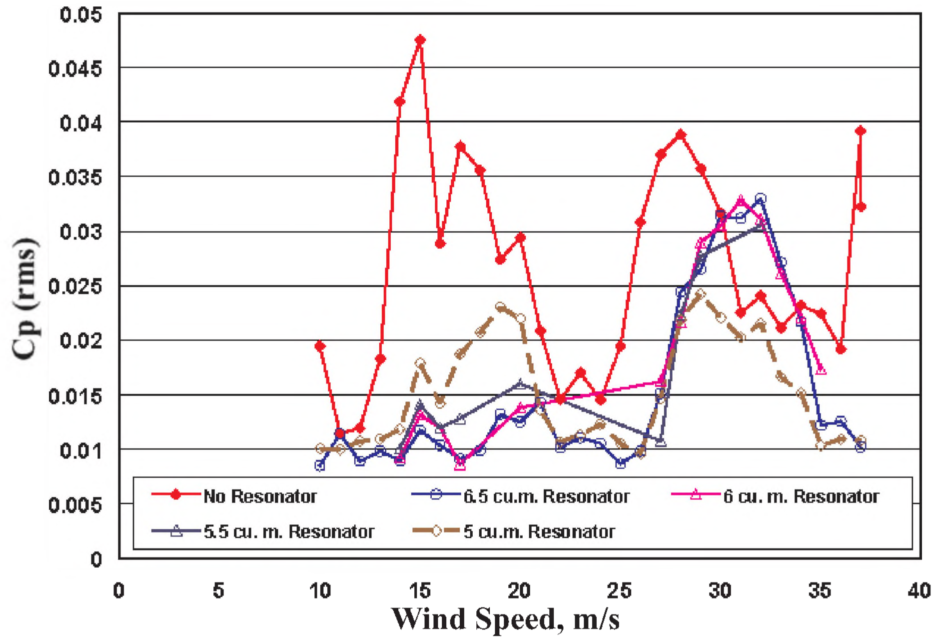

Figure 10. Overall Cp_{rms} values of the of the PWT with four large volume resonators

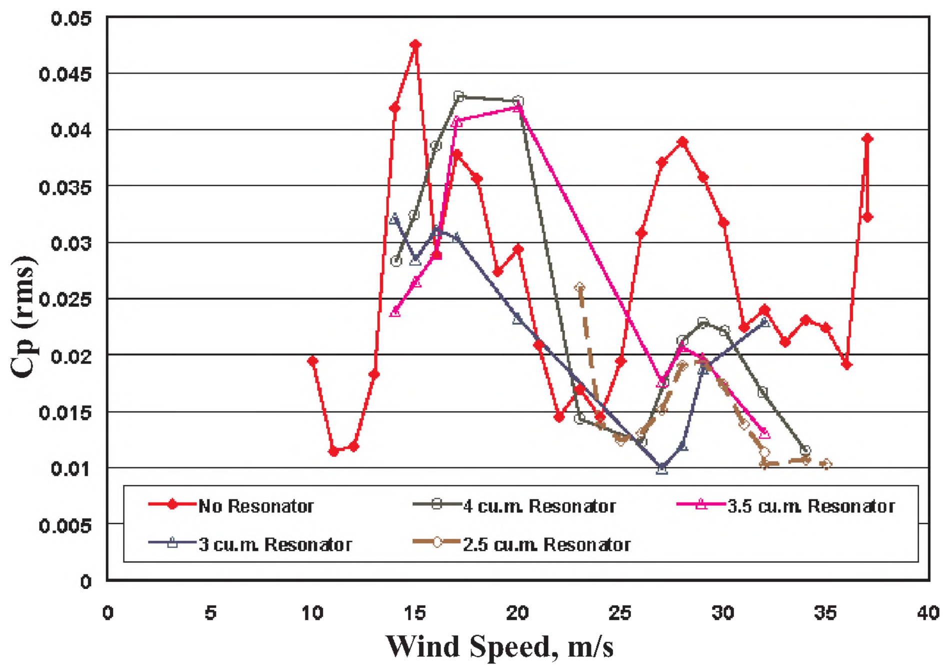

Figure 11. Overall Cp_{rms} values of the of the PWT with four small volume resonators

Measurements were performed across the wind speed range of the PWT for several different resonator volumes. Some of the salient results are presented in Figures 9 through 11.

The effect of the largest resonator, with a volume of 6.5 m^3 is shown in Figure 9. The results show that the large resonator was able to eliminate the pressure fluctuations in the 6 Hz band. However, the fluctuations generated at higher speeds in the 14 Hz band were still excited and the 6.5 m^3 volume appeared to have had little effect on these higher frequency fluctuations.

The volume of the resonator was adjusted sequentially downwards and the composite results for four large resonators are shown in Figure 10. The four resonator volumes were: 6.5 m^3, 6.0 m^3, 5.5 m^3, and 5.0 m^3 respectively. The 6.5 m^3 resonator was able to remove the lower frequency fluctuations successfully. As the resonator volume was reduced, the elimination of the lower frequency fluctuations became less prominent. At a volume of 5.0 m^3, the resonator was able to remove some of the higher frequency fluctuations at higher wind speeds but at the expense of reduced attenuation of the lower frequency components (and consequently higher wind speed fluctuations).

Results for further volume reductions are shown in Figure 11. The four small resonator volumes were: 4.0 m^3, 3.5 m^3, 3.0 m^3, and 2.5 m^3 respectively. The smaller resonators are seen to have reversed the trends of the larger resonators. These four resonators reduced the higher frequency fluctuations excited at the higher wind speeds but were ineffective at the lower wind speed resonances. Further, the attenuation of the pressure fluctuations provided by the larger resonators was more than the attenuation provided by the smaller resonators. The most efficient small resonator for this application was the one with a volume of 2.5 m^3.

6. CONCLUSIONS

A brief overview of mechanisms to suppress low frequency pressure fluctuations in open-jet wind tunnels showed that Helmholtz resonators could be a useful method. A pilot wind tunnel with a representative automotive test section was used, though with a collector that was not optimized for low pressure fluctuations. An adjustable resonator was installed and tests with variable volumes showed that Helmholtz resonators could be tuned to effectively suppress the key low frequency fluctuations.

7. ACKNOWLEDGEMENTS

The authors would like to thank Dr. Mark Rennie, who performed the tests in the IAR PWT. In addition, thanks are due to Gerrit Zorgdrager, who promoted the idea of using a resonator to control open-jet pressure fluctuations.

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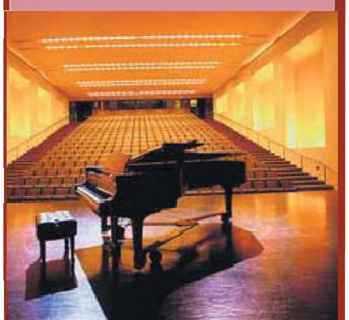

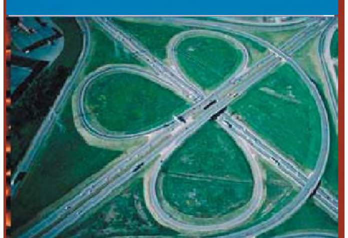
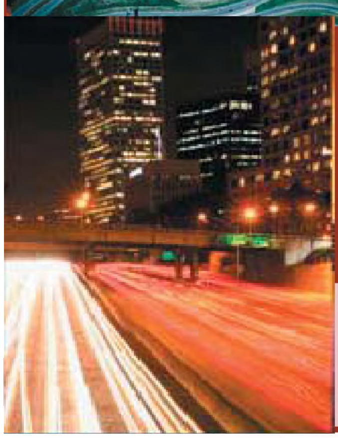

FEATURES

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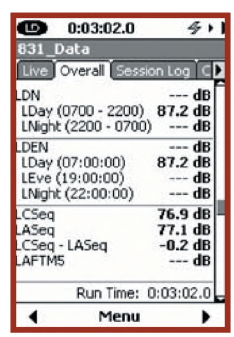
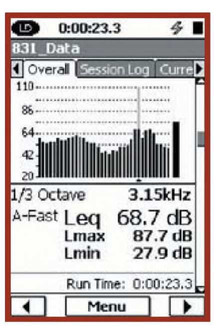
- Small size with large display. Ergonomic
- User friendly operator interface
- 120MB standard memory expandable up to 2GB
- Single measurement range from 20 to 140 dB SPL
- Up to 16 hours of battery life
- Provided with utility software for instrument set-up and data download
- Field upgradeable
- AUX port for connection to USB mass storage & cellular modems

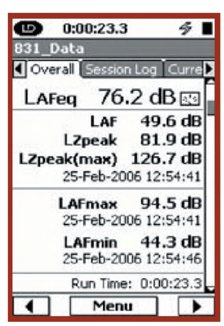


MEASUREMENT CAPABILITIES

- Real time 1/1 & 1/3 octave frequency analysis
- Simultaneous display of several noise measurements—ANY DATA (Leq, Lmax, Spectra, etc
- Automatic logging of user selectable noise measurements (Leq, Lmax, Spectra, etc…)
- Exceedance logging with user selectable trigger levels
- Audio and voice recording with replay







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