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Suppression of Open-Jet Pressure Fluctuations in the Hyundai Aeroacoustic Wind Tunnel

Mark Rennie
Aiolos Engineering Corporation

Moo-Sang Kim, Jung-Ho Lee and Jung-Do Kee
Hyundai Motor Company

ABSTRACT

Peak pressure fluctuation amplitudes in the ¾ open-jet test-section of the Hyundai Aeroacoustic Wind Tunnel have been reduced from root-mean-square levels equal to 6% of the test-section dynamic pressure to levels of less than 0.5% over almost the full wind speed range of the tunnel. The improvement was accomplished using a retrofit of the test-section collector. Using an analysis of the physics of the problem, it was found that the HAWT pressure fluctuations could be accurately modeled as a resonance phenomenon in which acoustic modes of the full wind tunnel circuit are excited by a nozzle-to-collector edgetone-feedback loop. Scaling relations developed from the theory were used to design an experiment in $1/7^{th}$ scale of the HAWT circuit, which resulted in the development of the new collector design. Data that illustrate the benefit of the reduction in pressure fluctuation amplitudes on passenger-car aerodynamic force measurements are presented.

INTRODUCTION

Designed to meet the aerodynamic and aero-acoustic testing needs of Hyundai Motor Company, the Hyundai Aero-acoustic Wind Tunnel (HAWT) is a state-of-the art test and research facility. Important features of the wind tunnel include:

- ¾ semi-open jet test section with 28 m^2 nozzle area,
- separate turntables for balance and dynamometer testing,
- a relatively long test section, 18 m, to achieve a nearly-constant static pressure over the 13 m long test region.

Additional design details are described in Reference [1].

Construction of the wind tunnel was completed in early 1999, and commissioning and startup tests commenced immediately thereafter. The initial wind-on runs revealed, however, that the wind tunnel was subject to large-amplitude fluctuations of the test-section static pressure over a substantial portion of its wind-speed operating range. Although static pressure fluctuations occur to varying degrees in all open-jet wind tunnels, the magnitude of the pressure fluctuations in HAWT over certain wind speed ranges were larger than acceptable for wind tunnels of this class. Work began immediately to determine a suitable correction to the problem.

An in-situ test program was started in the full-scale facility. Investigations with vortex generators attached to the nozzle lip showed that the fluctuation amplitudes could be considerably reduced, but with the following side effects:

- The vortex generators were a source of aero-acoustic noise that slightly increased the test-section background noise levels. (However, specified test-section background noise levels were still met with the vortex generators installed.)
- The vortex generators increased the negative static pressure gradient at the front of the test section to a level greater than the design goal for the facility.

Primarily because of their effect on the test-section static pressure gradient, the use of vortex generators to control the pressure fluctuations was considered unacceptable. In the interest of finding the best possible solution, investigation of the static pressure fluctuations was suspended in the full-scale wind tunnel, and an external investigation into the problem was undertaken. In the interim, the wind tunnel was prepared for use until a correction could be implemented.

Lack of complete understanding of the pressure-fluctuation problem, much less an ability to computationally model it, determined that the external investigation would be experimental in nature. This paper details the problem analysis, model design and verification, and the eventual determination and implementation of a solution to the HAWT pressure fluctuations. Vehicle force data are presented to illustrate the improvement in data quality that was realized by the corrective action taken.

THEORETICAL CONSIDERATIONS

The large size of the HAWT meant that experimental modeling of the circuit at or near to full scale would be difficult and costly. From a convenience standpoint, it is preferable to test in a scale model that has a size that is small enough so that different test configurations are easy to install and modify. On the other hand, extrapolating full-scale performance predictions from the results of model-scale tests becomes riskier as the scale of the model is reduced. The experiment design therefore began with an analysis of the physics of the problem, in order to aid in evaluating the potential for success of a reduced-scale test program.

Recent discussions of the physics of large-amplitude open-jet pressure fluctuations can be found in [2 - 5]. These references agree that the fluctuations occur when the frequency of a wind-speed dependent source of jet unsteady forcing matches the natural frequency of some part of the wind tunnel circuit. The frequency of pressure fluctuations is therefore determined by the wind tunnel geometry, while the wind speed at which the fluctuations occur is determined by the physics of the unsteady forcing mechanism.

UNSTEADY FORCING MECHANISMS

Two mechanisms were considered:

- “natural” vortex shedding,
- edgetone feedback.

Of these two mechanisms, wind tunnel designers are perhaps more familiar with the natural vortex shedding, which refers to the large, coherent, vortex structures that are found to exist naturally within the shear layer of a free jet [6]. For a ¾-open jet with rectangular nozzle, the preferred frequency for natural vortex shedding is given by a Strouhal number, based on nozzle hydraulic diameter D, given by [3]:

$$St_N = \frac{f\,D}{U} \approx 0.34 \tag{1}$$

For HAWT, with $D \approx 5$ m, and a maximum wind speed $U = 200$ km/h, Equation (1) demonstrates that the frequency of the natural vortex shedding in HAWT is quite low, in the range 0 to 4 Hz.

The edgetone feedback loop [7 – 10] was also considered as a potential source of open-jet unsteady forcing. In [8], it is indicated that the phenomenon should not exist for Mach numbers less than $M \approx 0.4$. As such, the edgetone-feedback mechanism has generally received less attention as a cause of open-jet pressure fluctuations in low-speed wind tunnels; however, it will be shown later in the paper that the edgetone-feedback theory shows very good agreement with our experimental data.

The equation describing the frequency of edgetone-feedback excitation can be derived from a simple analysis of the feedback loop, Figure 1 [7]. The loop begins with a coherent vortex shed from the nozzle lip, which convects downstream until it contacts the collector. Interaction of the vortex with the collector generates a pressure disturbance which propagates back upstream. The loop is closed when the disturbance reaches the nozzle, stimulating the shedding of a new vortex.

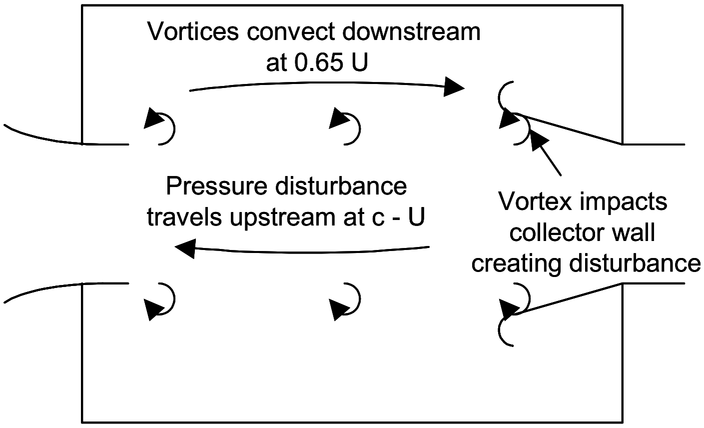

Figure 1: Diagram of edgetone-feedback loop in open-jet test section.

With the aid of Figure 1, the frequency associated with the edgetone feedback loop can be shown to be [7]:

$$f_E = \frac{1}{\left(\frac{1}{m}\right)\frac{L_{jet}}{0.65\,U} + \frac{L_{jet}}{c - U}} \tag{2}$$

The following comments can be made regarding Equation (2):

1. m is an integer variable that denotes the mode of the edgetone feedback. It represents the number of vortices that are resident in the test section at any instant in time.

2. The convection speed of a vortex in the shear layer of an open jet is approximately 65% of the wind speed in the core [3].

3. The upstream-propagating acoustic disturbance returns through the flow, so that its propagation speed is retarded by the flow velocity U [8].

In Equation (2), the term $\frac{L_{jet}}{c - U}$ is the elapsed time required for the upstream-propagating acoustic disturbance to travel from the collector back to the nozzle. For low flow speeds, this time is much shorter than the time for the shed vortices to convect from the nozzle to the collector. Although the full Equation (2) will be used later in the paper, additional insight into the edgetone-feedback mechanism can be gained by temporarily neglecting the acoustic propagation time. In this case, an approximate equation for the edgetone-feedback frequency becomes:

$$f_E \approx \frac{0.65\ m\ U}{L_{jet}} \tag{3}$$

Forming a Stouhal number from Equation (3) gives

$$St_E = \frac{f_E\ D}{U} \approx 0.18\ m \tag{4}$$

where the constant 0.18 in Equation (4) was obtained from the nondimensional jet length for HAWT, $\frac{L_{jet}}{D} = 3.5$. Thus Equation (4) demonstrates that edgetone-feedback is equivalent to vortex shedding over an infinite range of constantly-spaced Strouhal numbers. By coincidence, the m = 2 edgetone mode for the specific case of HAWT results in unsteady forcing with a Strouhal number that is almost precisely identical to the Strouhal number for natural vortex shedding, Equation (1).

According to [8], Strouhal numbers associated with edgetone-feedback excitations most commonly fall within the range 0.2 to 0.8. This finite range for St_E implies that, in practice, only the lowest few edgetone modes need to be considered; higher modes, representing a more complex jet structure, are more difficult to sustain and therefore less prevalent. Referring to Equation (4), the limitation $St_E < 0.8$ implies a maximum edgetone mode in HAWT of $m \sim 4$. Although this kind of direct comparison between [8] and a model derived specifically for HAWT must be considered an approximation at best, it will be shown later in the paper that our experimental data generally does in fact agree with this $m \sim 4$ upper limit. In any case, the bias towards the lowest edgetone-feedback modes means that edgetone forcing frequencies generated in HAWT should also be expected to be fairly low, less than around 10 Hz.

WIND TUNNEL RESONANCES

One of the conclusions of the preceding section has been that the important unsteady forcing mechanisms for large, low-speed wind tunnels typically occur at very low frequencies. As such, although mechanical resonances of wind tunnel structures have been reported [2], acoustic resonances of the wind tunnel internal cavities will generally dominate because of their low excitation frequencies.

Acoustic resonant frequencies depend inversely upon the characteristic length scales L of the resonating duct:

$$f = \frac{n\ c}{2\ L} \tag{5}$$

or resonating volume:

$$f = \frac{c}{2\sqrt{\left(\frac{L_x}{n_x}\right)^2 + \left(\frac{L_y}{n_y}\right)^2 + \left(\frac{L_z}{n_z}\right)^2}} \tag{6}$$

Dimensions for several components of the HAWT circuit and their first (n=1) resonant frequencies are listed in Table 1. The table shows that the resonant frequencies of the largest circuit elements (eg. the full circuit, or a test/return leg) are well within the range of excitation frequencies discussed in the preceding section. Further, some of the smaller circuit components, such as one of the cross legs, or the plenum, have resonant frequencies that might be attained by a higher mode of edgetone forcing. However, the very low resonant frequencies associated with the full circuit means that this resonance has the greatest chance of occurrence throughout the wind speed range of the wind tunnel, for the following reasons:

- Both forcing mechanisms show a Strouhal-type dependence on wind speed; thus the resonant frequency of the first full circuit mode is attained at a lower wind speed than any other potentially resonating component.

- The full-circuit resonance has the smallest frequency separation between resonant modes, and therefore has the largest number of resonant modes that can be excited over the wind-speed range of the facility.

As such, the full-circuit acoustic mode always deserves particular attention in any corrective investigation of pressure fluctuations in open-jet wind tunnels.

Component	*Length (m)*	*First Resonant Frequency (Hz)*
Full Circuit	210	0.8
Test or Return Leg	79	2.2
Cross Leg	26	6.5
Plenum	9 x 17 x 26	5.3 and up

Table 1: Dimensions and resonant frequencies of some structures in HAWT.

PRESSURE FLUCTUATIONS IN THE ORIGINAL FULL-SCALE HAWT

The theory of large-amplitude, open-jet pressure fluctuations, Equations (1) - (6), has been known for many years. The use of the theory to predict the potential wind speeds and frequencies of pressure fluctuations in new wind tunnel designs is a well established procedure. However, the theory does not predict the amplitude of pressure fluctuations, and thus definite conclusions regarding whether a pressure fluctuation problem will exist are difficult to make. Instead, reference must be made to the database of existing wind tunnels when attempting to gauge the potential for large-amplitude pressure fluctuations. Our past experience with previous wind tunnel designs did not indicate that large-amplitude pressure fluctuations would be a serious problem in the HAWT.

Pressure fluctuations levels were measured in the original HAWT test section as a normal part of the wind tunnel startup and commissioning test program. The pressure fluctuations were measured using a Setra Model 239 differential pressure transducer with 8 in water-gauge range. The positive-pressure port of the transducer was directly exposed to the plenum air, while the effect of unsteady pressure disturbances on the reference port of the transducer was filtered using a long coiled length of plastic pressure tubing. The length of the coiled tubing was chosen to give a transmission loss [11] that would ensure that any extraneous fluctuating pressure signals in the frequency range of interest would be fully damped before reaching the reference port of the pressure transducer. All measurements were made with the transducer placed in the test section halfway between the nozzle and collector, and approximately 1 m away from the plenum wall.

The spectra of pressure fluctuations detected by the transducer were recorded using a HP-3569A spectrum analyzer over the frequency range 0 – 25 Hz, with a bandwidth of $\Delta f = 0.016$ Hz. The spectra were acquired at wind speeds from 60 km/h to the maximum test-section wind speed of 200 km/h. Over the range of wind speeds tested, peaks in the pressure-fluctuation spectra were observed at only 2 frequencies, approximately 1.4 Hz and 2.6 Hz. The amplitudes and frequencies of these 2 spectral peaks were measured and manually recorded; however, the detailed spectra of these initial measurements were not otherwise retained.

RESULTS

The magnitudes of the pressure fluctuation peaks at 1.4 Hz and 2.6 Hz are plotted as a function of wind speed in Figure 2. The figure shows that pressure fluctuation spectral peaks equal to 4% to 6% of the test-section dynamic pressure (peak Cprms ~ 0.04 to 0.06) existed at wind speeds of 80 km/h and 130 km/h. Another maximum of approximately 3% occurred at a wind speed of 160 km/h.

The frequencies of the measured fluctuations are shown in greater detail in Figure 3. Each point plotted in Figure 3 shows the frequency of a pressure fluctuation peak and the test-section wind speed at which it occurred. Points corresponding to peak Cprms > 0.01 are also circled so as to give some indication of the amplitude of the pressure fluctuation associated with each point.

COMPARISON OF DATA WITH THEORY

Overlayed on Figure 3 are curves showing the frequency-versus-windspeed dependence calculated for an acoustic-type resonance, natural vortex shedding, and egetone feedback.

The tunnel acoustic modes shown in Figure 3 were computed using the full wind-tunnel circuit length. The figure shows reasonably good agreement between the measured pulsation frequencies and the frequencies of the full-circuit acoustic modes. Specifically, the largest-amplitude pressure fluctuations tend to cluster at discrete frequencies, around 1.4 Hz, and 2.6 Hz, that match very well the frequencies predicted for the full-circuit resonant modes. This good comparison implies that the dominant type of resonance in the original HAWT circuit was the full-circuit acoustic mode.

Also plotted in Figure 3 is the curve for natural vortex shedding (St = 0.34), Equation (1). On a plot of frequency versus windspeed, large-amplitude pressure fluctuations are predicted to occur when the curve for an aerodynamic forcing mechanism intersects a dominant resonant frequency of the tunnel, in this case, 1.4 or 2.6 Hz. Thus the curve for natural vortex shedding predicts the large-amplitude fluctuation at 80 km/h very well; however, it deviates noticeably from the fluctuation at 160 km/h, and completely fails to predict the fluctuation at 130 km/h.

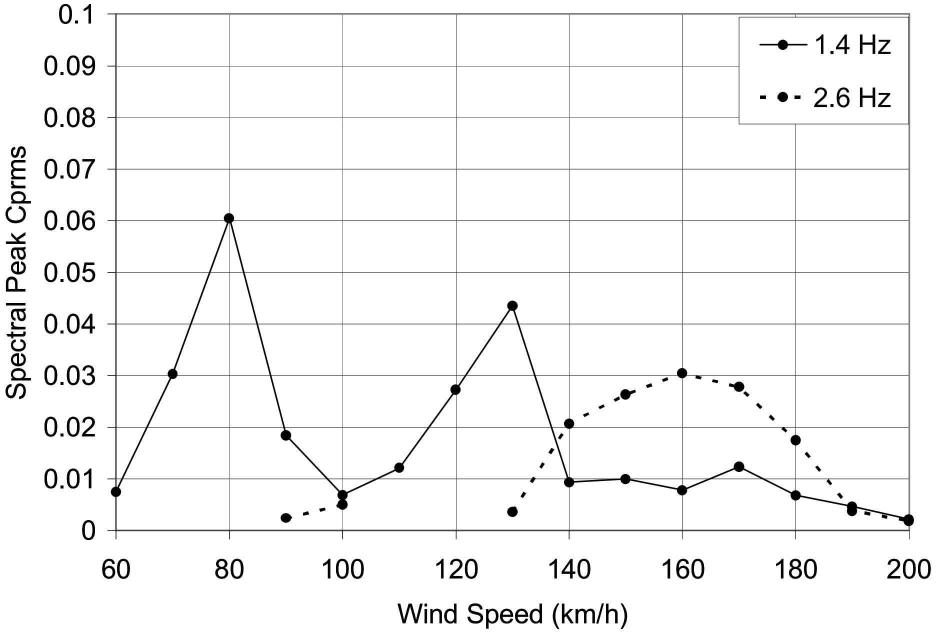

Figure 2: Pressure fluctuation amplitudes in the original HAWT test section

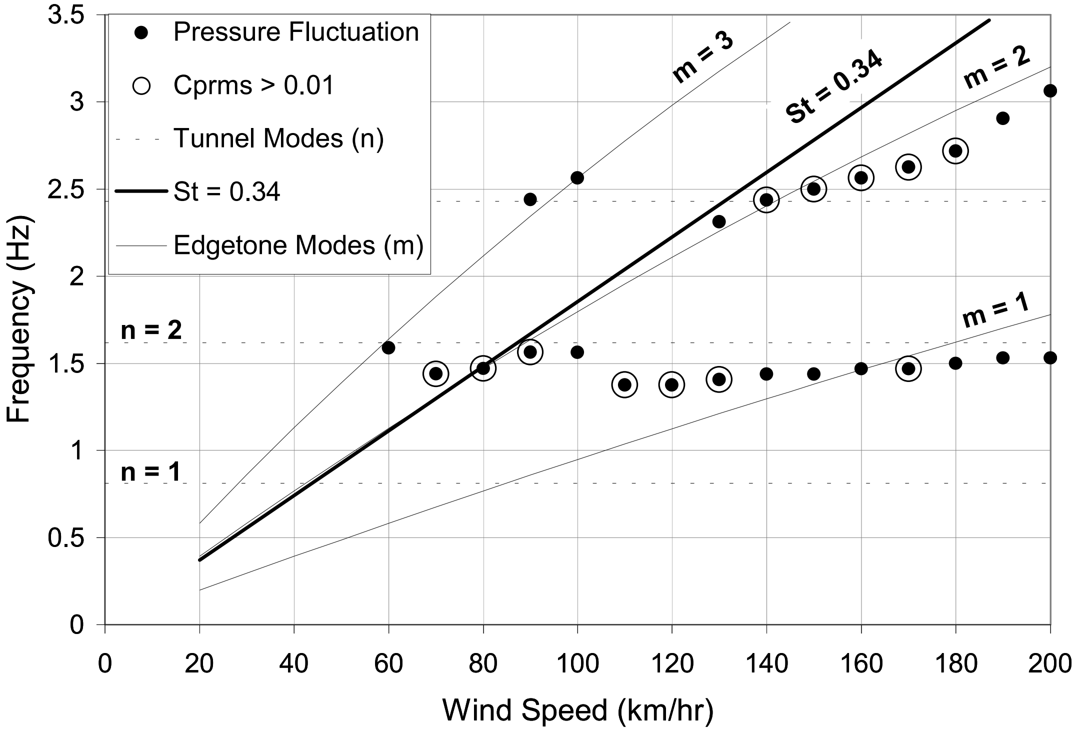

Figure 3: Frequency-windspeed dependence of pressure fluctuations in the original HAWT test section.

Finally, Figure 3 shows curves for the first 3 edgetone modes, Equation (2). These curves intersect the tunnel resonant curves very close to all three wind speeds at which large-amplitude pressure fluctuations were detected, 80 km/h, 130 km/h, and 160 km/h. As such, assuming the edgetone-feedback explanation, it is possible to deduce the sources of the three large-amplitude pressure fluctuations shown in Figure 2 as follows:

- The fluctuation at 80 km/h is due to an excitation of the n = 2 circuit resonant mode by the m = 2 edgetone mode.
- The fluctuation at 130 km/h is caused by excitation of the n = 2 circuit resonant mode by the m = 1 edgetone mode.
- The fluctuation at 160 km/h is caused by excitation of the n = 3 circuit resonant mode by the m = 2 edgetone mode.

Although the edgetone-feedback theory describes the experimental data better than the natural-vortex-shedding theory, the comparison shown in Figure 3 is still somewhat lacking. However, the remaining discrepancies between edgetone-feedback theory and the experimental data can be accounted for using the idea of resonant "locking in." Specifically, it is a well-known characteristic of resonant phenomena that the frequency of the forcing mechanism tends to "lock in" to the resonant frequency at conditions close to, but not matching, the exact resonant conditions. This type of behavior is clearly evident in the data shown in Figure 3, where large-amplitude fluctuations tend to occur at the same resonant frequency over large wind speed ranges.

In Figure 2, the existence of resonant locking in is also indicated by the behavior of the pressure fluctuations around the amplitude maxima, which shows an increase, leveling off, and finally a reduction in amplitude as the optimum resonant conditions are approached, reached and then passed. This behavior can be explained by the resonant locking-in concept as follows:

- Between 110 km/h and 130 km/h, the forcing frequency shifts away from the predicted frequency for m = 1 edgetone forcing, and locks in to the n = 2 full-circuit resonance frequency of 1.4 Hz.
- Between 140 km/h and 180 km/h, the excitation frequency for the m = 2 edgetone mode locks into the n = 3 circuit resonant mode.

The above points are illustrated in Figure 4.

In general then, the edetone-feedback theory provides a much more viable explanation for the pressure-fluctuation behavior observed in the original HAWT circuit than does the theory for natural vortex shedding. Assuming that edgetone feedback was the dominant forcing mechanism in HAWT, some additional observations can be made:

- The edgetone model also follows the non-linear behavior of the experimental data as the wind speed increases. Edgetone theory attributes this trend to the increasing effect of the acoustic pulse transit time on the overall feedback frequency, which causes the true edgetone forcing frequency,

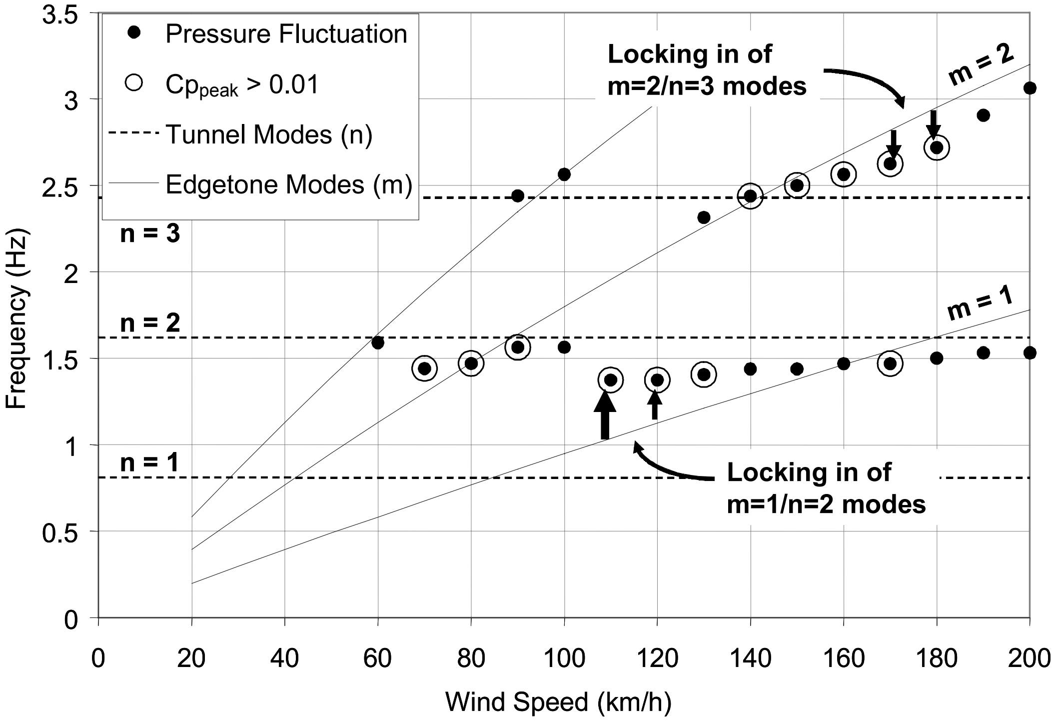

Figure 4: Resonant locking in of edgetone forcing.

Equation (2), to be slightly less at a given wind speed than the linear approximation given in Equation (4). This reducing-slope trend of the data is especially evident in off-resonant conditions, when the effects of resonant locking in are absent. The trend can be more clearly seen in the model-scale data shown later, Figure 7, in which the full non-linear theory of Equation (2) closely matches the measured pressure fluctuations even at non-resonant frequencies in between the tunnel modes n = 1 and n = 2.

- At 140 km/h, the m=1/n=2 resonance appears to become suppressed in favor of the m=2/n=3 resonance that peaks at 160 km/h. This shift of resonant energy may indicate a preference for the edgetone mode that is closest to the "natural" vortex shedding (St = 0.34).

This section has shown that a comparison of the pressure fluctuation data obtained in HAWT with an edgetone-feedback model for the excitation can be made with reasonable accuracy. This result contradicts the findings of Ahuja [8], where it was concluded that edgetone feedback should be absent as a source of pressure fluctuation excitation for M < 0.4. No explanation is given for this discrepancy, and further investigation is needed.

MODEL-SCALE TEST PROGRAM

The goals of the model-scale experiments were to:

- reproduce the pressure-fluctuation characteristics observed in the original HAWT circuit, shown in Figures 2 to 4,
- develop a strategy for reducing pressure fluctuation amplitudes to within limits acceptable for a facility of this class.

The time constraints placed on the experimental program precluded the possibility of building and commissioning a model of the HAWT from scratch. Instead, it was hoped that an existing wind tunnel of suitable size could be found and modified for the scale-model tests.

SCALING CONSIDERATIONS

The behavior of the pressure pulsations in a scale model can be predicted from the mathematical theory. Based on the good comparison between edgetone-feedback theory, acoustic resonator theory, and the experimental data acquired in the original HAWT, the relevant equations were taken to be Equations (2), (3) and (5). From Equation (5), the well-known scaling relation for resonant frequencies is obtained:

$$f_{\text{model}} = \frac{L_{\text{full scale circuit}}}{L_{\text{model circuit}}} f_{\text{full scale}} \tag{7}$$

Normally, Equation (7) is the only scaling relation that is necessary. However, it was realized that, since a complete model of HAWT would not be built, it could have proven difficult to modify an existing wind tunnel such that all parts of the HAWT circuit would be modeled using a uniform scale. In this case, the mathematical model indicates that the wind speed at which the pressure fluctuations occur can be affected by non-uniform scaling. This outcome is obtained from a simultaneous solution of Equations (3) and (5):

$$U = \frac{0.77\ n\ c\ L_{\text{jet}}}{m\ L_{\text{circ}}} \tag{8}$$

For similar resonant and edgetone modes, a scaling relation for pressure-fluctuation wind speeds developed from Equation (8) gives:

$$U_{\text{model}} = \frac{L_{\text{model jet}}}{L_{\text{full scale jet}}} \frac{L_{\text{full scale circ}}}{L_{\text{model circ}}} U_{\text{full scale}} \tag{9}$$

Additional comment regarding Equation (9) is warranted from the standpoint of model pressure-fluctuation amplitudes. In general, an accurate prediction of the scaling of pressure-fluctuation amplitudes between the model and full-scale facility is difficult to achieve. For example, it is reasonable to assume that pressure fluctuation amplitudes in the model might be influenced by different structural characteristics of the wind tunnels, or by different levels of acoustic treatment, since these factors may figure in the damping of acoustic resonances of the circuit. However, the amplitude of the unsteady pressure forcing is determined, to first order, by the strength of the vortices that are shed from the nozzle lip, and the strength of these vortices is determined for the most part by the velocity difference across the jet shear layer; that is, the test-section wind speed. It is therefore desirable to have one-to-one wind-speed scaling between the model and full-scale wind tunnels, since this will help to generate similar pressure-fluctuation amplitudes in the two facilities. As such, wind-speed scaling effects generated by non-uniform model scaling, as shown by Equation (9), should be avoided if possible.

MODEL WIND TUNNEL

A suitable candidate for the model-scale tests was found in the Pilot Wind Tunnel (PWT) at the Institute for Aerospace Research (IAR) laboratory of the National Research Council, Canada. The PWT is a 1/10th-scale model of the IAR 9 m wind tunnel located at Uplands, Ottawa. With a circuit length of 29 m, the tunnel was an ideal size in which to conduct the model-scale investigations. The wind tunnel was modified from its original configuration by replacing the test leg with a 1/7th-scale model of the settling chamber, contraction, test section and test-section diffuser of the HAWT. Although the remainder of the PWT circuit was unchanged, it very closely matched the chosen 1/7th scale of the return circuit of HAWT. A comparison of relevant model and full-scale dimensions is shown in Table 2. A drawing of the modified wind tunnel circuit is shown in Figure 5.

Wind Tunnel	*Circuit Length,* L_{circ} *(m)*	*Jet Length,* L_{jet} *(m)*
HAWT	210	18
PWT	28.6	2.54

Table 2: Important dimensions for HAWT and the scale-model wind tunnel, PWT.

Scale factors for the model tests can be computed using the data of Table 2:

- From Equation (7), frequencies for the full-circuit acoustic resonances in the model are 7.3 times greater than in the full-scale HAWT:

$$\frac{f_{\mathrm{model}}}{f_{\mathrm{full\ scale}}} = 7.3 \tag{10}$$

- Due to slightly mismatched circuit and jet length scale factors, large-amplitude pressure fluctuations in the model occur at wind speeds 4% greater than in the HAWT:

$$\frac{U_{\mathrm{model}}}{U_{\mathrm{full\ scale}}} = 1.04 \tag{11}$$

With the model test leg installed, the maximum wind speed in the PWT was 200 km/h, which exactly matches the maximum wind speed in HAWT. Given the approximate one-to-one wind speed scaling, Equation (11), this maximum wind speed parity between the model and full-scale facilities permitted the investigation of pressure fluctuations in the PWT over the full equivalent wind speed of the HAWT.

VERIFICATION OF MODEL

Initial model tests concentrated on verifying that the model would adequately duplicate the pressure fluctuation behavior observed in the original HAWT. Pressure fluctuations were measured in the PWT using a Setra model 238 differential pressure transducer with 0.1 psi range. The transducer was placed with one face exposed to the plenum air, and in the same (scaled) location in the model at which the measurements were made in HAWT. The pressure fluctuation spectra were measured using an HP-35655A spectrum analyzer. Most of the measurements were made over the frequency range 0 to 25 Hz with a bandwidth Δf = 0.0625 Hz; from Equation (9), this corresponds to an equivalent full-scale frequency range of 0 – 3.5 Hz, and bandwidth Δf = 0.0085 Hz. The spectra of pressure fluctuations were checked, however, up to 100 Hz, and no fluctuation peaks were found beyond 25 Hz. Measurements were made over the wind speed range of 20 km/h up to the maximum model wind speed of 200 km/h.

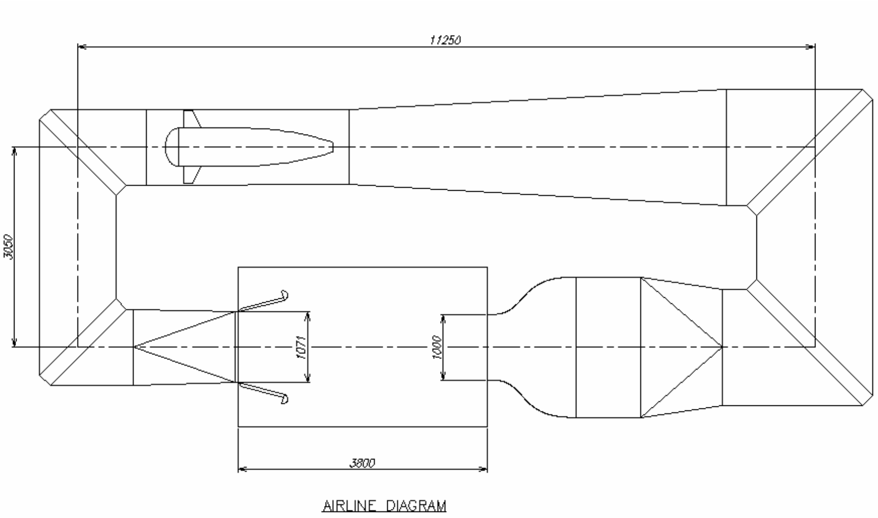

Figure 5: Diagram of PWT, used for 1/7th-scale model investigation. Dimensions in mm.

The amplitudes of pressure fluctuations measured in the PWT are plotted in Figure 6. The figure shows the peak Cprms of the spectrum acquired at each tested wind speed, and a Cprms that was integrated over the frequency range 3.6 – 25 Hz. This frequency range was chosen to allow comparison with integrated Cprms values determined for the full-scale HAWT, shown later, that were integrated over the same equivalent (scaled) frequency range. The overall shapes of the spectral peak and the integrated Cprms curves in Figure 6 are essentially the same, except that the integrated Cprms levels are 0.02 to 0.05 greater than the spectral peak at each wind speed. The integrated Cprms levels are larger partly because they account for all of the power associated with each pressure pulsation, which may reside in several adjacent frequency bins in the spectrum, while the remainder of the difference between the peak and integrated Cprms values is due to the broadband fluctuations over the integrated frequency range. Figure 6 shows that, at wind speeds where the pressure pulsations are very low amplitude, for example, 60, 70 and 200 km/h, the difference between the integrated Cprms and the spectral peak Cprms is roughly the same, around 0.02; this difference represents the approximate level of the broadband pressure fluctuations. Thus the pressure fluctuations measured in the PWT can be seen to consist of large-amplitude pressure fluctuation peaks superposed on a plateau of broadband fluctuations whose amplitude level is proportional to the dynamic pressure. The primary concern of the investigation was to reduce the levels of the large-amplitude fluctuation peaks; the broadband fluctuations are a fundamental consequence of the jet shear layer and cannot be attenuated.

A comparison of the frequency-windspeed dependence of the pressure fluctuations in the model and in the HAWT is shown in Figure 7. The model data were scaled according to Equations (10) and (11). As in Figure 3, all data with peak fluctuation Cp's greater than 0.01 are circled. The figure shows very good agreement between the model and full-scale results. In particular, the largest-amplitude pressure fluctuations in the model occur at the same scaled wind speeds and frequencies as in the full-scale HAWT, implying that the edgetone/full-circuit resonance was successfully modeled in the PWT.

Model and full-scale pressure fluctuation amplitudes are compared in Figure 8. The figure shows only the amplitudes of the largest fluctuation peak measured at each wind speed, since this is the only type of data that was measured in the original HAWT circuit. For the model data, the wind speeds have been scaled using Equation (11). Also, in order to give a more representative comparison of model and full-scale peak Cprms levels, the model spectral data were adjusted to a bandwidth of 0.017 Hz prior to determining the spectral peaks; this bandwidth is very close to the 0.016 Hz bandwidth used during acquisition of the HAWT data. As shown in Figure 8, the shapes of the model and full-scale curves, and the wind speeds at which the largest-amplitude pressure fluctuations occur, show very good agreement. Surprisingly, even the amplitudes of the peaks compare very well. Most importantly, Figure 8 shows that the amplitudes of the model fluctuations were easily measurable, and the good agreement between the model and full-scale pressure fluctuation behavior shown in Figures 7 and 8 demonstrates that the physics of the problem was successfully reproduced in the model.

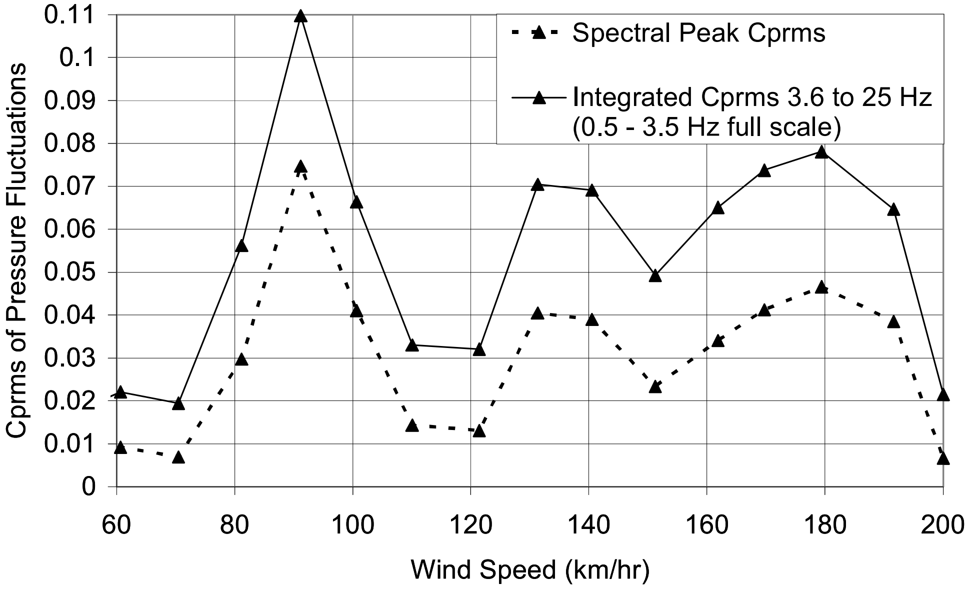

Figure 6: Pressure fluctuation levels measured in the PWT, with original collector configuration

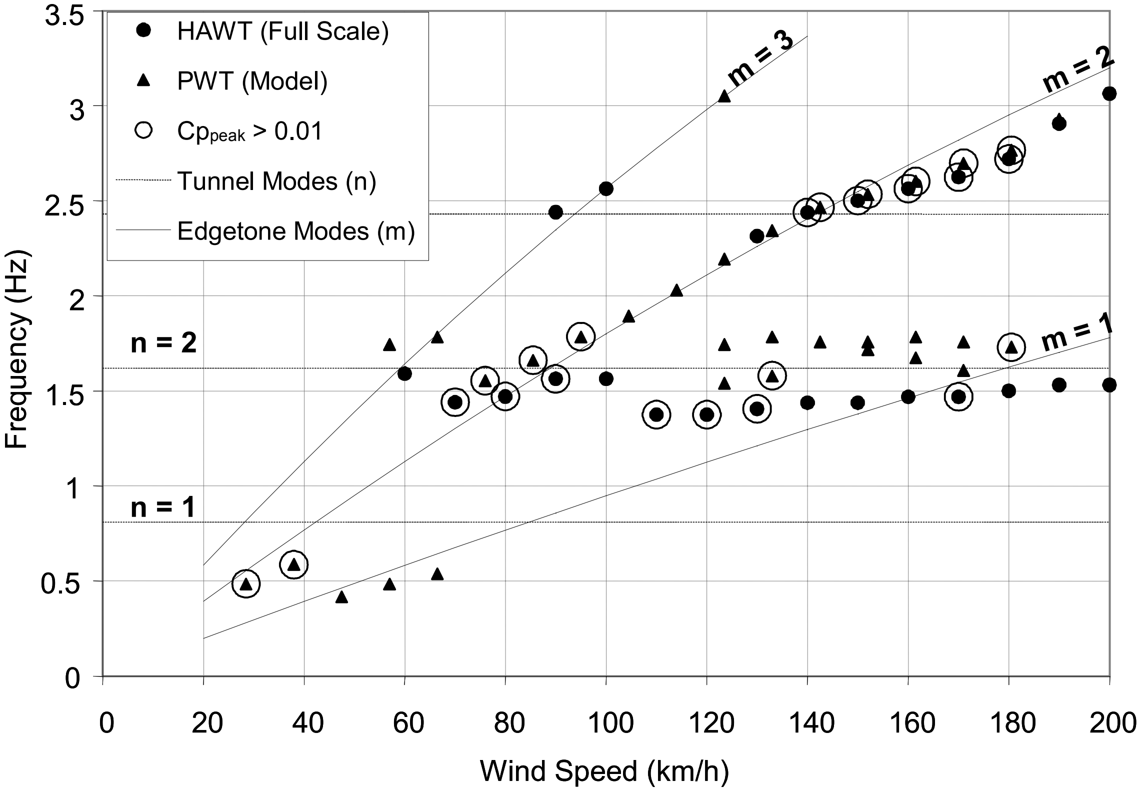

Figure 7: Comparison of frequencies and wind speeds of pressure fluctuations measured in PWT and HAWT, with original collector configuration.

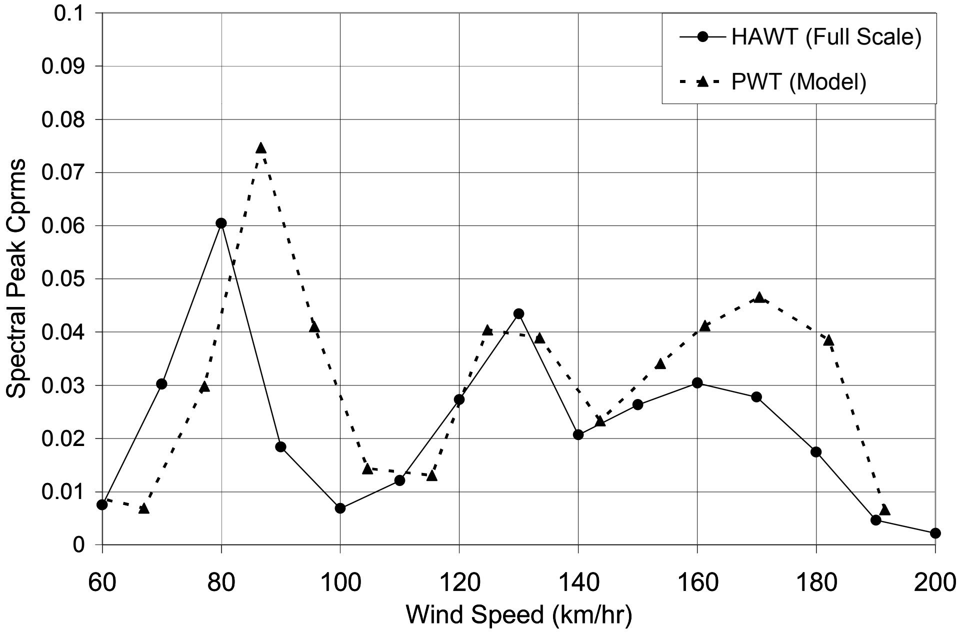

Figure 8: Comparison of pressure fluctuation levels measured in PWT and HAWT, with original collector configuration.

CORRECTIVE WORK

Investigations into a strategy to reduce the pressure fluctuations in the HAWT focused on the idea of implementing a breather between the trailing edge of the collector and the inlet to the test-section diffuser. This kind of collector design has been successfully used before to reduce pressure fluctuation amplitudes in open-jet wind tunnels, for example [12].

Development of the exact configuration of the collector was performed in the model-scale PWT. The tests concentrated on a design that would be a simple modification of the existing HAWT collector.

The model-scale tests showed that the breather gap worked very well in reducing pressure fluctuation amplitudes. The tests showed that the pressure fluctuation amplitudes decreased as the breather slot was widened until a limiting, low amplitude level of pressure fluctuations was attained.

The effect of the collector modification on pressure fluctuation spectra measured in the PWT is shown in Figures 9 - 11. The figures show spectra acquired at the wind speeds associated with the largest pressure fluctuation amplitudes, 80, 130 and 160 km/h, with the original collector, and with the modified collector with optimized breather gap. To permit an accurate comparison of amplitudes, all of the spectra shown in the figures have been adjusted to a common bandwidth of 0.06 Hz. The spectra acquired at 130 and 160 km/h show that the collector breather produced a noticeable reduction in pulsation amplitudes at the main resonant frequencies. However, at 80 km/h, the amplitude of the pressure fluctuations were not as greatly reduced, and the frequency of the pressure fluctuation peak at around 1.5 Hz was shifted to a slightly higher frequency.

The effect of the modified collector on pressure fluctuation amplitudes in the PWT is shown in Figure 12. The figure shows that the Cprms of the spectral peak of the pressure fluctuations was reduced to less than 0.005 for wind speeds greater than 90 km/h. Residual fluctuations still remain at 80 km/h, although these have also been considerably reduced below the original levels. The integrated Cprms levels were reduced to less than 0.02 over the same wind speed range; as discussed, this Cprms level is roughly the level of the broadband pressure fluctuations in the PWT (Figure 6).

The modified collector design that was developed in the PWT was retrofitted into the full-scale HAWT in the spring of 2001, over a period of 2 weeks. In order to make the breather gap, the collector was moved forward a short distance into the test section, thus reducing the test-section length slightly; this reduction in the test-section length had no measurable effect on test-section flow quality or operability of the wind tunnel. Pressure fluctuation spectra measured in HAWT with the modified collector installed are included in Figures 9 – 11.

Pressure fluctuation levels measured in HAWT after completion of the collector modification are shown in Figure 13. These data were acquired using the same measurement technique as before, except that a more sensitive, 0.5-inch water-gauge range pressure transducer was used. These data also show residual, but greatly attenuated, pressure fluctuation levels at 80 km/h, and at 150 km/h; otherwise the spectral Cprms peak of the pressure fluctuations was reduced below 0.005. Integrated Cprms levels were reduced to approximately 0.01 or less, except at the aforementioned wind speeds.

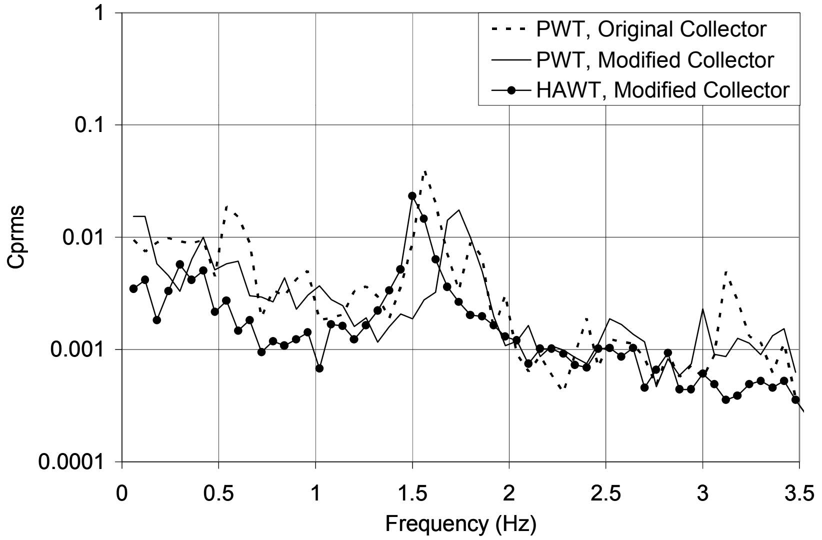

Figure 9: Measured pressure fluctuation spectra, 80 km/h

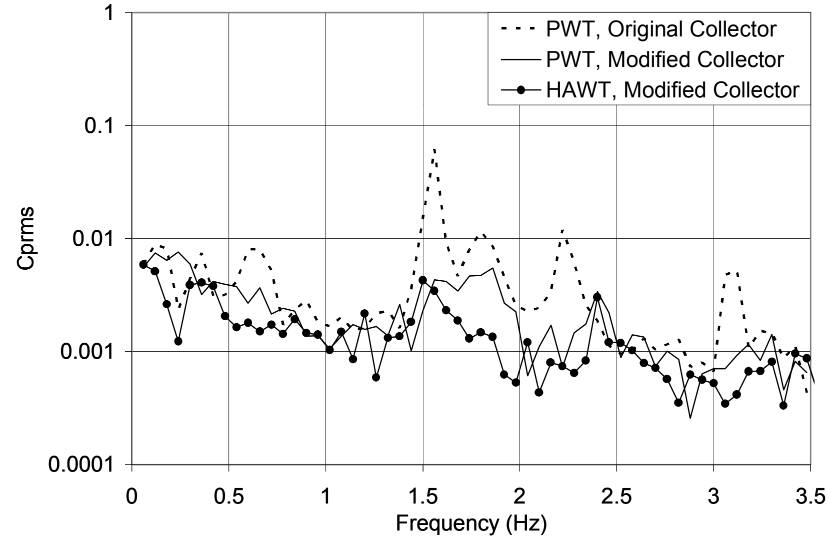

Figure 10: Measured pressure fluctuation spectra, 130 km/h

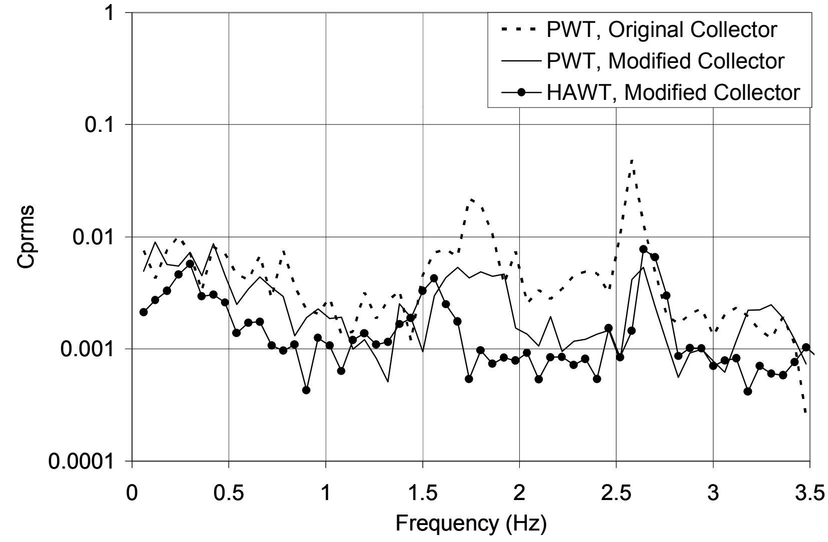

Figure 11: Measured pressure fluctuation spectra, 160 km/h

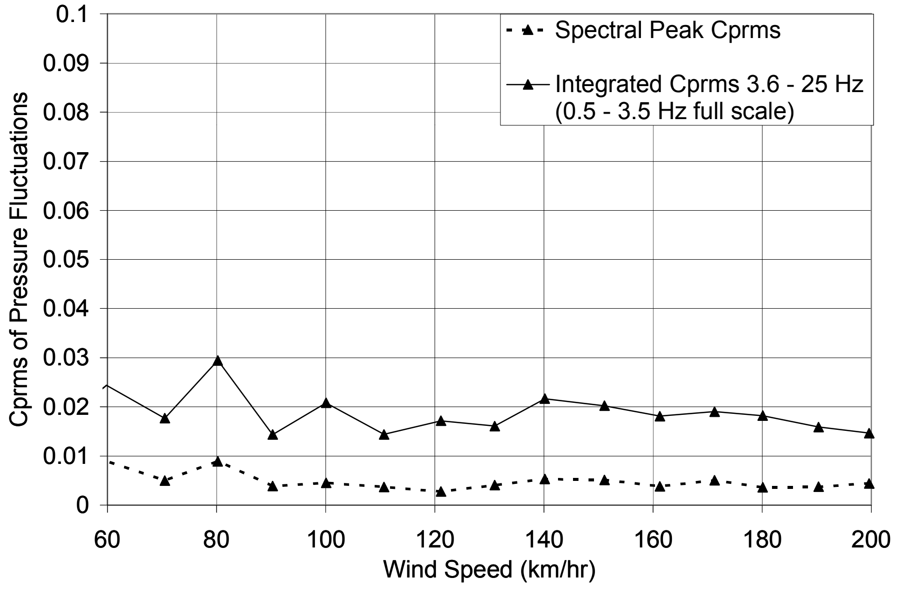

Figure 12: Pressure-fluctuation amplitudes in PWT with modified collector

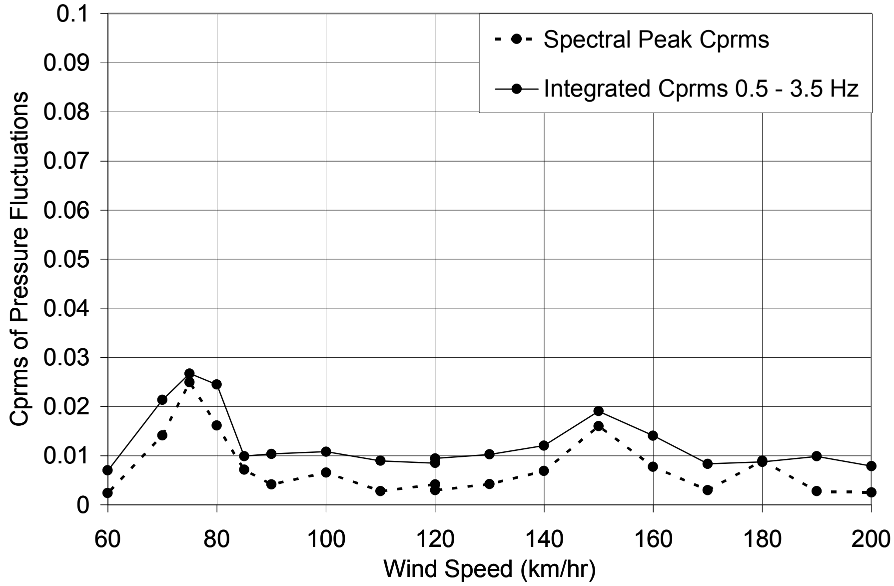

Figure 13: Pressure-fluctuation amplitudes in HAWT with modified collector

INFLUENCE ON AERODYNAMIC FORCE MEASUREMENTS

After installation of the modified collector, a re-commissioning of the HAWT was undertaken. Except for the reduction in pressure fluctuation amplitudes, no other appreciable change in the test-section flow quality was noted.

Vehicle aerodynamic force measurements performed before the collector modification were also repeated to evaluate the effect of the reduced pressure fluctuation levels on gross vehicle aerodynamic characteristics. In Reference [3], it was shown that low-frequency, large-amplitude pressure fluctuations can noticeably affect steady-state lift and drag measurements on standard vehicle body shapes. In general, it was shown that open-jet pressure fluctuations tend to cause a decrease in the steady-state CD and an increase in the steady-state CL.

Figures 14 to 17 show the wind-speed variation of the steady-state CD and CL for sedan and notchback shaped vehicles measured in the HAWT. Each figure shows data acquired with the original collector and with the modified collector. As is evident in the figures, the original- and modified-collector data sets for both vehicle shapes are offset by around 0.02 to 0.03 for both CL and CD. This offset is a consequence of the fact that the modified-collector data set was acquired several months after the original-collector data set; as such, the offset is attributed to unintended alterations in the vehicle's external shape, mounting arrangement, etc., that may have occurred between the two sets of measurements. In [3], no such offset in the comparison data is evident because the pressure fluctuations could essentially be turned on or off instantly using an active resonance control system, which permitted very short-term back-to-back measurements of vehicle forces with and without open-jet pulsations.

In spite of the offset in absolute values, the data shown in Figures 14 to 17 still display trends that agree with the major findings of [3], specifically,

- The CD and CL data acquired with the original collector generally show large excursions at or close to wind speeds corresponding to the largest amplitudes of pressure fluctuations: 80, 130, and 160 km/h.

- At the affected wind speeds, CD values generally show a sudden decrease, while CL values show a sudden increase.

With the modified collector, the CD and CL curves vary more smoothly and consistently, and give a more accurate representation of the true wind speed variation of the vehicle aerodynamics.

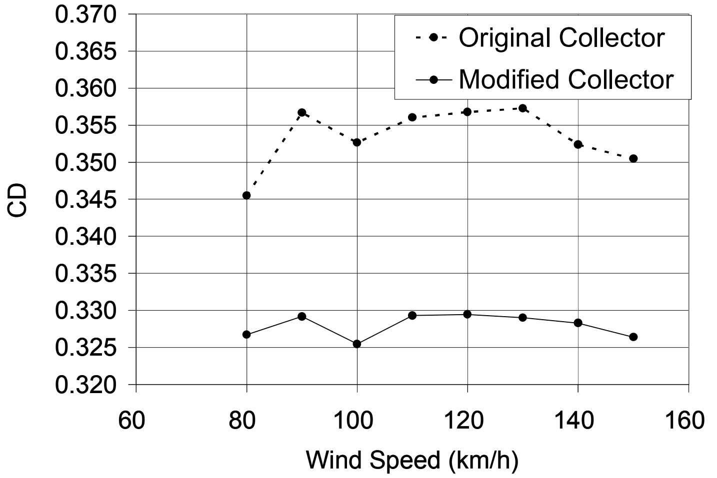

Figure 14: CD for a sedan-shaped vehicle in HAWT,with original and modified collector configurations

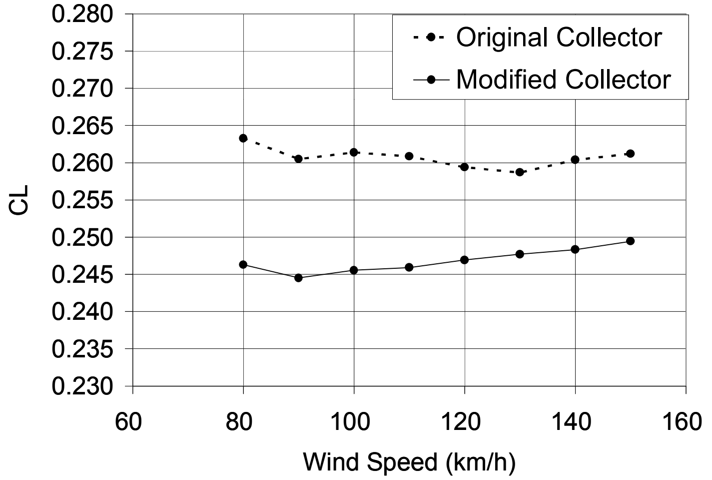

Figure 15: CL for a sedan-shaped vehicle in HAWT, with original and modified collector configurations

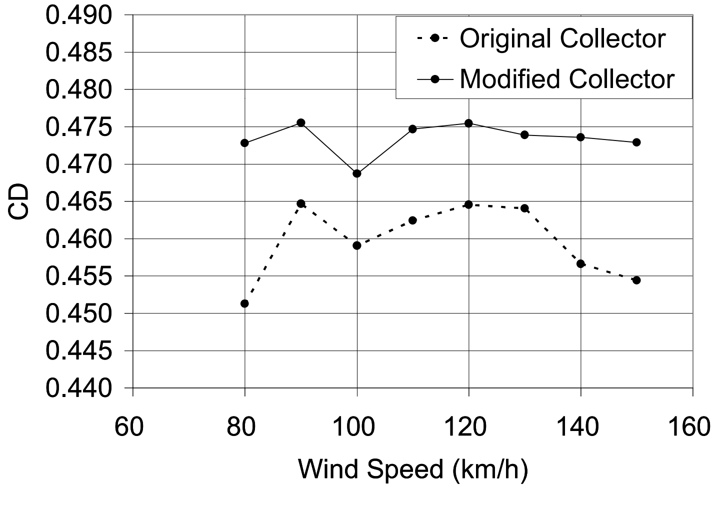

Figure 16: CD for a notchback-shaped vehicle in HAWT, with original and modified collector configurations

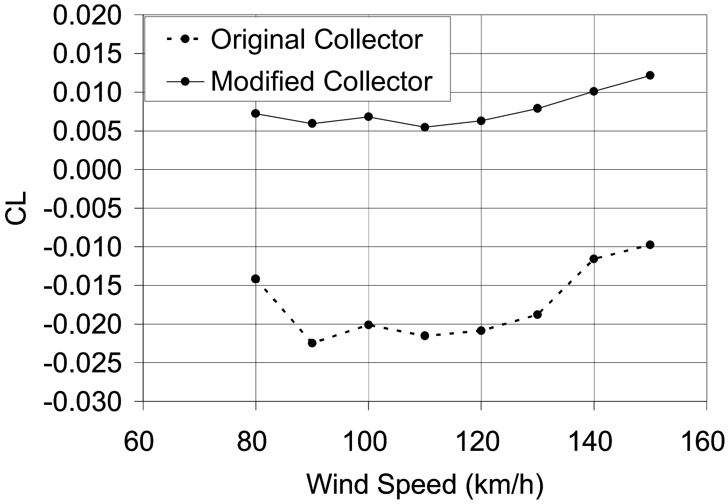

Figure 17: CL for a notchback-shaped vehicle in HAWT, with original and modified collector configurations

CONCLUSION

This paper has detailed an experimental investigation undertaken to suppress pressure fluctuations in the Hyundai Aeroacoustic Wind Tunnel. Analysis of the test data suggest edgetone-feedback as the source of excitation for the pressure fluctuations, in contradiction to the findings of [8]. No explanation is given for this outcome, and further research is required.

The investigation has led to a new collector design that was successfully developed using a 1/7th –scale model of the HAWT circuit. Using the proper scaling relations, very good agreement between the frequencies, wind speeds and peak amplitudes of pressure fluctuations measured in the model and the full-scale HAWT were obtained. With the modified collector design, spectral peak pressure fluctuation amplitudes in the HAWT were reduced to Cprms < 0.005, and integrated Cprms values to around 0.01, over most of the wind speed range of the wind tunnel. The reduction in pressure fluctuation amplitudes resulted in an improvement in the quality of aerodynamic force data, as evidenced by a more consistent wind-speed variation of CL and CD data. The success of the test program demonstrates the importance and benefit of model-scale investigations for pressure fluctuation effects.

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CONTACT INFORMATION

Dr. Mark Rennie: mark@aiolos.com
Dr. Moo-Sang Kim: mooskim@hyundai-motor.com
Mr. Jung-Ho Lee: jhlee@hyundai-motor.com
Mr. Jung-Do Kee: jdkee@hyundai-motor.com