REDUCTION OF ¾ OPEN JET WIND TUNNEL LOW-FREQUENCY FLUCTUATIONS

X. Amandolèse
CNAM-LAA, Saint-Cyr L'Ecole, France

C. Vartanian
GIE S2A, Montigny le Bretonneux, France

ABSTRACT

¾ open jet wind tunnels are subjected to undesired low frequency pressure and velocity fluctuations at distinct flow velocities. The aim of this paper is to present recent research done in the full scale automotive aero-acoustic facility of the S2A wind tunnel complex in order to characterise the physical mechanism causing the fluctuations, to clarify their impact on the aerodynamic measurements and to validate active or passive solutions that allow high quality aerodynamic and acoustic measurements over the entire velocity range of the wind tunnel.

1. INTRODUCTION

In order to facilitate complex acoustic measurements, most of the recent automotive wind tunnels have a ¾ open test section. Unfortunately, as for open jet wind tunnels, ¾ open test sections are subjected to undesired low frequency pressure and velocity fluctuations at distinct flow velocities. Efforts to understand the physics and to reduce the impact of those low frequency fluctuations on data quality and wind tunnel operation have been reported in many recent technical papers (Arnette and Buchanan, 1999; Wickern at al, 2000; Rennie et al, 2004; von Heesen and Höpfer, 2004).

If the exact mechanisms involved are not yet fully understood, fluctuations seem to occur when frequencies of wind speed dependent jet shear layer instabilities match acoustic resonant frequencies of the wind tunnel. In that context ¾ open jet wind tunnel fluctuations can be regarded as jet or mixing layer oscillations amplified/controlled by a fluid resonant system.

Self-sustained oscillations of non-impinging or impinging shear layers have been widely studied and a review of various configurations and their associated feedback mechanisms can be found in Rockwell (1983). The interaction of the inherent fluid instabilities with acoustic resonators have also received a large amount of attention and, as reported by Rockwell and Schachenmann (1982) for a pipeline-cavity system or by Morel (1979) for a so-called jet-driven Helmholtz resonator, the effect of resonators can strongly enhance the amplitude of jet fluctuations.

Due to the dimension of full scale automotive wind tunnels, the frequencies involved are very low (< 10Hz). According to wind tunnel designers the amplitude of those fluctuations can be limited by the careful design of the wind tunnel test section geometry. Unfortunately, in the recently commissioned full-scale facility of the S2A wind tunnel complex, undesired low frequency fluctuations still exist over distinct ranges of flow velocity and these corrupt both acoustic and aerodynamic measurements. At 60km/h a pressure fluctuation with a frequency close to 1.6 Hz is measured out-of-flow, with an amplitude of almost 100dB. This pressure fluctuation is strongly correlated with a velocity fluctuation of nearly 3% in the core of the jet.

Despite the fact that this low frequency can not be heard by the human ear, it affects the acoustic measurements and psychoacoustic judgments. Since aero-acoustic noise generated by a vehicle depends on the flow velocity, low frequency fluctuations of this velocity induce a modulation (and thus a corruption) of the acoustic measurement, which can not be removed by mean of a filtering procedure because the noise generation mechanisms involved are strongly non linear.

Velocity fluctuations can also significantly affect unsteady aerodynamic investigations, enhanced by non-uniform static pressure fluctuations in the plenum chamber. And last but not least, corruption of steady aerodynamic data is also observed, i.e. undesirable reductions in the measured drag coefficient as well as increases in the lift coefficient due to a disrupted static pressure distribution along the test section.

The aim of this paper is to present recent research carried out in the S2A wind tunnel complex, which comprises a full scale aero-acoustic wind tunnel and a 2/5-scale model wind tunnel. Extensive unsteady pressure and velocity measurements were carried out in both facilities. The objective of these tests was to characterise the physical mechanism causing the fluctuations, to clarify their impact on the aerodynamic measurements and to validate active or passive solutions that allow high quality aerodynamic and acoustic measurements over the entire velocity range of the wind tunnel.

2. PRELIMINARY TESTS IN THE FULL-SCALE FACILITY

An isometric view of the full scale facility of the S2A wind tunnel complex is shown in Figures 1. The ¾ open test section is characterised by a rectangular nozzle with dimensions of 3.7m (height) by 6.5m (width). Dimensions of the collector inlet cross-section are 5m (height) and 8.8m (width) with bell-mouthed leading edges. The jet length L (distance from nozzle to collector inlet) is about 14m, which gives a relative jet length (L/D_h) close to 3, D_h being the equivalent (hydraulic) diameter of the nozzle exit. The plenum (or test chamber) dimensions are 10.4m (height), 16.2m (width) and 22.7m (long) and the total length of the wind tunnel circuit, L_d, is about 200m.

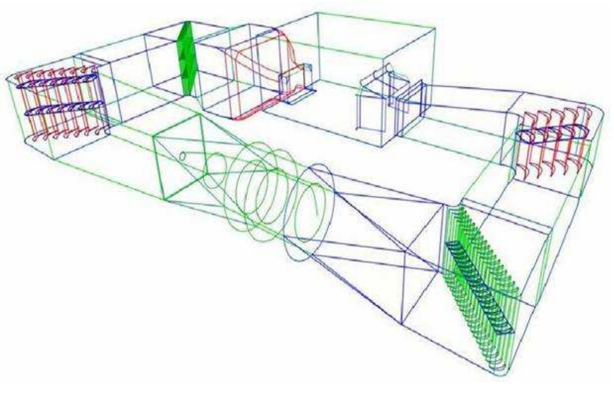

Figure 1: *Isometric view of the full scale facility of the S2A wind tunnel complex*

2.1 Characterisation of the low-frequency fluctuations

Pressure measurements were made out- of-flow along with unsteady velocity measurements using a hot-wire probe in both the core of the jet and in the shear layer region, with and without a vehicle in the test section. In both cases, the chamber pressure and the velocity (in both the jet-core and the shear layer) exhibit sequences of oscillations at varying distinct frequencies as the jet velocity increases. The RMS velocity fluctuation amplitude levels are shown in Figure 2 as a function of the wind tunnel speed, along with the dimensionless frequencies (i.e. Strouhal number based on the nozzle hydraulic diameter) associated with the peaks of the spectra of the unsteady velocity in the shear layer (at an axial distance of x/D_h =1.5 from the jet exit). These results clearly show resonant oscillations over four distinct ranges of the wind tunnel speed.

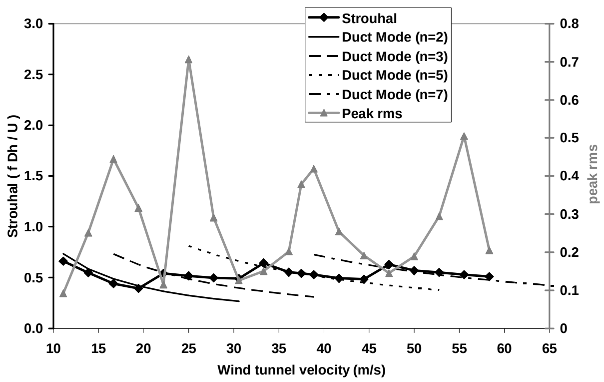

Figure 2: *Velocity amplitude and associated Strouhal number as a function of the wind tunnel speed (with a "Notchback" vehicle in the test section)*

Neglecting the end corrections and the internal damping, the resonant frequencies of the full circuit with constant mean flow can be obtained by:

$$f = n\frac{c}{2L_d}\left(1 - M^2\right) \qquad (1)$$

with M an average Mach number along the length of the circuit.

The dimensionless frequencies associated with the n=2, 3, 5 and 7 acoustic modes appear in figure 2. This clearly demonstrates the successive lock-ins of wind speed dependant unsteadiness of the jet with the acoustic resonant modes of the wind tunnel. These results also show that all the resonances

occur at a Strouhal number close to 0.5 which may be explained by a possible edge-tone feedback mechanism and its associated phase condition, due to the impingement of the jet shear layer on the collector. Indeed, as for jet-edge, jet-ring or mixing layer-edge systems, Rennie (2000) found a strong correlation between the frequency of the flow instability and the distance between the nozzle and the collector in a typical ¾ open jet wind tunnel. He then proposed a predictive model for determining the discrete frequencies at which the jet can oscillate, which is very similar to that proposed by Morel (1979) for a jet-hole configuration and by Rossiter (1964) for rectangular cut-outs under tangential flow.
According to these results the dominant frequencies should reasonably collapse using equation:

$$S_L \equiv \frac{f\,L}{U} = \frac{N-\beta}{\dfrac{U}{U_c}+M} \qquad (2)$$

where U_c is the convection velocity of the travelling vortex ring, the integer N is the number of wavelengths of the vortex pattern and β is a corrective term determined experimentally. With $U_c \approx 0.6\ U$, $\beta = 0.25$ and N=3, the Strouhal number based on the hydraulic diameter smoothly decreases from 0.54 to 0.5 over the operating velocity range of the wind tunnel. This tends to prove that the third mode of the impinging shear layer instability between the nozzle exit and the collector is the cause of the fluid excitation.

In figure 2 one can also notice that apart for the first resonance, the strongest oscillations are due to resonances with successive even-numbered modes. This is in accordance with the findings of Rockwell et al. (2003) for a pipeline cavity oscillation which involved coupling with long wavelength resonant acoustic modes of the pipe. Indeed, assuming that in the wind tunnel configuration the acoustic waves are reflected by the fan, the maximum resonance occurs for acoustic standing waves exhibiting a velocity anti-node at the location of the test section.
For the first resonance (at a wind velocity close to 17 m/s), the second mode of the full circuit could be involved and/or the Helmholtz resonance frequency associated with the plenum volume.
Assuming that the fluid in the collector behaves as an incompressible column with an effective length l_2 and an equivalent diameter D_2, an expression of the Helmholtz resonance frequency associated with the plenum volume V is:

$$f = \frac{c\,D_2}{4\pi}\sqrt{\frac{\pi}{V\,l_2}} \qquad (3)$$

For a jet driven cylindrical Helmholtz resonator Morel (1979) proposed the expression: $l_2 = L_2 + 0.6D_2$ for the effective length, where L_2 is the length of the exit orifice.
In the present configuration, taking L_2 and D_2 as the axial length and the hydraulic diameter associated with the mean cross section of the collector, equation (3) gives a frequency of approximately 1.6 Hz which is very close to the one associated with the second acoustic mode of the wind tunnel circuit (1.7 Hz).

2.2 Impact on the aerodynamic measurements

The variation of the drag coefficient (multiplied by the frontal area) of a "notchback type" vehicle along with the shear layer velocity amplitude are reported in figure 3 as a function of the wind tunnel velocity. These results clearly show a strong correlation between the drag reduction and the shear layer oscillations at resonant conditions. This is particularly evident at 25m/s where the drag is reduced by nearly 1%. These results are in accordance with the parametric study by Wickern et al. (2000) on a wide range of vehicles which shows a systematic decrease in the drag coefficient. According to Wickern et al, this corruption of the measured aerodynamic coefficient is due to a horizontal buoyancy effect, i.e. an increase in the static pressure upstream of the collector at wind tunnel velocities where the jet pulsations are large. A possible explanation of the mechanism involved could be found by studying the way the collector 'cuts out' the correct volume inflow to satisfy the continuity condition for the wind tunnel circuit. Indeed, the axial pressure distribution in an open jet wind tunnel is strongly influenced by the intake design according to the jet dimensions (Kramer et al, 1984). If the pulsating jet widens, the inlet area of the collector becomes too small, leading to a strong deceleration of the flow in the intake, and hence to the generation of reverse flow in the plenum which could explain an increase in static pressure upstream of the collector. Further investigations are necessary to confirm the exact mechanism involved.

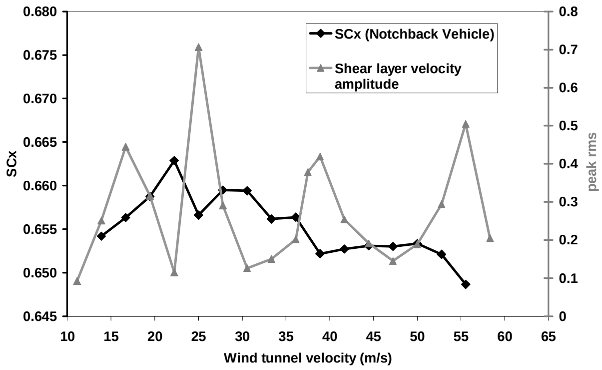

***Figure 3**: Drag coefficient of a "notchback" vehicle and the shear layer velocity amplitude vs wind tunnel velocity*

3. ATTENUATORS

Assuming that the undesirable oscillations are due to the lock-in of the inherent shear-layer instability with the acoustic resonant modes of the wind tunnel, two main strategies can be employed in order to reduce these oscillations and their impact: the mitigation of the excitation mechanism (i.e. the shear layer instability), or an active damping of the acoustic resonant modes of the wind tunnel. The later was successfully implemented in the Audi Aeroacoustic Wind Tunnel (Evert and Miehling, 2004) but needs considerable effort to be effective for each operational configuration.

The implementation of vortex generators is probably the most common example of the first strategy. As reported by Rockwell and Karadogan (1983), small scale vortex generators in the nozzle exit are very efficient in attenuating the lock-in oscillations involved in an axisymmetric pipeline-cavity system. Consequently, vanes, tabs or teeth that protrude into the airstream at the nozzle exit remain the most widely used method for reducing open jet wind tunnel pulsations. Unfortunately, vortex generators generally cause additional high frequency noise that increases the test section background noise to unacceptable levels for an aeroacoustic wind tunnel.

An in-situ experimental programme was carried out to assess the effect of various configurations of passive or active devices mounted on the nozzle exit, i.e. the jet separation edge.

3.1 Aerodynamic validation

Preliminary investigations were first conducted with various protruding configurations at the nozzle exit: vanes, tabs or teeth with different spacings and heights. Unsteady velocity measurements in the shear layer then confirmed that the generation of stream-wise vorticity and/or the destruction of the span-wise (or azimuthal) coherence on the flow separation was indeed very efficient in reducing the fluctuation amplitudes (see figure 4). These investigations also revealed that the main part of this effect was due to attenuators along the upper edge of the nozzle.

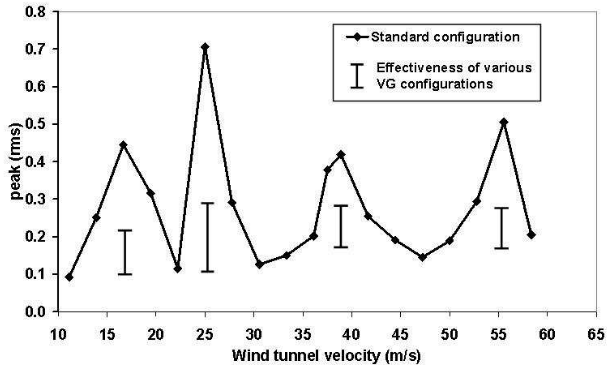

***Figure 4**: Impact of various protruding attenuators on the low frequency fluctuations*

Various other configuration were tested but only two will be presented in this paper. The first consisted of two rectangular flaps (see figure 5) of 1m x 0.2m along the upper edge of the nozzle exit with a small plunging angle. The second configuration (see figure 6) consisted of the same rectangular flaps made to vibrate by electro-dynamic shakers with simple open-loop control (single-frequency or band-limited random signals).

The effect on the measured drag coefficient of the best solutions tested (protruding teeth, passive flaps with a plunging angle of 6 degrees and vibrating flaps with a forcing frequency of 7.5 Hz) are presented in figure 7 as a function of wind velocity.

According to these results, the most effective solution is clearly the passive rectangular flaps with a plunging angle of 6 degrees. Indeed, this solution smoothes the drag variation as a function of wind velocity without changing the overall value. The shift in the measured drag over the entire velocity range is particularly strong for the protruding teeth solutions which, as for vortex generators, tend to increase the negative static pressure gradient at the front of the test section leading to an increase in the measured drag coefficient.

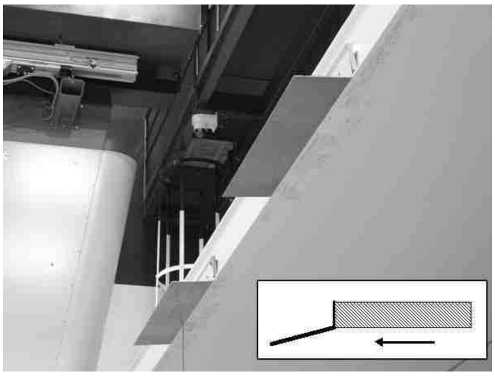

Figure 5: *View of the plunging rectangular flaps along the upper edge of the nozzle exit*

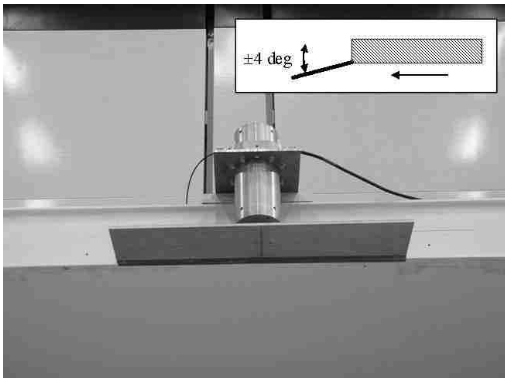

Figure 6: *View of one rectangular flap with its electro-dynamic shaker at the upper edge of the nozzle exit*

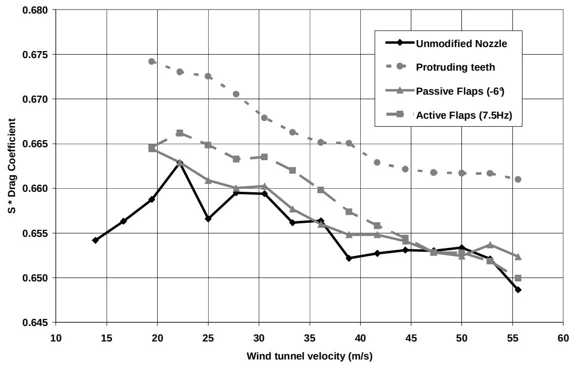

Figure 7: *Impact of protruding teeth, and passive or active flaps on the drag coefficient measured on a "Notchback" vehicle*

Additional tests were performed in the 2/5 model scale facility to confirm the effect of the passive flap solution on the static pressure gradient in the test section. Results are presented in figure 8 with and without attenuators, at a wind velocity of 14 m/s at which the strongest low frequency fluctuations were observed. The results with the passive flaps clearly show an increase of the zero pressure gradient area which leads to better quality aerodynamic measurements.

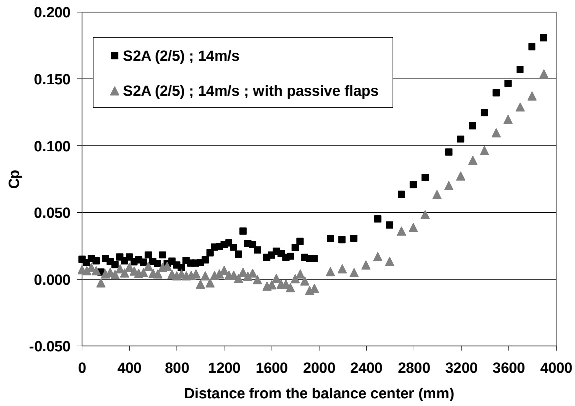

Figure 8: *Impact of passive flaps on the static pressure distribution between the balance centre and the collector*

3.2 Acoustic validation

An acoustic validation of the passive flap solution was performed. Background noise measurements were made out-of-flow over the whole wind tunnel velocity range with no vehicle in the test section. The "passive flaps" solution introduces no additional flow noise.

4. CONCLUSION

An investigation of the low frequency fluctuations in the full-scale facility of the S2A wind tunnel complex was performed. It was shown that the observed fluctuations were due to lock-ins of the impinging jet shear layer instability with the acoustic resonant modes of the wind tunnel. Four areas of significant oscillations were detected for wind tunnel velocities between 10 and 60 m/s. The first resonance seems to be due to a lock-in with either the second acoustic mode associated with the full wind tunnel circuit and/or the Helmhotz resonant mode associated with the plenum volume. The three others resonances are due to successive lock-ins with even order modes 3, 5 and 7 associated with the full wind tunnel circuit.

Additional drag and static pressure measurements confirmed that, at resonance, the drag coefficient measured on a vehicle is underestimated due to an increase in the static pressure upstream of the collector.

Various solutions were tested in order to assess their impact on the fluctuations and on the quality of the aerodynamic measurements. Rectangular flaps along the upper edge of the nozzle exit with a small plunging angle are particularly efficient in smoothing the variation of the measured drag coefficient as a function of wind tunnel velocity. Indeed these attenuators tend to increase the zero pressure gradient area which is a guarantee of improved aerodynamic measurements. Last but not least, this passive flap solution is less protruding than classical vortex generators and does not introduce additional flow noise.

Further investigations are ongoing in order to validate the efficiency of this solution for a wide range of vehicles and also to better identify the physical mechanisms leading to the reduction of the shear layer oscillations.

5. ACKNOWLEDGEMENTS

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