Aeolian Tones in Wind Tunnels

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1.0 INTRODUCTION

There has been a recent trend in new wind tunnels to require very low, test section, background noise levels. This trend can been seen for the most common types of low speed wind tunnels; including automotive climatic wind tunnels, and both automotive and aerospace aero-acoustic wind tunnels. Designers of aircraft and road vehicles are striving to produce quieter designs. A quiet aero-acoustic wind tunnel is a primary tool for the investigation of aerodynamic noise.

Climatic wind tunnels are primarily used for the development of automotive engine cooling systems, HVAC systems and testing all vehicle systems under climatic extremes. Quiet climatic wind tunnels allow the test engineer to use sound as a diagnostic tool; e.g. evaluation of drivability and engine knock.

The dominant source of noise in any low speed wind tunnel is the main fan, which provides the test section air flow. To reduce test section noise to the required levels, the wind tunnel designer will first endeavor to reduce the background noise at its source with a very efficient, custom fan design. The next step will be to make extensive use of acoustic treatment in the wind tunnel circuit to attenuate the fan noise. The fan noise can thus be reduced to essentially inaudible levels in the quietest recent aero-acoustic wind tunnels. In these facilities secondary sources of noise can dominate the test section background noise spectrum.

The usual source of secondary noise is the airflow noise produced by the wind tunnel flow as it impinges on obstructions within the flow path, or by the test section jet.

There are other mechanisms, not usually experienced in most wind tunnels, which produce strong noise levels within the circuit and thereby increase the test section noise levels. Two such mechanisms will be presented in this paper. These two mechanisms will be illustrated with examples from a climatic wind tunnel and an aero-acoustic wind tunnel. Both of the example wind tunnels were provided with extensive acoustic treatment to reduce background noise levels. The noise levels produced by the secondary mechanisms were so high that test section background noise levels actually exceeded noise levels typically found in wind tunnels without any acoustic treatment. Thus the mechanisms for the production of Aeolian tones discussed in this paper can be important for any wind tunnel.

2.0 CIRCUIT DESCRIPTION

A schematic diagram of a typical wind tunnel circuit is shown in Figure 1. A wind tunnel can be either horizontal or vertical and has four legs; with the two longer legs containing the main fan and the test section. The cross-section of the legs can be either rectangular or circular. The test section leg, between Corners 1 and 4, usually has the settling chamber, for conditioning the flow, the main contraction and a diffuser downstream of the test section. Unusual noise generating mechanisms located in this leg are the main focus of this paper.

3.0 HEAT EXCHANGER AND AEOLIAN TONES

A Heat Exchanger (HE) is used in the circuit to control the air temperature of the flow. The HE is usually placed in the settling chamber as this is the region of lowest wind speed and thus lowest pressure loss. The HE consists of rows of small finned tubes, usually 6 mm to 15 mm diameter copper pipes, which span the height and width of the settling chamber. The HE may consist of between 2 to 12 rows of tubes in the flow direction. The tube rows are staggered for better heat transfer performance. The flow speeds in the settling chamber are in the range of 3 to 12 metres/sec. The wind tunnel flow passing over the HE tube banks sheds vortices

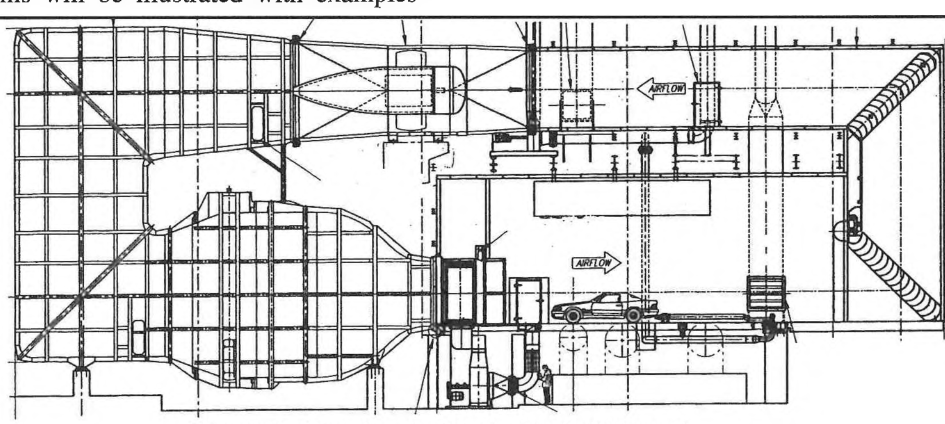


Figure 1. Details of a Typical Wind Tunnel.

with strong frequency preferences. If the shedding frequency coincides with the frequency of a room mode for the settling chamber, a very strong resonant tone may be produced. The noise that can be generated by the shedding vortices (Aeolian Tones) and possible mitigation measures will be discussed. General details of the flow-induced noise can be found in the literature. Wind Tunnel I is a recently constructed climatic wind tunnel for the automotive industry. A very strong acoustic resonance in the settling chamber was observed starting at a main fan speed of 450 rpm. This resonance was excited at a number of fan speeds between the initial 450 rpm speed and the maximum speed of 950 rpm. The resonance was not present at intermediate fan speeds between the discrete fan speeds.

When the resonance occurred the heat exchanger tubes and heat exchanger structure experienced large amplitude vibrations. Standing waves were readily observed in the settling chamber. The heat exchanger consisted of horizontal tubes and it has been shown in the available literature that this type of flow-induced resonance always excites a mode transverse to the direction of the tubes. At 450 rpm a pure vertical mode consisting of a 3 period standing wave was found (the (0,3) settling chamber mode). The narrowband noise spectra and a vertical survey which shows the mode shape is presented in Figure 2. The strongest resonances occurred when pure vertical modes were excited; i.e. the (0,3), (0,4), (0,5), (0,6) modes. As the vortex shedding frequency is directly proportional to fan speed, these strong resonances occurred at 450 rpm, 600 rpm, 750 rpm and 900 rpm. Resonances were also observed at intermediate fan speeds when a combined lateral/vertical mode was excited (e.g. (1,3) mode).

There are three basic approaches possible to solve this kind of noise problem and these are,

1. Change the boundary condition (apply acoustic treatment to the space)
2. Change the space natural frequency (e.g. position a splitter in the settling chamber)
3. Eliminate the forcing function (reduce the vortex shedding strength)

Figure 2a: Narrow Band Settling Chamber Sound Pressure Level, Fan speed = 450 rpm

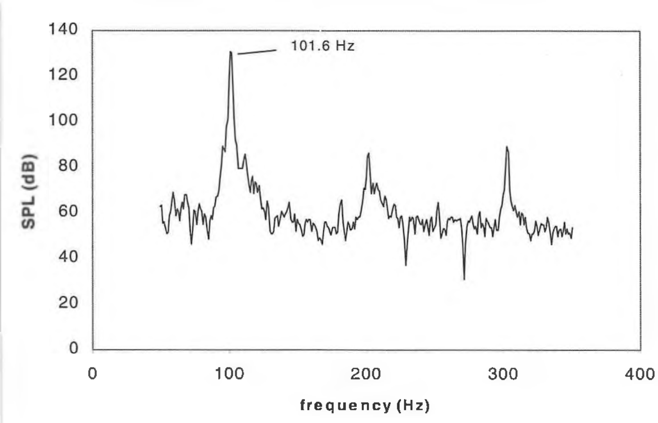
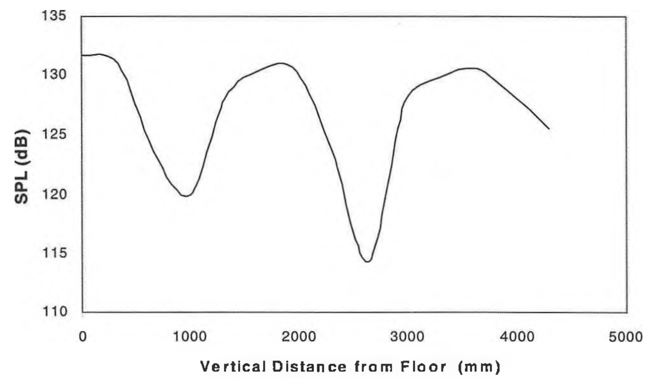


Figure 2b: Measured Peak SPL (101.6 Hz) for a Vertical Traverse, Fan speed = 450 rpm, (0,3) mode, settling chamber height = 5080 mm



Approach 1 and Approach 2 were tried without success (unlike in other Wind Tunnels cases). Several ideas to change the vortex shedding were tried and the idea that worked was to block the flow over critical tubes in the heat exchanger array. Flow obstructions, which ran across the full width of the heat exchanger, were attached to the upstream face of the heat exchanger to cover tubes located at several pressure antinodes for the mode that was being excited. In order for a resonance to occur, the feedback from the excited settling chamber mode must be able to synchronize the vortex shedding such that all of the vortices are shed in phase. It is conjectured that the flow blocking strips disrupted tube to tube communication, at critical points in the tube array, so that the vortex shedding was not able to lock on.

The final solution, to completely eliminate the resonance, required flow blocking strips attached to the upstream face of the heat exchanger as well as extensive acoustic treatment on the floor of the settling chamber.

4.0 BOUNDARY LAYER CONTROL SYSTEM AND AEOLIAN TONES

Wind Tunnel II is a horizontal wind tunnel with a solid wall test section used for aerospace applications. The wind tunnel was being renovated to improve its testing capability for automotive racing cars, as the test section was large enough for full-scale cars. One of the main requirements of an automotive wind tunnel is the control of the floor boundary layer in the region where the test vehicle is located. Aiolos was retained to design and install a Boundary Layer Control System (BLCS) with its attendant ducts and system fan. The main specifications, in addition to the aerodynamic performance, included a low noise level in the test section for the top speed of the boundary layer system fan. The peculiar noise generated by the BLCS is described below.

The BLCS consisted of two large openings covered with perforated plates, just downstream of the nozzle. The BLCS drew air from the test section through the perforated plates and down into the rest of the suction system ducting and fan.. The covers for the openings had to be able to withstand the weight of heavy forklift vehicles. Hence, the openings were covered with 26 mm thick perforated plates supported by heavy 100 mm deep catwalk grilles. The results presented in this paper are for those cases where the BLCS was operated without the wind tunnel main fan running. Similar trends in noise the noise levels were observed with thw wind tunnel main fan operating. Only the wind-off noise data was considererd as it simplified the analysis. A strong high frequency tone was generated at higher speeds of the boundary layer fan. The tone's intensity was high enough to be audible in adjacent buildings. Typical third-octave band spectra of noise levels, measured in the test section for selected fan RPM's are shown in Figure 3. Both noise and vibration measurements were conducted for different fan speeds and the results are summarized in the following observations:

a) The onset of tonal resonance noise started at around 400 RPM of the fan and continued through to maximum fan speed.

b) The dominant frequency increased with increasing speed The resultant intensity of the noise levels also increased with wind speed.

c) Intense plate vibration levels of the support grating as well as the perforated plate, followed the same frequency trend as the noise.

d) Impact tests of the plate/grating combination showed strong resonance at the noise frequencies.

The above observations led to the following conclusions:

1. the vortex shedding frequency of the plate perforations matched with the plate natural frequencies of both the 25 mm steel plate as well as the 100 mm deep grating support; and
2. the 100 mm cavities formed within the transverse and longitudinal bars of the grating amplified the shedding vortex sound.

The steel perforated plate was replaced by a thicker polyurethane plate with the same perforation pattern. The noise levels were reduced by between 5 and 10 dB, but the tonal resonance sound was still persistent. Since the grating was the main support mechanism, no major modifications were possible. The cross bars were then covered with 6 mm foam and the 100 mm deep cavities were filled with 50 mm diameter hollow foam tubes and the strong tonal resonance attenuated substantially. Figure 3 includes the noise levels after the installation of the above two control measures.

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Figure 3. Test Section Noise Levels at Different Fan Speeds
(Before modifications and after modifications)