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DEVELOPMENT AND VALIDATION OF A SMALL-SCALE ANECHOIC WIND TUNNEL.

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Abstract

After more than half a century of intense activity and the considerable development of complex numerical models, aeroacoustic research still relies heavily on experimental approaches. Experiments are essential to provide reference data for fundamental test cases, to understand highly complex and interacting phenomena, and to validate numerical simulations. At the University of Adelaide, the School of Mechanical Engineering is undertaking the upgrade and optimisation of its small-scale wind tunnel to support its increasing research activity in aeroacoustics. An experimental programme to start in 2007 requires a quiet 75 x 300 mm^2 rectangular cross-section jet with a maximum flow speed of 30 m/s, in an enclosure that is anechoic at frequencies above 200 Hz. This paper gives a brief outline of the process followed to upgrade the wind-tunnel, including the air supply system, flow treatment and jet cross-section. Additionally, the flow properties and acoustic performance of the wind tunnel are assessed through a series of validation experiments, and the main results are presented here against the initial design objectives. The results of a simple experiment consisting of a cylinder in cross-flow are also presented, and initial results are compared with a semi-empirical model to demonstrate the performance of the wind tunnel. Finally, a brief outline of the subsequent research work to be carried out in the wind tunnel is given.

1. INTRODUCTION

Recent developments in the research activities of the School of Mechanical Engineering at the University of Adelaide have necessitated a significant upgrade of the anechoic wind tunnel used until recently for the investigation of flow-induced noise and vibration [1]. Future research into some aspects of helicopter noise requires a significant increase in testing cross-section and mass flow rate capability [2]. This paper describes the upgraded anechoic wind tunnel and initial validation results are subsequently presented.

2. OVERVIEW OF THE ANECHOIC WIND TUNNEL

The anechoic wind tunnel consists of an 8 m^3 cubic room that is anechoic down to 200 Hz, enclosing a free jet in the potential core of which small scale models are tested. A new research programme requires the cross-section area to be increased from D_z x D_y = 50 x 50 mm^2 to D_z x D_y = 275 x 75 mm^2, which in turn necessitated an upgrade of the air supply system from compressed air storage tanks to a centrifugal fan to achieve a sustained flow speed of U_∞ = 40 m/s. Although the settling chamber was kept from the previous design, the new air supply system required a significant upgrade of the acoustic treatment. A new contraction was designed to accommodate larger experimental arrangements and a collector/diffuser was added at the downstream end of the chamber. The turbulent intensity on the flow was required to be less than 1% of the free stream velocity. A CAD rendering of the new wind tunnel as built is shown in Figure 1.

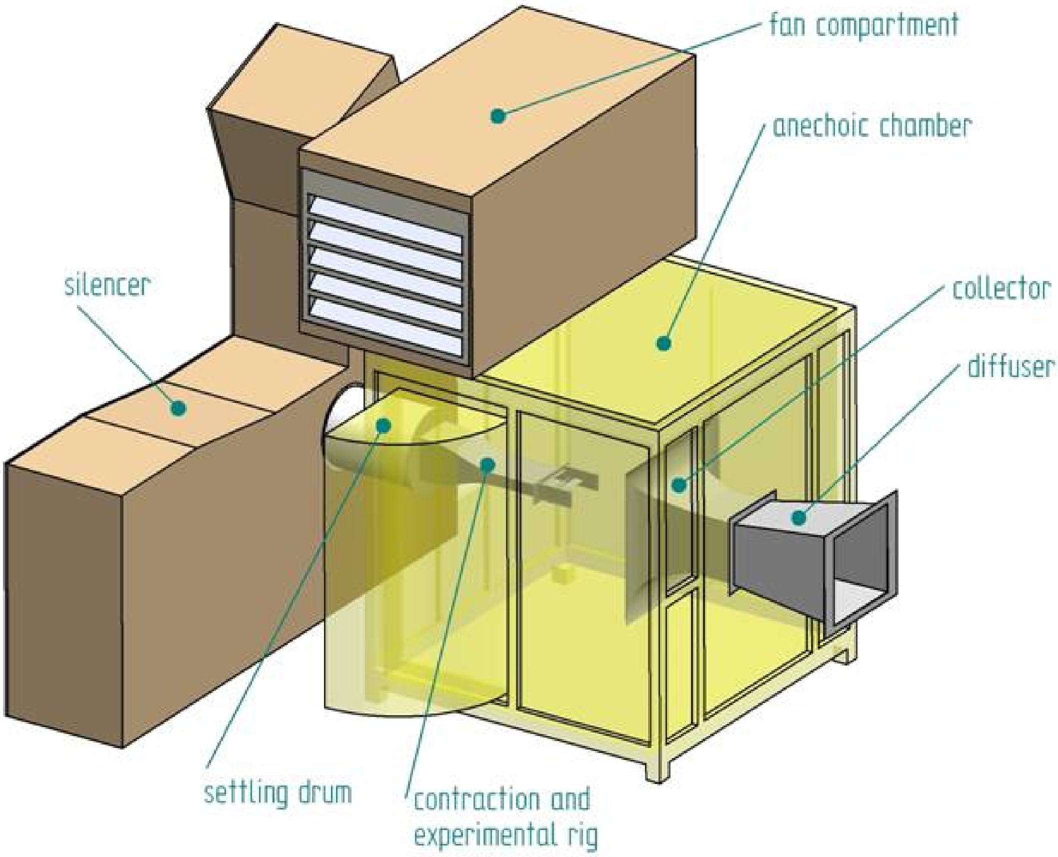

Figure 1 Model of the anechoic wind tunnel as built [4]

2.1. Fan Selection and Acoustic Treatment

The wind tunnel specification called for a test jet of 225 x 75 mm^2 and combined with budgetary and size constraints, resulted in the purchase of a 1.7 kW centrifugal fan capable of delivering a maximum flow rate of 0.85 m^3/s. The maximum static pressure rise of the fan is 2000 Pa, resulting in a maximum test flow velocity of 41 m/s or a Mach number of M = 0.12. The maximum unit Reynolds number is 2.73 x 10^6 /m.

The fan is housed in an acoustic enclosure, consisting of a plywood box, lined with acoustic foam. The enclosure is required to minimise acoustic emission to the laboratory to reduce experimental errors and for health and safety reasons. The air inlet of the enclosure is fitted with louvers, especially designed to minimise noise emission while providing a low pressure drop so as to minimise flow losses of the system, The fan is connected to the silencer via a connecting flange that is designed with a rubber vibration isolation strip and acoustic lining to again minimise noise radiated to the laboratory.

2.2. Silencer Design

The silencer is required to both quieten the test flow and to transport the test air from the fan to the anechoic chamber. The silencer is of MDF wood construction lined with 200mm thick acoustic foam. The foam has been specially cut using a computer controlled hot-wire cutter in order to provide correctly contoured flow paths to minimise aerodynamic losses. Turning vanes are also provided at each corner to also mitigate flow losses. The silencer has an overall length of 8m and an internal cross section of 0.4 x 0.4 m^2, and there are six right angle bends in the air path between the fan and the settling chamber that contains honeycomb and wire screens to straighten the flow and reduce test flow turbulence intensity. The insertion loss will be measured after adequate acoustic treatment is applied to the chamber outlet, but initial results presented below show that the silencer performance is adequate.

2.3. Contraction Design

A new contraction was required, to fit to the existing settling chamber. This requires a contraction ratio of 3.67, which is outside the normal recommendations for contraction design (usually 7-8 is recommended). Therefore, in order to obtain a test flow of high quality, we must ensure that the flow does not separate from the walls of the contraction. Also, the uniformity of the flow at the outlet must be within an acceptable tolerance (a standard deviation of 1% was the specification used for our design study).

A two-step method was developed and used to design the new contraction [2]. First, a potential flow solver was employed to obtain an inviscid solution of the contraction flow field. Then, a thin, laminar boundary layer was assumed to exist on the surface of the contraction and the potential flow solution was used as the boundary condition for the outer surface of the boundary layer. Boundary layer solutions were obtained using Thwaite's method. This technique is simultaneously able to determine if the flow separates and flow uniformity. Reference [2] contains more details of the contraction design method.

Using this method, a suitable two-dimensional contraction was designed using a 5^{th} order polynomial and overall length of 550 mm.

3. BACKGROUND NOISE AND FLOW MEASUREMENTS

3.1. Noise measurements

Background noise measurements were carried out over the entire flow speed range using two B&K Type 4133 microphones in the anechoic chamber. Microphone 1 was located in the exit plane 0.6 m above the jet centreline, and Microphone 2 was located 0.6 m downstream of Microphone 1. Both microphones were fitted with 65mm windscreens. Figure 2 shows that the sound pressure spectra measured at Microphone 1 contain a significant portion of the energy below 200 Hz where the wall sound absorption is poor. This is associated with the formation of large recirculation eddies in the chamber that couple with the free jet, and modifications of the chamber are currently being considered to reduce these recirculation effects. It should also be noted that these measurements were made without the diffuser, and that the chamber outlet was not acoustically treated, which allows external noise to freely propagate through this opening and contribute to the measured background noise. The low frequency tones are the third and sixth harmonics of the three-phase motor driving frequency. Other peaks at higher frequencies, which are also apparent when the flow speed is low, are due to ambient noise entering the anechoic room through the outlet, and the main sources of this type of noise are the cooling fans of nearby computers. This background noise is anticipated to decrease significantly once the diffuser is installed and acoustically treated.

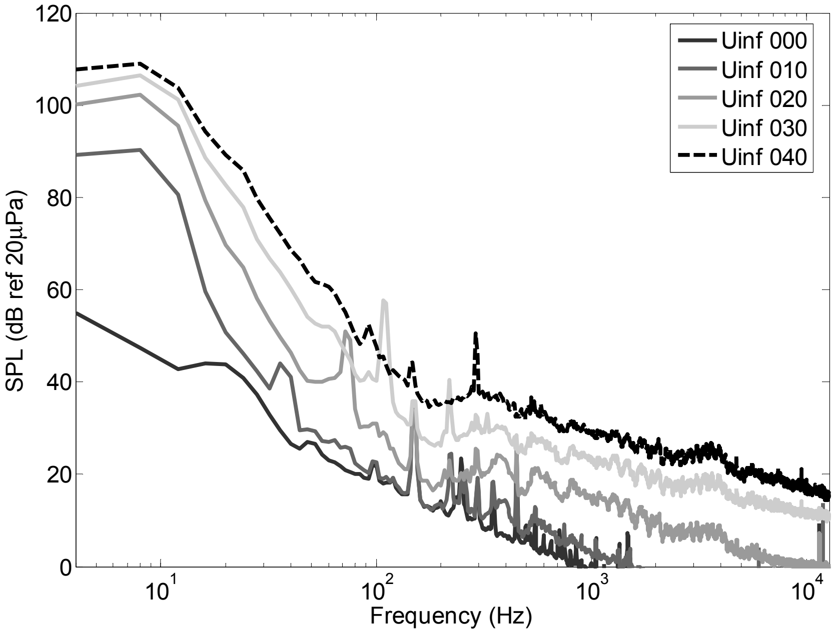

Figure 2 Background noise spectra measured in the anechoic chamber

at various flow speeds ranging from 0 to 40m/s as indicated in the legend.

Using A-weighting to eliminate the very low frequencies significantly reduces the overall levels, as shown in Table 1. Very similar results are obtained in linear levels if the spectra are integrated from 200Hz to 20 kHz.

U_∞ (m/s)	10	15	20	25	30	35	40
Mic.1 dB	93	101	104	107	109	111	112
Mic.1 dB(A)	34	39	44	48	53	55	59
Mic.2 dB	94	102	105	108	110	111	113
Mic.2 dB(A)	40	42	45	51	54	57	60

Table 1 Ambient noise levels (OASPL) in the chamber as a function of U_∞

3.2. Flow characterisation

Preliminary hot wire measurements were carried out to assess the quality of the flow in terms of turbulence intensity. The turbulent intensity measured at the centre of the contraction exit plane increases with free stream velocity up to approximately 15m/s, where it levels off at approximately 0.4%, as reported in Figure 3.

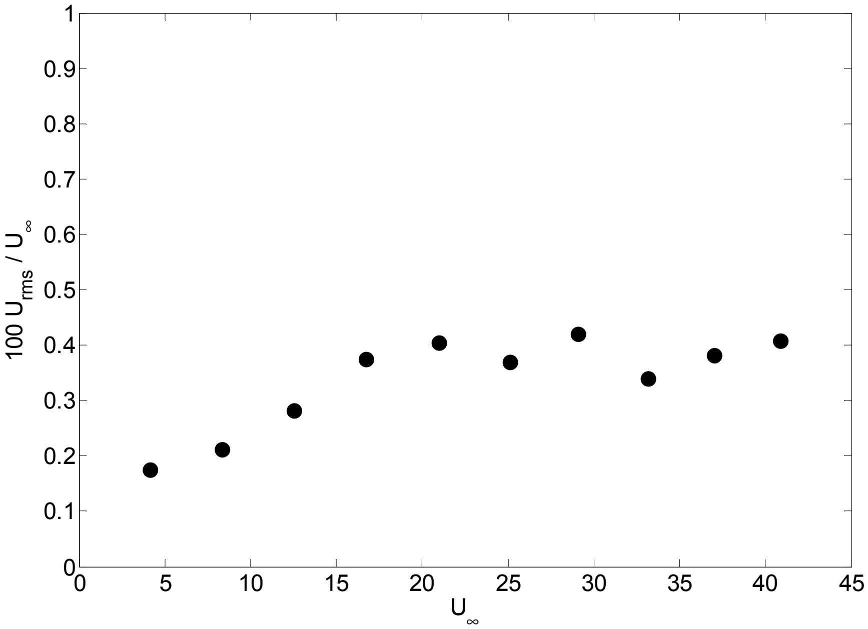

Figure 3 Turbulent intensity at the centre of the contraction exit plane as a function of flow speed.

A velocity profile measured with a Pitot tube along a vertical line in the middle of the contraction exit plane, presented in Figure 4, shows that the flow uniformity is good and the mean speed is within 0.3% of the mean free stream velocity away from the boundary layers. A boundary layer thickness of 6 mm is measured on the top and bottom walls of the contraction.

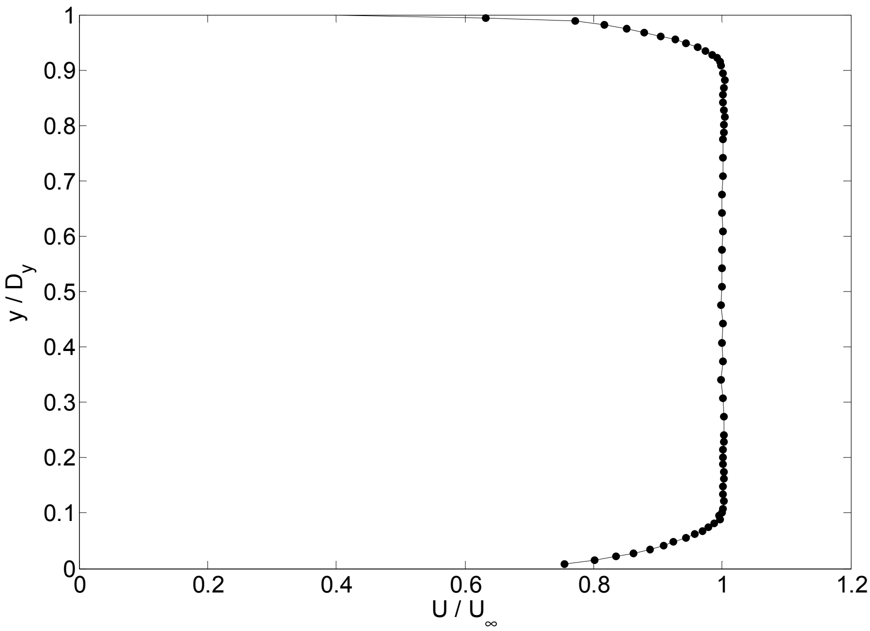

Figure 4 Mean velocity profile measured in the middle of the contraction U_∞=20m/s.

Although further characterisation of the jet flow is still required before definite conclusions can be drawn regarding the quality of the experimental conditions, the presented results are promising and a simple validation experiment was implemented to measure aeolian tones.

4. AEOLIAN TONE FROM A CYLINDER IN A CROSS-FLOW

As part of the wind tunnel commissioning process, a well documented test case was required so that results obtained in this wind tunnel could be compared with theoretical predictions as well as experimental data available in the published literature. A cylindrical rod of circular cross section was placed in the free jet, held in place between two plates extending from the side walls of the contraction. The cylinder span L was therefore equal to the width of the contraction L=275mm, and its diameter D was 8mm. The sound pressure spectra measured at Microphone 1 for 10 m/s ≤ U_∞ ≤ 40 m/s over-impose very well when plotted against the Strouhal number $S_t = fD/U_\infty$, where f is the frequency, and normalised by the sixth power of the free stream velocity that is representative of an aeroacoustic dipole [5]. The normalised data presented in Figure 5 show the presence of a tone that is more than 20 dB above the background noise for all flow speeds except at 10m/s, where the ambient noise in the laboratory affects the background noise in the anechoic room. It is anticipated that this limitation will be alleviated once the acoustic treatment is applied to the chamber outlet collector, and good performance will then be achieved in the low speed range.

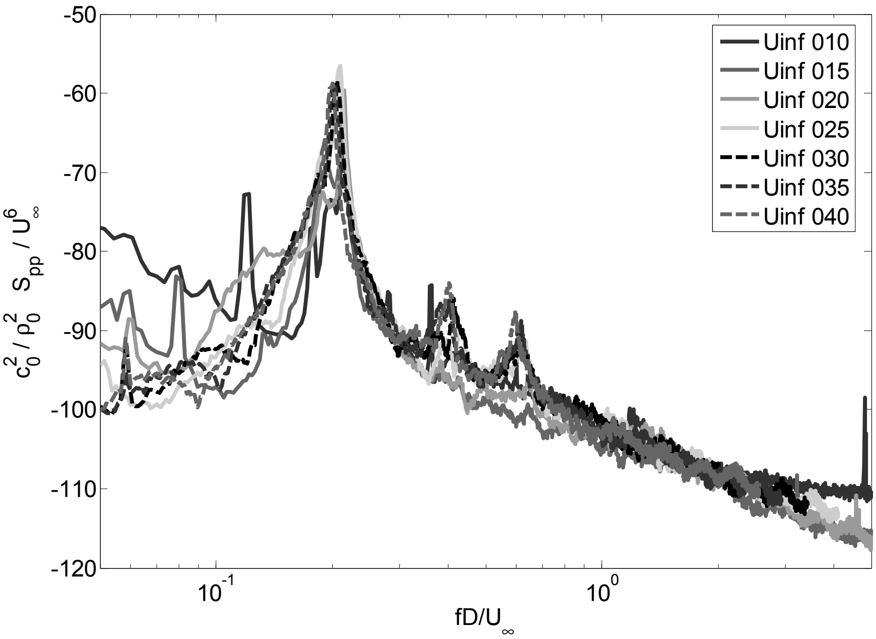

Figure 5 Normalised sound pressure spectra S_{pp} measured at Microphone 1 for various flow speeds. c_0 is the speed of sound, ρ_0 the density of air,

The measured Strouhal numbers, reported in Table 2 along with the Reynolds number for several flow speeds, shows little variation and remains close to the commonly observed value of 0.21 [6].

U_∞ (m/s)	5	10	15	20	25	30	35	40
$R_e .10^3$	2.69	5.38	8.06	10.75	13.44	16.13	18.81	21.50
S_t	-	0.21	0.21	0.21	0.21	0.21	0.20	0.20

Table 2 Reynolds number and shedding Strouhal number as a function of U_∞

Goldstein [7] proposes a predictive model for the sound radiated by a rigid cylindrical structure in a cross-flow. The expression is simplified on the axis that is perpendicular to the flow and the rod:

$$\overline{p^2} = \frac{\sqrt{2}\pi\kappa^2 S_t^2 l_c L \rho_0^2 U_\infty^6}{32 c_0^2 r^2} \tag{1.}$$

where κ is a numerical constant comprised between 0.5 and 2 that accounts for the sensitivity of the flow around the cylinder to the properties of the incoming flow. l_c is the spanwise correlation length scale of the flow field around the cylinder, and r is the distance between the cylinder and the microphone. The results predicted from this equation, using κ=0.5 and l_c=1.5D, are in good agreement with the measured sound pressure level, as illustrated in Figure 6.

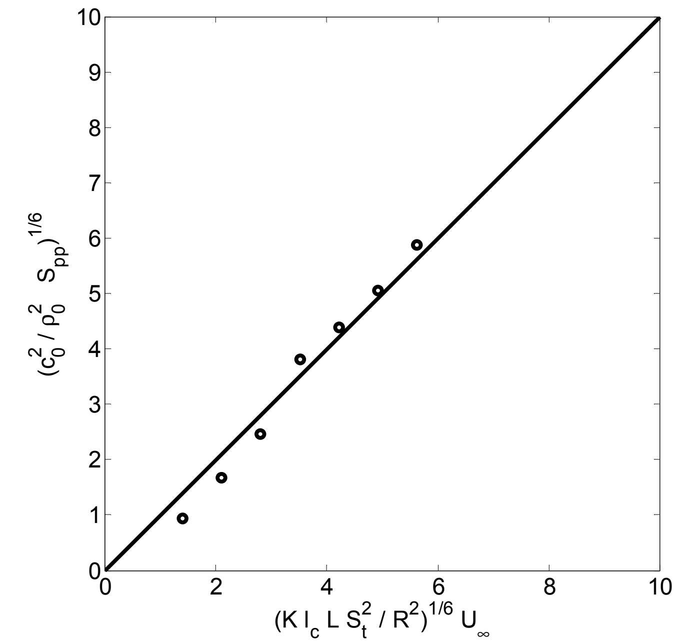

Figure 6 Comparison of the measured sound pressure

with that predicted from Eq.1 using κ=0.5 and l_c=1.5D.

The measurements are in good agreement with the theoretical prediction although it should be noted that two parameters, κ and l_c/D are based on commonly held assumptions regarding the wake structure of cylinders placed in high Reynolds number flows.

5. CONCLUSION

The results presented in this paper show that the performance of a recently upgraded anechoic wind tunnel is satisfactory in terms of acoustics and flow quality. Although further measurements are required to fully qualify this facility upgrade, the results obtained to date give confidence in the research potential of this anechoic wind tunnel, with ample provisions for subsequent upgrades. In the near term, however, the strong perturbations at very low frequencies can be attenuated with minor modifications to the anechoic chamber, such as the insertion of acoustically treated vents in the upstream and downstream wall to minimise the effect of unsteady recirculation entrained by the jet inside the chamber. Once the validation programme is completed and the necessary adjustments are implemented, the anechoic wind tunnel will provide a powerful and flexible platform to support current and future research programmes in aeroacoustics.

6. ACKNOWLEDGEMENTS

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