Hydroacoustic Characterisation of the AMC Cavitation Tunnel

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ABSTRACT

This paper presents recent results from an Industry-University-Defence collaborative project whose aim is to characterise the hydroacoustic environment of the Australian Maritime College Cavitation Tunnel. After summarising the operation of the tunnel, a methodology for measuring and processing the hydroacoustic measurements is presented that includes a technique for reducing the level of turbulent wall pressure fluctuations on the hydrophone measurement. The background noise levels of the tunnel are presented for a variety of operating conditions and they compare favourably with other hydroacoustic test faciltities internationally.

INTRODUCTION

Australia owns and operates a submarine fleet and needs a hydroacoustic design and test capability to support it. Further, it is likely that Australia will be involved in the design, build and sustainment of a new generation of submarines over the coming decades. In order to provide a quiet design, hydrodynamic and hydroacoustic testing are needed in Australia to ensure local designs are quiet and efficient.

As part of the effort to develop an Australian hydroacoustic test facility, Industry (ASC Pty Ltd), academia (Universities of Tasmania and Adelaide) and the Defence Science and Technology Organisation (DSTO) are in the process of characterising the acoustic environment of the Australian Maritime College (AMC) cavitation tunnel, in preparation for future hydroacoustic research and design work.

The aim of this paper is to provide an overview of the acoustic environment of the AMC cavitation tunnel. The paper will describe the acoustic measurement technique, data acquisition and post-processing methods before presenting measured background noise data at various operational conditions. The background noise data are compared with background noise data obtained from other hydroacoustic test facilities.

AMC CAVITATION TUNNEL

Experiments were carried out in the Cavitation Research Laboratory (CRL) variable pressure water (or cavitation) tunnel at the Australian Maritime College (AMC). This facility has been funded under the Australian Government Major National Research Facilities Program as part of the Australian Maritime Hydrodynamics Research Centre (AMHRC). The AMHRC is a joint venture between the Australian Maritime College, the Defence Science and Technology Organisation and the University of Tasmania. The facility has been developed for naval hydrodynamics research with particular emphasis on the modelling of cavitating and turbulent flow physics. The facility's specific capabilities include the ability to strictly control circuit water gas content (both dissolved and free), continuous high-volume injection and separation of incondensable gases, control of the boundary layer on one wall of the test section, and low background noise and vibration levels.

The tunnel test section is 0.6 m square by 2.6 m long in which the operating velocity and pressure ranges are 2 to 12 m/s and 4 to 400 kPa absolute, respectively. The tunnel volume is 365 m^3 with demineralised water (conductivity of order 1 μS/cm).

The tunnel has ancillary systems for rapid degassing and for continuous injection and removal of nuclei and large volumes of incondensable gas. This is important not only to control hydrodynamic phenomena but also for hydroacoustic research. Cavitation is an efficient noise source compared with turbulent flow noise generated by hydrofoils, hulls and propellers. Such fully-wetted noise sources can be considered similar to dipole or quadrupole sources, while cavitation-induced sound is similar to a monopole. As monopoles are more efficient acoustic radiators than their higher-order cousins, accurate control of cavitation inception is necessary for hydroacoustic measurements.

There are a number of potential noise sources that can degrade the signal-to-noise ratio of a desired experiment in the cavitation tunnel. These include the turbulent wall boundary layer, the main drive and pump, pressure system and ground-borne vibration. Apart from the turbulent wall boundary layer, these noise sources are most effectively controlled at the design stage. The cavitation tunnel was designed to minimise noise from these sources as much as practically possible at the time of construction. The cavitation tunnel design and specification is described in detail in Brandner et al. (2007). Only the design aspects relating to noise and vibration control are summarised in the present paper.

The siting of the tunnel on the AMC campus was not considered to be vulnerable to external noise sources such as loud machinery and therefore no special measures were taken to insulate the external building walls. However, the tunnel was designed as completely free standing with no connections to the enclosing building, including semi-compliant isolation between tunnel foundations and building concrete slabs and foundations. All ancillary machinery and pipework are isolated by rubber connections. Additionally, all continuously operating machinery such as air compressors, vacuum pumps and the main pump drive are located in an acoustic enclosure. The main pump drive train employs double compliant couplings between the gearbox and external main pump bearing for both improved drive dynamics and noise and vibration isolation.

Minimisation of flow noise has been addressed through careful design of bends and diffusers and by the need for a large tunnel volume that reduces circuit velocities. The flow conditioning devices throughout the circuit for bubble separation and promotion of dissolution also provide damping of noise transmission. The main pump is potentially one of the greatest sources of noise, and the new tunnel structure has been designed to facilitate its replacement with a larger diameter machine, if needed, in the future.

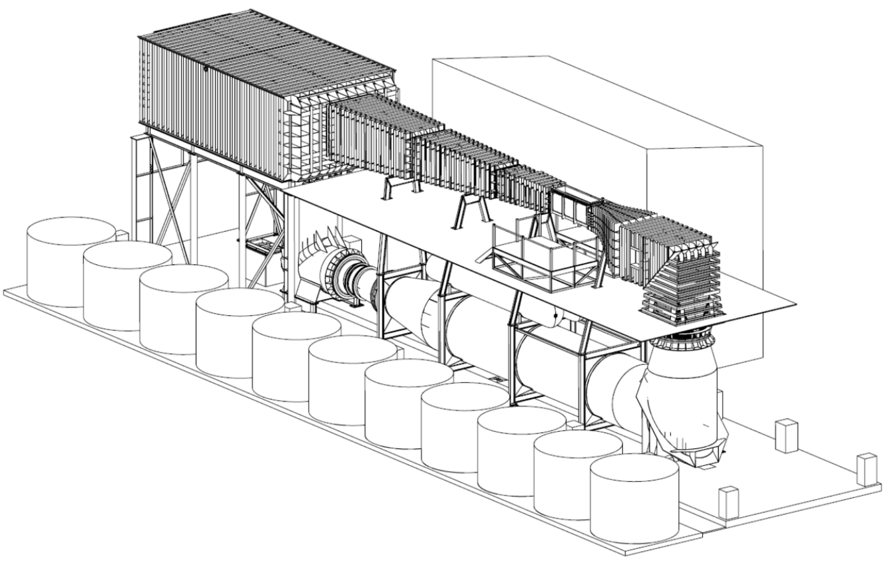


Figure 1. General arrangement of the cavitation tunnel. The test section is at the top.

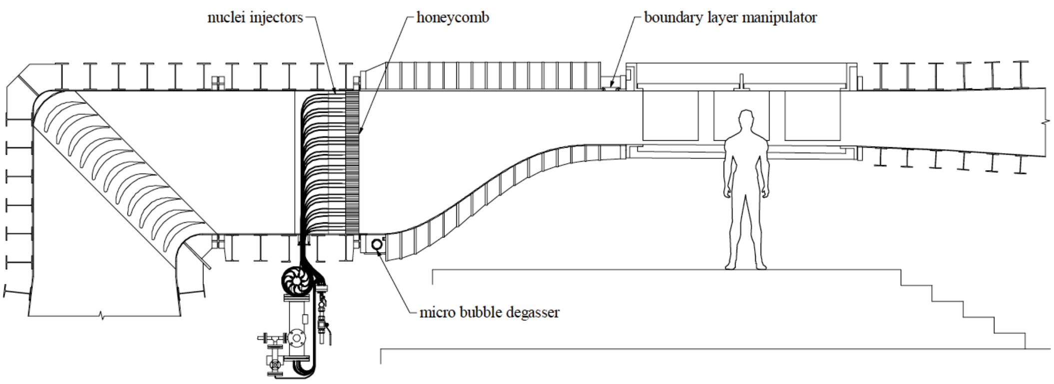


Figure 2. Vertical section of the contraction and test section.

Figure 1 provides an overview of the facility, with the test section where models are mounted and tested at the top. Figure 2 shows a vertical section through the contraction and test section. It gives an idea of the scale of the test section by comparing it with the size of an average human. Figure 2 also shows the locations of the degasser and nuclei injectors to control cavitation inception during testing. Finally, Fig. 2 shows the location of a boundary layer manipulator that allows independent control of the tunnel wall boundary layer thickness, which is necessary for understanding the interaction of turbulent boundary layers with hydrofoils and other underwater-vehicle components.

ACOUSTIC MEASUREMENT METHODOLOGY

Hydrophone mount

As previously mentioned, the pressure fluctuations from a turbulent boundary layer can be large and must be considered when taking acoustic measurements in a water tunnel. If a small transducer or sensing area is used, the turbulent signal will have high amplitude, most likely of the same order as the desired acoustic signal. However, increasing the size of the sensing element will act as a spatial filter and reduce the hydrophone's response to turbulent wall pressure fluctuations, while keeping its response to acoustic disturbances relatively unchanged (Corcos, 1963).

Using the theory of Corcos (1963), a hydrophone mount was designed to reject pressure disturbances from the turbulent boundary layer by providing a larger sensing area than is available on a hydrophone. Figure 3 provides an overview of the design. A Brüel and Kjaer 8103 hydrophone was mounted in a flooded cavity (kept at the same pressure as the tunnel test conditions) beneath a 10 mm polyurethane diaphragm, with a 149 mm sensing diameter.

Polyurethane was chosen for the diaphragm material, as its acoustic impedance is nearly the same as water, thus providing a near reflection-free acoustic interface. Figure 4 illustrates the ability of the hydrophone mount to attenuate turbulent wall pressure fluctuations. Here, the turbulent wall pressure power spectrum (Φ) for the cavitation tunnel was modelled using the empirical relationship developed by Goody (2004). Brandner et al. (2012) performed a comprehensive study of the cavitation tunnel wall boundary layers, and these data were used to predict the wall pressure spectrum in Fig. 4. Specifically, properties for a boundary layer measured 0.7 m downstream of the test section entrance were used. In this case, the free stream velocity was 10 m/s and the Reynolds number based on momentum thickness was Re_θ = 20,625. The effect of spatial averaging on the signal was determined using the theory of Corcos (1963).

As shown in Fig. 4, the large sensing area of the diaphragm provides good attenuation of the turbulent boundary layer pressure signal. The acoustic wavelength should be smaller than the diaphragm diameter above ~10 kHz. At these frequencies, the signal-to-noise ratio should not be significantly affected as the turbulent boundary layer pressure fluctuations will be at low levels. Other measurements using a similarly designed system (Barker, 1976) show that high frequency noise in cavitation tunnels is not related to the boundary layer over the transducer, rather it is due to overall facility noise.

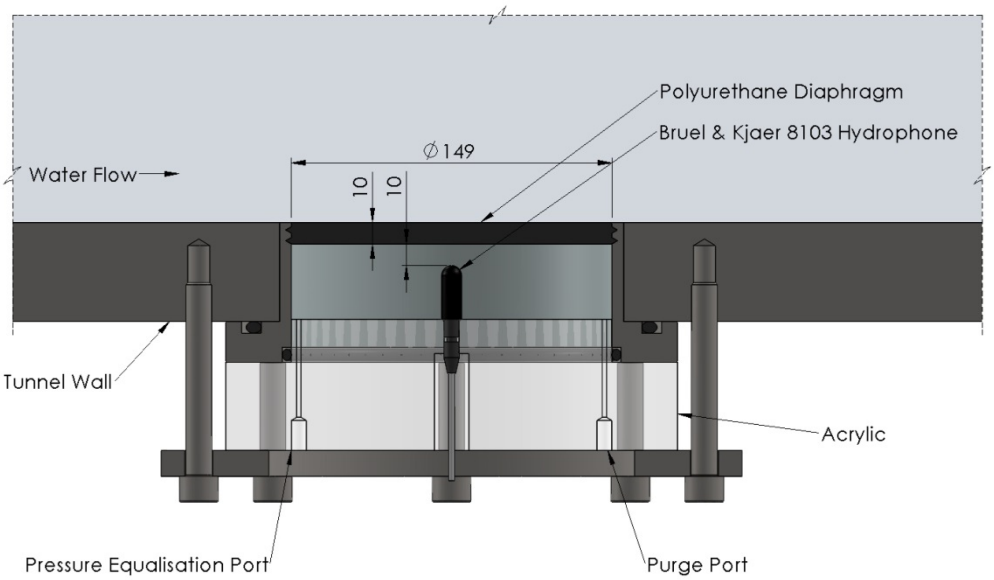


Figure 3. Hydrophone mount design (dimensions in mm).

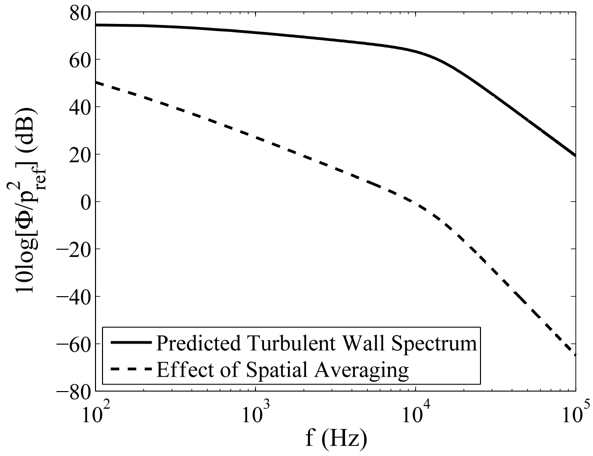


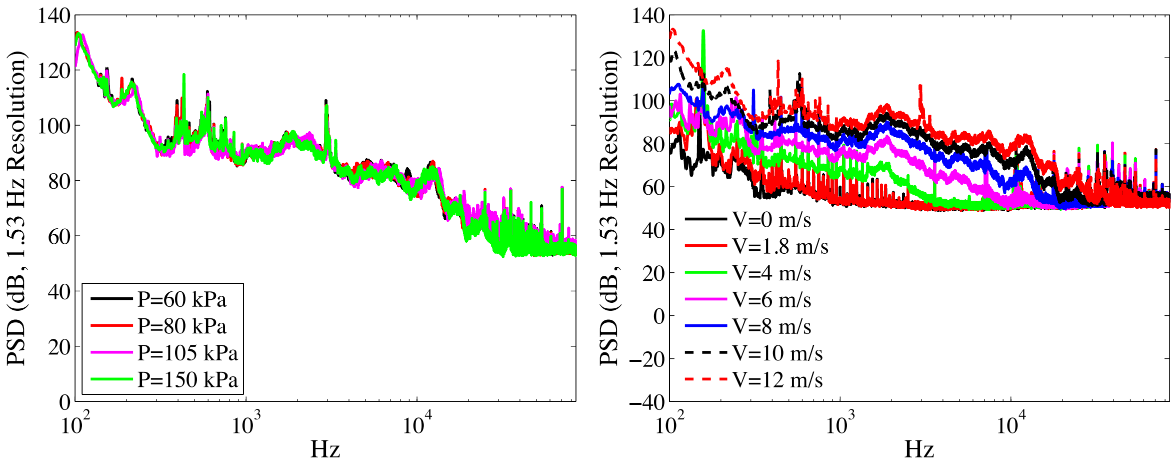
Figure 4. The effect of spatial averaging on the turbulent boundary layer power spectrum for a wall boundary layer characterised by Brandner et al. (2012) at 10 m/s and the dimensions of the mounting system used in this study.

Signal acquisition and Processing

Noise measurements were made for a range of the tunnel principal operating parameters, that is, the velocity and pressure. In all cases the water dissolved oxygen content and temperature were recorded. The dissolved gas content is a basic parameter in experimental modelling of cavitation and gas/liquid two-phase flows. The temperature is used to derive the fluid properties and hence the basic scaling parameters such as the Reynolds, cavitation and Weber numbers. Details of tunnel instrumentation are provided in Brandner and Pearce (2012) and Pearce and Brandner (2012).

All measurements were made using a B&K 8103 miniature hydrophone mounted in the holder described above. The holder was in-turn mounted in a 46 mm thick stainless steel 'window' on the bottom of the test section centred 0.7 m from the test section entrance. The hydrophone was conditioned using a B&K 2692 charge amplifier setup with 0.1 Hz and 100 kHz low and high pass filters, respectively. For each measurement 2^{23} data points (approximately 42 seconds) were recorded at 200 kHz acquisition rate using a National Instruments PXI 4492 (24 bit) card using LabView software. The supplier-quoted frequency-dependent voltage sensitivity calibration was used to correct the receiver hydrophone response.

The data were post-processed using Matlab. The time-domain signals were digitally bandpass-filtered between 100 Hz and 90 kHz using a fourth-order bandpass Butterworth filter. Power spectral densities were estimated from each time-series via Matlab's one-sided periodogram command (pwelch) with a Hanning window of one-sixteenth the total data length specified. A reference pressure of 1 μPa was assummed when expressing amplitudes in decibels.



(a) V = 12 m/s, various pressures (b) P = 150 kPa, various velocities

Figure 5. Background noise measurements, clean tunnel spectra.

RESULTS

Clean tunnel, or background noise spectra are shown in Fig. 5. In Fig. 5(a), clean tunnel measurements are shown for various tunnel operating pressures at a test section velocity of V = 12 m/s. As shown, the background measurements are insensitive to pressure. Frechou et al. (2001) noted that for the French cavitation tunnel (GTH) for sufficiently low dissolved gas content the background noise level is mainly a function of velocity. They also state that for noise and cavitation testing the tunnel water is degassed to a dissolved air content of 0.7 mg/ℓ (corresponding to about 30% of saturation at atmospheric pressure). For the present work the tunnel water was degassed to similar dissolved gas content. In this case the dissolved gas content is based on a dissolved Oxygen measurement which was maintained at about 3 ppm corresponding to 30% of saturation at atmospheric pressure.

In Fig. 5(b), measurements are shown for a clean tunnel at constant pressure (P = 150 kPa) and velocities that range from V = 0 m/s to V = 12 m/s. The background noise level increases with flow speed due to the extraneous noise sources associated with the tunnel operation. For low-mid velocities, the minimum resolved high frequency amplitudes appear to be limited by the hydrophone noise-floor. The spectra are broadband, with numerous tones due to electrical and machinery sources observed. The especially high amplitude tone at approximately 160 Hz in the 4 m/s case is attributed to excitation of a pump resonance at this flow speed.

Figure 6 shows the overall sound pressure levels (OASPL), calculated by integrating the narrowband power spectral densities over 200 – 100,000 Hz (to avoid the tone at 160 Hz), against the logarithm (base 10) of the tunnel free stream velocity. OASPL increases with tunnel velocity.

Velocity scaling can be used to understand the nature of the underlying background noise sources. If the OASPL can be described by a power law of the form

$$\text{OASPL} \approx 10n\log_{10}V + C \tag{1}$$

then the nature of the dominant multipole source can be characterised by the value of *n,* which may equal 4,6 or 8; these values correspond to monopole, dipole and quadrupole sources, respectively. It was found that for velocities 8 m/s and higher, the levels approached a power law scaling with $n = 8$ in Equation (1) (C = 50 dB), indicating that quadrupole sources are possibly dominant at higher flow speeds. Quadrupole sources are associated with turbulence, thus the major background noise is likely associated with boundary layer noise throughout the facility, rather than cavitation (monopole) or vortex shedding (dipole); however, a more sophisticated analysis is necessary over different frequency bands to make a more definite conclusion. Power law scaling was not observed for lower flow speeds, thus a mixture of mechanical and flow-induced noise sources may dominate below 8 m/s.

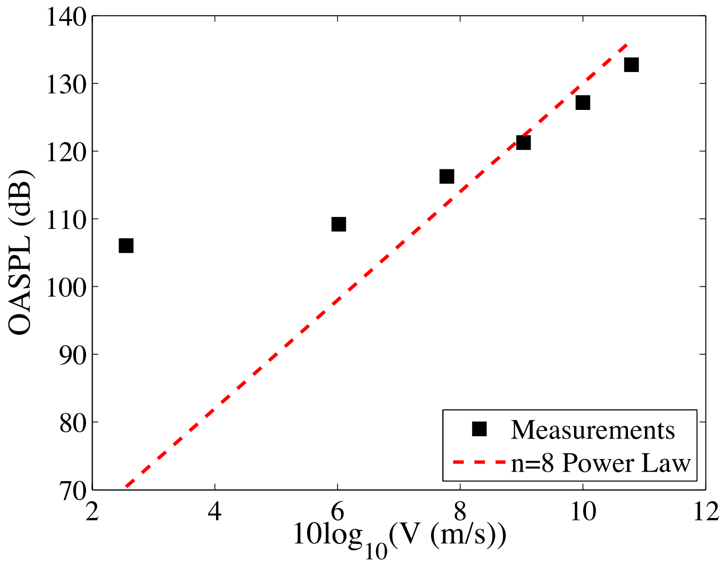
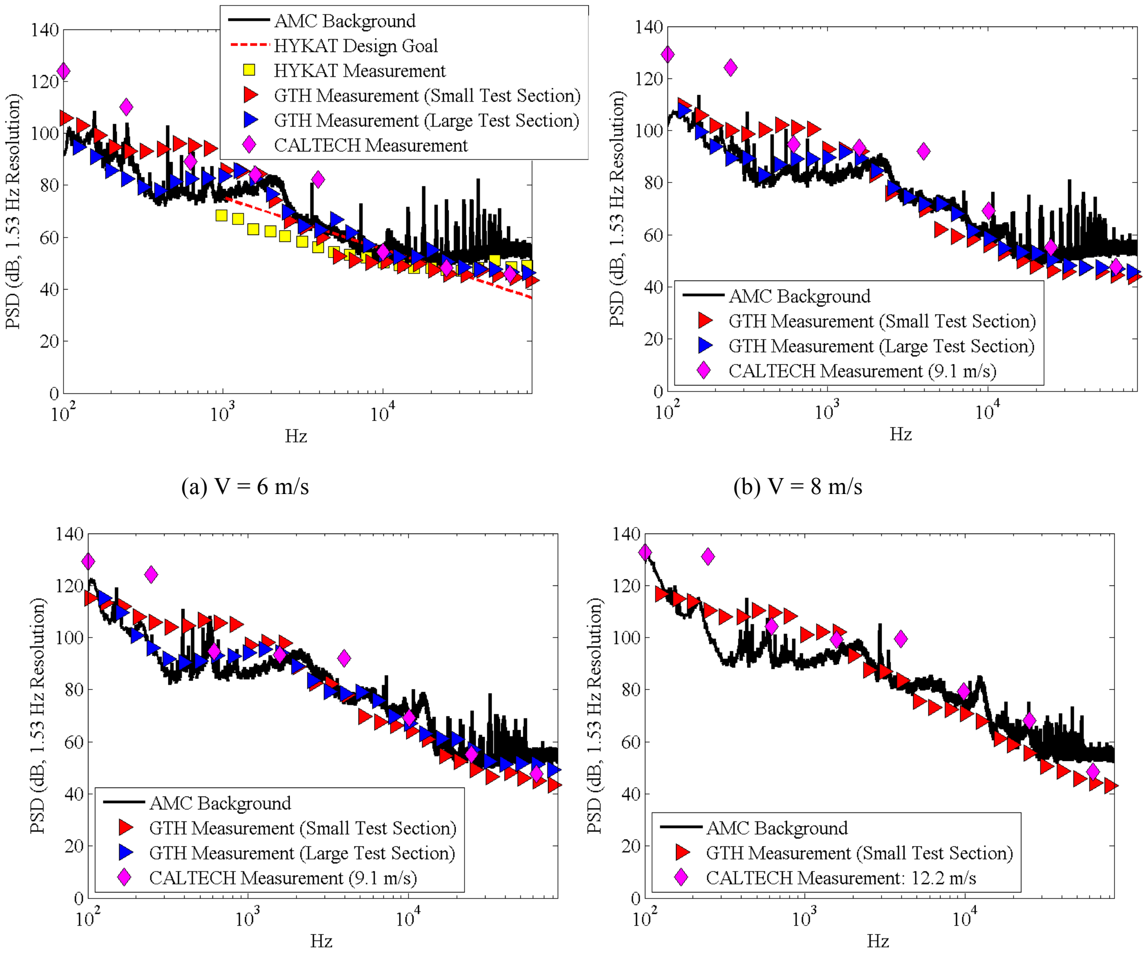


Figure 6. OASPL measurements at P = 150 kPa.



(a) V = 6 m/s

(b) V = 8 m/s

(c) V = 10 m/s

(d) V = 12 m/s

Figure 7. Comparison of clean tunnel background levels with other hydroacoustic facilities.

Figure 7 compares AMC cavitation tunnel background noise spectra (P = 105 kPa) against measurements from other hydroacoustic facilities (P = 1 atm) at V = 6-12 m/s. These facilities are the German HYKAT facility (Lydorf and Pollman, 1991); the French GTH facility (Frechou et al., 2001) and a research facility at CALTECH (Barker, 1976).

Each facility uses a different technique to measure background noise. In the HYKAT, a separate anechoic chamber is used beneath the test section. The anechoic chamber is separated from the main flow using near-acoustically-transparent plexiglass windows. An acoustic mirror and hydrophone array are used in the anechoic chamber to take measurements. Lydorf and Pollman (1991) also provide the acoustic design goal of HYKAT at V = 6 m/s and this is compared in Fig. 7(a) with the experimental data.

In the GTH facility, a hydrophone was placed in a polyurethane plug that was flush-mounted with the wall of the tunnel test section. The larger diameter of the plug provides a spatial filtering effect (as previously described). Also, the thickness of the polyurethane between the hydrophone and the wall acts to damp wall pressure fluctuations as well (Boissinot et al., 1991).

In the CALTECH facility, a similar measurement system to the present paper was used. In this case, a thin, 37.5 mm (1.5 in.) diameter polyurethane diaphragm was used over a flooded cavity that contained the hydrophone. This assembly was placed in the wall of the test section, similar to the AMC tunnel. Note that the diaphragm diameter is much smaller than the present AMC tunnel set up. The AMC diameter was chosen to fit the existing ports. The main effects of using a larger diameter are the ability to better resolve lower frequency noise components, compensation for the larger boundary layer thicknesses of the AMC facility and a lower frequency where acoustic waves are at the same size as the diaphragm (as mentioned earlier).

The information presented in Fig. 7 shows that the background noise levels in the AMC tunnel are comparable to those of other facilities. For example, At 6 m/s (Fig. 7 (a)), for which data exist for all facilities, the AMC data are seen to be comparable to the HYKAT design goal, HYKAT measurements, CALTECH measurements and GTH facility measurements.

CONCLUSIONS AND FUTURE WORK

A methodology was developed to measure noise in the AMC cavitation tunnel. The main conclusions of this paper are:

1. Spatial filtering using a large polyurethane diaphragm can be employed to reject turbulent wall pressure fluctuations and improve the chances of measuring the acoustic signals generated within a cavitation tunnel test section.
2. Background noise levels are insensitive to operating pressure.
3. Background noise levels rise with test section flow velocity. Velocity scaling shows that for 8 m/s and above, the background noise OASPL scales approximately with the eighth power of velocity. This suggests that turbulent flow noise dominates the background noise levels at these velocities.
4. The background noise levels compare reasonably well with other hydroacoustic test facilities.

The acoustic characterisation project is on-going and the results presented in this paper are only the initial steps in this work. The next major phase of the project is to better understand the reverberant field inside the test section and how this relates to a true acoustic free-field.

ACKNOWLEDGMENTS

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