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Noise From Sub-Boundary Layer Steps

C. J. Doolan[1], D. J. Moreau[1], P. A. Brandner[2], B. W. Pearce[2] and K. L. de Graaf[2]

[1]School of Mechanical Engineering
University of Adelaide, Adelaide, South Australia 5005, Australia

[2]Australian Maritime College
University of Tasmania, Tasmanina 7250, Australia

Abstract

Flow-induced noise data has been obtained under a wide range of conditions for a forward-backward sub-boundary layer step-pair, using both hydroacoustic and aeroacoustic experimental facilities. The unscaled noise data show that sound generation behaves similarly in air and water. A non-dimensional analysis was used to develop scaling laws of the noise generation process. Appropriate scaling shows the results from each facility collapse when the wavelength of sound is approximately lower than the dimensions of the hydroacoustic facility test section. Noise was found to radiate in both cross-stream and streamwise directions, thus suggesting that a new noise generation model is required for these types of steps. Noise scaled with velocity raised to a power of seven, in agreement with previous forward facing sub-boundary layer step experiments.

Introduction

Submarines and other marine vessels often have small obstacles (with height $h < \delta$, the boundary layer height) on their surface that can create unwanted sound. These *sub-boundary layer* obstacles interact with the complex turbulent flow within the boundary layer to create sound [8]. Many previous experimental studies [4, 9, 13] of sub-boundary layer obstacles have been performed in air because of the difficult nature of taking hydroacoustic measurements. Numerical investigation shows that the obstacle behaves acoustically as a streamwise dipole [10]; however, this behaviour is contained to cases when the obstacle is acoustically compact and thus depends on the Mach number of the flow [7]. The Mach number of experiments performed in air is larger than in water, which affects the way the sound is generated by the step and its directivity pattern [7]. It is therefore important to understand how sub-boundary layer obstacles create sound in both air and water in order to properly relate the results obtained in aeroacoustic test facilities to marine applications.

This paper compares the flow-induced noise created by sub-boundary layer steps (more precisely, a forward-backward step-pair) obtained in aeroacoustic and hydroacoustic test facilities. This type of sub-boundary layer step has not been reported in the literature, despite its significance to practical situations. The objective of this paper is to compare flow-induced noise data from two very different facilities, shed new light upon the nature of sub-boundary layer step noise generation and to illustrate the feasibility of using aeroacoustic and hydroacoustic test facilities in tandem to study a non-cavitating flow-induced noise problem.

Methodology

Test Case

An illustration of the sub-boundary layer step test case is shown in figure 1. The step has height h and length l and is situated on a solid wall immersed in a zero pressure gradient turbulent boundary layer that has a height δ at the location of the step if it were not present. The free stream flow above the boundary layer has a velocity U_∞. Noise created by the step is recorded at an observer at distance r and angle θ from the origin, as shown in figure 1.

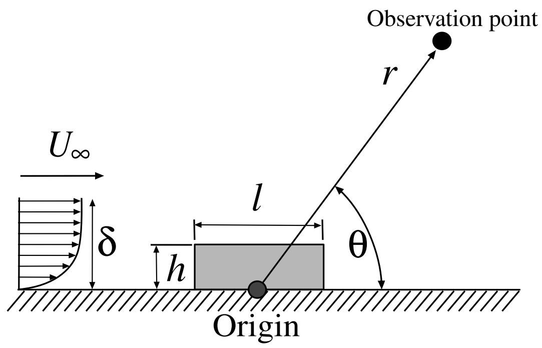

Figure 1: Illustration of the sub-boundary layer forward-backward step-pair test case (not to scale).

AMC Cavitation Tunnel

Hydroacoustic experiments were carried out in the Cavitation Research Laboratory (CRL) variable pressure water (or cavitation) tunnel at the Australian Maritime College (AMC) [3]. 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).

Recently, a hydroacoustic test capability was added to the cavitation tunnel [5]. 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. 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 thick polyurethane diaphragm, with a 149 mm sensing diameter. Such a design was shown to provide excellent attenuation of near-field turbulent pressure fluctuations from the tunnel wall boundary layer [5]. The hydrophone was mounted with $r = 600$ mm and $\theta = 90^\circ$ from the step. 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.

Three different step elements were tested by placing them on the ceiling of the tunnel, 0.7 m along the length of the test section.

The dimensions of the steps were: $l/h = [2.5, 4, 8]$ and $h/\delta = [0.25, 0.5, 0.8]$ where h is the step height, $\delta = 20$ mm is the nominal undisturbed boundary layer height (see Ref. [2]) at the step and $l = 40$ mm is the step length. The wetted span of the step was the width of the test section, 600 mm. Tests were conducted over a range of velocities $U_\infty = [3.8, 5.7, 7.6, 9.5, 11.4]$ m/s, corresponding to a Reynolds number range based on h of $Re_h = 10,000 - 96,000$. The Mach numbers of the tests were very small and varied over the range $M = 0.0025 - 0.0076$.

Anechoic Wind Tunnel

The aeroacoustic results have been previously presented in Ref. [13]. Experiments were conducted in air using an open-jet anechoic wind tunnel [11, 12]. A 275 mm × 75 mm nozzle produces a free-jet inside an anechoic room (internal dimensions 1.4 m × 1.4 m × 1.6 m) that provides a near reflection-free environment above 250 Hz. Three different step elements [13] were used: $l/h = [2.7, 4, 8]$ and $h/\delta = [0.26, 0.5, 0.8]$, $\delta = 9.61$ mm and $l = 20$ mm. The wetted span of the step was 75 mm. Each step was placed on a smooth, flat plate attached to the side wall of the exit nozzle, 30 mm downstream of the exit plane. All tests were conducted at $U_\infty = 35$ m/s ($M = 0.1$), and $Re_h = [5794, 11589, 17383]$.

Acoustic measurements were recorded at two locations using two B&K 1/2" microphones (No. 4190). The first microphone was located at an observer angle of $\theta = 93.3°$ to the step with $r = 520$ mm, while the second microphone was located at an angle of $\theta = 46.7°$ to the step with $r = 714.5$ mm. Data were recorded using a National Instruments board at a sampling frequency of 5×10^4 Hz for a sample time of 8 s.

Test Case Comparison

While the geometric parameters (l/h, h/δ) of the hydroacoustic and aeroacoustic experiments are similar, there are differences in Reynolds number and Mach number. The Reynolds numbers in each case are of the same order, thus it is assumed the flow scales (relative to step height) in each of the experiments are approximately the same.

The major differences between each test case is the Mach number; based on the data acquisition parameters, the hydroacoustic experiments can resolve sound over an approximate non-dimensionalised wavenumber range of $kh = 2 \times 10^{-4} - 6.7$ and the aeroacoustic experiments $kh = 0.01 - 3$, where $k = \omega/c$, ω is the rotational frequency in rad/s and c the speed of sound in each medium. Thus, the recorded wavelength of sound relative to step height is broadly similar in each facility, with the hydroacoustic facility able to record data over a wider relative range. This is because of the higher speed of sound in water and the ability of the hydrophone to resolve sound to 100 kHz, while the microphone is limited to 20 kHz. However, as will be discussed below, there are significant differences in signal-to-noise ratio in each facility, which also affects the ability to resolve flow-induced sound across wide wavenumbers.

Scaling

Dimensional analysis is used to obtain a suitable scaling law to interpret the results, following the work of Ref. [14]. The acoustic pressure can be written as a function (denoted as $\mathcal{F}(.)$) of a number of non-dimensional variables

$$p' = p_0 \mathcal{F}(r/\mathcal{L}, \theta, kh, M, Re_h) \qquad (1)$$

where $\mathcal{L}$ is a characteristic length scale of the flow and $p_0 = \rho U_\infty^2$. Converting to a power spectral density (S with units of

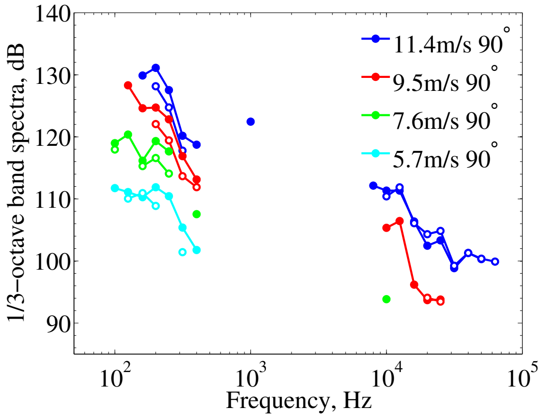

Figure 2: Unscaled hydroacoustic data from the AMC cavitation tunnel. Data collected in water and converted to 1/3 octave bands with reference pressure of 1 μPa. Solid markers represent steps with $l/h = 2.5$ and open markers represent steps with $l/h = 4$.

pressure^2/Hz) and explicitly stating the known $1/r$ dependency of acoustic pressure

$$S = \frac{p_0^2 \mathcal{L}^3}{U_\infty r^2} \mathcal{F}(\theta, kh, M) \qquad (2)$$

The Reynolds number dependancy has been dropped based on the discussion presented in the previous section. Next it is assumed that the spectral density has a power-law dependency with Mach number. Also, the power spectral density is converted to a mean square acoustic pressure (Φ) by integrating over a fixed frequency band. Dimensionally, $\mathcal{L}/U_\infty$ is equivalent to Hz, hence the functional relationship approximates

$$\Phi = \frac{p_0^2 \mathcal{L}^2}{r^2} M^n \mathcal{F}(kh) \mathcal{F}(\theta) \qquad (3)$$

The dependence on θ is assumed independent of wavenumber. Therefore, the data is expected to collapse if presented in the following non-dimensional form

$$kh \quad \text{vs.} \quad \frac{\Phi r^2}{p_0^2 M^n \mathcal{L}^2} \qquad (4)$$

The Mach number exponent (n) for sub-boundary layer steps can be determined directly from the data. It is assumed that the length scale $\mathcal{L} = \sqrt{hL}$, where L is the wetted span of the step.

Results

Unscaled hydroacoustic data obtained in the AMC cavitation tunnel are presented in figure 2. Here the results are presented in 1/3 octave bands normalised by a reference pressure of 1 μPa. One-third-octave band spectra were calculated using a filter bank from the time-series data. Only data that were 2 dB or more above the background level (measured when the step was absent and at the same speed) are shown. There was only sufficient signal-to-noise to resolve step noise at low frequencies (< 400 Hz) and at high frequencies (> 10,000 Hz). Solid markers represent steps with $l/h = 2.5$ while open markers represent steps with $l/h = 4$. An acoustic signal was not detected when $l/h = 8$.

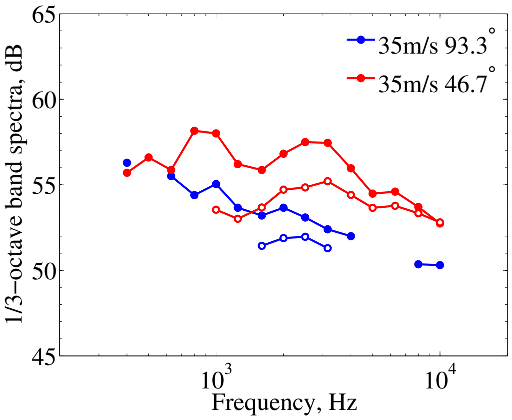

Figure 3: Unscaled aeroacoustic data from the University of Adelaide anechoic wind tunnel. Data collected in air and converted to 1/3 octave bands with reference pressure of $20\,\mu$Pa. Solid markers represent steps with $l/h = 2.7$ and open markers represent steps with $l/h = 4$.

The data in figure 2 show that measured noise generally increases with flow speed and to a lesser extent, with step height. The noise increase occurs across all frequencies that had sufficient signal strength to be recorded.

Unscaled aeroacoustic data obtained in the University of Adelaide anechoic wind tunnel are shown in figure 3. Again, data that were 2 dB or more above the equivalent background measurement are shown. The signal-to-noise ratio for these measurements are higher than that of the cavitation tunnel, yet are more restrictive in terms of wavenumber. As the data were recorded in air, they are presented in 1/3 octave bands normalised by a reference pressure of $20\,\mu$Pa. Solid markers represent steps with $l/h = 2.7$ while open markers represent steps with $l/h = 4$. Similarly to the hydroacoustic tests, the signal recorded for $l/h = 8$ was less than 2 dB from the equivalent background measurement and was therefore not used in this study.

The aeroacoustic data show similar trends to those obtained in the cavitation tunnel; more noise is created when larger steps are used. As previously reported in Ref. [13], the noise increases relatively uniformly across all frequencies. Higher noise levels were observed when the microphone was placed at $\theta = 46.7°$, indicating non-uniform directivity.

Data from all tests were scaled according to equation 4 and are shown in figure 4. When $n = 3$, giving on overall velocity dependence of U_∞^7, there is a good collapse of data taken at $\theta \approx 90°$ when $kh > 0.027$. This is a remarkable result, given that the data were taken in two very different facilities and in two different media. It shows, quite conclusively, that aeroacoustic and hydroacoustic facilities can be used together to obtain a complete data set on a complex problem. It also shows the suitability of studying flow-induced noise problems in both kinds of facilities. Note that the reference pressures for air and water are not used when scaling the acoustic data.

Data at low wavenumbers in the cavitation tunnel ($kh < 0.027$) do not collapse as well. The scaling at low wavenumber does not improve when a different exponent (n) is used or if different length scales are used to non-dimensionalise the wavenumber (such as δ and l). At these frequencies, the wavelength of sound $\lambda >> h$; moreover, the wavelength is larger than the cavitation tunnel test section, thus the acoustic environment is a complex, reverberant near-field containing progressive and evanescent waves and is unlikely to scale according to laws based on free-field acoustics.

The data at $\theta = 46.7°$ from the anechoic wind tunnel collapse well with each other (figure 4) but are offset from the data obtained in both facilities at $\theta \approx 90°$. This is to be expected, given the dependance on radiation angle that was determined via dimensional analysis ($\mathcal{F}(\theta)$ in equation 3). This function will depend upon how sound is created by the boundary layer-step interaction process.

The results obtained in both facilities are in broad agreement with previous studies. Refs. [1, 4, 6] measured broadband noise for forward facing steps and gaps. They show that noise measured directly above forward facing steps increases relatively evenly across all frequencies with the level having a strong dependence on h/δ. However, these forward-facing step studies show almost uniform noise directivity, while the results shown in this paper for the forward-backward step-pair case show increased directivity, even when scaled. Ref. [6] show that the level scales approximately with U_∞^7, similar to what has been measured in this study.

The confirmation that sound is radiated normal to the flow direction in air and water is important and helps understand the true flow induced noise mechanisms. Further, computational studies that assume the step radiates as an acoustically compact source [10] predict a strong streamwise dipole and no radiation in the cross-stream direction. This is in contrast to previous forward facing step experiments that show uniform directivity [1, 4, 6]; however, this study shows sound radiation in both streamwise and cross-stream directions. It might be expected (as shown in Ref. [4]) that diffraction effects from the sharp edges of the step will affect directivity and distort the sound field (shown computationally by [7]). However, the results shown in this paper show good collapse to very low wavenumbers, well below the diffraction limit for the steps used in this study. Therefore, it is concluded that the streamwise dipole radiation model is not sufficient for this kind of sub-boundary layer step and a new model is required.

It is speculated that this kind of step (a forward-backward step-pair) radiates as a complex dipole with both lift and drag components of the unsteady hydrodynamic force controlling its strength. This model allows radiation in both streamwise and cross-stream directions at low and high wavenumbers. Diffraction at high wavenumber will also alter the directivity pattern and level. Such non-uniform directivity was observed in the aeroacoustic test data at $\theta = 46.7°$. Higher levels were observed, most likely due to higher unsteady pressures on the vertical faces as well as the diffraction of the acoustic waves when their wavelengths are small.

This model is only preliminary at present and needs further theoretical, experimental and numerical study to confirm its applicability.

Conclusions

This paper presents what is possibly the first comparison of flow-induced noise data for a sub-boundary layer step in both aeroacoustic and hydroacoustic facilities. This study is also unique because it presents the results for a forward-backward step-pair, a test case that is practical, yet has not had much attention paid to it in the literature.

The results, while preliminary, show that quality noise data can be obtained in air and water. Scaling laws based on a dimensional analysis allow the data from each facility to be compared and understood. The results show, in agreement with prior for-

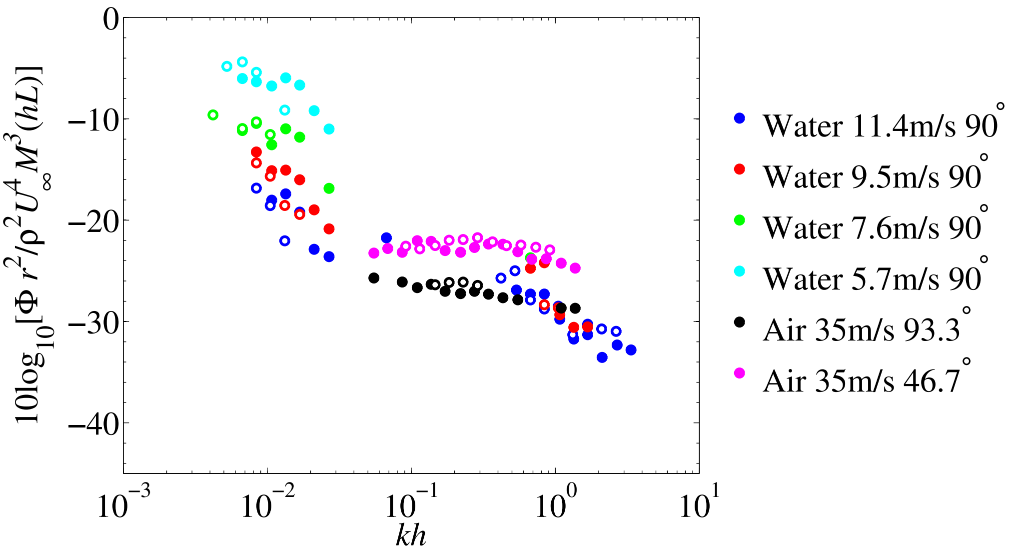

Figure 4: Scaled hydroacoustic and aeroacoustic test data. Open and closed symbols as per figures 2 and 3.

ward facing step studies, that unscaled noise levels rise with step height and scale according to U_∞^7. For non-dimensionalised wavenumbers $kh > 0.027$, the data collapse in each facility when recorded at the same observation angle θ. The limited results at different observation angles show there is some directivity to the sound source. These results suggest that for this kind of step, a new model for describing sound production is needed. It is speculated that a complex dipole model is appropriate, yet more work is required to prove that it is applicable.

The successful use of hydroacoustic and aeroacoustic facilities to study an involved flow-induced noise problem is novel and important. It allows the collection of data under a wide range of conditions, not normally available in a single facility. It also shows that aeroacoustic data can be used to help understand hydroacoustic problems. Complimentary acoustic testing in air and water, along with computational modelling of both, is most likely the best and most practical approach to develop quiet maritime technology.

Acknowledgements

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