Estimated Flow Noise Levels due to a Thin Line Digital Towed Array

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***Abstract*—Flow noise levels for a digital thin line towed array for normal operating speeds of an AUV were estimated using empirical models and towing experiments. The wavenumber filtering associated with the finite size and distribution of hydrophones in acoustic element of DTLA was applied to the empirical models of turbulent wall pressure spectra to estimate the expected flow noise levels. The empirical results were then compared with the noise spectra measured during towing experiments conducted in a quiet lake. The results showed rapid loss of flow noise energy with increase in frequency arising due to the very nature of turbulent noise spectra and flow noise averaging introduced by the finite size of the hydrophone.**

I. Introduction

With the advent of the Autonomous Underwater Vehicles (AUV) and Unmanned Surface Vehicles (USV) there has been an increased demand for the development of very light weight thin line towed arrays for applications like littoral water surveillance and survey, marine mammal studies etc. Acoustic Research laboratory (ARL) of Tropical Marine Science Institute, National University of Singapore has developed a digital thin line array (DTLA) that consists of 11 acoustic elements, a pressure sensor, a tilt-corrected heading sensor and associated digitizing and power conditioning circuitry packaged inside a 10 mm diameter PVC tube. One of the major concerns for the application of DTLA have been that a reduction in array diameter will increase the proximity and hence susceptibility of acoustic sensors to pressure fluctuations in the turbulent boundary layer (TBL). This could deteriorate the signal to noise ratio (SNR) of thin line arrays especially at low frequencies due to high levels of flow noise getting coupled to the sensors. In this paper, we discuss the empirical estimates of expected flow noise levels for the ARL DTLA and compare them with those estimated from an experiment conducted.

II. Empirical estimates of flow noise

Flow noise estimates for the DTLA were arrived at based on empirical model of frequency-wavenumber (F-K) spectrum of turbulent boundary layer (TBL) wall pressure fluctuations. Extensive studies have been conducted in the past to understand the characteristics of wall pressure fluctuation in turbulent boundary layers in flows over cylinders and plates as it is one of the key factors in design of aircraft fuselages, ship and submarine domes and towed array sonars [1]. Many of the observed structural features of the cylindrical boundary layer are similar to those observed in flat-plate turbulent boundary layers even though turbulence intensities for cylinder are lower than that for a flat plate case for most of the boundary layer (outer regions) as the small surface area of the cylinder limits the amount of vorticity introduced in to the fluid [2]. In this paper we use the frequency-wavenumber spectrum of TBL wall pressure fluctuations given by Carpenter and Kewley [3] as expressed in (1).This model was obtained modifying the chase spectrum [4] to express the wall pressure spectra on a cylinder as a function of frequency and wave number component along the axis of cylinder.

$$P(k,\omega) = C\rho^2 v_*^2 a^2 \frac{(12k^2a^2+1)}{12}\left(\frac{(\omega a - u_c k a)^2}{h^2 v_*^2} + k^2a^2 + b^{-2}\right)^{-2.5} \quad (1)$$

In equation (1), ρ is the fluid density; U is the tow velocity; $u_c = 0.68U$ is the convection velocity of turbulence; v_* is the friction velocity; and the constants are $C = 0.063, h = 3.17, b = 1.08$. The value of v_* was evaluated from the drag values measured during tank testing of the array[5] as $0.038U$ which is very close to the $0.04U$ used by Carpenter and Kewley [3].Application of this model is limited to the cases where $\delta >> a$ where δ is the boundary layer thickness and a is the radius of array tube. For the ARL DTLA, δ value under normal operating speed of 2-5 knots is about 100 mm.The frequency spectra of wall pressure fluctuations at DTLA tube surface for different tow speeds were then estimated by integrating $P(k,\omega)$ from (1) over the wavenumber range of interest.

Another independent estimate of wall pressure spectra on DTLA was obtained by scaling the non-dimensional spectra by Cipolla and Kieth [6]. The wall pressure spectra they measured on a full scale experimental towed array for different tow speeds collapsed well in to a single curve when scaled using tow velocity and array tube diameters as scaling variables. Fig1 shows the frequency spectra of wall pressure fluctuations at DTLA tube surface for different tow speed estimated using two methods described above. Even though the frequency spectrum obtained from empirical F-K model in (1) is approximately 10dB lower than the spectra obtained using the non-dimensional spectra reported by Cipolla and Kieth [6], the energy distribution across the frequencies follow the same trend.

Each acoustic 'super-element' in ARL DTLA consisted of 6 numbers of 8 mm long 2.3 mm diameter piezo-ceramic

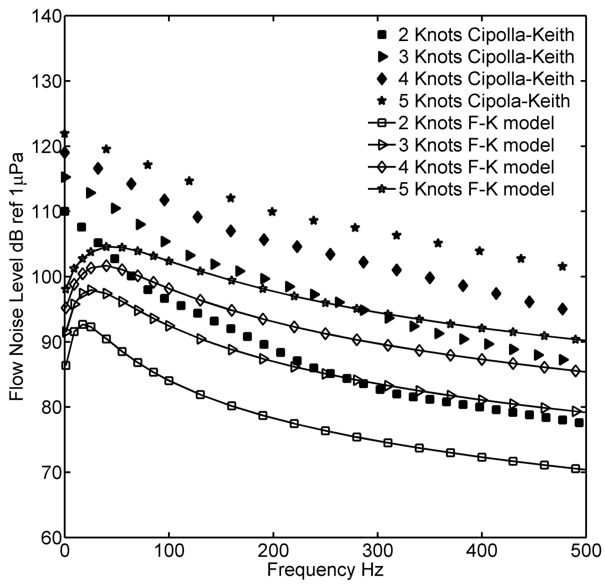

Fig. 1. Frequency spectra of wall pressure fluctuations for DTLA

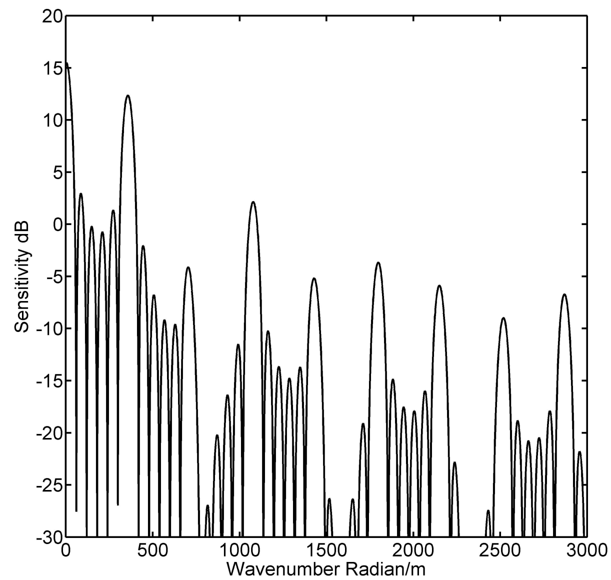

Fig. 2. Wavenumber filtering by DTLA acoustic element

hydrophones connected in series to achieve better sensitivity and also to increase the effective aperture of the transducer to improve TBL noise filtering. The flow noise filtering arising due to the finite dimension and distribution of multiple sensors in the acoustic element are accounted for through a procedure similar to the ones detailed in references [7], [8], [3]. Assuming uniform sensitivity along the length of the sensor, the wavenumber response characteristics of an acoustic element made of N sensors of length l connected series in can be expressed as

$$H_{k\omega} = S_{\omega}\frac{\sin(kdN/2)}{\sin(kd/2)}sinc(kl/2) \tag{2}$$

In (2), d is the distance between the individual sensors in the acoustic element and S_{ω} is the pressure sensitivity of hydrophone which depends on frequency. The wavenumber filtering characteristics of the DTLA acoustic element is shown in Fig 2.Frequency characteristics of flow noise filtering by the DTLA acoustic element will vary with tow speed as the propagation speed of turbulent pressure fluctuations in the boundary layer is directly proportional to the tow speed. Flow noise filtering for the frequency band of interest at a tow velocity of 5 knots assuming TBL noise propagation speed if $0.68U$ is shown in Fig 3. The individual contributions to flow noise filtering from finite size and distribution of hydrophones is also shown in Fig 3. It can be observed that majority of the noise filtering arises due to the finite size of the transducer.

In the current study, the wavenumber filtering characteristics of the tube is neglected and it is assumed that the hydrophone experiences the same wall pressure fluctuations experienced by the array tube. This assumption is valid for DTLA at frequencies below 400Hz according to the results obtained by Francis and Slazak [9]. The expected level of flow noise experienced by the DTLA acoustic element, calculated according to (3), is shown in Fig 4. The effects of wavenumber filtering by the DTLA acoustic element cannot be directly applied on the non-dimensional spectra as the energy distribution across the wavenumber is not available.

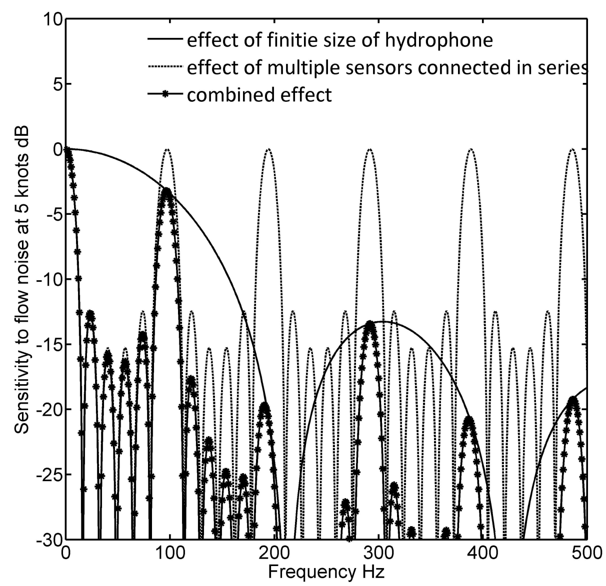

Fig. 3. Flow noise filtering by DTLA acoustic elements at 5 knots

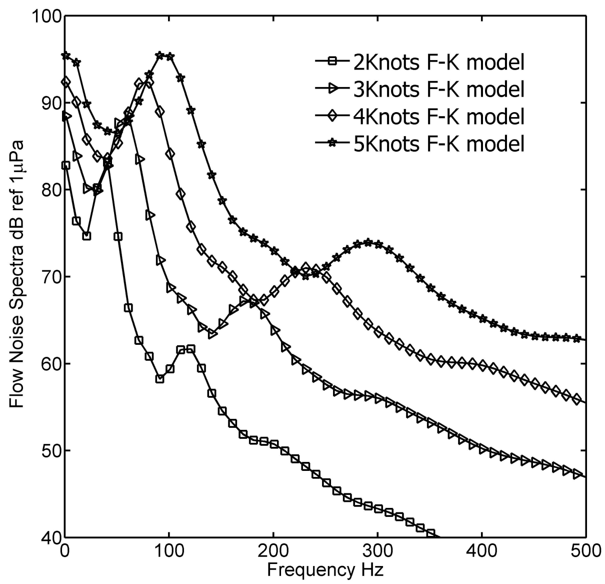

Fig. 4. Estimated level of flow noise at DTLA acoustic element for different tow speeds

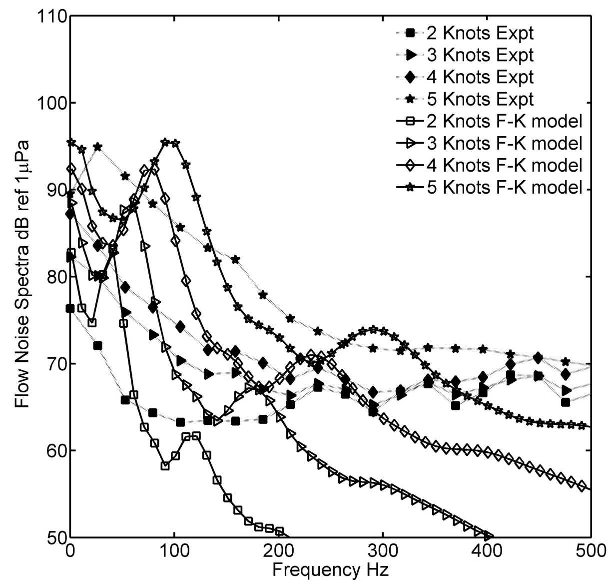

Fig. 5. Comparison of empirical estimate with experimental spectra

$$P_{FN}(\omega) = \int P(k,\omega) H_{k\omega} dk \tag{3}$$

III. Experimental results

Experimental investigation of flow noise levels for DTLA was carried out in a quiet lake. The DTLA was towed behind a dinghy, with its battery operated data acquisition system stowed inside the dinghy. To reduce contamination by propulsion noise, the dinghy was towed using a hydraulic winch mounted on a moored isolated floating platform. The experiments were carried out over typical operational speeds of DTLA ranging from 2-5 knots. Previous experiments have confirmed that the array stayed aligned with tow direction with minimal snaking for the tow speeds employed in the experiment and under small currents [5].

The signal levels across different acoustic channels of DTLA were found to be varying within $\pm 4dB$. The data section over which the array has achieved steady speed was used for the estimation of the flow noise. Fig 5 compares the spectra of flow noise recorded during the field trials with empirical estimates. Assuming a flat response in low frequency region, a sensitivity value measured at 2 kHz was used in the study. The peaks observed in the estimated spectra are due to the wavenumber response characteristics associated with the distribution of equally spaced sensors. In reality, the amplification due to coherent summation by multiple sensor configurations can be neglected for DTLA for frequencies above 50 Hz and normal tow speeds as the turbulent noise becomes almost incoherent as it travels a distance of 3 wavelengths [10]. Except at the peaks, empirical estimates compare reasonably with the experimental results showing the rapid loss of flow noise energy with increase in frequency.

IV. Conclusion

Expected levels of flow noise due to a thin line array under normal operating speed of 2-5 knots were estimated through empirical models and towing experiments. The empirical estimates compared fairly with the experimental results and showed that the power spectral density of the measured noise levels increased with tow speed up to a frequency of 400Hz. Even though the characterization of flow noise levels beyond 400 Hz was limited by the noise floor, it is apparent from the results that noise levels in high frequency bands for normal operational tow speeds of AUVs are well below the normally observed ambient noise levels of 70-80 dB ref $1\mu Pa$ observed in Singapore waters. It tend to suggests that the application of DTLA for field measurements using an AUV is not largely limited by the SNR degradation due to increased flow noise arising from a reduced diameter. The study also suggests that the increased spatial aperture of acoustic element through the distribution of multiple sensors connected in series is not significantly contributing to TBL averaging and to better the SNR at least for frequencies above 400 Hz for normal operating speeds of 2-5 knots

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