Near-Field Testing and Evaluation Method for Stream Noise of Linear Array Based on Laser Doppler Velocimetry

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Abstract: *Towed linear arrays have widespread applications in ocean monitoring and underwater detection, but their performance is often affected by stream noise. To accurately assess the stream noise characteristics of towed linear arrays in actual operational environments, this study proposes a near-field testing and evaluation method based on Laser Doppler Velocimetry (LDV). This method leverages the high-precision velocity measurement capabilities of LDV and integrates numerical analysis models to achieve precise testing and analysis of stream noise near the towed linear array. The results demonstrate that the LDV-based testing method can effectively capture the complex flow field characteristics around the towed linear array and accurately evaluate the stream noise levels. Compared to traditional methods, this approach enables testing within limited spaces, significantly reducing experimental costs and time. This research provides a novel technical means for evaluating stream noise in towed linear arrays, which is crucial for enhancing their performance in practical applications.*

Keywords: *Stream Noise, Linear Array, Laser Doppler Velocimetry*

1. INTRODUCTION

Linear arrays, particularly Towed Array Sonars (TAS), are essential tools in underwater acoustics for both defense and scientific research (e.g., marine mammal monitoring). Their effectiveness comes from deploying hydrophones over long distances, separating them from the towing platform's noise and allowing for directional sensing through beamforming. However, as the array moves through water, the flow over its surface generates significant self-noise, known as stream noise or flow noise.[1] This noise primarily arises from turbulent boundary layer pressure fluctuations and flow-induced vibrations.[1] Stream noise becomes a dominant limitation, especially at higher speeds, masking faint target signals and degrading the sonar's detection range and overall performance.[2] Accurately characterizing this noise, particularly in the near-field region close to the array surface where the noise originates, is crucial for understanding its mechanisms and developing mitigation strategies.[3]

The standard approach for measuring underwater sound, including stream noise, involves using hydrophones – sensors that convert pressure fluctuations into electrical signals.[4] In near-field testing, hydrophones are placed close to the array surface to capture the noise characteristics at the source.[5] However, this method suffers from a critical drawback: intrusiveness. The physical presence of the hydrophone and its mounting inevitably disturbs the local hydrodynamic flow field it aims to measure.[6] This disturbance alters the turbulent structures and pressure distribution.

Furthermore, the hydrophone measures a combination of true propagating sound and non-propagating hydrodynamic pressure fluctuations (pseudo-sound) associated with turbulent eddies. The intrusive sensor not only measures the flow's inherent pseudo-sound but can also generate additional pseudo-sound due to flow interaction with the sensor itself. This contamination makes it extremely difficult to isolate the true acoustic signal or accurately characterize the original hydrodynamic pressure field responsible for the noise.[7] Consequently, hydrophone-based near-field measurements can lead to significant inaccuracies, hindering the precise diagnosis of noise sources and the validation of noise reduction techniques. This limitation highlights a critical gap in current stream noise evaluation methods.

Laser Doppler Velocimetry (LDV) presents a powerful, non-intrusive optical technique for fluid velocity measurement.[5] It works by detecting the Doppler frequency shift of laser light scattered by small particles moving with the fluid.[8] By measuring this shift, LDV determines the fluid velocity components at a precise point without physical contact. The key advantage of LDV in this context is its non-intrusiveness. Unlike hydrophones, LDV probes the flow using light beams, eliminating the physical disturbance and sensor-induced pseudo-sound generation that compromise intrusive measurements.[8] LDV allows for the characterization of the undisturbed velocity field very close to the array surface. Since stream noise originates directly from hydrodynamic phenomena like turbulent velocity fluctuations, LDV provides direct access to the fundamental physics of noise generation. It can yield detailed data on turbulence intensity, velocity profiles, and flow structures near the wall. This accurate, non-intrusive velocity data is invaluable for understanding noise mechanisms, validating computational fluid dynamics (CFD) predictions, and assessing the effectiveness of noise control strategies, such as surface modifications. While LDV measures velocity, this information is directly linked to the pressure fluctuations responsible for noise and can be used to infer pressure characteristics without intrusive measurement errors.

This paper proposes and evaluates a near-field testing and evaluation methodology for linear array stream noise based on non-intrusive Laser Doppler Velocimetry (LDV). The primary objective is to overcome the accuracy limitations associated with conventional intrusive hydrophone techniques by leveraging LDV's ability to measure the undisturbed near-field flow dynamics. The paper will cover the theoretical background, describe the experimental setup using LDV with a linear array model in a flow facility, present the detailed velocity field measurements, analyze the results to understand the flow physics relevant to noise generation, and discuss the advantages of the LDV-based approach for stream noise assessment

2. THEORY FOR RADIATED NOISE CALCULATION

The predominant source of acoustic radiation from linear arrays is identified as trailing edge noise. This phenomenon is intrinsically linked to the turbulent boundary layer that develops along the linear arrays. Specifically, trailing edge noise is understood to arise from the scattering of acoustic waves generated by the turbulent flow as it convects past the hydrofoil's trailing edge.

Howe's empirical model provides a widely cited framework for predicting the characteristics of this radiated noise. The mean square sound pressure, $\langle p^2 \rangle$, is approximated by the following expression[9]:

$$< p^2 > \approx \rho_0^2 u_0^2 v^2 M_v \left(\frac{LI}{R^2} \right) \sin \alpha \sin^2 \left(\frac{\theta}{2} \right) \cos^3 \beta \quad (1)$$

where the $\langle p^2 \rangle$ is the mean square sound pressure, ρ0 is the fluid density, u0 is the uniform free stream velocity, v is the convection velocity, Mv is the turbulent convection Mach number, L is the, length of linear arrays, I is the displacement thickness of the turbulent boundary layer, R is the distance from the trailing edge to the observation point, β is the sweep angle of the trailing edge, α is the angle between the observation point and the hydrofoil trailing edge and θ is the direction angle.

2. NOISE MEASUREMENT TEST BASED ON LDV

The experiments were conducted in a recirculating water channel. This type of facility allows for controlled and continuous flow of water over an extended period, which is essential for detailed velocity measurements. The specific water channel to be used has overall dimensions of approximately 4.92 meters in length, 0.4 meters in width, and 2.34 meters in height. The test section, where the segment of the linear arrays was placed and measurements taken, has dimensions of 1.6 meters in length, 0.4 meters in width, and 0.4 meters in height. The water flow within the channel is generated by a pump system that allows for a range of flow velocities to be achieved in the test section. To ensure a uniform and stable flow entering the test section, several flow conditioning elements are incorporated upstream. The achievable range of flow velocities in this water channel spans from 0.5 m/s to 1.5 m/s in the test section.

The segment of the linear arrays is replaced by a cylinder. The submerged cylinder to be used in this experiment will be circular in cross-section. The cylinder has a diameter of 0.05 meters and a length of 0.15 meters, resulting in an aspect ratio (length/diameter) of 3. The cylinder was made of acetal (POM) 18, which provides a smooth surface finish suitable for noise measurement. The cylinder was mounted horizontal along the centerline of the test section, fully submerged, and fixed in place using supports that minimize interference with the flow in the region of interest.

A two-component LDV system will be employed to measure the streamwise and vertical components of the fluid velocity in the wake of the cylinder. The transmitting and receiving optics will consist of an 83 mm diameter optical fiber probe with a front lens of 360 mm focal length. The system was operated in backscatter mode, where the probe serves as both the transmitter and receiver of the laser beams, allowing for measurements with optical access from only one side of the water channel.

The velocity measurements were taken on a grid of points in the symmetry plane downstream of the cylinder to characterize the wake region. The spatial resolution of the measurement grid is finer in the near wake region (closer to the cylinder) where velocity gradients are expected to be higher, and coarser further downstream. Specifically, in the region from 0.5D to 5D downstream of the cylinder and -1D to 1D in the transverse direction (where D is the cylinder diameter), the measurement points were spaced at intervals of 0.1D. Further downstream, the spacing will be increased to 0.25D. The test layout is shown in Fig. 1.

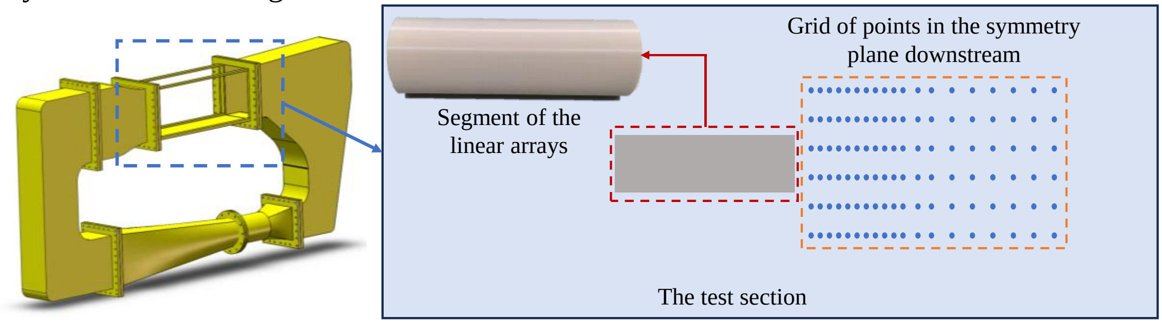

Fig.1: The test layout of the LDV flow noise test.

To facilitate comparison with the Laser Doppler Velocimetry (LDV) flow noise test results, the flow noise of the linear array segment was measured using an 8103 hydrophone array configuration with three equidistant measurement points, as depicted in the Fig. 2. The measurement points were uniformly spaced at intervals of 500 mm along the array segment.

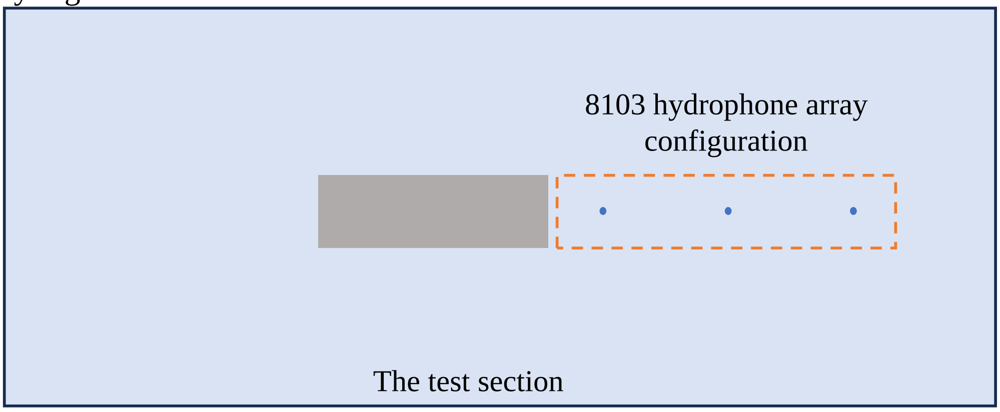

Fig.2: The layout of the hydrophone flow noise test.

3. RESULTS AND DISCUSSION

Fig. 3 presents a two-dimensional color contour map illustrating the velocity distribution within the designated test region under a nominal flow condition of 1 m/s.

According to the figure caption, this velocity field was derived using the finite difference method applied to data obtained from Laser Doppler Velocimetry (LDV) measurements. The map utilizes a color scale, shown on the right, to represent velocity magnitudes in meters per second (m/s). The scale ranges from approximately 0 m/s (indicated by dark blue) to a maximum of roughly 1.6 m/s (indicated by dark red). The velocity distribution exhibits a degree of symmetry about the horizontal centerline. The observed pattern, with a central low-velocity zone flanked by higher-velocity zones, is characteristic of flow phenomena because of wake formation behind an obstacle. The acceleration of the flow to speeds greater than the nominal 1 m/s in the outer regions suggests potential flow constriction. The regions of lowest velocity (dark blue) correspond to areas of flow separation or the near wake immediately downstream of an object.

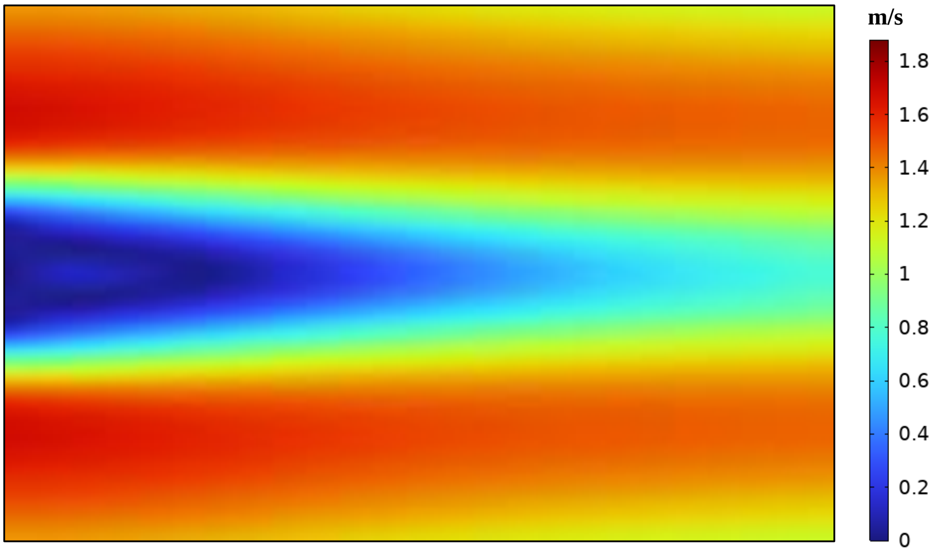

Fig.3: Velocity distribution maps of the test region at 1 m/s derived via the finite difference method based on LDV test results.

Furthermore, leveraging the detailed flow velocity distribution data obtained from the LDV tests, it becomes possible to estimate the radiated sound power. Specifically, by applying Equation (1), the sound power radiated in the direction of acoustic wave propagation at a distance of 1 meter can be calculated, which allows for the prediction of flow-induced noise based on the measured characteristics of the velocity field, as shown as in Fig. 4.

Fig.4 presents the comparison of the radiation noise level test results based on LDV and hydrophone. Both datasets demonstrate a clear positive correlation between flow velocity and radiation noise level; as the velocity increases, the noise level increases for both methods. This aligns with the fundamental principles of flow-induced noise generation, where higher flow speeds typically lead to more intense turbulent fluctuations and consequently higher noise levels. A significant observation is the consistent difference between the two datasets across the tested velocity range. The noise levels measured directly by the hydrophone are consistently higher than those estimated based on the LDV data. This discrepancy appears to widen slightly as the flow velocity increases.

While the LDV-based method likely focuses on estimating the noise generated directly by the flow phenomena around the object of interest (e.g., trailing edge noise, turbulence interaction), the hydrophone measures the total acoustic pressure at its location. This total pressure includes not only the direct flow-induced noise from the object but also any other noise sources present in the experimental facility. A plausible explanation for the elevated hydrophone readings is the potential contribution of facility background noise, particularly noise originating from vibrations of the circulating water channel walls. Such structural vibrations, induced by the pump, the flow itself, or other machinery, can radiate sound into the water, which is then picked up by the hydrophone. This facility-related noise component would add to the actual flow noise generated by the test object, leading to higher overall measured levels compared to the LDV-based estimation, which may inherently exclude or underestimate these extraneous sources. Therefore, the higher noise levels recorded by the hydrophone might be attributed, at least in part, to the inclusion of wall vibration noise from the circulating water channel in the measurement results.

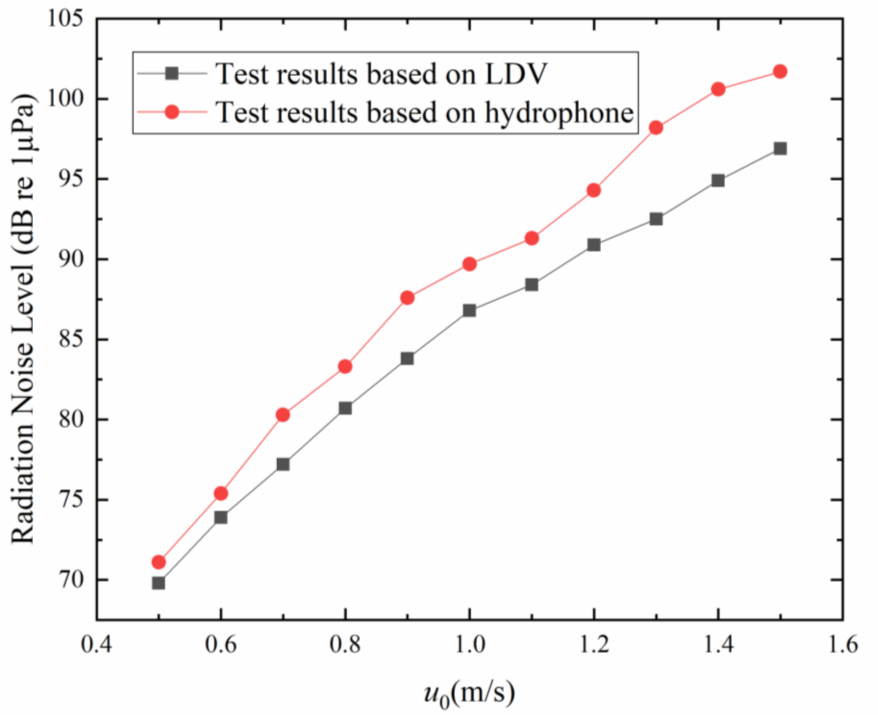

Fig.4 Comparison of the radiation noise level test results based on LDV and hydrophone.

4. CONCLUSION

This study proposed and validated a near-field testing and evaluation method for towed linear array stream noise based on Laser Doppler Velocimetry (LDV). Experimental results demonstrate that LDV effectively captures complex flow field characteristics near the array, enabling estimation of the associated stream noise. Compared to traditional hydrophones, the non-intrusive LDV method focuses more specifically on the array's self-generated noise. Consistently higher noise levels measured by hydrophones may be attributed to facility background noise, such as water channel wall vibrations. This LDV-based approach provides a valuable new pathway for accurate assessment and mechanistic study of linear array stream noise, contributing to performance optimization in practical applications.

5. ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Grant Nos. 12304502, 12304529).

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