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A Review of Noise Directivity Testing

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Abstract. Noise directivity testing is used to characterize the radiation strength of noise from a sound source in different spatial directions. It is supported by national standards. Conventional testing is not applicable to moving sound source scenarios, in which relative motion exists between the sound source and sensors; the Doppler effect interferes with measurement, making it difficult to obtain accurate sound source amplitudes. This paper reviews conventional rotational scanning, beamforming, the Deconvolution Approach for the Mapping of Acoustic Sources (hereinafter referred to as DAMAS), near-field acoustic holography, and virtual sound field testing techniques. It compares the advantages and disadvantages of these techniques and clarifies the engineering roles of standardized tests and modern acoustic imaging techniques. The results show that conventional rotational scanning testing in anechoic chambers is suitable for static sound sources and is supported by well-established national standards, but it cannot be applied to moving sound sources affected by the Doppler effect. Quantitative imaging of moving sound sources requires point spread function correction and Doppler effect compensation to restore the true sound source strength. Conventional acoustic testing and array acoustic imaging can complement each other. In the future, acoustic testing will develop toward lightweight deconvolution algorithms, multi-technology integration, AI-enabled capabilities, and virtual-real fusion, thereby supporting noise control and the research and development of acoustic equipment.

Keywords: Noise Directivity, Acoustic Testing, Deconvolution Algorithm, Moving Sound Source, Acoustic Imaging

1. Introduction

Noise directivity testing is a key technique for sound source identification and noise control in mechanical and aeronautical fields. The noise radiated by a source is not uniformly distributed in all directions, and noise levels differ significantly among directions; therefore, measuring the sound pressure level at a single point cannot fully reflect the actual noise radiation characteristics of a device. Traditional acoustic testing methods based on rotational scanning in an anechoic chamber have been incorporated into well-established national standards and widely applied to product noise quality inspection, including product noise assessment and compliance testing, localization of dominant noise sources to guide noise reduction optimization, assessment of the impact of external noise on the surrounding environment, and testing of algorithm performance to address the special requirements of certain moving sound source scenarios. Meanwhile, array-based acoustic imaging

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techniques, represented by beamforming and deconvolution algorithms for acoustic source imaging, have been gradually applied to noise testing of complex sound sources. For testing requirements involving moving sound sources such as unmanned aerial vehicles (UAVs) and rail transit, the existing technical framework still has notable shortcomings. When traditional testing methods are applied to moving sound sources, issues such as Doppler-induced errors and excessive computational overhead may arise. This paper combines a literature review with numerical simulation. Through model parameter definition, simulation of signal distortion caused by the Doppler effect, generation of simulated acoustic signals received by a microphone array, acoustic imaging algorithm processing, and comparative analysis of the results the influence of the Doppler effect on DAMAS-based sound source reconstruction is simulated using MATLAB (Matrix Laboratory). The results of this study provide a theoretical reference for the development of subsequent moving sound source imaging algorithms.

2. Existing standards and measurement methods

Noise directivity describes the spatial distribution of the intensity of noise radiated by a sound source and is an important basis for noise reduction optimization, product noise quality inspection, equipment fault diagnosis, and environmental noise impact assessment. The overall sound pressure level alone cannot fully reflect the spatial propagation characteristics of noise; therefore, noise directivity testing plays an important role in the research and development of acoustic equipment and noise control engineering [1]. After decades of development, a relatively complete national standard system for acoustic measurement has been established in China. GB/T 6882-2016 specifies precision noise measurement methods for anechoic and semi-anechoic chambers, GB/T 20247-2006 standardizes sound absorption and sound power testing procedures for reverberation chambers, and GB/T 34828-2017 provides implementation rules for free-field environment qualification and sound source directivity assessment, providing a unified normative basis for traditional rotational scanning directivity testing.

Traditional rotational scanning testing is generally carried out in an anechoic chamber. This method has a mature workflow and provides reproducible measurement results, and is suitable for product quality inspection of stationary sound sources such as household appliances and electric motors. However, this technique has clear limitations in its application. The entire test highly depends on the physical environment of the anechoic chamber, and the construction cost of an anechoic chamber is high. When the sound source is in motion, relative motion occurs between the sound source and the microphone, and the Doppler frequency shift changes the frequency and amplitude of the received signal, causing distortion of the directivity measurement results. Therefore, this method is difficult to directly apply to moving sound source testing scenarios such as UAVs and rail transit [2-4].

With the development of array signal processing technology, microphone array acoustic imaging technology has gradually compensated for the shortcomings of traditional testing. Mainstream technologies include beamforming, the DAMAS deconvolution algorithm, near-field acoustic holography, and virtual sound field testing technology [5]. Delay-and-sum beamforming is a fundamental algorithm for acoustic imaging. By performing time delay compensation on the signals received by each microphone, acoustic waves from the target direction are phase-aligned and constructively superposed, while signals from other directions are suppressed, thereby achieving sound source localization and directivity reconstruction [6]. Beamforming is computationally efficient, supports real-time far-field measurement, and is simple to implement in engineering applications. Therefore, it is widely used for rapid noise detection in industrial sites. However, basic

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beamforming suffers from severe sidelobe artifacts. Sidelobes can mask true weak sound sources, causing deviations in directivity results.

To suppress sidelobe interference in beamforming, the DAMAS algorithm can perform iterative deconvolution on the beamforming output via the array point spread function, thereby suppressing sidelobe interference and improving the quantitative accuracy of sound source strength. DAMAS can produce a quantitative sound source strength distribution and significantly improve the imaging dynamic range compared with basic beamforming, and it has been widely applied in noise identification of rotor-type sound sources. However, the DAMAS algorithm itself has inherent drawbacks. Its iterative solution process incurs enormous computational overhead, and the computational burden rises sharply when the grid is refined. At low frequencies, it still suffers from insufficient resolution due to array aperture limitations. Targeted modifications to the algorithm are therefore necessary before it can be used for quantitative imaging of moving targets [7]. At present, no lightweight improved framework capable of simultaneously correcting Doppler-induced shifts and low-resolution problems has been established in the publicly available literature.

Near-field acoustic holography is another important sound field reconstruction technique. It utilizes sound pressure information collected on a measurement plane, combines it with the acoustic wave equation, and exploits wave components to reconstruct the sound field distribution on the source surface, achieving excellent spatial resolution in the low- and mid-frequency ranges [8]. This method can reconstruct the sound intensity distribution on the source surface with high precision and is suitable for near-field noise mechanism analysis of equipment. However, near-field acoustic holography imposes very stringent requirements on testing conditions. The microphone array must be placed close to the sound source under test and must cover the entire radiating surface of the source. As the measurement distance increases, evanescent waves decay rapidly, and the reconstruction accuracy decreases sharply. A large number of measurement points are required, resulting in high data acquisition costs.

Virtual sound field testing technology is an emerging measurement approach in recent years. It relies on loudspeaker arrays to perform vector synthesis of the sound field, reproducing the radiated sound field of a target source in a local spatial region and enabling directivity evaluation without the need for a large anechoic chamber, thereby reducing the construction cost of physical laboratories. Virtual sound field testing does not depend on the actual motion of a real sound source and can flexibly simulate the radiation characteristics of sound sources at different orientations and in different motion states. However, owing to the limited spatial region of sound field reproduction, high sound field fitting accuracy is achieved only within a confined space, and the sound field reproduction error under large-scale and broadband conditions remains to be further reduced. Different testing techniques have their own applicable boundaries. The common measurement methods and their characteristics are summarized in Table 1.

Table 1. Multidimensional comparative summary of common measurement techniques

Measurement Method	Core Features	Applicable Scenarios	Influence of Doppler Effect under Moving Sound Sources	Doppler Effect Compensation Requirements
Traditional National-Standard Rotational Scanning	High degree of standardization; reliable measurement results	Ex-factory quality inspection of static sound source products	It is inherently a static measurement method and is not applicable to moving sound source conditions	Static quality inspection scenarios

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Table 1. (continued)

Beamforming	Fast array imaging; good real-time performance	On-site rapid screening	Affected by Doppler frequency shift, causing amplitude/phase deviations and directivity pattern distortion	Doppler compensation must be introduced into the signal/algorithm model, and the point spread function must be re-matched
DAMAS deconvolution	Deconvolution imaging; can quantify sound source strength	Mechanism studies requiring quantitative sound source strength	Affected by the Doppler effect; results are distorted under the stationary sound source assumption	Doppler compensation correction is required, and the point spread function must be re-matched to recover the true radiated intensity
Near-field acoustic holography	Near-field measurement; refined sound field reconstruction	Near-field refined sound field reconstruction	Affected by the Doppler effect; the higher the speed, the more pronounced the deviation	Doppler compensation correction is required; otherwise the reconstructed sound field is distorted
Virtual sound field [9]	Implemented by numerical simulation; low cost	Potential for low-cost simulation testing	The Doppler effect can be modeled in simulation	A Doppler model can be directly introduced into the simulation model

3. Simulation analysis of the doppler effect

Due to physical experimental constraints, it is difficult to conduct experiments involving moving sound sources in an anechoic chamber; therefore, numerical simulation has become an important means for studying the influence of the Doppler effect on noise directivity and acoustic imaging results. In the simulation, a moving point sound source model is first established, in which the source is set to undergo translational motion at a constant velocity. The propagation delay from the source to each microphone is calculated according to the source position at each instant, and the signal stretching effect caused by the Doppler frequency shift is simulated to generate the time-domain sound pressure signals received by the microphone array.

The array cross-spectral matrix with Doppler distortion is used as the input to the DAMAS algorithm, and two groups of comparative simulations are carried out. In the first group, the original static PSF is directly used for DAMAS deconvolution without Doppler compensation. In the second group, a time-varying PSF is introduced during the iterative process, and the source motion trajectory is incorporated into the PSF calculation to achieve Doppler effect compensation [10]. The simulation outputs sound source imaging contour maps and spatial directivity curves, and compares the source amplitude error, localization shift, and directivity pattern distortion before and after compensation. The simulation results clearly demonstrate that, without Doppler compensation, the imaging exhibits a shift in source position, underestimation of source strength, and distortion of the directivity curve. After the time-varying PSF is introduced to compensate for the Doppler effect, the source position and amplitude are effectively restored, and the directivity is closer to the true radiation characteristics of the sound source, as shown in Figure 1.

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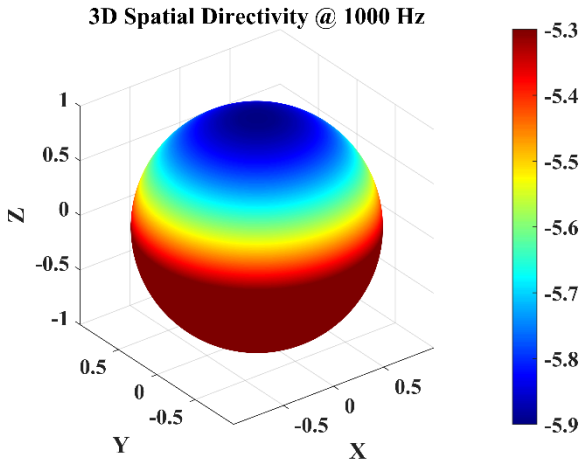


Figure 1. Example of a three-dimensional spatial directivity pattern

To quantitatively evaluate the simulation outputs and characterize the simulation results for noise hazard assessment, this study employs weighted sound exposure, maximum sound pressure level, and A-weighted equivalent continuous sound pressure level to calculate and analyze the time-domain sound pressure signals obtained from simulation. Weighted sound exposure reflects the accumulation of noise energy over a period of time, maximum sound pressure level characterizes the instantaneous peak of noise, and equivalent continuous sound pressure level represents the average noise level of time-varying noise. In the simulation scenario of a moving sound source, the received sound pressure fluctuates sharply over time as the sound source sweeps past the array. The above metrics can quantify the noise exposure level at different source velocities and can also be used to compare the deviations in noise parameters before and after Doppler compensation. The simulation results show that ignoring the Doppler effect not only distorts the spatial directivity pattern but also introduces computational errors in sound exposure and equivalent sound pressure level, thereby affecting the assessment of noise hazards from moving sound sources. This simulation study only conducts Doppler compensation simulation research on a sound source moving uniformly in a straight line; the method is not yet applicable to complex situations such as variable-speed sound sources and strong turbulent noise coupling.

In the simulation, the target rotational speed of the four motors of a quadrotor UAV was set to 720 rad/s, and the simulation duration was 2 s. The rotational speed time-history curve shows that the motor speed remained stable without fluctuation throughout the simulation, and the rotor excitation remained constant. A 1000 Hz single-frequency sound source was selected for acoustic simulation, the speed of sound was set to 340 m/s, and the sound source was assumed to move uniformly in a straight line. A planar microphone array was constructed to acquire time-domain sound pressure signals with Doppler distortion. Two comparative cases were established: one directly used a static point spread function for DAMAS deconvolution without Doppler compensation; the other introduced a time-varying point spread function into the iterative solution to achieve Doppler compensation. After the simulation, three-dimensional spatial directivity contour maps and horizontal-plane polar directivity curves were output, as shown in Figure 2; the sound source localization offset and amplitude error were then extracted, as shown in Figure 3. By combining weighted sound exposure, maximum sound pressure level, and A-weighted equivalent continuous sound pressure level, the effectiveness of Doppler compensation in improving sound source imaging and noise directivity testing results was quantitatively analyzed.

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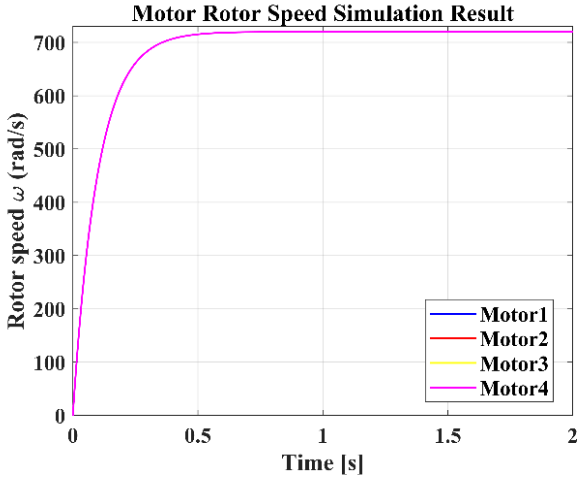


Figure 2. Rotor speed time-history curve of four motors

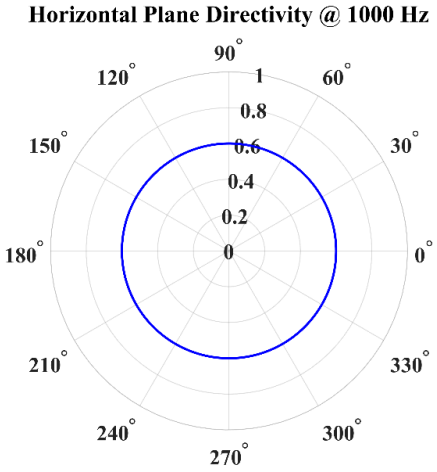


Figure 3. Directivity in the Horizontal Plane

4. Existing technical challenges and future development trends

Current noise directivity testing techniques still face several practical challenges. First, the challenge of quantitative testing of moving sound sources has not been fully resolved. Second, deconvolution-based acoustic imaging algorithms generally face a trade-off between computational efficiency and resolution. Third, physical anechoic chambers are expensive to build, and the broadband accuracy of alternative testing schemes such as virtual sound fields still needs to be improved.

In view of the above shortcomings in the simulation, future research can be further deepened and improved from multiple aspects. First, optimize the complexity of the simulation model, establish a sound source model that is more consistent with engineering practice, and introduce additional sound sources; expand the motion conditions by adding multiple motion modes such as acceleration and deceleration to reproduce more realistic operating states of moving sound sources; incorporate interference terms such as environmental reflection noise, sensor channel errors, and trajectory position measurement errors into the simulation to simulate real field testing conditions and examine the robustness of Doppler compensation algorithms under non-ideal conditions. Second, expand comparative simulations of algorithms. Within the same moving sound source simulation

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framework, conduct Doppler effect simulations for beamforming, improved DAMAS, and near-field acoustic holography algorithms, compare the amplitude errors and localization deviations of different algorithms before and after compensation, and select imaging schemes suitable for high-speed moving sound sources. Third, carry out simulation-experiment comparative verification. Port the compensation algorithm obtained from the simulation to an actual microphone array, compare the deviations between the simulation output and actual data, verify the performance of the compensation algorithm, and correct the deviations between the simulation and physical testing. Fourth, combine lightweight algorithms with artificial intelligence approaches.

5. Conclusion

The research results indicate that traditional rotational scanning testing in anechoic chambers is suitable for static sound sources and is supported by well-established national standards, but it is not suitable for testing moving sound sources affected by the Doppler effect. Quantitative imaging of moving sound sources requires correction of the point spread function and compensation for the Doppler effect before the true sound source strength can be recovered. Looking ahead, noise directivity testing technology will develop along four directions. First, lightweight deconvolution algorithms (e.g., DAMAS) will cut computational cost and hardware requirements while preserving imaging accuracy to realize real-time acoustic imaging. Second, an integrated multi-technology testing platform will combine standard testing, beamforming, deconvolution acoustic holography and virtual sound-field modules, automatically selecting optimal algorithms to satisfy both routine quality inspection and mechanism research. Third, AI-empowered acoustic testing will employ deep learning to correct Doppler distortion, suppress spurious sources and reconstruct sound sources under low-SNR conditions, overcoming limitations of conventional algorithms. Fourth, a virtual-real integrated testing system will adopt dynamic simulation to generate source time-series data and reproduce noise radiation via virtual sound fields. Conventional standard acoustic testing and array-based acoustic imaging should advance in parallel. The coordinated development of multiple technologies can provide more comprehensive technical support for noise testing engineering and the R&D of acoustic equipment.

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