

A review of noise testing methods for multirotor UAVs under the low-altitude economy context: standards, distortion corrections and future perspectives

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Abstract. With the rapid development of China's low-altitude economy, the deployment of multirotor Unmanned Aerial Vehicles (UAVs) has expanded rapidly, while the impact of rotor aerodynamic noise on residential areas and public spaces has become an increasingly prominent issue. Establishing a standardized measurement method for UAV aerodynamic noise serves as the core foundation for subsequent UAV noise control and noise reduction design. Drawing on ISO 5305 as a framework, this paper introduces the generation mechanisms of aerodynamic noise in multirotor UAVs and the fundamental principles of directional noise testing using phased microphone arrays, analyzes the advantages of multi-arm spiral phased microphone arrays as a mainstream configuration, and elaborates on the correction methods for distortions arising from downwash turbulence and the Doppler effect. This study also points out that the current testing system still faces challenges including difficulties in multi-interference coupling correction, high equipment costs, and insufficient localization of international standards. For future research, artificial intelligence can be leveraged to develop an integrated multi-interference correction method that takes into account turbulence, Doppler effects, and meteorological factors; develop lightweight microphone arrays to reduce array costs; and improve the localized testing specification of ISO 5305 adapted to domestic scenarios so as to support UAV noise testing, noise reduction optimization and low-altitude noise control.

Keywords: unmanned aerial vehicles, noise measurement, low-altitude economy, phased microphone arrays, aeroacoustics

1. Introduction

Low-altitude economy, as an emerging industry, has seen large-scale promotion and application in scenarios such as logistics delivery, urban inspection, and cultural tourism. According to statistics, China plans to expand the overall industrial scale of low-altitude economy to 1.5 trillion yuan by the end of 2025; by the end of 2023, the domestic commercial unmanned aerial vehicle market size had reached 117 billion yuan, and the scale of the entire low-altitude economy chain exceeded 500 billion yuan. It is predicted that the market size of commercial unmanned aerial vehicle sub-sectors will exceed 400 billion yuan in 2025, and more than 70% of the commercial unmanned aerial vehicle supply chain capacity in the world is concentrated in China. In the

first half of 2024 alone, Shenzhen completed 225,000 on-demand drone deliveries. Low-altitude freight flights in the region are projected to exceed 1.5 million by 2025, while the scale of urban low-altitude flight operations continues to expand. However, the aerodynamic noise generated by the rotation of the drone rotor blades will cause acoustic interference to residential areas and public areas in the city, which has become a practical problem that needs to be addressed for the commercialization of low-altitude economy [1]. The noise characteristics vary greatly under different models and flight conditions. In the absence of unified and standardized noise testing methods, objective assessment of UAV noise emission levels remains infeasible, and noise-reduction design and regulatory control cannot be effectively implemented.

The International Organization for Standardization has released ISO 5305, which establishes a whole-machine noise testing framework for multi-rotor unmanned aerial vehicles with a maximum take-off mass of less than 150 kg [2]. The standard includes various test sites, evaluation indicators, and measurement constraints; however, different test environments have their own advantages and disadvantages, and the measurement process is also subject to signal distortion caused by rotor downwash turbulence, motion Doppler effect, etc., which directly affects the reliability of the measurement results [3]. The introduction of this standard in China still confronts a series of practical engineering challenges, including site selection, equipment deployment, data correction, and local adaptation.

This paper uses the literature research method to systematically review the research results in the field of aerodynamic acoustics and unmanned aerial vehicle noise testing at home and abroad, and conducts a horizontal comparison of different sound fields, test sites, array topologies, and imaging algorithms. Based on the ISO 5305 standard, this paper conducts research on the noise testing methods of unmanned aerial vehicles, systematically reviews the noise mechanism, test site, core equipment, and signal distortion correction means, analyzes the limitations of the existing testing system and proposes future research directions. The research results of this paper are conducive to promoting the formation of domestic standardized unmanned aerial vehicle noise testing methods.

2. The aerodynamic noise principles of unmanned aerial vehicle rotors

The general theoretical analysis for the aerodynamic noise of the rotors of multi-rotor unmanned aerial vehicles is the Ffowcs Williams-Hawkins (FW-H) acoustic analogy equation. This equation divides the rotor flow field noise into three types of sound sources: monopole (thickness noise), dipole (load discrete noise), and quadrupole (turbulent broadband noise) [4]. For consumer-grade and industrial-grade multi-rotor unmanned aerial vehicles, the dipole noise is the main component. Specifically, as the blades rotate, aerodynamic lift and drag at any given position vary periodically, giving rise to periodic pressure fluctuations that correspond to dipole sound sources and produce tonal noise at the Blade Passage Frequency (BPF). This blade tonal noise is the primary component to which residents are most sensitive. The monopole and quadrupole noises usually contribute less to the noise.

2.1. The fundamental principles of acoustic measurement

The core principle of spatial positioning in acoustic measurement is derived from the human binaural hearing effect. The left and right ears of humans receive sounds with a time difference and phase difference, and the human brain can distinguish the location of the sound source (up, down, left, or right) based on these subtle differences. This is the principle by which microphone arrays locate the source of noise when measuring the noise of unmanned aircraft. However, the human auditory system has only two receivers, which limits spatial resolution. Therefore, in actual testing, multiple microphone arrays are used. The phased microphone array

expands the binaural effect to tens of synchronous microphones for synchronous collection of sound signals. The fundamental basis for localization lies in the phase and time-delay differences of sound waves reaching different microphones [2]. When a single-point sound source radiates spherical sound waves, the propagation distances of the sound waves received by different microphones differ, forming a fixed phase shift. From this, the Direction of Arrival (DOA) is determined. On this basis, the system traverses the preset spatial grid and compensates for the theoretical propagation phase for each grid point. Among them, only the sound signals from the actual noise location can achieve coherent superposition, forming a significant energy peak, while the signals from other positions cancel each other out. Finally, a noise distribution cloud map is output. Furthermore, raw time-domain sound pressure waveforms cannot be used to directly resolve frequency components. They need to be converted into frequency-domain data through Fast Fourier Transform (FFT) and a cross-spectrum matrix is constructed as the core calculation carrier for various beamforming algorithms, achieving multi-rotor multi-source separation identification and precise imaging.

2.2. Under the ISO standards, the A-weighted sound pressure level is used to measure the magnitude of the noise heard by the human ear

The microphone merely collects the original sound pressure signals generated by air vibrations objectively. However, human auditory sensitivity varies considerably across high- and low-frequency ranges. Directly using the raw sound pressure decibel values cannot accurately reflect the actual auditory irritation perception of human ears. According to ISO 5305, after the noise from the unmanned aerial vehicle is measured by the microphone, it must undergo A-weighting conversion. The physically measured sound pressure is converted into a perceived noise level within the audible frequency range. The principle is to amplify the noise in the 2,000-5,000 Hz frequency band and reduce the noise in the frequencies that human ears are not sensitive to, in line with the characteristics of human auditory perception. Two primary metrics are employed: (1) Equivalent Continuous A-weighted Sound Pressure Level measures the unmanned aerial vehicle in hovering or stationary fixed-point conditions, and calculates the average value of all A-weighted noise energy within the measurement period to represent the average disturbance level of the stable sound source; (2) A-weighted Sound Exposure Level integrates and normalizes the entire noise energy of the moving unmanned aerial vehicle during cruise, flight over, etc., to fully assess the auditory interference caused by a single flight. The domestic unmanned aerial vehicle detection regulations follow this conversion rule. Unmanned aerial vehicle noise detection standards in China also adopt the above conversion rules.

2.3. Characteristics of anechoic and reverberation chambers and their measurement applications

Per ISO 5305, acoustic testing environments comprise anechoic chambers and fully diffuse reverberation chambers. These two types of chambers have distinct characteristics, and the corresponding acoustic testing scenarios for Unmanned Aerial Vehicles (UAVs) have fundamental differences [3]. The first type is the anechoic chamber, where the entire ceiling, floor, and four walls of the sound-absorbing room are covered with sharp-angled high-absorption materials, allowing sound waves to be completely absorbed. No reflected sound or reverberation interference exists within the chamber. However, in a semi-anechoic chamber, the floor does not undergo sound absorption treatment, which leads to confusion in sound imaging during directional tests. The main application scenarios of these two sound-absorbing chambers are the hovering static noise tests for micro UAVs (with a maximum take-off and landing mass of less than 4KG), which is also the only compliant site for the entire aircraft standardization calibration. During the test, a multi-arm spiral phased array can be used to complete sound imaging, accurately collecting the aerodynamic noise of the UAV rotor, analyzing the sound imaging, and conducting research on the spatial directionality of the noise. These two

testing scenarios have high construction costs, but they can precisely locate the sound source and measure the blade noise. The other type is the full diffusion reverberation chamber. The walls, floor, and ceiling use high-rigidity hard reflective structures. The walls are equipped with hemispherical devices, which can fully scatter the incident sound waves. The sound waves undergo multiple reflections, ensuring uniform density and irregular propagation direction at any position in the room. This sound field is mainly applicable to the batch total sound power detection of independent components such as UAV rotors and power motors, allowing for quick comparison of the overall noise levels of different components, but it cannot perform sound source localization and can only obtain overall noise data. According to the ISO 5305 standard, this type of chamber cannot be used as a noise testing standard site.

3. Comparison of four types of noise testing sites under the ISO 5305 standard

For multi-rotor drones with an MTOM less than 150KG, different test scenarios are divided: Micro-drones with an MTOM of less than 4 kg are preferably tested in an anechoic chamber, where the indoor sound-absorbing structure eliminates sound wave reflections, enabling array-based sound imaging and static tests [5]. The data reproducibility is excellent [6]; medium-sized logistics drones with an MTOM ranging from 4 to 150 kg can be selected for use in an anechoic wind tunnel, simulating the forward flight condition. Closed wind tunnels exhibit boundary-layer pseudo-noise, whereas open wind tunnels suffer from shear-layer refraction distortion. Both types of interference require corresponding data correction methods [2]. Large drones with an MTOM ranging from 25 to 150 kg can undergo outdoor flight tests to replicate low-altitude urban noise; however, these tests are subject to significant environmental disturbances, exhibit poor repeatability, and lack the validity of factory calibration. There is also a reverberation chamber, but it does not meet the requirements for standardized testing of the entire machine. The comparison of the four types of noise test sites under the ISO 5305 standard is shown in Table 1.

Table 1. ISO 5305 Comparison of four types of noise testing sites under standard conditions

Test site	Suitable for the MTOM range of unmanned aerial vehicles	Recommended test conditions	Core advantage	Inherent defect	According to ISO 5305 standard
Full anechoic chamber	< 4 kg Micro unmanned aircraft	Hovering and static fixed- point variable test	Six-sided sound absorption to eliminate sound wave reflection; supports multi-arm spiral array sound imaging; excellent data reproducibility [6]	The construction cost is high; it cannot simulate the forward airflow; the space size is limited	MTOM < 4 kg The only compliant site for the factory calibration of the entire unmanned aircraft system

Table 1. Continued

Anechoic wind tunnel (open type/closed type)	4~25 kg Medium-sized unmanned aircraft; 25~150 kg Large unmanned aircraft (when wind tunnels are available)	Hovering, level flight cruise	Controllable airflow environment, precisely simulating flight aerodynamic noise; capable of conducting acoustic imaging and issuing compliant test reports [2]	Closed wind tunnels have boundary layer pseudo-noise; in open wind tunnels, the airflow shear layer causes acoustic wave refraction distortion, and a correction algorithm must be provided for it	4~150 kg Universal legal whole-machine testing site for all models; 4~25 kg The preferred choice for mid-sized machines
Outdoor aerial course	25~150 kg Large heavy-duty unmanned aircraft (when wind tunnel unavailable)	Flying over the actual low-altitude route	Completely restore the actual flight environment of urban residential areas, Close to the perception of human ear noise	Multiple environmental factors such as wind speed, temperature and ground reflection cause poor measurement repeatability	This is merely an auxiliary test for understanding the working conditions and cannot be used as the basis for factory compliance calibration

4. Core measurement device: multi-arm spiral phased microphone array

The multi-arm spiral phased array microphone array is the core measurement equipment for drone noise imaging and directional testing. Compared with traditional rectangular and circular microphone arrays, it has significant technical advantages. The array is composed of multiple logarithmic spiral arms arranged radially, with microphone units densely packed on the inner side and sparsely on the outer side, and non-periodically distributed. It performs spatial sound source inversion based on the phase differences of sound waves reaching each microphone, and combines beamforming algorithms such as CFDBF, CLEAN-SC, and DAMAS to generate noise thermograms, accurately distinguishing independent noise sources from rotors and motors.

The core technical advantages of this array are summarized as follows:

The multi-arm spiral breaks the uniform grid periodicity, significantly weakening the grating lobes and sidelobe clutters at the structural level, resulting in a clean sound imaging picture, suitable for the coupled high- and low-frequency noise spectrum of UAVs [2].

The test is highly versatile: The microphone is densely arranged in the central area of the array, significantly improving the discrete pitch resolution of the high-frequency BPF in the motor; The large aperture layout on the outer circle can effectively enhance the ability to identify the tip vortex and downwash wide-band low-frequency noise, and a single array can completely cover the entire frequency band of the drone's aerodynamic noise, without the need to replace the equipment.

There is no blind spot for sound source resolution: The front and rear beam resolution differences of the traditional circular array are obvious, while the multi-arm spiral array has a uniform beam width in any horizontal orientation, and multiple noise sources generated by quadcopters and hexacopters can be accurately separated, without measurement dead zones. It can be used for hovering and flying over tests.

The measurement accuracy is high: Compared with the same number of microphone channels, the multi-arm spiral array is more accurate in testing noise energy, and can clearly distinguish strong and weak noise

points: For example, the noise energy distribution of the propeller tip, blade, and motor respectively, fully meets the ISO 5305 complete aircraft sound source positioning supporting test requirements, and has strong adaptability to the environment, requiring only simple calibration for different measurement environments [3]. The array must be positioned according to specific requirements: it should be placed above the UAV to avoid downwash turbulence.

5. Typical correction methods for measurement-induced signal distortions

Two typical signal distortions arise in UAV noise testing: rotor downwash turbulence interference and the Doppler effect caused by relative motion between the aircraft and the stationary receiver. Both types of interference can cause acoustic imaging clutter, spectral distortion, and other problems [2, 4].

The rotation of the UAV rotor generates high-intensity downward turbulence, which directly impacts the microphone array, resulting in pseudo wind noise and changing the local sound speed to disrupt the signal phase matching relationship.

6. Discussion

Despite the advances discussed above, the current multirotor UAV noise measurement system still faces several unresolved challenges. Various distortion corrections can only handle one type of distortion separately and cannot simultaneously correct the distortions caused by climate, turbulence, and the Doppler effect. High-precision microphone arrays are extremely costly and require complex calibration, limiting widespread adoption [7]. ISO 5305 is not fully adapted to domestic conditions, and further professional exploration is required for its localized implementation in China. Currently, China lacks a comprehensive standardized noise testing protocol for UAVs. For future research, an integrated correction method for various distortions, such as downwash turbulence, the Doppler effect, and the integration correction of multiple factors such as different wind speeds and directions, different temperatures and weather conditions, can be developed based on artificial intelligence. Lightweight, low-cost microphone arrays should be developed to reduce the barrier to entry for testing equipment. Based on the local application scenarios and residents' noise perception needs in our country and relying on the ISO 5305 standard, a set of noise testing standards more suitable for our country can be designed, providing a normative basis for domestic unmanned aerial vehicle noise testing, noise reduction optimization, and noise control.

7. Conclusion

This paper, based on the existing literature research results, summarizes the testing methods for the aerodynamic noise of multi-rotor unmanned aerial vehicles in the low-altitude economy context. According to ISO 5305, it introduces the sources and principles of rotor aerodynamic noise, as well as the testing principles of microphone arrays and the testing standards and distortion correction methods for different environments. The research results show that the noise of multi-rotor unmanned aerial vehicles is mainly dominated by dipole load noise, and the corresponding blades' frequency noise is the main source of disturbing the environment. In the four types of testing sites specified by ISO 5305, the anechoic chamber is suitable for full-aircraft calibration of micro-UAVs, the anechoic wind tunnel can simulate forward-flight conditions, and the outdoor overflight test can restore the real low-altitude environment. However, the test repeatability is poor, and the reverberation room can only be used for component noise detection and cannot be used for the compliance testing of the entire vehicle. The multi-arm phased array microphone array, with the advantages of

suppressing grating-lobes, wide-band resolution, and omnidirectional imaging, is the core equipment for the acoustic source positioning of unmanned aerial vehicles. The rotor downwash turbulence and Doppler effect will cause acoustic imaging clutter and spectral shift. These can be corrected through physical layout optimization and time-domain resampling algorithms. Currently, the testing system still lacks integrated correction methods for multiple simultaneous distortions. High costs of testing equipment and the absence of standardized testing specifications tailored to local conditions in China prevent the provision of essential technical support for low-altitude economy governance.

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