音響減衰に基づく回転翼機の検出および距離推定システムの開発

Development of System for Rotorcraft Detection and Distance Estimation Based on Acoustic Attenuation

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1. Introduction

With the widespread adoption of drones, the risk of mid-air encounters between helicopters and drones is increasing. Traditional sensors such as radar and cameras, although effective, tend to be power-hungry and bulky, making them unsuitable for lightweight drone platforms. Moreover, simply detecting the presence of a helicopter is not sufficient for practical collision avoidance—accurate distance estimation is essential. While previous methods often relied on RPCA to extract the periodic features of helicopter rotor noise, these approaches are computationally intensive and power-consuming, making real-time onboard implementation difficult. To address these challenges, this study proposes a sliding-window-based periodicity detection method as a practical alternative to RPCA, greatly reducing computational complexity. Combined with a frequency-dependent acoustic attenuation model, our approach enables efficient detection and distance estimation of helicopters on resource-limited drone platforms. Experimental validation against GPS data demonstrates that the proposed method consistently achieves accurate distance estimation, with prediction errors remaining within acceptable safety margins even under drone noise interference. This robustness highlights the potential of the approach to serve as a reliable onboard module for real-time collision avoidance in low-altitude drone operations.

2. Previous Research

2.1 Analysis of helicopter noise components

Helicopter noise primarily originates from both aerodynamic and mechanical sources. Among these, main rotor harmonics—arising from phenomena such as blade–vortex interaction (BVI) and high-speed impulsive (HSI) noise—dominate the acoustic signature in far-field conditions(1). The tail rotor typically generates noise at higher frequencies, while both tonal and broadband vortex noise contribute to the overall spectrum. Of particular importance for detection are the harmonic components associated with the blade-passing frequency (BPF), which serve as reliable periodic features for identifying helicopter presence(2).

2.2 Detection methods: Fast-SC and RPCA

To improve detection in noisy environments, recent research has focused on the periodic structure of helicopter rotor noise. Fast Spectral Correlation (Fast-SC) is an efficient algorithm for extracting cyclic features such as the blade-passing frequency (BPF) and its harmonics. It leverages the short-time Fourier transform (STFT) followed by a Fourier transform along the time axis, enabling rapid and effective highlighting of periodic components, making it suitable for real-time drone applications(3).

Robust Principal Component Analysis (RPCA), on the other hand, decomposes spectral data into low-rank (periodic) and sparse (noise) components. Although RPCA is effective for isolating helicopter features, it is computationally intensive and time-consuming, which limits its use in real-time or lightweight drone platforms. Furthermore, RPCA requires careful parameter tuning and may be unstable in highly dynamic acoustic environments.

In this study, we specifically replace RPCA with a lightweight sliding-window-based algorithm for periodic feature detection**.** This approach achieves significantly lower computational cost while maintaining robust performance, making it feasible for real-time implementation on drone hardware.

3. Proposed Helicopter Detection Method

3.1. Proposed sliding window based detection method

In real-world applications, the Fast Spectral Coherence (Fast-SC) algorithm often suffers from decreased sensitivity when the periodic features of helicopter rotor harmonics are weak, transient, or masked by environmental or UAV noise. These limitations become especially critical in complex acoustic environments where broadband interferences dominate, and rotor harmonics only intermittently appear due to Doppler effects, terrain occlusions, or non-stationary propagation paths.

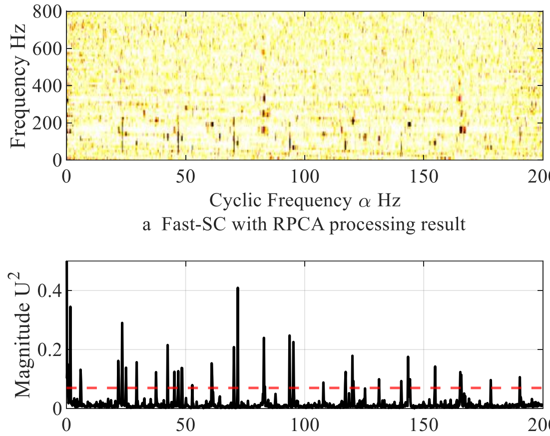
To enhance detection robustness under such conditions, this study introduces a sliding window-based spectral reinforcement method. The key idea is to emphasize temporally stable harmonic structures by averaging Fast-SC matrices across adjacent time frames. Periodic components—such as those originating from blade passing frequency (BPF) harmonics—tend to persist over time, whereas noise components fluctuate more randomly. Aggregating these matrices within a temporal window amplifies the aligned vertical structures associated with rotor harmonics and suppresses unrelated content.

Mathematically, let $C_t(f, \alpha)$ denote the Fast-SC matrix at frame t, where f is frequency and α is cyclic frequency. The enhanced matrix $\tilde{C}_t(f,\alpha)$ is computed as:

$$\tilde{C}_t(f,\alpha) = \frac{1}{w}\sum_{i=t-\lfloor\frac{W}{2}\rfloor}^{t+\lfloor\frac{W}{2}\rfloor} C_i(f,\alpha) \cdots\cdots\cdots (1)$$

3.2. Performance comparison with RPCA

To establish a baseline, we adopt the RPCA-based decomposition widely used in prior work, which separates the spectral coherence matrix into low-rank (periodic) and sparse (noise) components but incurs high computational cost.

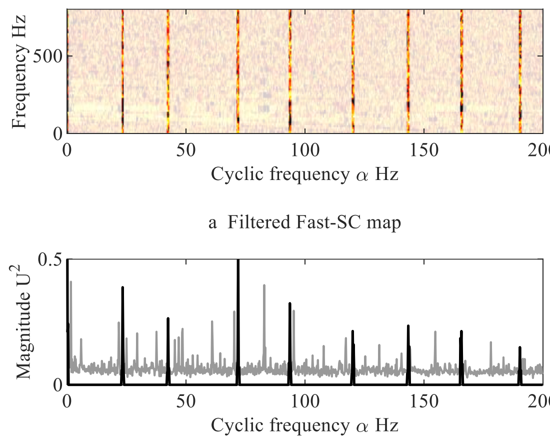


a Fast-SC with RPCA processing result

b Corresponding magnitude

Fig. 1. RPCA-based Fast-SC and U² results

We then apply the proposed sliding-window enhancement directly to Fast-SC outputs to emphasize temporally persistent harmonic structures with minimal overhead.



a Filtered Fast-SC map

b Corresponding U² curve

Fig. 2. Sliding window-enhanced Fast-SC and U² result

Contrasting Fig. 1 and Fig. 2 shows no loss in detection quality—BPF and harmonic ridges are equally clear or more continuous—while the proposed method cuts computation by about an order of magnitude and reduces memory usage, making it suitable for embedded UAV hardware. This demonstrates that the sliding-window algorithm retains the interpretability and accuracy of RPCA while greatly improving computational efficiency, thereby offering a practical solution for real-time onboard helicopter detection.

3.1 Innovative Acoustic Attenuation Modeling

In this study, a frequency-dependent acoustic attenuation model is applied to estimate the distance between a helicopter and the receiver based on the spectral characteristics of rotor noise. Instead of relying on the overall sound pressure level, the method evaluates how the amplitude of each frequency component is attenuated during propagation. The total attenuation is modeled by combining the effects of spherical wave spreading and frequency-selective atmospheric absorption. The frequency-dependent loss is expressed as:

$$\Delta L(f) = \{20 \cdot \log\left(\frac{r}{r_0}\right) + \alpha(f)\cdot r + \beta\} \cdots (2)$$

where

- $\Delta L(f)$: amplitude attenuation at frequency f;
- r: unknown distance to the helicopter;
- r_0: reference distance (such as 300 meters);
- $\alpha(f)$: frequency-dependent atmospheric absorption coefficient, determined by environmental factors (temperature, humidity, pressure, etc.);
- β: empirical correction factor for unmodeled influences and practical deviations.

In equation (2), the key quantity connecting frequency and attenuation is the frequency-dependent absorption coefficient $\alpha(f)$. This parameter is determined by several physical processes, including molecular viscosity and the relaxation effects of oxygen and nitrogen. The complete formula is given by:

$$\alpha(f) = 8.686 \cdot f^2 \cdot (z + v + b) \cdots\cdots (3)$$

where:

- z: absorption due to molecular viscosity
- v: oxygen relaxation absorption

- b: nitrogen relaxation absorption

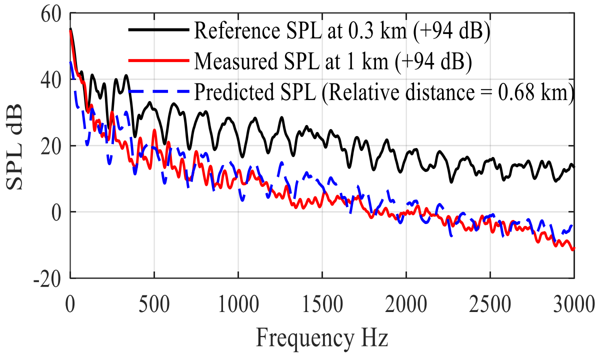


Fig. 3. Comparison of reference, measured, and predicted SPL spectra

3.2 Frequency-Domain Approach for Helicopter Distance Estimation

The proposed method estimates helicopter distance by segmenting the audio into overlapping frames and calculating the power spectral density (PSD) within the 15–3000 Hz range using Welch's method. For each time frame, the measured PSD is compared with a set of predicted spectra generated by applying a physical attenuation model—including spherical spreading and frequency-dependent atmospheric absorption—to a reference recording at a known distance. Environmental parameters such as temperature, humidity, and pressure are incorporated into the absorption coefficient to ensure accurate modeling of real-world propagation. The optimal distance for each frame is determined by searching for the candidate value that minimizes the mean squared error (MSE) [4] between the measured and predicted spectra. This approach enables robust, real-time distance estimation using only single-channel acoustic data. The effectiveness of this method is demonstrated by comparing the estimated results with ground-truth GPS measurements, as shown in Fig 1.

4. Results and Validation of Distance Prediction

4.1 Validation Using Helicopter GPS Data

Fig. 4. Observation point

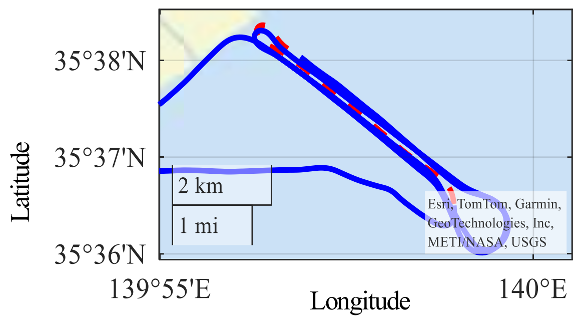


Fig. 5. GPS map

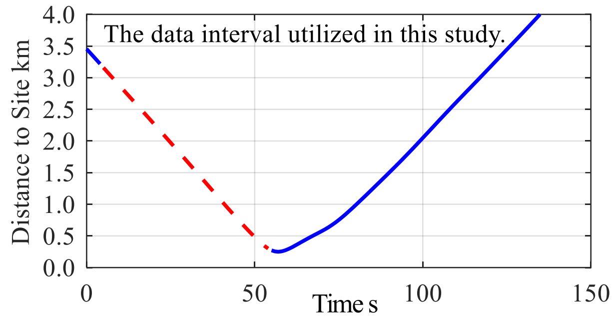


Fig. 6. Relative distance to the observation point

To validate the proposed distance estimation model, helicopter GPS data obtained from real-world field experiments were used. Figure 4 shows the measurement setup, while Figure 5 depicts the helicopter's flight trajectory. Figure 6 presents the time series of the helicopter's relative distance to the observation point. In order to evaluate the robustness of the proposed method under noisy conditions, additional drone noise (recorded at a distance of 1 meter) was manually superimposed onto the helicopter audio, and the resulting mixed signal was analyzed. Figure 5 illustrates the predicted distance trajectory for the combined signal. The estimated distances were compared with the actual GPS-measured movement during the overlapping time segment to assess the accuracy of the approach.

4.2 Comparison of GPS-Derived and Predicted Distances

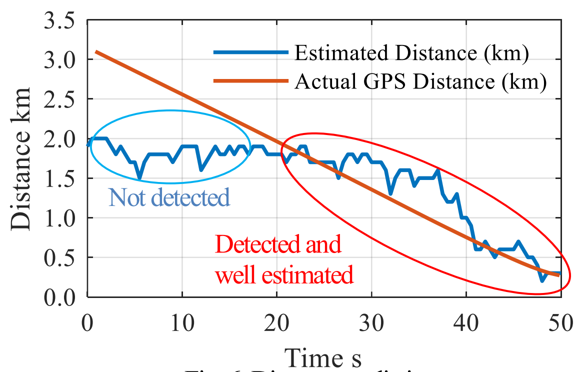


Fig. 6. Distance prediction map

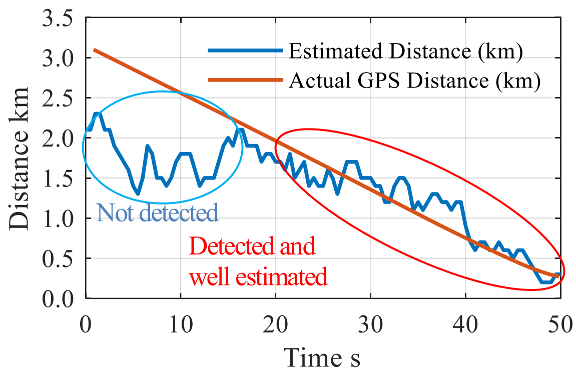


Fig. 7. Distance prediction map (with drone)

Figures 6 and 7 present a detailed comparison between the helicopter's actual distance, measured via GPS (red line), and the distance predicted by the proposed acoustic-based model (blue line) under two different noise conditions. Figure 6 illustrates the baseline case without drone interference, where the predicted trajectory closely follows the GPS reference with minimal deviation, particularly as the helicopter approaches within approximately 2 km of the observation point. In contrast, Figure 7 shows the performance when additional drone noise is superimposed, introducing interference in the mid- and high-frequency ranges. While the added noise slightly reduces prediction accuracy—as highlighted in the red-circled region—the model still captures the overall distance trend with high fidelity, and the mean error remains within an acceptable margin for practical use. This outcome underscores the robustness of the model even in acoustically challenging environments.

4.3 Effect of Drone Interference on Distance Prediction

In the presence of drone noise, the analysis bandwidth is restricted to frequencies below 500 Hz to avoid overlap with UAV acoustic components, which typically dominate higher-frequency ranges. Although this restriction inevitably reduces the available spectral information and leads to a moderate decrease in precision, the proposed model continues to demonstrate a reliable ability to track the helicopter's approach trajectory. The persistence of predictive capability under bandwidth constraints highlights the method's resilience and suitability for real-world deployment, where environmental and operational noise cannot always be controlled. Importantly, this result shows that the sliding-window-based detection combined with the frequency-dependent attenuation model retains sufficient discriminatory power to support early-warning systems in multi-aircraft low-altitude operations.

5. Conclusion

This study developed and validated a novel acoustic-based framework for helicopter detection and distance estimation in complex drone environments, with the following key findings:

(1) Detection:

A new detection algorithm based on Fast Spectral Correlation (Fast-SC) was introduced, replacing the conventional use of Robust Principal Component Analysis (RPCA) for periodic component separation. Compared to RPCA, the Fast-SC method significantly reduces computational complexity and energy consumption while maintaining high detection accuracy for rotor periodic features, even in noisy environments. This makes it particularly suitable for deployment on resource-constrained platforms such as drones.

(2) Distance Estimation:

For distance estimation, the proposed method utilizes a full-band acoustic attenuation model, achieving robust distance prediction by matching the frequency-domain spectra of reference and observed signals. Experimental validation demonstrates that the method maintains high accuracy and practical reliability even when the analysis bandwidth is limited to mitigate drone noise. Overall, this approach offers a promising technical solution for early warning and flight safety in low-altitude, multi-aircraft airspace. Future work will focus on adaptive frequency band selection and multi-sensor data fusion to further enhance robustness and practical applicability.

Acknowledgments

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