Numerical Analysis of Tonal Noise Emissions from Shrouded and Unshrouded Contra-Rotating Propellers

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Introduction

As market growth projections for Urban Air Mobility vehicles (UAMs) skyrocket, their presence in urban environments is likely to become increasingly prevalent, as will their noise. This creates a disturbance to both humans and wildlife, previously unaffected by aircraft noise. Further reinforcing the concern is the new multi-rotor designs, which introduce additional sources of noise.

Research on novel designs provides a limited understanding of the primary noise-generating mechanisms contributing to overall sound production. Among these innovative designs, complex geometries like open Contra-Rotating Propellers (CRP) and Shrouded Contra-Rotating Propellers (S-CRP) emerge. This study focuses on CRPs because they are anticipated to offer increased thrust with the same platform area, crucial for urban UAM operations. Additionally, shrouds are explored for their potential for increased thrust, acoustic shielding, and directivity manipulation, while also offering space for acoustic liners and increasing safety for ground operators.

The objective of this study is to isolate the aerodynamic and acoustic installation effects and identify the noise-generating mechanisms of the CRP and S-SCRP configuration.

Methodology

For this, the aerodynamics and acoustics of six propeller configurations are analyzed, including both the primary CRP and S-CRP geometries and sub-variants thereof. The exploration uses a hybrid numerical methodology, consisting of an aerodynamic flow solver based on the unsteady Reynolds-Averaged Navier-Stokes equations (uRANS) and a Finite Element Method (FEM) acoustic propagation solver. The latter generates acoustic sources from the aerodynamic solution using the source mode formalism.

This not only facilitates an aerodynamic understanding of the acoustic sources but can also detail near-field effects on acoustic propagation. While alternative methodologies achieving similar results necessitate high-fidelity simulations, the uRANS-FEM method can effectively capture aerodynamic and propagation effects within a moderate computational time. However, it also restricts analysis to tonal components of loading noise.

Results and Analysis

Aerodynamic Effects

In hover conditions, when compared with two isolated individual propellers, the CRP configuration generates 57.53% more thrust per area, although the efficiency is reduced by 27.13%. The aerodynamic interactions between propellers in a CRP system are due to two possible effects, the potential field distortion and the viscous wake including the tip vortex interaction. Of these two, this study suggests that the potential interference between the two propellers is important, if not dominant, on the rear propeller.

In the case of the S-CRP, the shroud itself generates about a third of the total thrust of the system. While it provides increased thrust per area compared to two single propellers, it does not outperform the open CRP configuration. The introduction of the shroud creates a large separation along its inner wall, detrimentally

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impacting the performance of both propellers. The lead propeller's proximity to the point of separation causes a lesser effect near the blade tips than the rear propeller, which experiences a large portion of the blade tip in stagnant or reversed flow. This reduces thrust across the span but, particularly the peaky region of the rear propeller thrust distributions.

Acoustic Effects

For the CRP, the interaction of the blades increases the noise at almost all tones, however, the first BPF (Blade Passage Frequency) is still dominated by steady noise and shows little change for individual blades. The interaction of the blades only generates unsteady loading noise at multiples of 2xBPF. This, along with the modulation of noise into higher harmonics, creates a repeating pattern for higher BPF harmonic directivities, one shape for odd multiples and one for even.

The total noise increase observed in the S-CRP system compared to the CRP system is concentrated in the rotor plane and ranges from 5 to 25 dB depending on the frequency and azimuth angle. This contradicts the previous predictions from the literature which predicts a lower decreased noise. Separating the aerodynamic installation and acoustic installation effects, the noise actually decreases by 1-2 dB due to the aerodynamic effects on the blade.

The acoustic installation effects are shown to be dependent on the position of the propeller within the shroud. The close proximity of the lead propeller to the leading edge of the shroud results in an increase in noise, indicating that the presence of the leading edge strongly influences the propagation of acoustic pressure away from the propeller sources. On the other hand, the rear propeller positioned in the middle of the shroud length shows a decrease at the 1st BPF and a decrease or lower increase at higher BPF harmonics, depending on the presence of a coaxial rotor, in noise within the rotor plane, aligning more closely with the literature.

Closing Remarks

This study provides a detailed analysis of the noise-generating mechanisms in CRP and S-CRP configurations and offers recommendations for the development of quieter and more efficient UAMs. This sets up future work for informed optimization of these configurations to enhance performance while minimizing acoustic emissions.