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AEROACOUSTICS OF UAV PROPELLERS WITH UNEQUALLY SPACED BLADES

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ABSTRACT

The study delves into the characterisation of the aeroacoustic response of low-Reynolds number propellers subjected to blade spacing angle modification. A numerical investigation was carried out on two-bladed propellers featuring blade spacing angles from 30 to 150 degrees, in 30-degree increments, as well as a conventional propeller with 180-degree blade spacing. The non-uniform blade spacing can mitigate tonal contributions at the blade passing frequency and its harmonics while introducing non-zero contributions at odd multiples of the shaft frequency. The objective of this work is to determine the effect of the blade spacing angle on the distribution of the acoustic energy spectrum and the aerodynamic quality of the propeller. The numerical analyses were performed by a potential aerodynamic solver based on a boundary integral method and an aeroacoustic solver based on the Farassat 1A formulation. The predictions were validated against experimental measurements for conventional and 90-degree blade spacing propellers. The time-averaged propeller thrust and tonal overall sound pressure level were accurately predicted. Propellers with uneven obtuse blade spacing angles displayed the largest addition of the acoustic energy towards the lower frequency domain while preserving the aerodynamic performance of the reference propeller.

Keywords: *aeroacoustics, aerodynamics, propellers.*

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1. INTRODUCTION

The prevalence of unmanned aerial vehicles (UAVs) utilising low-Reynolds number propellers is increasing, leading to the establishment of new economic sectors. The perception of noise pollution by humans and the subsequent public acceptance of UAVs represent one of the major barriers to the widespread adoption of these aircraft [1]. The optimisation of propeller designs aimed at mitigating the adverse effects of noise pollution presents significant advantages to emerging aerial robotics services. For this reason, academia and industry are making considerable efforts to investigate and design innovative solutions aimed at reducing the acoustic nuisance of these vehicles [2–4]. To this aim, it is evident that a profound understanding of the mechanism governing noise generation is essential to characterise the acoustic footprint of low-Reynolds number propellers, a topic that has become the focus of extensive literature [5–9].

This study investigates an approach to mitigate acoustic emissions, by manipulating the blade spacing angle that eliminates radial symmetry. Under the assumption of identical and evenly spaced blades, the tonal components of the emitted noise emerge at frequencies that are multiples of the blade passing frequency (BPF) [10]. Contrarily, with blades that are not equally spaced, the tonal noise components manifest at harmonics of the revolution frequency. Therefore, the premise is to utilise this redistribution of the energy content resulting from the uneven blade spacing to diminish the noise emitted at the multiples of the BPF, while recognising that the drawback is the onset of tonal contributions at the revolution frequency and its odd harmonics. It is critical to emphasise that the blade spacing, in principle, influences the aerodynamic performance. Hence, a balance between acoustic benefits and performance deterioration should be found.

In this context, a characterisation of the aeroacoustic response of uneven-blade spaced propellers was conducted. Six distinct propeller configurations were examined, featuring blade spacings of 30, 60, 90, 120, 150, and 180 degrees. Due to the apparent radial asymmetry due to uneven blade spacing, these propellers can be referred to as ”asymmetric” propellers. The numerical analysis was performed through the application of an aerodynamic solver based on a boundary integral formulation for potential flows and an aeroacoustic solver based on the Farassat 1A formulation for tonal noise prediction. Numerical simulations were supplemented by the experimental measurements of a conventional propeller configuration described by blade spacing of 180 degrees, referred to as VP-R, and a non-conventional design with blade spacing of 90 degrees, denoted by VP-9.

2. NUMERICAL METHOD

The aerodynamic analysis was performed through a Boundary Element Method (BEM) solver based on the boundary integral formulation introduced in [11], able to take into account the effects of significant body-wake interactions. Under the assumption of potential and incompressible flows, the potential field was defined as the superposition of an incident field, generated by doublets over the wake portion not in contact with the trailing edge (far wake), and a scattered field, generated by sources and doublets over the body and doublets over the wake portion very close to the trailing edge (near wake). This procedure allows the removal of the numerical instabilities arising when a doublet wake comes too close to or impinges on the body. Recalling the equivalence between the surface distribution of doublets and vortices, the contribution of the far wake was expressed as a net of thick vortices (i.e., Rankine vortices). In this approach, the wake shape can be either assigned (prescribed-wake analysis) or obtained as a part of the solution (free-wake analysis) by a time-marching integration scheme in which the wake points move according to the local velocity field.

Once the potential field was obtained, the Bernoulli theorem yielded the pressure distribution on the body that, in turn, was used both to determine the aerodynamic loads and to predict the radiated noise, being the input of the aeroacoustic solver. The aeroacoustic analysis was performed by a prediction tool based on the linear Farassat 1A boundary integral formulation [12]. Specifically, the acoustic pressure field was given as the superposition of only the thickness noise depending on body geometry and kinematics and the loading noise related to the pressure distribution over body surfaces (being the quadrupole term negligible in the analysed flight condition).

3. VALIDATION

The numerical aerodynamic and aeroacoustic solvers used in this study have undergone extensive validation against empirical data [13–15]. However, due to the unconventional propeller geometries examined herein, an additional validation set involving a propeller with unequal blade spacing angles has been presented.

All the numerical results presented in the paper were obtained by discretising each propeller blade in $6,000$ panels, whereas $43,200$ panels are used over the corresponding wake surface, which was assumed to be eight revolutions long, with 60 panels distributed along the radial direction. A schematic representation of the discretised geometry is shown in Figure 1 for the baseline propeller configuration. A free-wake algorithm was used for the aerodynamic solution. A non-dimensional time-step of 3 degrees was used for the aerodynamic analysis, whereas a step of $1/2$ degrees was used for the aeroacoustic one. It was verified that these computational mesh characteristics and time discretisation guaranteed converged numerical results.

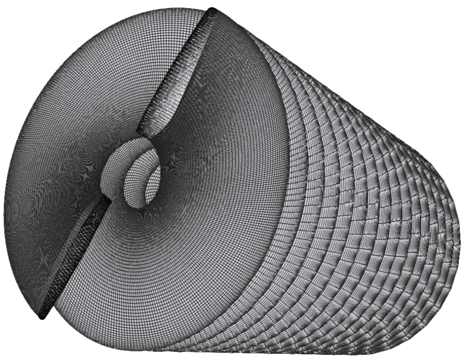

Figure 1. Discretisation of the reference propeller, VP-R.

3.1 Propellers

For validation of the numerical solver, two fixed-pitch, 16×5.5 inches lifting propellers were examined: the conventional, reference off-the-shelf propeller (VP-R) and a custom propeller with 90-degree blade spacing (VP-9), as illustrated in Figure 2. The designation "VP" refers to V-Propeller, named for its characteristic shape. Both propellers had equivalent blade geometry, solidity and tip radius, and were fabricated by a company specialising in the low-Reynolds number propellers manufacturing. To address the inertial imbalance in the plane of rotation for the VP-9 configuration, a finely tuned counterbalance pellet was fitted into the elongated hub of the propeller.

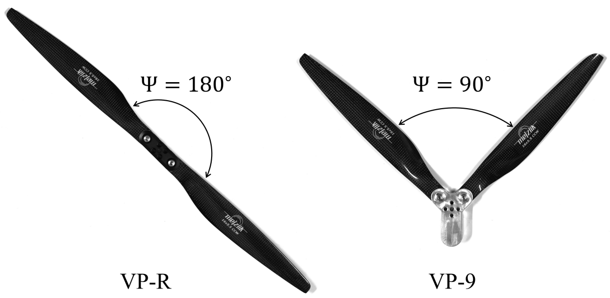

Figure 2. Propeller set. Reference propeller, VP-R, and propeller with 90-degree blade spacing angle, VP-9.

3.2 Test procedure

The aeroacoustic response measurements were carried out in an anechoic chamber with a cut-off frequency of 50 Hz at the University of Salford, instrumented to measure far-field aeroacoustic response for different observation angles. In particular, nineteen 1/2-inch far-field pressure microphones – nine Brüel and Kjær 4963 and nine GRAS 46AO – were installed on a two-and-half meter arc centred in the propeller hub and lying in the plane orthogonal to the propeller plane of rotation. The microphones were uniformly spaced across observation angles, θ, ranging from 0 to 180 degrees, in 10-degree increments, with the microphone at a 180-degree observation angle located within the propeller wake. The microphone signals were recorded at a sampling rate of 50 kHz.

3.3 Aerodynamic response

The comparison of the time-averaged static thrust predictions with the experimental data is presented in Figure 3 for the VP-R and VP-9 propeller. The agreement between simulated results and test data was deemed satisfactory, particularly in the $3,500$ to $5,000$ rpm domain. At rotational speeds below $3,500$ rpm the Reynolds number at 75% tip radius falls below $50,000$, leading to augmented effects of viscosity terms. At speeds exceeding $5,000$ rpm, the influence of compressibility becomes substantial. These effects are not captured by the governing equations of the aerodynamic solver, resulting in a slight decline in the level of agreement within these speed domains. Nonetheless, the observed discrepancies remained marginal. At a speed of interest, $5,000$ rpm, the percentage error between predicted and mean measured thrust for VP-R and VP-9 propellers were 2.9% and 1.6%, respectively. Regarding the effect of the blade spacing, it only

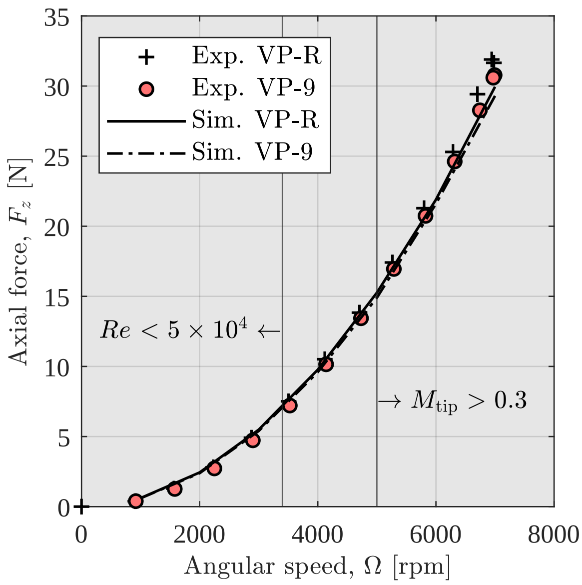

Figure 3. Validation of the predicted time-averaged static propeller thrust.

slightly affects the aerodynamic performance, and mainly for angular velocities higher than $6,000$ rpm. In particular, a thrust decrease as the propeller blade spacing decreases is observed, as captured both numerically and experimentally.

3.4 Aeroacoustic response

For the spectral analysis of the experimental data, a Hanning window was used, characterised by a constant partition size of 2^{17} and 75% overlap, giving a frequency resolution of 0.38 Hz. The power spectral density was obtained using Welch's method. The reference acoustic pressure level was assumed at 20 µPa.

The noise directivity in terms of zero-weighted overall sound pressure level (OASPL) is shown in Figure 4. The simulated OASPL had a tonal nature and solely incorporated the first ten harmonics of the rotational frequency. Consequently, only the tonal contributions of the measured sound pressure level spectrum were extracted and truncated at a fifth BPF harmonic, $0 < f^+ \leq 5$, to ensure that the experimental results remained directly comparable to the simulation output. The acoustic response was not reported for emission angles between 170 and 180 degrees due to the contamination of the recorded sound pressure signal by the propeller wake. In the case of a conventional propeller, VP-R, the mean discrepancy between the measured data and the simulation for all reported emission angles was found to be 3.9 dB. The most considerable discrepancies were observed at the emission angles corresponding to the suction side of the propeller, ranging from 0 to 20 degrees. In contrast, the OASPL predictions for the propeller with 90-degree blade spacing, VP-9, displayed a strong agreement with the experimental data, yielding a mean difference of 2.3 dB, with discrepancies consolidated in the domain from 60 to 110 degrees.

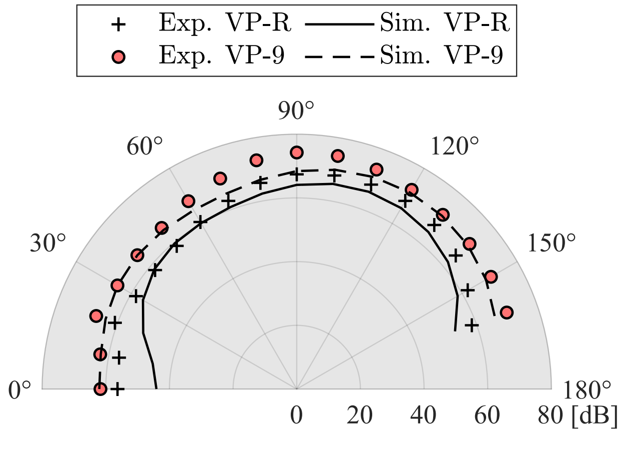

Figure 4. Tonal **OASPL** polar.

4. RESULTS

Upon validating the numerical solver against the experimental data corresponding to both the VP-R and VP-9 configurations, the solver was subsequently employed to asses the influence of the blade spacing angle on the aerodynamic and aeroacoustic responses of the propeller. Figure 5 shows the effect of the blade spacing angle on the time-averaged propeller thrust coefficient – computed at $5,000$ rpm in static flight conditions. In agreement with the experimental observation for the VP-R and VP-9 propellers, as well as findings reported in prior publications [16, 17], a decrease in blade spacing angle corresponded with a reduction in time-averaged propeller thrust. Especially, at a blade spacing angle of 30 degrees, a thrust reduction of approximately 9% was observed, a trend that displayed lesser impact for obtuse angles, with thrust reduction diminishing to less than 1% for blade spacing angles greater than 120 degrees.

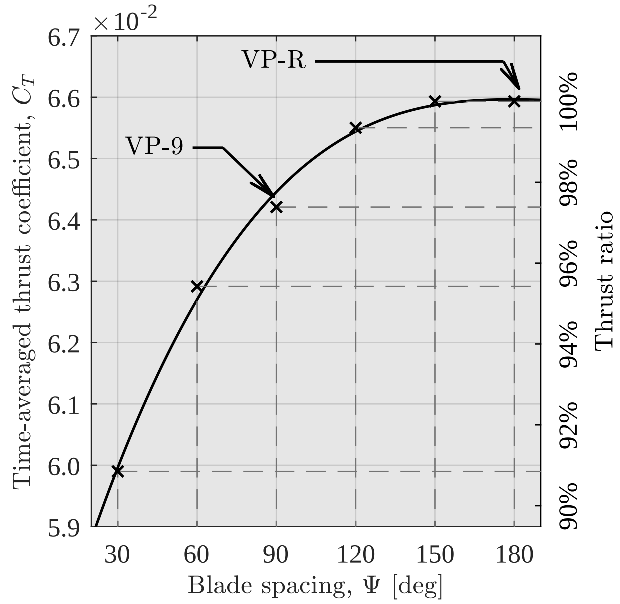

Figure 5. Variation of time-averaged propeller thrust coefficient as a function of the blade spacing angle.

The predicted tonal components of the sound pressure level are illustrated in Figure 6. As anticipated, propellers featuring uneven blade spacing demonstrated the emergence of tones at odd multiples of the shaft frequency. This observation suggests that the uneven blade spacing angle has indeed facilitated a redistribution of acoustic energy within the frequency spectrum. Furthermore, as the blade spacing was reduced a greater amount of acoustic energy was added to the spectra within the analysed frequency interval, $0 < f \leq 833$ Hz. However, it would be a misinterpretation to assert that reduced blade spacing negatively affects acoustic performance, as only the first five BPF harmonics were identified. The observed increase in peak amplitudes may be correlated with a shift in tonal energy toward the lower frequency domain, which must occur at the expense of the higher frequency energy content, thereby the total radiated acoustic energy must be preserved – subject to further investigation.

5. CONCLUDING REMARKS

A numerical and experimental study was conducted to analyse the aerodynamic and aeroacoustic characteristics of a two-bladed low-Reynolds number propeller with uneven blade spacing under static flight conditions. The correlation found between the measured experimental data and the numerical results enhances the fundamental understanding of the key factors affecting both the aerodynamic efficiency and the sound signatures linked to these configurations, while also confirming the effectiveness of the numerical solver for unconventional propeller designs.

A parametric analysis was performed to investigate how different blade spacing angles affect aerodynamic and aeroacoustic behaviours in propellers. The blade spacing angles considered were 30, 60, 120, and 150 degrees.The purpose of this study was to explore the possibility of optimising the blade spacing angle to shift acoustic energy content toward the lower frequency domain while also minimising negative effects on aerodynamic performance.

The implementation of uneven blade spacing facilitates a redistribution of the acoustic energy content towards the lower frequency domain. The uneven blade spacing added more energy into the spectrum in the frequency interval up to the fifth BPF harmonic. Understanding whether this increase in acoustic energy at the lower end of the frequency spectrum occurs at the expense of the higher frequency content remains a topic for further investigation.

6. ACKNOWLEDGMENTS

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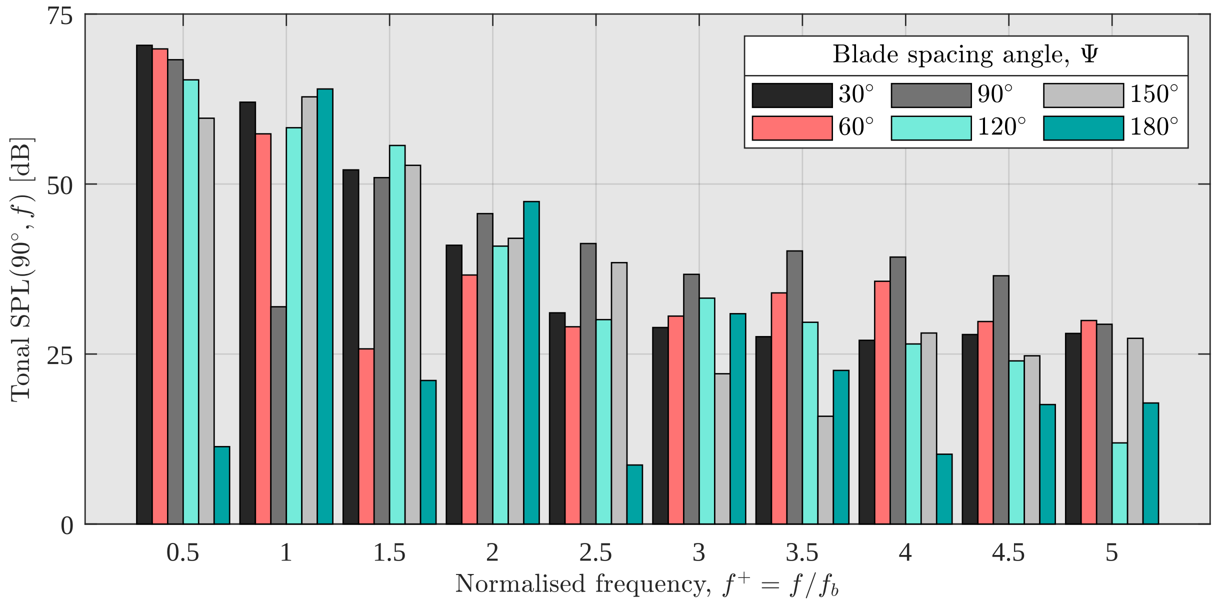

Figure 6. Frequency response of tonal sound pressure level as a function of the blade spacing angle in decibels at 5,000 rpm for an observer in the plane of rotation.

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