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An experimental study on rotor aeroacoustics under unsteady rotational velocity

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ABSTRACT

Acoustic annoyance is a keen factor in the social acceptance of novel urban air mobility concepts. Although regulations and certification requirements exist for such operations, they rely on measurements of the vehicle under controlled, and mostly steady, conditions. These conditions differ significantly from real envisioned operations, where turbulence from the urban environment, rapid maneuvers, system automatic control, and gusts can affect the vehicle's noise emissions. To assess such differences, this work focuses on the study of rotors, commonly applied to urban air mobility and transport vehicles, under varying rotational speeds. An experimental campaign is carried out in the anechoic wind tunnel of the Delft University of Technology, where an unsteady rotational speed of the rotor is prescribed. Acoustic measurements are carried out along with the integral loads of the rotor. The work explores both the aerodynamic effects of such an operation and its impact on noise emissions. The final goal is to create a global picture of the relevance and physics of rotor noise under non-steady rotational speeds.

1. INTRODUCTION

The social acceptance of novel Urban Air Mobility (UAM) and drone concepts is heavily influenced by their acoustic footprint, as noise annoyance remains a critical concern for communities in urban environments.

Although regulations and certification requirements exist for such operations, they rely on measurements of the vehicle under controlled, and mostly steady, conditions [1, 2]. Similarly, traditional research on propeller noise has predominantly focused on analytical predictions, experimental validations, and numerical simulations of isolated rotors operating at constant rotational speeds, neglecting the dynamic nature of real-world operations.

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Recent studies have since demonstrated how deviations of such conditions can have a strong influence on the noise emissions. In particular, unsteady loading caused by flow asymmetry, presence of surrounding bodies, such as wings, struts, or fairings, can strongly impact the noise emissions. Slight changes in the flow field due to interference effects significantly alter the noise signature. Studies on adjacent rotors show that the unsteady thrust produced by the rotors will be reduced compared to the isolated case, due to the complex flow field that forms [3–5]. As a result of the unsteady loading, the produced noise levels will increase and the noise directivity pattern is significantly altered [6, 7]. Similarly, interference between rotors and downstream wings [8], and struts [9], can increase the harmonic and broadband noise levels of the rotor. The previous studies demonstrate the importance of considering system integration on the estimation of rotorcraft noise.

Besides installation effects, other factors are expected to influence noise emissions. Urban Air Mobility and drone concepts are expected to operate in urban environments, where atmospheric gusts, and rapid maneuvers are necessary. For instance, transient rotorcraft maneuvers, such as a pitch-up, lead to particularly large unsteady loading fluctuations over a short time. This results in dramatic changes in noise magnitude and directivity, due to the particularly complex flow field that occurs [10]. This is but one example of the many varying flow conditions that can occur. For UAM applications, these operations are only possible with the use of automated control systems, which can swiftly change the conditions of the rotors and vehicle attitude, ensuring a safe and optimal operation. In such operations, rotor RPM, attitude, and operating conditions are expected to be always fluctuating, differing significantly from real envisioned operations, where turbulence from the urban environment, rapid maneuvers, system automatic control, and gusts can affect the vehicle's noise emissions. Several works have investigated the effects of speed-controlled rotors on aircraft dynamics [11, 12]; however, these were limited in their investigation of aerodynamic and aeroacoustic effects.

This work aims at exploring the effect of varying rotational speed on the noise emissions of an isolated rotor. An experimental campaign is carried out where harmonic variations of the rotor RPM are prescribed and integral loads and noise emissions are measured. Results describe the obtained data with focus on the discrepancies observed between the steady RPM conditions and the varying RPM ones.

2. EXPERIMENTAL SETUP

2.1. Benchmark rotor model, facility and rotor rig

The model rotor is based on an APC 9×6 propeller scaled to 0.3 m diameter, using NACA 4412 airfoil geometry. The propeller geometry is described in the work of Grande et al. [13].

Measurements are conducted in the A-Tunnel facility. The testing section of the facility comprises a semi-anechoic facility with 150 Hz cut-off frequency [14]. In this campaign no flow is used.

The rotor is mounted 0.3 m from the nozzle exit on a propeller rig. The propeller is driven by a Leopard Hobby 3536-5T 1520 KV motor. The motor is controlled by a siliXcon SX speed controlled operating in BLDC mode. The speed controller allows for analog throttle input, which is realized via a NI cDAQ 9262 voltage output module. This setup allows for prescribing the rotor speed as desired. It is here important to mention that the throttle control does not directly translate into the rotational speed. System mechanical and electrical inertia lead to deviations from the prescribed motion, especially relevant for fast harmonic variations.

Integral loads are assessed using a Futek mini 40 6-axis load cell. 8 GRAS 46BE microphones are placed on a directivity arc for assessing noise emissions from the rotor. Microphones have flat response up to 50 kHz (1 dB deviation) and verification of the calibration takes place with a GRAS 42AG pistonphone. Acquisition is controlled via an NI PXI chassis and PXI 4499 boards. Synchronously, load cell, microphone, throttle input, and encoder data are acquired. Acquisition

	ω_o [RPM]	A_ω [RPM]	f_ω [Hz]
Steady conditions	3,000, 3,050, ..., 4,950 , 5,000	-	-
Unsteady conditions	4,000	250, 500, and 900	0.25, 0.50, 0.75, 1
	4,000	250, 500, and 900	2, 3, 4, 5, 6, 7

Table 1: Experimental test matrix and data availability.

takes place during 60 seconds with a sampling rate of 204,800 samples per second.

3. TESTING CONDITIONS

Experiments are carried out in two different conditions, i.e. steady rotational speeds and prescribing harmonic variations of the rotational speed. The latter is based on a steady speed over which an harmonic motion is prescribed, following equation 1. Three different amplitudes of modulation and 10 different modulation frequencies are used. Table 1 summarizes the test matrix of the experimental campaign and the data availability.

$$\omega(t) = \omega_o + A_\omega \sin(2\pi f_\omega t). \quad (1)$$

4. RESULTS AND DISCUSSIONS

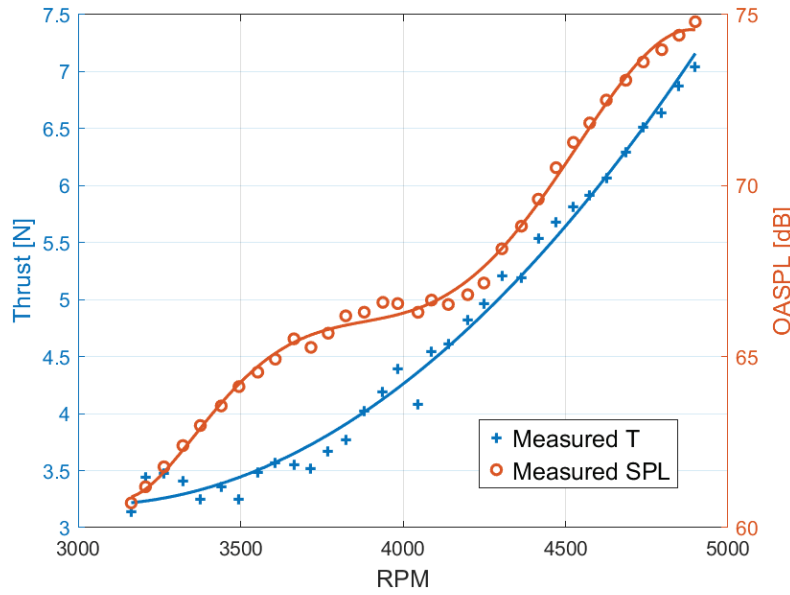
This section presents some of the results obtained from the experimental campaign. These provide a starting point for assessing the response of a rotor undergoing transient changes in rotational speed in terms of thrust and noise.

4.1. Overall load and noise

The propeller static thrust and overall sound pressure level (SPL) was measured in hover conditions, i.e. no axial inflow ($J = 0$) at various RPM modulations settings. This is depicted in Figure 1, which shows the measured thrust and noise as a function of RPM. The thrust is seen to increase quadratically from 3.1 N to 7.1 N as the RPM increases. The parabolic relation seen here is consistent with what is expected from theory and corresponds to static thrust measurements from other authors [15, 16]. It should be noted that, for this preliminary investigation, the thrust has not been non-dimensionalized to maintain consistency with the sources being compared to. The relation between SPL and RPM is also shown in Figure 1. In this case, a somewhat non-intuitive SPL vs. RPM is observed. In general, the noise emissions increase with the RPM, as expected. However, a somewhat smaller slope increase is seen in the range between 3,500 and 4,000 RPM. The noise level increases from 61 dB to a maximum of 75 dB. It is yet not sure what causes the noise levels to change its rate of increase between 3,500 and 4,00 RPM, and aerodynamic measurements are planned to understand the physical mechanism underlying these observations.

4.2. Transient Thrust Investigation

The propeller transient response is investigated by imposing a sinusoidal throttle input on the propeller RPM according to Equation 1. The effect of varying A_Ω and f_Ω on the average produced thrust can be seen in Figure 2. The propeller is observed to produce more thrust as A_Ω increases. This is expected following the quadratic relation between RPM and thrust. As such, the average of the modulated RPM will be lower bounded by the average at mean RPM and higher bounded by the thrust at peak RPM condition. This is seen even though the mean RPM value imposed by the throttle is the same for each case. Besides, a small change in the mean RPM happens as the frequency of oscillation is increased. This is caused by the inertia of the system which, during deceleration, yields


 Figure 1: Thrust coefficient and SPL versus RPM at $J = 0$

a deviation from the input throttle signal.

Important to note, the steady thrust value at 4,000 RPM is 4.25 N. When compared with $A_\Omega = 250$, which has a mean RPM of 4,000, the steady thrust is much greater. As f_Ω is increased, it approaches the steady thrust. It is still yet unsure what is the root cause of this result. It is believed that, the slower operation at low RPMs, and consequently low Reynolds numbers, leads to a delay on flow reattachment while the RPM is increasing, yielding lower thrust. Other authors [13] have demonstrated the onset of separation on this same rotor, which can be aggravated by the no axial flow condition used in this experiment.

At higher f_Ω the flow around the propeller might have a delayed time response on its development in comparison to the rate of change in RPM, leading to an aerodynamic lag effect. This could be connected to the higher thrust at higher modulation frequencies. A similar trend with f_Ω is seen for all amplitudes of modulation tested. At the highest amplitude ($A_\Omega = 900$ RPM), higher frequencies of modulation ($f_\Omega > 5$ Hz) yields no significant change in thrust. This is believed to be caused due to a smaller amplitude of RPM variation than quoted as, at such high amplitudes and frequencies, the inertia of the system yields a damping of the RPM modulation.

By averaging the measured thrust over one period of the transient throttle function, the thrust response to RPM changes can be investigated more thoroughly. For $A_\Omega = 250$, the effects of f_Ω can be seen over one throttle period, as depicted in Figure 3a. It shows the thrust as well as the RPM averaged for a single transient throttle phase. The black lines represent a modulation frequency of $f_\Omega = 0.25$ while the red ones show the results for a modulation of $f_\Omega = 4$.

For both of these cases, the mean RPM is approximately 4000 RPM. The RPM curve at both frequencies depicts similar amplitudes, showing that the propeller can follow the given throttle input with reasonable accuracy. More interesting, the same graph displays the thrust variation at the same phases of the propeller rotation. The thrust curve for $f_\Omega = 0.25$ shows large amplitude variations, as opposed to that of $f_\Omega = 4$. Although the measured mean RPM is similar for the two frequencies shown, the mean thrust is larger at higher frequencies. This suggests that the cause may be attributed to some transient effect that is the result of the frequency of change in velocity experienced by the rotor. Future investigation is planned to confirm the observed trends. In fact, for the highest modulation frequency, the thrust is seen to be leading with respect to the RPM variation slightly.

Figure 3b similarly shows the average thrust over one throttle period for $A_\Omega = 900$. The RPM

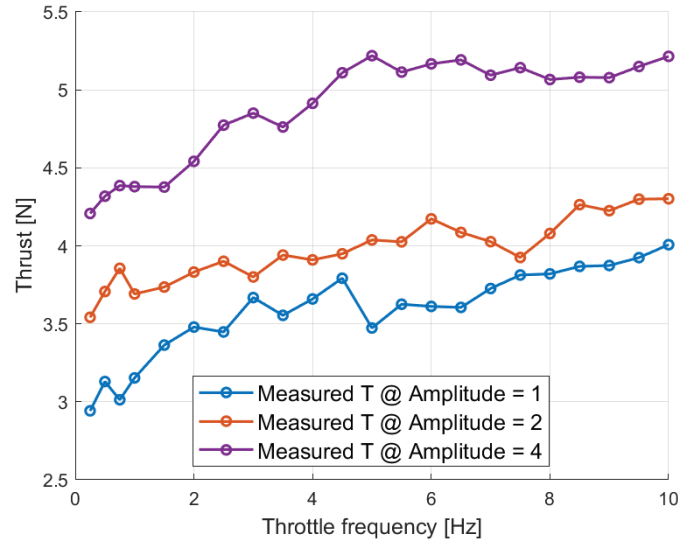


Figure 2: Comparison between propeller thrust for $A_\Omega = 250, 500$ and 900 versus f_Ω at $J = 0$.

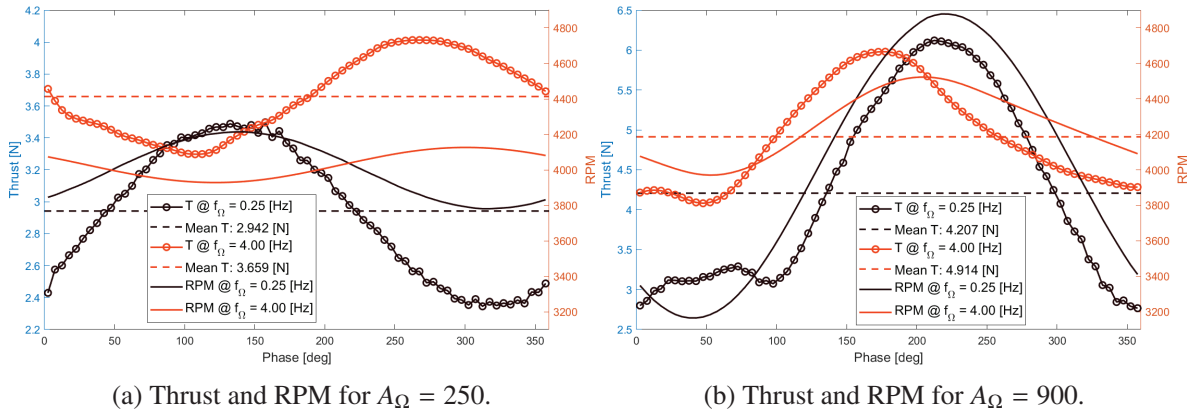


Figure 3: Thrust and RPM averaged over the phase of the throttle input function, Equation 1, shown for $f_\Omega = 0.25$ Hz and $f_\Omega = 4$ Hz.

curves show a much greater difference due to the increased amplitude. It can be seen that the shape of the thrust curve is distorted when the RPM reaches a minimum value for both of the frequencies depicted. This is likely a consequence of the RPM not being able to reach the minimum value imposed by the throttle input, as the lowest value of RPM is about 100 RPM higher than what would be expected from the throttle function. Another interesting observation is that, at $f_\Omega = 4$ Hz, the thrust leads the RPM phase more strongly, still in the order of tenths of degrees. Since the measurements of thrust and RPM are synchronized in time, this may be a more pronounced version of the aerodynamic lag effect.

To better illustrate the transient thrust response due to the sinusoidal throttle input, the acceleration-deceleration hysteresis effect is shown in Figure 4, where it is compared to the steady thrust-RPM curve. The hysteresis is obtained by separating the thrust values during the acceleration phase of the throttle from Figure 3 from those during the deceleration phase and taking the corresponding RPM. Figure 4a depicts the thrust hysteresis for $f_\Omega = 0.25$ Hz and $f_\Omega = 4$ Hz at $A_\Omega = 250$. The difference in amplitude over one phase between small and large f_Ω becomes clear here. Although the mean RPM for both investigated cases is around 4,000 RPM, the difference in amplitude is about 100 RPM at both ends. Even so, as f_Ω increases, the overall produced thrust approaches the steady RPM values. At lower RPM values, the $f_\Omega = 0.25$ Hz ascending curve shows

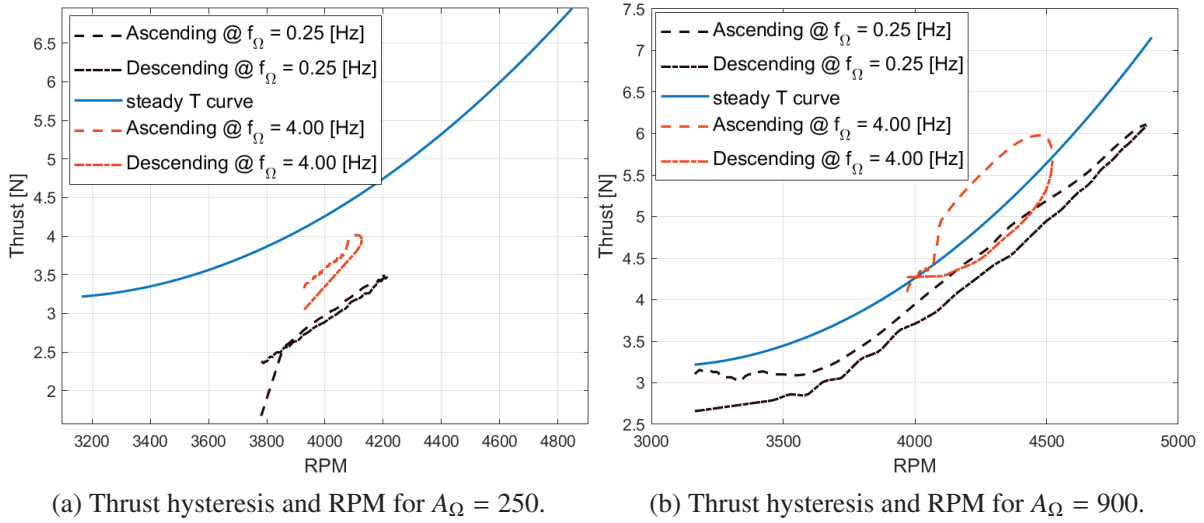


Figure 4: Thrust hysteresis and RPM averaged over the phase of the throttle input function, Equation 1, shown for $f_\Omega = 0.25$ Hz and $f_\Omega = 4$ Hz.

an acute rise in thrust. What causes this, at the point of transition from deceleration to acceleration, is not currently known as this phenomenon is not seen in other cases. Similar trends are seen for $A_\Omega = 900$, depicted in Figure 4b. For this large amplitude, the low frequency transient thrust is able to better follow the steady RPM curve. Still, the acceleration phase produces more thrust compared to deceleration. At the highest frequency ($f_\Omega = 4.0$ Hz) the hysteresis effect becomes significantly larger, deviating by as much as 1.0 N between increasing and decreasing RPM condition). During acceleration, the produced thrust surpasses the steady RPM thrust while during deceleration it is still below the steady RPM thrust curve.

4.3. Transient Noise Investigation

Figure 5 shows the effect of varying A_Ω and f_Ω on the produced noise in SPL. Similar to Figure 2, The SPL is depicted for $A_\Omega = 250, 500$ and 900 versus f_Ω . For $A_\Omega = 250$, with a mean RPM of 4,000, the noise remains relatively constant for the entire range of f_Ω at about 66.7 dB, which is almost equal to the steady noise level at 4,000 RPM depicted in Figure 1. When $A_\Omega = 500$, the noise levels are seen to decrease from 67 dB before evening out at around $f_\Omega = 4$. For the largest amplitude, $A_\Omega = 900$, the noise level steadily decreases with f_Ω . At the lowest modulation frequencies, the noise emissions are around 3 dB higher than the quoted steady value. The SPL values at low frequency are similar to steady RPM SPL values of the corresponding peak RPM of the transient cycle.

The SPL and RPM have been averaged over the phase of the throttle input function; Equation 1. This is depicted in Figure 6a for $A_\Omega = 250$ at $f_\Omega = 0.25$ Hz and $f_\Omega = 4$ Hz. Contrary to what was seen in Figure 3a for the thrust, the mean SPL values are quite close to each other. Figure 6b depicts the throttle function phase-averaged SPL and RPM for $A_\Omega = 900$ at $f_\Omega = 0.25$ Hz and $f_\Omega = 4$ Hz. Here, the low frequency RPM oscillations lead to a slightly greater overall noise level compared to higher frequency. There also seems to be some flattening of the noise at this frequency around 4,000 RPM, similar to what was seen in Figure 1. The noise curve at $f_\Omega = 4$ Hz flattens out during deceleration, corresponding to the mechanical limit when decelerating. Interestingly, a lag is seen between the noise levels and the RPM modulation at this modulation frequency.

A comparison of the noise spectra at fixed $A_\Omega = 900$ is presented in figure 7. The noise spectrum at the peak RPM achieved by the propeller during the throttle function has been isolated, and compared to that of the nearest steady RPM measurements. The frequency here is made non-dimensional by dividing it by the specific blade passing frequency (BPF) at each condition displayed.

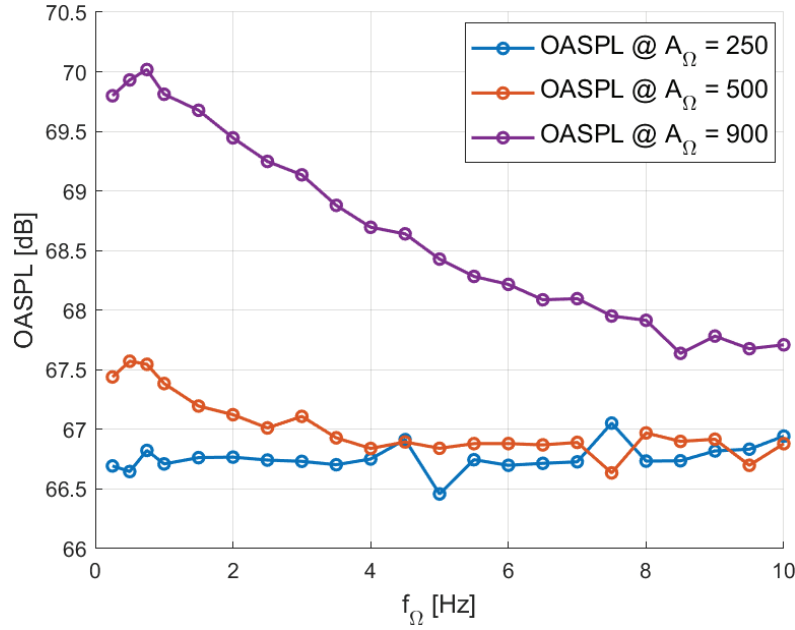
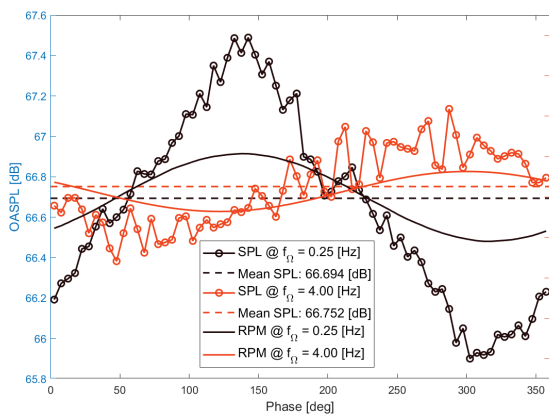
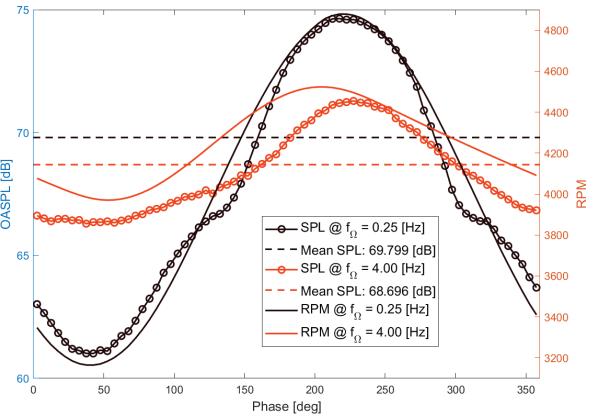


Figure 5: Comparison between SPL for $A_{\Omega} = 250, 500$ and 900 versus f_{Ω} at $J = 0$

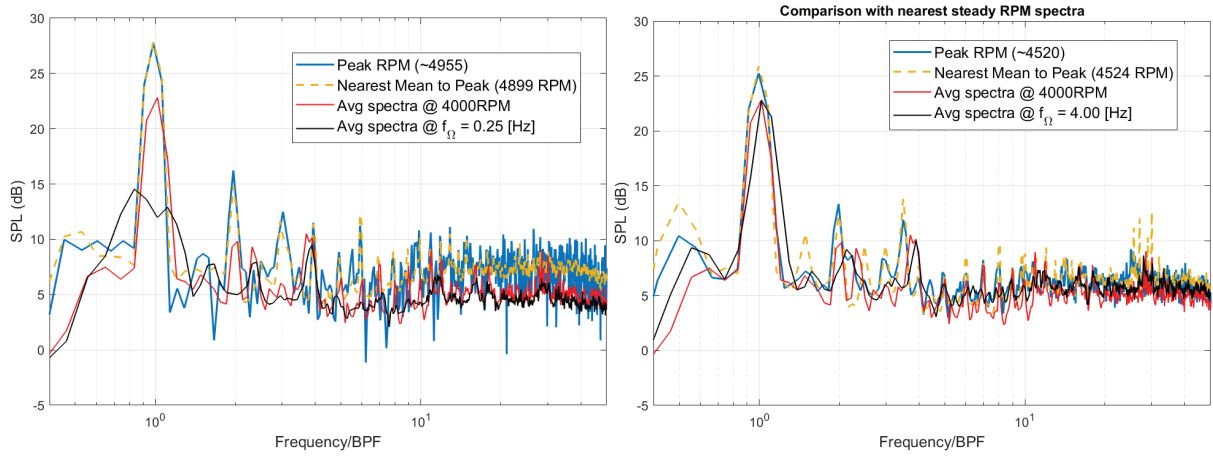


(a) SPL and RPM for $A_{\Omega} = 250$.



(b) SPL and RPM for $A_{\Omega} = 900$.

Figure 6: SPL and RPM averaged over the phase of the throttle input function, Equation 1, shown for $f_{\Omega} = 0.25$ Hz and $f_{\Omega} = 4$ Hz.



(a) Noise spectra at mean and peak rpm values during the throttle function, compared with that of the nearest steady RPM values for $f_{\Omega} = 0.25$ Hz. (b) Noise spectra at mean and peak rpm values during the throttle function, compared with that of the nearest steady RPM values for $f_{\Omega} = 4$ Hz.

Figure 7: Comparison of transient noise spectra with equivalent spectra at steady RPM, shown for $A_{\Omega} = 900$.

The complete transient spectrum for the given throttle function and that of the steady measurements at 4,000 RPM are also shown. The case for $f_{\Omega} = 0.25$ Hz is depicted in Figure 7a. All of the spectra present discrete tones which are expected at multiples of the BPF, and broadband contribution. The peak RPM noise ($\sim 4,955$ RPM) is nearly identical to that of the nearest steady RPM value ($\sim 4,899$ RPM). The biggest difference is in the broadband component in the high-frequency range, above 20 BPF (2.7 kHz, where the transient noise fluctuates more). The noise spectrum taken over the entire range of the transient function, exhibits a double peak at the first BPF, which corresponds to the minimum RPM first BPF and the peak RPM first BPF. If the frequency of this curve were to be normalized by the peak RPM BPF, the second peak would align with the spectrum at ~ 4955 RPM. Each of the cases depict a tone at multiples of the 1.5 BPF. This is attributed to the motor noise, as it corresponds to the harmonics of the propeller-off, motor-on measurements. Figure 7b depicts the noise spectra for $f_{\Omega} = 4$ Hz. Overall noise levels at this condition are lower than for $f_{\Omega} = 0.25$ Hz, corresponding to the observations from Figure 5. The motor harmonics clearly play a larger role at higher RPM as can be seen from the higher peaks at 0.5 and 1.5 BPF. The Harmonics exhibit fewer differences in general for this case, as the propeller does not operate at the full intended range of RPM. As such, the double peak seen at lower throttle frequencies is no longer present. The higher broadband noise for $f_{\Omega} = 4$ Hz compared to $f_{\Omega} = 0.25$ Hz, may be a result of the rotor operating over a smaller range of RPM. A Low-Reynolds number investigation of the same propeller at similar conditions [17], posited that the higher broadband noise could be attributed to a combination of trailing edge noise and turbulence impingement noise at the leading edge.

5. CONCLUSIONS

This work is focused on the effect of unsteady rotational velocity on performance and noise emissions from isolated rotors.

An experimental setup is proposed in which harmonic variations of the rotor rotational speeds can be imposed over a steady reference average speed. Simultaneous measurements of RPM, thrust, and far-field acoustic signals are carried out to build a complete dataset that allows for the aeroacoustic investigation of the phenomena.

Results focus on both thrust generation and overall Sound Pressure Levels (SPL). It is seen that the modulation frequency and amplitude have a significant effect on the average thrust produced by the

rotor. The latter follows the quadratic behavior of thrust vs. rotational speed, while the former is still yet to be understood. Further analyses will be carried out to try and isolate the physical phenomenon underlying the observations. Contrarily, the noise emissions are seen to reduce significantly as the modulation frequency is increased. At small amplitudes of modulation, the SPL remains fairly similar, while higher amplitudes show a ceiling noise that follows the SPL levels of the equivalent peak RPM in steady conditions.

Phase-locked thrust and noise analyses point to the influence of unsteady aerodynamic loading, which is aggravated as the modulation frequency and amplitude are increased.

This preliminary assessment has demonstrated that discrepancies in performance and noise emissions are seen when rotors operate under unsteady conditions of rotational speeds. Such conditions are inherent in novel aircraft concepts such as drones, micro UAVs, and eVTOL concepts. The study highlights the importance of further assessing such conditions for a reliable estimation of noise emissions of such applications. Importantly, the alterations of steady thrust and noise and the phase delays observed point to erroneous or misleading prediction of noise when compared to steady, or quasi-steady, conditions. Future research will focus on the underlying physics that causes the observed phenomena and the relation between aerodynamic loading and far-field noise emissions under such conditions.

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