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Time-varying broadband noise of multirotor aircraft

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Rotor broadband noise is typically analyzed over time scales encompassing multiple rotor periods. However, modulation of broadband noise levels with the blade passage frequency has been shown to be significant for human perception of wind turbine and helicopter noise. Time-varying broadband noise has not been extensively studied for aircraft with many rotors, such as unmanned aerial vehicles (UAVs) or advanced air mobility aircraft. In this work, significant broadband noise modulation was measured in flight and anechoic chamber tests of hexacopter UAVs. Envelope analysis showed that the modulation depth depends on the azimuthal phasing between rotors, demonstrating the potential for synchrophasing control to reduce broadband noise modulation. If rotors are not synchronized, as in typical flight, the phasing between rotors varies with time. This phase variation followed a uniform random distribution, resulting in modulation depth also varying randomly with time. The probability distribution of modulation depth was computed using offset copies of the modulation of a single rotor. These results contribute understanding to how the noise modulation of rotors sum together, demonstrating that broadband noise modulation is likely to be significant in flight.

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1. INTRODUCTION

Noise is a key barrier to the public acceptance of urban operations of rotorcraft. Rotorcraft noise research has historically focused on discrete frequency noise represented by the blade passage frequency (BPF) and its harmonics, with less emphasis on broadband noise. However, emerging multirotor electric aircraft, such as unmanned aerial vehicles (UAVs) or advanced air mobility (AAM) aircraft, have low blade tip speeds, thus reducing discrete frequency noise and increasing the relative importance of broadband noise. Most rotor broadband noise analyses compute time-averaged broadband noise over a time window consisting of many rotor revolutions. In this paper, the terms “time-varying broadband noise” and “broadband noise modulation” are used interchangeably to refer to temporal variation of broadband noise levels and/or spectra over time scales on the order of a blade passage. Research shows that this broadband noise modulation with the BPF is a significant factor in understanding human perception of noise generated by helicopters[1] and wind turbines.[2]

In contrast, time-varying broadband noise has not been extensively studied for UAVs and AAM aircraft. Time-varying broadband noise is expected to be even more important for these aircraft, as their multirotor configurations increase the likelihood of transient aerodynamic and acoustic interactions between rotors and/or the airframe.[3] Furthermore, their flight control systems typically continuously vary rotor rotation speeds and/or collective pitch, which can introduce time-varying noise.[4] To understand these time-varying noise sources, noise metrics must resolve short time scales, not average them out.[5]

Few studies in the literature have analyzed time-varying broadband noise of aircraft with many (4+) rotors. Psychoacoustics studies found that various sound quality metrics related to noise modulation are likely important for human perception of UAV noise.[6–8] Noise predictions of multirotor AAM aircraft found their broadband noise to be essentially time-invariant.[9] However, in these studies, variable rotor speeds and azimuthal phasing between rotors were not considered, like most rotor noise predictions. Although studied in predictions, multirotor broadband noise modulation has not been extensively studied through measurements. Furthermore, the directivity of multirotor broadband noise modulation has not been extensively studied in the literature. In contrast, for a single rotor, modulation is known to be greater closer to the rotor disk plane.[2,10,11]

These knowledge gaps in the literature motivate the research objectives of this paper:

1. Determine the significance of multirotor broadband noise modulation using measurements. This includes exploring the directivity of modulation.
2. Understand how the broadband noise modulation of multiple rotors sum together, including how this is affected by azimuthal phasing between rotors. This insight will be applied to understand the significance of multirotor broadband noise modulation, and help predict multirotor broadband noise modulation for general flight, where the phasing between rotors varies with time.
3. Determine the extent to which synchrophasing control can be used to reduce broadband noise modulation, like for tonal noise.[12,13]

2. TECHNICAL APPROACH

This section outlines the measurement and data processing procedures used in this paper. Section 2.A.i describes the acoustic flight tests, whereas Section 2.A.ii describes the anechoic chamber tests. These measurements were then processed as described in Section 2.B.

A. EXPERIMENTAL SETUP

Measurements of acoustic pressure, rotor rotation rates, and blade azimuth positions were taken for two different hexacopter UAVs: one in axial flight outdoors (see Section 2.A.i), and one in fixed hover in an anechoic chamber (see Section 2.A.ii).

i. Flight Testing

The flight test measurements analyzed in this paper were collected at Mid-State Regional Airport in Philipsburg, Pennsylvania: see Valente et al.[14] for details on the aircraft, measurement hardware, and flight conditions. Axial climb with a climb rate of 2.9 m/s was studied to minimize aerodynamic interactions between rotors. This corresponds to the start of Case Index 9, Run 1 in Ref. [14, Table 1], with a starting altitude of 80 ft and a tip Mach number of 0.23. The time segment studied was chosen for its steady climb rate, varying less than 0.03 m/s ($\sim$1%).

The microphones studied in this paper were inverted ground microphones: M5 has an elevation angle of 17° [15, Table 2], whereas M16 is located directly below the aircraft [14, Fig. 1]. Microphone 16 was found to be in the far field and was thus normalized to a "virtual" microphone 10 feet directly below the aircraft, moving with the aircraft. This normalization was applied using a spherical spreading correction with measured altitude time histories.[14] Microphone 5 is much further away from the aircraft (277 ft) than M16 (80 ft), so it is also in the far field. During the axial climb studied in this paper, the position of M5 relative to the UAV changes. However, since the time segment studied is short, this change is negligible: the observer distance only changes by 0.1 ft, and the observer elevation angle only changes by 0.1°.

ii. Anechoic Chamber Testing

Measurements were also collected in a flow-through anechoic chamber located in Hammond Building at Penn State University; see Valente et al.[13] for details on the aircraft, acoustic instrumentation, anechoic chamber facility, and the hardware and optimization algorithm used for synchrophasing. Measurements were taken for a different UAV [13, Table 1] than used in the flight test. The UAV was mounted to a test stand in the anechoic chamber. In this paper, the rotor speed set point studied was 2000 rad/s, corresponding to the thrust required for hover,[13] with a tip Mach number of 0.37. Only Rotors 2 and 3 were studied in this paper, whose rotation directions are shown in Fig. 1. In this paper, a positive azimuthal phase offset is defined as Rotor 3 leading. In this paper, results are analyzed for Microphone 9 in Ref. [13, Fig. 7], which is 23° below the rotor disk plane. Measurements of the other microphones in the array will be analyzed in future work. The microphone array was located on same side of the rotors studied in this paper, as shown in Fig. 1, to reduce the effect of scattering.

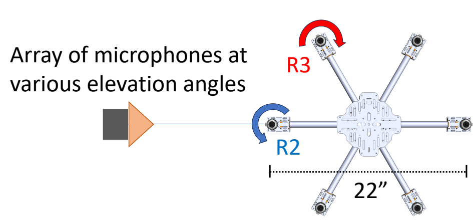


Figure 1: Top view schematic of UAV in anechoic chamber (adapted from Ref. [13, Fig. 6]).

Measurements were taken for Rotors 2 and 3 each operating individually, as well as simultaneously. In the results shown in this paper, no other rotors of the hexacopter were operating. Some of the simultaneous cases had no synchrophasing control, and were thus termed incoherent. In these incoherent cases, the rotation speed of each rotor is set (at 2000 rad/s), but small fluctuations in rotor speed inherent to any experiment, motor, and flight controller caused the azimuthal phasing between rotors to vary randomly with time. Measurements were also taken with the rotors synchrophased. These cases were:

- Nominally zero phase offset: the rotors (nominally) have the same azimuthal phase at all times. The term "nominal" is used here to emphasize that a truly constant phase offset cannot be maintained at all times in experiments. The effects of this are studied in Section 3.C.
- "Optimal" phase offset: the phase offset value the controller tries to maintain was determined by minimizing time-averaged overall sound pressure level (OASPL) for numerous observers.[13] Broadband noise modulation was *not* optimized for, hence the quotes around "optimal".
- "Pessimal" phase offset: the same approach is taken as for the "optimal" case, but instead the phase offset value is computed to *maximize* OASPL.

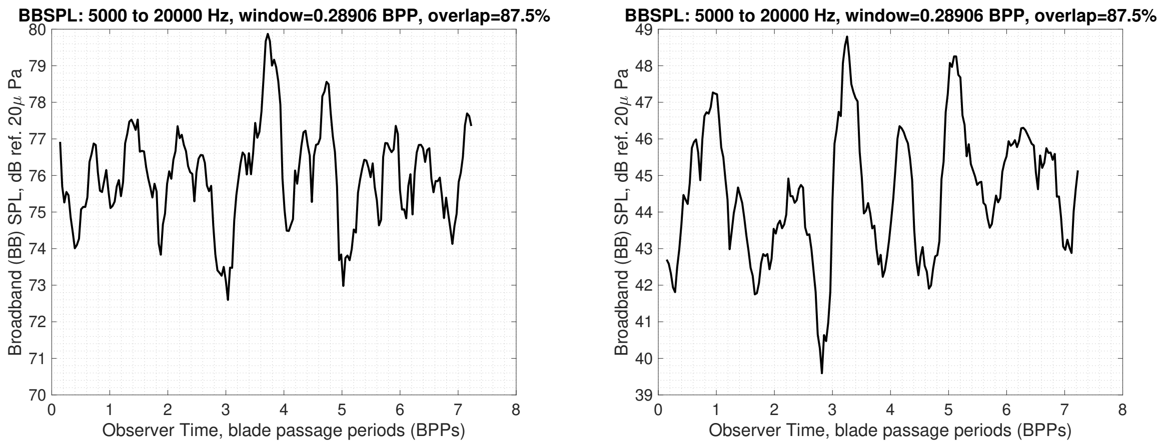
B. DATA PROCESSING

Measured acoustic pressure time histories (APTHs) were processed by:

1. Bandpass filtering to extract broadband (BB) noise. The frequency range to filter was chosen to be above the tones seen in the time-averaged SPL spectrum. These filters have linear phase responses to preserve the time variation of broadband noise.
2. Computing the mean-squared pressure (MSP) for overlapping windows of the broadband APTH. To resolve time variation of broadband noise levels within a blade passage, the window length is chosen to be less than a blade passage.
3. Summing the BB MSP time histories of different rotors. The random phase (i.e., incoherence) of noise frequencies characteristic of broadband noise allows summing the MSPs of different rotors. In contrast, the modulation is deterministic with the BPF. Therefore, the phase of the modulation must be considered when summing the broadband noise modulation of different rotors.
4. Converting the time history of BB MSP to decibels (dB). This outputs the time history of BB sound pressure level (SPL). Analyzing the time history of BB SPL rather time-frequency representations is suitable because the noise frequency content is not significantly detailed, but fairly uniform.

When analyzing time-varying broadband noise, it is important to determine the significance of including time variation. In this paper, the primary metric used to evaluate the importance of the time variation of broadband noise is the amplitude modulation depth ΔL: the difference between maximum and minimum SPL in dB. Increasing modulation depth has been shown to increase fluctuation strength and roughness,[16] which may be relevant for the time variation of rotorcraft noise.[1] For linear acoustics in the far field, ΔL is not expected to change with distance, as the SPL of both modulation peaks and troughs decay at the same rate of 6 dB per doubling of observer distance.

The dominant modulation frequency is typically the BPF, which generally fluctuates with time. To quantify the modulation depth at the BPF, the power spectral density (PSD) of the BB SPL was computed, decomposing the BB SPL into its *modulation frequency* content (not to be confused with noise frequency content). The PSD peak was integrated over its width until the results were insensitive to the modulation frequency range of integration. This PSD of BB SPL captures the periodic (ensemble) average modulation of all blade passages, but does *not* capture the aperiodic differences between blade passages. These aperiodicities arise from random turbulence pressure fluctuations that generate broadband noise, and variations in flight state variables.



(a) Processed Mic. 16: 10 ft below aircraft *(b) Mic. 5: 277 ft away, 17° below rotor disk plane*

Figure 2: Broadband (BB) SPL time histories for flight test.

3. RESULTS AND DISCUSSION

A. FLIGHT TESTS

The objective of this section is to determine the significance of broadband noise modulation for multirotor aircraft in flight, as discussed in Section 1. The time histories of BB SPL (see Section 2.B) are shown in Fig. 2, for the microphones discussed in Section 2.A.i. For both observers directly below the aircraft (Fig. 2a) and near the rotor disk plane (Fig. 2b), the modulation depths are significant (approximately 5-9 dB), unlike predictions in the literature.[9] Both observers have similar modulation depths, despite the microphones being at very different far field distances, which is consistent with the discussion in Section 2.B. Recall from Section 1 that for a single rotor, there is greater modulation for observers at small elevation angles relative to the rotor disk plane. However, here the observer along the rotor axis (Fig. 2a) has similar modulation depths to the observer near the rotor disk plane (Fig. 2b). Future work will investigate the directivity of multirotor broadband noise modulation in further detail.

B. ANALYTICAL MODEL

The research objectives of this section are:

1. To understand why multirotor modulation is significant in flight (see Section 3.A), contrary to predictions in the literature. As reviewed in Section 1, these predictions did not consider azimuthal phasing between rotors, which is typical for rotor noise analysis.
2. Accordingly, another objective is to determine the significance of azimuthal phasing on broadband noise modulation. This includes evaluating the potential for synchrophasing control of broadband noise modulation.

The approach taken in this section is to develop simple analytical models, which have fewer variables to consider and control for compared to experiments. One major advantage of analytical models is that they allow for truly constant rotor speeds, unlike experiments. This enables isolating the effect of azimuthal phasing alone, as the phasing remains constant with time. Another advantage of analytical models is the ability to prescribe a truly periodic sinusoidal time history of SPL. This removes sources of aperiodic modulation discussed in Section 2.B, to isolate the effect of azimuthal phasing.

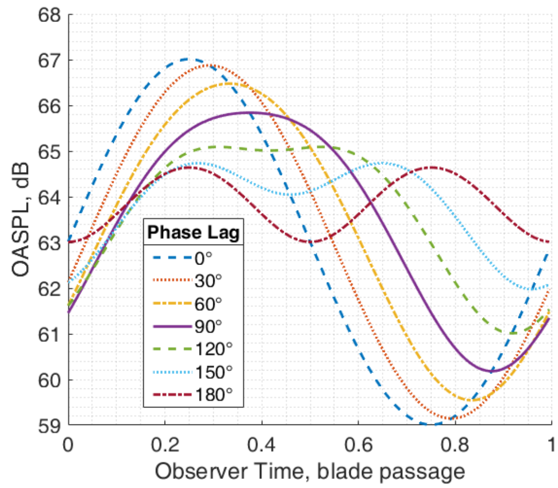


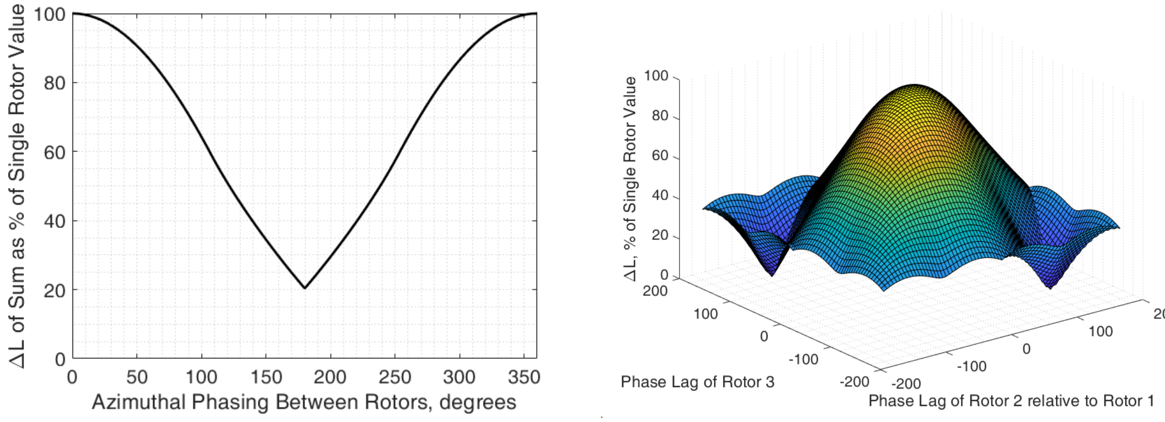
Figure 3: Parametric study of summed overall sound pressure level (OASPL) time history, as the phasing between two rotors is varied.

This is done here, prescribing input parameters of characteristic of measurements. In this section, the broadband noise modulation of each rotor is modeled using a sinusoidal time history of OASPL with a mean of 60 dB and an amplitude of 4 dB. The results are normalized by the modulation depth of a single rotor, which is twice the amplitude, 8 dB. Since the OASPL is prescribed, the exact APTH it models is not important, as its frequency content is integrated out in the OASPL. Summing rotors is modeled by adding copies of the OASPL time history with phase offsets, which can be caused by observer position, and/or azimuthal phasing between rotors.[13] The modulation of each rotor can be modeled as being identical to the others. The different distances of the rotors relative to the observer are not expected to cause significant differences in noise, as the distance between rotors is small compared to the distance of a far field observer. Furthermore, the azimuthal directivity of modulation is known to be nearly axisymmetric for a single rotor.[2,11]

i. Parametric Study Varying Azimuthal Phasing Between Rotors

Figure 3 shows the OASPL time history summed for two synchrophased rotors: each line represents a different value for the azimuthal phase offset between the rotors. From visual inspection of the mean of each line in Fig. 3, the time-averaged broadband noise is insensitive to the phasing but is about 3 dB greater than for a single rotor (60 dB: see Section 3.B), which corresponds to a doubling of mean-squared pressure expected when doubling the time-averaged MSP. As shown in Fig. 3, the least modulation occurs when the two rotors are 180° out of phase. This is similar to tones: two copies of a sinusoidal APTH destructively interfere to zero when summed 180° out of phase. However, when summing sinusoidal OASPL time histories (not APTHs), the result is not fully destructive interference, but instead modulation with twice the original modulation frequency, but a greatly reduced modulation depth. The greatest modulation occurs when the two rotors are in phase, like constructive interference for tones. However, unlike tones, where in-phase addition results in the sum having twice the original amplitude, the greatest modulation possible is the modulation depth of a single rotor. This is because decibels are non-linear units, and the time-averaged OASPL increased, as discussed above.

Figure 4 shows modulation depth as a function of the azimuthal phase offset for two (Fig. 4a) and three rotors (Fig. 4b). Each horizontal axis represents the phase offset of a rotor relative to the reference Rotor 1, which defines the phase to which the phase offset of other rotors are measured. The parametric study results for two rotors in Fig. 4a summarizes the results of Fig. 3. The parametric study results for three



(a) 2 rotors *(b) 3 rotors*

Figure 4: Modulation depth as a function of azimuthal phase offset between rotors.

rotors in Fig. 4b shows a wide range of modulation depths in a complicated function. Like for two rotors, the minimum modulation is small, but not zero. Like Fig. 4a, the maximum modulation depth is the value for a single rotor, which is typically large. Parametric studies were also conducted for 4+ rotors, but these results are difficult to visualize when plotting one axis for each phase offset (like in Fig. 4, as they result in plots with 4+ dimensions. These results are processed and presented in the following Section 3.B.ii.

In summary, the results shown in this section demonstrate that multirotor broadband noise modulation can be significant depending on the phasing between rotors. Therefore, it is difficult to separate the topics of importance and phasing. Therefore, phasing must be considered for accurate analysis and predictions of broadband noise modulation. Phasing might help explain why broadband noise modulation was observed to be important in flight tests (see Section 3.A), but not in predictions in the literature (see Section 1), which did not consider phasing, like most studies. Furthermore, the large range of modulation depth depending on phasing demonstrates the potential for synchrophasing control to reduce broadband noise modulation.

ii. Probability Distribution of Modulation due to Azimuthal Phase Variations

The results of Section 3.B.i assumed constant azimuthal phase offsets between rotors at all times; i.e., the rotors were synchrophased. This is generally not the case in flight, as motor controllers typically vary rotor speeds for flight control. In Section 3.B.i, although modulation depth as a function of phase was computed, the phase offset values (and their corresponding modulation depths) that actually occur in flight were not considered. Accordingly, the goal of this section is to predict broadband noise modulation in general flight without synchrophasing.

Since the results of Section 3.B.i found that modulation depth depends on azimuthal phasing, and azimuthal phasing varies throughout (non-synchrophased) flight, therefore, modulation depth also varies throughout flight. If azimuthal phasing is modeled as a random variable, then modulation depth is also a random variable. The approach taken here to achieve the objective of predicting modulation depth in flight is to characterize the probability distribution of azimuthal phase offset throughout flight. When this is combined with functions describing modulation depth as a function of phasing (from Section 3.B.i), this characterizes modulation depth as a probability distribution.

This approach requires a quasi-steady assumption. Specifically, a pair of rotors with a time-varying phase offset (i.e., non-synchrophased flight) that instantaneously has a phase offset of Θ_X is assumed to have the same modulation depth as the same rotors with the same phase offset Θ_X at all times (i.e., syn-

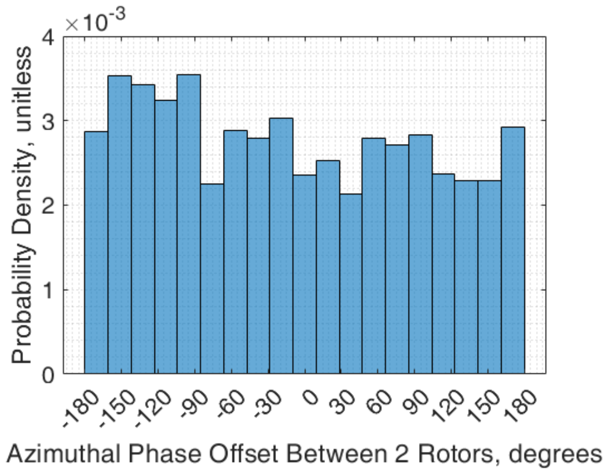


Figure 5: Probability distribution of phasing between two non-synchrophased rotors in anechoic chamber.

chrophased), where Θ_X can take any value. This assumption is justified by the rotor rotation speeds changing slowly over a blade passage, such that rotor speeds remain essentially constant over a blade passage.[4] Accordingly, the azimuthal phase offset remains nearly constant over a single blade passage, such that a full modulation cycle can be completed before a substantial change in rotor speed occurs.

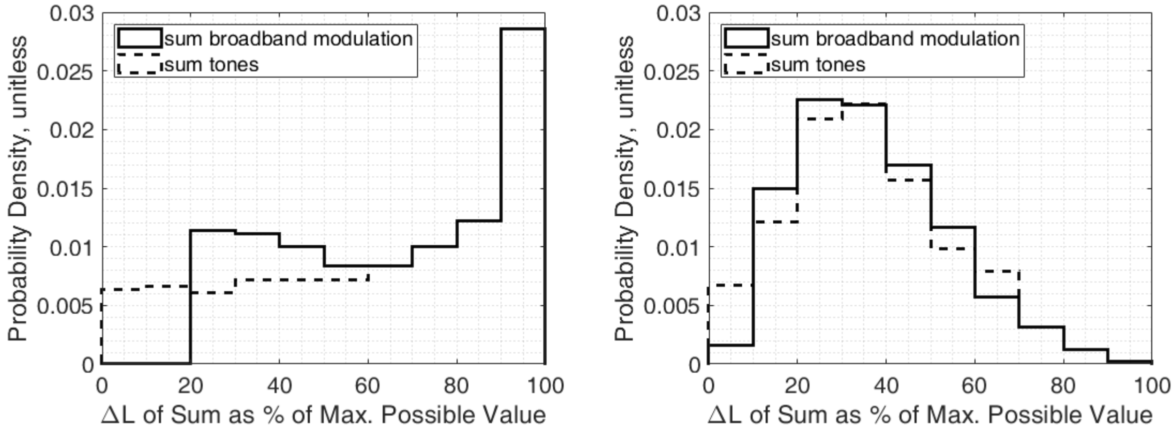
It is also assumed that variations in rotor rotation speed do not significantly affect the broadband noise modulation generated by a single rotor. Accordingly, it is assumed that the only effect of variable rotor speed is to vary azimuthal phasing with time. Studying the significance of variable rotor speed on the broadband noise modulation generated by a single rotor is outside of the scope of this study.

To determine the probability distribution of azimuthal phasing in flight, measurements of the blade azimuth time histories of two non-synchrophased (i.e., incoherent) rotors were taken inside an anechoic chamber (see Section 2.A.ii). Although these measurements were taken for fixed hover, they are representative of a typical flight controller without synchrophasing. A histogram of the azimuthal phasing between the rotors is shown in Fig. 5, which shows an approximately uniform distribution.

Assuming the azimuthal phasing follows a uniform distribution, the probability distribution of modulation depth can be directly constructed by computing histograms of the results of Fig. 4. This is because the parametric studies shown in Fig. 4 were conducted using uniformly-spaced phase offset values. The resulting probability distributions of modulation depth are shown in Fig. 6, for two (Fig. 6a) and six rotors (Fig. 6b). The authors acknowledge that true Monte Carlo simulations estimating a probability distribution should use random sampling, rather than sampling azimuthal phasing in a uniform 'grid' of evenly-spaced values. Such studies will be conducted in future work. Nonetheless, the results shown in Fig. 6 provide valuable insight.

The results for summing broadband noise modulation are compared to results for summing tones.[17] Generally, both summed tones and broadband noise modulation have similar probability distributions in Fig. 6, when normalizing the summed amplitude by its maximum possible value (see Section 3.B.i). One notable difference is that low modulation depths (below 20% of the maximum possible value) do not occur when summing two rotors, as seen in Fig. 6a, consistent with Fig. 4a.

For six rotors, the modulation depth values that are most likely to occur lie between 20% to 50% of the single rotor value (see Fig. 6b). This modulation is still likely to be significant, as the modulation depth of a single rotor (which recall from Section 3.B.i is the maximum possible value for summed rotors) is typically large (e.g., 8 dB). This may help explain why broadband noise modulation is significant and aperiodic for a hexacopter in flight (see Section 3.A).



(a) 2 rotors *(b) 6 rotors*

Figure 6: Probability distribution of modulation depth for uniform random azimuthal phasing. Results of summing tones from Ref. [17, Figs. 2 and 3].

In summary, without synchrophasing, azimuthal phasing and modulation depth both vary throughout flight, and can be modeled as random variables. Predicting the probability distribution of multirotor modulation depth can be achieved by summing offset copies of the modulation of a single rotor. This process reveals similarities and differences between summing the sinusoidal MSP time histories of broadband noise modulation compared to summing the sinusoidal APTHs of tones. Overall, the trends similar are similar for both, but lower amplitudes are less likely for broadband noise modulation, as there is not fully destructive interference, unlike for tones. This results in the most likely modulation depths to be over 20% of the single rotor modulation depth, which is typically large. Therefore, these probability distributions of modulation depth might help explain why broadband noise modulation is significant in flight, even for aircraft with many rotors.

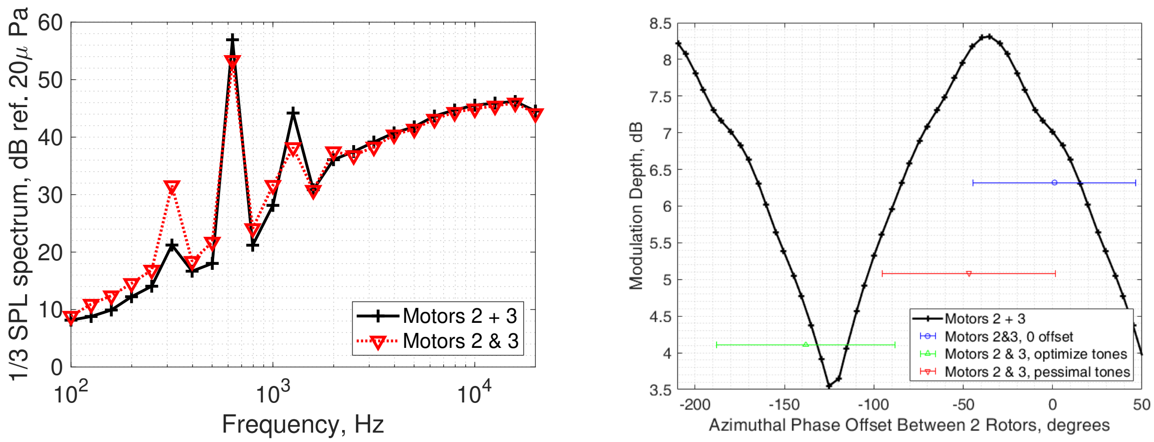
C. ANECHOIC CHAMBER

The goal of this section is to confirm the findings of Section 3.B in experiments, where rotor speeds fluctuate, even with synchrophasing. This section seeks to determine if these fluctuations significantly affect the importance of phasing on noise modulation, and the potential for synchrophasing control of this modulation.

The approach of summing rotors taken in Section 3.B is applied here to individual rotor measurements. Any phase offset can be set using the tachometer measurements. To ensure that the APTHs of all rotor periods have an equal number of data points, they were upsampled to have 256 points per revolution, resulting in an effective azimuthal resolution of 1.4°.

This summation is valid if there are no significant aerodynamic interactions between rotors. This was verified by comparing the time-averaged broadband noise spectra for the sum (+) of individual rotors, compared to the simultaneous (&) operation of the same rotors. This approach and notation was used by Zawodny et al.[18] Since the spectra of Fig. 7a match, the summed noise of individual rotors has been validated as an accurate model of their simultaneous operation. The time-averaged spectra of Fig. 7a were found to be insensitive to phasing, consistent with finding that time-averaged broadband noise is insensitive to phasing (see Section 3.B.i). The frequency range over which the spectra in Fig. 7a match gives the broadband noise frequency range, as tonal noise does not sum incoherently. Accordingly, the calculations of this section bandpass filter the APTH between 3-20 kHz (see Section 2.B for details).

Parametric study results of modulation depth as a function of the phasing of two rotors is shown in



(a) Time-averaged spectra for "pessimal" case ***(b) Parametric study of modulation depth***

Figure 7: Broadband noise modulation of synchrophased anechoic chamber measurements: comparing sum (+) vs simultaneous cases (&); see Section 2.A.ii.

Fig. 7b. Fig. 7b shows similar trends to the analytical model parametric study of Fig. 4a, with the modulation depth covering a range of approximately 5 dB. These summed results are compared to synchrophased operation of the same rotors to study the effect of rotor speed and phase fluctuations caused by controller errors. These simultaneous cases are represented by the three isolated markers on Fig. 7b; see Section 2.A.ii for details on these cases. Fig. 7b shows a good match between the sum and simultaneous results for the zero offset and "optimal" cases, but a poor match for the "pessimal" case. That being said, even disregarding this data point, there still exists a wide range in modulation depth caused by phasing.

The error bars in Fig. 7b represent the 95% confidence interval: $\pm 2\sigma$ for a Gaussian random variable. For all synchrophased cases, the azimuthal phase offset between the rotors was found to follow a Gaussian distribution centered on the chosen offset, with a standard deviation $\sigma \approx 24°$. Since this σ was similar across all cases, it does not provide an explanation for the discrepancy between the sum and simultaneous results for the "pessimal" case. Explaining this discrepancy is an important area of current and future work.

Since azimuthal phasing strongly affects modulation depth in experiments, there exists potential for synchrophasing control to reduce broadband noise modulation, even with fluctuations in phase caused by real controller errors. Note that in Fig. 7b, the phase angles at which the "optimal" and "pessimal" broadband noise modulation occur are accurately predicted by the summed rotors, despite the modulation depth of the "pessimal" sum being overpredicted compared to the simultaneous case. Also recall from Section 2.A.ii that tonal, not broadband noise was optimized. A phase offset between tonal and broadband noise is known to occur in the literature.[10] Such an offset may be present in Fig. 7b, it seems small ($\sim 10°$). This offset will be investigated in more detail in future work.

In summary, this section used experiments to confirm the findings of the analytical model of Section 3.B:

- There is a large range of possible modulation depths depending on the phasing between rotors.
- There exists potential to predict multirotor modulation by summing individual rotors.
- There exists potential for synchrophasing control to reduce broadband noise modulation, which is also likely to simultaneously reduce tonal noise.

4. CONCLUSIONS

This paper showed that broadband noise modulation is significant in flight, with modulation depths of approximately 5-9 dB seen in this paper for far field observer elevation angles both near and far from the rotor disk plane. Analytical models and anechoic chamber measurements showed that this modulation is significantly affected by azimuthal phasing between rotors, with approximately 5 dB difference seen in experiments in this paper. This paper demonstrated potential for synchrophasing control of broadband noise modulation like for tonal noise, even with rotor speed and phasing fluctuations, which are inherent to controller errors.

If synchrophasing control is not implemented, which is typically the case, azimuthal phasing and modulation depth vary continuously with time. This paper showed that this modulation can be predicted by characterizing azimuthal phasing as a random variable with a known probability distribution (shown to be uniform random in measurements), combined with parametric studies of modulation depth for various phase offsets between copies of a single rotor. This process characterizes modulation depth as a probability distribution. This contributes understanding into why the broadband noise modulation of rotors may sum to be significant.

The findings of this paper show that analysis methods (e.g., predictions and processing measurements) of broadband noise modulation should:

- Account for rotor phasing and its time variation caused by variable rotor speeds in flight.
- Characterize modulation depth not as a single value, but quantify its variability. Sources of variability include variable rotor speeds and azimuthal phasing. This variability in modulation depth can be characterized as a probability distribution, as shown in this paper.

A major implication of this variability in modulation depth is that a large number of repeated tests may be required to characterize the broadband noise modulation of a multirotor aircraft.

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REFERENCES

[1] A. Christian, J. Caston, E. Greenwood, and A. Branch, "Regarding the perceptual significance and characterization of broadband components of helicopter source noise," in *Vertical Flight Society 75th Annual Forum & Technology Display*, Vertical Flight Society (2019).

[2] S. Oerlemans and J. G. Schepers, "Prediction of wind turbine noise and validation against experiment," International Journal of Aeroacoustics **8**(6), 555–584 (2009).

[3] E. Greenwood, K. S. Brentner, R. F. Rau II, and Z. F. T. Gan, "Challenges and opportunities for low noise electric aircraft," International Journal of Aeroacoustics **21**(5-7), 315–381 (2022).

[4] Z. F. T. Gan, B. Mukherjee, J.-P. Theron, M. Botre, K. S. Brentner, E. Greenwood, and J. F. Horn, "A New Distributed Electric Propulsion Aircraft Simulation Tool for Coupled Flight Dynamics, Free Wake, and Acoustic Predictions," in *Vertical Flight Society 77th Annual Forum & Technology Display* (2021).

[5] D. Read and C. Roof, "Research to support new entrants to public airspace and aircraft noise certification," in *Quiet Drones 2020*, Institute of Noise Control Engineering (2020).

[6] D. Y. Gwak, D. Han, and S. Lee, "Sound quality factors influencing annoyance from hovering UAV," Journal of Sound and Vibration **489**, 115651 (2020).

[7] S. A. Rizzi, N. S. Zawodny, and N. A. Pettingill, "On the use of acoustic wind tunnel data for the simulation of sUAS flyover noise," in *25th AIAA/CEAS Aeroacoustics Conference* (2019).

[8] A. J. Torija and R. K. Nicholls, "Investigation of metrics for assessing human response to drone noise," International Journal of Environmental Research and Public Health **19**(6), 3152 (2022).

[9] S. K. Li and S. Lee, "Prediction of Urban Air Mobility Multirotor VTOL Broadband Noise Using UCD-QuietFly," Journal of the American Helicopter Society **66**(3), 1–13 (2021).

[10] W. J. Baars and D. Ragni, "Low-frequency intensity modulation of high-frequency rotor noise," in *AIAA AVIATION 2023 Forum* (2023).

[11] Z. F. T. Gan, K. S. Brentner, and E. Greenwood, "Time Variation of Rotor Broadband Noise," in *Vertical Flight Society 9th Biennial Autonomous VTOL Technical Meeting* (2021).

[12] K. A. Pascioni, S. A. Rizzi, and N. H. Schiller, "Noise reduction potential of phase control for distributed propulsion vehicles," in *AIAA SciTech 2019 Forum* (2019).

[13] V. T. Valente, E. Greenwood, and E. N. Johnson, "An experimental evaluation of an electronic rotor phase synchronization system for multirotor aircraft noise control," in *Vertical Flight Society 80th Annual Forum & Technology Display* (2024).

[14] V. T. Valente, E. Greenwood, and E. N. Johnson, "An Experimental Investigation of eVTOL Flight State Variance on Noise," in *Vertical Flight Society 79th Annual Forum & Technology Display* (2023).

[15] N. B. Konzel and E. Greenwood, "Ground-based acoustic measurements of small multirotor aircraft," in *Vertical Flight Society 78th Annual Forum & Technology Display* (2022).

[16] H. Fastl and E. Zwicker, *Psychoacoustics: Facts and Models*, 3 ed. (Springer, 2006).

[17] J. O. Flower, "Probability distributions of randomly-phased combinations of sine waves of equal amplitude," Applied Acoustics **19**(2), 131–138 (1986).

[18] N. Zawodny, N. Pettingill, and C. Thurman, "Identification and reduction of interactional noise of a quadcopter in hover and forward flight conditions," INTER-NOISE 2022 **265**, 2947–2958 (2022).

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16. Abstract

Rotor broadband noise is typically analyzed over time scales encompassing multiple rotor periods. However, modulation of broadband noise levels with the blade passage frequency has been shown to be significant for human perception of wind turbine and helicopter noise. Time-varying broadband noise has not been extensively studied for aircraft with many rotors, such as unmanned aerial vehicles (UAVs) or advanced air mobility aircraft. In this work, significant broadband noise modulation was measured in flight and anechoic chamber tests of hexacopter UAVs. Envelope analysis showed that the modulation depth depends on the azimuthal phasing between rotors, demonstrating the potential for synchrophasing control to reduce broadband noise modulation. If rotors are not synchronized, as in typical flight, the phasing between rotors varies with time. This phase variation followed a uniform random distribution, resulting in modulation depth also varying randomly with time. The probability distribution of modulation depth was computed using offset copies of the modulation of a single rotor. These results contribute understanding to how the noise modulation of rotors sum together, demonstrating that broadband noise modulation is likely to be significant in flight.

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