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APPLICATION OF ATMOSPHERIC WIND FILTER ARRAYS FOR ACOUSTIC MONITORING UAVS

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ABSTRACT

The application of Uncrewed Aerial Vehicles (UAVs) in low frequency acoustic measurements is, among other factors, limited by the disturbances induced by atmospheric wind noise. The infrasound sensor networks used in the seismic activity monitoring consists of a wind filter array that filter the acoustic disturbances caused by the atmospheric turbulence. These arrays function as spatial filters, eliminating the incoherent noises generated by the wind. In this study we design and test wind filter arrays for their application in a UAV based measurement platform. Different configurations of the wind filters such as the Rosette filter, porous circular pipes and several other derived configurations were studied. The frequency response function of the filters indicated a significant distortion from the acoustic resonance in the filter tube for some designs. Acoustic plane wave theory is used to tune these wind filter arrays for shifting these resonances beyond the frequency range of the measurement. In addition, an investigation is made by coupling arrays of varying dimensions to increase the effective frequency range of the filter.

Keywords: *infrasound measurement, wind noise filter, atmospheric turbulence, sensor array, uav measurement*

1. INTRODUCTION

The increasing growth of renewable energy converters, e.g. Wind turbines, has raised a low frequency noise concern in the nearby residential areas [1], [2]. The blade passing frequency of wind turbines and rotor blade interaction with wind generates an infrasound noise that are measured several kilometres in the downwind direction [3]. Sound power characterisation of wind turbines involves ground based measurements based on the standard guidelines in IEC 61400 – 11 [4]. Microphones equipped with spherical windscreens are used to measure the Sound Pressure Level (SPL) in a linear array of points to estimate the sound power of the wind turbines. Application of this technique for infrasound frequencies is infeasible because longer wavelengths require measurements with network arrays. Moreover, the acoustic signal in the low frequencies is masked by atmospheric wind noise making it difficult to measure infrasound noise.

Infrasound Monitoring Stations (IMS) developed as a part of the Comprehensive Nuclear Test Ban Treaty Organisation (CTBTO) employ wind filter arrays to reduce the disturbance caused by atmospheric wind [5], [6]. These filter arrays are constructed with a series of pipes and their working principle is that the atmospheric wind induced turbulence is incoherent with a shorter wavelength in comparison to the infrasound signal which is filtered with a sensor array larger than the turbulent scale. The most common design is the rosette filter, consisting of multiple pressure sensing inlets distributed in a geometric pattern in a larger perimeter. As stated in the reference text, for filtering the wind noise in the frequencies below 5 Hz, a filter diameter of at least 18 m is required. The rosette filter design is limited by the acoustical resonance effect which is addressed with another form of wind filter design using porous pipe in a circular loop [7], [8]. It differs from the rosette filter design in that a single tube with porous inlets is used rather than a series of tubes. The circular filter, however, undergoes degradation due to defects arising over time. Furthermore, the remote location of IMS permits the

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construction of these large infrasound filter arrays which are otherwise difficult to build near a residential area. For the measurement of infrasound noise in areas with limited spaces, spherical porous domes or large windscreens are used to shield the microphone from turbulence effects producing a maximum of 7 dB noise reduction [9], [10].

In recent times, the application of UAVs for remote sensing and environmental condition monitoring has gained traction for its improved accessibility to remote terrains [11]. The limiting factor in the use of UAVs for acoustic monitoring is the inherent noise they generate, which has been studied extensively [12], [13]. In our previous experimental study [14], we measured the low frequency noise signature of UAVs and concluded that in the low frequencies, the self-noise of the drone is minimal. Hydrodynamic fluctuations caused by the rotor thrust masked the acoustic signal in low frequencies, but it was limited to the downstream direction of the rotors. Having figured out the sweet spot for sensor location, in this study, we construct a wind filter array for measuring the infrasound noise using UAVs. We equip the UAV with the rosette filter, porous hose filter, and circular filter configuration and measure the filter response in the vicinity of the reference infrasound source of known sound power output [15].

While the porous wind filter domes are effective in infrasound range [10], their application in UAV measurements is prevented by the payload limitations of the drone. Except for the dimensional differences, both windscreens and wind domes average out the turbulence effects in the wind by integrating the sound pressure over a larger surface area. In addition, the porosity of the windscreen creates viscous and inertial losses which further reduces the atmospheric turbulence effects [16]. Measurements performed with various windscreens in a wind tunnel showed a significant noise reduction performance in low frequencies [17]. So, we constructed a circular microphone array using the microphones equipped with windscreens. Further, to filter the incoherent turbulences in the atmosphere, the spatial filter technique from the rosette pipe design was adopted. The construction of the array and the filters are explained in section. Results for each of the filter configurations tested are summarised in section 3. Finally, discussions and conclusions from the present study are provided in section 4 along with the future research plan.

2. METHODOLOGY

2.1 Measurement setup

2.1.1 UAV assembly

Measurements in this study are performed with PM X6 Pro Hexacopter drone with a payload capacity of 5 kg. We equipped the drone with 3D - printed attachments to carry the measurement hardware. Measurement data is acquired remotely using National Instruments NI 9181 DAQ. The sound pressure signal was recorded with a half - inch infrasound condenser microphone GRAS 47 AC powered by GRAS 12 AL CCP power module. The measured data is then relayed to a PC through a Wi-Fi router. For extending the Wi-Fi range while flying, a Wi-Fi bridge is mounted on the drone along with the power backup. The assembly of the measurement system on the drone is shown in Fig 1 (a).

2.1.2 Rosette filter design

Flexible PET pressure hose of 4 mm inner diameter and 1 mm wall thickness were used in constructing the filter. Filter was designed using the parametric relations given in the electroacoustic model developed by B. Alcoverro [6]. The inlet pipes of the filter are supported by the carbon tubes attached to the arms of the drone. Pneumatic connectors were used in connecting the inlet pipes to the secondary pipes. The secondary pipe is interfaced to the infrasound microphone through a 3D printed manifold of 30 mm × 30 mm × 5 mm volume. The constructed filter has a diameter span of 2.32 m and consists of six pressure inlets. The assembly of the rosette filter is shown in Fig 1 (b).

2.1.3 Porous hose design

For the porous filter design, holes of 2 mm diameter were drilled in the inlet pipes of the rosette filter. Holes were made for 300 mm length from the open end with an interval of 50 mm resulting in 36 pressure inlets in total. Porosity length was limited to avoid hydrodynamic fluctuations of the rotor. The rest of the assembly of the filter is similar to the rosette filter design described above.

2.1.4 Circular filter design

For the circular filter, 7.5 m pressure hose is made porous with 1 mm diameter hole with 100 mm interval. There were a total of 69 pressure inlets and the filter was looped around the ends of the carbon tubes at 2.32 m diameter. While one end of the filter was closed the other end was connected to the manifold. The filter construction is shown in Fig 1 (c).

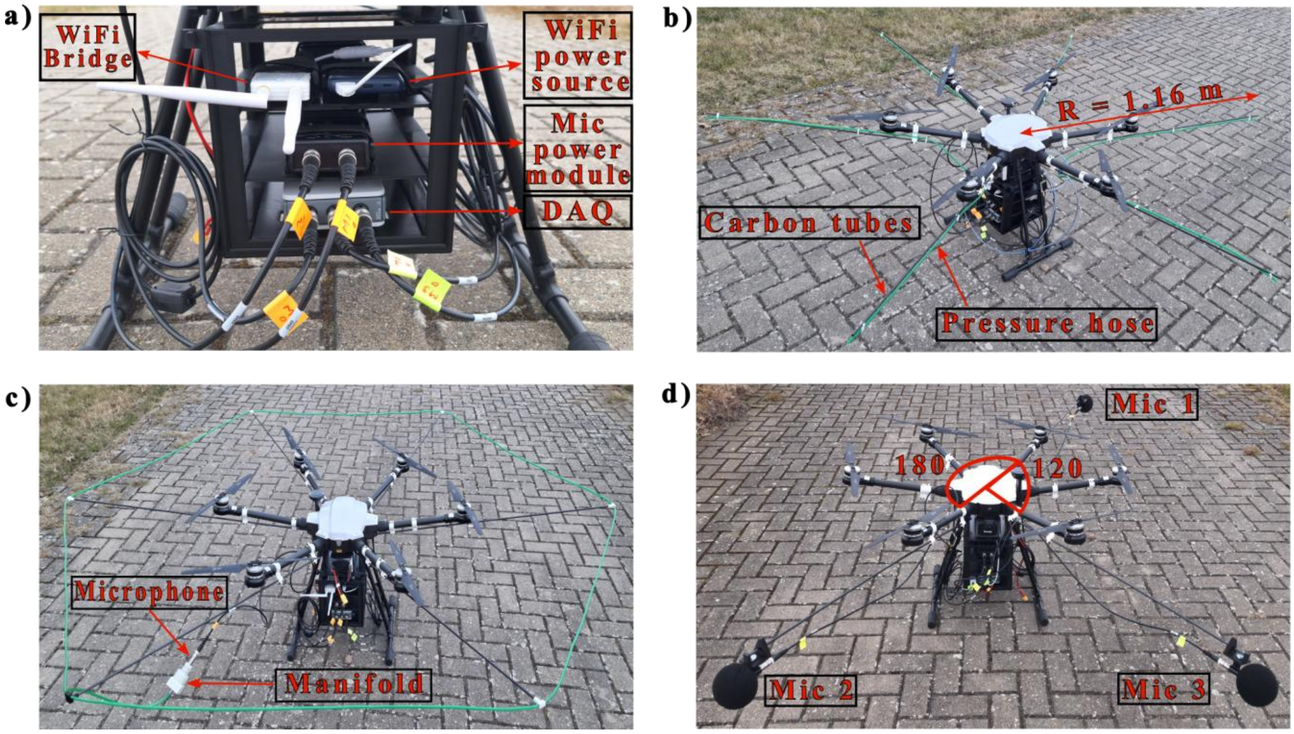

Figure 1. Picture showing the measurement setup in the UAV. a) DAQ hardware assembly, b) Rosette filter assembly, c) Circular filter assembly, d) Three microphone array assembly.

2.1.5 Three microphone array

A circular microphone array was built with three infrasound microphones (GRAS 47 AC). At the end of the carbon tubes, the microphones were mounted with a 3D printed support and GRAS 90 mm windscreens were attached to the microphones. The microphone filter array has a diameter span of 2.37 m. Two microphones were mounted 180 degrees apart and the third microphone was mounted at 120 degrees from the first mic to have a different separation distance as shown in Fig 1 (d).

2.2 Data acquisition

Measurements were performed at PTB's open field on a slightly windy day with an average wind speed of 10 kmph (forecasted value). The reference infrasound source [15] was used to radiate a 10 Hz tonal noise. Sound pressure was measured at ground level at 10 m from the source with the drone turned off and at an altitude of 10 m above the reference source with the drone in hover mode. The time signal was acquired for 300 seconds. Using Welch's algorithm [18] in Python, the measured time signal is converted to the frequency domain with 1 Hz resolution and 300 averages. Further, the background wind noise is measured without the infrasound source for comparative study. In addition, sound pressure is measured using a reference microphone stationed at the geometric centre of the filters tested.

3. RESULTS

The measurement results are plotted in terms of SPL spectra for a frequency bandwidth of 1 – 100 Hz. While the Power Spectral Density (PSD) is used for calculating the filter array SPL, Cross Spectral Density (CSD) is used for three microphone array results. The window correction factor, bandwidth correction factor, and microphone sensitivity are applied in estimating the exact SPL values in each case.

Fig 2 shows the comparison of SPL spectra measured with the three filter configurations (Rosette filter, Porous hose filter, and Circular filter) along with SPL spectra measured with the reference microphone. The background noise measured at the ground level in Fig 2 a) indicates that the designed filter is less effective in reducing the wind induced noise compared to the single microphone with windscreen attached. Comparing the spectra of the three filter configurations, the rosette filter provides a better noise reduction for most of the bandwidth. Particularly in the infrasound range, the rosette filter response was 10 dB lower than the other two filter configurations. From the electroacoustic model [19], the high frequency cut off for the rosette filter with the given dimensions and 10 kmph wind speed was calculated to be 70 Hz (approx.) which agrees with the measurement result. As pointed out in the literature, the rosette filter response was affected by the internal resonances of the pipes around 40 Hz frequency.

The porous hose filter response resembles the rosette filter response except for the higher amplitude level. The increase in the SPL can be an effect of an increased number of pressure inlets. Likewise, for the circular filter, the SPL level is identical to that of the porous hose filter, but the resonance effects were shifted towards higher frequencies. Despite the absence of resonance in the frequency range of interest, the circular filter was least effective in filtering the wind noise.

However, the comparison of background noise at 10 m altitude in Fig 2 b) indicates a better performance with the circular filter. This is mainly due to the resonance effects in the rosette and porous hose filter amplifying the background noise. Also, the porous hose filter provides a better noise reduction in frequencies below 8 Hz, unlike the background noise measured at ground level. At higher altitudes, tonal noise corresponding to the shaft frequency of the drone rotors is generated around 70 Hz which is measured in all filters. Because of the variation in the rotational frequency of the rotor in each arm of the drone, the peak appears broader. However, the overall noise level measured with the filter has increased further by 10 to 15 dB at higher altitudes in comparison to the spectra measured at the ground.

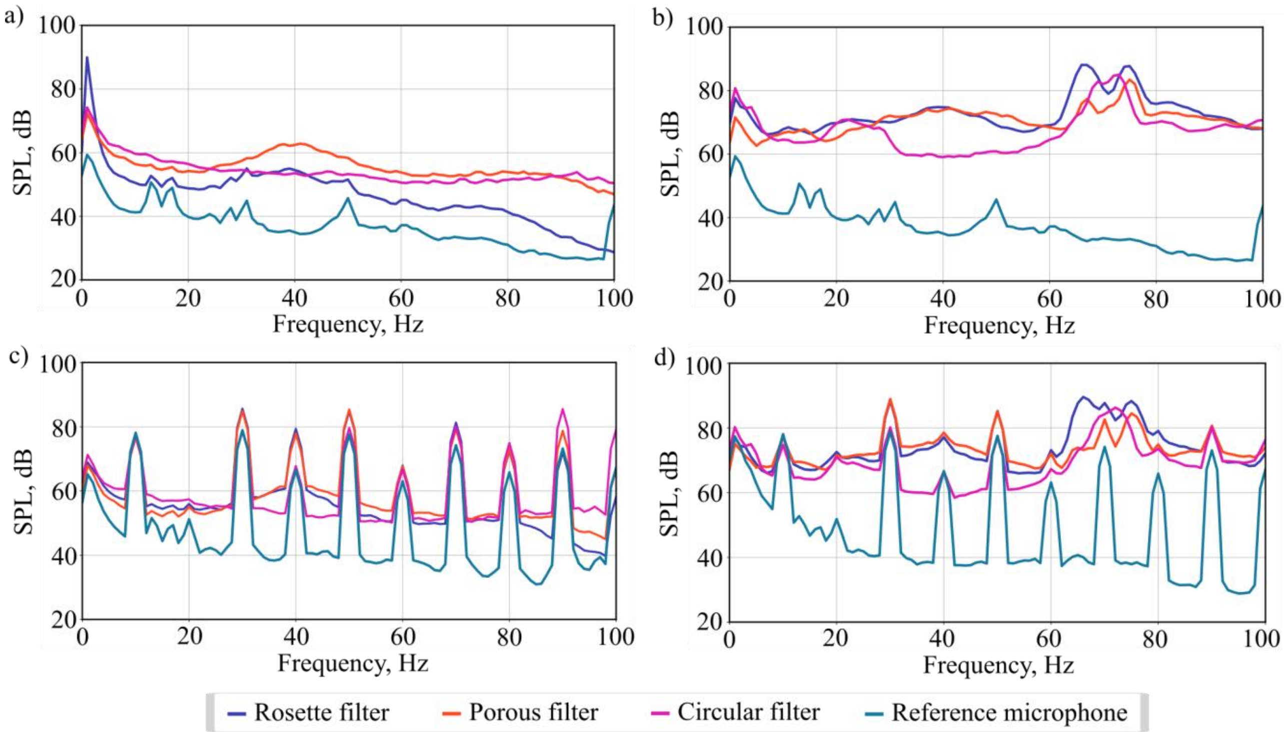

Figure 2. Comparison of SPL spectra measured with the filters and the reference microphone. a) Background noise at ground, b) Background noise at 10 m height, c) Infrasound source noise measured at ground, d) Infrasound noise measured at 10 m height.

To quantify the filter effects on the measured amplitude levels, an investigation using the infrasound noise source is performed. The source noise measured at the ground level is plotted in Fig 2 c). All filter configurations measured the same amplitude level of the 10 Hz tone as the reference microphone. The amplitude levels of the overtones between 30 Hz to 50 Hz were higher with rosette and porous hose filter due to the internal resonances. Beyond 70 Hz, the porous hose filter and circular filter gives a higher amplitude level, which could be the result of amplification caused by the increased number of inlets.
The source noise measured at 10 m altitude plotted in Fig 2 d) shows little difference in the frequency response of the filters. The 10 Hz amplitude peak remained identical among the filter spectra while the overtone peaks were amplified due to resonance and shaft noise of the rotor. Nevertheless, it is evident from Figure 2 that the spatial filter configurations tested had a minimal effect on the wind noise reduction in comparison to the spherical windscreens. Therefore, the three-microphone array was investigated as an alternative solution.
The advantage of using two or more microphones over a single microphone for filtering the atmospheric wind noise is showcased through the comparison of the CSD of the microphones with the auto spectra of a single microphone in Figure 3. Note, in the figure only the CSD spectra of Mic 1 and Mic 2 is plotted. The background noise comparison at ground level is shown in Fig 3 a). As seen from the plot, the frequency response with the microphone array overlaps the single microphone response in higher frequencies. But, in infrasound frequencies below 15 Hz, noise reduction of at least 10 dB is achieved. Similarly, the background noise measured at 10 m height is plotted in Fig 3 b) and it shows that the microphone array gives a noise reduction of at least 7 dB across the bandwidth. Furthermore, the source noise measured with the microphone array at 10 m height is shown in Fig 3 c) and it indicates negligible difference in the amplitude levels.

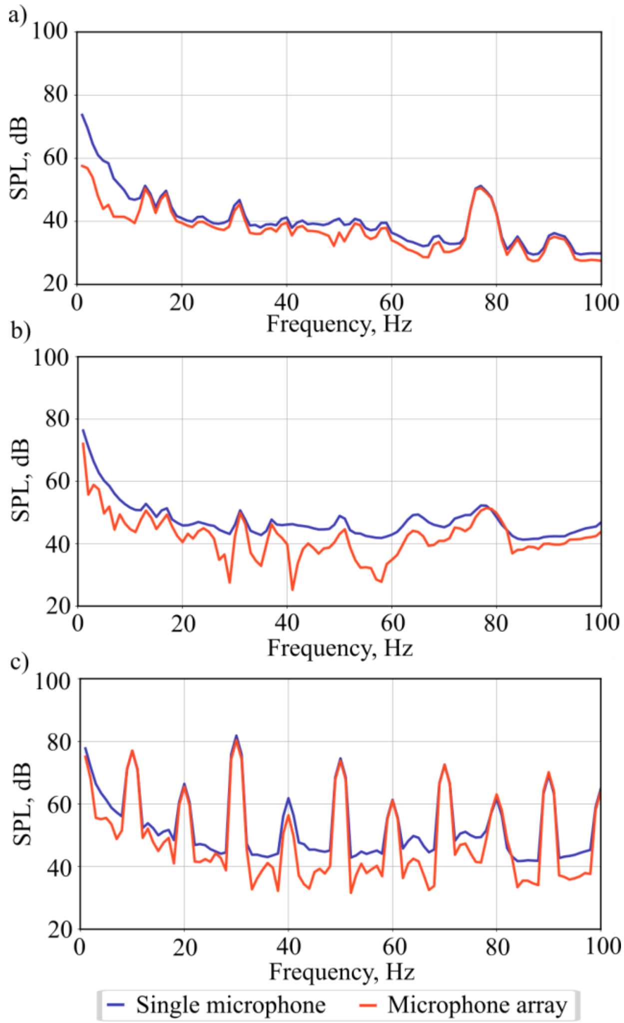

Figure 3. SPL spectra of microphone array compared to a single microphone spectra a) Background noise at ground level, b) Background noise at 10 m altitude, c) Infrasound source noise at 10 m altitude.

4. DISCUSSIONS AND CONCLUSION

The lack of effectiveness of the wind filter arrays in comparison to a microphone with windscreens is a result of the design complications involved in the filter construction. Only the rosette filter with solid pipes gave a better noise reduction efficiency in the comparative study with various filter configurations. However, one of the primary limitations in the rosette filter design is the resonance effects that reduce the effective bandwidth of the measurement. By combining arrays of different sizes, the measurement range can be extended like in the study performed by Hedlin [5] and Alcoverro [6], where 18 m and 70 m rosette filters were used to measure two different frequency ranges. Nevertheless, implementing those designs on UAV based measurement platform is difficult as we end up in the downwash region of the rotor that masks the actual acoustic signal. Further, the resonance effects arising due to the impedance mismatch in the filter design were found to introduce phase delays in the measured signal [20]. Capillary plugs matching the characteristic impedance of the tube were used to break the internal resonances in the tube. However, the design complications of the capillary plugs further result in a complex filter design. Also, the efficiency of the rosette filter was found to be dependent on the grazing angle of the waves at the inlet [6], [21]. This might introduce some decay in the frequency response and geometric symmetry of the filter must be ensured to eliminate these effects [21]. Since the filter is subjected to vibration during the flight, geometrical symmetry becomes questionable at higher altitudes with UAVs.

The porous hose filter was tested with the assumption that multiple inlets of varying distances increase the bandwidth of the measurement. Rather these inlets only increased the averaging effect which was confirmed in a previous empirical study as well [22]. While the filter was partially effective in frequencies below 10 Hz, they were found to amplify the signals in higher frequencies making their application obsolete. The circular filter configuration, which is an extension of a porous filter, suffered from a similar issue, though the resonance issues in the low frequency were eliminated.

Considering the aforementioned reasons, the application of a microphone with a windscreen for low frequency measurement in UAVs seems beneficial. A comparative measurement was performed on a windy day (15 kmph forecasted value) between the microphone with and without windscreen attached and noise reduction of at least 10 dB was achieved in the infrasound range. Also, previous experimental studies revealed that larger windscreens (> 60 mm diameter) effectiveness in low frequencies [17] which explains the better performance achieved in our case with 90 mm windscreens.

However, the efficiency of windscreens in high turbulence conditions is reduced [23]. The analytical model [24] and numerical simulation model [25] can be used in estimating the turbulence induced noise in the measurement. But these methods are complicated in that the turbulence parameters such as stability and roughness, and the stagnation pressure are to be estimated. Also, the application of the models is limited by the estimation accuracy of these parameters. In comparison, by using the CSD of two or more microphones that are spatially separated, the incoherent atmospheric turbulence effects are straightaway averaged out resulting in a simpler measurement protocol. Hence, the noise reduction mechanism of a windscreen is combined with the mechanism of a spatial filter array improving the noise reduction further. But the wind noise reduction achieved with the microphones separated by 60 degree angle (Mic 2 and Mic 3) was less than the noise reduction attained with 180 degree separation (Mic 1 and Mic 2). This implies that a longer separation distance between the sound pressure inlets provides a better averaging of the turbulence effects.

For further validation of this experimentation method, a comparison study with the analytical and numerical models discussed before would be beneficial. Also, measurement campaigns on varying wind profile conditions are required to quantify the efficiency and applicability of the microphone array for low frequency noise measurements with UAVs. Moreover, studies targeting design variations of the array and improving the data processing techniques are necessary for increasing the number of sensors thereby, to have better averaging of atmospheric turbulence.

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