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Aeroacoustic measurements on a free-flying drone in a WindShaper wind tunnel

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Summary

In the near future, drone usage in inhabited areas is expected to grow exponentially. The inherent noise generated is one of the concerns for this kind of vehicle.

Conventional aeroacoustic wind tunnels can be used to investigate uniform-flow generated noise. Flyers are generally solidly tethered to a sting in these wind tunnels. However, the interaction of complex environmental flows with the drone fans is expected to generate different harmonic content, especially during unsteady maneuvers. Being able to probe the aeroacoustic signature of a free-flying drone in a realistic urban and wind environment is a necessity, in particular for future certification procedures.

We have developed a new family of wind tunnels, the "WindShaper" (Noca et al. 2019 Wind and Weather Facility for Testing Free-Flying Drones, AIAA Aviation Forum), able to generate complex unsteady flows reproducing environmental gusts and shear flows. The WindShaper

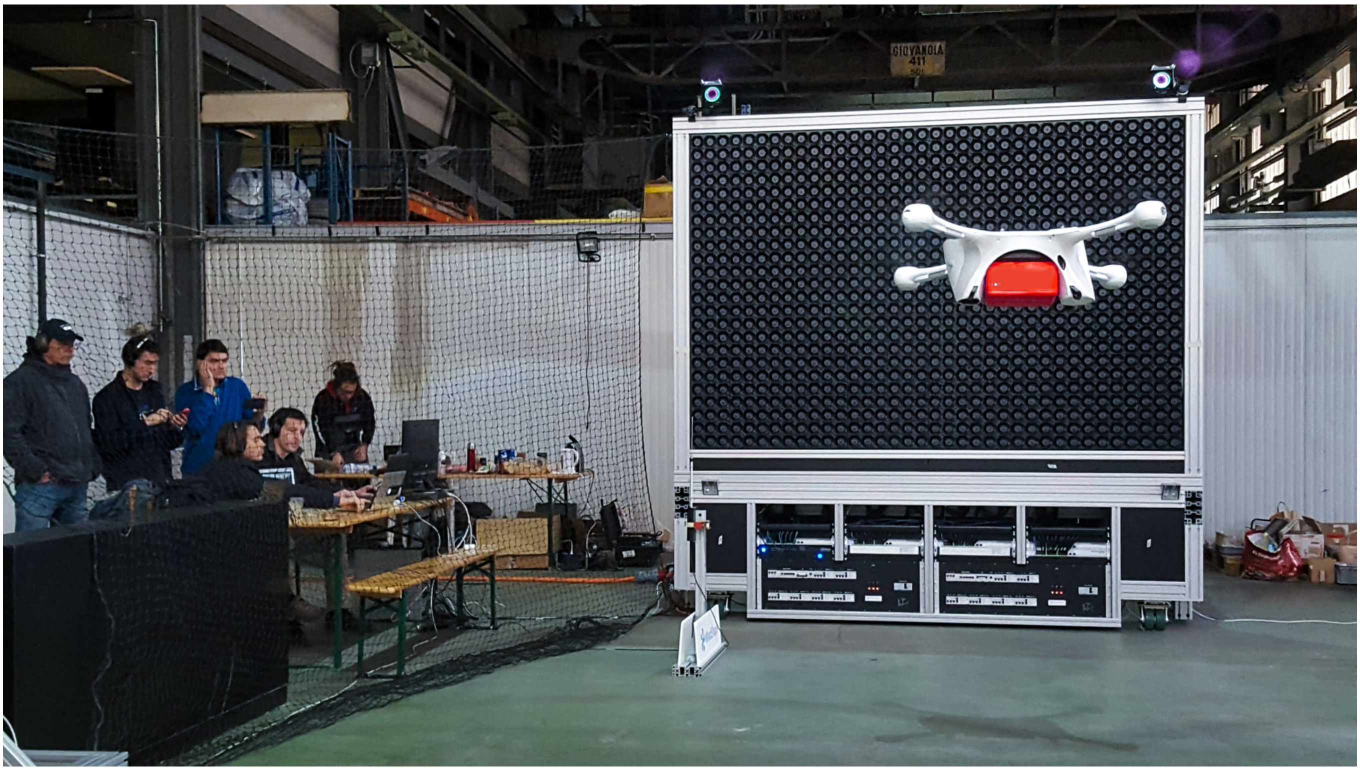


Figure 1: In November 2019, WindShape tested Matternet drone in various wind conditions within a WindShaper.

consists of an array of a large number of fans (wind-pixels) that may be arranged in various patterns on demand. It is in some ways a digital wind facility that can be programmed to generate arbitrary winds of variable intensity and direction. Various weather conditions (such as rain, snow, hail, fog etc.) that reflect real world situations can be introduced. Drones are in a free-flight configuration (untethered) as in their natural state. These tests can rate drones according to their capacity in maintaining a proper flight attitude and tackling flight perturbations, especially in an urban environment.

A WindShaper was modified in order to allow aeroacoustic measurements around a free-flying drone in a turbulent flow. Particular attention was given to a design that allows the drone aeroacoustic signature to be segregated from the aeroacoustic signature of the multi-fan facility. Details on the results achieved in this new infrastructure will be presented and discussed.

1 Introduction - Why drones need to be tested and certified

Drones are aerial vehicles that fly without an onboard pilot. In the past, the terminology *drone* was restricted to military platforms. The word *drone* is today accepted worldwide to refer to both military and civilian systems. If they are unmanned, they are classified officially by the FAA (Federal Aviation Administration) and the ICAO (International Civil Aviation Organization) as Unmanned Aircraft Systems or UAS (which also include associated ground systems), although they are also commonly called Unmanned Aerial Vehicles (UAV). If they carry a handful of passengers, drones are known as Urban Air Mobility (UAM) aircrafts, drone-taxis, or Advanced Air Mobility (AAM) vehicles, although no official label yet exists since these vehicles are still experimental. UAVs are used nowadays for multiple applications, from recreational to industrial and commercial activities such as mapping/cartography/inspection and delivery. In turn, UAMs are expected to thrive in the coming decade through the efforts of traditional aircraft or helicopter manufacturers as well as a number of burgeoning startups.

Drones can be remotely piloted (as in traditional recreational radio-controlled flyers), but the trend is towards fully *autonomous* systems, whether for unmanned or manned drones. However, such automation entails a number of risks and challenges that need to be mitigated.

Similarly to the aircraft industry, the performance of drones needs to be assessed in order to minimize the occurrence of such risks in the future. Above a certain size or weight (yet to be standardized), drones will be certified to fly following traditional aircraft procedures (which will need to be amended for the autonomous aspect).

However, for smaller size drones (including single passenger drone-taxis), certification procedures will need to be greatly revised since these vehicles are extremely prone to weather conditions, including gusts and shear, which could also affect their noise signature.

Additionally, these flyers will evolve closer to the ground and to people. Therefore the social acceptance of this technology is another great challenge. Certifying drones with respect to their noise emission could offer access to populated areas only to those drones that respect a given noise rating.

Nowadays, it is natural for most drone manufacturers to run operational demonstrators or obtain waivers for specific operations but in the near future this industry will need to rely on performance and safety standards. Various international regulatory agencies are in the process of setting up regulations for the operation of drones. It is for the good of the industry that drones will have to pass official testing procedure (as it is the case today for traditional transportation systems), and will be rated according to their ability to tackle realistic scenarios (Figure 1), such as adverse weather conditions [2], but also according to aspects such as noise emission performance.

2 Background - WindShape technology

2.1 General description

In order to resolve the issues associated with traditional wind tunnels or outdoor testing protocols, we have developed a real wind and weather simulator [9, 10] for testing flying vehicles in various and controllable atmospheric conditions, including arbitrary wind speed, temperature and direction (even vertical flow for simulating landing/descent configurations), as well as turbulence, hail, rain, snow, and sandstorms. The novel wind facility allows free-flight maneuvering, is completely modular, can be assembled in any desired geometry, and can be made as large as desired while maintaining a small footprint. It is capable of generating gusts (temporally varying winds) and arbitrary wind profiles (shear flows) in any direction. Foremost, the flyer is always at hands-reach from the tester while performing actual flight maneuvers. A motion tracking system (motion capture cameras or mocap) is integrated into the facility in order to measure the drone position and attitude (Figure 2).

2.2 Multiple-fan technology

The wind facility is based on a multiple-fan technology, which is not novel in itself. A number of conventional tunnels use multiple-fan, although they are made to rotate at the same speed (such as in the National Full-Scale Aerodynamics Complex at NASA Ames Research Center, Moffet Field, CA, USA). Atmospheric boundary layers have been simulated with arrays of individually-controlled jets [14] and fans [8, 13, 15]. Fan arrays have been used to generate gusts and shears around pliable structures [6, 3] or micro-air vehicles (MAVs) [5]. One hundred years ago, the single-fan technology used by Eiffel and Prandtl was not novel either (the Wright brothers and

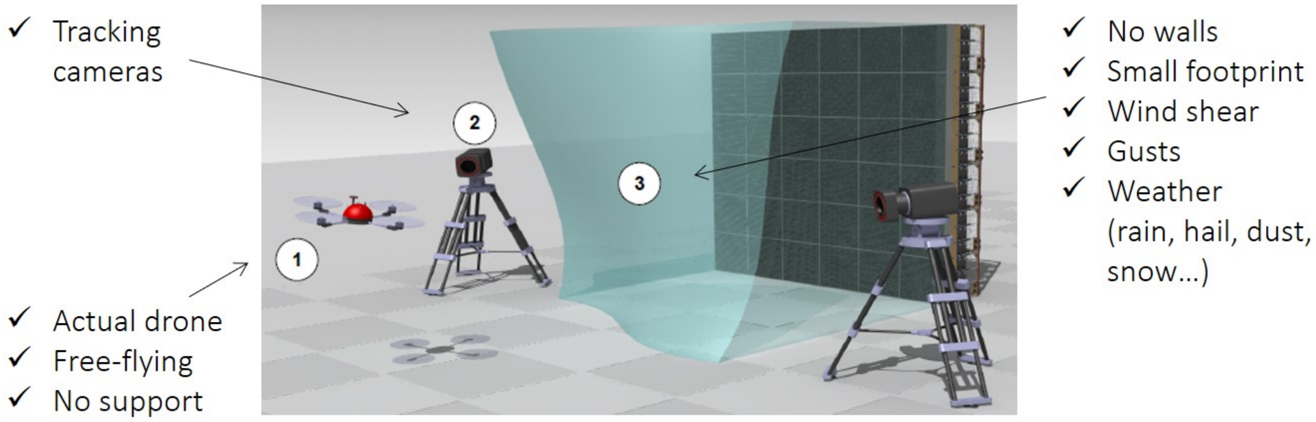


Figure 2: Wind facility for drone-testing based on multiple-fan technology [9].

others had experimented with similar devices), but the tunnels they designed were a unique and innovative tool for the aircraft industry. Similarly, WindShape technology is distinctive as it addresses the needs of the drone industry. In particular, the patented modular fan system [9] enables the stacking of an unlimited number of fans (1'296 for the Caltech facility CAST) for high resolution and fast response, as well as arbitrary wind-generating geometries that can be modified at will and over time.

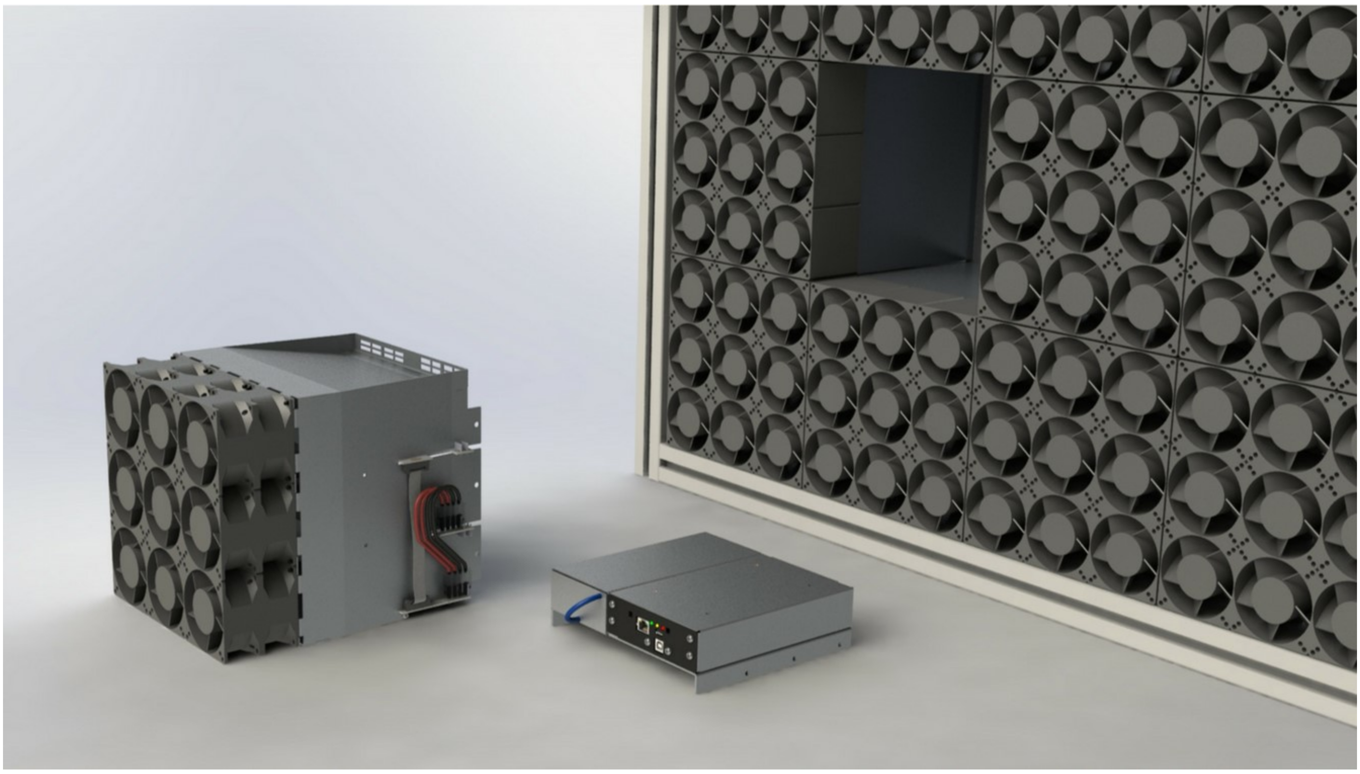
2.3 Wind pixels

The technology consists of an array of a large number of fans (approximately 150 fans per square meter) stacked in arbitrary fashion. Each single fan can be controlled independently and can, thus, be assimilated to a wind pixel (wpx). WindShape wind walls are composed of a great number of wind pixels (12.5 wpx/m in the Caltech configuration). This feature allows fine control over the generated wind properties, which in traditional tunnels requires extra flow management devices (proper nozzle geometry, flow control devices, vanes etc.). In addition, the low inertia of small-size fans enables fast changes in wind speed. Gusts of wind and shear flows can be faithfully reproduced. Laminar wind conditions, with a turbulence intensity below 1 %, can be achieved by adding screens and honeycombs in front of the fans, while preserving the independent character of every single wind pixel. Alternatively, traditional wind testing can be performed by placing the model on the aspiration side and by integrating appropriate tunnel walls.

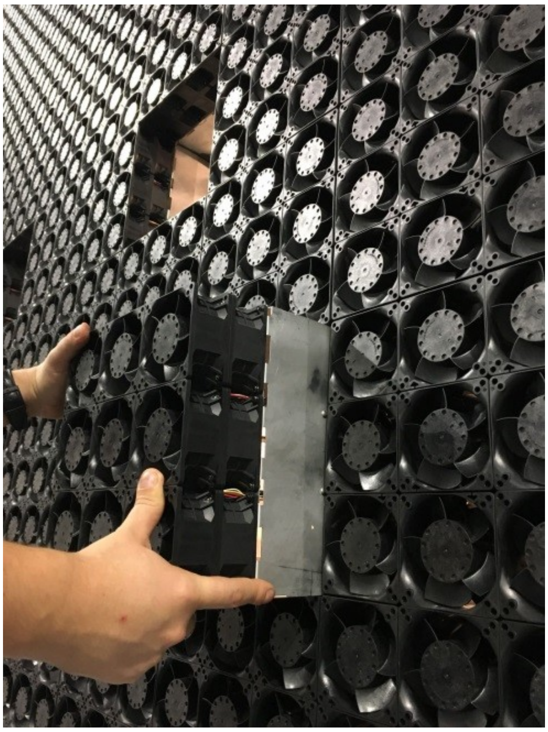
2.4 Wind modules

The basis of the product is what we call a wind module – a wind generation unit composed of nine small fans (Figure 3a), acting like a building brick or Lego™ block. These modules are designed to be assembled manually into an array to shape surfaces of fans (Figure 3b). These modules can be arranged onto surfaces of any shapes (Figure 3c). One current version of the module has a square section of 0.058 m^2, can generate winds up to 16 m/s, and requires about 1.1 kW of electrical power at maximum output.

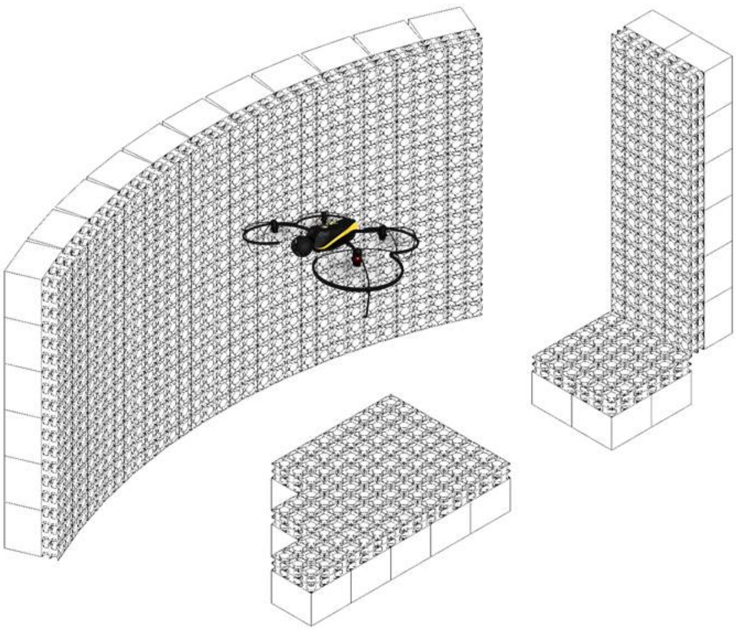
The facility being highly modular, thus, lends itself to an unlimited variety of wind configurations, spatially or temporally (Figure 3b): a wind wall can be enlarged simply by adding more modules to the wall; by moving the modules around, one can change the aspect of the wall (rectangular, square, etc.); the wall orientation can be easily modified: for instance, one can recreate the apparent wind of the descent (landing) phase of a multirotor by choosing to place the wind modules in a horizontal plane.



(a)



(b)



(c)

Figure 3: (a) The basis of WindShape technology is what we call a wind module – a wind generation unit composed of nine small fans with integrated power, which acts like a building brick or Lego™ block. (b) These modules can be rapidly assembled into an array to shape surfaces of fans. (c) Wind modules can be stacked into arbitrary shapes and sizes, thus enabling the testing of drones of various dimensions, from small UAVs up to drone-taxis, in arbitrary wind configurations (cruise flight, descent, cross-winds etc.).

3 Experimental methodology

3.1 Instrumentation

Wind facility A WindShaper with 3x6 modules (9x18 fans) is used. The cross-sectional dimension of the free jet is 1.50 m x 0.75 m, and is 0.80 m from the floor. Background details are given in Section 2. The WindShaper can be supplemented with a settling chamber that acts as a flow management device, composed of a series of screens with varying porosity and a honeycomb structure. It has the same cross-sectional area as the WindShaper and is 1 m in length. In such a configuration, the flow turbulence level varies between 0.5% and 1.0% depending on wind speed.

Acoustics Acoustic measurements are carried out with and without flow using a *01dB Fusion* sound level meter (SLM) and the *01dB dBTrait* and *dBInside* softwares for the post-processing of the data. Reverberation time (RT60)[4], defined as the time in seconds for a signal to decay to 1/1000 or 60 dB of its original amplitude, is used to assess the ability of the wind tunnel environment to synthesize a free sound field. Blank pistol shots creating a sufficiently loud noise were used as sound source to assess the reverberation time. In this study, RT60 is calculated from RT20, which is the RT value extrapolated from the time required for sound to decay by 20 dB. The calculation of sound pressure level is used to provide baseline data on the background noise.

Drones The test subjects considered in this study are well known, small commercial drones - either a *Parrot Bebop 2* or a *DJI Mavic Pro*. Both of these drones use a down-facing camera along with inertial sensors for stabilization and present a good ability in maintaining flight position when subjected to perturbations.

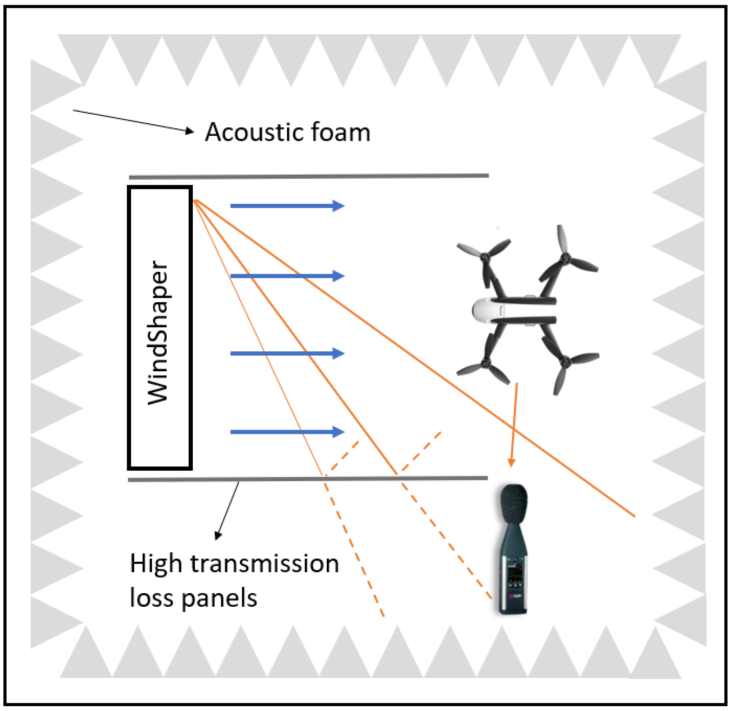
3.2 Aeroacoustic environment for WindShapers

In addition to the aeroacoustic design aspect of the wind tunnel, appropriate acoustic treatment is also required in order to achieve the aeroacoustic signature of a free-flying drone. The challenge is therefore to provide a test environment capable of generating high-quality fluid dynamic and acoustic measurements. Acoustic treatment in the aeroacoustic wind tunnel is needed: 1) to prevent the fan and fan motor noise from propagating into the test section and 2) to create an anechoic sound field and simultaneously reduce background noise in the test environment.

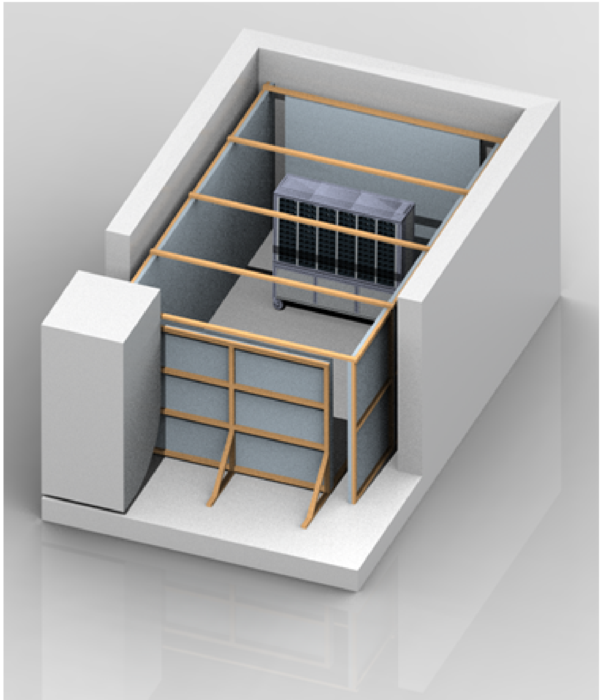
Conventional aeroacoustic wind tunnels [7, 12, 11, 1] damp these disturbances by a twofold approach based on the use of silent blocks to minimize structure-borne sound transmission and on the use of aerodynamic mufflers and acoustic liners to diminish the sound propagation along the wind tunnel ducts.

Due to the unique architecture of the WindShaper, the use of silent blocks and lined ducts was not deemed a viable solution to reduce background noise to levels compatible with aeroacoustic measurements. As shown in Figure 4a, in order to limit the influence of direct sound radiation from the WindShaper's fans on the measuring microphones, heavy panels characterized by a high transmission loss were used on the sides of the wind tunnel. Moreover, the wind tunnel itself was placed within a semi-anechoic environment to damp reflected sound that would contribute to increase the background noise.

Figure 4b shows the semi-anechoic environment that was designed to fit around the wind tunnel. The semi-anechoic environment of the test room (4.5 m x 2.7 m x 2.0 m) is composed by: 1) 48 mm thick melamine foam panels (Keller Läermschutz Dinaphon® B810) placed at a distance of 20 cm from the walls; 2) 30 mm thick polyurethane foam panels with profiled surface (Keller Läermschutz Dinaphon® M 8041) placed at a distance of 60 cm from the ceiling. The floor



(a)



(b)

Figure 4: (a) Aeroacoustic environment foreseen for the WindShaper; (b) CAD drawing of the semi-anechoic environment designed for the WindShaper.

is left tiled (no acoustic treatment). The heavy panels with high transmission loss used to line the exit of the wind tunnel are of type Keller Läermschutz Idikell(R) M4021-05.

3.2.1 Acoustic performances of the semi-anechoic environment

To take quality acoustic measurements, walls, ceilings and floors should not reflect sound back into the room. To this end, an anechoic chamber would best fit the task. However, due to wind tunnel manipulation issues and measurement simplification, a semi-anechoic environment was designed and built on purpose (Figure 4b). The acoustic performance of the aeroacoustic wind tunnel is first evaluated without airflow from the measurement of the reverberation time (RT). Reverberation time is generally on the order of 0.1 s (or less) in fully anechoic chambers. Based upon the size of a room, standing waves will occur at certain frequencies. When there is a standing wave, there is maximum pressure at an anti-node and no pressure variation at a node. In order to account for this uneven distribution of acoustic pressure, RT measurements were taken at several different positions in the room and the results were averaged.

Figure 5 shows the RT values calculated by one-third octave bands in comparison to the data measured in a traditional anechoic chamber (64 m^3, cut-off frequency $f_c = 100$ Hz). As can be seen in Figure 5, there is a good agreement for frequencies higher than 800 Hz, meaning that the current aeroacoustic wind tunnel provides a free sound field environment in the mid-high frequency range. In low-mid frequencies, however, further acoustic improvements are needed to increase the sound absorption capacity within the test environment. This discrepancy was expected in the design phase and is consistent with a foam thickness of 5 cm and wall-foam distance of 20 cm.

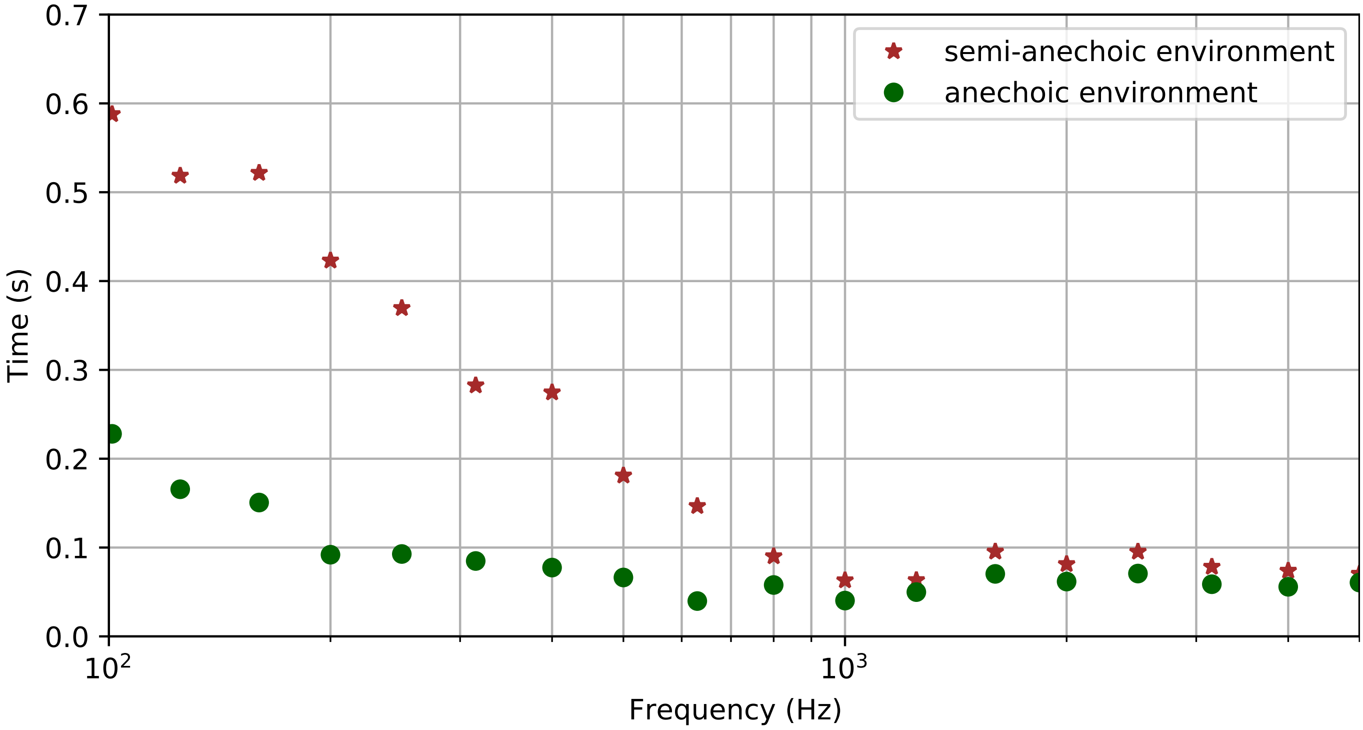


Figure 5: Anechoic chamber Vs Semi-anechoic environment RT60 reverberation times comparison.

3.2.2 Wind tunnel background noise

In order to properly assess the aeroacoustic signature generated by the drone-airflow interactions, the background noise level within the WindShaper environment should be as low as possible. The background noise determines the nominal effective noise floor at a given speed setpoint. As is generally accepted, a signal-to-noise ratio of at least 10 dB is required to make quality noise measurements. As depicted in Figure 6, four configurations were tested in order to attenuate the self-induced noise from the WindShaper:

- **Configuration A** The bare WindShaper was placed in the semi-anechoic environment (Figure 6a and Figure 4b);
- **Configuration B** A wooden structure lined in high transmission loss panels was placed around the flow to impair direct sound propagation from the WindShaper fans to the microphone;
- **Configuration C** A wooden settling chamber, of the same cross-sectional area as the WindShaper and 1.0 m in length, was placed at the exit of the WindShaper;
- **Configuration D** Both settling chamber and high transmission loss panels were placed at the exit of the wind tunnel.

The sound level spectrum was measured in these four configurations to determine the frequency response of the aeroacoustic wind tunnel at different nominal wind speeds.The position of the measurement microphone relative to the wind tunnel air exit (Figure 6) is given in Table 1.

The acoustic spectra measured for each configuration are shown in Figures 7 and 8 when the WindShaper is operating at 50% and 80% of nominal wind speed, respectively.

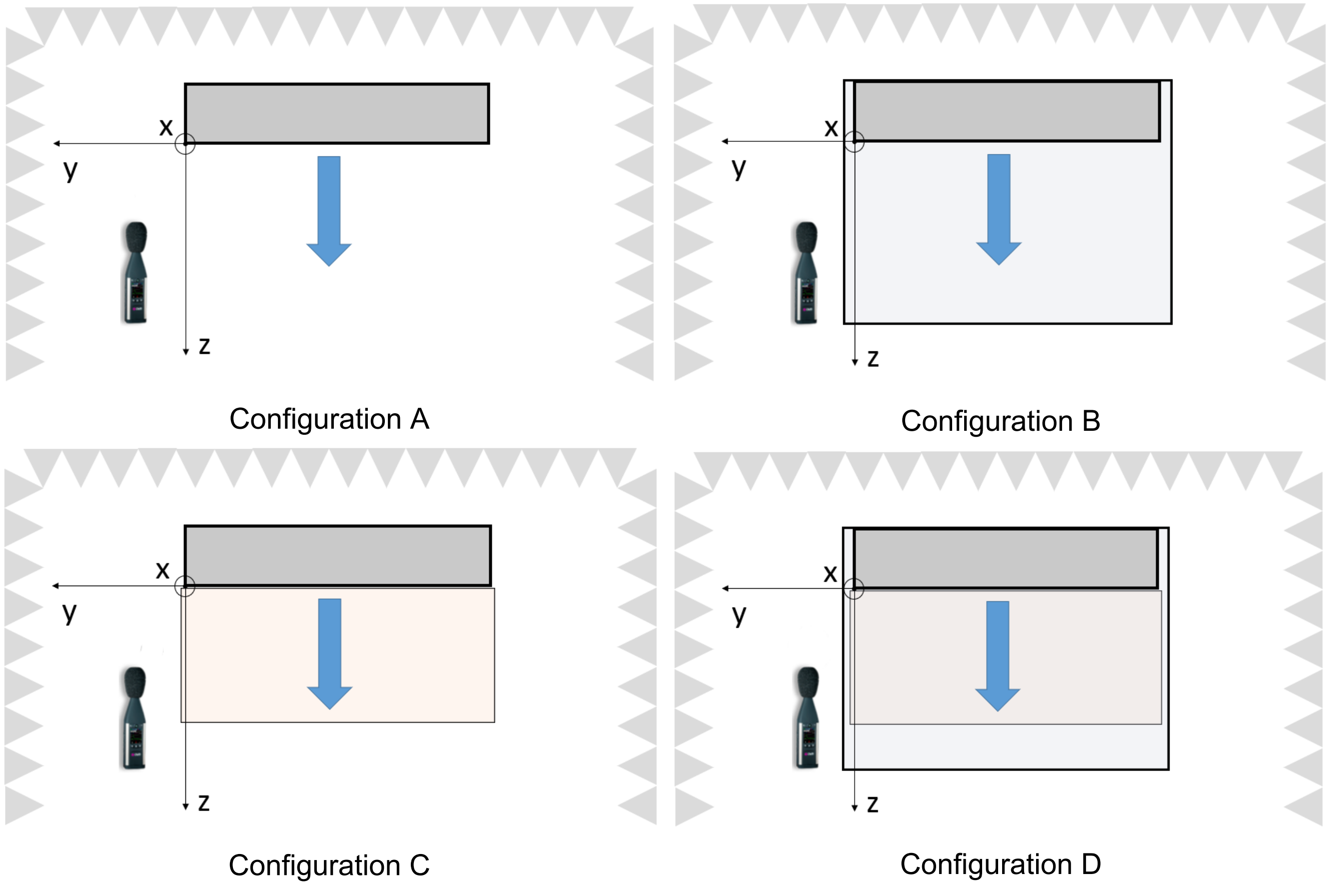


Figure 6: WindShaper's background noise investigation configurations in the semi-anechoic environment. Configuration A: bare wind tunnel; Configuration B: heavy panels lining wind tunnel exit; Configuration C: settling chamber lining the wind tunnel exit; Configuration D: settling chamber and heavy panels lining the wind tunnel exit.

X	Y	Z
1200 mm	150 mm	600 mm

Table 1: Microphone position relative to the wind tunnel exit.

As can be seen in Figures 7 and 8, the background noise when the WindShaper is operating contains tonal components typical of a fan noise source. On Figure 7, at 50% of the regime, two peaks at 525 Hz and 850 Hz respectively, correspond to the rotation speeds of the counter-rotating fans fitted to the WindShaper. The frequency and sound level of these peaks increase with the nominal wind speed, and in Figure 8, at 80% regime, the peaks move respectively at 800 Hz and 1275 Hz.

As expected, a decrease in the background noise level is observed by installing either the high transmission loss panels or the wooden settling chamber. This decrease is observed to be comparable in the two configurations.

At 50% of the nominal speed (Figure 7), the use of both high transmission loss panels and wooden settling chamber results in a reduction of the background noise of approximately 9 dB in the frequency range between 400 and 1000 Hz. The background noise reduction increases for higher frequencies up to 25 dB.

At 80% of the nominal speed (Figure 8), the same configuration reduces the background noise of approximately 12 dB in the frequency range between 400 and 1000 Hz. For higher frequencies, the reduction increases up to 25 dB.

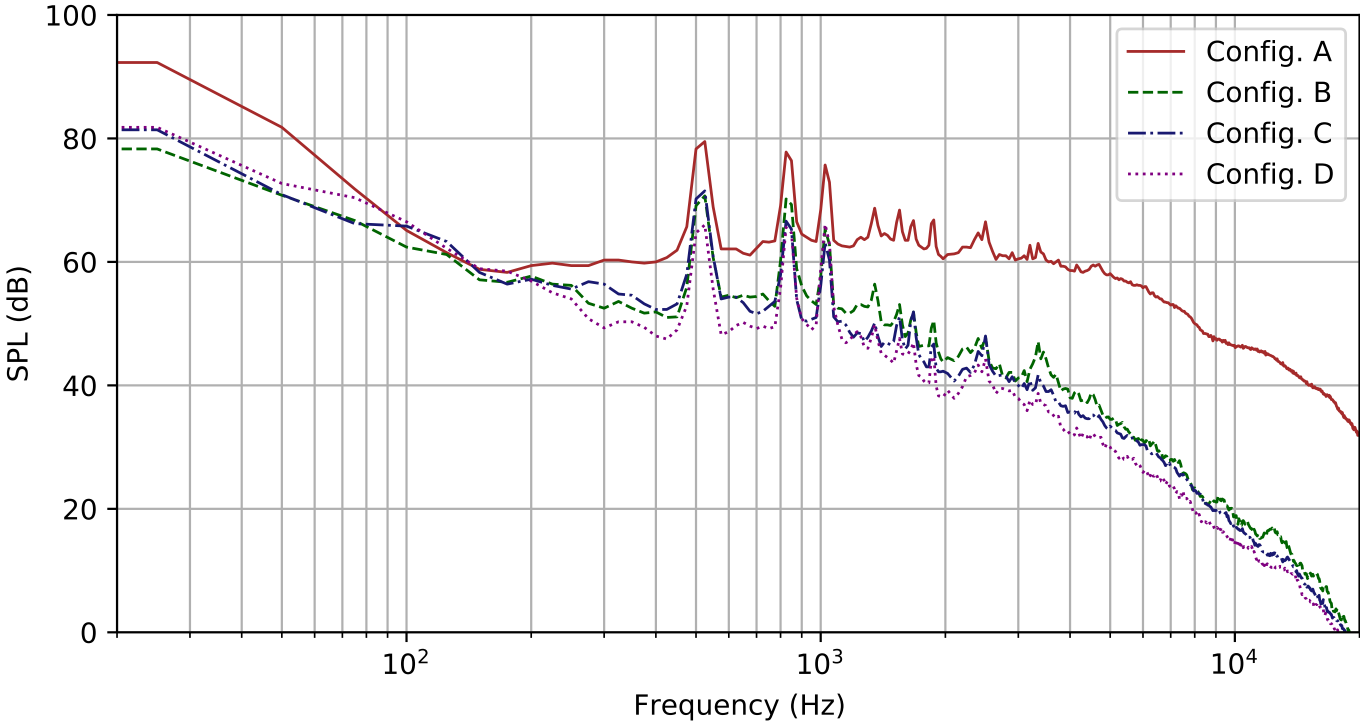


Figure 7: WindShaper Background noise SPL spectrum at 50% of maximum velocity.

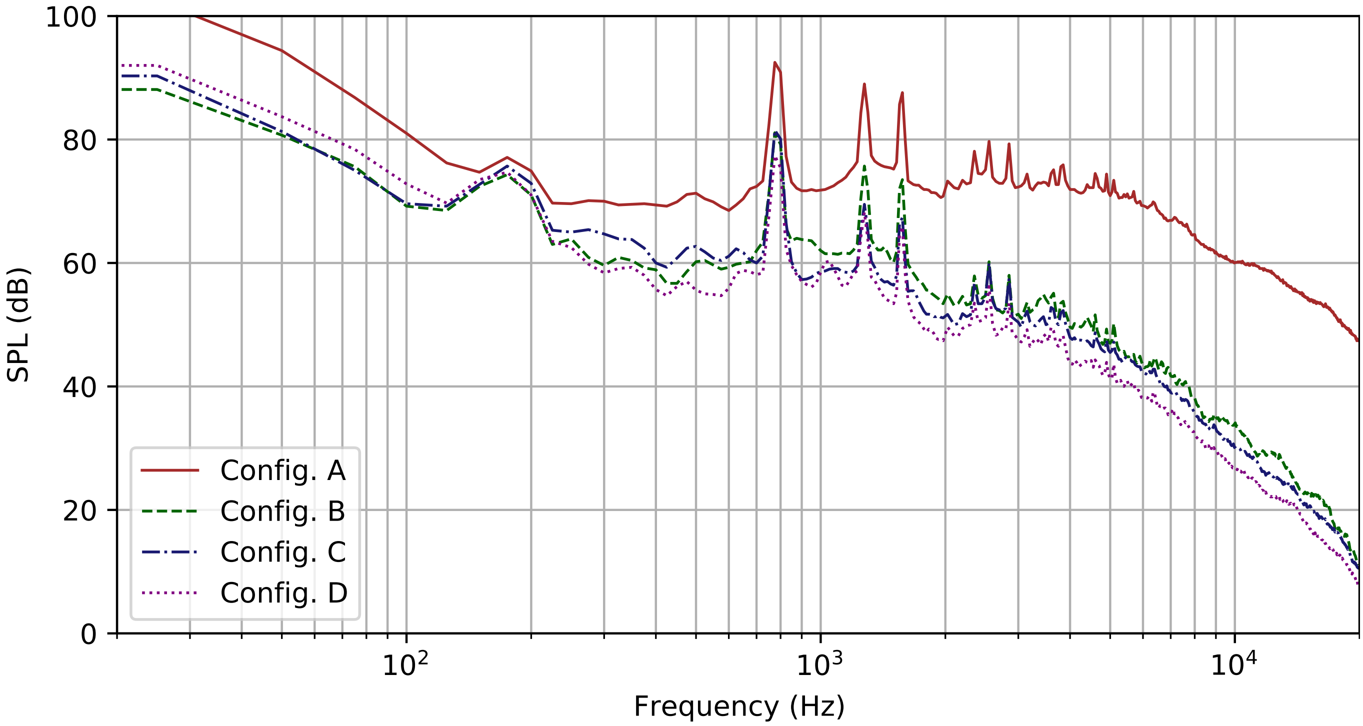


Figure 8: WindShaper Background noise SPL spectrum at 80% of maximum velocity.

Between 400 Hz and 1000 Hz the use of both settling chamber and heavy panels reduces the noise by approximately 12 dB, whereas for higher frequencies the reduction increases up to approximately 25 dB.

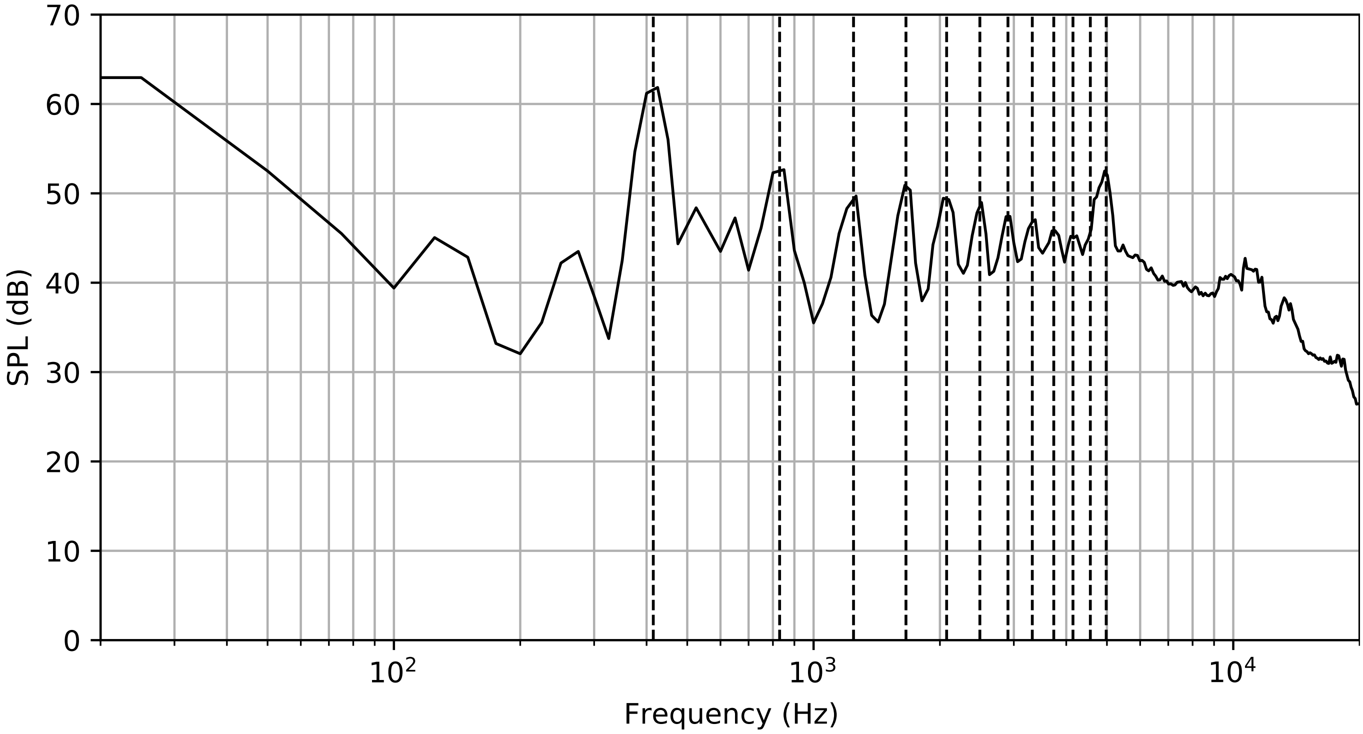


Figure 9: Drone SPL noise spectrum in the semi-anechoic environment.

3.2.3 Drone noise testing in the WindShaper

A lightweight *Parrot Bebop 2* drone in steady flight was tested both in the anechoic chamber and in the semi-anechoic environment with comparable results. Figure 9 shows its SPL spectrum in wind-off semi-anechoic environment. As can be seen in Figure 9, the prominent noise in hovering flight is the tonal noise of the blade passing frequency at 415 Hz and its harmonics.

Acoustic investigations were also carried out on the drone with WindShaper operating at 30%, 40%, 50% and 60% of its nominal wind speed. During these tests, the WindShaper was equipped with both high transmission loss panels and settling chamber as depicted in Figure 6d. Figures 10 and 11 show the SPL spectrum of the drone and of the WindShaper at 30% and 40% of its nominal speed.

Figure 10 shows that operating the WindShaper at 30% of its nominal velocity, the sounds emitted by the drone for frequencies higher than 2000 Hz can be considered more than 10 dB above the background noise. For frequencies ranging between 1400 Hz and 2000 Hz, the 10 dB difference with respect to the background noise cannot be guaranteed. For frequencies lower than 1400 Hz, the magnitude of the drone noise becomes comparable or lower than the WindShaper's.

Figure 11 shows that for higher wind speeds the WindShapter's background noise becomes more important, and the exploitable frequency range gets smaller. For WindShaper at 40% of its nominal velocity, a 10 dB difference with respect to the background noise can be observed above approximately 8000 Hz.

Due to clear superposition of the background noise with the drone's emissions for higher wind speeds, the measurements for these configurations are not shown in the present paper.

4 Conclusions

An overview of the aeroacoustic wind tunnel has been presented including the several acoustic treatments implemented. The current semi-anechoic environment generates a free field for frequencies higher than 800 Hz (TR60 <0.1 s). Room improvements will aim at increasing the free

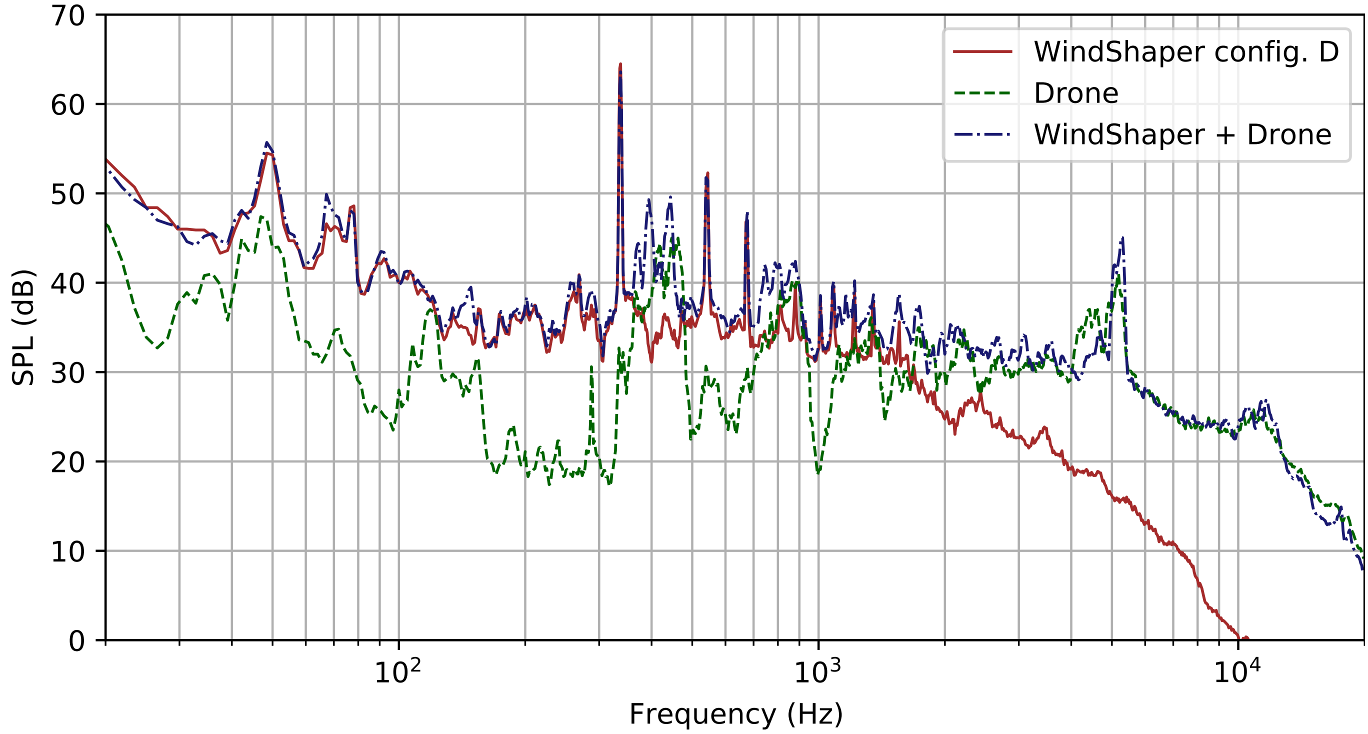


Figure 10: Drone SPL noise spectrum in the semi-anechoic environment with wind-tunnel at 30% ot its nominal velocity.

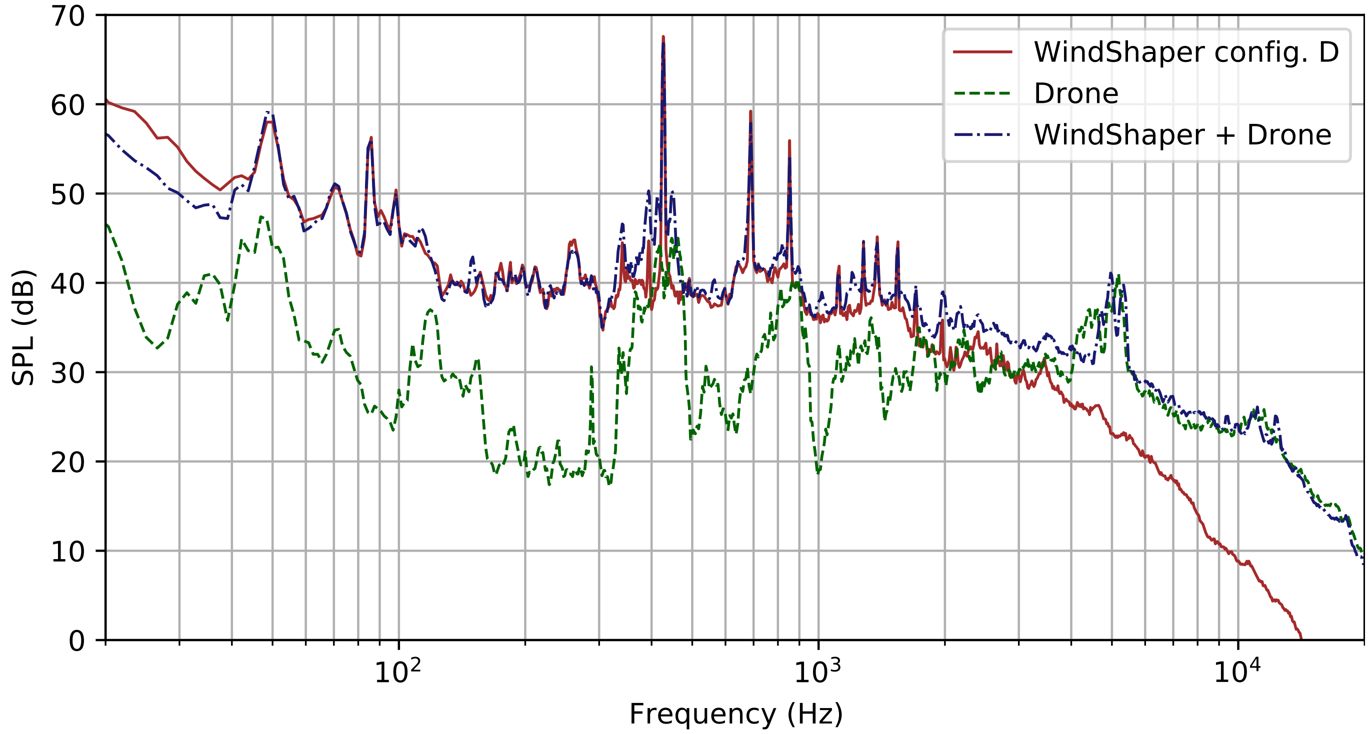


Figure 11: Drone SPL noise spectrum in the semi-anechoic environment with wind-tunnel at 40% ot its nominal velocity.

field frequency range.

With airflow, background noise levels are competitive, but further reduction is desired to achieve sufficient signal-to-noise ratio. Acoustic sidewalls surrounding the WindShaper used to prevent the propagation of fan motor noise have been found to be effective, reducing the background noise by 9 to 25 dB depending on the configuration. Nevertheless, this noise damping is observed to be not sufficient to make use of the WindShaper at higher regimes. For a *Bebop 2* like drone, at 30% regime the frequencies where the WindShaper is considered do be exploitable for aeroacoustic investigations are 1400 Hz and higher. At 40% regime, the lowest exploitable frequency is considered to be 8000 Hz.

On the other hand, it has to be noted that the sample drone used here to investigate the WindShaper's acoustic capabilities is a lightweight device that constitutes a worst case scenario: commercial drones that will need certifications are likely to be heavier, and to produce louder sounds. However, particular attention will have to be paid in further investigations to damp the WindShaper's background noise and harmonic behaviour, whose frequencies vary with the wind speed in a range of amplitudes common to many drones. In future developments, effort will be put in the identification of the background noise sources in order to damp the acoustic disturbances at their origin. Moreover, investigating the properties of different sidewall configurations will be useful to establish a baseline reference for designing future experimental setups. On this topic, on-purpose designed resonant systems such as acoustic liners are likely to be effective both on the broadband and tonal noises.

From the measurement system point of view, single microphone techniques are suited to measure the overall sound level occurring at a certain position, which makes it impossible to distinguish whether a sound is generated by the drone or by the WindShaper. In future works it is planned to study how accurately aeroacoustic sound sources can be detected and quantified within a WindShaper using phased array microphone techniques.

Acknowledgements

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