

A LOW-COST ANECHOIC CHAMBER FOR ROTOR AEROACOUSTICS

RESEARCH: DESIGN AND VALIDATION

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ABSTRACT

A new anechoic chamber was built at the Łukasiewicz Research Network – Institute of Aviation in Warsaw, Poland, for the purpose of research on aeroacoustics of rotor systems. In order to minimize costs and construction time, a drywall-based design was employed, consisting of a steel frame placed on vibration isolators, mineral wool insulation, and plasterboard cladding. The interior of the chamber was lined with acoustic foam wedges to ensure the anechoic condition. The average background noise level in the chamber was measured at 18.1 dB(A), and the anechoic condition was confirmed down to 315 Hz, and under certain conditions down to 125 Hz, in accordance with the ISO 3745 standard. The acoustic performance of the chamber was further validated through aeroacoustic tests of a benchmark rotor. The results showed very good agreement of the rotor's acoustic characteristics with the reference data, including precise replication of key harmonics, confirming the chamber's suitability for aeroacoustic testing.

Keywords

anechoic chamber, aeroacoustics, rotors, UAV.

1. INTRODUCTION

The rapid growth in the diversity and popularity of unmanned air vehicles (UAVs) and urban air mobility (UAM) vehicles has resulted in increased scrutiny of their safety and environmental impact [1]. Simultaneously, awareness of the impact of noise on human health and wellbeing has been rising steadily [2], leading to implementation of stricter noise-related regulations. Examples include the European Union's Environmental Noise Directive [3], regulations on noise operating restrictions at airports [4], and mandatory certification of UAVs, which includes evaluation of their acoustic emissions [5-6]. As a result, manufacturers are now under increased pressure to reduce the noise generated by their products. In the case of unmanned air systems, the bulk of acoustic emissions is typically generated by the

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propulsion system. While some noise is generated by motors, be they combustion or electric, the most significant and often highly irritating contribution comes from the rotors, which emit distinctive tones [7].

Development of effective noise reduction technologies depends on the ability to precisely determine the noise generated by a specific vehicle configuration [8,9]. This may be done either numerically, using computational fluid dynamics or simpler, analytical or empirical methods, or experimentally, using physical models and measurements. In both cases, the aim is to replicate the operating conditions as closely as possible. Despite the advancement of numerical methods, they unavoidably rely on models and approximations of physical mechanisms; therefore, experimental validation is typically required to confirm their accuracy. Furthermore, the main challenges in predicting noise generated by UAM and UAVs involve accurately modelling rotors operating in the low Reynolds number range [10] and with a large share of the broadband noise component [5]. The difficulty inherent in the first issue results from complex transitional flow phenomena, which are beyond the capabilities of typical turbulence closure models used in Navier-Stokes solvers [11]. Broadband noise prediction, on the other hand, often requires accurate simulation of a wide range of turbulent scales or the use of a semi-empirical method. Both challenges further emphasise the need to experimentally validate computational models using well-defined benchmarks.

Although testing of complete unmanned air systems is useful for verifying the acoustic performance of the final product, including all aerodynamic and acoustic interaction effects [12], individual components are often tested in isolation in the development phase. This makes it easier to maintain controlled conditions and reduces variability between tests, resulting in improved measurement reproducibility and accuracy. When measuring the noise generated by UAV rotors, an appropriate acoustic environment must be ensured. Whereas a reverberation chamber would suffice for determining the sound power level of a rotor, the high directivity of rotor noise means that an anechoic or semi-anechoic environment is preferable for research purposes. The latter might be approximated at an open-air location, but high background noise and changing atmospheric conditions, including precipitation and wind, make anechoic chambers preferable. Despite their limitation to the hover condition, anechoic chambers are widely used for the study of rotor aeroacoustics, including isolated rotors [10, 13-20], coaxial rotors [21], ducted rotors [22-24], the rotor-arm interaction [25-27], noise reduction technologies [24, 28], and complete multi-rotor vehicles [29-33].

In order to enable testing of new solutions for rotor noise reduction, and to support numerical studies by providing experimental validation, a new anechoic chamber was built at the Łukasiewicz Research Network – Institute of Aviation (Ł-ILOT) in Warsaw, Poland. As the chamber does not have an airstream passing through it, only hover tests are currently possible, although the possibility of adding a stream at a later time is under consideration. In order to validate the newly

commissioned facility, a benchmark rotor was tested, and its acoustic characteristics were compared against those reported in the reference benchmark study.

2. DESIGN AND CONSTRUCTION OF THE CHAMBER

2.1 Chamber specifications

In order to enable accurate measurements of the noise generated by rotors, the acoustic environment must satisfy two conditions:

1. A low background noise level, to separate the noise generated by the object from other noise sources. According to the ISO 3745 standard [34], which describes research methods involving anechoic chambers, the background noise level, i.e. the noise level without a test object, should be at least 10 dB lower than the noise generated by the object across the entire frequency range of interest. However, according to common best practices, the difference should be much greater for high-quality measurements.
2. The anechoic (free-field) condition, i.e. a lack of sound reflections from surfaces surrounding the test object. This ensures that sensors measure only the noise generated by the object itself, and not waves reflected from the walls, floor, roof, door, equipment, etc. Compliance is verified by comparing the decrease in sound pressure level at increasing distances from the source with the inverse square law, with the measurement procedure and permissible deviations defined by the ISO 3745 standard. In theory, this applies only to a point source producing a spherical wave, but the sound field produced by a source with multiple speakers can approximate a spherical wave at a sufficient distance from the source.

Furthermore, it is desirable to maximise the internal volume of the chamber for two reasons. Firstly, the larger the internal volume, the lower frequencies may be measured accurately and the larger objects may be tested. Secondly, increasing the length and cross-sectional area of the chamber allows rotor wakes to disperse more gradually, and reduces the intensity of the resultant flow recirculation.

The design specifications of the anechoic chamber were formulated based on the above criteria and the planned scope of research applications. Retaining partial modularity was an additional aim incorporated into the design, to enable subsequent modifications to the configuration of the chamber.

2.2 Construction of the chamber

The anechoic chamber was constructed as a freestanding unit within an existing hall, using a semi-custom drywall system from Knauf. This type of construction, as opposed to a concrete structure, lowered the costs, provided a degree of modularity,

and did not require any interference with the existing structure of the building. The external dimensions of the anechoic chamber, which fill the available space allocated for its construction, are 4.55×4.80 m, with a height of 5.57 m.

The majority of the weight of the chamber is supported by 6 steel “CUBO” pillars, positioned at the corners and in the middle of the longer walls. The structure of the roof is supported by UA 150 (150 mm-wide) steel profiles spanning between the pillars and across the width of the chamber. In order to maximise sound insulation, the walls were constructed using a double layer of UW 75 and CW 75 steel profiles, filled with two 75 mm-thick layers of mineral wool. Additional 27 mm-wide elastic steel profiles were mounted underneath the structure of the roof to reduce vibration transmission, and the roof was filled with a 100 mm layer of mineral wool. Both the walls and the roof were covered with a double layer of dense 12.5 mm-thick plasterboard (Knauf Akustik Plus), both inside and outside. This resulted in a total wall thickness of 200 mm and a roof thickness of 227 mm.

In order to isolate the chamber from vibration and noise transmission from the ground, it was built on a wooden floor structure resting on an array of mechanical vibration isolators. The wooden structure was filled with 100 mm of mineral wool, and additional layers of chipboard, mineral wool and rubber formed the floor of the chamber, resulting in a total floor structure height of 340 mm. Finally, an acoustic door from Porta, with a declared rating of 42 dB, was installed at the entrance. The final internal dimensions of the chamber are 4.15×4.40 m, with a height of 5.00 m. The chamber during construction and after completion is shown in Fig. 1.



Fig. 1. The anechoic chamber at Ł-ILOT during construction and after completion.

2.3 Acoustic treatment

In order to ensure the anechoic condition within the chamber, all internal surfaces, including the walls, roof and floor, were covered with foam wedges, with corners filled with appropriate rectangular blocks, leaving no hard surface exposed. Melamine foam Basotect G+ was used on the walls, door and roof for its low weight and fire resistance, whereas polyurethane foam was used on the floor because of its mechanical durability. The wedge layout is shown in Fig. 2.

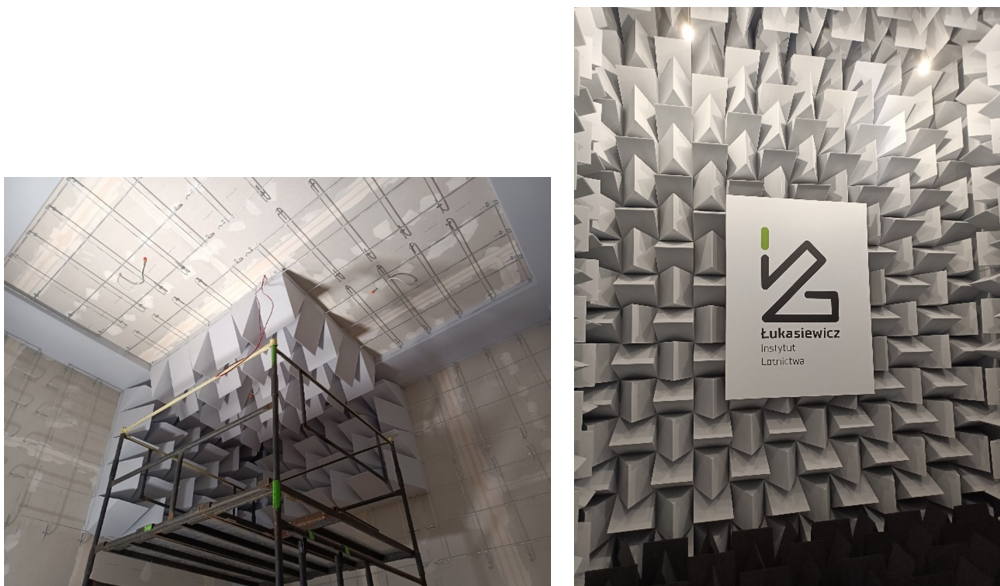


Fig. 2. The acoustic lining of the chamber, during installation and after completion.

The height of the wedges was determined as a compromise between their cut-off frequency, i.e. the lowest frequency with effective dissipation of sound waves, and their cost and the internal tip-to-tip volume. A common rule of thumb states that such wedges are effective for dissipating sound with wavelength up to four times their height. A final height of 500 mm was chosen, which should yield a cut-off frequency of approximately 170 Hz. The wedges have a base of 300×300 mm with a thickness of 100 mm. Custom-shaped blocks with heights of up to 680 mm were installed on the door, in order to maximise sound scattering and absorption while allowing the door to be opened without a collision with the frame. The resulting tip-to-tip dimensions of the chamber are $3.40 \times 3.15 \times 4.00$ m.

Whereas the corner and door blocks were attached using an adhesive, the wall and roof wedges were mounted using custom steel meshes, as shown in Fig. 2. Made of 6 mm galvanised rods, the meshes had 300×300 mm openings to fit individual wedges, and bent tips around the circumference, allowing them to be screwed onto

the surfaces, leaving a gap of 50 mm. This construction makes it possible to remove and reinsert individual wedges at will, significantly increasing the reconfigurability of the chamber.

2.4 Equipment

The chamber is equipped with LED spot lighting in the corners, a smoke detector, and two acoustically sealed cable channels, manufactured by icotek, through one of the walls. The channels, made of plastic frames and interchangeable rubber inserts, enable transmission of up to 48 cables of varying diameters without compromising the acoustic properties of the chamber.

3. TESTING OF THE ACOUSTIC ENVIRONMENT

3.1 Data acquisition

All acoustic measurements were performed using PCB 378B02 free-field microphones, mounted on telescopic tripods. The data acquisition system consisted of an NI cDAQ-9189 chassis with NI-9250 cards. Microphone signals were acquired at 51.2 kHz, and were sampled for 10 s during measurements of background noise and verification of the anechoic condition, and for 5 s during rotor testing. The acquired signals were split into 0.5 s-long, Hanning-windowed Welch blocks for the calculation of the power spectral density (PSD) of acoustic pressure, with a frequency resolution of 20 Hz and a reference pressure of 20 μ Pa used for all measurements. All sound pressure level (SPL) values are calculated by integrating the spectra of acoustic pressure between 100 Hz and 20 kHz, which corresponds to the operating range of the chamber.

3.2 Background noise mapping

The aim of background noise mapping was not just to determine the average SPL of background noise, but to examine its frequency characteristics and spatial variability. The latter is particularly important given the presence of the entrance door and cable channels, which could contribute to sound leakage. For this purpose, the internal tip-to-tip volume of the chamber was divided into 12 partitions of equal volume (2×2 horizontally and 3 vertically), and microphones were positioned at their geometric centres. Measurements were taken with typical ambient conditions outside of the chamber, with no additional sound source. All partitions were tested simultaneously, which eliminated the impact of temporal fluctuations.

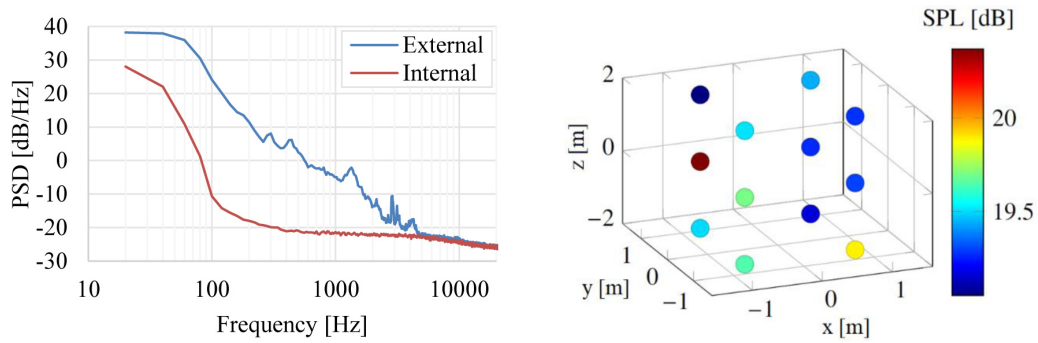


Fig. 3. Background noise in the anechoic chamber: PSD of acoustic pressure at position $[0.79, -0.85, 0]$ and outside of the chamber for reference (left), and SPL spatial distribution (right).

A spectrum of acoustic pressure from one of the microphones inside the chamber is plotted in Fig. 3. The chosen microphone was located at the horizontal mid-plane of the chamber ($z = 0$), at $x = 0.79$ m and $y = -0.85$ m, according to the reference frame from Fig. 3. This position corresponds to the region most frequently used for rotor measurements. Furthermore, the PSD of external noise, obtained using an additional microphone outside of the chamber, is plotted for reference. The SPL inside the chamber, averaged from all microphones, was equal to 19.4 dB, while the external SPL was 39.2 dB, which constitutes a reduction of 19.8 dB. For reference, the average A-weighted SPL inside the chamber, calculated from the entire spectrum, was equal to 18.1 dB(A). The internal background noise spectrum shows that the PSD of acoustic pressure inside the chamber is below -10 dB across the entire frequency range above 100 Hz, and below -20 dB above 300 Hz. Comparison with the external spectrum shows that the walls and acoustic lining of the chamber are particularly effective around 100 Hz, with the sound level reduction exceeding 30 dB. For lower frequencies the insulation effectiveness is progressively lower, but the relatively low external background noise, combined with the insulation of the chamber, result in background noise of less than 30 dB even at 20 Hz. These results suggest that a drywall construction is sufficient for an anechoic chamber if the frequency range of interest is not below 100 Hz, and depending on the required sensitivity, it might be sufficient even for lower frequencies.

The spatial variations of the sound pressure level are shown in Fig. 3. Total SPL variation is within 1.35 dB, and only a minor increase is observed near the door, which is located near the $[-1, -1]$ corner of the floor (bottom left of the figure). This suggests that there is no significant localised leakage of sound through the structure and lining of the chamber, i.e. no particular weak point.

3.3 Anechoic condition

The anechoic condition within the chamber was verified according to the ISO 3745 standard [34]. For this purpose, an omnidirectional sound source was placed in the horizontal centre of the chamber, 1.025 m above wedge tips, i.e. 0.975 m below the geometric centre of the internal volume of the chamber. The tests were carried out using a Norsonic Nor276 source, containing 12 individual speakers, with a Norsonic Nor282 amplifier, which is able to generate pure tones between 12.5 Hz and 20 kHz, as well as several other types of noise.

The ISO 3745 standard [34] defines the measurement procedures required to verify the anechoic condition, and specifies 5 directions away from the source that should be tested for complete verification of the whole chamber. Because of limitations of the test setup, only two horizontal directions have been tested so far: towards a dihedral corner (parallel to the z-plane, 43.6° off the x-axis) and towards the door (parallel to the z-plane, 11.2° off the y-axis). However, all measurements and data processing were carried out in accordance with the standard. For each direction, the microphones were placed at distances from 50 cm to 160 cm away from the geometric centre of the source, at a resolution of 10 cm. At each position, pure tones were generated at centre frequencies of one-third octaves between 50 Hz and 10 kHz, resulting in 24 frequencies. The sound pressure level generated by the source varied depending on the frequency, but exceeded the background noise level by at least 30 dB at all frequencies, and by at least 70 dB at frequencies of 100 Hz and above, for all microphone positions.

The expected sound pressure level $L_p(r_i)$ at each distance from the source r_i was calculated using the formula:

$$L_p(r_i) = 20 \log \left(\frac{\sum_{i=1}^M r_i^2}{r_i \sum_{i=1}^M r_i 10^{-0.05 L_{pi}}} \right)$$

where $M = 12$ is the number of microphone locations and L_{pi} is the sound pressure level for the given one-third octave at a distance r_i . The deviation from the expected SPL, which corresponds to the inverse square law, is then calculated from:

$$\Delta L_{pi} = L_{pi} - L_p(r_i)$$

The deviation of the measured SPL from the inverse square law for two directions in the anechoic chamber is plotted for centre frequencies of all tested octaves in Fig. 4.

It can be seen that the measured SPL curves fit within the bounds defined by the ISO 3745 standard (± 1 dB for 630 Hz < f < 6300 Hz, otherwise ± 1.5 dB) between 500 and 2000 Hz, confirming the anechoic condition in this frequency range.

At 4000 Hz the measured curves deviate from the expected trends significantly. This is attributed to non-uniformities of the sound source used in these tests. As the source consists of 12 individual speakers, interference patterns form around it. At certain frequencies and locations around the source, destructive and constructive interference occurs. The frequency of 4000 Hz corresponds to a wavelength of 8.5 cm, which is of the same order as the distances between the individual speakers (the diameter of the source is approximately 33 cm). For this reason, strong interference may be expected at this frequency, and therefore the deviations from the inverse square law are assumed to be caused not by the characteristics of the anechoic chamber, but rather by the characteristics of the test apparatus. A similar trend may be observed close to the source at frequencies up to 8000 Hz; the same assumption is made for these frequencies, and the anechoic condition in the chamber is assumed to hold in this frequency range.

Another significant pattern evident in Fig. 4 are the apparent standing wave patterns at frequencies up to 315 Hz. These patterns, with varying strength and at wavelengths which match the excitation frequencies and the internal dimensions of the chamber, suggest the formation of standing waves within the chamber in this frequency range. The expected cut-off frequency of the wedges was approximately 170 Hz, which suggests that their performance might be below expectations. However, the chamber has parallel walls on all sides and no air gaps behind the wedges, and these factors improve conditions for standing wave formation. Nevertheless, the strength of the standing waves is small enough that most of the curves fit within the bounds permitted by the standard, especially in the direction of the door. This indicates that sound reflections in this frequency range are still significantly damped by the acoustic lining of the chamber. It is also worth noting that the magnitude of the standing waves is much higher in the direction of the dihedral corner, which is situated at an angle of approximately 45° to both the x- and y-axes and therefore can identify waves along both those axes, than in the direction of the door, which is nearly parallel to the y-axis and so can only identify waves along this axis. Therefore, it may be concluded that the standing waves form mostly in the direction of the x-axis. The walls normal to this axis are covered in uniform wedge layouts, in contrast to one of the walls normal to the y-axis, with wedges on and around the door of the chamber breaking up the uniform layout. This suggests that varying the lengths of wedges or disrupting their layout might be an effective way of lessening the resonance in the chamber.

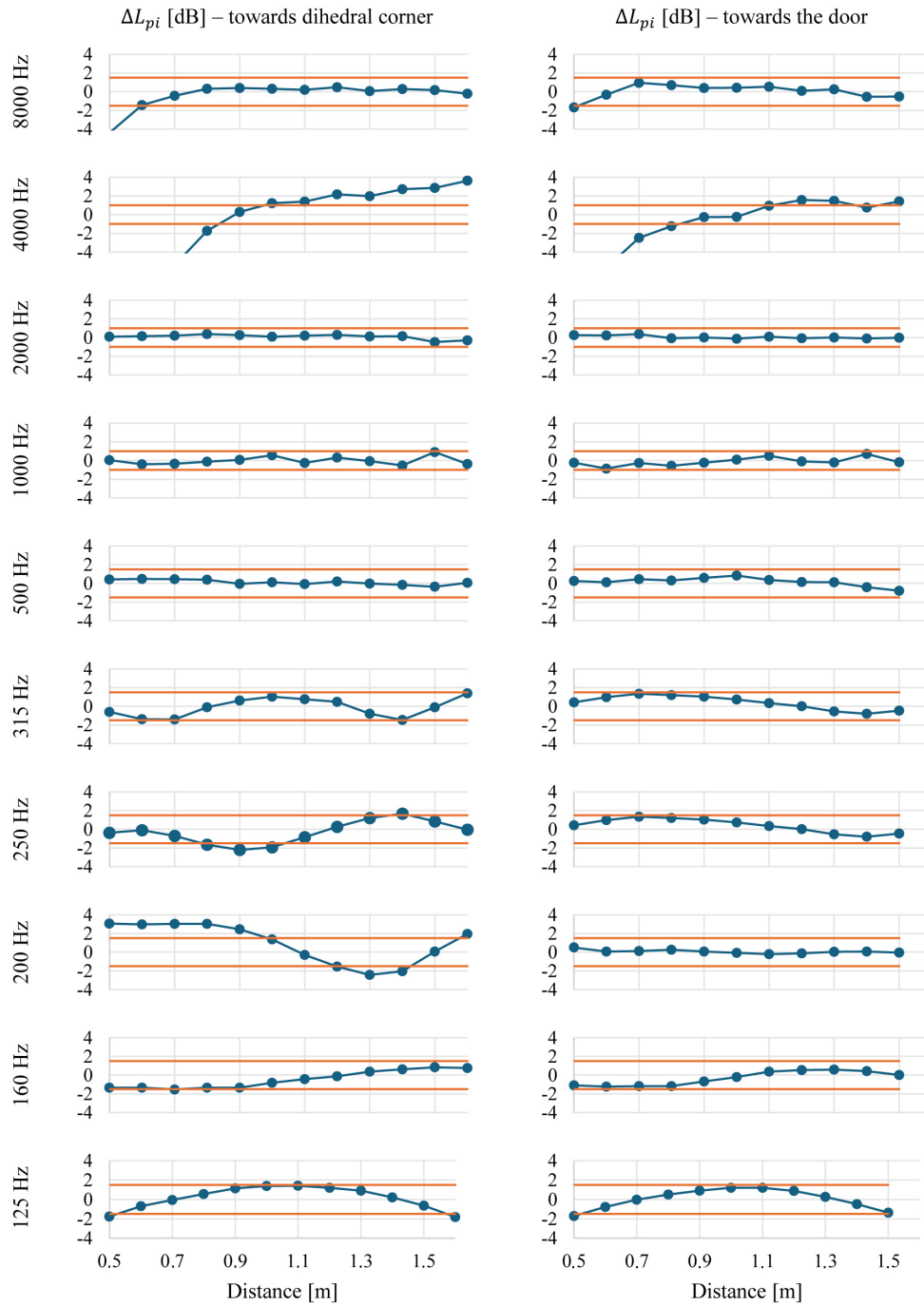


Fig. 4. SPL deviations from the inverse square law in the anechoic chamber; maximum deviations permitted by the ISO 3745 standard are plotted in red.

The formation of standing waves will be investigated in more detail in future tests, including the z-direction, which was not tested for this work. Nevertheless, the results shown here are indicative of a very high-quality anechoic condition, exceeding the

initial objective, similar to the background noise level. The attained acoustic environment enables accurate and repeatable measurements of acoustic characteristics of test objects across a wide range of frequencies. However, caution should be taken when quantitatively interpreting measurements below 400 Hz due to the formation of standing waves.

4. VALIDATION USING AN AEROACOUSTIC BENCHMARK

In order to validate the quality of the anechoic environment using a representative test object, a series of tests of a benchmark rotor were performed. The obtained acoustic characteristics were compared to those presented in the benchmark study, and some additional aspects were examined, such as isolation of motor noise and flow recirculation inside the chamber.

4.1 Benchmark description

The benchmark used in this work was published by researchers from the Delft University of Technology (TU Delft) [10]. A two-bladed rotor was used, derived from the APC 9×6 model, scaled to a 30 cm diameter, and with profiles reshaped using the NACA4412 airfoil. The rotor was machined out of aluminium and was rotated at 5000 RPM in both hover and forward flight conditions, the latter at several advance ratios. Noise characteristics were determined using a column of microphones, mounted 1.2 m away from the axis of the rotor, with the central microphone mounted in the rotor plane. Twelve additional microphones were mounted above and below the plane of the rotor, at separations of 15 cm. The rotor was rotated using an electric motor, and thrust and torque were measured using dedicated sensors, with all components embedded within a 50 mm aluminium tube.

4.2 Testing methodology

In the current study, the rotor was tested using a custom-made rig, which comprised an electric motor, a rotational speed sensor and thrust and torque sensors, all embedded within a 50 mm steel tube. However, the results presented in this article were obtained with the final section of the tube removed, as the motor had a tendency to overheat when shrouded, due to the absence of a cooling system. The axis of the rotor was vertical in order to direct the rotor wake along the longest dimension of the chamber. The length of the tube was such that the rotor was installed approximately 1.8 m above the ground (1.3 m above wedge tips). This position is below the geometric centre of the chamber, so the rotor was tested upside-down, i.e. generating downward thrust and blowing the air upwards. Similar

to the benchmark study, the rotor was machined out of aluminium. The fully assembled rig, albeit with the final section of the tube still in place, is shown in Fig. 5. A comparison of rotor noise measured with and without the shroud around the motor is presented in Fig. 6. The only noticeable effects of removing the shroud are slightly weaker spurious tones around 1000 Hz, likely due to the lack of vibrations of the shroud, and some spurious noise above 10 kHz, which the shroud likely absorbs.

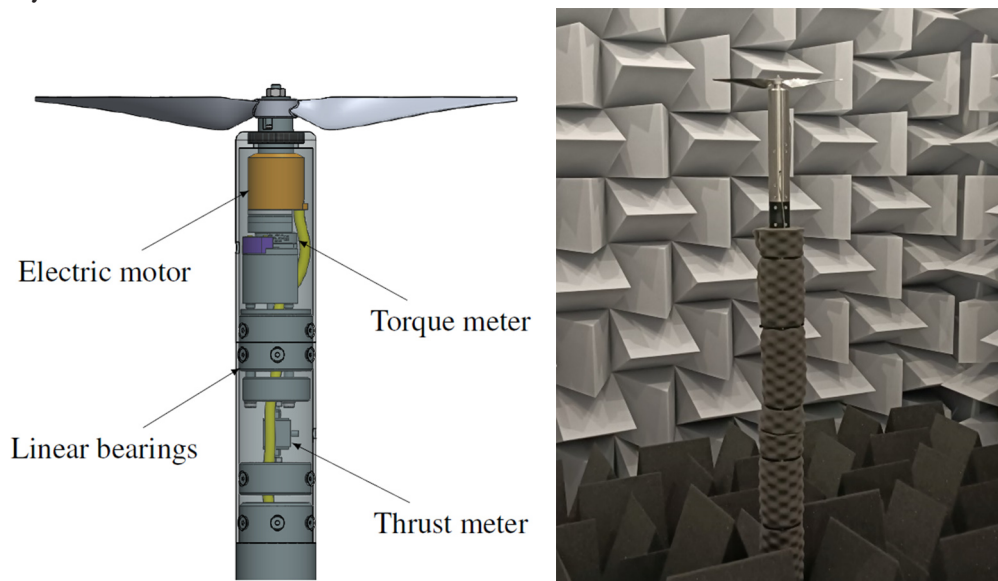


Fig. 5. Rotor testing rig: schematic and the assembled setup in the anechoic chamber.

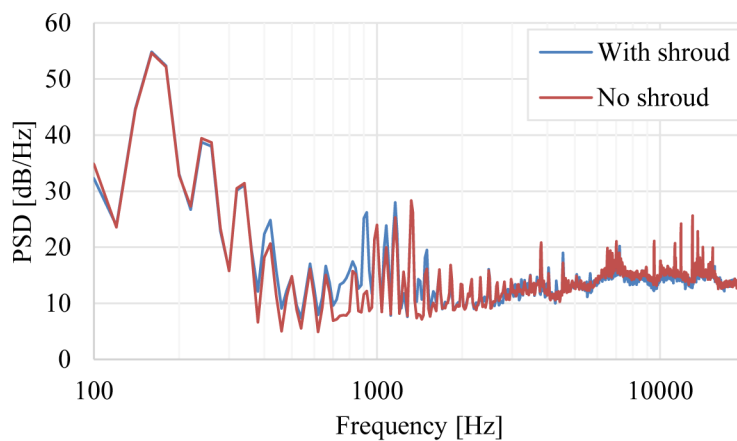


Fig. 6. Sample sound spectra of a rotor obtained with and without the shroud.

The data acquisition system for the rig consisted of an NI cDAQ-9189 chassis with NI-9203 and NI-9205 cards for load, rotational speed and atmospheric sensors. All of these parameters were sampled at 10 kHz, while microphone signals were sampled at 51.2 kHz; all signals were sampled simultaneously. In these tests the

microphones were mounted along an arc with a 1.2 m radius, facing the rotor hub. The central microphone was mounted in the plane of the rotor, which corresponds to the location of the in-plane microphone in the benchmark study [10], therefore it is used for the cross-study comparison. The subsequent microphones in the current study were mounted at polar angles of 20° and 40° upstream of the rotor plane, and 20° , 40° and 60° downstream of the rotor plane.

4.3 Flow recirculation considerations

A crucial concern when testing propulsion systems in enclosed rooms, such as in the case of rotor testing in an anechoic chamber, is flow recirculation [20, 30, 35-36]. As the rotor is operated in a stationary position, it draws in air from a wide angle of upstream directions, while downstream it ejects a much more concentrated wake, which dissipates gradually as it travels further downstream. Whereas in atmospheric flight this wake would dissipate due to the effectively infinite volume, further aided by the wind, in an enclosed room this wake is forced to turn around and travel back towards the low pressure region upstream of the propeller. Thus, a strong recirculation pattern is formed, as illustrated in Fig. 7.

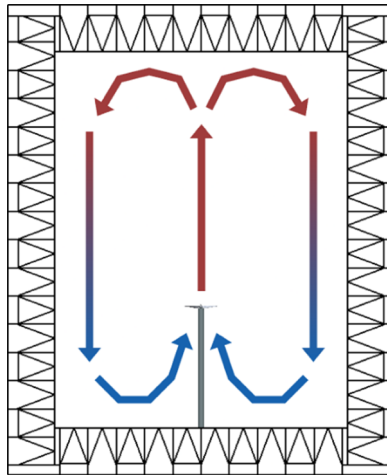


Fig. 7. Diagram of the flow recirculation pattern forming during rotor operation in the anechoic chamber.

The recirculation pattern does not form immediately when the rotor is started – it takes some time for it to form and then stabilise. Hence, in the first few seconds of rotor operation it draws in “clean” airflow, but once the recirculation pattern forms and stabilises, it starts to draw in a stream of air that is already traveling at a certain velocity and is more turbulent. This changes both the rotor’s aerodynamic performance and its acoustic signature. Therefore, it is desirable to only utilise the first few seconds of rotor operation for measurements when using closed anechoic

chambers, as those conditions are not only the most stable and repeatable, but also the most representative of open-air operation [15, 21, 26, 30, 35]. The amount of time needed for the recirculation pattern to form depends on the size and thrust of the rotor, as well as on the cross-section and length of the chamber – the greater the mass flow rate in the wake of the rotor and the smaller the volume of the room, the quicker such a pattern will form [36].

In order to examine the severity of recirculation in the anechoic chamber at Ł-ILOT, extended tests were performed at a range of rotational speeds. Fig. 8 presents time series of SPL deviation for several rotational speed values, calculated from the PSD between 100 Hz and 20 kHz at a temporal resolution of 0.1 s, and adjusted so that all curves start at the moment the rotational speed stabilised at the target value. The furthest downstream microphone was used (at a polar angle of 60° relative to the propeller plane), as the effect of recirculation on acoustic emissions is the most apparent at this microphone position. A reference test was carried out both with and without a windscreen on the microphone, and the results were analogous, confirming that the microphone is outside of the wake of the propeller, and that the measured deviations are due to acoustic effects at the propeller, rather than increased flow velocity over the microphone.

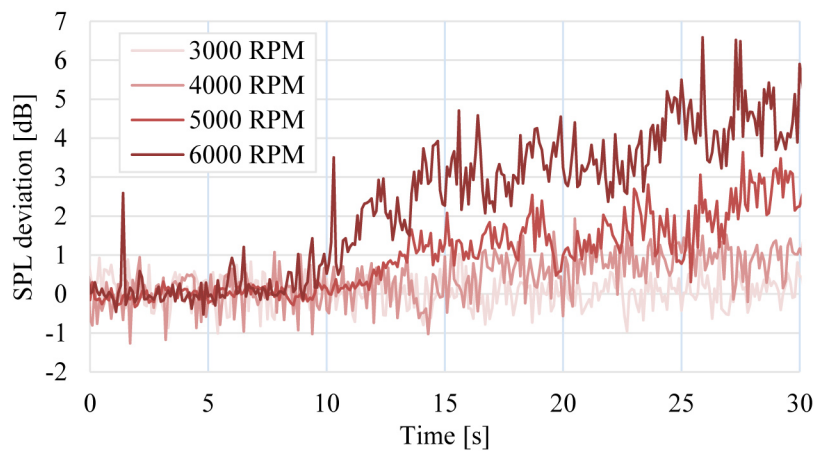


Fig. 8. Time series of SPL deviation for the benchmark rotor tested in the anechoic chamber at different rotational speeds, starting from the moment of stabilisation of rotational speed.

The curve obtained at 3000 RPM, shown in Fig. 8, shows a stable trend, with no noticeable SPL deviation over time. At 4000 RPM, a deviation of up to 1 dB appears after 15 seconds, but does not diverge further over time. At the rotational speed of 5000 RPM, which corresponds to the benchmark validation tests, the SPL begins to deviate after approximately 12 seconds, and diverges by up to 3 dB at the 30-second mark, still increasing at that point. Finally, at 6000 RPM the deviation begins after only 8 seconds, and reaches 6 dB by the 30-second mark.

This data shows a clear trend: increasing the rotational speed, and therefore the mass flow rate of the rotor wake, reduces the duration of the stable period before recirculation begins to affect the performance of the rotor, and increases the magnitude of this effect. This trend, as well as the lengths of stable periods at each value of rotational speed, are further corroborated by thrust and torque measurements, which are omitted here for brevity.

These results indicate that the size of the anechoic chamber at L-ILOT is sufficient for conducting aeroacoustic measurements for rotors 30 cm in diameter at rotational speeds of up to 6000 RPM. This is in line with practices adopted by other researchers, who have used sampling times as short as 4 seconds in similar tests [21, 30]. However, higher rotor diameters or rotational speeds might yield insufficient stable periods for accurate acoustic characterization.

To address this limitation, the installation of wake dispersion devices, in the form of a series of meshes downstream of the rotor, is planned. These devices have been shown to significantly reduce the effect of flow recirculation during rotor testing in anechoic chambers [30, 35]. However, care should be taken in all tests, with or without the meshes, to only use the initial stable period for analysis, as extending the samples further might lead to results skewed relative to open-air rotor operation.

4.4 Benchmark test results

In the benchmark study at TU Delft, acoustic measurements were sampled over a period of 30 seconds, beginning once any recirculation has stabilised [10]. Although the facility in the benchmark study includes a wind tunnel loop, which would help the wake of the rotor to dissipate, it is unlikely that it would dissipate completely. Therefore, two types of measurements were collected in the present study at L-ILOT – short, 5-second measurements immediately after the rotor attained its target rotational speed, i.e. prior to formation of the recirculation pattern, and 30-second measurements once recirculation in the anechoic chamber stabilised (beginning approximately 60 seconds after attaining the target rotational speed). The 30-second measurements are not analogous to the TU Delft measurements due to the lack of a wind tunnel loop in the L-ILOT chamber, but should enable the effects of recirculation to be separated from those of mechanical noise within the system. Furthermore, the validation tests were performed in two conditions: one with equal thrust, and the other with equal rotational speed to the benchmark study.

Spectra of acoustic pressure from the tests are shown in Fig. 9 and 10. The TU Delft test was performed at a rotational speed of 5039 RPM, which resulted in a thrust of 7.71 N. In the L-ILOT tests, the matching thrust of 7.71 N was achieved at 4815–4832 RPM, whereas a matching rotational speed of 5039 RPM resulted in a thrust of 8.33–8.48 N. Data from the in-plane microphone is shown for both the matched thrust ($T = 7.71$ N) and matched rotational speed (5039 RPM) cases.

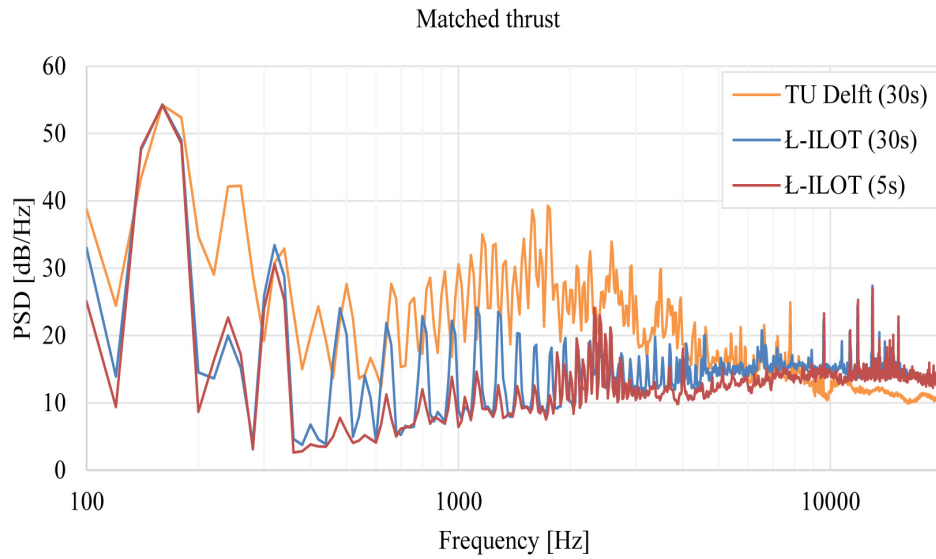


Fig. 9. Sound spectra of the benchmark propeller. Comparison between the benchmark study and the results obtained in the Ł-ILOT anechoic chamber in two conditions, for the in-plane microphone, with matched thrust.

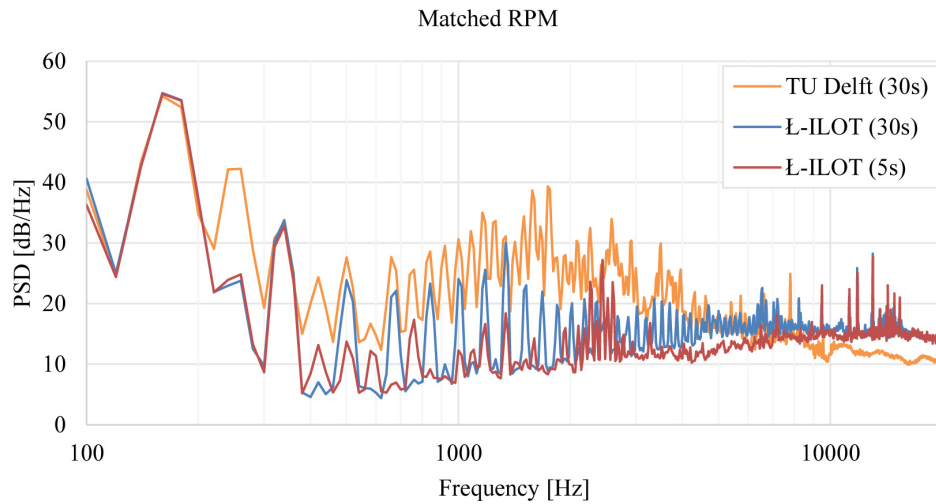


Fig. 10. Sound spectra of the benchmark propeller. Comparison between the benchmark study and the results obtained in the Ł-ILOT anechoic chamber in two conditions, for the in-plane microphone, with matched rotational speed.

The first notable feature is the good agreement of the peak at the blade passing frequency (BPF), at approximately 160 Hz, especially in the matched RPM case. Both the peak sound level and the width of the peak are similar, with the slight

difference in shape in the matched thrust case caused by a shift in peak frequency, smaller than the resolution of the PSD curve (20 Hz). The second harmonic of the BPF, at ~320 Hz, is reproduced very precisely in the matched RPM case, with a further discrepancy in the matched thrust case. A significant difference is present in the ~240 Hz peak, which corresponds to the third harmonic of the rotational speed, but is not expected in aeroacoustic propeller noise, as it corresponds to $3/2$ of the BPF. This peak is significantly higher in the benchmark study, suggesting that there might have been a significant source of mechanical noise in their setup, for example due to imperfect balancing of the system around the rotor axis.

At frequencies above the second harmonic of the BPF, the measurements from the benchmark study are dominated by a large number of higher harmonics of the rotational speed (at approximately 500, 670, 750 Hz, etc.). Above 1500 Hz, a more irregular, but still highly tonal noise is present. The authors of the benchmark study attributed this irregular tonal noise between 800 and 6000 Hz to motor noise. In the $\mathbb{L}$ -ILOT measurements, there are notable differences between the pre-recirculation 5-second measurements and the 30s measurements. In the latter, higher harmonics of the BPF are significantly stronger, likely caused by the ingestion of spurious turbulence by the rotor. However, odd harmonics of the rotational speed are in most cases negligible. In both cases, the tonal noise is weaker than in the TU Delft measurements. Motor noise dominates between 1800 and 3000 Hz in the $\mathbb{L}$ -ILOT data, but the peak magnitude is still approximately 10 dB lower than in the TU Delft data. These results indicate that the test setup at $\mathbb{L}$ -ILOT is much quieter mechanically, enabling investigation of mid-frequency broadband noise from microphone measurements, which would be challenging using the data presented in the benchmark. However, the 2000-3000 Hz range in the $\mathbb{L}$ -ILOT measurements is still affected by motor noise at this rotational speed, making further improvements to the test setup desirable.

Significant discrepancies are also present in high-frequency noise, above 10 kHz. The $\mathbb{L}$ -ILOT data includes several tones in that range, and the broadband noise is higher than in the benchmark data by up to 5 dB. The source of the tonal noise, as well as the discrepancy in broadband noise levels, will be investigated in further tests.

In summary, the comparison with the benchmark study shows that the current acoustic environment and test setup enables very accurate measurement of rotor tonal noise, and that, mechanically, the setup is quiet enough to permit examination of broadband noise. However, it is not possible to verify whether the measured levels of broadband noise are accurate due to the significant contamination of noise spectra in the benchmark study.

5. CONCLUSIONS

Acoustic validation of the anechoic chamber newly constructed at Ł-ILOT confirms that it provides a high-quality testing environment suitable for research on aeroacoustics of UAV rotors. Mapping of the background noise in the chamber did not reveal any significant weak points in terms of acoustic insulation, and indicated background noise with the PSD under -10 dB above 100 Hz, and under -20 dB above 300 Hz. At frequencies below 100 Hz the chamber structure is not as effective at sound insulation, resulting in a background noise level of up to 30 dB at 20 Hz, and approximately 15 dB at 50 Hz.

Verification of the anechoic condition using an omnidirectional sound source, in accordance with the ISO 3745 standard, indicates that the condition is satisfied down to 125 Hz, across a large portion of the chamber volume. Some deviations were observed near the sound source at specific high frequencies, but are attributed to the characteristics of the source and are not expected to affect test results. A more significant issue is the apparent presence of standing waves at frequencies of 315 Hz and lower. Although the strength of these is small enough that the curves generally fit within the bounds prescribed by the ISO standard, caution must be taken during quantitative interpretation of measurements in the affected frequency range.

In order to assess the impact of flow recirculation on rotor measurements, extended tests were performed at a range of rotational speeds. The results showed a clear trend: increasing the rotational speed reduces the length of time available for measurements, but at least 5 seconds of stable measurements are possible at rotational speeds of up to 6000 RPM for a rotor with a diameter of 30 cm. At lower rotational speeds this length might increase up to 30 seconds or more, but care should be taken to avoid sampling beyond the stable period, as strong fluctuations appear in the noise spectra and SPL values, especially downstream of the propeller, as well as in measurements of aerodynamic performance.

To verify the suitability of the chamber for aeroacoustic measurements of rotors, a series of tests was carried out using a benchmark rotor. A comparison with the reference study showed very good agreement of key features of the acoustic characteristics, including the level of the first and second harmonics of the blade passing frequency. At frequencies above 400 Hz, 30-second measurements carried out with the recirculation fully formed exhibit strong peaks corresponding to higher harmonics of the BPF. These peaks are much weaker or negligible in 5-second measurements taken prior to formation of recirculation, indicating that ingestion of the turbulent circulating stream significantly impacts those harmonics. However, odd harmonics of the rotational speed were mostly negligible regardless of the acquisition time, enabling examination of broadband noise across the spectrum. This suggests significantly higher mechanical quality of the setup at Ł-ILOT compared to the data presented in the benchmark paper, where odd harmonics of the rotational speed were strong enough to completely obscure broadband noise at the 20 Hz spectrum

resolution. The accuracy of broadband noise levels measured at Ł-ILOT could not be verified because of the pollution of the benchmark spectra, but these results emphasise that mechanical quality of any setup is of critical importance for investigation of acoustic characteristics of rotors. Furthermore, the results confirm that it is preferable to measure the initial period prior to formation of recirculation, as this enables more accurate estimation of high-frequency tonal noise.

The methods and results presented in this article can serve as a reference for establishing effective acoustic environments for testing of rotors and other small aerodynamic devices or vehicles. The findings show that a low-cost, cuboidal anechoic chamber can provide sufficiently low background noise and the anechoic condition in the required frequency range. However, if low-frequency measurements are essential, denser and thicker walls and absorptive materials may be required. This study also showed how the impact of flow recirculation depends on the rotational speed of the rotor, emphasising that the volume of the chamber is essential if high-thrust configurations need to be tested.

Future work regarding the performance of the chamber at Ł-ILOT will include verifying the anechoic condition for more paths within the internal volume, attempting to disperse the wake of the rotor and therefore weaken the influence of recirculation on measurements using meshes suspended above the rotor, and a thorough investigation of standing wave formation at low frequencies, to improve our understanding of its impact on measurements.

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