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Streamlined numerical prediction of drone urban noise impact

Session: Propeller and rotorcraft noise modelling 1

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Abstract The innovative aeromobility market is currently experiencing growth in civil and commercial applications. Increasingly, companies are proposing new missions of various sizes, whether manned or unmanned, based on VTOL (Vertical Take-Off and Landing) platforms. This growth has intensified the need for predictive models capable of estimating the acoustic impact on complete missions, as these increasingly take place in urban airspace, at least in some of their phases.

The modelling of aircraft performance and associated noise cannot be restricted solely to stationary or isolated conditions, where variations in speed, power, and configuration that significantly affect the sound signature are ignored. While the computational cost of calculating a complete mission is prohibitive, it is possible to capture the evolution of the acoustic field throughout the different operational phases of an aircraft. This work presents an aeroacoustic model for a complete mission, based on an EASA (European Aviation Safety Agency) Category C2 quadcopter, using trimmed, experimentally validated CFD (computational fluid dynamics) simulations.

URANS simulations are performed using Simcenter STAR-CCM+ calculation software, where the rotors are modelled using the Actuator Disc and Actuator Line Models, thereby reducing computational costs while maintaining fidelity for acoustic predictions. The simulations are coupled with a trimming algorithm based on P-I (Proportional-Integral) control, which determines the rotor attitude angles and angular rotation speeds to ensure that the force and moment equilibrium equations are satisfied, given the boundary conditions. The acoustic model is based on Hanson's model for steady-state simulations and the Ffowcs Williams-Hawkings (FW-H) permeable formulation for transient cases, capturing the propagation of the noise to a set of receivers distributed on a sphere, as specified in ISO 3745. Then,

this noise source is propagated to a 3D model of a selected urban environment through the CNOSSOS-EU methodology, as implemented in the NoiseModelling software package.

Individual simulations are validated through experimental tests in an anechoic chamber, where the isolated drone is placed, and windless propulsion system configurations are accurately reproduced. The comprehensive methodology enables the creation of mission-specific noise maps, which, in turn, facilitate design optimisation and the evaluation of compliance with potential regulatory limits on noise pollution.

Preliminary results demonstrate that integrating trimmed CFD simulations with medium-fidelity aeroacoustic models is a robust tool for predicting acoustic behaviour across a complete mission profile, enabling a balance between computational cost and physical representativeness.

1. INTRODUCTION

Nowadays, the interest in the market of innovative air mobility (IAM) is reaching new heights. A case in point is the multitude of new companies offering innovative designs that are competing for the same market as the eHang EH216-S (EHang, 2026) double octacopter, which has performed its first pilotless passenger flight, the Multi-gyrodrone of Mightyfly (MightyFly, 2026), or the Chaparral of ElroyAir aircraft (ElroyAir, 2026), both for cargo missions inside and between cities, just to mention a few.

Since the primary mission of most aircraft in this field involves vertical take-off in urban environments as well as flight within them, there is a clear need to study and characterise both performance and acoustics. The assessment of the acoustic impact of the IAM vehicles is increasingly required from a regulatory perspective. Existing environmental noise regulations, such as the European Directive 2002/49/EC (European Parliament and Council of the European Union, 2002), together with the ongoing development of certification and operational frameworks by EASA (European Union Aviation Safety Agency, 2023) and ICAO (International Civil Aviation Organization, 2017) for novel aerial vehicles, highlight the need for accurate acoustic characterisation to support compliance and future IAM integration into urban environments.

Furthermore, a proper modelling cannot be solely based on a stationary condition, since the variations of speed and power during the course of the mission will affect the product of noise emissions. However, to simulate a full dynamic mission is computationally prohibitive, which is why other simulation strategies are needed, since obtaining real flight data is just as difficult, if not more so. In this project, the evolution in performance and noise emissions of a small quadcopter is obtained across three operational phases of the same mission. In order to reduce the costs of the simulation while maintaining enough accuracy for evaluating a truly representative case, a determined Computational Fluid Dynamics (CFD) study approach is proposed. The CFD study combines three aspects, first the modelling of the rotors through actuator disk modelling (ADM) coupled with blade element method (BEM). Secondly the use of Ffowcs Williams–Hawkings (FW-H) formulation for calculating far-field noise spectra. Finally, the employment of steady-state simulations with a trimming algorithm. This way, the overall computational costs are reduced for every single simulation. The data obtained is then employed as an input for a noise propagation model, allowing for the study of the noise effect at a city-level size, which would be unviable only using CFD.

The remainder of the manuscript is organised as follows. section 2 describes the specific case study under consideration, although the method is general enough to be applied to other cases. After this, section 3 describes the different methods used by the authors, from the initial numerical set-up to the final simulation with NoiseModelling. The validation of the



Figure 1: Render of the Hunter quad-rotor Unmanned Aerial Vehicle manufactured by UAV-Works.

approach is presented in section 4, whereas the main results and their discussion are shown in section 5. The manuscript ends with the main conclusions in section 6.

2. CASE STUDY

The numerical model of the Unmanned Aerial Vehicle (UAV) employed throughout the current work is based on the Hunter quad-rotor UAV manufactured by UAV Works (UAV-Works, n.d.). A render of the multirotor is presented in Figure 1. The aircraft has a wheelbase L_{UAV} of 0.487 m and an All Up Weight (AUW) of 1.12 kg when it is not carrying a payload. Further details regarding its physical characteristics and its propulsion system are listed in Table 1.

Parameter description	Value
Physical characteristics	
Airframe dimensions	383 mm $\times$ 348 mm $\times$ 156 mm
Wetted area	0.1721 m ²
Propulsion	
Rotor model	T-MOTOR MS1101
Rotor diameter (D_P)	27.94 cm (11.0 inches)
Rotor pitch	10.7 cm (4.2 inches)
Motor model	T-MOTOR MN2806
Motor KV	400 RPM/V

Table 1: Physical and propulsion system characteristics of the Hunter UAV.

The UAV's acoustic footprint is evaluated over a single flight through a section of Urban Lab, a designated Advanced Air Mobility (AAM) testing ground in the Southeastern city of Benidorm, Spain. The simulated mission is made up of three distinct segments designated leg 1, leg 2, and leg 3 respectively. The flight begins with an ascent phase during which the UAV travels vertically at a speed of 3.0 m/s while facing North. This initial leg is followed by a cruise phase during which the UAV covers a horizontal distance of 131.1 m at a speed of 12.0 m/s. During cruise, the UAV faces its direction of travel, in other words its yaw angle is equal to its track angle. The mission ends with a third and final leg during which the UAV descends vertically back to ground level at a rate of 3.0 m/s. The yaw angle during the third leg is not changed relative to that of the second leg. The start and end points of the

segments are defined as waypoints (WP) 1 through 4, the coordinates of which are listed in Table 2 following a North-East-Down axis definition. The origin of the chosen coordinate system is located at (38.54547° N, 0.12278° W) and 19.0m above sea-level in Benidorm, Spain. The UAV's heading for each leg of the trip is reported in Table 3.

Waypoint	x (m)	y (m)	z (m)
WP1 (start)	78.75	-61.88	-25.50
WP2	78.75	-61.88	-169.50
WP3	-26.25	16.88	-169.50
WP4 (finish)	-26.25	16.88	-19.50

Table 2: Coordinates of the waypoints that define the UAV's trajectory during the simulated mission.

All CFD simulations described in this work were carried out using the Simcenter STAR-CCM+ commercial software (Siemens Digital Industries Software, n.d.), version 2310. Both steady-state and transient simulations were computed using up to 784 cores on the Universitat Politècnica de València's (UPV) Sirius Scientific Computing Cluster (*Sirius Scientific Computing Cluster web-page*, n.d.) equipped with 33 nodes with 2× Intel Xeon 8480 CPUs, and connected through 200 Gbit/s Infiniband fabric.

3. METHODOLOGY

3.1 General description of the workflow

To begin, the Unmanned Aerial Vehicle's (UAV) trajectory through a designated urban area is established by defining a set of waypoints. Following this, a steady-state Computational Fluid Dynamics (CFD) simulation of the quad-rotor is carried out for each individual leg of the mission. The CFD solver is coupled to a Proportional-Integral (PI) based trimming algorithm, which determines the combination of UAV body angles and rotor angular rates that result in trimmed and physically representative flight conditions. In the current work, the UAV is assumed operate in quasi-steady flight conditions. In other words, the UAV's heading, direction of flight, and ground speed, and the wind's magnitude and direction are considered

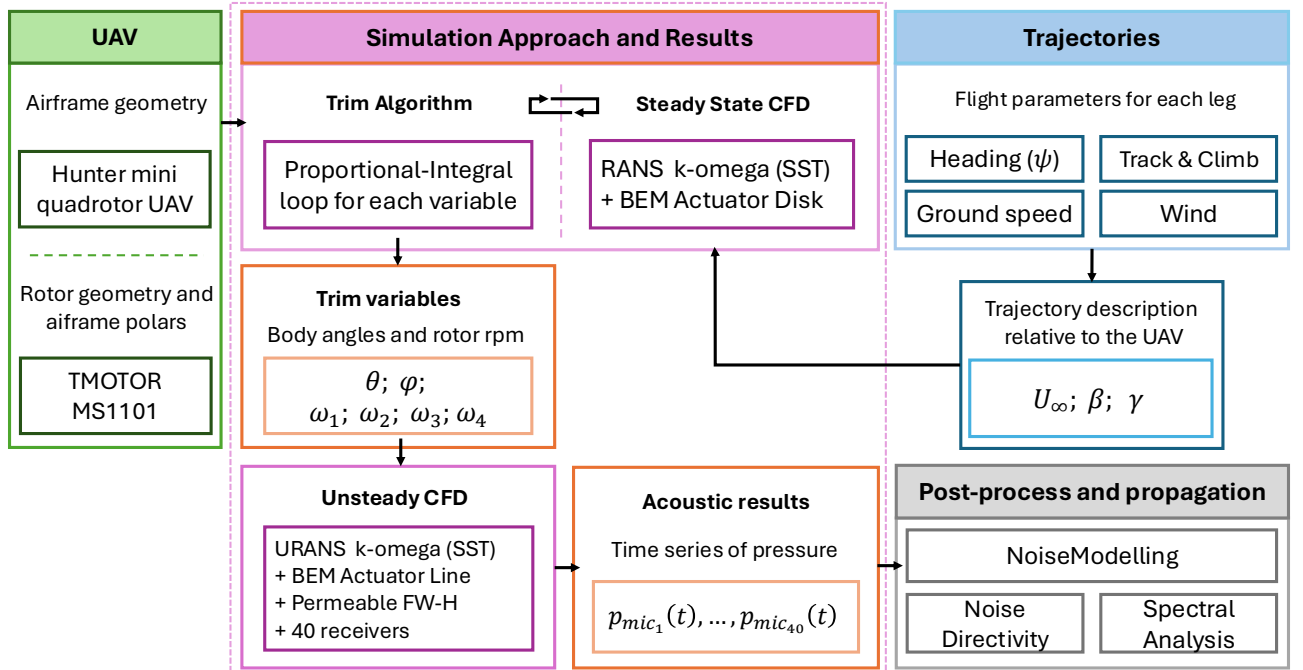


Figure 2: Functional block diagram describing the workflow employed in the current study.

constant during each individual leg of the mission. The trim parameters are subsequently used to set-up an equal number of unsteady CFD simulations in which the sound pressure fluctuations caused by the UAV's operation are recorded at several receiver locations. Finally, the acoustic data from the transient simulations is propagated in the virtual urban environment using the NoiseModelling software. The functional block diagram presented in Figure 2 summarizes the aforementioned workflow.

3.2 Preparing the trajectory descriptions

The steady-state CFD and trimmer simulation approach proposed by L.M.García-Cuevas et al. (García-Cuevas González, García-Tiscar, Varela, & Mullen, 2025), and employed in the current work, requires a description of the incident flow relative to the UAV's local horizon frame through the means of a side-slip angle (β), a flight-path angle (γ), and an incident flow magnitude (U_∞). These three parameters must be computed from the heading, the track and climb angles, the ground speed, and the wind direction for each leg of the mission.

The first step involves computing the flight direction for each leg based on the list of waypoints defined in the Case Study in Section 2. The UAV's flight direction during each leg is described in terms of its components and in terms of a track and climb angle in Table 3. The track and climb angles are defined as the angle between the UAV's trajectory and North, and between the trajectory and the horizon respectively.

Leg	Components [–]			Angles [deg]		
	$x(N)$	$y(E)$	$z(D)$	Track	Climb	Yaw (Ψ)
Leg 1	0.0	0.0	-1.0	0.0	90	0.0
Leg 2	-0.8	0.6	0.0	143.1	0.0	143.1
Leg 3	0.0	0.0	1.0	0.0	-90.0	143.1

Table 3: The UAV's direction of flight described in terms of normalized components (NED) and angles and its heading for each leg.

Next the UAV's ground speed and the wind speed are accounted for. The wind's velocity magnitude and direction are obtained by time averaging the velocity profile over each leg. The flow velocity data is sourced from yet unpublished Large Eddy Simulations (LES) of Benidorm's Urban Lab. The wind speed is subtracted from the ground speed to compute the components of the UAV's airspeed. All three velocities' components in NED are reported in Table 4.

Leg	Ground speed [m/s]	Wind speed [m/s]	Airspeed [m/s]
Leg 1	[0.00, 0.00, -3.00]	[-0.973, 0.102, -0.576]	[0.973, -0.103, -2.42]
Leg 2	[-9.60, 7.20, 0.00]	[-7.08, 0.272, -0.476]	[-2.53, 6.93, 0.476]
Leg 3	[0.00, 0.00, 3.00]	[-5.40, -0.690, -0.336]	[5.40, 0.690, 3.34]

Table 4: Components of the wind speed, and the UAV's ground speed and airspeed for each leg of the mission. The components are expressed following a NED axis convention.

Finally, using the yaw and airspeed data presented in Table 4 and Table 3 respectively, the components of the UAV's airspeed can be expressed as an incident flow velocity magnitude, a flight-path angle, and a UAV-relative side-slip angle as follows:

$$\beta = \text{atan2}(V_E, V_N) - \Psi, \quad (1)$$

$$\gamma = \text{atan2}(V_D, \sqrt{V_N^2 + V_E^2}), \quad (2)$$

$$U_\infty = \sqrt{V_N^2 + V_E^2 + V_D^2}, \quad (3)$$

where V_N , V_E , and V_D are the UAV's airspeed components in NED. The final UAV-relative side-slip angle (β), flight-path angle (γ), and the incident velocity magnitude (U_∞) perceived by the UAV for each leg is reported in Table 5.

Leg	β	γ	U_∞
Leg1	-5.98°	67.92°	2.61 m/s
Leg2	-33.10°	-3.69°	7.39 m/s
Leg3	-135.85°	-31.57°	6.39 m/s

Table 5: UAV relative trajectory description for each leg.

3.3 Computational Fluid Dynamics simulation set-up

The CFD simulation approach employed to evaluate the aeroacoustics of a multirotor UAV in trimmed and physically representative flight conditions was originally proposed by the authors in a previous work (García-Cuevas González et al., 2025). Since the present study builds upon this methodology without major modifications, a concise description is provided in the following section, and the reader is referred to the original publication for further detail.

3.3.1 Computational domain and boundary conditions

The computational domain is defined as a sphere, and its radius is set to 25 times the UAV's wheelbase. The airframe surface is defined as no-slip wall, while the computational domain's outer surface is defined as a freestream boundary condition. At the freestream, the flow's turbulence intensity is set to 1%, its turbulent viscosity ratio is set to 10, and its temperature and pressure are set to 25°C and to 101325 Pa, respectively. The incident flow's velocity magnitude (U_∞) is imposed to that of the target airspeed, and its direction is computed based on the UAV's body (θ, ϕ) and trajectory angles (β, γ) for each simulation. Since simulations are carried out in the body frame and the UAV's pitch (θ) and roll (ϕ) angles are updated as the trimming algorithm searches for the trimmed state, the incident flow direction evolves during each the steady-state simulations. It is then fixed for the subsequent unsteady simulations.

3.3.2 Geometry preparation and meshing

To prepare the UAV's 3-D model for CFD analysis, minor exterior features on the airframe are removed to establish a closed manifold with smooth surfaces. Sharp corners and edges are filleted and rounded off, while larger and characteristic features such as the legs are explicitly retained.

The computational domain is discretised using a hybrid polyhedral-prism mesh strategy, coupled with a low-wall y^+ approach for near-wall boundary layer modelling. A total of 17 prism layers are used near the surface (Figure 3) with a growth ratio of 1.24 and a total thickness of 3 mm. The polyhedral cell size varies between a minimum size of 0.15 mm near the airframe surface and 1 m at the freestream. An additional volumetric refinement is applied in the vicinity of the UAV for the purpose of wake refinement and additionally providing sufficient spatial resolution to capture the pressure fluctuations in the unsteady simulations. The aforementioned refinement extends 1.2 m from the UAV and the cell size within this refinement sphere is equal to 10 mm, providing a spacial resolution of at least 20 cells per wavelength for frequencies up to 1.7 kHz. These meshing parameters result in a cell count of 1.2×10^7 .

A grid independence study was conducted to verify that the flight conditions and trim parameters predicted by the steady-state simulations are sufficiently independent of the

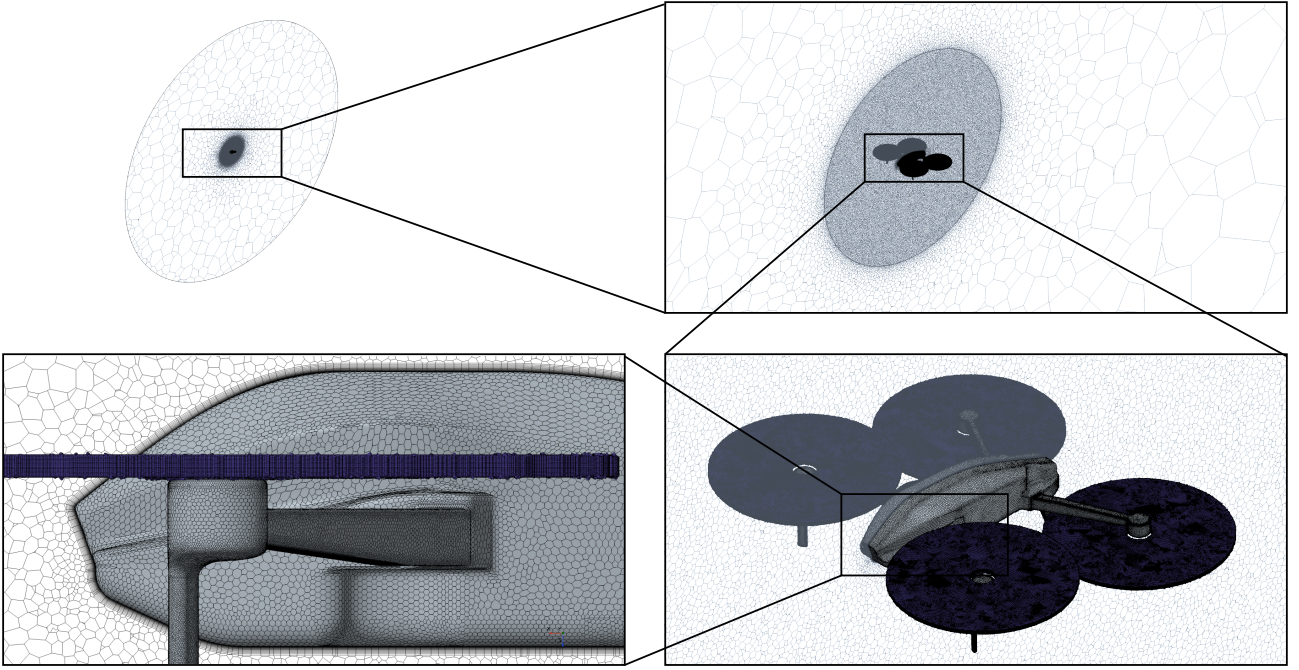


Figure 3: Several representations of the computational domain's discretization.

meshing parameters. To this end, all meshing parameters were scaled by factors of 2, 1.5, 0.75, 0.6 and 0.5 relative to the baseline, generating meshes ranging from 5.65×10^6 to 5.64×10^7 cells. The UAV is simulated in forward flight conditions at an airspeed of 15.0 ms^{-1} . Key results of this study are reported in Table 6. The results show that all three aerodynamic quantities are largely insensitive to mesh refinement. The total thrust varies by at most 1.1 %, the total mechanical power by at most 0.9 %, and the fuselage drag by at most 1.18 % between successive refinement levels. The 12.6 M cell mesh produces results that differ by no more than 1.1 % from the finest mesh considered for any of the three quantities, while offering a significant reduction in computational cost. It is therefore selected as the baseline mesh for all subsequent simulations.

# cells [M]	Total thrust [N]	Total power [W]	Fuselage drag [N]
5.65	11.37 (0.5%)	117.8 (0.9%)	3.034 (1.09%)
7.20	11.31 (0.1%)	116.7 (0.7%)	3.001 (1.18%)
12.6	11.33 (1.1%)	115.9 (0.5%)	2.966 (0.02%)
21.8	11.45 (0.3%)	116.5 (0.2%)	2.967 (0.47%)
35.9	11.48 (0.1%)	116.8 (0.7%)	2.981 (0.96%)
56.4	11.47 (–%)	116.0 (–%)	2.952 (–%)

Table 6: Mesh independence study for the FVM simulation. Percentage difference compared against the next more refined mesh.

3.3.3 Rotor modelling

The rotors' effects are included through the Actuator Disk Model (ADM) for steady-state simulations and the Actuator Line Model (ALM) for the unsteady simulations. The models are referred to as the *time-averaged* and *time-accurate Virtual Disk* in the Star-CCM+ software. The models are low-fidelity rotor modelling approaches originally designed to model the bulk flow effects of helicopter rotors on the surrounding flow field. Both version incorporate the aerodynamic effects of the rotors as a momentum source, with source strengths computed

through the Blade Element Method (BEM). The distinction between them lies in the fact that the time-accurate model accounts for the real-time location of the blades. The model parameters used in the current study are identical to those listed in the original work by L.M. García-Cuevas González et al. (García-Cuevas González et al., 2025).

3.3.4 Steady-state simulation and trimmer set-up

The steady-state simulations are carried out using the Reynolds-Averaged Navier-Stokes (RANS) approach. The closure model selected is Menter's k- ω Shear Stress Transport (SST) linear eddy viscosity model (Menter, 1994), treating the air as an ideal gas. The governing equations are integrated using an implicit-coupled approach with a maximum Courant–Friedrichs–Lewy (CFL) number of 50 and an explicit relaxation factor of 0.3.

The steady-state CFD solver is directly coupled with a simple Proportional-Integral (PI) based trimming algorithm. At each iteration, the aerodynamic forces on the airframe and all four rotors predicted by the CFD solver are used to compute the six balance equations that describe the UAV's state. For each balance equation the trimmer employs a PI-loop to adjust one of the UAV's trim parameters. The UAV's pitch and roll angles are acted upon to trim the forward and lateral sums of forces, while the collective rotor angular rate is adjusted to trim the vertical component of the sum of forces. The angular rate differential between the front and back rotors, port and starboard rotors, and diagonally opposed rotors trim the pitching, rolling, and yawing moments respectively. The iterative exchange of aerodynamic loads computed by the CFD solver and the new trim variable computed by the trimming algorithm is repeated until a trimmed state is reached and the CFD converges.

3.3.5 Unsteady simulation set-up

The subsequent unsteady aeroacoustic simulations are conducted using a Unsteady RANS (URANS) approach. Additionally, the Farassat 1A formulation (Farassat, 2007) of the Ffowcs Williams-Hawkins (FW-H) aeroacoustic model is employed to propagate the UAV's noise to an array of virtual receivers. The array is formed of 20 receivers positioned around the UAV according to the UNE-EN ISO 3745 norm for the determination of sound power levels and sound energy levels of noise sources using sound pressure (Acoustics, 2010). The receivers are placed at a distance of 2.0 m from the UAV. Following the methodology recommended by A. Broatch et al. (Broatch, Navarro, García-Tíscar, & Ramírez, 2024), an internal interface surrounding the noise source is selected as a permeable FW-H integration boundary, and its radius is set to 2.5 times the UAV's wheelbase. In this set-up, only monopole and dipole terms are considered.

For each of the unsteady simulations, the time step is selected such as the fastest spinning rotor rotates 1° per time step. This results in a time step of 3.3×10^{-5} s, 2.02×10^{-5} s, and 3.55×10^{-5} s for legs 1, 2, and 3, respectively. This temporal discretisation provides a sampling rate at least 70 times higher than the fourth harmonic of the highest Blade Passing Frequency (BPF) in each simulation. This criterion for selecting the time step was shown to be sufficient by Geng Qiao et al. (Qiao, San Martin, & Barakos, 2025).

3.4 Noise propagation

Acoustic propagation to the 3D urban environment is computed using the CNOSSOS-EU standard method implemented in the open source software NoiseModelling 4.0.5. (Bocher, Guillaume, Picaut, Petit, & Fortin, 2019). The aircraft is characterized as a noise source using the well-known "noise sphere" method, in which acoustic propagation is simulated in CFD up to a spherical surface in the acoustic far field. To avoid the requirement of a very

detailed computational mesh up to this far-field location, the Ffowcs Williams–Hawking (FW-H) approach is used, where an integrating spherical surface is put close to the aircraft, and then propagation is computed by FW-H to a series of receptors that are placed following ISO-3745 recommendations so that each one covers a proportional part of the sphere.

Once that acoustic data is available on the surface of the outer FW-H sphere, individual noise spheres are computed for each octave between 63 and 8000 Hz, and then the data is imported into NoiseModelling for propagation. In this example, the chosen urban environment is Benidorm, Spain, one of the Urban Labs for the European UAV airspace management project U-ELCOME (U-ELCOME, 2026). The building geometries used to compute propagation are obtained from Spanish cadastral data made available under the European INSPIRE directive.

Once the acoustic source and building 3D geometries are loaded into NoiseModelling, several receptors are defined both on the ground and over the buildings, and then the propagation is computed. This is repeated for all the required aircraft positions. The resulting noise data is then exported in GeoJSON format and imported into the open source ParaView software for visual rendering. Additionally, the maximum amplitudes for each receptor at any point of the flightpath are computed in MATLAB and also exported in GeoJSON format to be rendered in ParaView.

4. AEROACOUSTIC VALIDATION

4.1 Experimental set-up

The experimental validation was carried out in the CMT – Clean Mobility & Thermofluids research institute’s anechoic chamber facility. The UAV is placed on a static test bench capable of rotating along the vertical axis thanks to a servo. Six Type 4190 free-field microphones from Brüel & Kjær are placed such that they form a vertical semicircle at a distance of 2.0 m from the UAV. The microphones are placed at increments of 30°. The signal from all six microphones is acquired simultaneously by a PULSE Type 3560-D Data Acquisition System from Brüel & Kjær at a sampling frequency of 65.5 kHz. Thanks to the 6-microphone array and the rotatable mount, the UAV’s acoustic footprint is measured for a total of 42 distinct microphone positions, covering yaw angles ranging from 0.0° to 180.0° with increments of 30.0°, and pitch angles ranging from –60.0° to 90.0° with increments of 30.0°. Although multiple motor throttle combinations were measured for each yaw angle, the experimental data used for the validation of the acoustic modelling in the current work corresponds to a collective throttle level of 85% for all four rotors.

4.2 Numerical set-up for validation

A dedicated unsteady simulation is carried out to assess the accuracy of the aeroacoustic simulation approach. Unlike the cases for the trajectory, the UAV’s body angles and rotor angular rate are imposed directly to replicate the experimental conditions rather than being obtained from a preceding steady-state simulation. The body angles are both set to 0.0°, and the rotor angular rate is determined from the frequency of the first tonal peak in the experimental spectrum. The average experimental rotor angular rate for a throttle level of 85% is determined to be 5820 revolutions per minute. Moreover, the FW-H receiver array is adapted to replicate that of the microphone placement in the experimental set-up. The rest of the numerical set-up is identical to that detailed in Section 3.3. The UAV is simulated for a total physical time of 0.6 s, and the pressure fluctuations are recorded during the last 0.5 s at a sampling frequency of $1/dt = 49.6\text{ kHz}$.

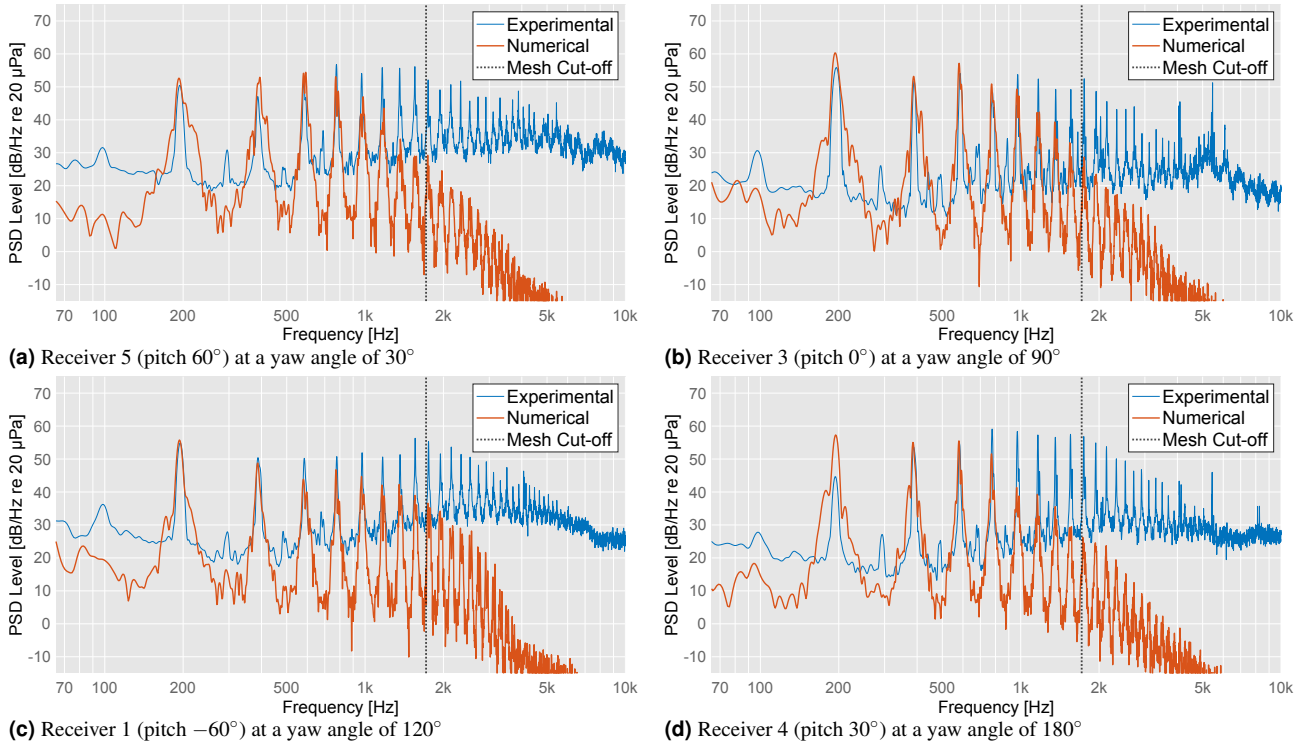


Figure 4: Comparison of the experimental and numerical Power Spectral Density for several receiver locations.

4.3 Power Spectral Density Comparison

A comparison of the Power Spectral Density of experimental and numerical noise measurements for several microphone positions is shown in Figure 4. The frequency for which the spatial resolution of the CFD mesh within the permeable FW-H integration sphere falls below the threshold of 20 cells per wavelength is indicated with a dashed line in all four plots. The four receivers for which the PSD is compared are selected to cover a representative range of yaw and pitch angles, spanning the best and worst agreement cases observed across the full set of 42 positions. The PSD was estimated using Welch’s method. A target frequency resolution Δf is set based on the numerical signal, using a window length equal to half its signal length. The experimental signal’s window length is adjusted to match this frequency resolution. An overlap of 50% between windows and an fast Fourier transform length zero-padding factor of 4 is used to process for both signals.

The alignment of tonal peaks across all microphone locations validates the extraction of the rotor angular rate from the experimental spectrum, and suggests that the rotor speed remained stable throughout the experimental measurements. Although the tonal peaks show varying levels of agreement across receiver locations and frequencies, a large number of peaks match the experimental measurements within a few decibels. Tonal noise is generally well captured below 1.0 kHz, but agreement deteriorates sharply at higher frequencies, beyond the mesh cut-off. The broadband floor is consistently under-predicted in the numerical results. Nevertheless, this is expected given the URANS turbulence modelling approach and the inherent inability of the ALM and BEM rotor modelling to capture broadband noise mechanisms such as trailing-edge noise.

4.4 Tonal noise directivity

4.4.1 SPL extraction and sensitivity

To compare the tonal noise characteristics and their directivity, the SPL at the first four harmonics of the Blade Passing Frequency (BPF) is computed at all receiver locations using

a narrowband bandpass filtering approach. For each microphone signal $p(t)$, the mean pressure (p_{mean}) is first subtracted:

$$p'(t) = p(t) - p_{\text{mean}}. \quad (4)$$

A Finite Impulse Response (FIR) bandpass filter is then applied around the target frequency $f_{\text{target}} = n \cdot f_{\text{BPF}}$, where $n \in \{1, 2, 3, 4\}$ and f_{BPF} is the blade passing frequency, with a passband defined as:

$$\left[f_{\text{target}} \cdot \left(1 - \frac{\Delta/2}{100} \right), f_{\text{target}} \cdot \left(1 + \frac{\Delta/2}{100} \right) \right], \quad (5)$$

where Δ is the bandwidth expressed as a percentage of the target frequency. The SPL of the filtered signal (p_{filtered}) is then computed as:

$$L_p = 20 \log_{10} \left(\frac{\text{rms}(p_{\text{filtered}})}{p_{\text{ref}}} \right), \quad (6)$$

where $p_{\text{ref}} = 20 \times 10^{-5} \text{ Pa}$ is the standard acoustic reference pressure. The filter is further characterised by its stopband attenuation and steepness, which govern the sharpness of the roll-off outside the passband. The influence of these parameters, together with the choice of the relative passband size, is assessed through a sensitivity analysis for both experimental and numerical signals. As the SPL results were found to be virtually insensitive to the stopband attenuation, a value of 10 dB is applied throughout the current work and the sensitivity analysis is only reported for the filter steepness and passband size. The results of the sensitivity analysis are reported in Figures 5 and 6 for the numerical and experimental results respectively. The receiver selected for this analysis is located at a yaw angle of 0° and a pitch angle of -60° for both numerical and experimental signals, and was chosen arbitrarily.

The sensitivity analysis exhibit similar trends across the four harmonics for both numerical and experimental pressure signals. For the BPF, 2nd, and 3rd harmonics, the computed SPL is largely insensitive to the passband size for steepness values of 0.65 and above, with variations remaining below 1.0 dB across the full range of passband sizes considered. The highest steepness value of 0.95 produces a slight but consistent underestimation at small passband sizes, converging only as the passband widens. The 4th harmonic shows greater sensitivity, particularly to filter steepness, where low steepness values result in increasing SPL with passband size, indicating energy leakage from neighbouring spectral content being captured within the passband. Steepness values of 0.75 and above produce stable estimates at the 4th harmonic for both datasets. Based on this analysis, a filter steepness of 0.85 and a passband size of 5 % are selected for the remainder of the study, striking a balance between tonal peak isolation and insensitivity to the exact parameter choice.

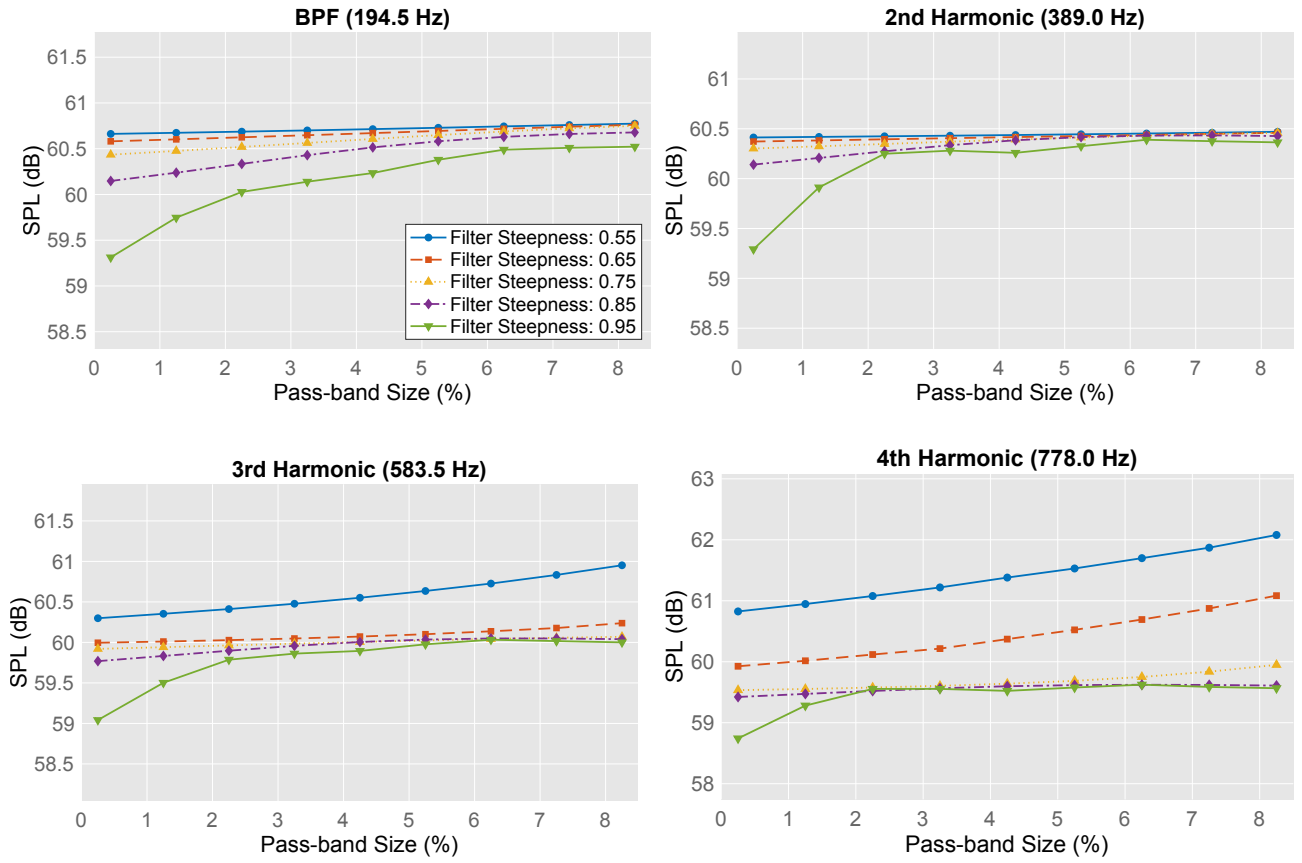


Figure 5: Numerical sound pressure level sensitivity to filter steepness and full passband size. The results are computed using a stopband attenuation of 10.0 dB.

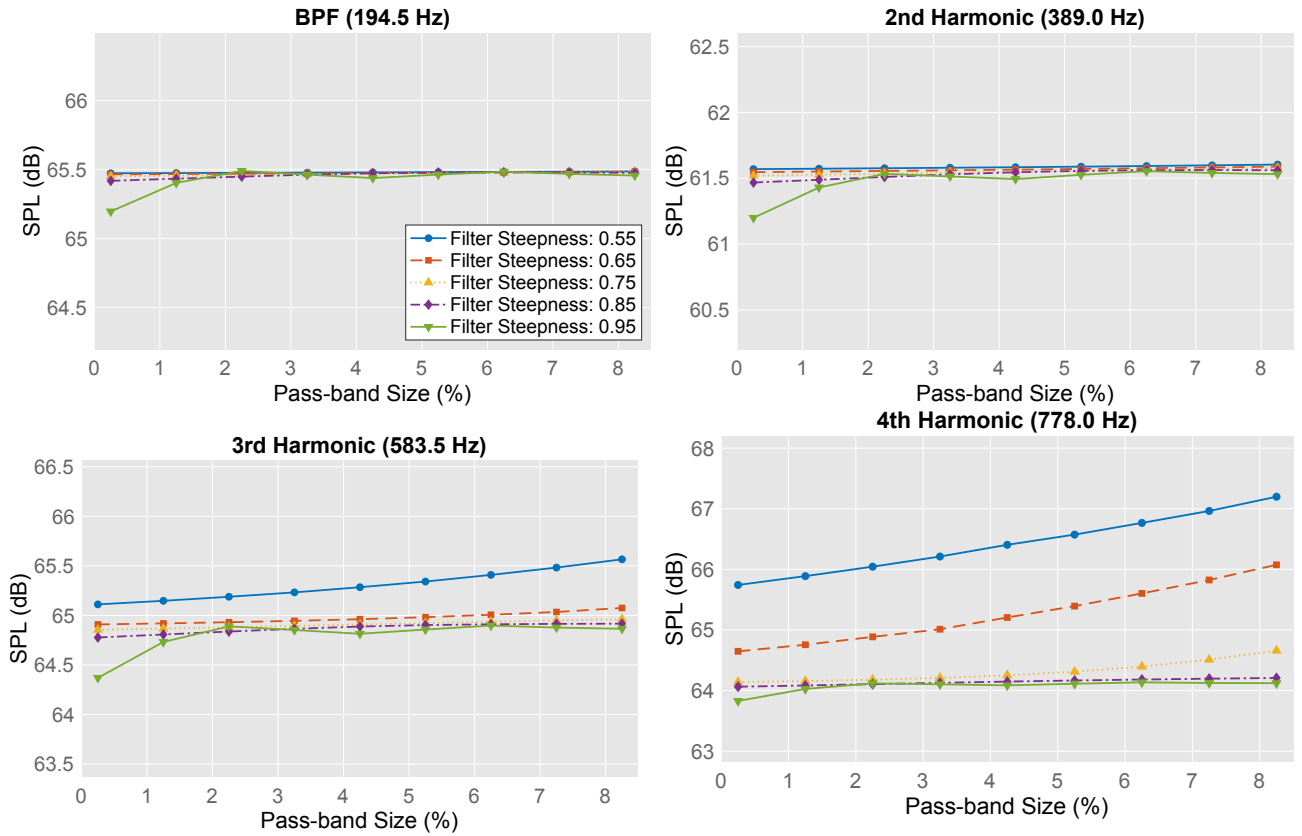


Figure 6: Experimental sound pressure level sensitivity to filter steepness and full passband size. The results are computed using a stopband attenuation of 10.0 dB.

4.4.2 Comparative analysis for the blade passing frequency

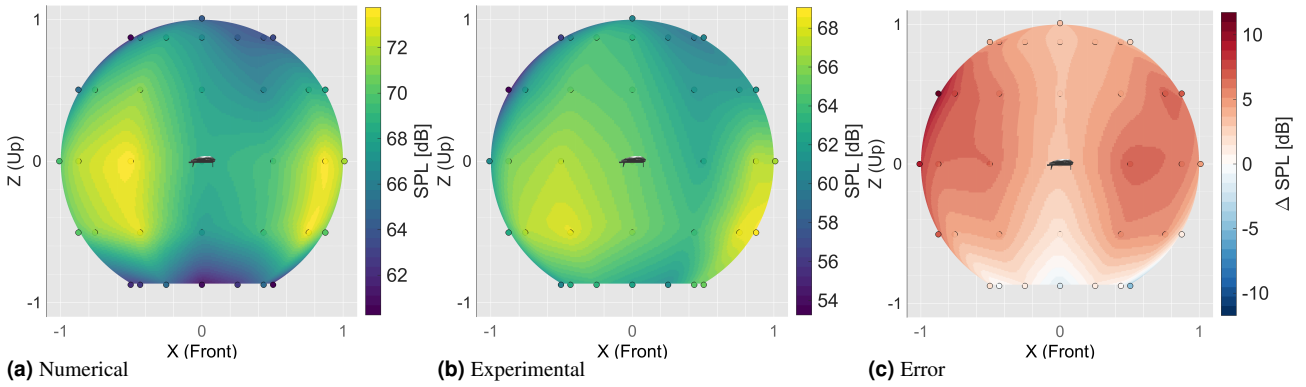


Figure 7: Noise Sphere comparison of the experimental and numerical Sound Pressure Level for the Blade Passing Frequency.

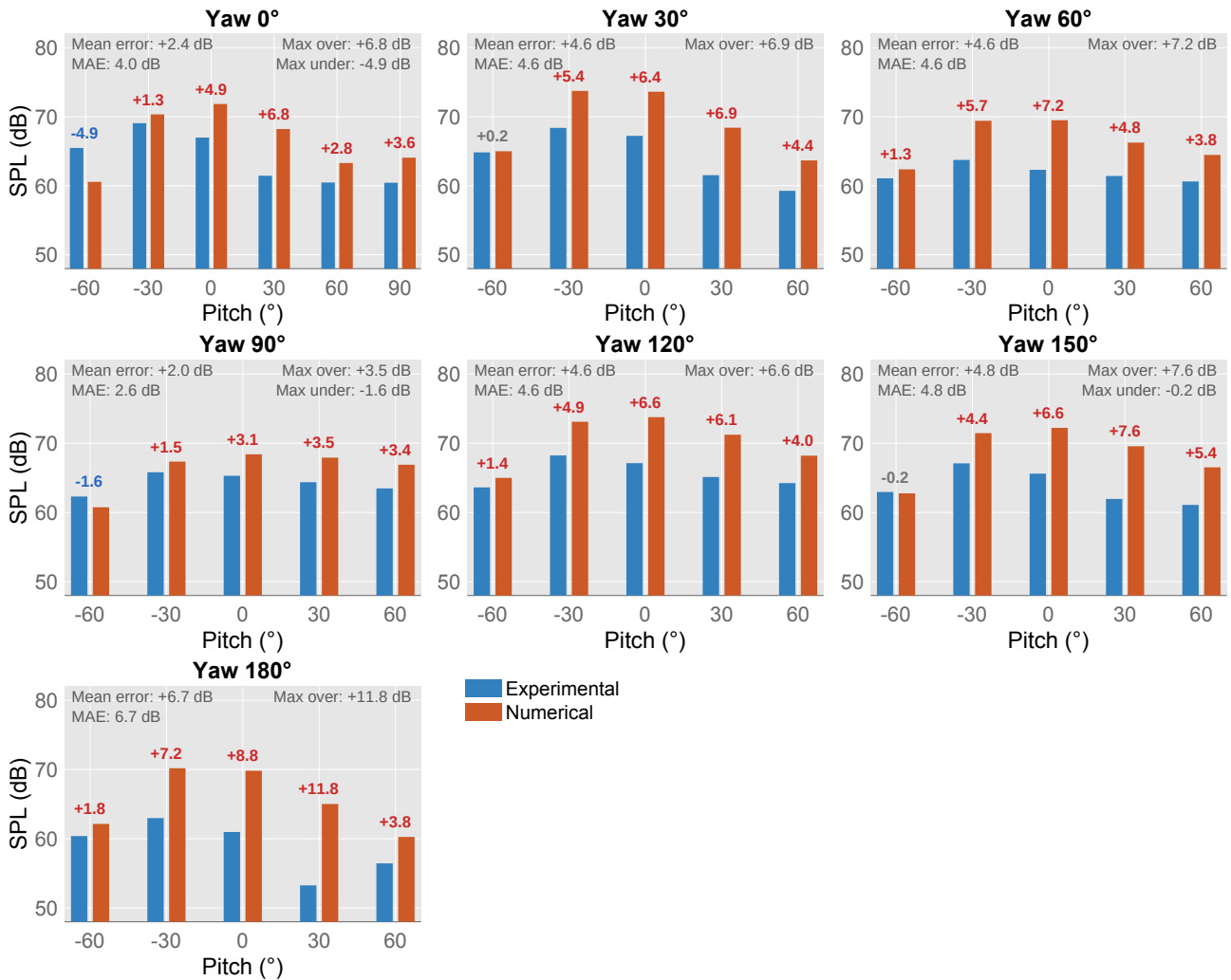


Figure 8: Sound Pressure Level for the Blade Passing Frequency comparison between experimental and numerical campaigns for all receiver locations in terms of Pitch and Yaw.

Two methods are employed to compare the noise directivity. The first consists of plotting the SPL values at each receiver location on the surface of a sphere, with linear interpolation over the pitch and yaw angles, and is referred to hereafter as the Noise Sphere approach. The second is a direct receiver-by-receiver comparison presented as bar charts, allowing the error between the numerical and experimental results to be quantified more explicitly. The

noise spheres for the numerical and experimental BPF SPL are shown in Figures 7a and 7b respectively, with the corresponding error represented in Figure 7c. The receiver-by-receiver comparison is presented in Figure 8, where the mean error, mean absolute error (MAE), and maximum over- and under-prediction by the simulation are also reported for each yaw angle.

The simulation consistently overpredicts the SPL across nearly all receiver locations, with discrepancies typically ranging 1 dB to 7 dB. However, near $\psi = 90^\circ$ and the south pole, the error is close to zero and the agreement is good. Both datasets nonetheless agree well on the overall directivity shape, with noise peaking in the rotor plane and attenuating towards the poles. The least accurate predictions occur at $\psi = 180^\circ$, where the largest errors are observed and the directivity trend is least well reproduced. Overall, the simulation overpredicts the experimental SPL for the BPF with a mean error of +4.2 dB and a MAE of 4.6 dB.

4.4.3 Comparative analysis for the blade passing frequency and its harmonics

The bandpass filtering procedure described in the previous subsection can be applied simultaneously to a set of target frequencies by configuring the filter as a comb filter centred on the BPF and its harmonics, enabling a comparison of the combined tonal noise between the simulation and the experimental measurements. For this comparison the first four harmonics are taken. The noise sphere and bar chart comparisons are presented in Figures 9 and 10, respectively.

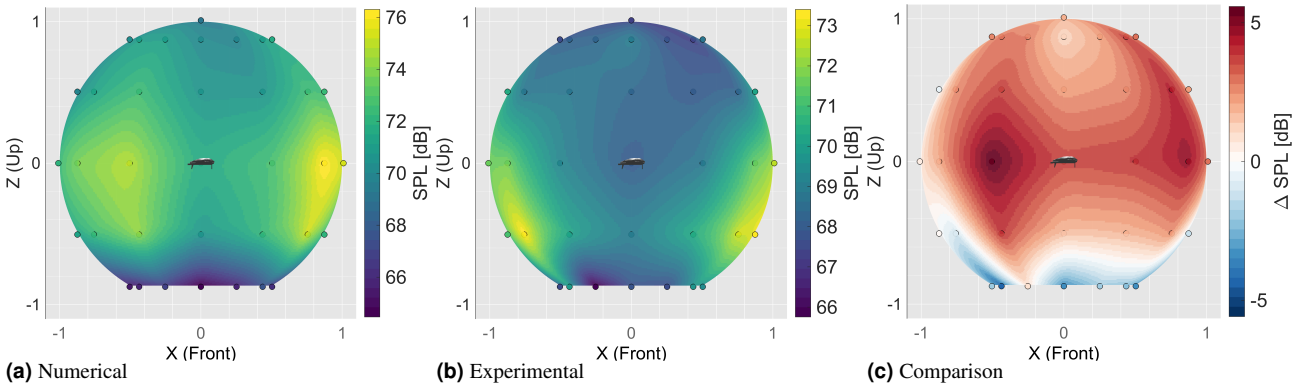


Figure 9: Noise Sphere comparison of the experimental and numerical Sound Pressure Level for the first four harmonics.

The combined tonal noise comparison for the first four harmonics reveals a more balanced agreement between the simulation and the experimental measurements than the isolated BPF analysis. The overall discrepancy is reduced, with the simulation still overpredicting in general but by no more than 5.6 dB, and with a mean error of +1.5 dB and a MAE of 2.6 dB. However, near the south pole ($\theta = -60^\circ$) the simulation systematically underpredicts the SPL across most yaw angles. The overall directivity shape is again reasonably well captured, though the spatial distribution of the error is slightly less uniform than in the isolated BPF comparison.

5. RESULTS AND DISCUSSION

5.1 Trim settings and balance of forces

The UAV trim parameters obtained from the steady-state trimmer for each leg are listed in Table 7. During leg 1 (ascent), the wind is low and aligned with the UAV's reference line from north to south, so the UAV requires little pitch or roll correction and the four rotor angular rates remain close to one another. During leg 2 (cruise), the UAV pitches forward due

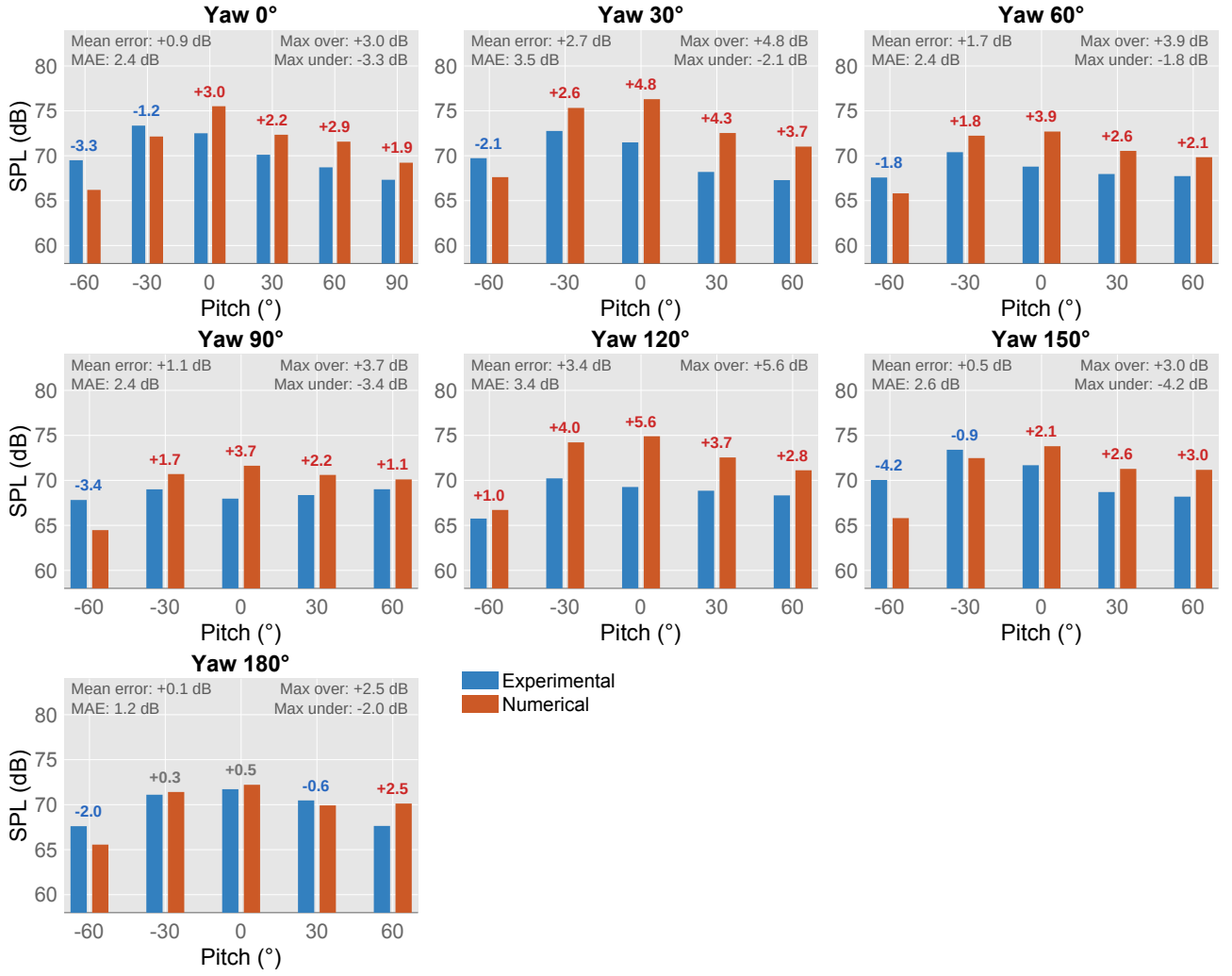


Figure 10: Sound Pressure Level for the first four harmonics comparison between experimental and numerical campaigns for all receiver locations in terms of Pitch and Yaw.

to its forward velocity, requiring higher angular rates on the aft rotors. The crosswind also causes the UAV to roll toward the starboard side and generate compensating aerodynamic moments, resulting in all four rotors operating at distinct angular rates. During leg 3 (descent), the UAV is exposed to a significant incident flow from behind and from the starboard side, again requiring an angular rate differential to compensate the aerodynamic moments. In this case, the four rotor angular rates split into two distinct groups arranged by diagonal pair.

Leg	Body angles [deg]		Angular rates [rpm]			
	Pitch	Roll	Rotor 1	Rotor 2	Rotor 3	Rotor 4
Leg 1	-0.69	-0.16	5045	5044	5026	5043
Leg 2	-5.74	-4.32	4097	4636	4759	5080
Leg 3	0.67	-2.11	4684	4086	4577	4015

Table 7: The UAV's trim variables for each leg of the mission.

The trim parameters presented above were used to set-up the transient simulations for each leg. Although the steady-state trimmer predicts perfectly trimmed flight conditions, transient flow phenomena are not accounted for in the said approach. Furthermore, the ALM may produce different averaged loads to those predicted by the ADM used during trimming. As a result, the trim parameters do not always yield perfectly balanced conditions in the unsteady simulations, even under identical flight settings. The resulting force and moment

balance errors in the transient simulation for each leg are reported in Table 8.

Leg	Balance of forces error [N]			Balance of moments [N.m]		
	ΣF_x	ΣF_y	ΣF_z	ΣM_x	ΣM_y	ΣM_z
Leg 1	1.44e-02	-2.61e-02	6.35e-01	1.13e-03	2.00e-02	7.36e-04
Leg 2	4.36e-02	1.06e-01	1.18e+00	5.18e-03	-4.98e-02	-7.74e-02
Leg 3	3.68e-01	-1.71e-01	8.47e-01	-3.47e-02	1.62e-02	2.32e-02

Table 8: Time-averaged error in the balance equations for the transient simulations of the UAV for each leg of the mission.

The results demonstrate that the trimmed state is well maintained throughout the transient simulations. All time-averaged net moments remain below 0.1 N.m, and all force balance errors are kept below 0.2 N with the exception of the vertical component. The error in the vertical component of the sum of forces ranges from 0.6 N to 1.2 N depending on the leg, which, while the largest error observed, remains small relative to the total UAV weight and is considered acceptable given the complex flight conditions simulated in this analysis.

5.2 Flow visualizations

Figure 11 shows the UAV during the three distinct legs of the mission. The time derivative of pressure and the regions of high vorticity in the vicinity of the UAV are shown. The ascent phase exhibits a relatively clean and symmetric flow features. In contrast, the cruise and descent phases display significantly more complex flow structures, with stronger rotor wake interactions with the airframe and between individual rotors, driven by the higher incident flow velocities and the asymmetric rotor angular rates required to maintain trim. The increased edgewise flow and the UAV's airframe geometry further intensify these interactions, resulting in a markedly higher level of unsteadiness in the near field during legs 2 and 3.

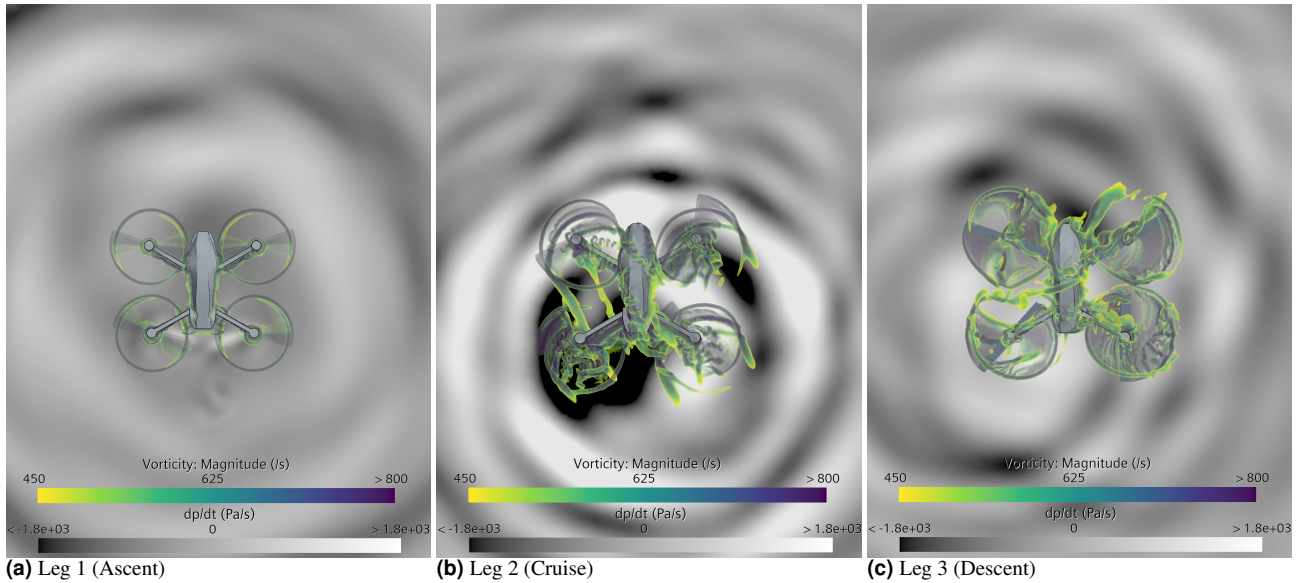


Figure 11: Pressure time derivative maps of first leg (left), second leg (centre), and third leg (right).

5.3 Spectral analysis

Figure 12 shows the narrowband SPL spectrum averaged across all receiver locations for each leg of the mission. The shaded region indicating the standard deviation over the microphone array. Moreover, the BPF of each individual rotor is overlaid on the corresponding spectrum. As expected, the simplest spectrum is observed for leg 1. The near-identical rotor

angular rates for all four rotors result in a noise signature dominated by clear tonal peaks at the collective BPF and its harmonics. The spectra associated with legs 2 and 3 are considerably more complex. During leg 2, the spread in rotor angular rates causes the individual BPF tones to separate. Their harmonics overlap, producing a much denser tonal structure overall. Despite the fact that the tonal energy is distributed across four distinct BPFs rather than one collective frequency, the peak SPL levels remain comparable to those observed during leg 1, which can be attributed to the higher rotor angular rates and the increased incident flow velocity during cruise. The descent phase (leg 3) exhibits a similar level of spectral complexity.

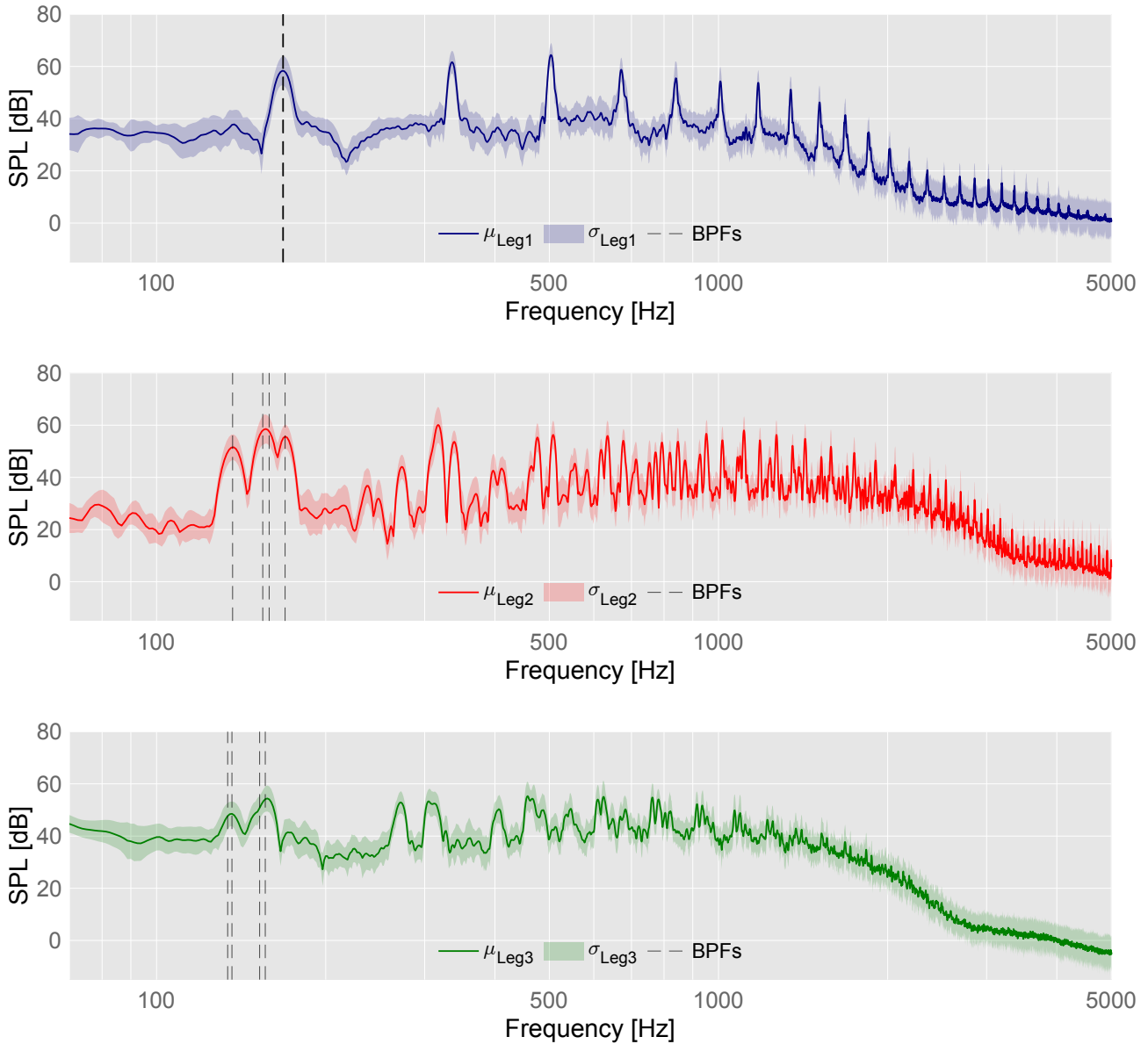


Figure 12: Narrow-band SPL spectra averaged over the receiver array for each leg of the mission. The shaded area represents the standard deviation across all receivers, whereas the solid line represents the average data and the dashed lines indicate the blade passing frequencies.

5.4 Propagation maps

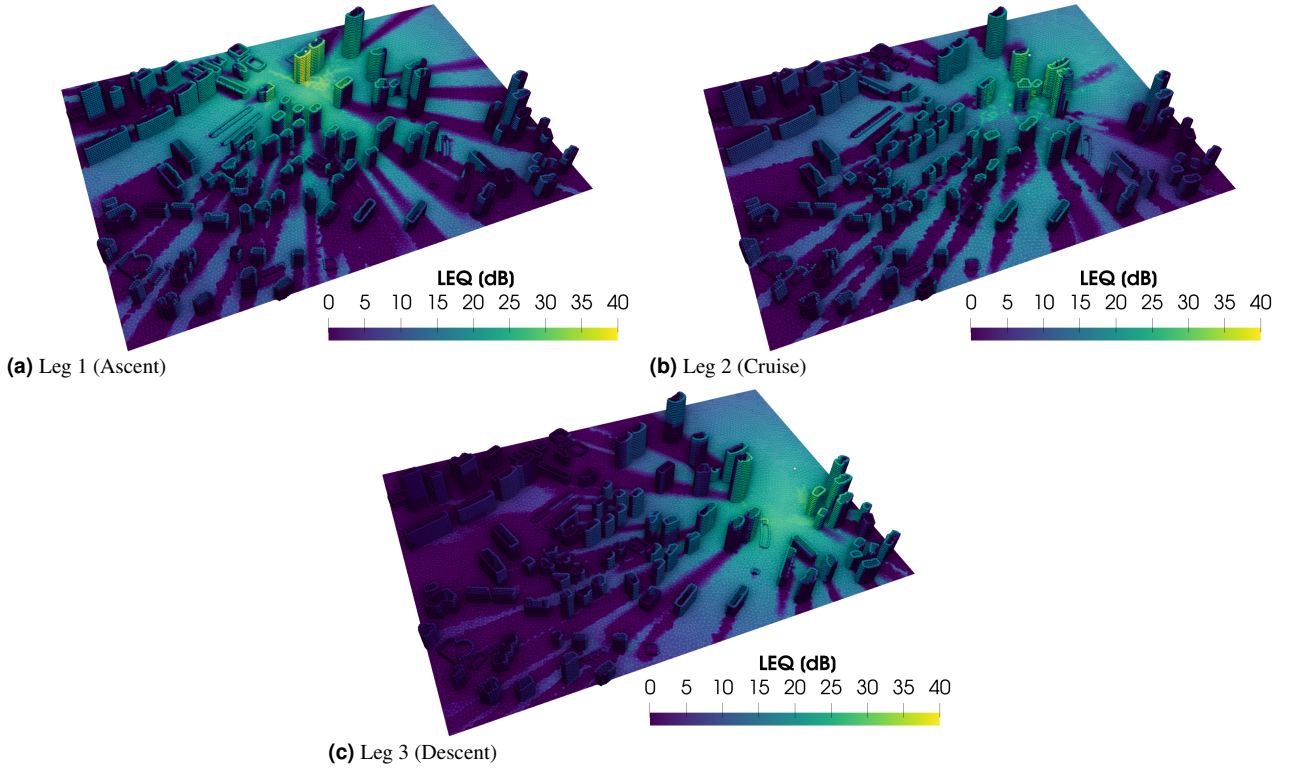


Figure 13: Noise propagation maps representing the equivalent continuous sound pressure level (LEQ) caused by the UAV during an instant of each leg of the mission.

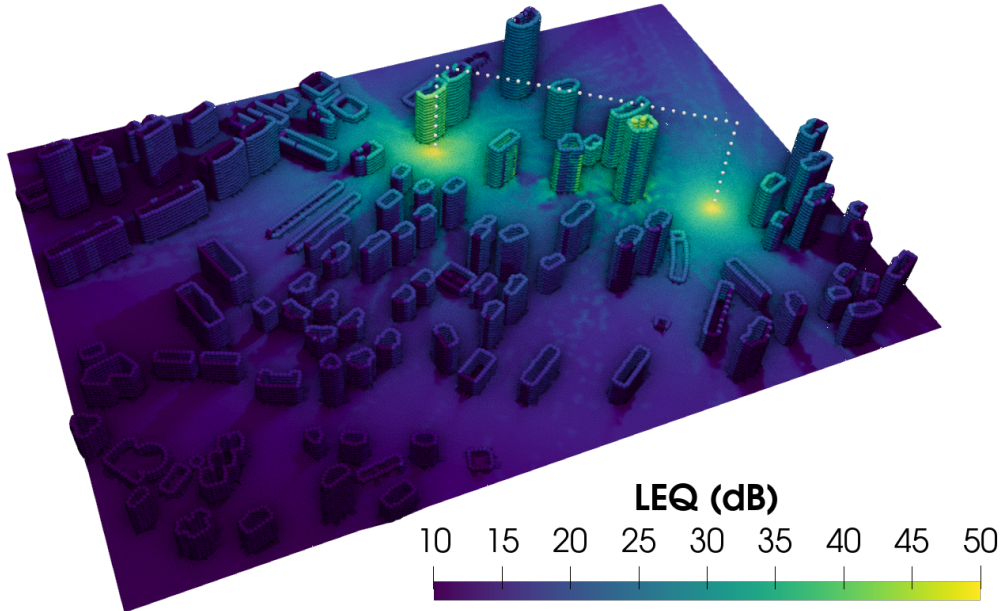


Figure 14: Noise propagation map representing the maximum equivalent continuous sound pressure level (LEQ) caused by the UAV during its mission.

Figures 13 and 14 present the L_{eq} noise propagation maps for each leg of the mission and the overall mission envelope, respectively. The results show that the noise footprint is strongly correlated the the UAV's position relative to the buildings. During ascent (leg 1), the UAV takes off and ascends in close proximity to a building, resulting in a concentration of noise near the take-off area with L_{eq} values reaching up to 40 dB in the immediate vicinity.

The acoustic shadow regions created by the surrounding buildings are clearly visible as the dark streaks radiating outward from the noise source. During cruise (leg 2), the UAV flies far away from the ground causing lower the peak L_{eq} levels than during ascent. The descent phase (leg 3) produces a footprint similar in character to the ascent, with noise again concentrated around the landing area. The overall mission L_{eq} map (Figure 14) reveals two distinct hotspots corresponding to the take-off and landing locations, connected by a corridor of moderate noise exposure along the cruise trajectory. Peak values approach 50 dB at the areas in which the UAV approaches the ground, while the cruise corridor remains below 35 dB for most ground locations. The building shielding effect is again clearly visible, with significant L_{eq} reductions observed in the acoustic shadow of taller structures.

6. CONCLUSIONS

This work presents a streamlined methodology for predicting the acoustic impact of a UAV mission in an urban environment. The approach combines trimmed steady-state CFD simulations with a PI-based trimming algorithm, unsteady URANS aeroacoustic simulations using the Actuator Line Model and the Ffowcs Williams–Hawkings analogy, and noise propagation via the CNOSSOS-EU methodology implemented in NoiseModelling. The framework was validated against experimental measurements in an anechoic chamber, demonstrating satisfactory agreement in tonal noise directivity, with a mean error of +4.2 dB and a MAE of 4.6 dB at the BPF, improving to +1.5 dB and 2.6 dB when the first four harmonics are considered together. The broadband noise floor is consistently underpredicted, which is attributed to the inherent limitations of the URANS approach and the ALM rotor model in capturing broadband noise mechanisms. The spectral analysis of the three mission legs highlights the strong influence of flight condition on the noise signature. The ascent phase produces a simple, well-defined tonal spectrum dominated by a single collective BPF and its harmonics, while the cruise and descent phases exhibit considerably more complex spectra due to the spread in rotor angular rates and stronger rotor–airframe interactions. Despite the distribution of tonal energy across four distinct BPFs during cruise, peak SPL levels remain comparable to those of the ascent phase. The noise propagation maps demonstrate that the urban building geometry plays a critical role in shaping the ground-level noise exposure, with strong acoustic shadowing effects visible throughout the mission. The highest L_{eq} values are observed near the take-off and landing sites, where the UAV operates in close proximity to the ground and surrounding buildings. Nevertheless, the cruise phase still produces a non-negligible noise corridor and should not be overlooked in flight path design. The primary advantage of the proposed framework lies in its modularity and relatively low computational cost, making it well suited for systematic acoustic impact assessments across complex mission profiles.

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