Experimental database for AAM noise assessment in urban environment

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Abstract

Environmental noise is an important public health issue that has negative impacts on human health and well-being. Due to the increasing urbanization of Europe, the impact of noise due to Advanced Air Mobility (AAM) in cities and suburbs on the quality of living will only increase. This stresses the importance of AAM noise prediction capabilities for policy makers and developers of drones. Literature shows the development of multiple noise source models focused on electrically driven rotors and/or propellers as well as the development of noise propagation models that work for noise in urban environments. However, there is a great lack of experimental measurement data for validation of these prediction tools. This paper describes the measurement campaign on a multirotor or Unmanned Air Vehicle (UAV) in a simulated city environment, resulting in an experimental database that can be used for noise model validation of both multicopter noise source models as noise propagation tools, as well as for AAM noise assessment in urban environment. It will conclude with the validation of NLR's CNOSSOS-EU based noise propagation model against the developed database.

1. NOTATION

Acronyms:

AAM	Advanced Air Mobility
EASA	European Union Aviation Safety Agency
CNOSSOS	Common Noise aSSessment methOdS
ICAO	International Civil Aviation Organization
MTOW	Maximum Take Off Weight
NORAH	NOise of Rotorcraft Assessed by a Hemisphere approach
RPM	Rotations Per Minute
S/N	Signal to Noise ratio
SPL	Sound Pressure Level
UAM	Urban Air Mobility
UAV	Unmanned Air Vehicle

2. INTRODUCTION

Over the past decade, drones have become an integral technology across various sectors. Advancements in drone technology and sensors, declining costs, and evolving regulatory frameworks are driving the creation of drones that are more accessible, efficient, and capable than ever before. One of the most promising commercial applications is the delivery of goods by drones or transport of passengers in urban environments, so-called Urban Air Mobility (UAM). Environmental noise is an important public health issue, featuring among the top environmental risks to health. It has negative impacts on human health and well-being and is a growing concern among both the general public and policymakers in Europe. Due to the increasing urbanization of Europe, the impact of noise due to Advanced Air Mobility (AAM) in cities and suburbs on the quality of living will only increase. This stresses the importance of AAM noise prediction capabilities for policy makers and developers of drones. Literature shows the development of multiple noise source models focused on electrically driven rotors and/or propellers as well as the development of noise propagation models that work for noise in urban environments. However there is a great lack of experimental measurement data for validation of these prediction tools. This paper describes the measurement campaign on a multicopter or Unmanned Air Vehicle (UAV) in a simulated city environment, resulting in an experimental database that can be used for noise model validation of both multicopter noise source models as noise propagation tools, as well as for AAM noise assessment in urban environment.

3. ROTORCRAFT NOISE MODELLING

The existing international guidelines for aircraft noise modelling, such as ICAO Doc 9911, ECAC Doc 29, and Directive 2015/996, have a significant limitation: they only address fixed-wing aircraft. Helicopters are already generating localized noise disturbances, and the impending introduction of drones and new urban mobility aircraft is likely to create additional noise concerns in densely populated areas. This lead the European Commission, with technical support from EASA, to prioritise the development of a methodology to compute rotorcraft noise, i.e. NORAH [1]. NORAH is a hemisphere based approach suitable for modelling the noise of helicopters and future transport modes such as drones and urban air mobility aircraft.

While NORAH is already in use by the Dutch government for the prediction of helicopter noise around airports [2], the implementation of NORAH for the modelling of AAM noise still has some hurdles to overcome. The most notable are 1) the current lack of available AAM noise source hemispheres and 2) the implementation of noise propagation in urban environment. While NORAH2 allows for the modelling of topography and noise shielding by a (single) building, it is currently not suitable for the modelling of rotorcraft noise in an urban environment. To solve the first issue alternative AAM noise source prediction models are being developed [3][4]. The noise hemispheres resulting from these predictions can be directly used with NORAH or with different noise propagation methods, such as the guidelines set out in CNOSSOS-EU [5]. However, one of the largest roadblocks for the validation of these models was the lack of suitable experimental data for validation. This paper describes the generation of such a database.

4. NOISE MEASUREMENTS

4.1. Test site

In order to generate the experimental database for multirotor noise assessment purposes, a field test campaign has been performed in NLR Drone DigiCity. It is an innovative test facility where drones and systems can be operated in a simulated urban environment, see Figure 1: This 'smart city' comprises 24 shipping containers that can be configured in various ways. To monitor this environment a high-tech digital infrastructure is developed with sensors and measurement devices in the city and on drones [6].

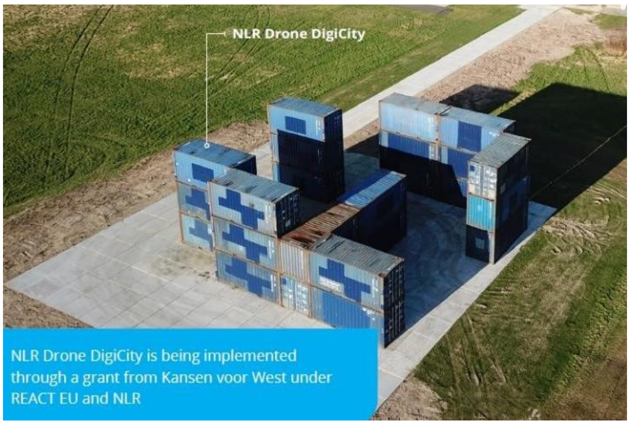


Figure 1: Picture of NLR Drone DigiCity

4.2. Test setup

The drone noise was captured by an acoustic array consisting out of 22 PCB 378A06 free-field microphones that were mounted on tripods of 1.2m height above ground level. They were synchronously recorded using the gbm Viper-HDR data-acquisition system [7] in combination with m+p software [8]. Before and after the measurements, the sensitivity at 1 kHz was checked for all array microphones using a calibrated GRAS 42AG sound calibrator. Frequency-dependent sensitivities of individual microphones were taken from calibration sheets. The microphones are fitted with B&K windscreens to reduce the influence of wind noise and are directed upwards. The microphones can be divided into 3 groups, i.e.:

• 11 microphones inside DigiCity arranged in a cross-like shape to capture noise directivity,

• 2 additional microphones inside DigiCity to specifically measure reflection and diffraction effects near corners,

• 10 microphones alongside DigiCity, arranged in a cross-like shape to capture noise directivity,

• 1 microphone in the far field that can be used as a free field reference.

7 hover spot were defined, of which were located in and around the city, with one located in the free field. A schematic drawing was made of this setup and is depicted in Figure 2.

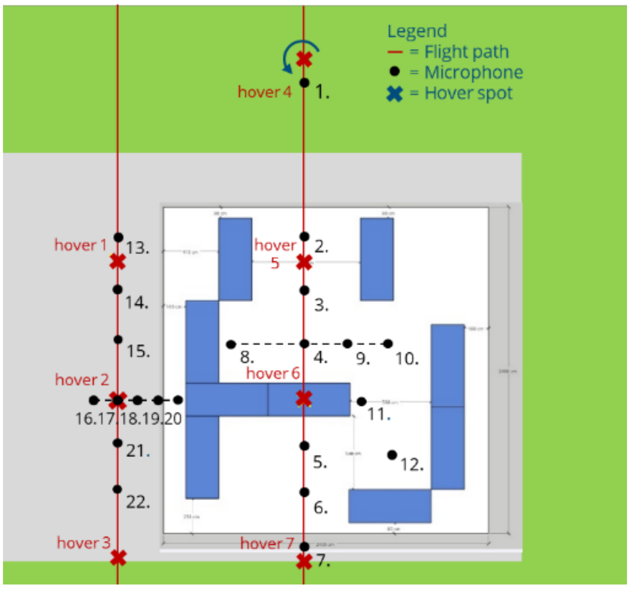


Figure 2: Top view of test site with flight paths, hover spots and microphone locations

Both OASPL,1/3 Octave band and narrowband spectra were acquired with a ‘high-pass’ filter of 1.5Hz and a sample frequency of 65.535 kHz. The measurement time was dependent on the flyover time.

4.3. Test objects

A DJI Matrice M600 drone has been operated to simulate a multirotor UAV. A picture of the drone can be found in Figure 3. It has been used in several other drone studies and has an existing, but not yet validated, noise source prediction model based on a FLIGHTLAB performance model [9]. It has a (Maximum Take-Off Weight) MTOW of 15.5kg. The Drone was outfitted with an RPM sensor for each rotor, enabling the autopilot system to track and record the drone's position and orientation. Furthermore, a temperature sensor was installed on the drone to measure the local air temperature.

During certain phases of the flight through DigiCity, the drone will enter a Beyond Visual Line of Sight (BVLOS) condition for a brief period of time. To mitigate potential risks and ensure safe operation, a trained observer was positioned on the east side of DigiCity, maintaining real-time communication with the pilot through a dedicated headset. This setup enables the observer to provide immediate feedback and support to the pilot, ensuring the safe execution of the flight. A picture of the drone flying through Drone DigiCity can be seen in Figure 4.

Figure 3: Photo of the DJI Matrice M600 drone with instrumentation

Figure 4: Photo of the test campaign: the DJI Matrice M600 drone flies through DigiCity

To validate noise propagation models without the added complexity of developing and validating drone noise source models a stationary sound source was measured within DigiCity at hover spot 2 and hover spot 5, as shown in Figure 2. The OmniPower Sound Source Type 4296 is an omnidirectional sound source that gives of a uniform directivity for noise frequencies up to 500Hz. It is mounted on a tripod of 2m as can be seen in Figure 5. Technical specifications of the omnidirectional sound source can be found in Figure 6. Measurements with this sound source are conducted to validate the sound propagation model and quantify and remove the uncertainty associated with the directivity of sound propagation. A range of pure tones (100, 200, 300, and 400 Hz) and broadband sounds were transmitted to gain a comprehensive understanding of sound propagation.

Figure 5: Omnidirectional sound source on a tripod

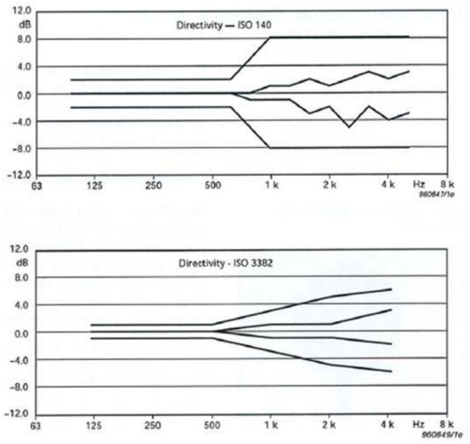


Figure 6: The two diagrams depict the deviations in directivity relative to two distinct ISO standards

4.4. TEST MATRIX

The test matrix consists out of noise measurements obtained from 2 test objects, i.e. the omnidirectional source and the DJI Matrice M600 multicopter UAV. For the UAV there were three main flight conditions:1.) a flight path along DigiCity, 2) a flight path through DigiCity and 3.) hover at the hover spots. The flights through and along DigiCity were performed at 2 different flight speeds, i.e. 1m/s and 10m/s, and at two different heights, i.e. 8.5m and 20m. The hover measurements were performed at the same heights as the flights along and through DigiCity, with a hover rotation at the far-field position to account for any non-symmetries in the noise directivity.

5. PROPAGATION MODELLING

NLR's propagation model [3] predicts noise propagation in an urban environment. The omnidirectional sound source is modelled by a noise source hemisphere with a constant SPL in all directions similar to the sound source. DigiCity is described in terms of 2D outlines of the 'buildings' accompanied with a certain height. It uses an algorithm that finds the relevant paths between the sound source and the observer.

This raytracing algorithm takes direct paths, diffracted paths and reflection paths into account up to 3 levels deep. Once the relevant paths have been found, the resulting noise level at the observer point is calculated via the method prescribed in CNOSSOS-EU [5]. This model takes geometric spreading of sound power, the source directivity, atmospheric absorption, reflecting material and diffractive damping into account. Figure 7 shows a visualization of the propagation paths for a flyover. The noise source given in green, the observer in blue, reflection points in purple and diffraction points in yellow.

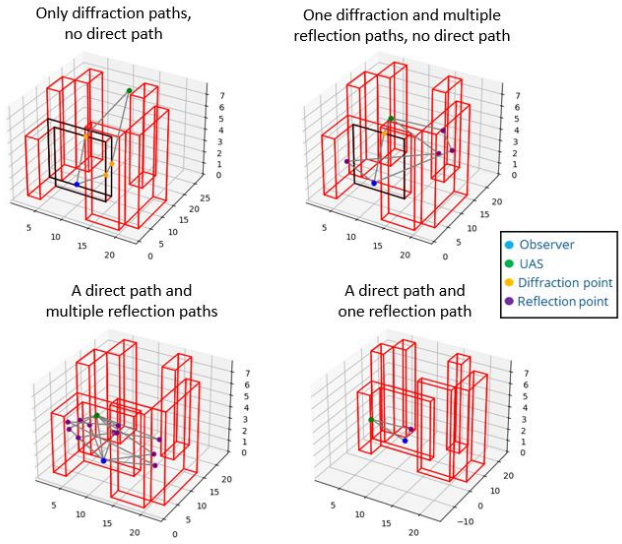


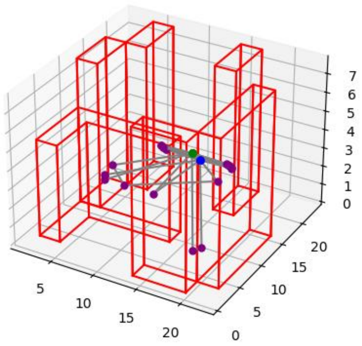
Figure 7: Visualization of calculated propagation paths for flyover at 6 meters height [3].

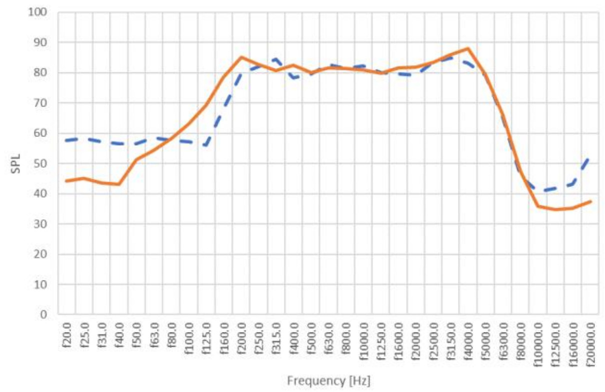
6. RESULTS

The experimental database for AAM noise in urban environment can be used for the validation of noise propagation models that are applicable to urban environments. To demonstrate this fact, a comparison has been done between NLR's propagation model and the experimental data and the measurement data from the omnidirectional noise source in DigiCity at the different microphone positions.

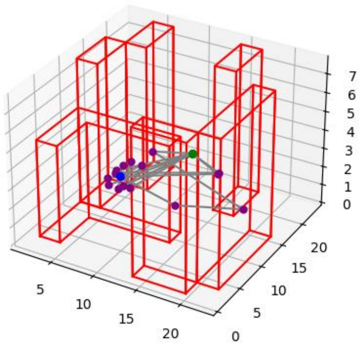
For the validation of the propagation tool, 3 different scenarios have been evaluated: 1) only reflection, 2) only diffraction, 3) both reflection and diffraction.

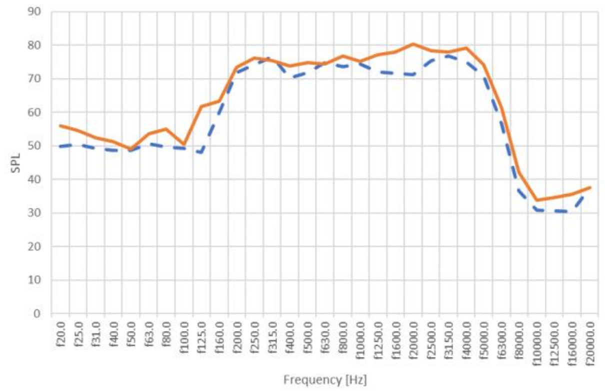
The scenario is evaluated by comparing the broadband measurement of the sound source at hover spot 5 towards microphone 2, 8 and 10. For these microphones there is no diffraction, just reflections as can be seen in Figure 8 , where the raytracing is visualized in a simulation of DigiCity. The noise source is given in green, while the microphone/observer is given in blue and the wall reflections are given in purple. In Figure 9 the comparison between the measurement, in solid orange, and the simulation, in dashed blue, is given. It is clear that the sound source only operates in the range between 160Hz and 6.3kHz. There is a good agreement between for all three the cases without diffraction within the range of the omnidirectional sound source both in trend and in absolute levels.





a)





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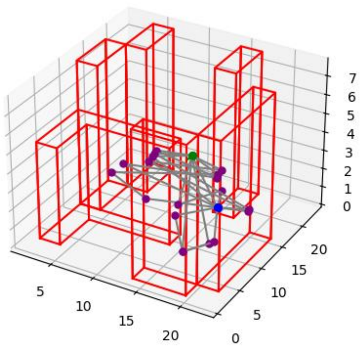

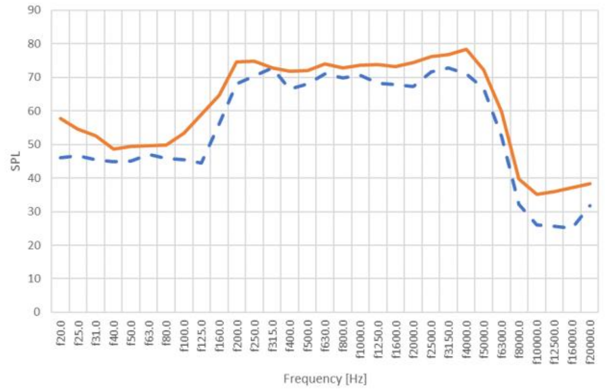

c)

Figure 8: calculated noise propagation paths from the noise source located at hover spot 5, in green, to microphone 2 (a), microphone 8 (b) and microphone 10 (c), in blue. Wall reflections are denoted as purple and diffraction point in yellow.

Figure 9: Comparison between calculated noise propagation paths from the noise source located at hover spot 5 to microphone 2, 8 and 10 and measurement data. The orange solid line denotes the measurement data, the dashed blue line denotes the simulation results.

For the cases with diffraction, e.g. microphone 7, a significant difference between measurement and simulation can be observed, as seen in Figure 10. While both the simulation and the experimental data follow a similar trend within the range of the sound source, there is a severe underprediction of 10 to 15dB. The background noise was plotted as well to show that this was not due to a low S/N ratio. The reason behind this underprediction requires further research.

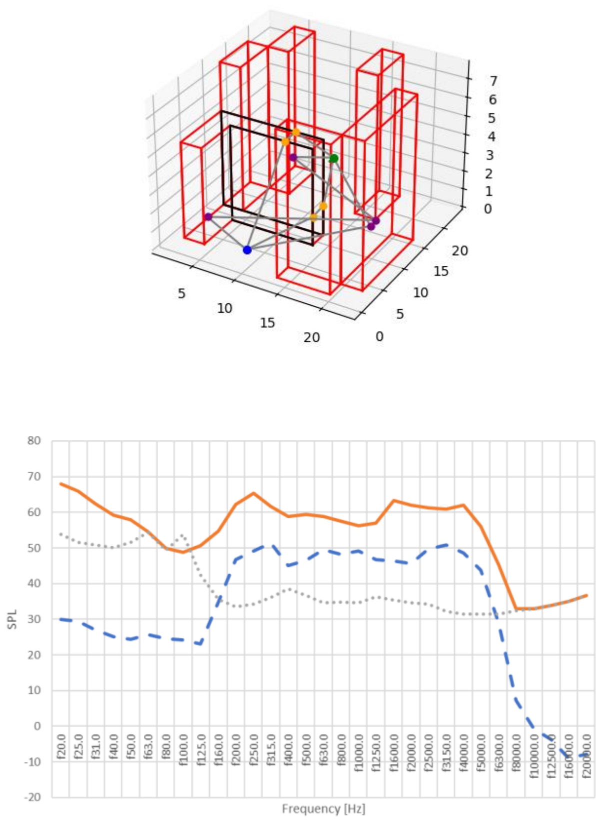

Figure 10: (top) calculated noise propagation paths from the noise source located at hover spot 5, in green, to microphone 7, in blue. Wall reflections are denoted in purple and diffractions in yellow. (bottom) Comparison between calculated noise propagation paths from the noise source located at hover spot 5 to microphone 7 and measurement data. The orange solid line denotes the measurement data, the dashed blue line denotes the simulation results, the dotted grey line are the background noise levels.

The database was also used for the validation of multi-rotor broadband noise models for AAM in urban environment [4]. This validation exercise has highlighted a tendency towards underprediction of both tonal as broadband rotor noise. This result underlines how crucial it is to have reliable experimental data in the development of (multi)rotor noise source models and propagation simulation.

7. CONCLUSIONS

1. An extensive noise measurement campaign of a multicopter UAV in a simulated city environment has been performed. This resulted in an experimental database that can be used for model validation of multicopter noise source models and noise propagation tools, as well as for the full AAM noise assessment in urban environment.
2. It was shown that through the choice of the microphone locations the measurements of the omnidirectional sound source can be used independently for different propagation scenarios, i.e. paths with only reflection, paths with only diffraction and paths with a combination of reflection and diffraction, without requiring a (validated) UAV noise source.
3. The experimental database has been used for the validation of the CNOSSOS-EU based propagation model from NLR. This comparison showed that noise propagation that is dominated by noise reflections show very good agreement the simulations, however noise propagations simulations dominated by diffraction show a severe underprediction.
4. This experimental database was successfully used for the validation of multi-rotor broadband noise models for AAM in urban environment.

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