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INVESTIGATION OF THE IMPACT OF REAL ATMOSPHERIC CONDITIONS ON NOISE PROPAGATION FROM SMALL AIRCRAFT TECHNOLOGIES

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ABSTRACT

The commercialization of urban air mobility (UAM) is increasingly coming into focus. Their range of operation is often limited by noise restrictions in urban areas. Besides psychoacoustic factors, the noise perception of individual flights on the ground is strongly affected by sound propagation through the atmosphere. Recent work has focused on scenario predictions of ground-perceived noise originating from large aircraft. Current prediction models use standardized atmospheric conditions to calculate sound propagation. Previous research shows that at high flyover altitudes and scenario calculations, neglecting meteorological factors gives accurate results for the noise perception on the ground. However, a single small aircraft flies at low altitudes such that assumptions as the strong damping of high-frequency noise propagating from an aircraft to an observer are no longer applicable. Therefore, this study quantifies the differences between standard atmospheric conditions in comparison to real atmospheric relations for low flyover altitudes. The impact of several meteorological state variables is investigated. The atmospheric sound propagation is performed by a numerical Lagrangian sound particle model comparable to ray tracing. The analysis highlights the limitations of current modeling approaches. Future work could suggest optimizing flight paths for local weather conditions to minimize the impact of noise on communities.

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1. INTRODUCTION

The demand for air travel has steadily increased as the economy has grown and is expected to continuously increase. Due to the growing traffic for individual and cargo transport in congested metropolitan regions, developing urban air mobility concepts is becoming progressively important. Currently, transport drones, unmanned aerial vehicles as well as helicopters are considered innovative solutions for urban traffic problems [1]. However, due to the new vehicle designs, the required infrastructure, and the density of operations, new challenges for aviation arise [2]. Since UAMs are initially used for short-range, low-altitude operations over densely populated areas, the application of UAM technologies depends especially on social acceptance. In this context, social acceptance is mainly influenced by noise immissions. Aircraft noise has often been called the most undesirable feature of life in the urban community because of its negative health effects, including annoyance, sleep disturbance, and cardiovascular diseases [3]. Therefore, in addition to noise reduction at the source, it is necessary to consider sound propagation through the atmosphere and evaluate the impact of noise on the population.

Noise-power-distance (NPD) data [4], which are specific to each aircraft, are widely used to estimate aircraft noise exposure. NPD provides noise level predictions for a given aircraft type in a given flight condition and at a given distance to the observer. However, constant weather conditions are assumed, i.e. no variation of air temperature and wind speed in both vertical and flow directions are considered. Existing semi-empirical aircraft noise prediction models use simplified atmospheric conditions to compute sound propagation, neglecting real weather conditions. Nonetheless, several studies by Browne et al. [5] and Parry et al. [6] have shown, that unsteady propagation effects have a significant impact on ground noise levels and need to be accounted for. Research by Binder [7] has dealt with the meteorological influence on sound propagation from large aircraft at high altitudes. However, noise caused by UAMs at low altitudes was not investigated. The published work by Rizzi et al. [8] highlights the state of the art in UAM noise and identifies the importance of including sound propagation models that can consider wind and temperature effects, as well as ground effects, to improve noise predictions.

The focus of this work is on the application of the simulation model AKUMET to evaluate sound propagation from low-flying aircraft. Previously, AKUMET was only applied to static, non-moving sources, such as wind turbines. There, the simulation model shows that meteorological conditions can be accurately reproduced. In this study, the model is now successively adapted to aircraft noise. The aircraft is a dynamic, moving source with different sound pressure levels than wind turbines. Therefore, the primary objective is to verify whether the applied simulation model provides feasible results with respect to aircraft noise. The emphasis is on the investigation of atmospheric refraction effects caused by temperature and wind speed gradients. In addition, various ground effects are analyzed. In the future, it is planned to compute the noise impact on the population for low-flying UAMs with the simulation model used here.

The remainder of this paper is structured as follows. In order to bring all readers to the same level of knowledge, in section 2 the fundamentals of sound propagation are explained. Section 3 describes the methodological approach by presenting the framework of the simulation for the aircraft. Then, in section 4, the results are presented and discussed. Finally, in section 5, a summary of the work is given.

2. FUNDAMENTALS OF SOUND PROPAGATION

A detailed overview of outdoor sound propagation is given by Attenborough et al. [9]. Outdoor sound propagation is influenced by atmospheric conditions. For instance, temperature gradients and wind gradients cause sound velocity gradients and affect sound paths by refraction.

2.1 Definition of sound pressure levels

Sound can be defined as mechanical energy transmitted by pressure waves in a material medium. The sound pressure level (SPL), given in dB, describes the strength of a sound event, which is defined as a logarithmic ratio between the measured sound pressure p and a reference sound pressure $p_0 = 0.00002\ \mathrm{Pa}$ as follows [10]:

$$SPL = 20 \cdot \log(\frac{p}{p_0}). \tag{1}$$

In order to consider the volume sensitivity of humans, frequency weighting curves are applied to the measured values at different frequencies. Frequency weightings account for the frequency dependence of human sound perception. The low-frequency noise components that are not perceived as loud and the high-frequency noise components that are perceived as very loud are appropriately damped during measurement. The most commonly used weighting factors are the so-called A-frequency weighting factors, specified in $\mathrm{dB(A)}$. A detailed description and calculation of the A-rated sound pressure level are provided by Möser et al. [10].

The speed of sound c describes the velocity in $\mathrm{m/s}$ at which a sound wave propagates. The speed of sound c depends on the type and condition of the medium. Assuming air is an ideal gas, the speed of sound c is given by:

$$c = \sqrt{\kappa R T^*} \tag{2}$$

where $R = 287\ \mathrm{J/kgK}$ is the gas constant and the isentropic exponent is given by $\kappa = 1.4$ for air [11]. T^* describes the temperature in K. Approximately, the formula can be simplified to:

$$c = 331.5 + 0.6T. \tag{3}$$

where T is the temperature given in $^\circ\mathrm{C}$.

2.2 Atmospheric effects on sound propagation

To calculate sound propagation through the real atmosphere, it is fundamental to take into account the physical variables that change in time and space. Indeed, these include temperature gradients and wind speed gradients, which are responsible for the refraction of acoustic waves.

2.2.1 *Temperature effects*

According to existing semi-empirical aircraft noise prediction models, the temperature gradient in the troposphere is assumed to be constant, however, this is not representative for many real conditions. Based on Ruijgrok et al. [12], the temperature-induced variation of the sound speed is given by:

$$c(z) = c_0 + \frac{dT(z)}{dz} \cdot \frac{c_0}{2T_0} \cdot z \tag{4}$$

where c_0 is the speed of sound at sea-level, z the height above sea-level and T_0 the sea-level temperature, given in K. The green line in Fig. 1 shows the profile of the speed of sound $c(T)$ as a function of temperature T and altitude z that is used in this study. Thereby, the temperature decreases linearly with altitude by $dT/dz = -10\,\mathrm{K/km}$.

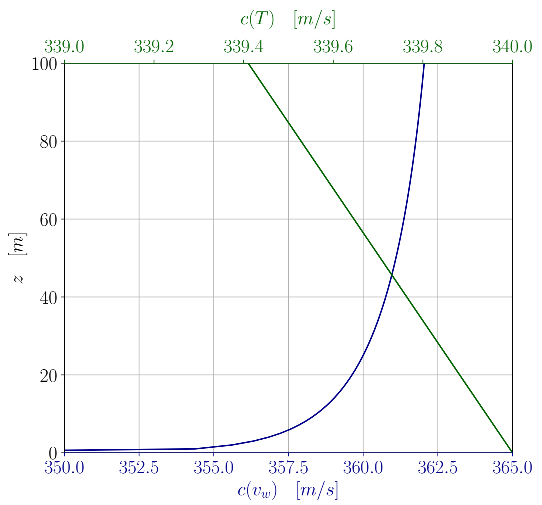


Figure 1: Speed of sound as a function of altitude.

2.2.2 *Wind effects*

The effective sound speed c_{eff} describes the speed of sound, which is affected by the horizontal wind velocity v_w. The effective sound speed c_{eff} is defined as:

$$c_{eff}(z) = c + v_w(z) \tag{5}$$

Vertical wind profiles can be described by various relations. For instance, Hellmann et al. [13] use the power law to determine the wind speed at any given height. Moreover, vertical wind profiles can be represented by logarithmic relations [14]. The logarithmic vertical wind profile for the horizontal wind speed $v_w(z)$ is obtained by:

$$v_w(z) = v_r \cdot \frac{\log(z/z_0)}{\log(z_r/z_0)} \tag{6}$$

where v_r is the wind velocity at a reference height $z_r = 10\,\mathrm{m}$, related to data from Suisse Eole [15]. The variable z_0 represents the height at which the horizontal wind speed would disappear according to the logarithmic law. The height z_0 depends on the surface structures of the base and is called the roughness length. Fig. 1 displays in blue the profile of the speed of sound $c(v_w)$ depending on the altitude z, where v_r is set to a value of $15\,\mathrm{m/s}$ in the wind direction, as it is applied later in this study. It can be seen that the gradient of the wind velocity at low altitudes has a stronger influence on the speed of sound than the temperature gradient.

2.2.3 *Ground effects*

Depending on the surface, the sound can either be absorbed by the ground or reflected. In the latter, the direct sound is then superposed with a reflection from the ground. Depending on the time shift of direct and reflected sound, this produces constructive or destructive interference. The result can be a significant increase in noise. If the sound is reflected by the ground, several cases are distinguished. Generally, the ground can be characterized as hard ground, porous ground, or mixed ground. Based on the surface type, such as tamped ground or vegetation, the sound is reflected differently [16]. Later in this work, a sonically hard ground is used to represent the reflection on the ground.

Besides temperature gradients, wind gradients, and ground effects, the sound level from the source to an observer is also influenced by other atmospheric effects, such as atmospheric humidity and absorption. Additionally, turbulence in the atmosphere affects sound propagation. Turbulence can cause a dispersion of the sound rays, thus even in shadow zones a sound entry can be present. However, since this paper mainly focuses on wind and temperature, other effects will not be further discussed.

3. METHODOLOGICAL APPROACH

This section shows the systematic procedure of this work. In the following, the numerical sound particle model AKUMET is described. Then we present the applied case study.

3.1 Numerical model

For long-range propagation, ray tracing is advantageous over wave-based methods since ray tracing requires less computational effort. Ray acoustic methods assume the existence of wavefronts and the presence of rays, which provide a three-dimensional representation of sound propagation and energy flow [17].

The Lagrangian sound particle model AKUMET, which is used in this study, is based on sound ray theory. AKUMET is designed to simulate the propagation of sound in an inhomogeneous atmosphere under consideration of various ground effects. At an acoustical source a large number of sound particles is emitted into the environment. The sound particles move with the speed of sound along sound rays and transport the sound energy into the model area. In order to determine the sound pressure level at defined receiver points, the number of sound particle passages is counted in grid cells.

3.2 Application

In this paper, the Parametric Aircraft Noise Analysis Module (PANAM) [18] is used to simulate the aircraft noise emission at the sound source. Differently, from the NPD method, PANAM [18] is able to model each individual source with directivity and frequency spectrum. Since no small aircraft are implemented in PANAM [18] at present, a conventional aircraft, the A320, is simulated in this work. Although the motivation of this paper is focused on small aircraft, the knowledge gained about the meteorological influence can also be applied to small aircraft and thus to UAM. As the topic of UAM is increasingly growing, small aircraft with propeller propulsion systems are currently also being implemented in PANAM [18]. In the future, the sound propagation under real atmospheric conditions of small aircraft can also be investigated with the method shown here.

For the investigation of sound propagation considering wind gradients and temperature gradients, the simulated A320 is held at a flight point at an altitude of $80\,\mathrm{m}$. Fig. 2 shows the emission sphere around the A320, which is radiated by the aircraft, made by PANAM [18]. The airplane's flight direction is in the positive x-direction. The aircraft does not radiate sound homogeneously in all directions. Besides operating conditions, the directivity depends on airplane geometry, such as the configuration of engines, flaps, and landing gear. For noise exposure on the ground, the directivity of an aircraft has to be considered.

For convenience, we assume that the aircraft represents a point sound source. Therefore, all individual sound power levels of the directivity are averaged into a total sound power level. This simplification is made to reduce the computation time during the simulation. Since the primary objective of this work is to analyze the meteorological influence on sound propagation, the assumption of the aircraft as a point source is sufficient.

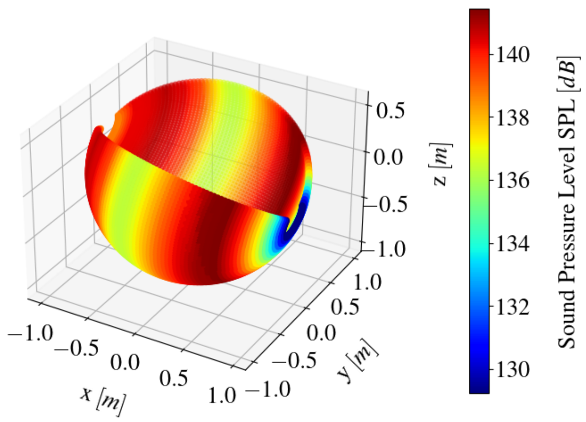


Figure 2: Emission sphere of the reference aircraft during a simulated take-off (altitude = $80\,\mathrm{m}$, thrust = $68.3\,\mathrm{kN}$, true airspeed = $86\,\mathrm{m/s}$).

As described in the previous section, the sound propagation of aircraft noise is simulated with AKUMET. Information about the sound source is provided by PANAM [18]. This data is used as input for the propagation model. The dimensions of the acoustical model are chosen as follows: The acoustic grid has 278 cells in the x-direction, 201 cells in the y-direction, and 32 cells in the z-direction. The mesh size is $8\,\mathrm{m}$ in each dimension. The particle number N describes how many particles are emitted from the aircraft sound source. In this study, N is set to 5 million particles. Preliminary investigations have shown that a particle quantity of 5 million provides feasible results.

Several non-homogeneous atmospheric conditions are simulated in this work. The temperature gradient dT/dz is varied from $-10\,\mathrm{K/km}$ to $+10\,\mathrm{K/km}$, which are typical atmospheric values. A logarithmic wind profile is applied, where at $10\,\mathrm{m}$ above the ground the wind speed w_s becomes $15\,\mathrm{m/s}$. The wind blows from the west, thereby the wind direction w_d equals $270\,°$. Finally, the surface of the ground is investigated by assuming a totally reflecting ground. The standardized atmosphere, commonly used in most aircraft noise prediction models, is used as a reference in this study. The standard atmosphere is a non-windy environment ($w_s = 0\,\mathrm{m/s}$ and $w_d = 0\,°$) where no temperature gradients occur and the ground totally absorbs the sound.

4. RESULTS AND DISCUSSION

In the following, we present the numerical results and the corresponding impact of temperature gradients, wind speed, and ground effects.

4.1 Effect of temperature gradients

The results of the non-homogeneous atmosphere with a change in temperature gradients are considered and compared with the standard atmosphere.

Since temperature generally decreases linearly with altitude, sound rays emitted by the aircraft are refracted upward in the absence of wind for a negative temperature gradient of $dT/dz = -10\,\mathrm{K/km}$, displayed in Fig. 3. The refraction upwards is due to the fact that the upper part of the wavefront moves more slowly than the lower part (prevailing conditions) [19].

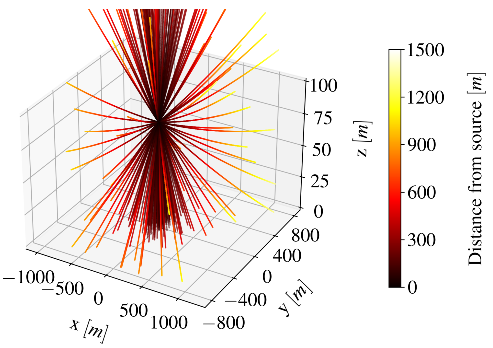


Figure 3: Three-dimensional path of sound rays for a non-homogeneous atmosphere at a negative temperature gradient of $dT/dz = -10\,\mathrm{K/km}$ and no wind.

On the other hand, if the temperature increases with $dT/dz = +10\,\mathrm{K/km}$, which is called thermal inversion, the sound rays are refracted downward, as shown in Fig. 4. Then the upper part of the wavefront moves faster than the lower part and the effect is reversed (conditions often at night) [19].

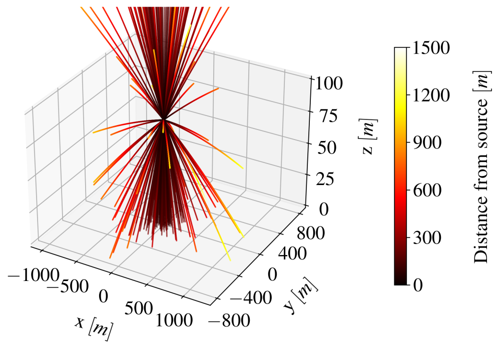


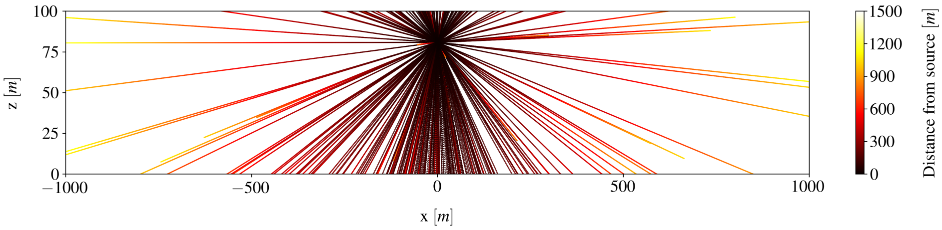
Figure 4: Three-dimensional path of sound rays for a non-homogeneous atmosphere at a positive temperature gradient of $dT/dz = +10\,\mathrm{K/km}$ and no wind.

4.2 Effect of wind

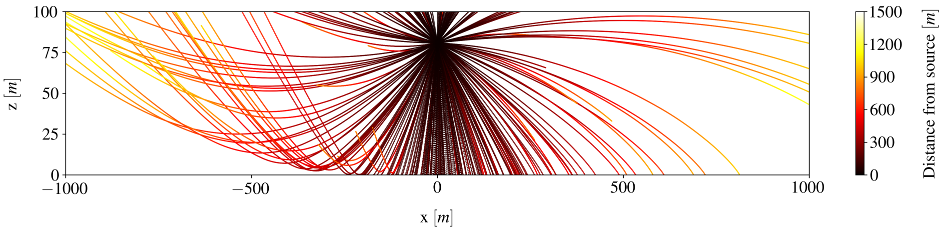
In this section, the influence of wind on sound propagation is investigated in comparison to the windless atmosphere.

Fig. 5a shows the sound ray path in a homogeneous windless atmosphere, where no temperature gradients are present. We see that the sound rays radiated by the aircraft pass straight through the environment and are not refracted. Whereas Fig. 5b presents the refraction of the sound rays when the wind blows from left to the right and the wind speed at a height of $z = 10\,\mathrm{m}$ is equal to $w_s = 15\,\mathrm{m/s}$. The logarithmic wind profile, as shown in Eq.6, is applied.

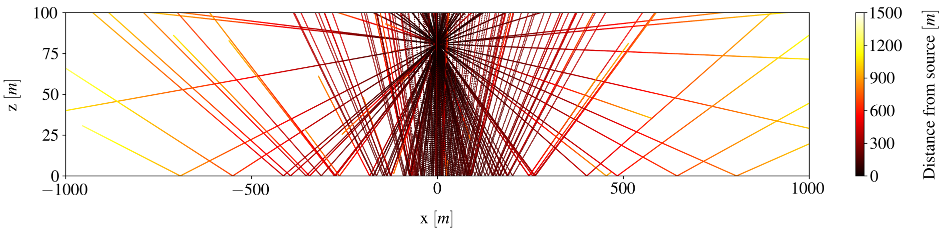
In the upwind direction of the aircraft, the sound rays are refracted upward. A refractive shadow zone is created. We note that an observer on the ground more than $x = -457\,\mathrm{m}$ away from the aircraft does not receive any sound particles, see Fig. 7. The located observer does not perceive any noise disturbance. In the vicinity of the sound source, a comparatively small curvature is apparent and becomes more effective with a lower visible incidence angle. Depending on whether the sound source is in the downwind or upwind direction, the wind speed is added



(a) Homogeneous atmosphere with absorbing ground ($dT/dz = 0\,\mathrm{K/km},\ w_s = 0\,\mathrm{m/s},\ w_d = 0\,^{\circ}$).

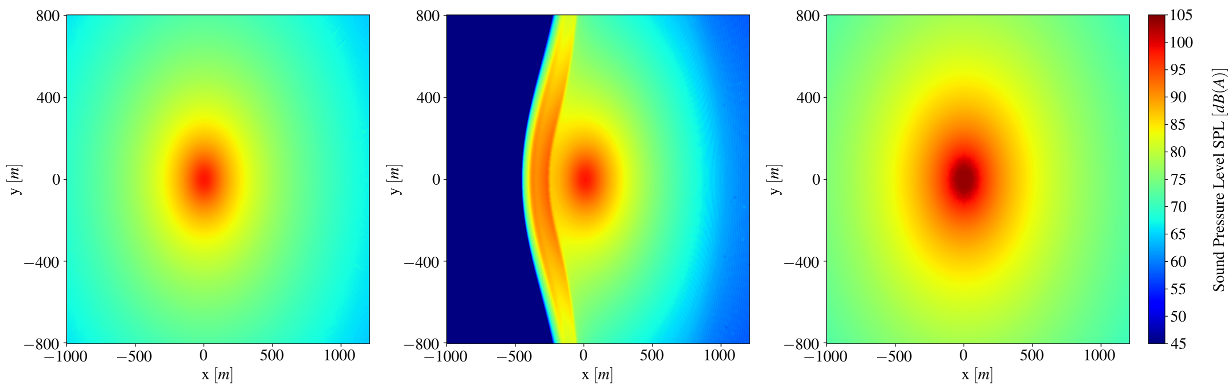


(b) Non-homogeneous windy atmosphere ($dT/dz = 0\,\mathrm{K/km},\ w_s = 15\,\mathrm{m/s},\ w_d = 270\,^{\circ}$).



(c) Homogeneous atmosphere with reflecting ground ($dT/dz = 0\,\mathrm{K/km},\ w_s = 0\,\mathrm{m/s},\ w_d = 0\,^{\circ}$).

Figure 5: Two-dimensional path of sound rays from a coherent point source at an altitude of 80 m for different conditions.



(a) Homogeneous atmosphere with absorbing ground.

(b) Non-homogeneous atmosphere with $dT/dz = 0\,\mathrm{K/km}$, $w_s = 15\,\mathrm{m/s},\ w_d = 270\,^{\circ}$.

(c) Homogeneous atmosphere with reflecting ground.

Figure 6: Sound pressure level on the ground from a coherent point source at an altitude of 80 m for different conditions.

or subtracted from the sound speed. According to the logarithmic wind velocity profile, the horizontal wind speed increases with altitude, resulting in an upward sound curve with a shadow region upwind and a downward curve toward the ground.

Furthermore, on-ground noise footprints are displayed in Fig. 6. The shadow zone caused by the wind is well visible as a dark blue area in Fig. 6b. With a growing distance from the sound source, the sound pressure level is expected to decrease steadily. Nevertheless, a characteristic wavefront can be recognized. The orange graph in Fig. 7 illustrates the sound pressure level evolution from the non-homogeneous windy atmosphere as a function of distance. It can be seen that at a distance of $x = -250\,\mathrm{m}$ (upwind direction), the sound pressure level decreases continuously from $SPL = 98.2\,\mathrm{dB\,(A)}$ to $SPL = 87.0\,\mathrm{dB\,(A)}$. At this point, the sound pressure level rises up again to $SPL = 93.2\,\mathrm{dB\,(A)}$. This phenomenon repeats until the shadow zone appears at a distance of $x = -457\,\mathrm{m}$.

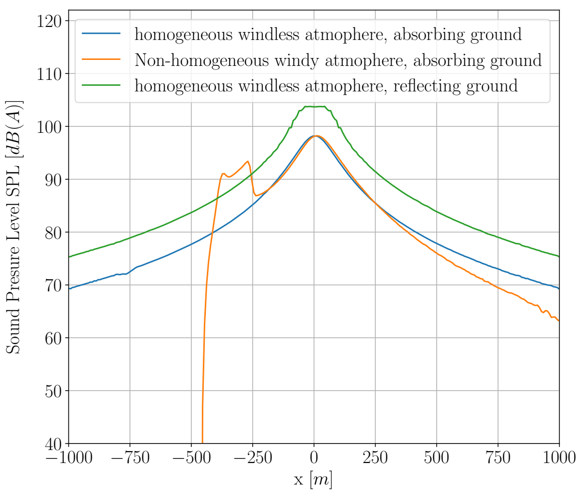


Figure 7: Sound pressure level profile as a function of distance for different conditions for a coherent point source at an altitude of 80 m.

The occurrence of this effect is based on the assumption of interference phenomena. The sound pressure level increase may occur due to contrary interference in the case of coherent sources [20]. In the simulation performed, a coherent point source was used, which radiates in phase. However, an aircraft is an incoherent sound source, so this effect is not expected for aircraft noise.

4.3 Ground effects

A further factor that needs to be considered for the evaluation of aircraft noise is the reflection on the ground.

Fig. 5c visualizes that compared to an absorbing ground, see Fig. 5a, the sound rays are reflected at the ground. Sound reflection leads to a significant increase in sound pressure level, as displayed in Fig. 6c. In this study, the sound pressure level at distance $x = 0\,\mathrm{m}$ increases from $SPL = 98.2\,\mathrm{dB\,(A)}$ for an absorbing ground to $SPL = 103.9\,\mathrm{dB\,(A)}$ for a reflecting ground, as shown in Fig. 7. The sound pressure level deviation at the ground is $\Delta\,SPL = 5.7\,\mathrm{dB(A)}$ at any distance. In theory, with a totally reflecting ground and a coherent sound source, an increase in sound level of $\Delta\,SPL = 6.0\,\mathrm{dB(A)}$ would be expected. Fig. 5c shows that a crossing of a direct incident sound ray with a reflected ray can occur near the ground. At the intersection, the waves of the direct ray and the reflected ray superpose with a path difference, so that the amplitudes at this point amplify. Therefore, the difference of $\Delta\,SPL = 0.3\,\mathrm{dB(A)}$ could be due to the phase shift of the rays.

5. CONCLUSION

Considering the challenges that would emerge with the widespread adoption of UAM, noise impact in urban regions is one of them. This paper addresses the problem of aircraft noise emanating from low-flying aircraft. Existing aircraft noise prediction methods show limitations in including real atmospheric conditions and ground effects.

The meteorological effects on ground noise are investigated with a propagation model based on ray acoustics. The noise footprints on the ground are computed for a standardized atmosphere, as well as for non-homogeneous atmospheres, in the presence of temperature gradients and wind gradients. Besides, different ground effects were taken into account.

The results have shown that a negative temperature gradient causes an upward refraction of the sound rays, whereas a positive temperature gradient induces a downward refraction of the rays. We observed that in the upwind direction of the sound source, the refractive shadow zone appears. Furthermore, we presented that the ground surface has a significant impact on the noise signature. In comparison to an absorbing ground, a reflecting ground shows an increase in sound pressure level about $\Delta\,SPL = 5.7\,\mathrm{dB\,(A)}$. The given investigation demonstrated that various atmospheric conditions have a large impact on the propagation and perception of aircraft noise, and consequently should not be neglected in noise prediction models.

In the present methodology, some limitations have to be recalled. Most UAMs have propeller propulsion, instead of jet propulsion. For the preliminary assessment, a large aircraft with jet propulsion, the A320, is used simply to prove that meteorology has an impact on aircraft noise. However, with respect to small aircraft in the UAM sector, the aircraft design as well as the size of the sound source are different. Consequently, the contribution of sound power and sound perception on the ground will be less for small aircraft. Moreover, the simulated aircraft is assumed to be a coherent point source radiating equally in all directions. The aircraft is held at one point, although it is a dynamic source, changing its altitude and its operating condition with time. Besides, frequency dependencies are not considered in this analysis. All of the mentioned factors have to be considered in a future study. Thus, the present work is only one step toward the inclusion of atmospheric effects in aircraft noise propagation for small aircraft technologies.

6. ACKNOWLEDGMENTS

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