Ground reflection with turbulence induced coherence loss in flyover auralization

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EXECUTIVE SUMMARY

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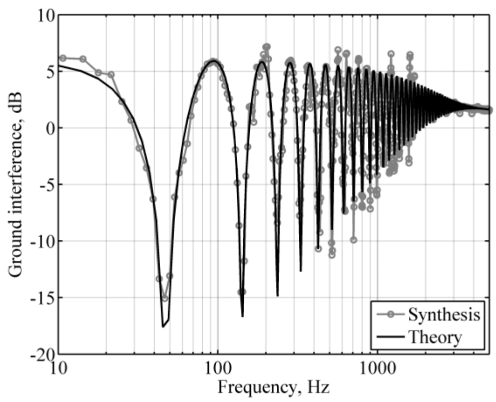

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Knowledge area(s)
Aircraft Noise
Aeroacoustic and Experimental Aerodynamics Research

Descriptor(s)
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Noise propagation
Digital signal processing
Virtual community noise simulator

Problem area

In the case of generating artificial aircraft noise (auralization), the ground interference effect is often exaggerated. This is caused by ignoring coherence loss that is usually induced by atmospheric propagation. Previous research hypothesized a novel method to include this phenomenen. However, that method was still in need of improvement and further validation.

Description of work

The equations from earlier research have been modified. This new method updates the transfer function necessary for the coherence loss and inverse filter as proposed in earlier research. To validate this approach, the developed method was used in a comparison of auralized results to real-life measurements. Besides broadband components, tonal contributions that stem from aircraft engine fans were explicitly studied in light of the possible modulation of these tones by the ground interference.

This report is based on an article published in the International Journal of Aeroacoustics, volume 13, no. 5-6, 2014, pp 449-462.

Results and conclusions

The upgraded method follows the theoretical predictions closer than the previous method. Hence, the improvement of the equations was successful. By comparing the measured result to an auralized result, it was found that the new method brought the auralization more in line with everyday experience. Furthermore, the tonal modulation experienced in auralization of fan tones due to ground interference was reduced. This helps in the perceived realism of auralizations.

Applicability

NLR's virtual acoustic simulator, the 'Virtual Community Noise Simulator' (VCNS) can be immediately equipped with the filters proposed in this study. Since the current method is tailored at real-time computation, it can be used in almost every virtual acoustic simulator. As a result, other research institutions such as NASA (USA) consider implementing this method for their own benefit.

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Content

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Ground reflection with turbulence induced coherence loss in flyover auralization

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ABSTRACT

A method to include the effect of coherence loss due to turbulence is proposed for real-time auralization of aircraft noise. By modifying the direct ray contribution relative to the ground reflected ray, using filters, the coherence loss effect can be included in a propagation scheme. The results of this approach match with the theoretical predictions thereby verifying the ability of the method. Furthermore, the modulation of aircraft tonal components, due to changing ground interference during a flyover, is diminished as a result of the proposed method. Application to an auralization and comparing to a measurement shows that auralizations can benefit from this method. Therefore the current method forms an essential addition to the techniques currently used in the auralization of aircraft noise.

1. INTRODUCTION

Auralization of aircraft noise transforms theoretical predictive calculations of aircraft noise into audible results. Consequently, aircraft that are on the drawing board can be listened too [1]. In potential auralizations can be used as a tool to provide feedback to aircraft designers regarding the acoustic implication of future designs. Besides future aircraft, auralizations are used to simulate current aircraft and provide an audible impression of different departure routes at a specific position within a community [2]. As such, they provide means to predict the changes in an appealing audible way rather than traditional noise contours. Besides aircraft or route related differences, auralizations may aid in explaining day to day differences due to weather [3]. Other applications range from various aircraft types [4] or re-synthesis of measured flyover noise [5].

At the National Aerospace Laboratory (NLR) in the Netherlands, the Virtual Community Noise Simulator (VCNS) is used for presentation of such auralizations. The VCNS was originally constructed by NASA and AuSIM[3] and its models have been in development ever since [6, 7]. The VCNS allows people to experience, in a realistic virtual environment such as their backyard, the audible implications of new procedures, aircraft designs or atmospheric conditions. In the VCNS, the propagation of sound emanating from a source can be executed in a real-time fashion. Therefore, assuming

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[3]http://www.ausim3d.com/, accessed on 27-02-2014

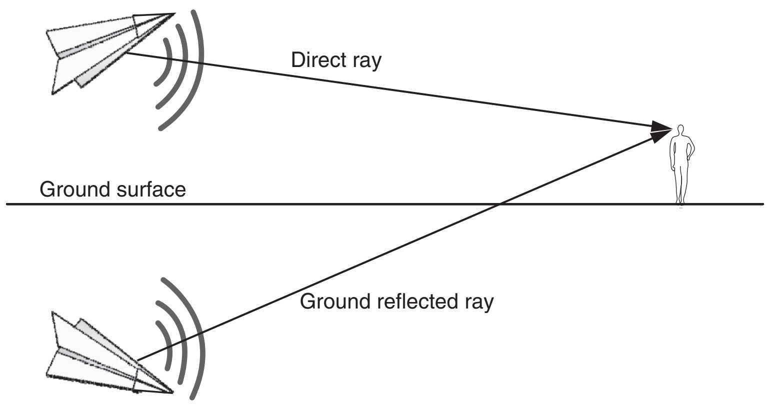

Figure 1: The mirror-source approach mirrors the original source and direct ray in the ground surface.

the source noise remains the same, the trajectory of the aircraft can be adjusted to assess the acoustical implications on the spot. Recent developments in the propagation software include parallelizing the ray tracing algorithm for curved path implementation [8] in order to obtain, in the future, a real-time curved path propagation implementation in the VCNS.

During the auralization efforts it was noted that the correct inclusion of the ground reflection of sound waves is very important for perceived realism. An aircraft noise auralization becomes distinctly recognizable as a flyover if the ground effect is included. In all the aforementioned literature, the mirror-approach is used. The mirror-source approach mirrors the source in the ground surface and adds that contribution to the direct ray path, see Figure 1.

For auralization this means that two waves need to be synthesized (transformed from frequency to time domain) and added at the listener position. Due to the difference in ray path length, the ground reflected wave reaches the observer at a phase offset with respect to the direct wave. This causes an amplitude enhancement or cancellation depending on the phase difference. As the source (aircraft) is moving, the incidence angle and path length is constantly changing, leading to a continuously changing phase difference resulting in the characteristic ground interference pattern.

When including ground interference effects in this way in auralization, in absence of turbulent atmospheric disturbances, the interference pattern is too pronounced which is not experienced (to the best of the authors knowledge) in real flyover situations. This is especially true for hard ground conditions and is caused by the perfect coherence of the direct and ground reflected ray in the simulation.

For instance, one of these side effects is the modulation of tonal noise sources of an aircraft. Due to the ground interference the tone is modulated in amplitude. Especially when the aircraft is flying directly overhead this becomes noticeable and might lead to an improbable representation compared to everyday experience. This effect is reduced in the case of an acoustically soft ground since the amplitude of the ground reflected wave is reduced. In real life this effect is further diminished by coherence loss due to phase disturbances caused by turbulence.

Another audible effect associated with ground reflection was previously reported by the authors in ref. [2]. Due to the ground, an interference pattern was present that provided a “rasping” sound effect. The auralization was compared to measurements that, upon inspection, did not demonstrate this effect. This recording was executed at 10 meters altitude, a common practice for noise monitoring stations, to minimize interference by utilizing the effect of turbulence. Therefore it was hypothesized in ref. [2] that the effect of turbulence on ground interference should be included to minimize this effect.

By including an acoustically soft ground reflection in auralization, these side effects are usually already diminished although not completely gone. Including a soft ground is possible using the approach of Rizzi [9]. To get a closer match to everyday experience, thus eradicating unexpected audible side effects, it is necessary to include the effect of turbulence on ground reflection. In ref. [10], this effect was included by correcting the source spectrum to fill in the interference dips. The resulting very long filter kernel prohibits this approach for inclusion in real-time auralizations. Furthermore, such an approach does not comply with the current doctrine in aircraft noise auralizations where the source, propagation and listener effects are separately treated. Therefore a new method was devised [11] to treat these shortcomings.

The current study updates the equations of ref. [11] to improve the match with theory. Furthermore, including this turbulence effect on ground reflection and the consequences for the aforementioned tonal modulation and rasping sound is studied.

2. THEORY

Turbulence affects both the amplitude and phase of a wave due to phase randomizations. In the literature [12], a comprehensive theoretical foundation of atmospheric inhomogeneities is provided. A pragmatic method was outlined in [13], based on the theoretical foundations of [14, 15], and is briefly explained. For the case of a specular ground reflection (mirror-source as in Figure 1), the Weyl-van der Pol equation [13] forms the starting point,

$$p = \frac{e^{ikr_1}}{r_1} + Q\frac{e^{ikr_2}}{r_2} \tag{1}$$

where, p is the acoustic pressure, k is the wave number, i is the imaginary unit, Q is the ground reflection coefficient and r is the path length and the subscript denotes direct (1) or ground reflected (2) path. The ground reflection coefficient is a complex number for an acoustically soft ground and depends on the incidence angle and surface impedance. Q is calculated by,

$$Q = R_p + \left(1 - R_p\right)F, \qquad R_p = \frac{Z\sin\left(\theta\right) - 1}{Z\sin\left(\theta\right) + 1} \tag{2}$$

where, R_p is the plane-wave reflection coefficient, F is the spherical wave correction factor, Z is the normalized ground impedance and theta is the ray incidence angle with respect to the horizontal. The spherical wave correction factor depends on the ground impedance. The normalized ground impedance is calculated by the model proposed by Delaney & Bazley [16],

$$Z = 1 + 0.0511\left(\frac{f}{\sigma_e}\right)^{-0.75} + i0.0768\left(\frac{f}{\sigma_e}\right)^{-0.73} \tag{3}$$

where, σ_e is the effective flow resistivity and f is the frequency. The spherical correction factor is calculated by [17],

$$F = 1 + iw\sqrt{\pi}e^{-w^2}\operatorname{erfc}\left(-iw\right), \qquad w^2 = ik\frac{r_2\left(\sin\left(\theta\right) + Z^{-1}\right)^2}{2\left(1 + \sin\left(\theta\right)Z^{-1}\right)} \tag{4}$$

where, w is referred to as numerical distance and erfc is the complex complementary mathematical error function.

Equation 1 is derived for a non-moving source. In case of a moving source such as an aircraft, the instantaneous (Doppler shifted) frequency is used in Eq. 1. Such a heuristic modeling methodology is in general valid for low speed sources and compared to a more rigorous analysis in [13].

Equation 1 is the basic propagation paradigm in auralization. Two audio buffer streams are created, i.e. synthesized source sound is generated and mixed together, one for the direct ray and one for the ground reflected ray. Each of these streams has a time-varying gain that accounts for the spherical spreading. A Variable Delay Line (VDL) takes the travel time of the rays into account. As a result of the change in travel time, due to changing ray lengths by a moving source, Doppler shift is invoked. A Finite Impulse Response (FIR) filter takes the absorption into account and is applied after the Doppler shift. More details are included in [2] as well as a graphical representation of the signal processing steps.

The ground interference effect in Eq. 1 is implicitly included by the different path lengths r_1 and r_2. A phase offset occurs when the two waves reach the microphone position since the travel time of the ground reflected ray is always larger than the direct ray. This effect is explicitly apparent when calculating the root-mean-square (rms) version,

$$\left\langle p_e^2 \right\rangle = \frac{1}{r_1^2} + \frac{|Q|^2}{r_2^2} + \frac{2|Q|}{r_1 r_2}\cos\left(k\left(r_2 - r_1\right) + \varphi\right) \tag{5}$$

where $Q = |Q|e^{i\varphi}$ with a phase change φ due to the ground reflection and the ground attenuation $|Q|$. In case of auralizations including an acoustically soft ground, Q is transformed into an FIR filter and applied to the ground reflected path.

Equation 5 shows that the signal at the listener position contains three terms. The first is the direct ray modified by the spherical spreading law. The second term is similar to the first, although modified by the absorption of the amplitude due to the ground. The third term includes the interference effect. The cancellation and reinforcement occurs due to the cosine term depending on the phase. If this factor is taken into account, the sound waves are added in a coherent fashion. If the phase of the rays is affected by turbulence, the coherence between the two signals is diminished. This results in a modification of the interference. To include this effect, Clifford and Lataitis [14] introduced the coherence factor T in Eq. 5,

$$\left\langle p_e^2 \right\rangle = \frac{1}{r_1^2} + \frac{|Q|^2}{r_2^2} + \frac{2|Q|T}{r_1 r_2} \cos\left(k\left(r_2 - r_1\right) + \varphi\right) \tag{6}$$

where, T ranges from zero to one and follows from an extensive analysis assuming that the phase and amplitude fluctuations are Gaussian distributed. As such, the coherence factor T can nullify the interference and is calculated by,

$$T = e^{-\sigma_t^2 (1-\rho)} \tag{7}$$

with,

$$\sigma_t^2 = A\sqrt{\pi}\left\langle \mu^2 \right\rangle k^2 r L_0 \tag{8}$$

and

$$\rho = \frac{\sqrt{\pi} L_0}{2h} \operatorname{erf}\left(\frac{h}{L_0}\right) \tag{9}$$

where, k is the wave number, σ_t^2 is the phase fluctuation variance and ρ is the phase covariance. The phase covariance depends on the maximum path transverse distance h defined by,

$$\frac{1}{h} = \frac{1}{2}\left(\frac{1}{h_s} + \frac{1}{h_r}\right) \tag{10}$$

where the subscripts s, r denote the source and receiver height. Daigle found that half the value for h, as calculated by Eq. 10, provided better results [18], which is therefore applied. The phase fluctuation variance depends on the fluctuating index of refraction $\langle \mu^2 \rangle$ and coefficient A follows as,

$$A = 1/2, \quad d \gg k L_0^2 \tag{11}$$

or,

$$A = 1, \quad d \ll kL_0^2 \tag{12}$$

where, d is the distance from the source to the observer. The fluctuating index of refraction can include both the temperature and wind variations. Although the current model is strictly valid for temperature fluctuations only [13], wind fluctuations and/or different spectra (von Karman instead of Gaussian) could be used [13, 19]. However, the objective of this study is not to re-invent the turbulence model, but to apply the behavior to auralization using a proper method. Therefore we stick to the relative simple Gaussian method.

Since the interference term is included implicitly in auralization, a method was devised to include the effect of (de-)coherence due to turbulence on ground reflection. This is not trivial since transforming T into a filter, and applying it in Eq. 1 to the ground path, would result in an absence of the ground reflected sound in cases when T is zero. In other words, the ground reflected wave would be completely lost instead of added incoherently.

To solve this issue we propose to counterbalance this effect by enhancing the direct wave. Consequently, we need to apply a filter, following a reciprocal behavior of T to the direct wave. The form of this filter must be established from an equation, similar to Eq. 1, of the following form,

$$p = R\frac{e^{ikr_1}}{r_1} + TQ\frac{e^{ikr_2}}{r_2} \tag{13}$$

where, R is a reciprocal filter that should counterbalance the loss of the ground reflected wave should T become zero (high-frequencies, strong turbulence). With respect to our previous approach [11], where $\sqrt{T}$ was used, we now use T. Although the square-root is not entirely wrong, i.e. since the factor T is applied to a term that appeared when calculating the rms, better results are obtained by applying T. Since, in that case, the interference pattern is modified by T rather than $\sqrt{T}$, which is consistent with Eq. 6. Calculating the rms of Eq. 13 yields the following behavior,

$$\left\langle p_e^2 \right\rangle = \frac{R^2}{r_1^2} + \frac{|Q|^2 T^2}{r_2^2} + \frac{2R|Q|T}{r_1 r_2}\cos\left(k\left(r_2 - r_1\right) + \varphi\right) \tag{14}$$

where the difference with Eq. 6 is in the second term and by the inclusion of R in all terms. In our auralization approach the effect of turbulence on ground reflection is included by filter functions. Therefore the gain and time-delay remain unaffected. Consequently, the following equality can be established by comparing the numerators of Eq. 6 and Eq. 14,

$$1+|Q|^2+2|Q|T = R^2+|Q|^2 T^2+2R|Q|T \tag{15}$$

where, the left hand side of the equality is the desired behavior due to the filter terms in Eq. 3 and the right hand side due to the proposed reciprocal approach. R can be solved and yields (retaining the positive root),

$$R = -T|Q| + \sqrt{|Q|^2+2|Q|T+1} \tag{16}$$

Equation 16 is the main result of this study. By using R for the direct ray, it is possible to correct the loss of the incoherent addition when applying T to the ground reflected ray. Due to the fact that T is a relative smooth function, it is possible to use a relatively short filter. Consequently, this method is applicable for real-time implementation in the current virtual acoustic simulators.

3. RESULTS

To verify the method, a test case is considered in which a straight and level aircraft flyover (velocity of 100 m/s at 200 meters altitude) is simulated. Spherical spreading losses and absorption [20] are included (Relative humidity is 80%, temperature is 15 deg. Celsius, pressure is 101.325 kPa). The source is a white-noise signal of 140 dB. The microphone height is 1.8 meter.

Usually, for horizontal propagation, the outer (inertial) scale of turbulence L_0 is assumed to equal the source height or receiver height [13]. It is reported [20] that this value, in case of ground reflection, should range from 1 to 7 meter. A commonly used value is 1.1 m, as deduced from measurements [15]. Therefore, throughout this paper, this parameter is assumed to equal the microphone height. The filters are realized with 128 taps. The ground surface is comparable to roadside dirt (σ_e = 550 kPasm^{-2}) [21], which is not too soft and therefore leads to clear interference patterns, thereby providing an adequate test of the method. A typical fluctuating refractive index $\langle\mu^2\rangle$ range is from $2\cdot10^{-6}$ (weak turbulence) to $1\cdot10^{-4}$ (strong turbulence) [13]. To test the reciprocal filter technique, a medium level of $1\cdot10^{-5}$ is used in this study.

For this case, an example of the transfer functions associated with the individual filters is plotted in Figure 2 for a ray incidence angle of 15 degrees.

Figure 2 illustrates the form of both the transfer function of the coherence function (T) and the reciprocal filter (R). The reciprocal filter transfer function is not allowed to become smaller than unity because it would otherwise eliminate the direct ray contribution. The transfer function of the atmospheric absorption filter has been included in these figures because it is applied to both the direct and ground reflected ray. This does not impact the modeling of the turbulence effect.

The resulting spectrograms of this (pseudo-) flyover, i.e. currently we are ignoring aircraft source spectrum and directivity by assuming white noise, are shown in Figure 3.

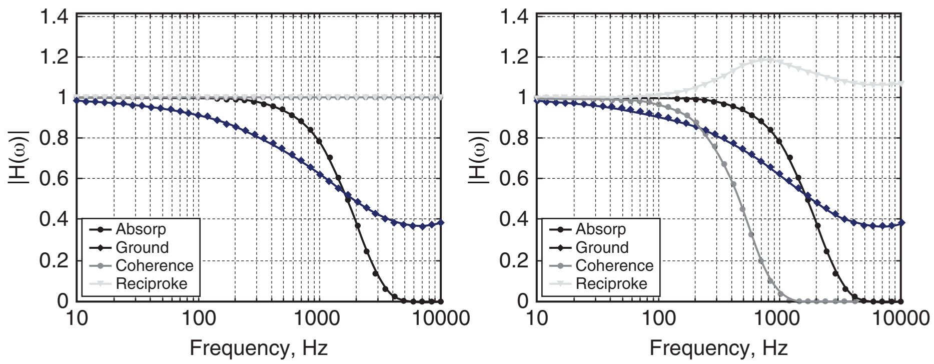

Figure 2: The filter transfer functions for a non-turbulent (left) and turbulent (right) atmosphere. For a non-tubulent atmosphere the coherence and reciprocal transfer functions are equal.

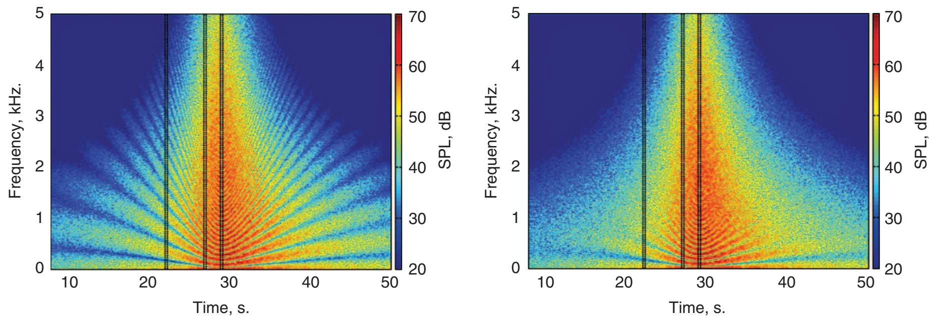

Figure 3: The spectrograms for a non-turbulent (left) and turbulent (right) atmosphere.

The spectrograms in Figure 3 both show the ground interference pattern, although the interference pattern for the non-turbulent case is more pronounced. This is due to the coherent assumption of the interfering rays. In case of a turbulent atmosphere, the ground interference pattern has been removed above 2.5 kHz. The overall effect on flyover noise metrics like $L_{A,\,max}$ and SEL(A) is small, in the order of 0.2 dB(A). However, there are audible differences. This illustrates the importance of modeling small effects (in the absolute dB sense) that add to the overall perception of an auralization. The black lines depict short time intervals (at incidence angles of the direct ray at 15, 45 and 90 degrees) that are further analyzed to assess the proficiency of the current method.

Figure 4 shows the interference patterns at the intervals indicated in Figure 3. The grey results follow from applying the auralization technique with (turbulent) or without (non-turbulent) the proposed reciprocal filter method. The theoretical results (black line) are calculated for the same situation by Eq. 3. The two results match very well and the reciprocal method follows the theoretical behavior closely. Noteworthy is the

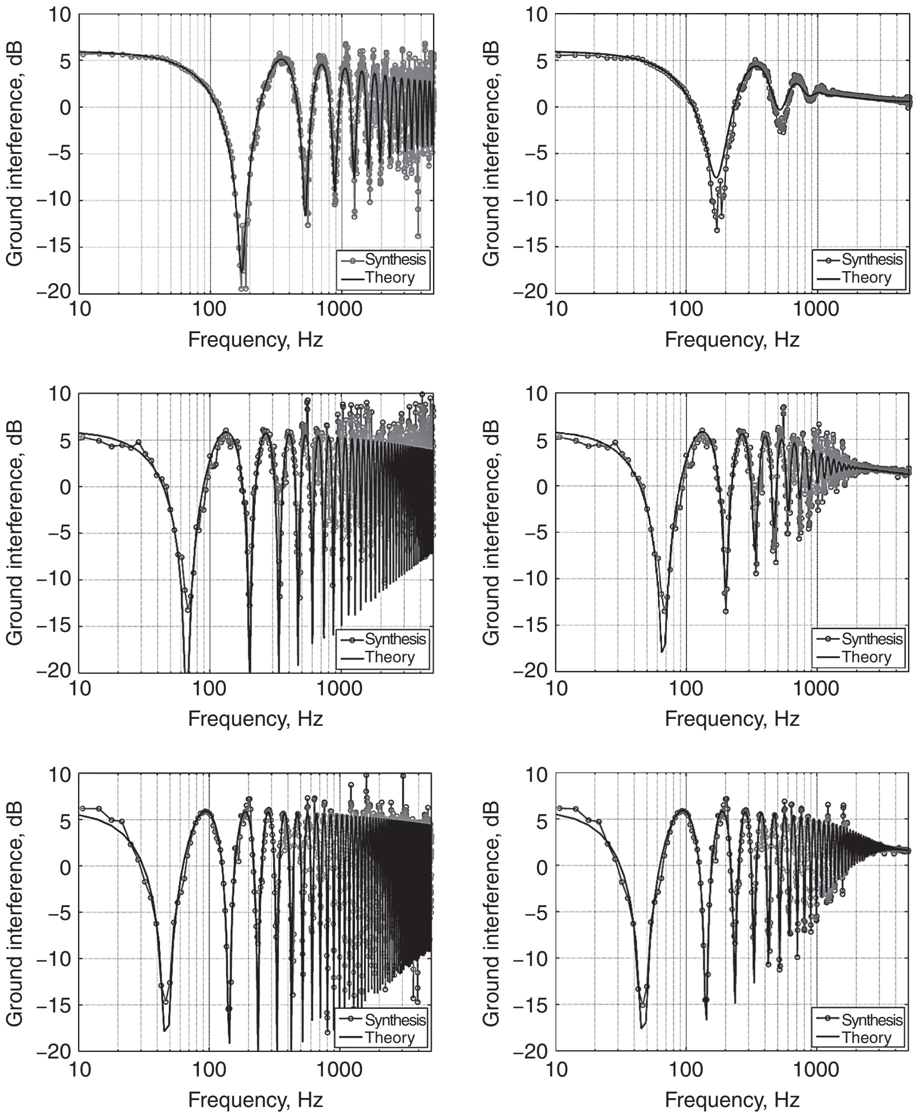

Figure 4: Ground interference pattern at 15 degrees (top row), 45 degrees (middle row) and 90 degrees (bottom row). The left column contains non-turbulent atmosphere results; the right column contains the turbulent results.

incoherent addition present at higher frequencies at 45 and 90 degrees in case of the turbulent atmosphere. The obtained results are slightly better than those presented by the equations in [11] due to the renewed formulation of Eqns. 13 through 16.

The proposed method is used to evaluate if the mentioned artifacts (tonal modulation and rasping sound) are positively affected. By simulating the same flyover, using a

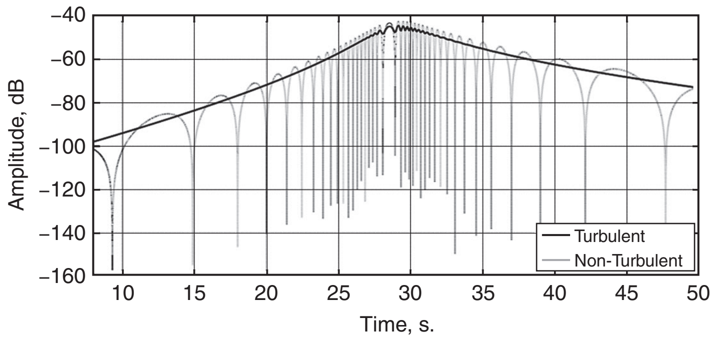

Figure 5: Amplitude attenuation of a 2000 Hz tone in the simulated turbulent and non-turbulent conditions.

single source tone of 2000 Hz, results of the proposed methodology on tones are assessed. The ground surface is changed to simulate an acoustically hard reflection to maximize the ground interference modulation. By applying a Hilbert transform to the auralized waveform, constructing an "analytic signal" [22, 23], the amplitude and frequency modulation are tracked. The amplitude shows, in Figure 5, the combined effect of spreading, absorption and ground interference.

From Figure 5, it is deduced that the amplitude modulation of the tone at the listener is strong in the case without turbulence, especially near the time of the flyover (25–32 s). The amplitude can easily vary 60 dB within a few seconds, which is clearly audible. Notice that the amplitude is not symmetric around the time of the aircraft passage (28 s), because the Doppler shift has lowered the perceived frequency at the listener. Due to the effective lower frequency of the tone, the atmospheric absorption has decreased leading to higher amplitudes. In case of turbulent atmospheric conditions, the incoherent addition of roughly 3 dB due to the ground is noticeable throughout the entire flyover. Only during the passage of the aircraft directly overhead, i.e. short propagation distance, some of the coherent addition remains.

The signal resulting from the simulation including the effect of turbulence on ground reflection is more in line with real-life experiences of flyover noise. In aircraft flyovers and auralizations, the tonal modulation is often masked by the broadband content of the signal. However, in case of auralizations utilizing a hard ground reflection, the tonal modulation can still be noticed, despite the broadband content, if the effect of turbulence on ground reflection is not included. Therefore the proposed method is attractive since it offers a way to limit this effect based on physical arguments and models.

In ref. [2], a rasping sound due to the ground interference effect was audible. It was hypothesized that this was due to the absence of turbulence. We are now able to revisit that hypothesis and see if the proposed method improves the audible effect. To that end, the analysis in ref. [2] is repeated for flight number two of that study. That flight is a departing Boeing 747–400 from Amsterdam Airport Schiphol, which was auralized and compared to measurements of a noise monitoring station to validate our auralization capabilities. Although the radar tracks were available, weather information was limited.

The variance in temperature or wind were not available during those measurements, therefore a turbulence level has to be assumed. Consequently, the same value ($\langle \mu^2 \rangle = 1 \cdot 10^{-5}$) is used. Regarding the outer scale of turbulence, the microphone height was used but limited at 7 meters, i.e. the maximum as indicated in ref. [20]. Hence, our results are only suited for a qualitative comparison to validate our hypothesis if the rasping sound in the auralization was caused by the absence of this turbulence effect.

Figure 6 shows the results of the simulations without turbulence and with turbulence and compared to the measured result at the noise monitoring station. It should be noted that an anti-aliasing filter was used in the measured recording to lower the sampling rate

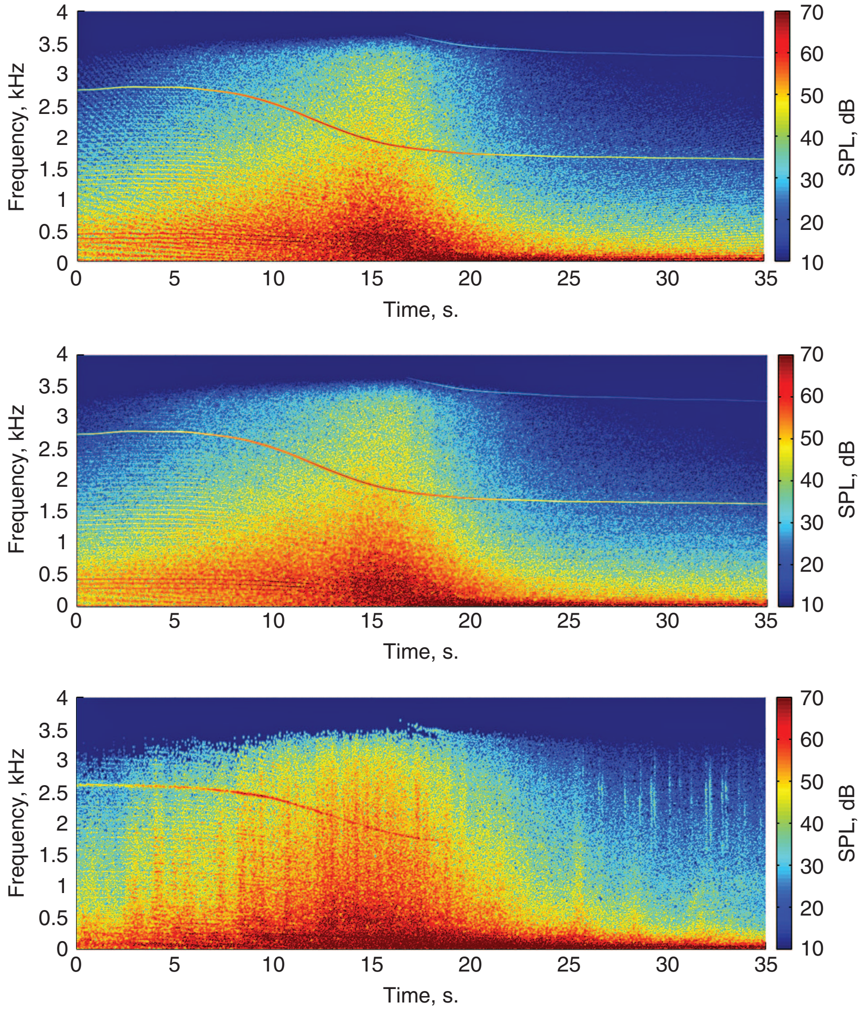

Figure 6: Original auralization (top), modified ground reflection due to turbulence (middle) and measured result at a noise monitoring station (bottom).

to limit the memory of the stored recordings. Therefore a similar filter has been used to the modeled results with a cut-off frequency of 3400 Hz.

It is observed that the ground interference pattern is diminished when the turbulence is included and, consequently, matches the measured result a lot better. When listening to the results it is noted that the rasping sound has disappeared. This confirms our hypothesis regarding the importance of including the effect of turbulence on ground reflection in auralizations.

4. CONCLUSION

Auralization of aircraft noise strives to transform predictive calculations into audible results. The virtual acoustic simulator environments at different research establishments allow doing this in a real-time fashion. Use is made of empirical aircraft source noise prediction and basic atmospheric propagation to allow a very computational efficient implementation. This permits control of parameters in a laboratory environment and therefore to study the relation between aircraft procedure and atmosphere on the perceived noise on the ground.

The propagation algorithms apply spherical spreading, atmospheric absorption and ground interference in the time domain. These effects are easily modeled in real-time fashion, but including the effects of turbulence in auralization remains an open topic. In literature, turbulence is reported to affect the coherence between the direct and ground reflected ray. However, some shortcomings in auralization can be identified if turbulence on ground reflection is not included. Therefore a novel method is proposed that includes this effect with a relative short filter implementation.

The method performs well and follows the theoretical predictions closely. In case of auralizing strong tonal components of the aircraft, the ground interference pattern may cause a modulation of the tonal amplitude that does not comply with common experience of flyover noise. The current method leads to an incoherent addition thereby diminishing the modulation. Furthermore, when comparing results from a noise control monitoring station to auralizations, an audible difference was noted which was believed to be caused by the absence of turbulence in the simulation. By using the current method for inclusion of the effect of turbulence on ground reflection, this audible difference has been resolved.

Consequently, the proposed method forms an essential addition to modeling the behavior of ground interference in auralizations. Further research should be conducted to include the effect of amplitude fluctuations due to turbulence or gusts. This could further enhance the perceived realism and therefore the acceptance of (aircraft) noise auralizations.

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