Modeling of ground reflection effects in aircraft flyover noise synthesis

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EXECUTIVE SUMMARY

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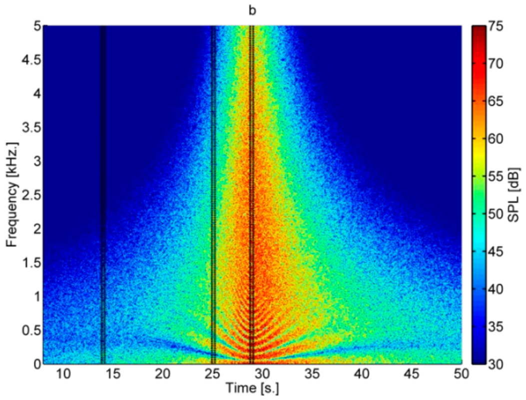

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Knowledge area(s)
Aircraft Noise
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Descriptor(s)
Turbulence induced coherence loss
Ground reflection
Reciprocal filter approach
Virtual community noise simulator

Problem area

In the case of generating artificial aircraft noise, also called aircraft noise synthesis, the ground interference effect is often simulated by plane wave reflection coefficients. Furthermore, the effect of turbulence on ground interference is usually ignored. Both assumptions might lead to unrealistic simulations compared to real-life situations and were therefore the subject of the current study.

Description of work

Differences between the plane and spherical wave reflection coefficient were calculated using well established equations. Furthermore, a novel method to include the effects of turbulence induced coherence loss is proposed. This novel method diminishes the ground reflected ray contribution by adopting a frequency dependent coherence loss filter. This mimics the effect of turbulence under real atmospheric conditions. However, a trivial implementation of this effect would neglect the incoherent addition of the direct and ground reflected ray. Hence, the proposed correction methodology includes this effect as well. To

This report is based on a presentation held at the Noisecon conference, Denver (CO), USA, 26-28 August 2013.

that end, equations, describing the filter characteristics, have been derived.

Results and conclusions

Differences due to a plane and spherical wave ground reflection coefficient could be noticed, especially for grazing incidence angles and low frequencies. Furthermore, the proposed method to include turbulence induced coherence loss in flyover noise synthesis works relatively well. Since short filters can be used, the proposed method is able to be integrated in real-time applications. However, some deviations with respect to the theoretical results can still be noticed.

Applicability

NLR's virtual acoustic simulator, the 'Virtual Community Noise Simulator' (VCNS) can be immediately equipped with the new filters. However, further research should be executed into the actual benefit of this method by comparing to real-life measurements.

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Content

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Modeling of Ground Reflection Effects in Aircraft Flyover Noise Synthesis

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ABSTRACT

During the flyover of aircraft, the perceived sound at a receiver position is modified by the ground. This causes a specific ground interference pattern in the sound spectrum at the receiver. During an aircraft flyover the sound angle of incidence is constantly changing and therefore a characteristic ground interference pattern emerges. This interference pattern results from coherent addition of the direct and ground reflected contribution. The contribution of the ground reflection is frequently based on a calculation employing a plane-wave assumption. This method is extended to incorporate the effects of a spherical-wave front and differences between the two assumptions are demonstrated. Another effect on ground reflection is due to turbulence. Turbulence destroys the coherence between the two contributions. A method to incorporate these effects, based on a reciprocal filter of the coherence loss applied to the direct ray path, is studied and demonstrated. The results imply that the suggested method works well for plane-wave front reflection coefficients. For spherical-wave fronts the results tend to diverge a bit more from the theoretical prediction. In general, the method is able to incorporate the turbulence coherence loss effects and provides reasonable results that can be adapted easily in current aircraft noise synthesis simulations.

1. INTRODUCTION

Modeling of the ground interference effect is included in most of the virtual acoustic simulators [1, 2]. Due to a difference in travel time, caused by the additional path length of the ground reflected contribution, constructive and destructive interference can occur. This is due to sound waves reaching the microphone perfectly in-phase or out-off phase. In the case of in-phase arrival, a theoretical 6 dB amplification occurs whereas for out-off phase conditions complete cancellation of sound is predicted. This ground reflection effect makes a perceptual difference in the flyover noise experience.

The most common inclusion is based on an acoustically "hard" reflection, i.e. all the sound energy is reflected specular without a phase change. Soft reflections, i.e. including sound attenuation and phase change, are also possible using a plane-wave assumption [3]. From literature it is well known that under certain conditions spherical-wave fronts interact differently with the ground [4]. Consequently, additional contributions from surface and ground waves can occur. Therefore this study tests the inclusion of spherical wave fronts for a "soft ground", using the method employed in [3], and compares the results to the regular plane-wave assumption.

Turbulence is known to have adverse effects on the coherence of the ground reflected sound. Due to coherence loss the ground interference effect will not be as pronounced as for a non-turbulent atmosphere [4]. The net effect is that the cancellation minima and maxima are not as pronounced, as was also found in [5]. Their analysis did not use a separate modeling of source sound effects and ground reflection. They updated the source noise prediction to counterbalance the effects of the coherence loss. In [6] the ground reflection was modeled based on measurements thereby ignoring the possible use of the theoretical models. Using measurements is likely to inherently include, to some extent, turbulent coherence loss.

In virtual acoustic simulation, the Variable Delay Line (VDL) is used to simulate the phase interference effect. There is also a distinction between propagation and synthesis of sound in that both effects are treated separately. The solution to counterbalance propagation effects at the synthesis stage is undesirable for our flyover noise synthesis framework [7] since this is based on the separate treatment of both. A method to include the turbulence loss is therefore proposed that allows including the coherence loss effect without having to precondition the synthesis stage.

2. MODELLING APROACH

The ground effect is usually calculated by adding the two contributions, i.e. direct and ground, as separate waves according to:

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

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 distance and the subscript denotes direct *(1)* or ground *(2)* path. The denominator factors incorporate the spherical spreading loss of a monopole sound wave. In equation 1, the second term refers to the ground reflected contribution. Please note that the notation of equation 1 assumes unit amplitudes for both sound waves.
In aircraft noise synthesis, equation 1 is applied through the separate modeling of a direct and ground reflected contribution. Each contribution undergoes spherical spreading losses by a gain, sound wave travel time by VDL processing and atmospheric absorption through a Finite Impulse Response (FIR) filter. The atmospheric absorption filter applied for the ground reflected contribution is convolved with a filter based on the ground reflection coefficient. This was first exercised in [3].

To evaluate sound intensity in the frequency domain, use is made of the effective pressure instead of the wave amplitude. The effective pressure is established as the root-mean-square (rms) of the acoustic pressure. The mean-squared (effective) pressure (p_e) equates to [4]:

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

where, $Q = |Q|e^{i\varphi}$, φ is the phase change due to the ground reflection and the denominator terms incorporate the spherical spreading effect. The first two terms in equation 2 emanate to the incoherent addition of two effective pressures. The second term is however incorporating the ground absorption effect based on the magnitude of the ground reflection coefficient. The third term adds the contribution due to the phase change in ground constitution and path length, i.e. $r_2 - r_1$. Applying the third term together with the first two describes the coherent addition of two sound waves on an effective pressure basis. In equation 2 it is again assumed that the effective pressure of both contributions is of unitary magnitude. This assumption effectively ignores the traditional inverse $\sqrt{2}$ contribution when calculating the rms. value based on sound wave amplitude. The ground reflection coefficient, of both equation 1 and 2, can be calculated by:

$$R_p = \frac{Z\,sin(\theta)-1}{Z\,sin(\theta)+1}, \tag{3}$$

$$Q = R_p + (1 - R_p)F, \tag{4}$$

where, R_p is the plane-wave reflection coefficient, Z is the normalized ground impedance, θ is the ray incidence angle with respect to the horizontal and F is the spherical wave correction factor. If a plane-wave reflection is assumed, as frequently done in aircraft noise synthesis, the spherical correction factor is zero. From equation 4 it can be deduced that due to the spherical correction factor an additional sound reflection effect is simulated, these form the aforementioned surface and ground wave contribution. This factor is dependent on the ground constitution modeled by the normalized ground impedance which is calculated by the model by Delaney & Bazley [8] as:

$$Z = 1 + 0.0511\left(\frac{f}{\sigma_e}\right)^{-0.75} + i\,0.0768\left(\frac{f}{\sigma_e}\right)^{-0.73}, \tag{5}$$

where, f is the frequency and σ_e is the effective flow resistivity. The simplicity of this model, i.e. the impedance only depends on one-parameter, made it popular. Other models exist and can be used although that is not the focus of the current investigation. With the impedance available, the spherical correction factor is given by [9]:

$$F = 1 + iw\sqrt{\pi}\, e^{-w^2} \mathrm{erfc}\,(-iw), \tag{6}$$

$$w^2 = ik\frac{r_2}{2}\frac{(sin(\theta)+Z^{-1})^2}{1+sin(\theta)Z^{-1}}, \tag{7}$$

where, w is referred to as numerical distance and erfc is the complex complementary mathematical error function. This error function is a standardized mathematical function and can be found in mathematical reference books [10] or is also outlined in acoustics books [4]. Equations 3-7 describe the calculation of the spherical-wave front correction as used in the current study.

The aforementioned effect of coherence loss of the ground reflected contribution due to turbulence is integrated, based on equation 2, by [4]:

$$\langle {p_e}^2 \rangle = \frac{1}{{r_1}^2} + \frac{|Q|^2}{{r_2}^2} + \frac{2|Q|}{r_1 r_2} cos(k(r_2 - r_1) + \varphi)C, \tag{8}$$

where, the factor C models the coherence loss due to turbulence and forms the only difference compared to equation 2. This coherence loss factor ranges from 1 (low frequency) through 0 (high frequency) depending on the turbulence characteristics. This variable can effectively nullify the interference effect. Different methods to calculate C exist, here we follow the method outlined in [4], i.e.:

$$C = e^{-\sigma_t(1-\rho)}, \tag{9}$$

$$\sigma_t = A\sqrt{\pi}\langle\mu^2\rangle k^2 r L_0, \tag{10}$$

$$\rho = \frac{\sqrt{\pi}L_0}{2h}\,\mathrm{erf}\left(\frac{h}{L_0}\right), \tag{11}$$

where, k is the wave number, C is modeled for a Gaussian turbulence spectrum having a phase fluctuation variance σ_t and a phase covariance ρ. The phase fluctuation variance depends on the fluctuating index of refraction $\langle\mu^2\rangle$, coefficient A depending on the distance and frequency, distance r, and the outer scale of the turbulence spectrum L_0. The phase covariance depends furthermore on the maximum path transverse distance h and the mathematical error function erf. Not all equations to establish all coefficients of equation 10 and 11 are described explicitly here for the sake of brevity. Interested readers are referred to the excellent book [4] from which this method was adopted.

Although different turbulence spectral models exist (v. Karman and Kolmogorov), the current Gaussian approach is used to study the ability to include these effects in aircraft flyover noise synthesis. A filter, based on the coherence function, is applied to the VDL processed signal to include this effect. This trivial implementation ignores the second term in equation 8 if, due to turbulence, the coherence factor becomes zero at a particular frequency. This term is important since it adds the ground reflected signal in an incoherent fashion and therefore cannot be excluded. Realizing that a frequency dependent incoherent addition is desired, the idea is hypothesized to apply a reciprocal filter (reciprocal of C) to the direct path that counterbalances the exclusion of the second term in equation 8. Therefore we apply a principle similar to equation 1:

$$p = R\frac{e^{ikr_1}}{r_1} + \sqrt{C}Q\frac{e^{ikr_2}}{r_2}, \tag{12}$$

where, R is the reciprocal filter of the coherence contribution $\sqrt{C}$. The square root stems from the fact that the definition in equation 8 is on a mean square basis. This equation forms the modified basis for calculating the propagation effects in aircraft flyover noise synthesis. The processing of the spherical spreading (gain) and path length difference (time difference for VDL) are unaffected by this modification. The difference stems from the application of filters, dictated by R and $\sqrt{C}$, to mimic the behavior of equation 8. Therefore, a comparison between the desired and actual filter behavior, ignoring gain and VDL terms in equation 12, is established as:

$$1 + |Q|^2 + 2|Q|C = R^2 + |Q|^2C + 2|Q|R\sqrt{C}, \tag{13}$$

where, the left hand contain the desired filter terms from equation 8 and the right hand side the actual mean square filter terms if calculated by equation 12. Calculating R is executed through solving for a quadratic root of R and keeping the positive solution, which results in:

$$R = -\sqrt{C}|Q| + \sqrt{1 + |Q|^2 + 2|Q|C} \tag{14}$$

By applying R (using an FIR filter) to the direct path sound, the total exclusion of the ground reflection effect through a filter based $\sqrt{C}$ is corrected. The incoherent addition of the first and second term of equation 7 is retained whereas the interference effect is diminished by turbulence. Equation 14 is the main result of this study and forms a way to include the turbulence induced coherence loss on ground reflection.

3. APPLICATION RESULTS & DISCUSSION

In aircraft noise synthesis the broadband component is usually based on white noise. To examine the functioning of the proposed calculations, raw white noise is used as a test input signal. The aircraft is flying at 500 meters altitude at 100 m/s and is directly overhead after 30 seconds. Spherical spreading losses and absorption [11] are included (80% Rel. Hum., 15 deg. C, 1013.25 hPa). The microphone height used is 1.8 meters.

To demonstrate the difference between the plane- or spherical-wave assumption, the ground interference is calculated (equation 2) for three incidence angles using an acoustic "soft" ground. A value of 25 kPa·s·m^{-2} is used for the effective flow resistivity in equation 5 to simulate a snowy ground surface. Using a "soft" surface allows evaluation of plane- and spherical-wave front differences since the effect of ground and surface waves is more prominent. Figure 1 shows the results for both the plane- and spherical-wave reflection coefficient.

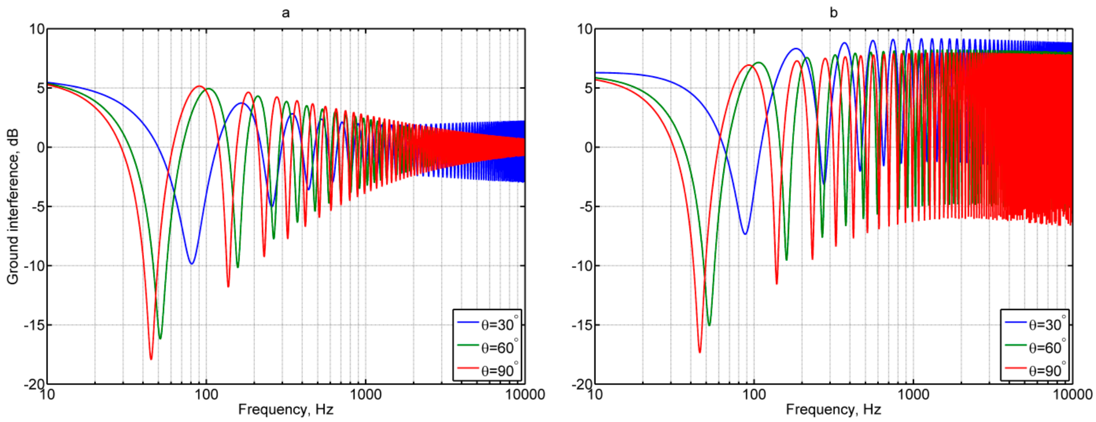

Figure 1: (a) The theoretical ground interference assuming a plane-wave reflection coefficient. (b) The ground interference, similar to the conditoins of (a) but utilizing a spherical-wave reflection coefficient.

From Figure 1 it becomes clear that the plane-wave reflection coefficient predicts a different behavior than the spherical-wave assumption. Especially at the high frequencies the plane-wave coefficient seems to diminish the interference effects whereas this does not occur for the spherical-wave assumption. Furthermore, the constructive interference is higher than 6 dB for the spherical assumption due to additional surface and ground waves. For a "hard" reflection surface (asphalt) the interference patterns are more alike. The differences in the spectrograms, after processing the white noise using the VDL, gains and filters, thereby mimicking the aircraft noise synthesis process, are shown in Figure 2. This is for the same "soft" surface constituency as Figure 1.

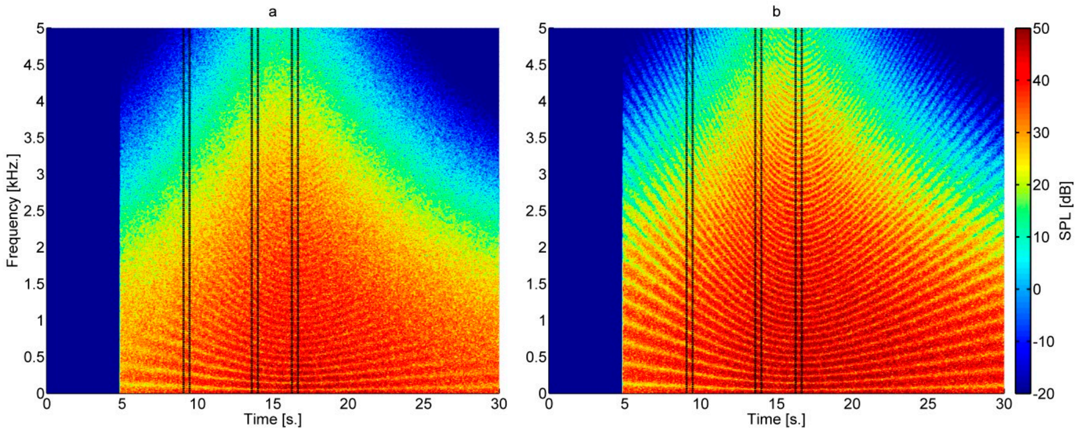

Figure 2: (a) Spectrogram using the plane-wave assumption. (b) Similar conditions as (a) but utilizing a spherical-wave reflection coefficient. The black lines in both spectrograms refer to a time instant where the incidence angles are roughly 30, 60 and 90 degrees, i.e. equal to the conditions in Figure 1.

The first five seconds of the spectrograms in Figure 2 there is no sound due to absolute delay of the sound towards the receiver. The areas in between the black lines of Figure 2 refer to the angles employed for the interference patterns of Figure 1. If the interference pattern of the synthesized noise would be analyzed at these specific incidence angles, the same patterns as the theoretical results of Figure 1 appear. The only small difference is that the interference patterns of the synthesized results are not as deep as predicted by equation 2. This can be explained by the fact that the theoretical results hold for single-frequency sound whereas broadband sound is simulated. Furthermore, the finite amount of samples used to feed the FFT has a small influence as well since a varying interference pattern is still present in this small time frame.

The fluctuating refractive index $\langle\mu^2\rangle$ can range from $2\cdot10^{-6}$ (weak turbulence) to $1\cdot10^{-4}$ (strong turbulence) [4]. To test the reciprocal filter technique a medium level of $3.9\cdot10^{-5}$ is used in this study. The transfer functions, used to establish the filters, are shown in Figure 3.

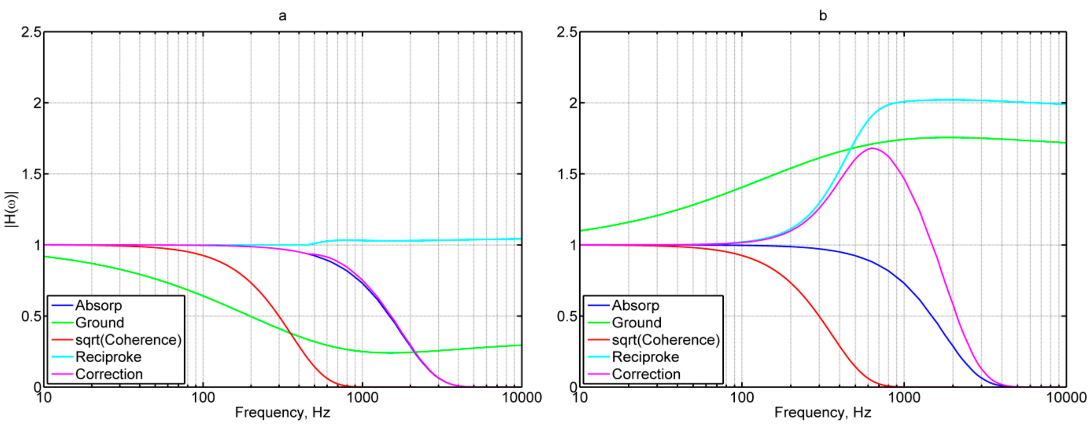

Figure 3: (a) The transfer functions using the plane-wave assumption, (b) shows the same transfer function but uses a spherical-wave reflection coefficient. Both figures are for an incidence angle of 30 degrees.

Figure 3-a shows the transfer functions for five different filters. The reciprocal transfer function (cyan) is calculated by equation 14. The magnitude of this transfer function value is limited to not become smaller than 1, otherwise it would dampen the direct ray contribution. The correction (magenta) transfer function corresponds to the convolution of the reciprocal and absorption transfer function. The resulting spectrograms, after applying the reciprocal filtering approach, are shown in Figure 4.

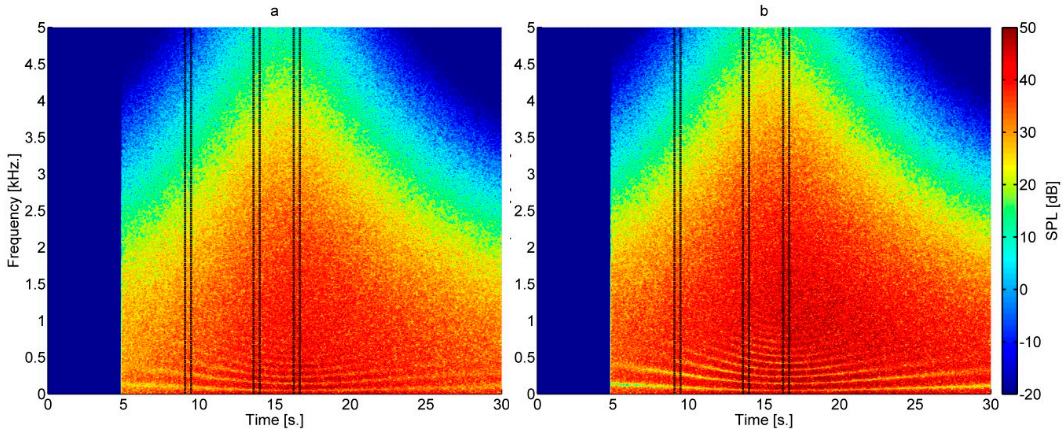

Figure 4: The resulting spectrogram including turbulence for a plane-wave reflection coefficient (a) and a spherical-wave reflection coefficient (b). The black lines denote samples used in the FFT analysis of Figures 5-7.

Comparing Figure 4 with Figure 2 shows the differences that can be expected when including the effect of coherence loss due to turbulence. The ground interference pattern is severely reduced and results in an audible difference. To compare the results of applying the reciprocal approach of equation 14 in synthesis to equation 8, an FFT at the aforementioned incidence angles is analyzed. Figures 5-7 shows the results for both the reciprocal approach as used in synthesis (blue) to theoretical results (green) obtained by equation 8.

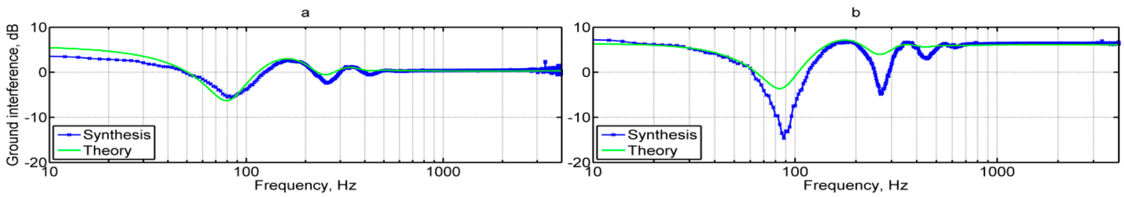

Figure 5: Results at an incidence angle of 30 degrees for a plane (a) and a spherical-wave (b) reflection coefficient.

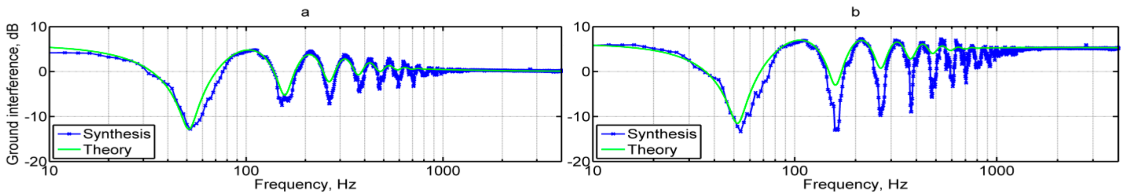

Figure 6: Results at an incidence angle of 60 degrees for a plane (a) and a spherical-wave (b) reflection coefficient.

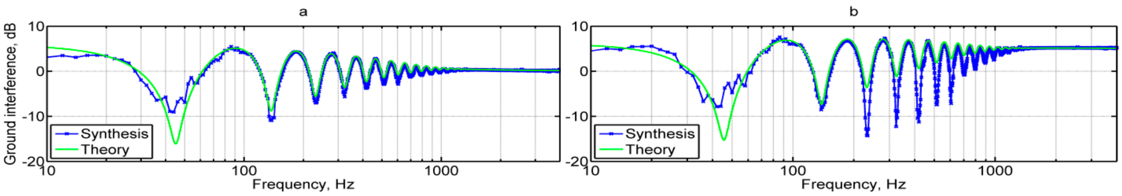

Figure 7: Results at an incidence angle of 90 degrees for a plane (a) and a spherical-wave (b) reflection coefficient.

From Figures 5-7 it seems that the theoretical results are followed more closely for the plane-wave assumption. If differences between theory and synthesized results appear, the reciprocal method (as applied in the synthesis) appears to over predict the interference pattern. For both assumptions the fidelity of the reciprocal method improves with increasing incidence angle.

The general improvement with increasing incidence angle is found at other turbulence strengths and ground constitutions as well. When effects of spherical-wave ground reflection and turbulence becomes less, the reciprocal correction method results improve. Further analysis is necessary to evaluate if the method can be improved and where differences stem from.

4. CONCLUSIONS

Improvements in the modeling of ground reflection in virtual acoustic simulations, applied to flyover noise synthesis, have been proposed. Assuming spherical-wave fronts instead of plane-wave fronts will affect the ground reflection for acoustically “soft” ground. These interference effects are weakened by coherence loss due to turbulence and a method is proposed to include this effect. The proposed method provides adequate results for plane-wave fronts, for spherical-wave fronts the methods results become slightly worse.

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