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The wind turbine sound amplifying forest

Elis Johansson and Martin Almgren
ÅF, P.O. Box 1551, SE 401 51 Gothenburg, Sweden
Elis.johansson@afconsult.com and martin.almgren@afconsult.com

Abstract

In the future, more wind turbines may be located in forest terrain. Sound from wind turbines located in open terrain has been under study by many researchers and models for determining the noise level of receivers at different distances exist. But sounds from wind turbines located in forest terrain is a rather new field, which haven't been under study in the same extent. After measurements performed in Sweden (Almgren et al WTN 2009 see [1]) of a wind turbine located in forest terrain it was discovered that the sound level measured inside the forest was higher than expected. The uncertainty of the cause of why the calculated level was lower than the measured level created the need for this investigation. Various hypotheses have been compiled which may explain a possible increase of the sound pressure level inside the forest. Promising hypotheses is the reverberation in the forest, refraction from local climate, scatter effect from the tree trunks that contribute to the reverberation but also reduces the attenuation of the ground effect.

Measurements were made at different times, places and meteorological conditions. The main measured parameters are: reverberation for different distances in the forest, the attenuation of noise for different distances in the forest, wind speed and temperature at different heights of the forest, the trees in average diameter, number of trees per hectare and humidity of the air inside the forest. A calculation method has been developed and compared with measured data. The calculation method has integrated a model used within room acoustics to combine the reverberation with sound pressure level in the forest. Thus, the forest has been regarded as a room. Its weakness is that it's difficult to determine the dimensions of the "forest room". A scale factor has been used to model forest room volume. Results from this comparison show that the reverberation is in relatively good agreement with the calculated reverberation time based on the volume multiplied by the square of the measurement distance.

The calculation model C.N.P.E. (Crank Nicholson Parabolic Equation) has been used to calculate the sound pressure level with distance under the action of refraction created by wind and temperature gradients with height.

Introduction

Sound from wind turbines can be perceived as annoying and may lead to a deterioration of the living environment and the quality of life for people exposed by the noise. It is therefore important to ensure a good sound environment in the process of environmental permission of new wind turbines. Homes are rarely settled inside the forest, but sometimes a target value of 35 dBA for the sound level is set in quiet outdoor areas. In recent years there have been discussions about the establishment of wind turbines in forests. The knowledge on how a forest reduces and scatters the sound is important in the establishment of new wind turbines in a forest terrain. An increasing number of wind turbines are planned to be located in forests in Sweden. The Swedish company Vattenfall has built two wind turbines at Ryningsnäs, close to Hultsfred in Småland. They have been built in connection to a wind measuring mast. The purpose of these turbines was to gain sufficient experiences of wind turbines in forests in order to establish larger wind turbine projects more efficiently [2].

In a Swedish research program called “Vindforsk”, the company ÅF-Ingemansson (Gothenburg, Sweden) measured the sound from a wind turbine in a forest terrain. The measurements were made inside the forest; see [1]. Both sound emission (sound power level, L_W) from the wind turbine and the sound immission (sound pressure level, SPL or L_p) inside the forest were measured. The measurements were compared with predictions of the noise level by commonly used calculation models e.g. Nord2000 (a Nordic propagation model for outdoor sound), but without taking the forest into account. It was discovered that the sound immission in the forest was 1 to 2 dB higher than expected from calculations. A conclusion was that the available calculation models do not predict the sound immission in the forest correctly and further investigation needs to be done. The exact reason for the difference between the calculation model and measurements is not fully known. However, various hypotheses exist trying to explain the higher levels of sound immission in the forest. Two examples of possible hypotheses are the reverberation in the forest and due to strengthened wind and temperature gradient with height in the canopy. The measurements presented in this paper are made in coniferous forests, which is the common forest type in Sweden.

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Sound propagation in forest

The sound propagation in forest is complex and influenced by many factors. The general factors of outdoor sound propagation are attenuation due to geometrical divergence, wind and temperature changing the speed of sound, air absorption, absorptive properties within ground. Special factors for forests are absorption by vegetation, changed wind and temperature profile, and scattering-/ and reflective properties due to the forest geometry, shape (age) and tree type.

Changed wind profile in forest

Just above the canopy in forests the air can be turbulent causing large deviations in the wind speed. Inside the forest it is often calm and the wind speed is dramatically decreased to find a speed which is much lower compared with open field at same height.

Swearingen and White calculated the wind velocity profile for open field and forest, using a model by Heimann [3] and compared them in a figure. This figure is an example of differences between wind speed at open field and in forests can be seen in Figure 1 [4 p. 4].

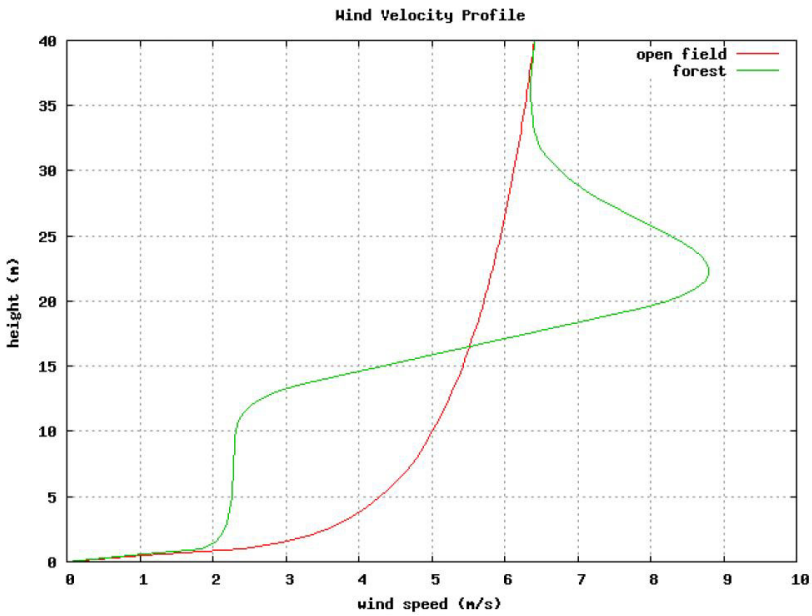

Figure 1. Wind profile over open field and forest, by Swearingen & White [4]

In figure 1 it can be seen that the wind velocity for the open field has a logarithmic shape, but the wind velocity inside the forest has a more varying shape. In [4] it is stated that the condition for this calculation is that the canopy starts at 10 m height, seen from the ground, and making the total tree height of 15m. In figure 1 the canopy is exposed to a rapidly increasing wind velocity between 2.4-4.4 m/s. The wind velocity increases even more above the canopy, ranging from 4.4 to 8.7m/s. At 40m height the open field and the forest reaches the same value. The differences can be regarded as two layers, one below the canopy and one above. The difference will probably cause downward refraction, i.e. sound reaching the forest will undergo refraction and the sound intensity will be increased close to the ground.

Changed temperature profile in the forest

The temperature in the forest may have a large vertical variation, which is usually different from the case of open field. Surfaces directly exposed by the sun are heated faster compared with the surfaces lying in the shade. Temperature differences want to be compensated but the process will be delayed, which creates variations over the day.

Phenomenon of daily variation is described by A. Tunick [5], for deciduous trees explaining how different trees are able to balance the surface temperature to the ambient air temperature. This is shown in Figure 2 below:

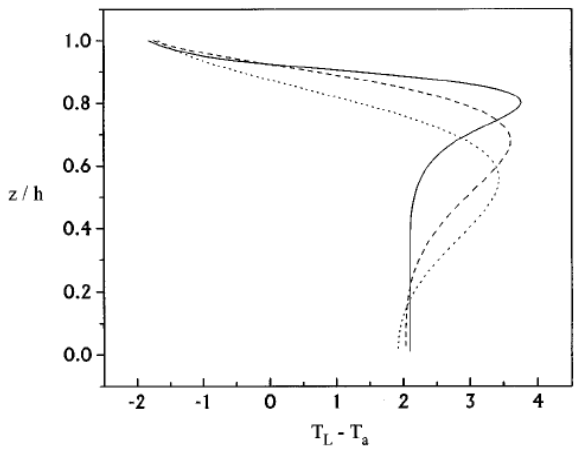

Figure 2. Profiles of the leaf-to-ambient temperature (T_L-T_a) differences (^oC) for different trees, z=height above ground, h=height of canopy, picture from A. Tunick [5 p. 1799]

In Figure 2 one can see the difference between leaf (T_L) and ambient air (T_a) temperature. Close to the ground the T_L is 2 ^oC higher than T_a. At height of half the tree (z/h=0.5) differences can be seen among the trees. The dotted line has the peak in temperature difference of 3.5 ^oC at z/h=0.55, the dashed line has a value of 3.6 ^oC at z/h=0.68, and the solid line has a value of 3.75 ^oC at z/h=0.8. After each peak all tree types strive towards a negative temperature difference, at z/h=1.0 (the top of the tree) all trees has a value of -1.7 ^oC. At this height the curves from the different tree types gather together. A reason for this may be that the balance between incoming solar energy absorbed by leafs in canopy and the outgoing long-wave energy emitted is negative, [5 s. 1799]. At the height of z/h ≈ 0.9 the temperature difference is zero. Here the incoming solar energy and the outgoing heat from the leaves are balanced.

Keith Attenborough presents the diurnal variation of temperature gradient in a pine forest in his paper [6]. Among other figures he presents figure 3:

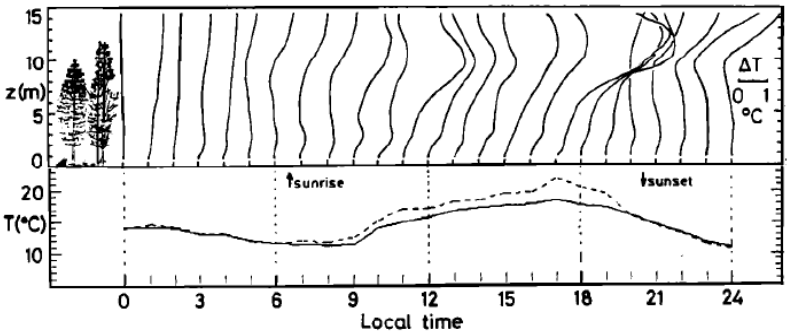

Figure 3. Temperature variation with height over one day, from Keith Attenborough [6 p. 2666]

In the upper part of figure 3 the temperature difference, ΔT (horizontal), for different heights (vertical, z) is described. The lower part of figure 3 shows the temperature variations over a day. It can be seen that the greatest influence of positive temperature gradient occurs in the hours around sunset, but also at noon. The main effects can be seen in the height range between z=8-12m.

Changed speed of sound profile with height in forest

Due to changed wind profile and temperature profile the speed of sound will have a resulting profile which usually is different compared with sound propagation over open field. Under these conditions the sound propagation will be influenced by refraction. An example of downwards refraction for an assumed sound speed profile can be seen in figure 4 below:

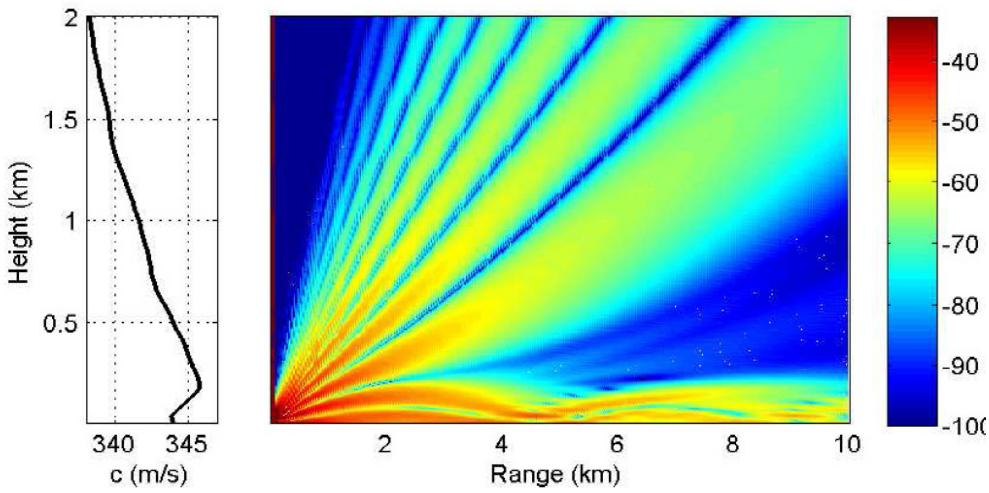

Figure 4. Propagation for an assumed speed of sound profile [7 p. 25]

The left part of figure 4 shows the speed of sound profile with height. Close to the ground (0-200m) the sound speed increases, above 200m it decreases. The right part of figure 4 shows the calculated sound pressure level for the corresponding sound speed profile. The sound pressure level is plotted over a horizontal range (x-axis) and height above ground (y-axis). The highest sound levels are marked as red and lowest levels as blue. In the figure it is showed how the downward refraction causes an increased level compared with other areas, as can be seen close to the

ground. In these areas a vertical concentration of the propagated sound is occurring close to the ground. The downward refraction is caused by the characteristic speed of sound profile, which is seen to the left as a function of height. From ground level to about 200m height there is a positive gradient, which also can be seen in the colour plot. At higher levels the gradient becomes negative, hence the colour plot shows an upwards refraction.

Compilation of hypotheses for higher sound level in forest

In order to study the phenomenon with sound pressure increase inside forests, it would be interesting to investigate if this is a common phenomenon, if it is known since earlier. According to [8 p. 16] forests has an attenuating effect, but may in some cases induce increased sound pressure levels. Also, in the presence of a solid barrier, the complex mechanisms of sound propagation may create local unstable conditions with increased or decreased sound pressure levels. Also Defrance [9 p. 5], writes about increased sound levels in the forest. It is described that for long distances sounds forests can be increased when unfavourable conditions are present. On the other hand it is also described that this phenomenon is of little importance because the levels of these distances are relatively low. According to [10 p. 22], sounds containing frequencies mainly below 1 kHz “perceive” the forest as being transparent, i.e. parts limiting the horizontal propagation are not present, e.g. scattering obstacles or absorptive surfaces. Sounds above 1 kHz attenuate mostly due to absorption of the forest. One clue to the problem may therefore be that the potential noise increase inside the forest mostly occurs at low frequencies or at least is frequency dependent. Researchers have discovered that animals communicate acoustically in specific frequency ranges. Many birds communicate in 1-3kHz. This may be because that sounds in this frequency range is more easily propagating and less attenuated [11]. Therefore it can be assumed that low and mid frequency regions may be used by large mammals in the forest. This may indirectly show that some frequency ranges make sound propagation easier.

Reverberation in forest

When regarding the reverberation in the forest, forest may be treated partly as a room and partly as being free field. This must be simplified. An ordinary room has clear and obvious dimensions, but the forest room is geometrically unclear, because of no definite points where walls, ceiling or floors starts and ends. Therefore it is not for certain that the Sabine formula can at all be applied to a forest. However, if so assumed, some dimensions of the forest must be assumed, in order to make the calculation model possible. The layer between the ground and the lower part of the canopy contain a temperature gradient which limits the sound energy in this layer. Sound from e.g. wind turbine is then concentrated in the area under the canopy and attenuates horizontally. This attenuation will occur more slowly with time compared with the one for open field, because of higher concentration of sound energy due to backscattering from tree trunks.

Temperature and wind gradient causing downward refraction

In a forest there is usually a different temperature gradient compared with open field. The possible refraction caused by the temperature gradient may increase the sound at an observer. The phenomenon with refraction is very sensitive in forests due to the sometimes strong temperature gradient; see Figure 3. The temperature gradient can

limit the vertical sound, as Figure 4 shows. Horizontally the sound is not limited and propagates in all directions. Vertically the sound is limited due to the refraction and therefore not propagating to higher altitudes in the same extent, e.g. causing sound shadow. Compared with other effects influencing the sound propagation, e.g. scattering by trees or ground reflection, the atmospheric profile is the most important [12 p. 117] and is affected by the temperature gradient. Wind turbines located at oceans are expected to have higher levels during spring and beginning of summer. This is due to that a positive temperature gradient is created between the cold sea water and the warm air. This causes a downwards refraction of the sound. The sound is in this way concentrated close to the surface of the ocean. In contrast, a negative temperature gradient during the autumn is causing upwards refraction of the sound. The sound from wind turbines located at the sea may therefore be seasonally dependent. In analogy this seasonal dependency could be seen in the forest. Although the same effect could appear during sound pressure measurements of wind turbines close to lakes in forests.

Scattering effects

Scattering is caused when the sound is reflected at a surface or when reaching turbulent air and hence the propagating direction changes randomly. The scattered sound interferes with direct sound or other reflections and can build a diffuse sound field. If a sound source is put inside a forest the horizontal sound propagation will be affected by scattering from trunks. This horizontal scattering may theoretically be separated from the vertical scattering through the canopy layer, because of the differences in propagation direction. Within the horizontal scattering the sound is being scattered and reflected by the trunks, which have cylindrical shape, and extend the sound horizontally in the forest. The trunk scattering is mainly a phenomenon in mid frequency region, i.e. the wavelength is approximate the same as trunk diameter. The effect caused by scattering is mainly attenuation, but the reverberation, turbulence or interference effects caused by scattering may increase the sound pressure level [8 p. 53]. The possible increase of sound in forests can be related to that the sound is trapped as reflections between the trunks. The trunks are rather hard compared with the porous ground, which will make reflections possible. The attenuation by tree trunks increases linearly with increasing trunk diameter. It also increases with increased tree height. Trunk scattering reduces the ground effect, because it disturbs the coherence between direct and reflected waves. In favourable conditions the ground effect dip may therefore be reduced and the sound pressure level can be underestimated.

Measurements of sound in forest

In order to understand more about what possible caused the difference between the measured and predicted levels described in [1], different forests in the surroundings of Gothenburg has been investigated. The purpose was not to simulate the sound from a wind turbine, but rather to understand more about the phenomenon influencing the sound propagation in forests. The measurements have been performed at two locations, the first at Fjällhult during 9th Dec 2009, north of Lerum, and the second at Holmevatten, north of Kungälv close to the nature reserve of Svartedalen during the 19th of March and 9th and 13th of April. Another purpose of the measurements was to compare it with predictions, making better conditions for verifying or developing a calculation model.

During the 9th Dec 2009 the reverberation time was measured in a Swedish pine forest. The measurement was performed at several different positions with a loudspeaker as source. A result from that measurement is shown in figure 5 below. The figure shows results from measurements from position no. 5, 6, 11, 14, 15 and 23. The distance to source were: pos 5,6 = 9m, pos 11 = 7m, pos 14 = 9.2m, pos 15 = 10.5m and pos 23 = 10.2m. The mean value is shown as a thick curve.

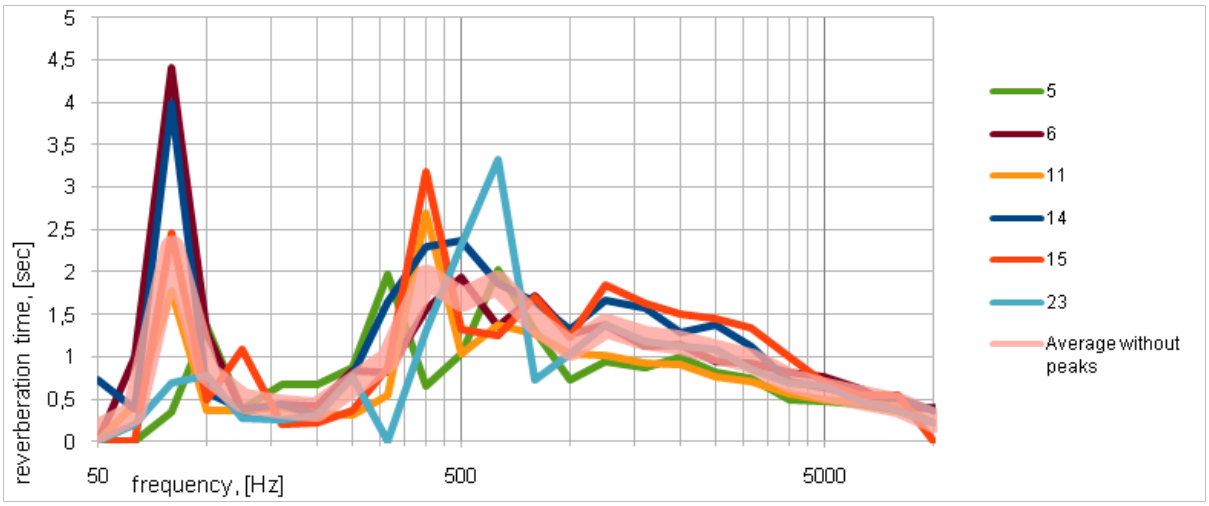

Figure 5. The reverberation time (RT) measured at different positions

Probably there are many reasons for the character of the reverberation time. According to the Sabine's formula the reverberation time is directly dependent on the amount of absorption, i.e. long reverberation is due to little absorption [13]. If this concept would be used for characterization of results in figure 5 the frequencies containing highest values of reverberation also contains the smallest amount of absorption. This means that the sound has been absorbed as most in frequencies 125-315Hz but also to a great extent at high frequencies. At very low frequencies (<100 Hz) the sound treats the forest as being transparent, according to [10], and the reverberation should be long. The long reverberation time at 80 Hz cannot be explained for the moment. Vegetation, trees and ground absorb sound from the loudspeaker and decrease the reverberation. Also the long wavelengths of low frequencies generally demands large dimensions of the absorbing surfaces. But this does not concur with the results in Figure 5, where there must have been some measurement error at 50 Hz. This could be caused by that the loudspeaker lacked the ability to excite the sufficient reverberation at low frequencies, which also resulted that the reverberation could not be measured and become RT=0 sec.

During the 19th of March the reverberation time (T_{30}) for different distances was measured and the results can be seen in Figure 6 below. During this measurement the ground in the forest was covered with snow and gunshots were used as sound source.

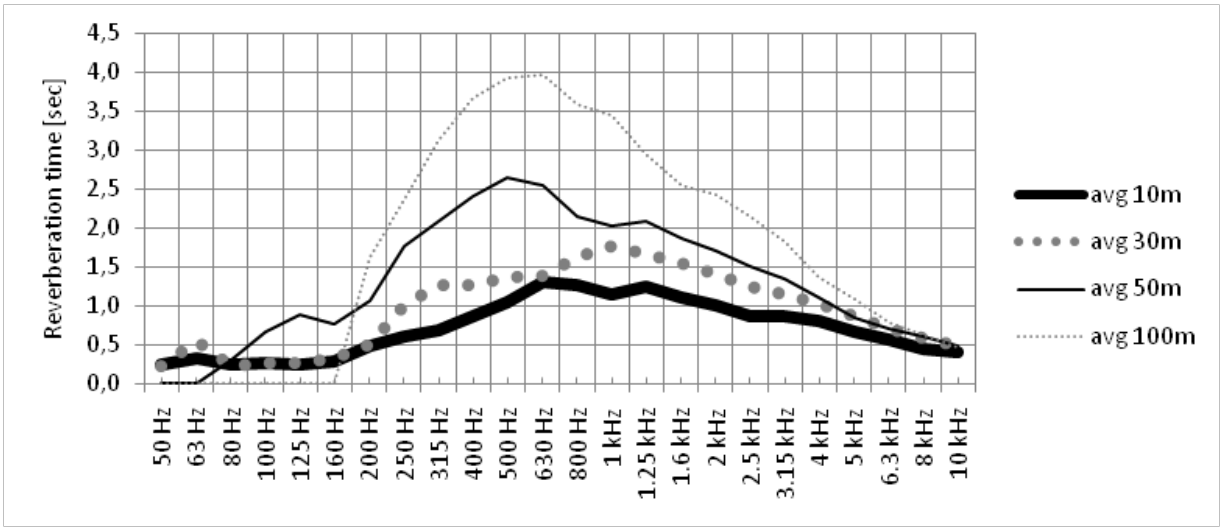

Figure 6. Average reverberation time (T_{30}) for different distances

In figure 6 it can be seen how the T_{30} have a peak at around 500 and 630 Hz for the case of 100m distance. Here the T_{30} reaches a value of almost 4 seconds. Comparing the different distances it can be seen that for frequencies lower than 500 Hz, increased distance also give increased T_{30}. And for frequencies higher than 500 Hz, decreasing almost linearly (in this logarithmic plot) with increased frequency, the longest distance decrease fastest. It should be noted that the high levels of snow surely have influenced the results. The peak at 80 Hz in figure 5 could not be repeated in the experiments for figure 6.

Calculation model

Mainly two calculation models has been used, one is referred to two British mathematicians John Crank and Phyllis Nicholson and one is developed by this author during the time of project. The first is the CNPE-model (Crank Nicholson Parabolic Equation). This can be used in acoustics to solve problems with long distance sound propagation, where parameters as wind and temperature gradients can be used. The second is an attempt to model the forest according to Sabine´s room equation, together with introducing a scale factor of the volume which should correspond the volume of the “forest room”. Here the model show good agreement with the investigated forest, but may not be implemented generally to other forests.

CNPE-model

When using the CNPE-model to calculate the sound propagation in a forest, the change in wind profile can be introduced. A wind profile possible for forest was incorporated into the 2Dmodel. This is shown in figure 7 and figure 8. In figure 7 the used profile is taken from figure 1, a profile developed by Swearingen & White (here shortened to only Swearingen wind). The CNPE script has been developed and provided by Jens Forssén at Chalmers University of Technology.

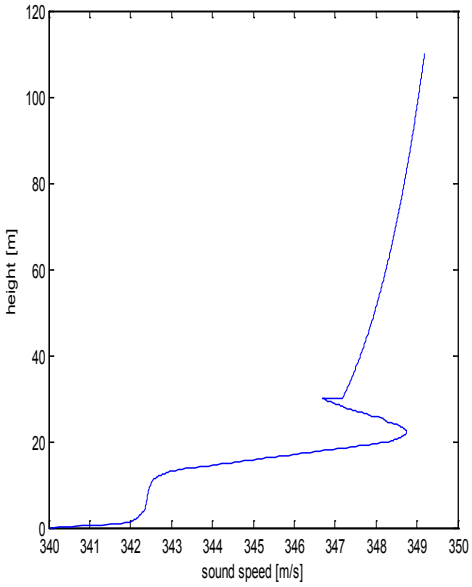

Figure 7. Forest sound speed profile up to 30m, above 30m logarithmic wind profile

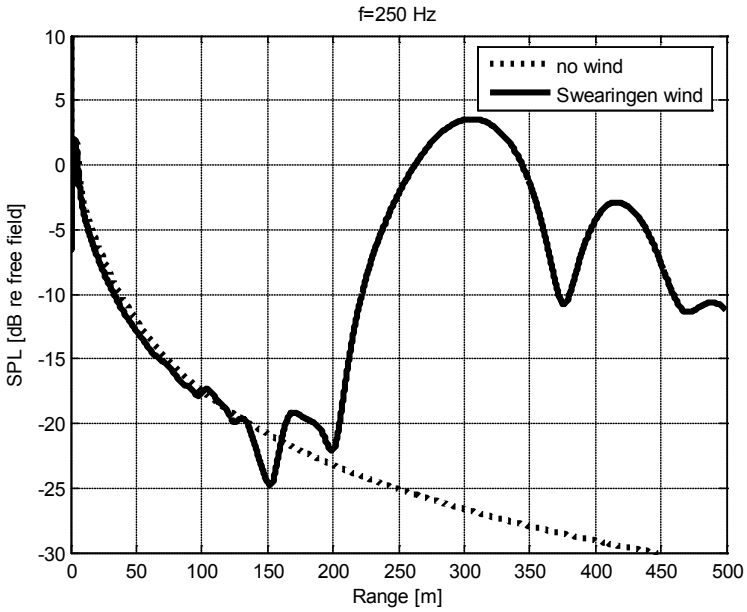

Figure 8. Rel SPL for f=250Hz and for a range 0-550m

Figure 7 shows the speed of sound profile corresponding to a forest climate (developed by Swearingen & White) and figure 8 shows the relative sound pressure level (rel SPL) for frequency f=250Hz and for a range between 0-550m. The source and receiver height was chosen to 1.5m above ground. In figure 8 the resulting sound shows a peculiar pattern. The level drops and finds its minimum of -24dB at 150m distance. Then a dramatic increase of the sound appears and a maximum of 4dB at 300m distance is found. This can be interpreted in a way that the sound is refracted downwards and concentrated at a distance of 300m. Comparing other frequencies (which are not shown here) one finds that the maximum level occurs at low and mid frequencies, first in broad distance range at 50-80Hz, then peaks at 250-350 m for 250-315Hz.

The developed model (RT-forest)

The developed model (RT-forest) regards the forest and predicts the sound pressure level at a distance in a forest stand. The developed model takes air absorption, ground effect, scattering by trees and reverberation into account. The input variables are the source and receiver geometry, the dimensions of the forest, meteorological conditions, measured RT and the sound power level used for calculations. In the model the reverberation time (RT) is related to the sound pressure level by the classic room acoustic formula:

$$L_p = L_w + 10log\left(\frac{1}{4\pi r^2} + \frac{4}{A}\right)$$

L_p: *sound pressure level* $[dB]$

L_w: *sound power level* $[dB]$

r: *distance to source* $[m]$

A: *absorption area* $[m^2]$

Here the RT is included in the absorption area. Changing the RT will also change the Lp. The sound power level L_W is calculated from the sound pressure level at 12m distance, including ground effect and divergence. The basic formulas used are:

I $L_p = L_W + \Delta L_{air} + \Delta L_{ground} + \Delta L_{scattering} + \Delta L_{divergence}$ *Excl. reverberation*

II $L_p = L_W + \Delta L_{air} + \Delta L_{ground} + \Delta L_{scattering} + \Delta L_{divergence+reverberation}$ *Incl. reverberation*

The ground effect is using the parameter model by Delany & Bazley and the tree trunk scattering effect is modelled using the approach in Nord2000 which gives an attenuation. In figure 9 a result from the RT-model is presented.

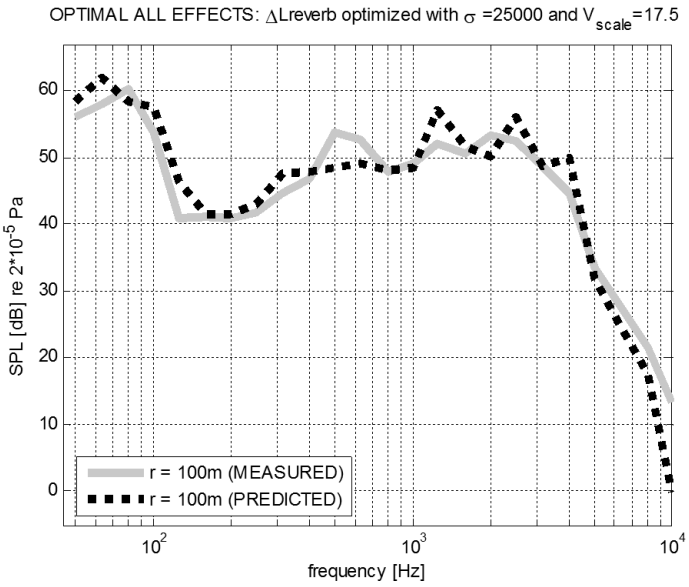

Figure 9. RT-model, all effects included with volume adjustments (V_{scale})

The two curves in figure 9 shows a measured and a predicted sound level at 100m in a forest stand. The average difference for the case of all effects and unadjusted volume became +12.33dB and for the case of adjusted volume +0.036dB. The parameter V_{scale} is a factor with purpose to adjust the volume of the "forest room" and used in calculations as follows:

$$V = r \cdot \frac{r}{2} \cdot H_{trees} \cdot V_{scale}$$

The parameter is chosen to an appropriate value, e.g. V_{scale} =1 the volume remains unchanged, V_{scale} =2 the volume is doubled or V_{scale} =0.5 the volume has half the size. It was found that when the parameter V_{scale} was chosen to 17.5, an optimal adjustment to measurement was obtained, shown in figure 9 above. This means that when the tree height remain the same, the forest area for unadjusted model would be 5000m^2, i.e. half hectare, and for adjusted model about 90000m^2, i.e. 9 hectare.

Conclusions

The promising hypotheses, which may increase the sound pressure in forest, are reverberation, scattering and sound concentration through refraction.

Reverberation makes the sound energy trapped below the canopy due to horizontal backscattering from tree trunks and vertical scattering by the underside of canopy. It has been shown that the reverberation in forest increases with distance. This is related to a larger amount of scattered sound energy and increased volume of the “forest room”.

The backscattering by tree trunks reduces the ground effect at medium and low frequencies, when the scattered sound disturbs the coherence between reflected and direct sound. However, the strongest reason for the increased sound pressure level is probably the microclimate inside the forest causing downward refraction of the sound.

From the compilation part it can be understood that attenuation at low frequencies is due to the ground effect and at mid frequencies due to scattering effects. When the propagation is changed into favourable conditions due to downward refraction, the concentrated sound energy may increase the sound pressure level inside the forest.

The calculation model, CNPE, uses an advanced approach and gives the resulting sound pressure level over range and height. The CNPE-model has the meteorological parameters (wind and temperature over height) which are necessary for predicting refraction effects.

Even though that the developed model “RT-forest”-model shows good agreement in figure 9, crucial components make it not applicable for other conditions, i.e. other forest. Here the best value of V_{scale} = 17.5 was obtained but this may differ from situation to situation. The good agreement was probable given because that the same meteorological conditions appeared when measuring the RT and measuring the sound pressure level.

The results from the calculations show that there can be a significant sound pressure level increase inside forests, but mainly for low and mid frequencies. The ground effect may not increase the sound pressure level more than +6dB. For sound waves passing through a forest, the sound is attenuated more than if the forest was not there.

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