Optimal tree canopy shape for improving downwind noise barrier efficiency

Timothy Van Renterghem and Dick Botteldooren

University Ghent - Department Information Technology, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium
timothy.van.renterghem@intec.ugent.be

The presence of a row of trees behind a highway noise barrier significantly reduces the screen-induced refraction of sound by wind. In this paper, the influence of quantitative tree properties, such as the pressure resistance coefficient of the canopy and the distribution of biomass over height, was studied numerically. Three computational models were involved. First, computational fluid dynamics (CFD) software is used to accurately predict the wind fields. The finite-difference time-domain (FDTD) method is then used to simulate sound propagation in the direct vicinity of the noise barrier in combination with trees. In a last step, the Parabolic Equation (PE) method is used to predict sound fields at larger distances. As a general conclusion, it was found that coniferous trees are superior to deciduous trees to improve downwind noise barrier efficiency.

1 Introduction

This numerical study deals with the problem of enhanced downward refraction for receivers downwind from noise barriers, resulting in a significant decrease of the shielding efficiency.

The use of a row of trees, acting as a natural windscreen, was proven to be beneficial to improve downwind barrier efficiency. This was shown by means of scale modeling [1], by an extensive field experiment [2] and by a number of numerical simulations [3].

This study deals specifically with the effect of variation in the aerodynamic properties of the crown of trees with height. It was shown e.g. in Ref. [4] that canopy shape is an important factor when looking at ground deposed particles in air quality modeling. Changing the wind reducing properties of the canopy with height will largely alter the wind field. Taking into account this effect is interesting to reveal what kind of tree species is preferred behind a noise barrier to limit negative wind effects.

2 Flow field modelling

The CFD software Fluent 6.3 is used to simulate the two-dimensional flow near the noise barrier. The Reynolds-averaged Navier-Stokes equations are solved by applying a standard k-ε turbulence model. Boundary equations expressing a neutral, atmospheric boundary layer in equilibrium [5] are applied. The equation describing the horizontal flow velocity in function of height is given by

$$u_x = \frac{u_*}{\kappa} \ln\left(1 + \frac{z}{z_0}\right) \tag{1}$$

where u_* is the friction velocity, κ is the Von Karman constant (equal to 0.4), z is the height above ground level, and z_0 is the aerodynamic roughness length. For the results presented in this paper, a friction velocity of 0.8 m/s is used, and the aerodynamic roughness length equals 0.01 m.

The air flow through the canopy of trees results in a pressure drop. The pressure resistance coefficient k_r is commonly used to quantify this pressure drop, and is defined as

$$\Delta p = k_r \frac{\rho u_x^2}{2} \tag{2}$$

The pressure resistance coefficient can be related to physical characteristics of the canopy of trees [6]:

$$k_r \approx C_d \cdot LAD \cdot D \,, \tag{3}$$

where D is the width of the canopy layer in horizontal direction, C_d is the dimensionless drag coefficient of the elements of the canopy, and LAD is the leaf area density.

The drag coefficients of trees elements and values of LAD (or the equivalent Needle Area Density, NAD) are common quantitative measures in plant research. Deciduous trees have a smaller drag coefficient than coniferous trees. The typical LAD is smaller than the NAD as well. The distribution of the LAD•D follows a more or less ellipse-like profile, while NAD•D is modelled in this study as a linear decrease with height. Only the distribution of k_r with height is studied here. For a fair comparison, the average k_r over the full height is kept the same for both the deciduous and coniferous row of trees. The flow fields with and without a row of (coniferous) trees is shown in Fig. 1.

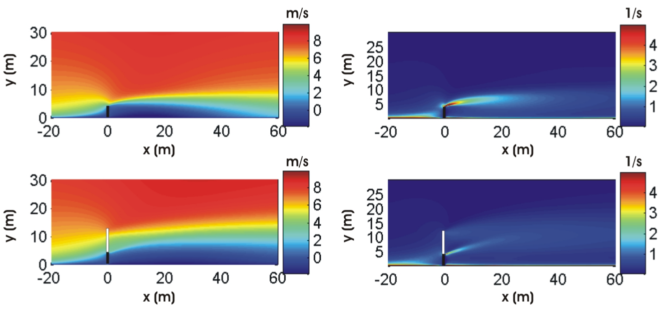

Fig.1 Fields of the horizontal component of the wind speed (u_*=0.8 m/s) (on the left) and fields of the vertical gradient in the horizontal wind speed (on the right), near a 4-m high noise barrier. The figures above depict the situation in absence of trees, the figures below show these fields when a row of coniferous trees is situated directly behind the noise barrier. The canopy extends 8 m above the noise barrier (u_*=0.8 m/s , k_r=2).

3 Sound propagation modelling

A coupled 2-D Finite-Difference Time-Domain (FDTD) - Parabolic Equation (PE) method [7] is used for the sound propagation calculations. The FDTD method, solving the moving-medium sound propagation equations, [3] is used directly near the noise barrier. The (stationary) flow field calculated with the CFD software is used. Refraction of sound by wind is accounted for accurately. Perfectly matched layers are applied to simulate an unbounded atmosphere where needed. A lowest-order staggered-in-space scheme is used, combined with the prediction-step staggered-in-time (PSIT) approach [8]. Such a scheme was shown to be an interesting compromise between accuracy, numerical stability, and computational efficiency.

The Green's Function PE (GFPE) method is used to model sound propagation from the source region to the receivers at larger distance. The GFPE calculations start from a column of complex pressures, derived from the FDTD domain. GFPE uses the effective sound speed approach, and the wind speed profiles are range-dependent.

The hybrid FDTD-PE model was shown to be computationally very efficient, without resulting in loss of accuracy [7]. It combines a very detailed modelling of the effects of the complex flow near the noise barriers and trees, and still allows estimating effects at large distance from the barrier.

The noise barrier has a height *H* of 4 m, and a thickness of 0.1 m. Downwind sound propagation is considered. The source is placed at 2*H* upwind, and the source height is taken at 0.3 m. The noise barrier and the ground in the FDTD region are modelled as rigid planes, while in the PE region (which starts directly downwind from the noise barrier) a grass-covered ground is modeled (with a flow resistivity of 200 kPas/m^2). Scattering of sound on atmospheric turbulence and scattering by leaves/branches/twigs is not considered.

4 Numerical results

Fig.2 clearly shows the large negative influence of wind on noise barrier efficiency. The magnitude of the screen induced-refraction of sound by wind is shown, i.e. the sound level field in the presence of wind minus the sound level field in a still atmosphere. The octave band of 1000 Hz is presented here, which has a major contribution to road traffic noise. Starting from about 60 m downwind (15*H*), more than 10 dB of the barrier efficiency is lost by the action of the wind.

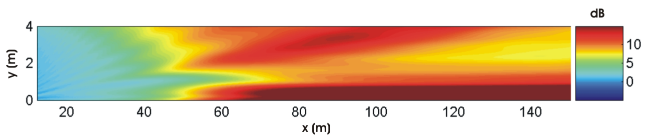

Fig.2 Magnitude (dB) of the screen-induced refraction of sound by wind near a 4-m high noise barrier (at x=0 m), for the 1000 Hz octave band (u_*=0.8 m/s).

In Figs. 3 and 4, the improvement by the presence of a row of trees behind the noise barrier is shown. The sound level fields in wind, in absence of trees, minus the sound level fields in wind, with trees, are calculated. The average value of k_r over the full canopy height equals 2 in both simulations. In Fig. 3, a typical deciduous pressure resistance coefficient distribution is modeled, while in Fig.4 a coniferous profile is used. The zone with significant improvements starts from about 60 m (15*H*) downwind, and ends at about 120 m (30*H*). Closer behind the noise barrier, wind effects are limited (see Fig. 2). At larger distances, the effect of a noise barrier is limited in practice, even in absence of wind.

Both types of trees significantly improve the downwind noise barrier efficiency. The reduction of wind speed gradients, as is clear from Fig. 1, explains this. There is however a clear preference for coniferous trees, since the magnitude of the improvement is larger when modeling an equal averaged k_r. Furthermore, typical k_r-values of conifers are larger, and this will further strengthen this preference.

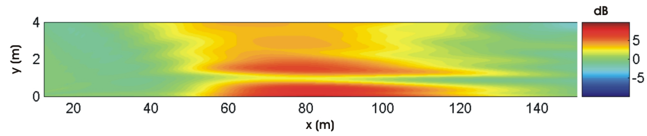

Fig.3 Improvement (dB) in barrier efficiency by the presence of a row of deciduous trees, for the 1000-Hz octave band (u_*=0.8 m/s, k_r=2).

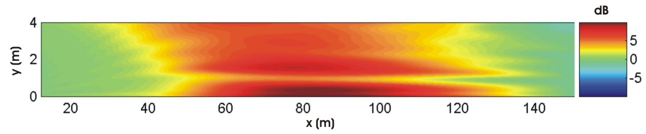

Fig.4 Improvement (dB) in barrier efficiency by the presence of a row of coniferous trees, for the 1000-Hz octave band (u_*=0.8 m/s, k_r=2).

5 Conclusion

Based on numerical calculations, it can be concluded that the presence of a row of trees results in an important improvement of the downwind noise barrier performance, up to a distance of 30 times the noise barrier height. Coniferous trees were found to be more suited to limit the (negative) wind effects. This typical distribution of mass over its canopy results in a more interesting wind field. Furthermore, the typical pressure resistance coefficient of a coniferous tree is larger than for deciduous trees. Another advantage is that coniferous trees remain in leaf/needle throughout the year.

References

[1] T. Van Renterghem, D. Botteldooren, W. Cornelis, D. Gabriels, "Reducing screen-induced refraction of noise barriers in wind with vegetative screens", Act. Ac. Ac. 88, 231-238 (2002).

[2] T. Van Renterghem, D. Botteldooren, "Effect of a row of trees behind noise barriers in wind", Act. Ac. Ac. 88, 869-878 (2002).

[3] T. Van Renterghem, D. Botteldooren, "Numerical simulation of the effect of trees on downwind noise barrier performance", Act. Ac. Ac. 89, 764-778 (2003).

[4] J. Donat, B. Ruck, "Simulated ground deposition of fine airborn particles in an array of idealized tree crowns", Boundary-Layer Meteorol. 93, 469–492 (1999).

[5] P. Richards, R. Hoxey, "Appropriate boundary conditions for computational wind engineering models using the k-ε turbulence model," J. Wind Eng. Indust. Aerodyn. 46-47, 145-153 (1993).

[6] J. Wilson, "Numerical studies of flow through a windbreak", J. Wind Eng. Indust. Aerodyn. 21, 119-154 (1985).

[7] T. Van Renterghem, E. Salomons, D. Botteldooren, "Efficient FDTD-PE model for sound propagation in situations with complex obstacles and wind profiles", Act. Ac. Ac. 91, 671-679 (2005).

[8] T. Van Renterghem, D. Botteldooren, "Prediction-step staggered-in-time FDTD: an efficient numerical scheme to solve the linearised equations of fluid dynamics in outdoor sound propagation", Appl. Ac. 68, 201-216 (2007).