Acoustic analysis of wind turbines is an important part of the environmental review process, and sound impacts can have a significant effect on project planning.

If expected sound levels are too high, wind turbines will often need to be relocated — or in some cases, removed from a project. Therefore, determining potential sound impacts accurately is of considerable importance for projects in which sound levels are a potential issue.

A number of factors can affect perceived sound levels — including wind turbine sound power levels, wind speeds, atmospheric conditions, terrain and ground effects. The factor discussed in this article is the ground effect, which is the absorption of sound reflected from the ground surface, and sound reduction due to a phase shift between incident and reflected sound waves.

The ground effect can change wind turbine sound levels by several decibels and can vary considerably among turbine locations, depending upon the ground composition in the vicinity of the noise receivers.

As mentioned, the ground effect consists of two parts: absorption of sound reflected by the ground, and changes in phase of the ground-reflected sound waves due to the ground material, which causes inter-
fence with sound directly radiated from the wind turbine.

These effects tend to vary according to both the type of material covering the ground and the frequency content of the incident sound. In general, higher frequencies are absorbed more readily by the ground surface.

Frequencies in the middle range have a higher cancellation of sound, due to phase differences between incident and ground-reflected waves. This phase effect is most pronounced in the speech sound frequency range between about 100 Hz and 1000 Hz.

For reflective materials such as pavement, packed soil, ice or water – the ground effect increases the sound levels, as most of the sound is reflected off the ground in phase with the incident sound field. Softer materials – such as vegetation, leaves, loose soil and snow – can cause the ground to both absorb and change the phase of the sound waves so that they interfere with the incident sound from the wind turbine, leading to lower sound levels at the receiver.

In practice, the difference between hard ground and soft ground can cause a difference of several decibels in sound pressure level at a given location and can be the difference between permittable and non-permittable wind turbine sound levels.

**Modeling the ground effect**

In general, in the case of a single surface boundary, the total sound field at a receiver is the sum of the direct and reflected waves.

To quantify the sound field for this case, one would typically solve the Helmholtz equation in the presence of appropriate boundary conditions of continuity of the normal derivative of the incident pressure field on the reflecting surface.

For the case of a boundary with absorption coefficients varying both spatially and with frequency, the reflected sound field can be computed via boundary integral equation methods, where the boundary is discretized and numerically integrated over the boundary elements for each frequency to obtain the reflected sound pressure field.

For semi-analytic solutions involving planar boundaries, the phase shift of the waves due to reflection off an absorbing boundary is incorporated using complex reflection coefficients and an image source accounting for the geometrical spreading of the reflected wave.

In order to simplify the calculations for an average sound pressure level, the ground effect is usually computed by averaging the reflected waves over each octave band, and the octave bands are then summed to determine the overall sound pressure level.

A frequency-dependent correction is used to quantify the difference in absorption and phase shift for each octave band. This correction peaks over the frequency range of greatest interest to wind turbine sound analysis – between 125 Hz and 1000 Hz – and is also considerably higher when closer to the ground.

A parameter $G$ is then introduced. This parameter varies between 0 and 1 – with 0 representing hard ground and 1 representing soft ground. This parameter is used in an empirical formula for each different octave band, which approximates the ground effect.

Note that for receiver heights of greater than 10 meters, the ground effect has relatively little impact on observed wind turbine sound levels.

**A-weighted sound levels**

This computation method is used internationally to compute the ground effect, and it is the method most commonly utilized in the computation of wind turbine sound levels by current software packages.

Here, we are using the Cadna/A sound calculation model, which is widely used in the evaluation of wind turbine sound and which implements International Standard ISO 9613-2. Other sound modeling packages employ the same algorithms.

In this example, the ground effect at a receiver height of 1.5 meters (typical ear height) for three different turbines at typical hub heights are being examined. The sample turbines include a 100 kW turbine at a height of 40 meters, a 600 kW turbine at a height of 70 meters, and a 2.3 MW turbine at a hub height of 100 meters.

These models represent typical small, medium and large wind turbines likely to be used for commercial on-site applications, community wind applications and large-scale wind farm applications – each at the hub height typically found in these applications.

The turbines were modeled as a point source at hub height placed on flat ground – a typical configuration used in most wind turbine permitting studies.

The total A-weighted sound power levels used are 93.4 decibels, 96.1 decibels and 104.0 decibels for the 100 kW, 600 kW and 2.3 MW turbines, respectively. These levels were measured downwind when the wind was blowing about 8 m/sec – a typical case when the wind most greatly exceeds the background level.

These conditions are the worst-case scenario generally examined for most wind turbine permitting studies.

The octave band levels used were obtained from actual octave band manufacturers' data for each representative unit. It is important to note how the peak frequency shifts with increasing turbine size; it is highest at 1000 Hz for the 100 kW unit, at 500 Hz for the 600 kW unit, and 65 Hz for the 2.3 MW unit.

These results are as expected, as larger turbines emit sound at lower
frequencies. The shift in peak frequency also has an impact on the ground effect.

For each turbine, three sets of ground conditions were examined: hard ground with a G of 1.0, average ground with a G of 0.5 and soft ground with a G of 0.

A 45 dBA sound level is typically considered the upper bound for acceptable wind turbine sound levels. The distance at which the sound level measures 45 dBA is considerably further away for the hard-ground case than for the softer-ground cases — indicating that the permissible distances vary considerably depending on ground conditions.

In general, the 45 dBA distance for the hard-ground case is nearly double that of the soft-ground case, meaning that nearly four times more area is inside the 45 dBA contour — a notable result for wind permitting.

**Output spectra**

Octave band levels also show that the ground type has a significant effect on the expected sound levels at each location.

For the smaller turbine, the ground effect is less than for the larger turbines. The difference between the expected maximum sound level for the 100 kW turbine for the case of G=0 and G=1 was about 3.7 dBA, while for the larger (2.3 MW) turbine, the difference was about 5.1 dBA — an increase of nearly 1.5 dBA. These results are consistent with expectations, as the smaller turbine is closer to the ground for a given distance.

Note also that the soft-ground distance to the 45 dBA contour for the 600 kW turbine was actually less than the distance for the 100 kW turbine, suggesting a greater ground effect reduction for the larger turbine, in addition to the effect of increased distance due to higher hub height.

A comparison of the output spectra at each location shows that the sound emitted by the larger turbines has an A-weighted peak in a lower frequency range, one which corresponds to the peak in the ground-effect sound-reduction spectrum.

An examination of the 250 Hz and 500 Hz bands shows how the sound is much more highly attenuated in these bands — where the ground effect is greatest — than in the adjacent ones. This finding accounts for the difference in ground effect attenuation between the smaller and larger turbines.

When the ground effect was modeled for three different ground characteristics and three different turbine sizes and heights typical of those encountered in wind turbine installations, the ground effect caused a change in expected sound levels of between 3 dBA and 5 dBA for typical wind turbines, with larger turbines experiencing a greater ground effect.

This change corresponds to a near doubling of the necessary setback distance — for most turbines — on hard ground relative to soft ground.

For siting decisions, this difference can be critical. It means that in hard-ground areas, such as in urban locations or near ponds or packed soil, much greater setbacks are needed for wind turbines relative to those needed in areas with soft soil, such as forests and fields.

Accordingly, modeling of the ground effect is important in wind turbine sound analysis, and this effect must be carefully evaluated to ensure accurate results for sound permitting studies. **WP**

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