Wind farm layout optimization with special attention on noise radiation

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Abstract. This work presents a new wind farm layout design methodology that calculates the noise radiation using an advanced sound propagation model. Firstly, the wake velocity in wind farm is calculated via an improved engineering wake model. Then, the aero-acoustic noise source of wind turbine is obtained using the BPM method. To simulate the noise level at far field, the basis of propagation model is built on the parabolic wave equation (PE) method. The cost of energy for wind farm is assessed via an engineering model. Finally, based on the genetic algorithm (GA) optimization method, and taking the noise radiation level into account, a new wind farm layout design methodology is developed to solve a trade-off between cost and noise for wind farm.

1. Introduction

Wind turbine noise affects the wind turbine layout design due to its negative impacts on nearby human and animal. For wind farm layout design, the cost and energy yield of wind farm are frequently considered as main objectives at the process of wind turbine location optimization [1, 2]. Nevertheless, some newly constructed wind farms are closer and closer to residential areas, which requires a smart layout design. Furthermore, because noise is one of the main obstacles achieving a broader public acceptance of wind farm, the accurate assessment of noise generated from the wind farm is even more than a necessity. Wind farm noise radiation has gained more attention in its design phase.

However, if noise is set as one of design objectives, the total cost of wind farm might be increased. This work aims to solve such a problem. Firstly, the wind turbine wake interaction in wind farm needs to be predicted correctly in order to assess the inflow wind speed in front
of each wind turbine. Hence, the engineering wake models such as Jensen wake model [3] and improved Jensen wake model [4,5] are built to calculate the wind speed profile of a wind turbine. Secondly, a numerical tool that combines noise source prediction and its far field propagation needs to be established. Then, a feasibly optimization strategy is required to maintain a low cost and a low noise level of wind farm[6,7]. Several design methods were proposed based on the ISO-9613-2 standard[8], which were coupled with Jensen’s wake model for wind farm Micro-siting. Nevertheless, the wind turbine noise generation and propagation are inherently complex phenomena that are influenced by a number of factors, such as the temperature, air dissipation, ground reflection and so on. In this paper, a method based on BPM [9,10]and Parabolic Equation (PE) methods[11,12] is developed for wind turbine realistic noise source and propagation simulation, and the method is integrated into the GA optimization platform to search the best trade-off of low cost and low noise wind farm layout.

The paper structure is as follows: in Section 2, the simulation methodologies are described including the wind farm wake model, noise source calculation, noise propagation calculation method, wind farm layout optimization procedure. Subsequently, in Section 3 the results are reported. The conclusions are summarized and further directions are indicated in Section 4.

2. Methodology
The numerical simulation method that involved in this study are described as follows: (1) Wake modelling; (2) BPM wind turbine noise source modelling; (3) PE sound propagation method; (4) Wind farm cost of energy modelling; (5) Wind farm Layout optimization algorithm.

2.1. Wake modelling
The variable wind speed results in a noise source level variation during the operation of a wind turbine. Thus, at each location in wind farm, the noise source level varies due to different wind turbine operational conditions as well as the local inflow wind speed. In a wind farm, the standard Jensen wake model is frequently used to calculate the wakes of wind turbines. In this paper, an improved Jensen engineering wake model is used for accurate wake profile simulation. The model is a 2D approach and its wake profile is a COS function, such as

\[ u(x,r) = f_{\text{cos}}(x,r) + u^*(x) \]  

where \( u(x,r) \) is the wake flow speed, \( u^*(x) \) is the wake flow speed calculated with the standard Jensen wake model. The COS function \( f_{\text{cos}}(x,r) \) is defined as:

\[ f_{\text{cos}}(x,r) = \left( u_0 - u^*(x) \right) \cos \left( \frac{\pi r}{r_s} + \pi \right) \]  

where

\[ a = (1 - \sqrt{1 - C_\lambda^2}) / 2 \]  

\[ r_s = k_w \sqrt{x + r_d} \]  

\[ r_d = r_s \sqrt{1 - a^2} / (1 - 2a) \]  

\[ k_w = 0.5 / \ln(z / z_s) \]
where \( a \) is the axial induction factor calculated from the thrust coefficient \( C_T \) of wind turbine; \( r_s \) is the spread wake radius; \( r_d \) is the rotor radius of wind turbine; \( r_1 \) is the characteristic downstream rotor radius representing the expanded wake radius immediately downstream of wind turbine; \( z \) is the hub height of a local terrain; \( z_0 \) is the surface roughness height of a local terrain; \( k_0 \) is the wake decay constant; \( k_{\text{wake}} \) is the wake decay rate by taking into account the effective wake turbulence; \( u_0 \) is the free-stream wind speed of wind farm; \( u^* \) is the wake velocity calculated by the standard Jensen wake model.

### 2.2. Noise source calculation method

Considering the wake effect and wind direction change of wind farm, the wind turbine sound pressure level varies with different wind speeds and wind directions. In this study, the semi-empirical BPM noise source is used in the calculation of wind turbine sound pressure level and sound power level. In the BPM method, the noise source is mainly generated from two parts that: (1) turbulent inflow noise; (2) airfoil noise of blade. Furthermore, the airfoil self-noise is classified into the following five mechanisms:

- Turbulent Boundary Layer Trailing Edge (TBL-TE) noise, including both pressure side and suction side
- Separation-Stall (SEP) noise
- Laminar Boundary Layer Vortex Shedding (LBL-VS) noise
- Tip Vortex Formation (TIP) noise
- Trailing Edge Bluntness Vortex Shedding (TEB-VS) noise

For a turbulent inflow noise, a convenient model for predicting turbulent inflow noise is that due to Amiet[13]. For wind turbine blades this model was modified and adopted by Lowson[14]. The blades of wind turbine are divided into a number of airfoil sections or blade elements. The two-dimensional airfoil self-noise prediction theory is applied for each blade section and the total noise level is determined by summing up all the noise sources. For the \( i^{th} \) blade element, the total noise sources are given as follow:

\[
SPL_{\text{total}} = 10 \log_{10} \left( \sum_j 10^{\alpha_j \cdot \kappa_s} \right)
\]

where \( j \) denotes the different noise sources such as inflow noise and airfoil self-noise, \( \kappa_s \) is the A-weighting filter. The TIP noise is not activated except for the blade elements near the tip region. The SPL (Sound Pressure Level, SPL) radiated from a single wind turbine is the logarithmic sum of the sound pressure levels from all blade elements:

\[
SPL_{\text{total}} = 10 \log_{10} \left( \sum_j 10^{\alpha_j \cdot \kappa_s} \right)
\]

### 2.3. Noise propagation simulation

For a wind farm layout optimization design, an efficient and accuracy method is necessary and significant for predicting the noise level in wind farm. In this study, the noise propagation can
be simulated via solving the parabolic equation in frequency domain, calling the PE method. The parabolic equation is present as follows:

\[ 2ik \frac{\partial \Psi}{\partial t} + \frac{\partial^2 \Psi}{\partial t^2} + \left( k_x^2 - k_y^2 \right) \Psi = 0 \]  

Solving the PE using the Crank-Nicholson approach, we will have the attenuation of sound propagation, which is defined as \( \Delta L \) in this paper. It represents the sound pressure deviation from phenomena, such as ground reflection, atmospheric refraction, atmospheric turbulence, irregular terrain and noise barriers.

The previously calculated wind turbine sound power level \( L_w(f) \) is the initial condition for calculating long range noise propagation. At each frequency, the sound propagation loss is computed as

\[ L_p(f) = L_w(f) - 10 \log_{10} \left( 4 \pi D^2 - \alpha D + \Delta L \right) \]  

Here \( L_w(f) \) is the sound power level, and it does not vary with distance. The term \( 10 \log_{10} 4 \pi D^2 \) is the geometric attenuation corresponding to the spherical spreading of sound waves from the source. The effect from atmospheric absorption is calculated with the term \( \alpha D \). The attenuation is proportional to the propagation length \( D \), and the coefficient \( \alpha \) corrects the air absorption at given frequency, temperature, pressure and humidity. In the present simulations, a relative humidity of 70% and a temperature of 10°C are assumed. Thus, at a given receiver location, we can get the total noise spectrum by superimposing the noise levels from \( n \) wind turbines at receiver \( r \).

\[ L_r(f) = 10 \log_{10} \left( \sum_{i=1}^{n} L'_i(f) \right) \]  

2.4. LCOE modelling

The economic indicators are the key optimization objective of a wind farms. It is known that the LCOE of wind farm depends on the overall costs and AEP. The cost of a wind farms can be divided into two parts: the capital cost \( C_{CP} \) and the Operation and Maintenance (O&M) cost. Thus, denoting the annualized O&M cost as \( C_{OM} \), we can use the model as follow:

\[ LCOE = \frac{C_{CP} + C_{OM}}{AEP} = \frac{C_{CP} + C_{OM} \text{Capacity} \left[ 1 + 0.5 \left( \frac{CF - CF_{ref}}{CF_{ref}} \right) \right]}{AEP} \]  

Where \( CF \) is capacity factor, \( CF = \frac{P_{total}}{\text{Capacity}} \), \( \text{Capacity} \) is the total capacity of wind farm. \( CF_{ref} = 0.4 \) is the baseline capacity factor[15].

2.5. Optimization algorithm

In a wind farm layout optimization, the binary variables (0 and 1) are used to signify the absence or presence of wind turbines. The GA method is used to solve the multi-objective problem of wind farm layout optimization. The cost and sound pressure level objectives are given:

\[ \text{minimize}(LCOE(x, y), SPL(x, y)) \]  

where \( (x,y) \) are the locations of wind turbines, \( SPL(x, y) \) are the noise propagated and received at the prescribed locations. The optimization procedure is shown in Figure 1.
3. Results and discussions

3.1. Wake modelling validation

We start the long-range noise propagation simulation from a single V80 wind turbine. Firstly, the aerodynamic noise sources are simulated at different inflow wind speed conditions. When the inflow wind speed is 12 m/s, the wind turbine aerodynamic noise spectra are shown in Figure 2(a). As introduced before, the total sound pressure level (SPL-total) is obtained by summing up all the noise sources. In the present case, the SPL is recorded on the ground level with a horizontal distance of 110 m, which equals to the tower height plus rotor radius. The sound power level is a measure of sound power strength, which does not change with distance. Figure 2(b) shows the sound power spectra at various wind speeds. The sound power spectra are A-weighted to correct the sensitivity of human ear. It is seen that the variable operation conditions have different sound power levels for a wind turbine. Moreover, the sound power level is increased with increasing the wind speed under the rated wind speed. However, the 12m/s operation condition is reduced due to the pitch angle generating.

![Figure 2](a) Wind turbine noise source: (a) sound pressure level, 12m/s; (b) sound power level with different inflow wind velocities of 5m/s, 8m/s, 11m/s, and 12m/s
Figure 3 shows the attenuation of sound pressure ($\Delta L$) during a propagation with range and height. The noise source is placed at the hub height. The absorption layer is set on the top part of the domain such that the radiated noise is not reflected back into the domain. The reflected waves from the ground are superimposed with the direct waves which show different characteristics at different frequencies. At $f = 80$Hz, 630Hz and 1600Hz, when the wavelength becomes smaller, a higher resolution of the mesh is required to capture the high frequency wave propagation.

![Figure 3. Relative sound pressure level in different frequencies](image)

3.2. Wind farm layout optimization case

The wind farm under study consists of a number of V80-2MW wind turbines. The land-use is limited in $8 \times 8$ squares. In the following simulations, proximity constraints are enforced on the wind turbine locations, such that the distance between any pair of wind turbines is equal or larger than 5 rotor diameters. Two stochastic noise receivers (e.g. two houses) nearby the wind farm are assumed to affect the wind farm optimization. In the optimization process, the number of wind turbines is fixed at 36. The optimization generation and population are 100 and 100, respectively. The small square size is $5D \times 5D$. For wind direction and wind speed distribution, the wind rose and Weibull distribution ($A=8.5m/s$, $c=1.85$) of this wind farm are considered as shown in Figure 4.
The optimization shows the pareto front solutions considering cost-noise trade-off, as seen in Figure 5. A common feature of this front solutions is that the SPL value decreases while the LCOE increases. Three solutions are used for analysing the wind farm layout and noise distribution, as shown in Table 1. In Figure 6(a)-(c), the optimal layouts of wind farm are shown, where most wind turbines are located away from the noise receiver locations. A few wind turbines are distributed in the centre of wind farm due to the influence of wind turbine wake and wind direction. To reduce the LCOE value, the wind turbine will expand nearby boundary of wind farm when layout is optimized, which is shown comparing Solution 1 and Solution 2. For Solution 3, the lower SPL value requirement cause hardly any wind turbines closing the receiver. Thus, the wind farm layout results depend on noise receiver location and wind resource situation. The SPL nearby the noise receiver meets the noise limit as shown in Figure 6(d). The noise propagation attenuation contributes to the noise distribution reducing with increasing the distance from the wind farm.

| Solution | SPL/(dBA) | LCOE/(€/MWh) |
|----------|-----------|---------------|
| Solution 1 | 44.7721 | 53.0186 |
| Solution 2 | 39.7515 | 53.1181 |
| Solution 3 | 33.3511 | 53.8286 |

Figure 4. Wind rose for wind farm

Figure 5. Pareto front and solutions of a wind farm layout optimization
4. Conclusion and future work

The connection of wind farm wake and noise propagation is through the wind turbine noise source prediction. The rotor aerodynamic noise sources are characterized by a few noise mechanisms, which are related to wind speed, wind direction and turbulence intensities in wind farm. The sound power level is increased with increasing the wind speed until rated power. The noise level is reduced after rated wind speed 12m/s due to the significant change of pitch angle. The results obtained in this section were obtained on a Linux DELL workstation with Intel Xeon Scalable Gold 6140 CPUs and an installed memory of 128GB. For the wind farm study with 36 WT's, there were 80 populations and 150 generations used in the optimization process. The computational time spent for this case are approximately 101 CPU hours.

The cost-noise trade-off is accomplished in micro-siting through a multi-objective optimization approach with the aim of minimizing the cost and noise SPL values. The wind turbine wake model is combined with the wind farm noise source and propagation models. A wind farm layout optimization is tested with the above mentioned method, which provide a feasible solution for wind farm layout design. In the future work, finding an optimal number of wind turbines in a wind farm will be investigated, such that the inherent relationship between power and noise will be analysed under a complicated unsteady operation condition. Besides,
the wake model and PE method will be extended for wind farm layout optimization in complex terrain.

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