Modeling of ice throw from wind turbines.

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Ice throw from wind turbines is sometimes a concern in the siting and construction of wind turbines near roads, residences or other areas with public access. Predictive models of ice throw (such as the one described in Biswas et al, 2011) can be used in order to determine the zone of impact surrounding a wind turbine. The ice throw model was been developed to calculate the impact locations of ice fragments thrown from a rotating wind turbine under different conditions. A range of model results were obtained by assigning values of different parameters such as initial position, mass, density and drag coefficient of the ice fragment. Other variables considered include meteorological conditions and wind turbine specifications. In combination with wind information one can then determine the probability of impacts in the area surrounding either a single turbine or within an array of turbines. Coupled with, for example, traffic information, one can then estimate the likelihood of ice fragment impacts with vehicles as well as impacts on stationary structures.

**ABSTRACT** A model of the trajectories of ice fragments thrown from a rotating wind turbine blade is used to estimate the ground impact locations that could occur under different scenarios. Wind speed, ejection position on the blade and turbine rotation rate all play a role in determining the impact point, as well as mass, density and drag coefficient of the ice fragment. For ‘compact’ ice fragments, the trajectory depends on the combination \( \frac{C_D A}{M} \) where \( C_D \) is the drag coefficient, \( A \) is the frontal area and \( M \) the mass of the ice fragment. Sensitivity tests show that ice fragments can travel further laterally for low \( C_D \) and further downwind for high \( C_D \). For plate-like fragments, aerodynamic lift can increase the distance travelled if the plate maintains an orientation to maximize lift. Although this may be a relatively rare event, we provide an example where a 1 kg plate-like fragment could travel up to 350 m from the base of the turbine. Copyright © 2011 John Wiley & Sons, Ltd.
Initial ice throw reports just used estimates based on GLGH report data plus statistics of number of ice days per year and number of ice fragments released per ice day to estimate impacts per square meter per year in areas affected by the wind farm.

But turbines vary, hub height, rotation speed, tilt, etc. and distributions are also affected by the winter wind statistics.
Figure 1: Trajectory (x,y,z) of a single, 1 kg ice fragment released at angle, Θ=45 degrees. Rotor speed, ω =14.5 rpm, r = 45 m, C_D A/M = 0.02 m^2kg^-1. U_h = 15 ms^-1.
\[ M \frac{d^2 x}{dt^2} = -\frac{1}{2} \rho C_D A \left( \frac{dx}{dt} - U \right) |V| \]  

(1)

\[ M \frac{d^2 y}{dt^2} = -\frac{1}{2} \rho C_D A \left( \frac{dy}{dt} \right) |V| \]  

(2)

\[ M \frac{d^2 z}{dt^2} = -Mg - \frac{1}{2} \rho C_D A \left( \frac{dz}{dt} \right) |V| \]  

(3)

Here, \( M \) = mass of ice fragment

\( A \) = effective frontal area of ice fragment

\( C_D \) = drag coefficient \hspace{1cm} \( \rho \) = air density

\( U(z) \) = wind speed, with the x axis oriented parallel to the wind

\[ |V| = \sqrt{\left( \frac{dx}{dt} - U \right)^2 + \left( \frac{dy}{dt} \right)^2 + \left( \frac{dz}{dt} \right)^2} \] (relative wind speed)  

(4)

\( g \) = gravitational acceleration
Landing positions for release at various radial positions and all angular positions of the blade:

Hub height wind speed = 15 m/s.

\( \text{omega} = 14.5 \text{ rpm.} \)
Figure 7: Co-ordinates (x,y) of ice fragment landing points for different hub height (100 m) wind speeds. Computations for rotor speed = 14.5 rpm, r=45 m, C_D=1, z_0=0.01 m.
a) Initial stage with $w > 0$, $v < 0$, $u < U$.

b) After reaching highest point, $w < 0$, $u < U$, $v < 0$.
Lift force directions will be highly variable, plates can rotate etc. Diagrams above are for "worst case" scenarios - lift upwards or outwards in all cases.

c) Final phase, $w < 0$, $u > U$, $v < 0$. 
Figure 10. Landing positions for 1 kg ice fragments with and without lift. Fragments released from various angles, $\theta$, at $r = 45$ m with $UH = 15$ ms$^{-1}$. Basic compact fragment case has $A = 0.02$ m$^2$ and $C_D = 1.0$. Plate like fragments have $A = 0.08$ m$^2$. With no lift but oriented normal to the relative airflow $C_D = 2.0$. With lift, and preferred orientations as discussed $C_D = C_L = 1.0$. Increments in $\theta$ are 10 degrees except for the lift case with 1 degree
Figure 11  z-x and y-x traces for selected release angles (45 deg increments), at $r = 45$ m with $U_H = 15$ ms$^{-1}$. Plate like fragments optimally oriented: $A = 0.08$ m$^2$, $C_D = C_L = 1.0$. 
Typical concerns

Frequency of ice fragment impacts on a particular property.

Frequency of ice fragment impacts on a section of road?

Frequency of ice fragments striking a moving vehicle along that road?

Mitigation measures that can be taken.

Appropriate signage on roads near the wind farm.
How to address the concerns

Icing day frequency information. Icing events during wind monitoring. - biggest problems at high (>600m elevation) sites that may be in cloud some times. How many ice fragments shed per event or per icing day?

Size and shape of ice fragments?

There is a serious lack of data!

Model calculations

Select a suitable representative ice fragment.

Run many trajectory calculations (usually 36000) for a range of hub height wind speeds 0-30 m/s (usually 1 m/s increments) with appropriate turbine rpms.

Combine with winter joint frequency distributions for wind speed and direction to get a geographic plot of frequency of impact per ice fragment release per unit area.

Integrate over any areas of special interest.
If there are turbines sufficiently close, add probabilities from multiple turbines.

Estimate the number of ice fragment releases per year and, typically, generate numbers like 20 impacts per year in field X, 1 impact per 10 years on building Y, 1 moving vehicle impact per 100, or 1000 years on road Z.

Zephyr North have undertaken several ice throw assessments and developed computer programs coupled to GIS systems to assist in computing and displaying estimates.