How can we model the ice trajectory from a wind turbine?

Introduction

Wind power has become an important source of renewable energy, offering a clean and sustainable alternative to traditional fossil fuels. However, in colder climates and areas with inclement weather, where wind energy represents an increasing part of the production of electricity, such as Nordic countries and high-altitude areas; the build-up of ice on wind turbine blades is a frequent occurrence.

Figure 1 - Ice falling from wind turbine (image taken from: https://unsplash.com/es/s/fotos/wind-turbine-winter)

When ambient temperatures drop below freezing, humidity in the air can condense and freeze on the turbine surface, leading to ice formation. This is a massive threat because the ice accumulated on the turbine can fall at any moment.

This constitutes a risk for the surrounding environment, especially for people, vehicles and infrastructures and has an impact on the turbine itself.
Differently from ice fragments that fall from buildings and pylons, which usually start from a stationary state, ice ejected from a rotating wind turbine has an initial velocity and can land at larger distances.
Because of these two different phenomena, it is defined as ice falling the detachment from a stationary turbine while as ice throwing is when the wind turbine is rotating.
Even though there are some anti-icing strategies, such as heating elements or coatings, ice throw is still a relevant problem because ice can detach when the de-icing is activated.

Background studies

Different approaches can be followed to examine the mobility and trajectory of the ice that fell or was thrown from wind turbines, even if gathering experimental data can be difficult for a variety of reasons.

First of all, on-site observations present difficulties in terms of timing and safety, it is hard to predict when the ice will form and detach and when it does, conducting experiments close to the wind turbine can be dangerous for both the people and the equipment used.

Additionally, the option of reconstructing the precise starting point of the ice-fall after the phenomena is not very reliable and could be misleading.

Lastly, conducting experiments in climatic wind tunnels, large tubes with air blowing through them which are used to replicate the interaction between air and an object flying across it, while valuable, can be cost-prohibitive.

Another option could be trying to obtain the trajectory of the ice using CFD (Computational Fluid Dynamics) that is the use of applied mathematics, physics and computational software to visualize how a gas or liquid flows, as well as how the gas or liquid affects objects as it flows past.
However, this type of computation could be very demanding depending on the precision of the mathematical model used. Therefore, the common option is to calculate the forces and moments prior to the ice trajectory.

Finally, because these were all simulations of hypothetical trajectories and behaviours, a real experiment has been investigated: the researchers collected ice fragments fallen from a wind turbine in the Austrian Alps and prepared realistic 3D replicas, adjusting the density of the model to achieve accurate representations. After that, the samples were then launched using a device that acted as a miniature wind turbine, and then they reconstructed the trajectory in a three-dimensional model and compared it with a ballistic one (that describes the launch of projectiles through the air until they hit their target), finding many differences.

Model considered

Regarding the modelled form of ice in simulations, initially in the scientific literature, it has been considered a spherical ice shape (so that the wind speed is the same from every point of view), due to its simplicity for the computation of the trajectory.

Further on, the model was improved by adopting a semi-cylindrical shape rather than a spherical one while maintaining the focus on motionless systems. However, it has been found that the trajectory and so the falling range of the ice, depend mostly on the wind speed and its direction more than the shape of the ice concretion. In fact, the maximum throwing distance introduced by Seifert et al, (2003) was assumed to be d= 1.5*(D+H) considering d as the throwing distance, D the rotor diameter and H the height of the wind turbine.

Summing up, in order to save computational time and to rely on a realistic model, this study is based upon the already-made force database generated by this last-mentioned experiment and aim to confirm the values obtained, in order to validate the model.

This study started by manipulating said database given that collected the forces and the momentum, the factor that measure the rotation dynamics, for two different ice shapes in *Figure 2* and *3* (the most relevant ones).

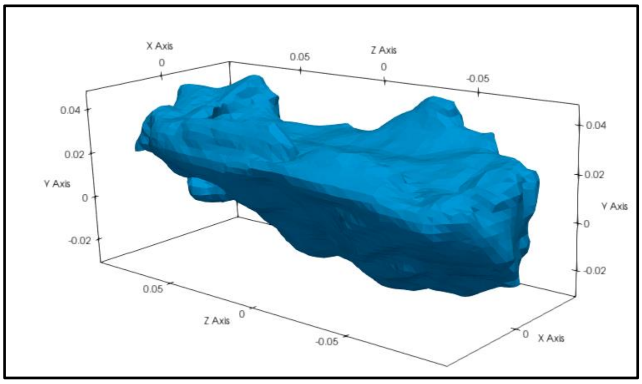


Figure 2 – DAV ice shape

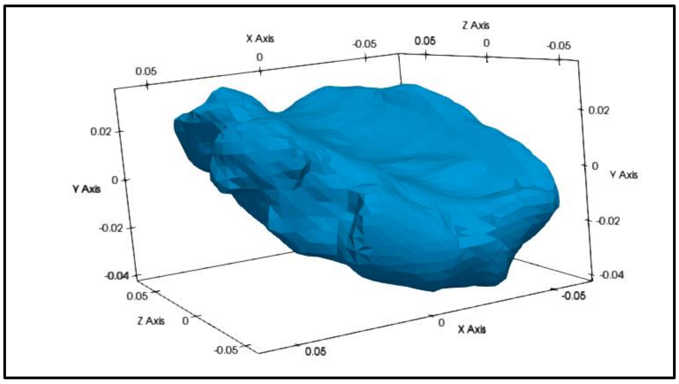


Figure 3 – DAD ice shape

Thesis development

In this research the following questions were asked:

1. How is the force behaving in function of the velocity?
2. What effect does turbulence modeling have?
3. How do the analysed parameters affect the calculation sensitivity of the trajectory computations?

Velocity effect on the forces

Aerodynamic forces, like the push or pull on an object caused by the wind, are closely related to how fast the wind is blowing.

Usually, these forces get bigger as the wind speed increases: they tend to grow much faster than the wind speed itself. For example, if the wind blows twice as fast, the forces on an object can become four times larger, they have a quadratic relations.

We wanted to test if this rule was also true in the Austrian case presented before. If it does, we could make things easier by calculating the forces just once and then adjusting them based on the square of the wind speed. This method would save time and effort while keeping the accuracy intact.

As we predicted, the results of this types of simulations confirm our hypothesis: as soon as we increase the speed of the flow the rescaled forces (divided by the square of the wind speed) do not modify much their value as pictured in *Figure 4*. The red area represents higher forces while the blue area the lower forces region, they increase generally with the speed (on the axes, from -40 m/s to 40 m/s).

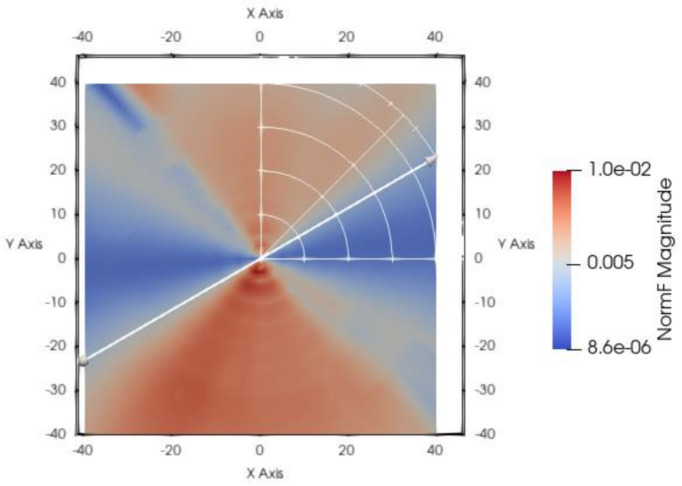


Figure 4 - Force plot in function of the speed for the DAV ice shape

This behaviour is more evident for the most irregular ice shape, at low speeds the variation is more relevant than for high speed, also taking into account how the forces rate modify in function of the shape object.

So finally, there is no correlation in between the forces and the type of flow is lost, the motion of the ice does not depend on the type of flow considered.

Turbulence models effects

Secondly, it has been explored how different turbulence models influence the accuracy of the force field, so, how the different mathematical models used to describe the air flow can modify the measure of the forces. And, for increasing detailed simulations, we expect a better evaluation of the forces acting on the ice.

To picture the turbulence phenomena, we can think of the smoke generating after blowing out a candle, initially it follows the same straight pattern as before, but while it goes up, it tends to be less and less vertical and some vortexes start to compare.

It is important to understand the mathematical models used have different sensitivity depending on the number of equations used and the type of grid defined, as shown in *Figure 5*.

In this research, two models were applied: the first more gross but faster simulation in which it is considered the mean flow of the ice (RANS); and a finer, way slower, second model in which the flow is calculated instantaneously (LES).

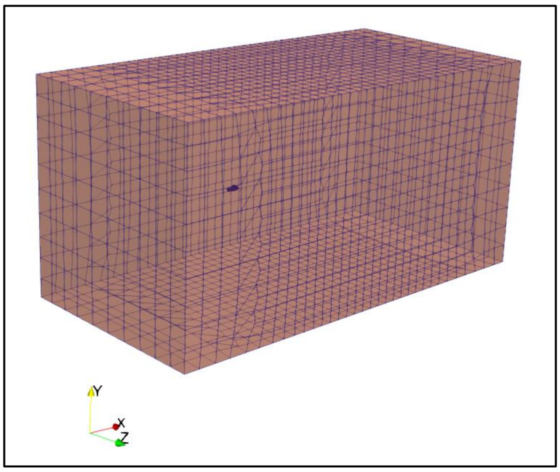


Figure 5 - Representation of the volume considered surrounding the ice

For the RANS models, as shown in the results of *Figure 6*, as soon as we increase the precision of the model used, the force values come closer and closer to the one predicted by the database, in the dotted line in *Figure 6*.

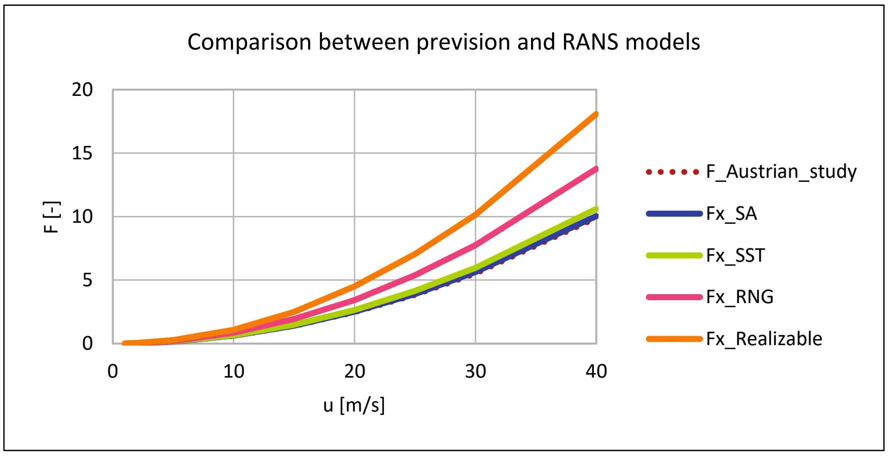
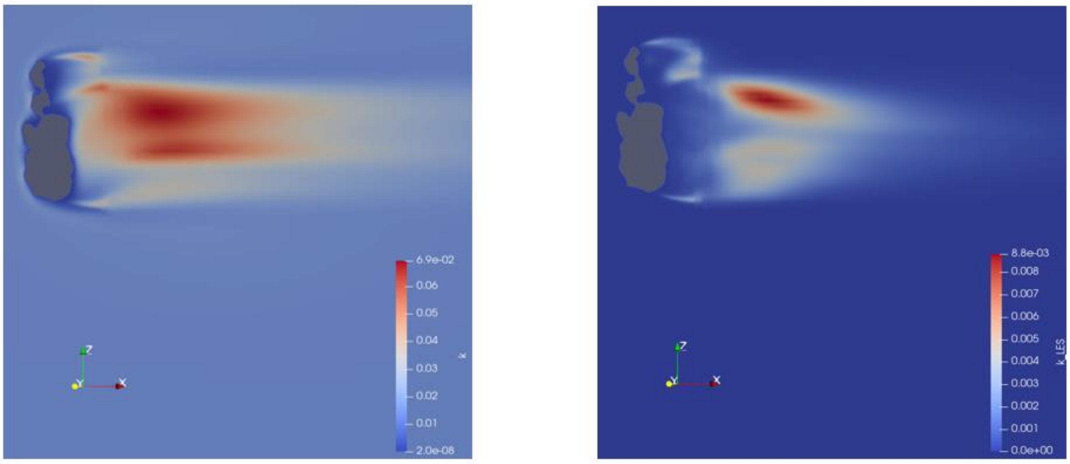


Figure 6- Results of the first model compared to the Austrian study

Nonetheless, is necessary to check this results with the more accurate LES analysis.
They give more detailed results due to the fact that they consider the instantaneous velocity and not the mean one, as in the RANS.

In *Figure 7* is shown the kinetic energy, proportional to the square of the speed, which is higher in the red areas and lower in the blue ones. In the left image, for a RANS model, the red area is much bigger than in the LES model. Therefore, we can conclude that this last one is more accurate because is showing exactly where the speed in increasing and not just the area where this phenomena occurs.



SST-k-ε model

LES model

Figure 7 - Kinetic energy comparison for RANS model (left) and LES model (right)

Sensitivity of the trajectories

Lastly, we seek to investigate how precise the measurements of the ice fall trajectory from the wind turbine. This additional accuracy study has been implemented to take into account the possibility of random fluctuations when calculating the force and the momentum.

This error can have several reasons: grid resolution, initial and boundary conditions, solution methods etc.;. So, it would be interesting to know how the effect of the magnitude variation of these inaccuracy has on the trajectories while maintaining constant the overall value of the force.

The deviation has been evaluated from a 1% and up until a 50% difference with the initial force from the database. From the results we can conclude that if the fluctuation of the force considered is low, the final impact point will have a final error of maximum one meter, so an acceptable error, considering the total throwing distance around 100m. On the other hand, if the variation increases the imprecision can reach 8-9 m.

To put it into perspective, if we consider that a car has a length of about 4m, in the worst case, the model used is mistakenly taking the impact point with a wrong distance of about two cars; and it starts to be dangerous for realistic implementations.

In conclusion, these outcomes have important ramifications for both theoretical and practical researches. Reynolds-dependence, proper turbulence models and advanced trajectory computation techniques, can contribute to help researchers improve the precision and dependability of their findings. This study lays the preliminary investigations for future advances in understanding fluid dynamics and makes significant recommendations for future research in related domains