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Reduction of wind turbines blade tip noise

- Perception and research with the aim of improving the distance rule "wind turbine to residential houses"–

The building areas for wind turbines on land (onshore wind turbines) are limited because there is a 1km distance rule in Germany. Noise from wind turbines disturbs people or even makes them ill.

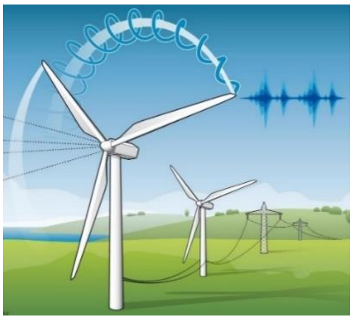
From the literature, it is possible to summarise what people hear. Simplified, the disturbing noise can be described as a whoosh-whoosh sound /1/. When these disturbing noises become harmful to health is a question for physicians and psychologists. Periodic shadows and blotting the landscape with wind turbines also play a role. These aspects will not be considered further here. The present work is about disturbing audibility and the possibility of eliminating this audibility in principle, so that a large distance to residential buildings becomes obsolete.

The present research idea takes up common knowledge of the flow around airfoils. The special feature here, however, is that for the studies of various preliminary designs a particularly simple commercial numerical calculation method is used to represent the fluid flow topology with vortices according to the so-called Q-criterion. Regarding this at first sight very own research approach, a quantitative assignment of this "vortex topology" to sound pressure levels and their spectral distribution is still completely missing. Here it is now about the description and plausibility of this research idea and the description of necessary further investigations. Further investigations are motivated so that an application becomes possible immediately and at least the disturbing aspect of the audibility of an onshore wind turbine disappears. Aspects of quiet owl flight, bionic tubercles and porous materials are taken up from basic research. By means of numerical flow simulation, it is shown how the causal blade tip vortex can be influenced and eliminated.

With regard to noise quality, a simulation is used to show that the energy of a low-frequency modulation frequency, i.e. the whoosh-whoosh noise, is distributed over the entire frequency spectrum and is not only recognisable as a fundamental frequency, as is actually expected and sometimes also claimed/2/,/3/. As a result, an interpretation of this frequency, which is referred as the technical term "blade passing frequency", as an infrasound component is inadmissible.

Hypothesis

If a profile is used at the blade tip of a rotor blade which generates lift (asymmetric profile), a blade tip vortex is created. The hypothesis is that this vortex is the main cause of the whoosh-whoosh noise /4/. Figure 1 shows a flow simulation that is in accordance with the schematic sketch of the DLR (German Aerospace Centre). Measurement results known for some years with the use of beamforming methods (acoustic camera) show the blade tip as a noise source of a wind turbine, Figure 2.



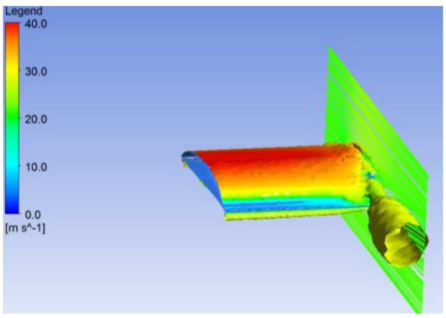


Figure 1: Schematic representation of the noise issue, source DLR, and blade tip vortex as a numerical simulation, own calculation ANSYS CFX.

https://www.gfaitech.com/applications/wind-turbine https://corvus-works.com/?portfolios=acoustics

Figure 2: Measurement results known for some years by used beamforming methods, which show the blade tip as a main noise source for wind turbines.

The type of this blade tip noise will be shown now in the following discussion and description. Residents describe the noise as a whoosh-whoosh sound /1/. With a numerical simulation using a periodic carrier frequency and a broadband noise this noise is shown in Figure 3. The data can be listened to on YouTube, see link in the caption of Fig. 3. More details of the frequency components you can see as a zoom of the frequency spectrum in Figure 4. The measurement and simulation environment Dasylab is used, which enables mathematical evaluation, a graphical representation of the noise in the time and frequency domain with and without the A-weighting oriented to the human ear, as well as auralisation.

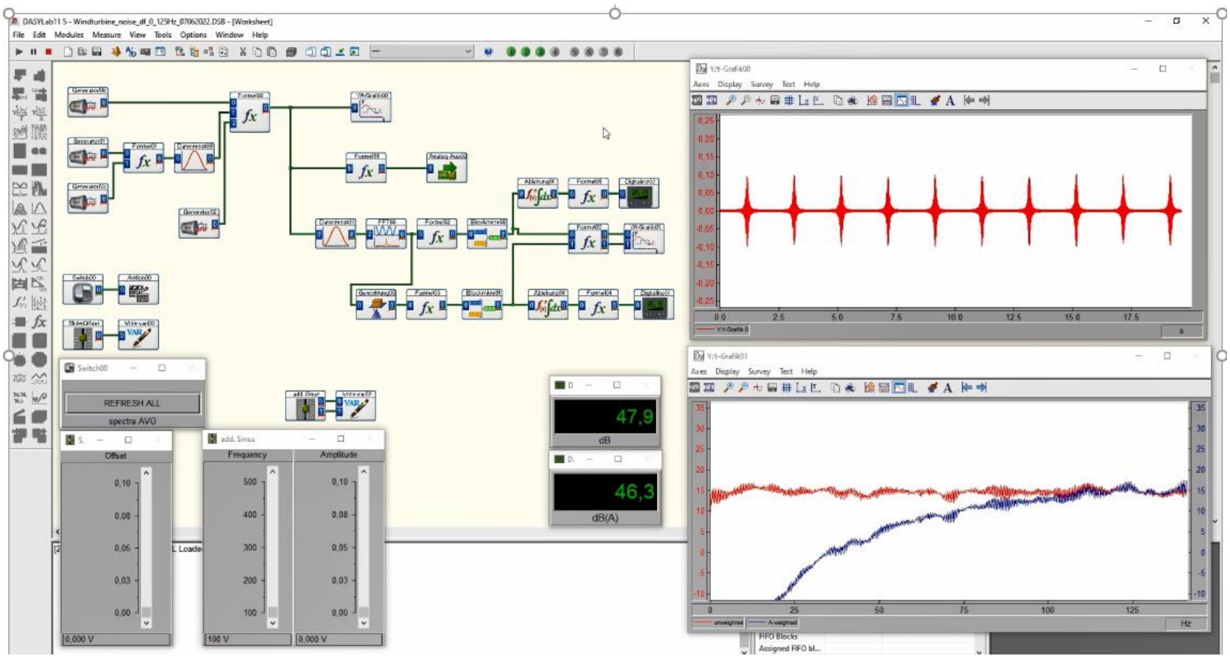


Figure 3: Whoosh-whoosh noise/1/ simulated by Dasylab as a time course and unweighted (red) and A-weighted (blue) frequency spectrum, audible under (go to minute 1:00 ff https://youtu.be/cuBdmR02XxE)

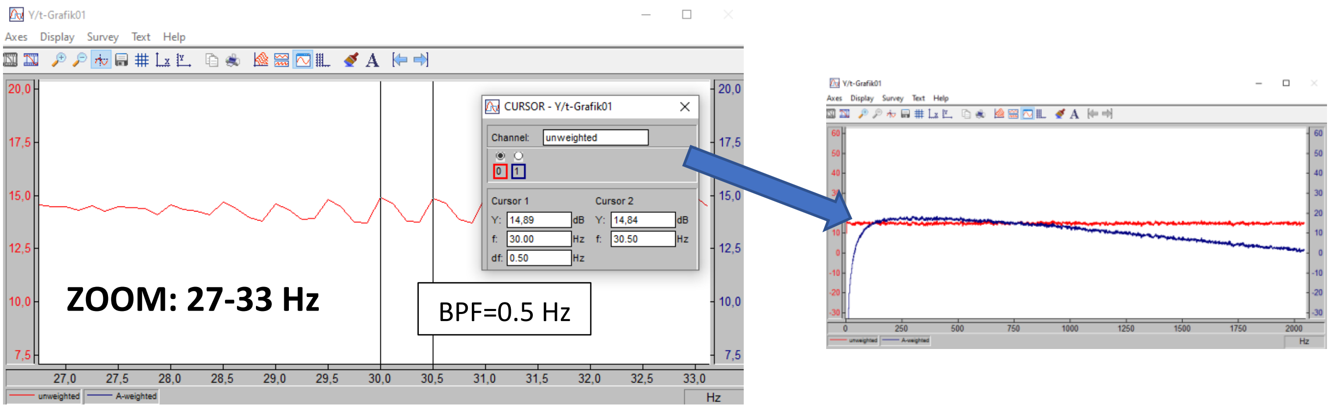


Figure 4: Zoom into the frequency spectrum of the whoosh-whoosh sound with the energy of the modulation frequency distributed broadband - the modulation frequency of 0.5 Hz is the so-called blade passing frequency (BPF).

Blade tip vortex noise

It is now shown how the vortex is generated at the blade tip and it is the cause of the audible noise, cf. also /5/. Responsible is the flow around the blade tip caused by the pressure difference from the pressure side to the suction side, which, together with the incident flow, rolls up into a vortex. If one visualises the flow around a symmetrical blade tip, there is no vortex, see Fig. 5. The reason for this is that such a profile also generates no lift. An asymmetrical profile generates lift and thus also the noise-generating vortex, see Fig. 5 on the right.

Presentation of Vortex Structures with the Q-Criterion

In order to compare vortex pattern from the numerical CFD calculation with the topology flow around an airfoil tip, an extensive vector analytical computation of the flow velocity gradients is necessary. In order to visualize vortices, the Q-criterion was used from Ansys CFD post processing, so that coherent vortex structures of the velocity gradients are visible. Generally, a shear strain is specified as a gradient of the velocity

$$\text{grad}\,\underline{u} = \begin{pmatrix} \frac{\partial u}{\partial x} & \frac{\partial v}{\partial x} & \frac{\partial w}{\partial x} \\ \frac{\partial u}{\partial y} & \frac{\partial v}{\partial y} & \frac{\partial w}{\partial y} \\ \frac{\partial u}{\partial z} & \frac{\partial v}{\partial z} & \frac{\partial w}{\partial z} \end{pmatrix} = \frac{\partial u_i}{\partial x_j}$$

This gradient can be converted with following formulas:

$$\underline{S} = \frac{1}{2}\cdot(\text{grad}\,\underline{u} + \text{grad}\,^{T}\underline{u}) \text{ and}$$
$$\underline{\Omega} = \frac{1}{2}\cdot(\text{grad}\,\underline{u} - \text{grad}\,^{T}\underline{u})$$

to the symmetric shear rate tensor $\underline{S}$ and the antimetric vorticity tensor $\underline{\Omega}$

$$\text{grad}\,\underline{u} = \underline{S} + \underline{\Omega}$$

The Q criterion is derived out of both of these tensors

$$Q = \frac{1}{2}\cdot(|\underline{\Omega}^2| - |\underline{S}^2|) > 0$$

$$Q = \frac{1}{2}\cdot\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] -$$

$$\left[\frac{\partial v}{\partial x}\frac{\partial u}{\partial y} + \frac{\partial w}{\partial x}\frac{\partial u}{\partial z} + \frac{\partial v}{\partial z}\frac{\partial w}{\partial y}\right]$$

The already shown and the following figures of the numerical calculation of the flow around the blade tip show the vortex patterns are calculated with this Q-Criterion.

In order to understand the mechanisms for eliminating a blade tip vortex here, within this preliminary framework as a kind of reversed engineering process: a vortex was first created on the symmetrical profile in the following step to create poor flow conditions. The understanding of this negative mechanism is then used in further steps to influence or even reduce the “natural” vortex of the asymmetric profile. Figure 6 shows a rotating cylinder that was placed in the blade tip of the symmetrical profile. A velocity was applied to the wall of the cylinder or the cylinder was simulated as a rotating object with strong wall friction of the fluid. Figure 7 shows the resulting synthetic blade tip vortex. This vortex is now dimensioned in such a way that it just corresponds to the negative of a real vortex with an asymmetric profile of the blade tip. Figure 8 shows the reduction of this measure in comparison: asymmetric profile without and with rotating cylinder in the blade tip. The vortex is completely eliminated in the wake downstream of the blade tip with the rotating cylinder. Figure 9 shows the necessary transport of fluid particles from the suction to the pressure side to eliminate the real vortex. However, such a measure in the blade tip of a real wind turbine still seems rather unrealistic at present, as high speeds of the rotating wall are necessary. The exact value must be determined by means of refined numerical simulations. Furthermore, subsequent investigations must prove that the eliminated vortex really leads to the complete elimination of the noise. Inspired by designs mainly from the aviation industry and Formula 1, some variants have been studied numerically and it is shown that with clear creativity further variants can and should be generated.

The central consideration of this preliminary design process is, to simulate “not more than necessary”. The approach is just to have an eye on the size, i.e. length and diameter, of the vortex core visualized with the Q-criterion. A complete simulation of the noise generated by aerodynamics needs high speed calculations on high performance computers. Here, just a simple machine fulfils the requirements for a calculation process of several minutes. More time as for the numerical calculation process itself is needed for the 3-D design and sometimes also for the meshing of especially thin structures. The quality of the used mesh is related with the auto-meshing process not high but good enough for studying vortex structures. Detailed lift and loss values cannot be calculated in such way. The simplified preliminary process is one of the main central issues of the here explained process to optimize the complex flow field and finally to reduce the annoying noise of a wind turbine. The prediction of noise levels and details of the spectral distribution of the noise is not available with such initially here given procedure. This exact noise prediction is not the aim of these first step considerations.

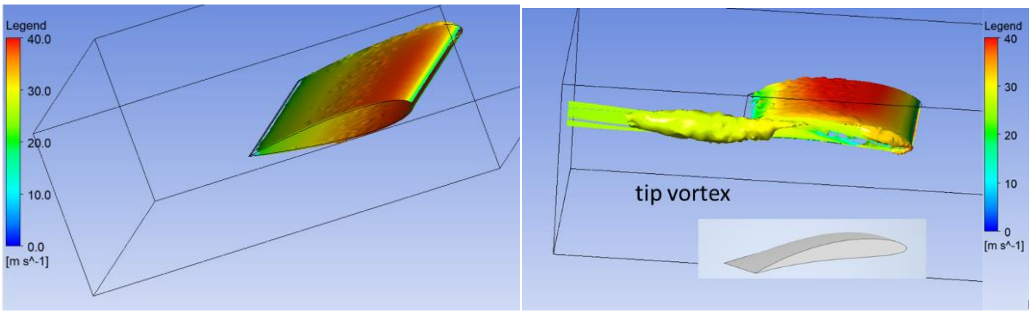


Figure 5: Flow around a symmetrical and an asymmetrical profile, 30 m/s, no vortex at the blade tip for the symmetrical profile (left).

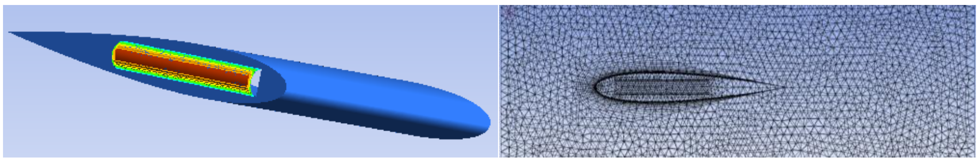


Figure 6: Cylinder in the blade tip with rotating wall and used simple mesh for the CFD.

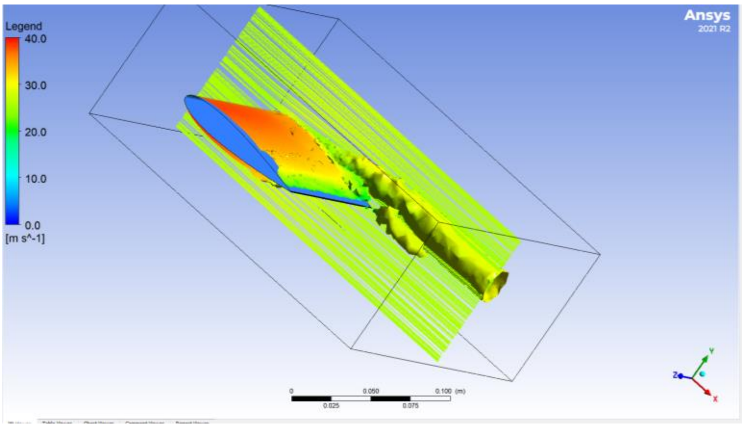


Figure 7: Flow around a symmetrical profile with a rotating cylinder in the blade tip.

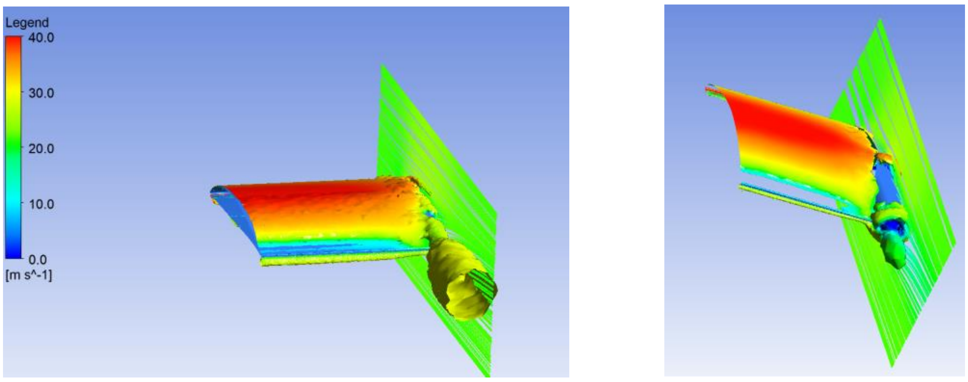


Figure 8: Comparison of asymmetrical profile with (right) and without a rotating cylinder (left) in the blade tip.

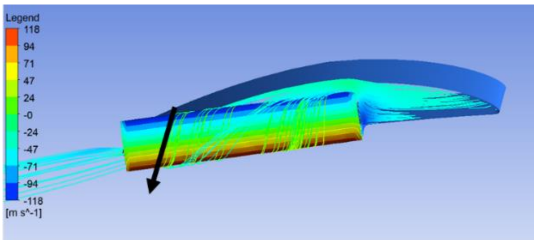


Figure 9: Mechanism of fluid transport from top to bottom through the rotating cylinder.

Figure 10 shows two variants for catching the blade tip vortex by means of a closed or an open cone, both of which, however, do not lead to a positive influence or reduction of the blade tip vortex. Comparisons with designs on aircraft wings, as collected by the French engineer Christian HUGUES www.minix.fr (Fig. 11) and further developed into a patent of his own in 2002, were the basis for his own designs on the blade tip shown in Figs. 12 to 15. Here, Figure 17 shows a further developed MINIX design, which will be explained in the further contend of these descriptions.

Figure 12 shows the simple implementation of a winglet as a flat plate at the blade tip. Figure 13 shows an attempt of a technical implementation with slots in the airfoil wall running from the suction to the pressure side, following the example of the silent owl flight /6/. Figure 14 shows the combination of winglet and slots. All three variants change the blade tip vortex, but they do not eliminate it. Figure 15 shows an attempt to technically simulated feathers in the sense of an owl. The flow simulation shows how the compact vortex is divided into smaller vortices by the technical feather elements. A step towards elimination, but not yet the extinction of the blade tip vortex.

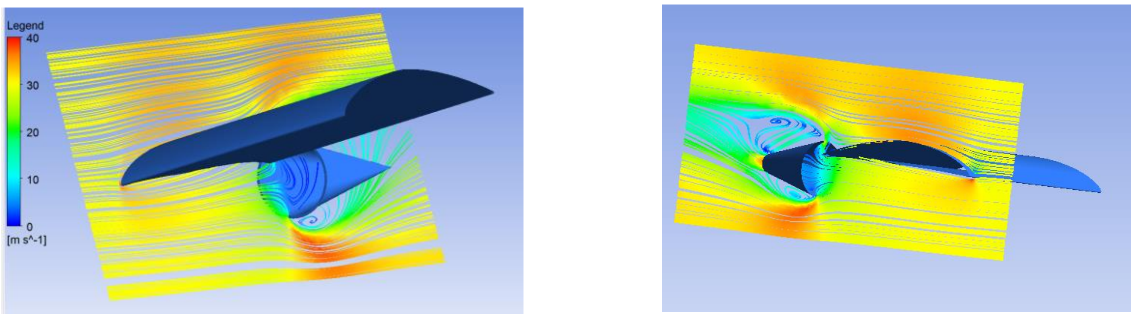
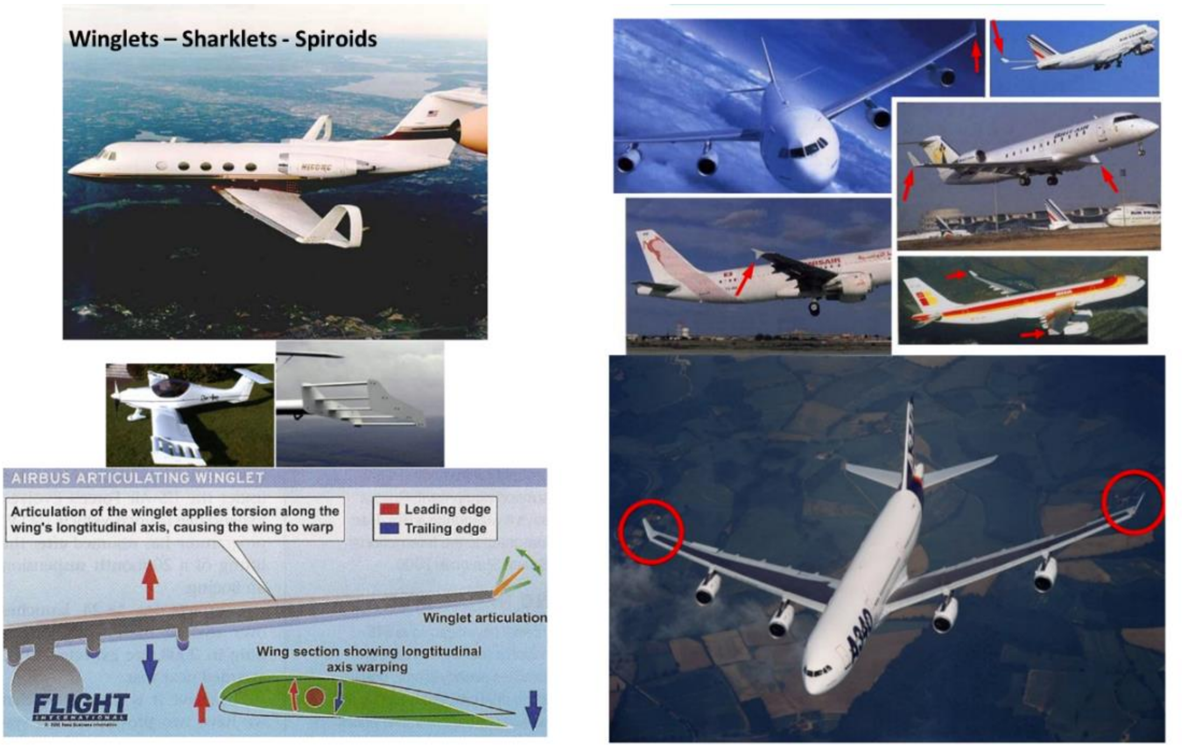


Figure 10: Catching the vortex by means of an open or closed cone.



Minix - Wingtip devices

Figure 11: Inspire aviation designs, www.minix.fr .

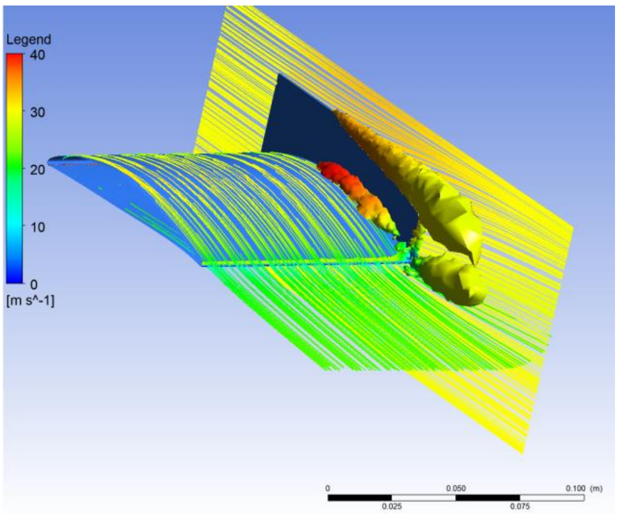
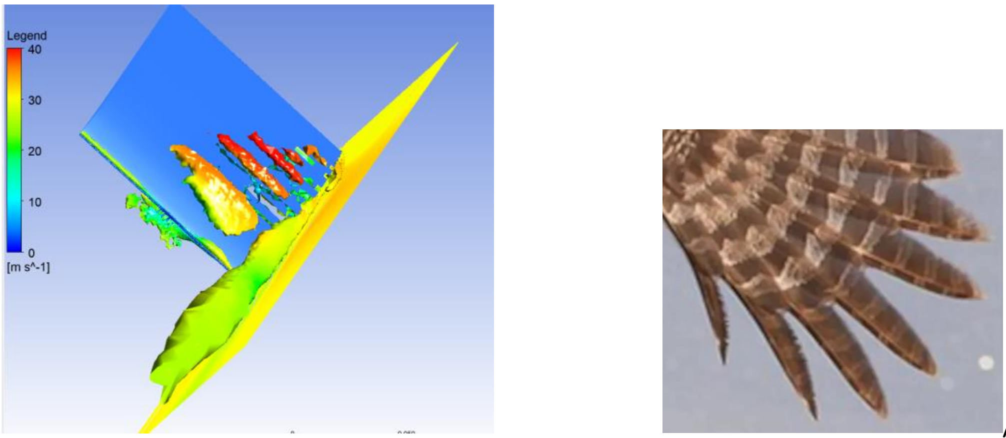


Figure 12: A flat plate at the profile blade tip as a winglet.



/6/

Figure 13: Straight slits with enlarging length to the trailing edge at the blade tip inspired by the silent flight of owls /6/.

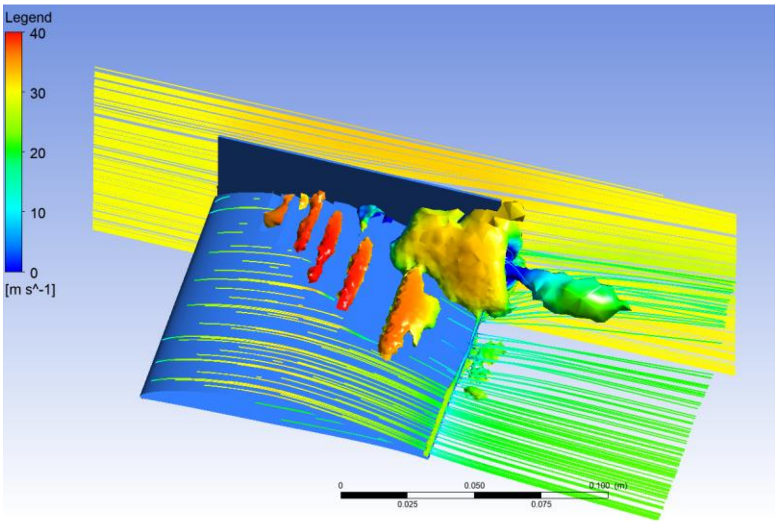


Figure 14: Slots and winglet as a combined configuration.

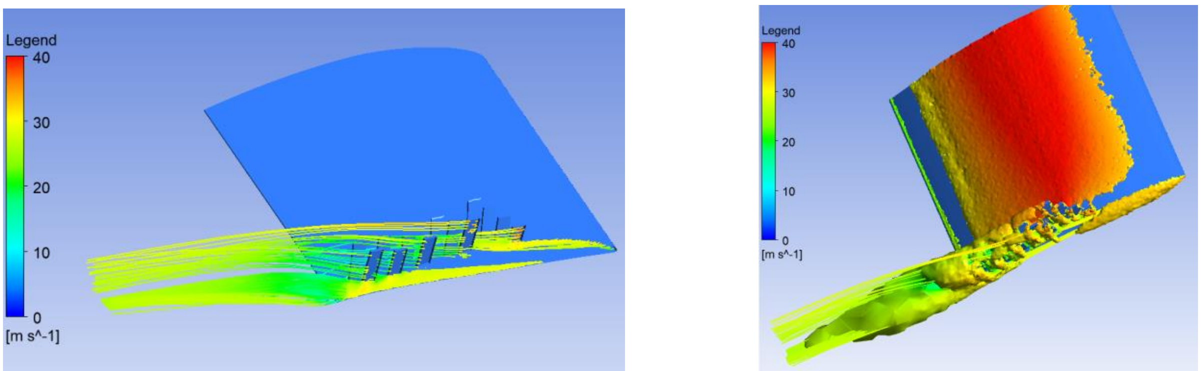


Figure 15 So named "technical feather" configuration split the compact vortex - no extinction of the blade tip vortex.

The methods described in the literature by means of blowing out or sucking the vortex /7/,/8/ are to be investigated numerically in further simulation steps. In Figure16, however, a different approach is taken, which shows a promising step forward: A profile that continuously deforms from an asymmetric to a symmetric profile reduces the blade tip vortex respectably. This approach is also not new and can be found in /9/. However, all these aspects of noise reduction are not considered comprehensively.

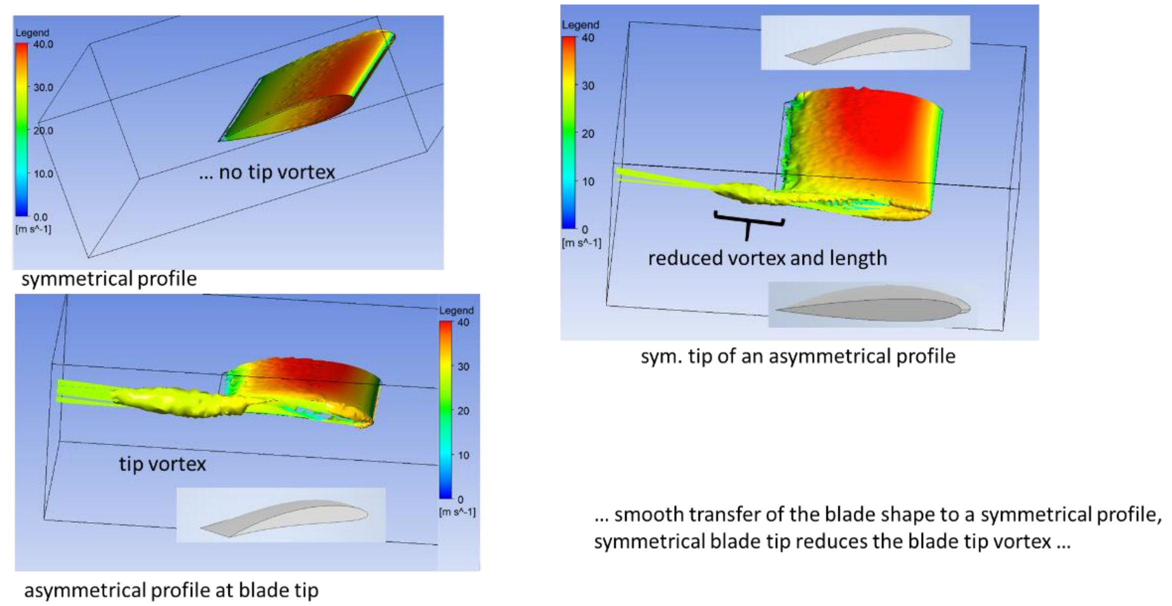


Figure 16: Sliding transition to symmetrical blade tip reduces blade tip vortex.

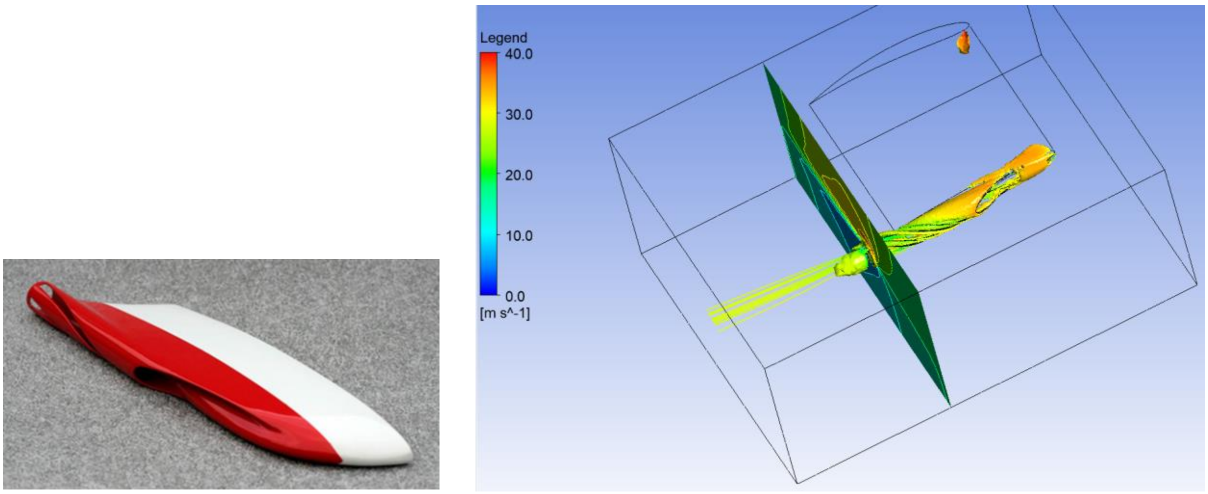


Figure 17: Blade tip design of minix.fr /21/ and an own CFD simulation with two parallel spiral-finned gaps (further developed MINIX-design). The big blade vortex decreases in size and thin vortices matche in the slits upstream of the blade trailing edge.

Figure 17 shows a more than 20 year old design from France (minix.fr /21/) which was proved on blade wing tips of small aircrafts at that time. The numerical simulation with an already optimised design of Duesseldorf, University of Applied Sciences, shows clearly a reduced blade tip vortex topology. The vortex length is reduced downstream of the blade. It looks like, that the vortex is completely disappeared but this conclusion needs further and more deeper detailed investigations. Obviously, the vortex structures are visible in smaller formations in the spiral-finned slits upstream of the blade trailing edge. This results then in a much more smaller blade tip vortex as without such a MINIX blade tip design.

Research concept

Further investigations are necessary for the technical implementation on real wind turbines. Noise reduction methods that have been successful with quiet drones and published submarine investigations of their silent propulsion systems should also be included in the considerations of the research. The advantage of the method presented here is that the numerical simulations have extremely short runtimes and numerous geometries can be investigated. Parametric optimisation, which was not used in the preliminary study presented here, will also be helpful.

The quiet owl flight is most likely related to the soft, permeable feather material, which can technically be considered a porous material. If applied, such a material could possibly amplify high frequencies but still reduce the noise globally. The possibilities for practical implementation need to be investigated. Maintenance and durability are open questions. How a quiet owl flight can technically be permanently transferred to the blade tip of a wind turbine has been successfully demonstrated here in a rudimentary way. The vortex of the "technical feather" configuration, which is still clearly present in the wake, must be further frayed and reduced. Eliminating the vortex by means of the design of technical feathers seems rather unlikely.

In the context of the present study, a suitable approach for a practical "improvement" in the sense of an evaluation of affected people is missing so far from the portfolio of possible noise reduction methods, see /10/,/11/,/12/. Standardised measurement methods of the sound of wind turbines according to DIN procedures do not give any progress for the residents. Determination of the sound power of large machines is a problem in general, as it is not possible to comply with the conditions for measuring on an enveloping surface of the sound radiation. Nobody measures what is radiated upwards from a wind turbine. Furthermore, the wind conditions in which wind turbines are extremely annoying are "tricky":

1. low wind speed conditions,
2. but fast enough for turbine operation and electrical power production.

At the Duesseldorf, University of Applied Sciences, elementary model experiments can be carried out on the acoustic wind tunnel and also numerically or synthetically. It would be evaluated whether the situation for affected people can be improved by applying the findings of basic research in order to present new arguments for a modified distance regulation between wind turbine and residential area.

Available expertise

In recent years, the Fluid Mechanics and Acoustics working group at Duesseldorf, University of Applied Sciences, has extensively investigated serrated leading edges, whose model is a whale tubercle, from point of aeroacoustics on airfoils with the transfer to axial flow machines /13/,/14/,/15/. Figure 18 also shows a certain similarity to the leading edge of an owl's wing.

Experience is available at Duesseldorf, University of Applied Sciences, in the area of blade tip vortex noise. Various demonstrators have been set up and the Institute of Sound and Vibration has an especially own developed quiet acoustic wind tunnel in which, for example, a short blade segment can be operated in rotation also according to a real blade tip of a wind turbine. In the course of industrial developments, various features for noise reduction were tested, quantified and even developed into patents. For example, the Dreamliner flies as a Boeing 787-8 with a turbulence generator developed by the Duesseldorf, University of Applied Sciences, on the outflow valve, which guides the passengers' exhaust air to the outside /17/.

Rotating sound sources were investigated at the institute, which radiate tonal sum and difference frequencies as Doppler effects in the sense of amplitude modulation. Synthetic sound scenarios as sound design is helpful to auralise the flow around the car's exterior mirror. Limits of the perception of "noise" can be defined in this way. Model experiments can now be carried out with rotating acoustic measuring equipment guided also by a robot.

Numerically, fine-scale numerical investigations of the blade tip flow have been applied to car engine cooling fans /18/ which also results in a patent /19/. Experience exists in the complex 3-D visualisation of flow topologies.

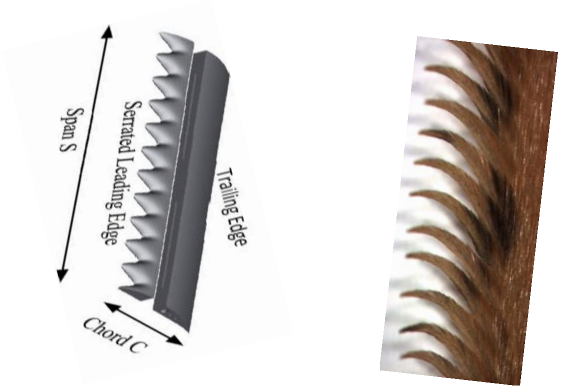


Figure 18: Technical copy of whale tubercles compared to the leading edge of a Barn Owl Wing /15/, /16/.

The measurement of infrasound beyond standardised measurement methods, as they have to be used by authorities, led to the identification of industrial emitters. In this context, experience is also available on psychoacoustic impact mechanisms of quiet noise sources. In order to avoid negative scenarios in the sense of an infrasound myth, those affected were extensively involved.

We are looking for industrial and academic partners and funding to continue our research activities.

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