Like a fish in water, rotor blades are to move sleekly through the wind and be able to react quickly to turbulence.

Photo: Fotolia / Hendrik Schwartz

Go with the flow

The efficiency of a wind turbine begins with its rotor blades. Now, these blades are to learn to react to the wind.

Wind power now plays a crucial role in global energy production. But as its success story continues, demands on wind turbines increase, as does international competition for the buyer's market. Turbines have to become more efficient to be more competitive. The key parameter is "cost per kWh." To improve that metric, the capacity of turbines has to increase even as the costs of investments, operation, and maintenance are lowered.

In addition to improvements to operations, technological developments are important. Modern wind turbines have a rotor diameter of up to 150 meters. In developing turbines, expert engineers consistently face new challenges despite the industry's many years of experience and the high performance of modern-day computers. Research is currently also being intensified in aerodynamics and rotor blade design. Here lies the key to greater efficiency.

Simulations push PCs to the limit

The complex aerodynamic and structural events that take place at wind turbines have not been completely researched. The interplay of complex physical events makes it hard to describe the overall system down to the smallest detail. A turbine runs in a constantly changing, turbulent wind field, and the aerodynamic forces of elastic rotor blades are passed on to the unit's entire structure ("aeroelasticity"). Furthermore, it is hard to map the material response of complex sandwich structures. Finally, blade rotation causes centrifugal and Coriolis forces, which lead to special flow phenomena along the blades. As a result, a holistic, detailed simulation quickly pushes even modern supercomputers to their limits.

The development of a rotor blade that works optimally under all operating conditions is an unsolved challenge for the industry. Demands are increasing because technical factors are no longer the only thing that has to be taken into account during design. The additional factors include

- high performance
- low cost
- ease of production
- transportability
- reliable operation (even under soiling)
- low noise during operation

To meet all of these requirements, engineers use modern computer software to design and simulate new rotor blades. Wind tunnel experiments are also used in the search for the best blade design. Nonetheless, current blade lengths are already at the limits of what is technically feasible. Weight is the main problem because it causes dynamic loads that fatigue the material and shorten the blade's service life. Various researchers and manufacturers are looking into ways of pushing back these limits. Germany's Smart Blade is developing new rotor blade concepts beyond conventional designs.

Next-generation rotor blades will have elements that influence airflow. They can be divided into two groups: passive and active.

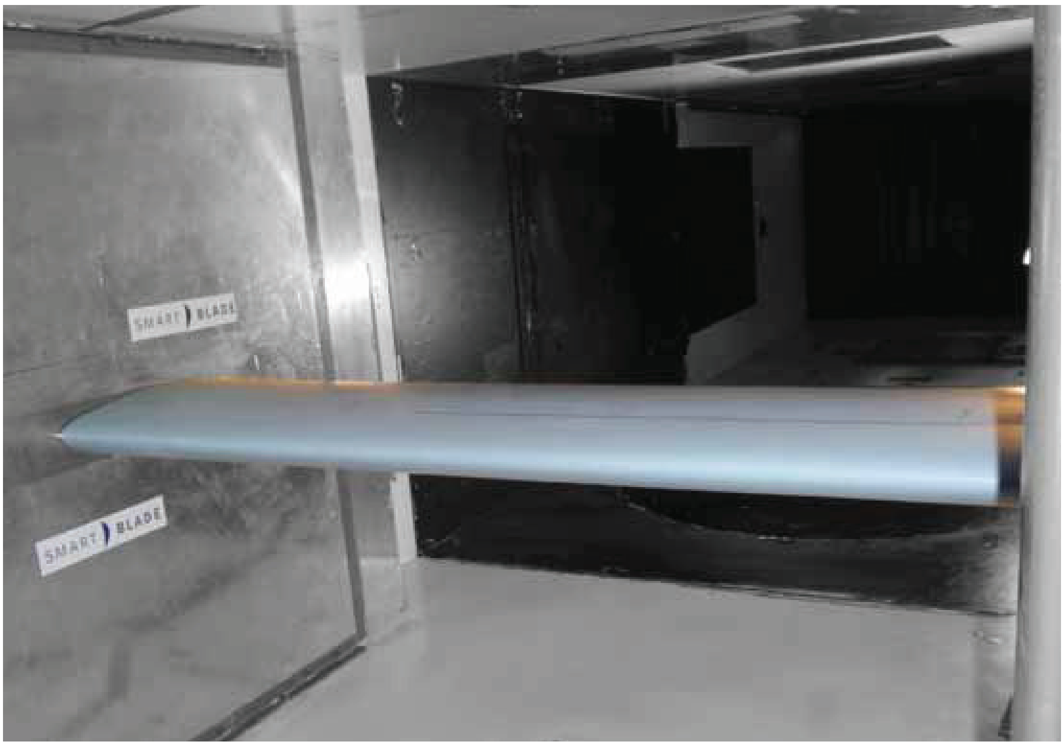
Passive flow control

Passive flow control (PFC) concerns immobile elements that are nonetheless able to change the way air flows over the rotor blade. This technology has long been used on wind turbines and is known as a vortex generator (see picture above); it is intended to prevent the flow from slowing down by giving the flow fresh energy at the blade's surface. Manufacturers and turbine owners often retrofit their rotor blades with vortex generators to improve blade performance.

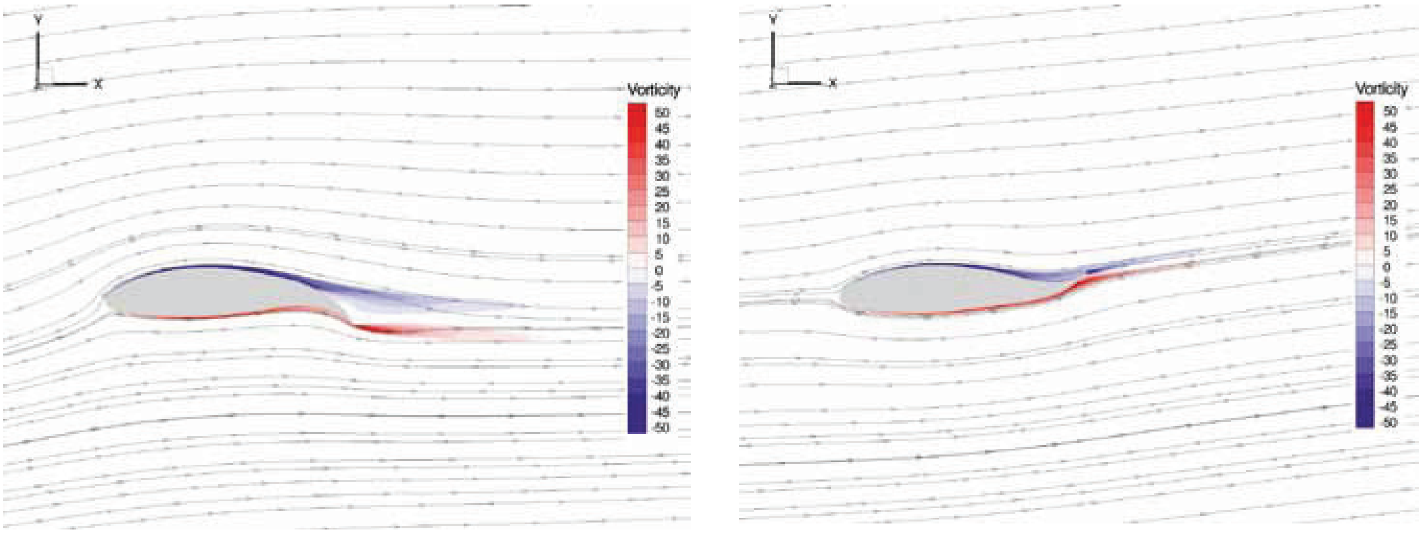
Another promising way of increasing the performance of modern rotor blades is called leading-edge slats. The concept comes from airplanes, where it is generally used for takeoff and landing; here, the slats are retractable. Smart Blade recently conducted simulations and experiments that revealed the great potential of leading-edge slats for wind turbines. The firm found that the slats reduce drag and increase lift. In particular, the slats increase rotor performance on the side of the blade facing the hub, where the rotor cuts through the air at a sharp angle.

The "Gurney flap" is another interesting PFC concept. Developed in the late 1930s for airlines, it was later used in Formula 1 racing after being rediscovered by Dan Gurney. From there, it was

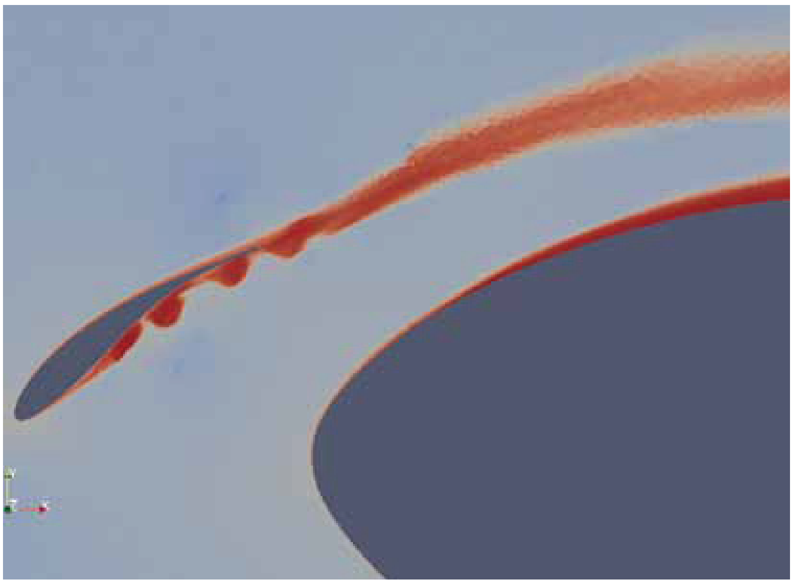
For some time now, "vortex generators" have been used on roller blades to keep wind flowing past the surface of the rotor blade.
Photo: Wikipedia / Williamborg



One of Smart Blade's prototype blades is set up in the wind tunnel for testing. Despite complex simulations, real tests are still needed.
Photo: Smart Blade GmbH



CFD simulation of a flexible trailing edge in both extreme positions. Lift is greater when it tapers to the bottom and less when it tapers to the top.
Source (3): Smart Blade GmbH



CFD simulation of a rigid leading-edge of a wing shows where pressure slows down airflow.

adopted by the wind sector to increase aerodynamic lift in order to optimize performance. Smart Blade has conducted several CFD simulations and wind tunnel tests to step up the development of customized Gurney flaps for wind turbines. The technology increases lift at the blade and improves resistance and noise characteristics.

In addition to the rotor blade's absolute performance, another decisive factor determines a turbine's profitability: rotor blade load management. Over their service life, rotor blades go through several million load cycles as the rotor spins through stochastic wind. The loads add up and can lead to fatigue over the long term.

Active flow control

Active flow control (AFC) can reduce the stress on the rotor blade structure and prevent the blade from being seriously damaged. Unlike passive elements, AFC requires energy because sensors and actuators are connected to the control system. The rotor blade can then actively react to changing flow conditions. Such systems are, however, far more complex than passive systems.

Long list of projects

A lot of wind turbine manufacturers and research institutes are currently investigating AFC concepts. The goal is to produce "smart" rotor blades – a future technology that firms are using a number of approaches to develop:

- flexible trailing edges
- flexible leading edges
- active miniflaps
- spoilers

Many of these concepts, such as spoilers, come from the aviation industry, and nature also provides inspiration that is used in bionics. For active flow control to be used on wind turbine rotor blades, however, more detailed analyses are needed. Technical implementation also needs to be further investigated.

The design, simulation, integration, and control of active elements are complex. Experience from aviation cannot be simply transferred to wind turbines, where wind turbulence characteristics are different and the blades rotate. The specific operating conditions and the limiting cost factor of the two applications vary greatly.

Better dynamics with muscle power

In developing new AFC methods, the engineers at Smart Blade are not so much focusing on individual scientific studies, but are instead taking a holistic look at wind turbines. The mechanical design of active elements is closely related to their aerodynamic design and ease of integration in the rotor blade. Furthermore, new sensor systems and control strategies are also being investigated.

Smart Blade is closely working with Tembra to develop an AFC concept: a flexible trailing edge within the rotor blade's structure based on the principles of biomechanics. Nature uses the principle of shape variation in many ways. For instance, birds, fish, and sea mammals have wings and fins that change their shape to optimally suit special ambient conditions.

AFC development is developing towards applying structural flexibility for wings and fins to a new rotor blade concept. With this principle, a test wing has been developed that can change the shape of the rear 25 percent of its wing depth. Flexible trailing edges are also based on a bionic concept thanks to pneumatic "muscles" made by FESTO. They imitate the way natural muscle fibers work and use air as a drive medium. Anisotropic contraction provides compressed air. When the pneumatic actuators draw back, they apply force to the flexible structure, which changes the shape of the flexible trailing edges.

An end to blade pitch adjustment

Aerodynamically, the wing profile's different shape changes the flow and hence the profile's aerodynamic properties. The rotor blade's aerodynamic response can be continually optimized by changing the motion of the flexible trailing edge during operation. Atmospheric turbulence and other irregularities caused by operation are quickly compensated for, reducing the overall and peak loads on the rotor blade and on the wind turbine as a whole.

As loads decrease, the turbine's reliability increases. Technical availability rises, while the frequency and cost of maintenance and repairs decrease. Despite the high upfront costs, an AFC system is therefore an especially good idea for offshore turbines, where the cost of blade maintenance and exchanges is very high.

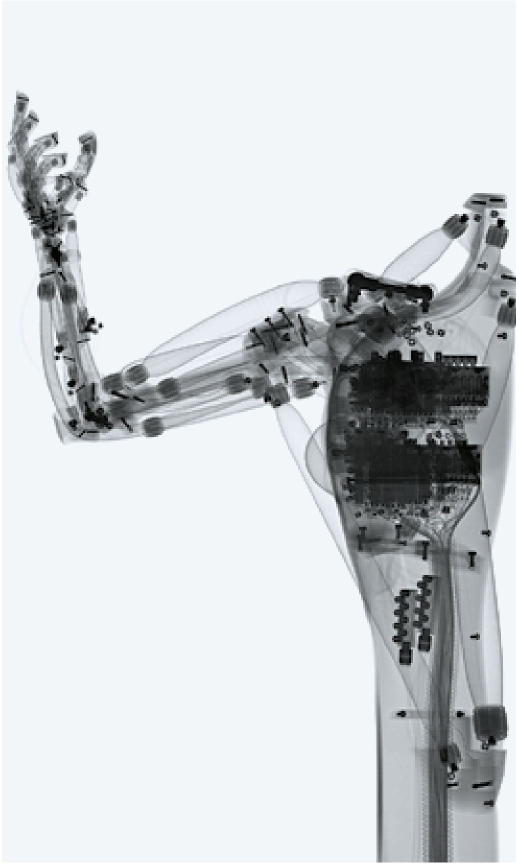
But the foremost goal of flexible trailing edges is to do even more. They would not only reduce loads, but also be able to completely control the turbine's output, making the traditional pitch system currently used unnecessary. When the pitch system and its bearings can be done without, the round blade-hub connection can also be done away with. At that point, the door is wide open to designs for future rotor blades – both aerodynamically and structurally.

Several CFD simulations already conducted confirm the great aerodynamic potential of flexible trailing edges. In addition, wind tunnel tests conducted on the pneumatically driven test wing at the Technical University of Berlin's Hermann Föttinger Institute's large wind tunnel were all positive and confirm the CFD simulation results [1].

At the moment, the AFC system is being studied using special aeroelastic simulation software to see the response of an entire wind turbine with flexible rotor blade trailing edges. In addition, new control strategies are being worked up for the load and output management of the entire turbine.

Smart blades of the future

In the foreseeable future, we can definitely expect to see smart rotor blades on the wind energy market because they will offer a number of benefits that classic blade design doesn't. The intelligence will come from numerous sensors and actuators in the rotor blades to allow a wind turbine to simultaneously detect and react to changing ambient and operational conditions. This technology will be greatly beneficial to the wind energy market because the reliability and energy output of the overall turbine will improve. Smart Blade and Tembra want to play a part in that future and come up with a market-ready concept for active flow control on rotor blades. ■



A pneumatic muscle controls Smart Blade's trailing edge. Festo, a company that has long been applying the principles of nature in technologies, made the muscle. The muscles in the AirArm are also pneumatic.
Photo: Festo AG & Co. KG

[1] G. Pechlivanoglou et al: "Active Aerodynamic Control of Wind Turbine Blades with High Deflection Flexible Flaps." 48th AIAA Aerospace Sciences Meeting, Orlando, Florida, 04 – 07 January 2010.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