A partially static turbine – first experimental results

F.Bet, G.Cabras, M.Ceschia, D.Cobai,
M.Cobal, C.Del Papa, H.Grassmann

Dipartimento di Fisica, Universita’ di Udine

The power of a wind turbine increases, when one bends a wing around it. This has recently been demonstrated in a fluidodynamic simulation based on the program Star-CD. We now present first experimental results from a prototype. This paper is a status report on work in progress. It was written on the occasion of PowerGen, Milano, june 11-13, as part of our effort to find partners in industry.

Introduction
In [1] we have shown, that it is possible to double the power of a wind turbine by installing static wings around the rotating propeller. In our model [1] the power of the turbine was 30% above the Betz limit [2] for an ideal turbine (in spite of the fact, that our very simple turbine was far from being ideal). The studies presented in [1] are based on the Star-CD simulation program.
In this paper we summarize experimental results from a prototype, which consists of a commercial wind turbine and a shroud system identical to the one used in [1]. The shroud system decreases the pressure behind the propeller.
Increasing the power of a wind turbine by means of a static shroud system can be of advantage from an economic point of view: the power of a wind turbine is determined by the area which is covered by its rotor. With a conventional wind turbine it costs between 250 and 400 Euro to cover one m² of airflow. If one can double the power of the turbine with a shroud system, which is cheaper than that, the price for wind energy would decrease.
Up to now we have studied wind turbines only, but all of the arguments should apply to water turbines as well.

Difference to existing technology
In the past there have been many attempts to improve the power of a wind turbine by means of a shroud system. The most recent example [3] is a diffuser system, which was originally developed by the company Grumman, the company Vortec built a number of prototypes. But all of the past attempts have failed, including [3]. As will be explained in more detail, these failures can be traced back to two conditions, which have not been met by the past designs:
First, the shroud system must do work for exercising a force on the moving propeller blades. Secondly, the pressure drop in the propeller cannot be larger than the energy density of the ambient air (in first approximation).
The shroud
Imagine a wind turbine with a huge vacuum cleaner placed behind it. As long as the vacuum cleaner is operating, the power of the wind turbine will be increased, due to the low pressure field created behind it. But as soon as the vacuum cleaner is switched off, the power of the turbine will go back to its normal value. The vacuum cleaner needs to do work, in order to increase the energy output of the turbine.
This remains true, if one uses a shroud to create a field of low pressure behind the turbine, instead of a vacuum cleaner. The shroud must exert a force on the propeller blades, and since these blades are moving, energy is needed to maintain this force. This energy can only come from the flow of air through the shroud.
In [3] and in similar proposals, the turbine is neatly embedded in a diffuser shroud, there is little or no space between the tips of the rotor and the inner surface of the shroud. The airflow through the propeller and the air flow through the shroud system are identical - the propeller and the shroud system would need to extract energy from one and the same flow of air. But one cannot extract energy from the same flow twice. And therefore the effectiveness of the system [3] must be very limited. (We have performed a fluidodynamical simulation of the system described in [3] and found, that the shroud increases the power of the turbine by 30% only, in spite of the large dimensions of the shroud system.)
Our solution to the problem is, to mount the wing at a relatively large distance from the propeller - the flow of air, which passes between wing and propeller is about as large as the flow of air, which passes through the propeller itself.

The propeller
Energy conservation must be required also for the propeller: if air flows through a propeller at the speed v, the propeller causes a drop in pressure, Δp, which is Δp = αv^2, α being a constant given by the propeller design. This pressure drop corresponds to the energy being extracted from the flow of air, and it cannot be larger than the kinetic energy (density) of the ambient airflow, of velocity \(v_{amb}\), that is \(1/2 \rho v_{amb}^2\). Therefore for conventional wind turbines, \(\alpha\) should be typically between \(\rho\) and \(2\rho\) (\(\rho\) density of air).
When one increases the speed, \(v\), at which air flows through the propeller, the value of \(\alpha\) must decrease, so that \(\alpha v^2\) remains smaller than \(1/2 \rho v_{amb}^2\). A shrouded wind turbine must have a small efficiency \(\alpha\).
We note, that this discussion is approximate, in so far as it considers the propeller to be a disc which absorbs energy. A more detailed discussion of what happens in a real propeller must be left to a future investigation.
Of course, the blades of a shrouded turbine should also be optimized from a purely aerodynamic point of view, like in a conventional turbine, in the sense that they shall not excessively cause turbulences or friction.
The studies in [1] had the primary goal to explore the wing system, and the propeller was not a primary subject of our studies. The propeller actually consisted of 36 small two-dimensional blades (baffles), which were created by simply distorting somewhat the mesh of the simulation domain.
The prototype
In order to keep the cost of the entire project as low as possible, we have purchased the smallest commercial wind turbine, which we could find in the market, the Aerogen 2 from the British company LV motors. It has a diameter of 56 cm.
For reasons of consistency we used a shroud system which has the same geometry as the one described in [1], consisting of two wings. The wings were constructed in fiberglass and wood by the company A. Sturli, Italy.
This Aerogen turbine comes equipped with propeller blades, which do have the same angle of inclination with respect to the ambient wind direction all over their radius.

Measurement procedure
Up to now we had no wind tunnel available. In order to do some first tests we therefore mounted two turbines on the top of a car, numbered “1” and “2”. Driving at various speeds, we record the tension produced by each of the two electrical generators, V1 and V2. We do this first without a shroud system, then we repeat the measurement with a shroud system mounted around turbine 2. In this way we can measure the increase of voltage V2 caused by the shroud system, as a function of V1. When we operate the generators as open circuits, the voltage is simply a measure of the speed of rotation of the propellers. When we use an ohmic resistance R as a load, we can measure the power provided by the generator, V^2/R.

First results
According to Star-CD, the original propeller blades of the Aerogen generator cause a large vortex behind the propeller, because their inclination with respect to the ambient wind direction does not change over their radius. This vortex gets further enlarged by the external wing structure. As a consequence, in the simulation the shroud increases the power of the turbine by only 20%. This is in agreement with our measurements.
As a first step towards getting more suited blades, we made a design which is identical to the original blades, but it does have an inclination which changes over the radius of the blade, in such a way, that the apparent wind always has the same direction with respect to the blade (provided the true wind velocity is constant over the area covered by the propeller).
Based on this design, the rapid prototyping laboratory of Prof. C. Bandera of the University of Udine (with M.Zanzero and M.Felice), created a set of new blades for our turbine. Though these blades are not yet optimized, the performance of the turbine should already improve.
Figure 2 compares the voltages measured at the two turbines, V1, V2, without and with shroud mounted at turbine 2.
Figure 3 shows the factor by which the shroud increases V2 as a function of V1. We see that the voltage, and therefore the speed of rotation of the turbine increases by 27% without any ohmic load. If the output terminals are connected by a resistance, the increase in voltage is 25% at high wind speeds, and up to 40% at low wind velocities. This corresponds to an increase in power of 55% to 100%.
The power of the turbine as predicted by Star-CD is shown in figure 4, at a wind velocity of 5 m/s and at different speeds of rotation, \( \omega \). (In good approximation one can obtain
from figure 4 also the power curves at different wind velocities: for a wind velocity which is larger than 5 m/s by a factor $\beta$, one would simply multiply the scale of the horizontal axis by $\beta$ and the vertical axis by $\beta^3$.) Figure 4 also shows the power of a hypothetical generator as function of $\omega$. One can see, that the system of generator and propeller should respond to the external wing system with a power increase of about a factor of two at small wind velocities and of about 50% at large wind velocities. This is in agreement with the experimental observation. (We can measure the voltage of the generator for different speeds of rotation and for different loads in the laboratory. This would allow to reconstruct the power of the turbine in function of $\omega$ from the experimental data. This will be done in the near future.)

We think that at this point we can already firmly conclude, that a coupling between the low pressure field built up by the wing and the low pressure field behind the turbine does take place in our experimental device, confirming the fluidodynamic simulation (one can actually see the strong increase in absolute pressure of the air flow between propeller and wing in Star-CD). To the best of our knowledge it is the first time that this effect has been described and proven experimentally, and doing that was our major concern up to now.

We need next need to optimize the propeller. One of the concerns there is to design a propeller with low $\alpha$ ($\Delta p = \alpha v^2$). As a matter of fact, we find that both our turbines, the one in the simulation in [1] and the prototype itself, are limited by their $\alpha$: in both cases, the propellers indeed extract about the same energy density $1/2 \rho v_{amb}^2$ from the air flowing through them ($v_{amb}$ ambient air velocity). The velocity of the air when passing the propeller, $v$, is about 1.2·$v_{amb}$ in [1], and about 0.7·$v_{amb}$ in our present prototype.

Possible applications of the new technology

One could substitute a large size wind turbine with a system of equal size, consisting of a small wind turbine and a shroud system, in order to reduce the production price for wind energy. For reasons of consistency we have used for our prototype a system of two wings, as in [1]. But in meanwhile we have found, that one can also use one single wing as a shroud, or simply a bent two-dimensional surface, like a sail. We have tried a few “sail shapes” together with the turbine used in [1], and always found a power increase between a factor of 1.9 and 2.0, an example is shown in figure 5.

The price of a conventional wind turbine is between 250 Euro and 400 Euro per m$^2$. To double the power of a turbine, one needs a shroud with about the same surface as is covered by the propeller, therefore the shroud needs to cost less then 250 to 400 Euro: One m$^2$ of sail costs about 10 Euro, to this one must add the cost of the supporting structure and labor. One would prefer to have a professional estimate of the cost of such a sail, but it is hard to imagine that it should cost more than 100 Euro per m$^2$. Actually, even a flat plate can be used, instead of a sail, though at the price of a lower efficiency. It should however be possible to avoid this disadvantage when combining a multitude of small plates. This again might offer alternatives for a low budget production.

Instead of mounting one shroud around a single turbine, it might be possible to insert an array of small turbines into one large shroud. Large wind turbines suffer from the fact that wind speed increases with height over ground. As a consequence, the turbines are subject to oscillating forces, and
furthermore the blades cannot be run at the optimal inclination. Installing a wing structure in the lower part of the propeller, one can increase the wind speed there. This would at the same time eliminate oscillations and it would increase the power of the turbine. Important applications for this new technique might be found in flows of water. There one cannot only extract the kinetic energy, but also the potential energy. We did not yet make simulations with water, but instead investigated a flow of air in a closed tube, as shown in figure 6. Part of the flow passes between the wall of the tube and the turbine. Due to the bending of the wall, the turbine extracts energy from this flow. Of course, one could insert additional bent surfaces and in this way one could substitute for instance a large Kaplan turbine with a small one, inserted into a system of static bent blades. Our system would allow to make efficient use of very small differences in water level (since it causes an increase of the pressure drop at the turbine). Also, the turbine and its associated shroud system should be able to create this difference in water level in a dynamic way, without a static dam being needed. And since most of the water would not need to flow through the turbine itself, also fish could migrate through the device. These would be interesting advantages from an ecologic point of view and consequently water power might become usable in places, where one cannot use it nowadays.

Conclusions
We have achieved for the first time a significant increase in the power of a turbine (55% to 100%) by means of a small size shroud system (the surface of the shroud is about as large as the propeller). This confirms experimentally, that indeed a coupling of the low pressure systems caused by the wing and by the propeller, respectively, does occur, and that therefore the propeller extracts energy from a flow of air, which does not pass through the propeller itself. The effect we observe in the experiment is in agreement with the prediction from Star-CD. The power of our system is limited by the properties of the propeller. Star-CD predicts, that with an improved propeller the power of the turbine should double. We are in the process of improving the propeller.
The size of the wing structure is about as large as the area covered by the propeller. Since wind turbines cost about 250 to 400 Euro per m$^2$ covered by their propeller, one can decrease the cost of wind energy, if the shroud system costs less than 250 to 400 Euro. A professional calculation of the cost of such a shroud is not yet available and needs to be a high priority. However, there are arguments which reasonably suggest, that a shroud can be built for less than 250 Euro per m$^2$. Increasing the power of our turbine by a factor of 2 serves us merely as a reasonable milestone for our activity, the factor of 2 does not represent a fundamental limit. From a physics point of view larger increases in power should be possible.

The principle described in this paper can also be applied to a flow of water. It should be possible to substitute large size turbines by small ones, which are embedded in a fixed structure of bent blades. It should be possible to exploit also small differences in the water lever before and after the turbine. Since furthermore only a small fraction of the water flow needs to flow through the turbine itself, a power generating system can be thought of which would avoid all of the disadvantages of conventional hydrodynamic systems from an ecological point of view.
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Figure 1: Prototype mounted on car.
Figure 2: turbine 2 without and with shroud mounted.
Figure 3: increase in generator output voltage $V_2$ due to wing system, as function of $V_1$. Generator 2 is operated without load (open circuit, dotted line), and with a load of 72 Ohm or 110 Ohm, respectively. A wind velocity of 8 m/s corresponds about to $V_1 = 53 \text{ V}$, and at 4 m/s we have about $V_1 = 18 \text{ V}$. The error bar at the right indicates the uncertainty of the measurement.
Figure 4: power absorbed by the propeller for different speeds of rotation, $\omega$, at a wind speed of 5 m/s, as calculated by Star-CD. The power of our generator is proportional to $\omega^2$. In the figure we indicate the power of a hypothetical generator in function of $\omega$ : $a\omega^2$, The dotted line would indicate a “stronger generator” of the same kind. One can see from the figure, that for this stronger generator the increase in power is larger. This amounts to saying, that for a given generator the increase in power will be larger at small wind velocities.
Figure 5: as in [1], but wings are substituted by sail shaped surface.

Figure 6: air flow in a closed tube with sail shaped surface.