Laser Anemometry for Control and Performance Testing of Wind Turbines

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Contract JOR3-CT98-0256

Publishable Final Report

01.07.98 to 29.09.01

Research funded in part by
THE EUROPEAN COMMISSION
in the framework of the
Non Nuclear Energy Programme
JOULE III

CONTENTS

ABSTRACT

The basic idea for the current project is to have a laser anemometer mounted on top of the nacelle. The laser anemometer is remotely measuring the wind velocity in front of the turbine by scattering laser light from the airborne aerosols. The measurement will automatically be in the upstream direction, as the nacelle will always - by means of a yawing system - be pointing towards the wind direction. Three main purposes of the project are addressed: Design and build such a laser anemometer, including assessment of the end production costs and reliability into the design considerations. Analysis both theoretically and experimentally, of the application of the laser anemometer wind measurements for improving the operation of wind turbines. And, analysis of the use of the laser anemometer as a substitution for the masts with cup anemometers for performing power curve and other test measurements.

The main outputs of the project are:

- A "demonstrator" of a dedicated, fairly inexpensive laser anemometer for test of operational principles and quality of measurements.
- Theoretical model(s) of the wind flow in front of the wind turbine.
- Analyses of the task and problems related to controlling a wind turbine using a laser anemometer, to provide a decision basis for the possibilities of using the laser anemometer.

Risø National Laboratory has gained experience with laser anemometry through systems built for plasma physics research under the nuclear fusion programme. The laser anemometer, built during the current project, focuses a single laser beam through the region where the wind velocity is to be measured. The wind velocity along the laser beam is measured from the Doppler shift of the light, scattered backwards from the elongated region where the laser beam is focused. Due to cost considerations, the detection method implemented does not allow the laser anemometer to tell velocities toward the instrument from velocities away from the instrument. The laser beam is assumed to always be pointing against the wind direction.

An investigation was conducted with the aim of providing a measured up-stream wind speed for control purpose. A set of measurements was made with a mast cup-anemometer. The investigation was concentrated on finding the standard- and maximum deviation between the wind speed measured with the laser anemometer, and the actual wind speed that the turbine was subjected to. In the investigation the following main themes were included: Deviation within the averaging time of the measured signal; deviation due to lack of correlation between the measured wind speed and the significant wind speed at the rotor and deviation due to the influence from control system response time. To provide comparison data for methods competitive to the up-stream measuring method, a persistency method based on the nacelle cup-anemometer wind speed, and the same based on the turbine power were included in the comparison.

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2. OBJECTIVES OF THE PROJECT

The general objective of the project is to improve the market position of wind power by reducing cost of the energy produced and by enhancing the credibility by more accurate performance assessment. Optimisation of the efficiency of wind turbines and, in turn, measurement of that quantity include accurate measurement of the wind speed upstream the wind turbine.

The technological development in the wind power industry points towards having the wind turbines built with pitchable blades and variable rotational speed of the rotor. This increased operational flexibility of the turbines potentially allows for a number of improvements: Higher efficiency through a variation of the rotational speed of the rotor, while above a certain wind speed the task is reversed to limiting the power to match the capacity of the electric generator. The removal of excess power fluctuations enables a reduction of the dynamic loads on the transmission system. Further, in conjunction with power electronics, full control of blade pitch settings and rotor speed will facilitate a better integration to the surrounding electric power grid and provide for a minimisation of acoustic noise.

To fully utilise such flexibility of future wind turbines, an expanded control system must be implemented. The design of such a control system implies extended modelling of the wind field in front of the turbine and the development of new control techniques to be incorporated in the computer programme. A possible new type of input to this control system is a forecast of the wind speed extending a few seconds ahead.

A laser anemometer mounted on the nacelle and focusing a laser beam in front of the wind turbine will be able to measure the wind speed ahead of the turbine. Laser anemometers have not previously been nacelle-mounted and applied for the purpose of control and performance assessment because of excessive size and costs of the equipment. It is believed that the technological development now makes it possible to design, build and apply a laser anemometer at an acceptable cost and size.

Presently, cup anemometers mounted on the wind turbines are used for operational control, and conventional cup anemometers mounted on towers in front of the wind turbine serve as reference for power curve measurements. The basic idea for the current project is to have a laser anemometer mounted on top of the nacelle that remotely measures the wind velocity in front of the turbine. The measurement will automatically be in the upstream direction, as the tower will always be pointing towards the wind direction. The best choice for this device is found to be a laser anemometer that focuses a single beam of laser light in front of the turbine. Three main purposes of the project are addressed: Design and build such a laser anemometer, including the ending production costs and reliability into the design considerations. Analyze both theoretically and experimentally, the application of the laser anemometer wind measurements for improving the operation of wind turbines. And, analyze the use of the laser anemometer as a substitution for the masts with cup anemometers for performing power curve measurements. The project is aimed directly at present bottlenecks in wind turbine development.

The target output of the project is

- A fully flexible “general purpose” laser anemometer for test of operational principles and quality of measurements.
- A “demonstrator” of a dedicated, fairly inexpensive laser anemometer for operational control and measurements. It is expected that the fully developed (dedicated) anemometer can be made compact, with dimensions 20x30x50 cm, which will make it applicable for operational control as well as test purposes.
- A theoretical model for the wind flow in front of the wind turbine.
- Analysing of the task and problems related to controlling a wind turbine using a laser anemometer, to provide a decision basis for the possibilities of using the laser anemometer, and to provide further demands on the dedicated laser anemometer.

3. SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE PROJECT

The scientific and technical description of the project is discussed task-by-task as given by the contract.

3.1. System definition and requirements

The concept is based on a laser anemometer mounted on the nacelle of a wind turbine. The anemometer shall measure the wind coming upstream the wind turbine. The measuring principle is as follows: The laser anemometer is mounted on top of the nacelle (or in the hub) and focuses a beam of laser light at a distance in front of the wind turbine, see Figure 10. The airborne aerosols in the focal region of the laser beam are scattering a small amount of the transmitted laser light backwards to the laser anemometer. The aerosol particles are assumed to have the same velocity as the air mass carrying them. The velocity component of the aerosols along the laser beam introduces a Doppler shift on the frequency of the back-scattered laser light and the wind velocity is determined from this Doppler shift. The laser anemometer is only measuring the wind component along its line of sight. As the whole instrument is mounted on top of the nacelle and the nacelle is constantly pointing against the average wind direction, the errors on the measured wind velocity due to an angle between the wind direction and the laser beam pointing direction are small. Likewise, the laser anemometer needs not to be able to determine the wind direction.

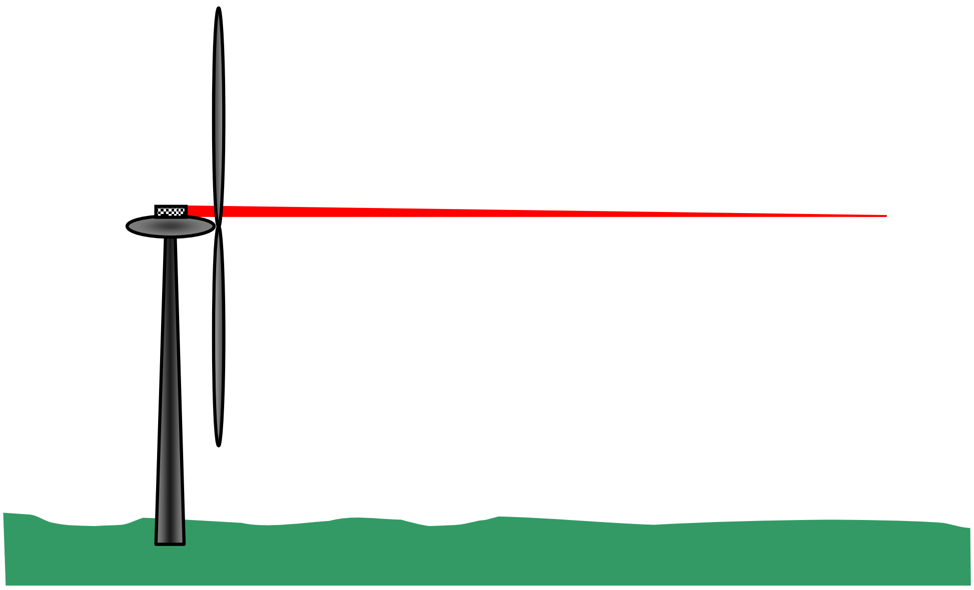

Figure 1. The laser anemometer mounted on top of the nacelle and focusing a beam of laser light against the wind direction in front of the turbine.

The requirements below determine how far away the wind speed shall be measured:

1. The measured wind should be unobstructed by the turbine and
2. The measurement should be done so far away that a ‘feed forward’ control, which compensates for the response time of the turbine itself, could be applied.
3. For power performance assessment of wind turbines, the measuring distance is related to the cross-section of the turbine. According to the test criteria given by the IEC61400-12 norm, the wind velocity should be measured two rotor diameters in front of the turbine. For turbines in the MW-range a rotor diameter of about 60 m is anticipated.
4. The measured wind velocities are, to some extend, an average value of the velocities contained within the focal region of the focused laser beam. This spatial averaging must occur on a scale smaller than the rotor diameter.
5. The width of measured spectrum of the Doppler return is broadened by the air turbulence along the focal region. A broadening of the Doppler spectrum causes difficulties in determining the temporary position and frequency of the weak Doppler signals in an otherwise noisy detector signal.

The above requirements have led to a target measuring (focusing) distance of 150 m, and a maximum length of the focal region of 40 m. The general-purpose laser anemometer should be capable of doing measurements in different directions and at different distances. The dedicated anemometer measures only in a fixed direction and at a fixed distance.

The accuracy of the wind velocity determined from 10 min. averaging of the wind speed should be as good as obtainable with present cup-anemometers, i.e. approximately within 2% of the average velocity.

3.2. The dedicated and the general-purpose instrument

The original project programme included a “general-purpose” instrument and a “dedicated” instrument. The general-purpose instrument should be able to measure the wind velocity at variable distances and directions whereas the dedicated instrument should be designed for a fixed measuring distance and direction. The design of both instruments can threaded in common. The dedicated instrument is the same as the general-purpose instrument but with the telescope mirrors in a fixed position. The whole instrument can be turned in order to change the direction of measurement. In the following, the otherwise separated tasks for designing the dedicated and the general-purpose instruments are combined.

3.2.1. System architecture

The laser anemometer focuses a beam of laser light to the desired measurement distance. The airborne aerosols in the focal region scatter a small amount of the transmitted light back to the laser anemometer. The optics, the electronics, and the computer internally in the anemometer performs the optical and electrical processing of the back-scattered signal. Each measured wind velocity is transmitted through an Internet TCP/IP connection to the remote computers; running appropriate client software, see Figure 2. Likewise the remote computers are able to switch the laser on and off for safety.

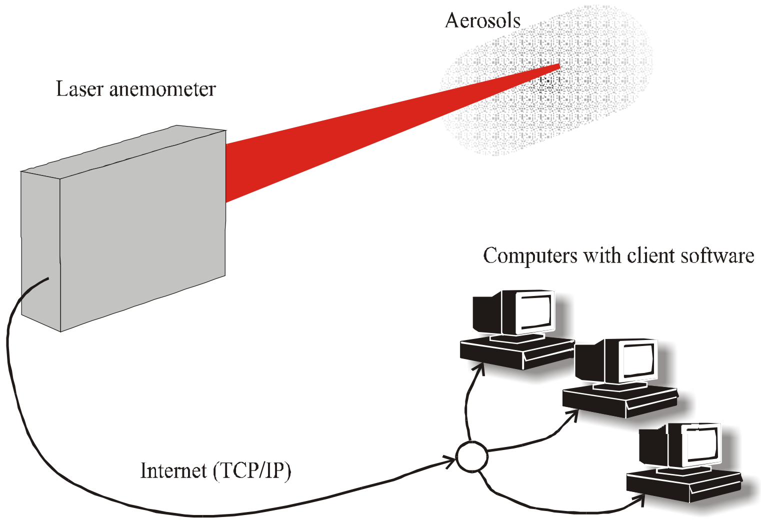

Figure 2. The laser anemometer is controlled from, and transmits the measurement results to remote computers via the Internet.

The velocity of the aerosols introduces a Doppler shift on the backscattered light. This Doppler frequency is only proportional to the component of the velocity along the laser beam, $f_d = 2\frac{v}{\lambda}$, where v is the velocity component towards the laser anemometer, and λ is the wavelength of the laser optical output (λ=10.59µm for the CO_2 laser). The velocity-to-Doppler frequency factor becomes 188.679 [kHz/(m/s)]. At wind velocities from 2m/s to 40m/s implies the

Doppler frequencies to be in the range from 370kHz to 7.5MHz. From measurements,[1] the backscatter coefficient for the aerosols at low altitudes and 10.6μm optical wavelength is found to be in the order of $\beta \cong 10^{-6}$ $[(m*sr)^{-1}]$. This quantity is to a high degree dependent on the number of aerosols carried by the air masses. Integrating the total back-scattered intensity collected by the transmitting aperture from the measuring volume yields the total intensity backscatter coefficient for the collection of aerosols, $\Gamma_0 = \beta * \lambda$, which becomes approximately $\Gamma_0 \cong 10^{-11}$.

The detection scheme employed is a heterodyne scheme. The set-up, shown in Figure 3, is the heterodyne set-up employed in the demonstration version of the instrument. The laser output is linearly polarised in the horizontal direction and passes the Brewster window with a little reflection left for the local oscillator. The λ/4-mirror turns the polarization of the laser output into a circular polarized state, which is focused on the aerosols. The polarisation of the back-scattered light is turned into a linear vertical polarization by the same λ/4-mirror. The Brewster window reflects all the back-scattered light towards the detector. A small fraction of the output beam is reflected backwards from a partially reflecting window, located just after the λ/4-mirror, this reflection constitutes a local oscillator - or reference beam. The reflected reference beam obtains the same aligning and polarisation state as the received back-scattered light when it is reflected off the same λ/4-mirror on its way back to the detector. The back-scattered signal interferes with the local oscillator on the detector surface. The detector detects the beat frequency between the two beams, which is the Doppler frequency. In the set-up the telescope consists of a set of off-axis parabolic mirrors, see Figure 3. The laser and the optics are mounted on the heat sink for the laser.

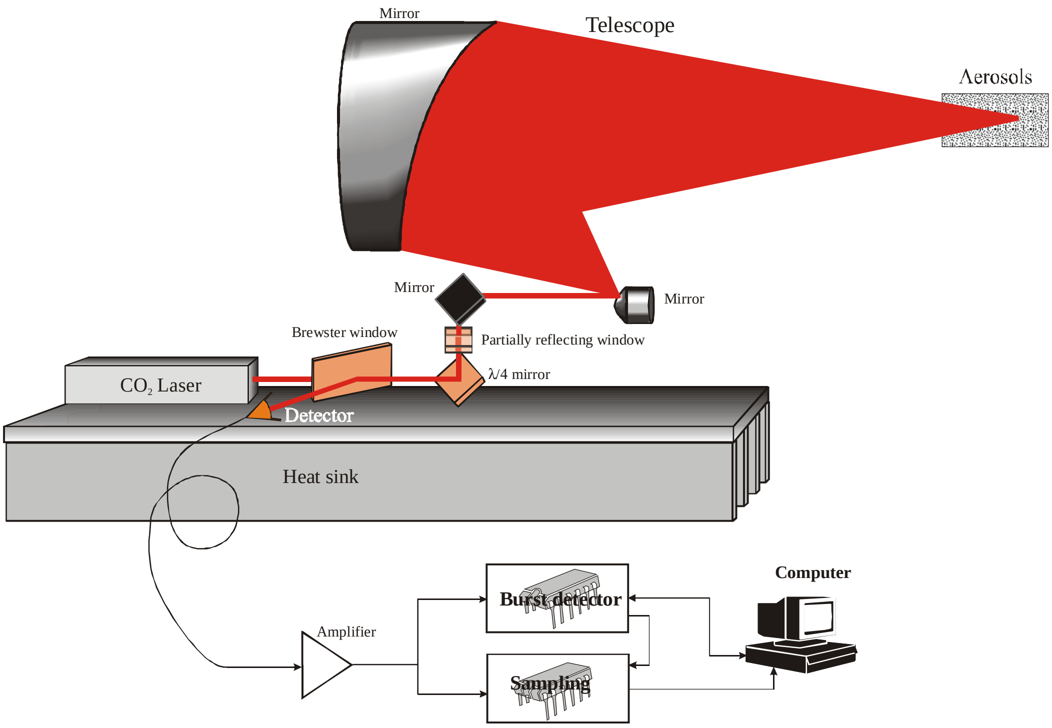

Figure 3. The set-up of the final demonstration version of the laser anemometer. The local oscillator is obtained by reflecting a fraction of the output power from a partially reflecting window. The same λ/4-mirror can then be re-used for both the signal and the local oscillator. The detector signal is amplified by very low noise amplifiers. The signal is digitised and further processed digitally by a PC-computer.

The detector signal is amplified by very low noise amplifiers, digitised, and further processed by a PC-computer.

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[1] David A. Bowdle, Jeffry Rothermel, J. Michael Vaughan, Derek W. Brown , and Madison J. Post, "Aerosol Backscatter Measurements at 10.6 Micrometers With Airborne and Ground-Based CO_2 Doppler Lidars Over the Colorado High Plains 1. Lidar Intercomparison" J.

The minimum acceptable volume scattering coefficient is predicted assuming that the airflow does not contain any turbulence. The presence of turbulence will broaden the measured Doppler frequency spectrum and thereby decrease the maximum signal level. In presence of turbulence the power spectrum of the Doppler signal from the detector is given by the Gaussian distribution,[2]

$$S(f) = \tfrac{1}{2} v_{signal}^2(f) = S(f_d)\exp[-\frac{\lambda^2}{2\sigma^2}(f - f_d)^2] \qquad [W/Hz], \tag{3.1}$$

where $S(f_d)$ is the peak power density of the signal at the centre Doppler frequency, and σ^2 is the variance of wind velocity (the turbulence) along the focus region (measuring volume). The total signal power, S, is related to the back-scattering coefficient of the aerosols. The peak power in the spectrum is thus given by

$$S(f_d) = \frac{\lambda}{\sqrt{2\pi}\sigma} S = \frac{\lambda}{\sqrt{2\pi}\sigma} \tfrac{1}{2} G^2 \, R_D^2 \, P_{AC}^2, \tag{3.2}$$

where R_D is the detector voltage responsivity, G amplifier gain and P_{AC} is the optical signal. As seen, turbulence is broadening the spectrum of the Doppler signal and decreasing the signal peak. Turbulence within the measuring volume can thus affect the possibilities of measuring the wind velocity.

3.2.2. Laser

The most suited laser for the laser anemometer has been found to be the CO_2 laser emitting at 10.6µm wavelength, as discussed above. Based on the light scattering configuration it is concluded that 5 watts of laser power are adequate. Ferranti Photonics Ltd has extensive experience with CO_2 lasers including waveguide types. Waveguide lasers are attractive because they are very compact and robust. The wavelength of the output from the laser is λ=10.6µm ±0.1µm.

3.2.3. Optics

Due to a wider range of production possibilities and to avoid any reflections of the output beam back into the optics, the telescope is constructed of reflective optics. The telescope consists of two off-axis parabolic mirrors, a small convex mirror in front of the laser and a large concave output mirror focusing the output beam. The output window to protect the whole set-up from dust and moisture is also shown. Normally, the window will be made from ZnSe or Ge materials.

3.2.4. Detector

3.2.4.1. The detector

A photoconductor type of detector has been selected since it provides the best performance at 10.6 µm. The detector material is a cadmium-mercury-telluride (CMT) semiconductor compound. This detector temperature is 226K. The non-linearity of the detector response puts a limit to the maximum intensity of the reference wave, and thereby the sensitivity of the instrument obtainable by increasing the intensity of the reference wave. The minimum acceptable volume scattering coefficient for the airborne aerosols is approximately $\beta_{min} = 2 \cdot 10^{-6}\ m^{-1}\ sr^{-1}$. In the literature, β has been measured in 2km altitudes and upwards. At 2km altitude, the volume scattering coefficient is approximately $1 \cdot 10^{-7}\ m^{-1}\ sr^{-1}$ and increases with decreasing altitude.[3] Extracting the data down to zero altitude gives an estimate of the back scattering, $\beta_{earth\text{-}surface}$, above $10^{-6}\ m^{-1}\ sr^{-1}$. The current sensitivity of the instrument is estimated to be just adequate for doing measurements at altitudes typical for wind turbines.

3.2.4.2. Detector amplifier

The signal from the detector must be amplified without adding noise to the signal. Especially the preamplifier stage must be low noise. After amplification is the detector digitised by 20M sample/s.

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[2] J.H. Churnside and H.T. Yura, Speckle statistics of atmospherically backscattered laser light, Applied Optics, 1 September 1983, Vol. 22. No. 17, 2559-2565

[3] Aerosol Backscatter Measurements at 10.6 Micrometers With Airborne and Ground-Based CO2 Doppler Lidars Over the Colorado

3.2.5. Mechanical structure

The heat sink for the air-cooled laser forms the optical base for mounting the optics for extracting the reference wave, the detector with amplifier, and the two mirrors for the telescope. The whole optical assembly is seen on Figure 4.

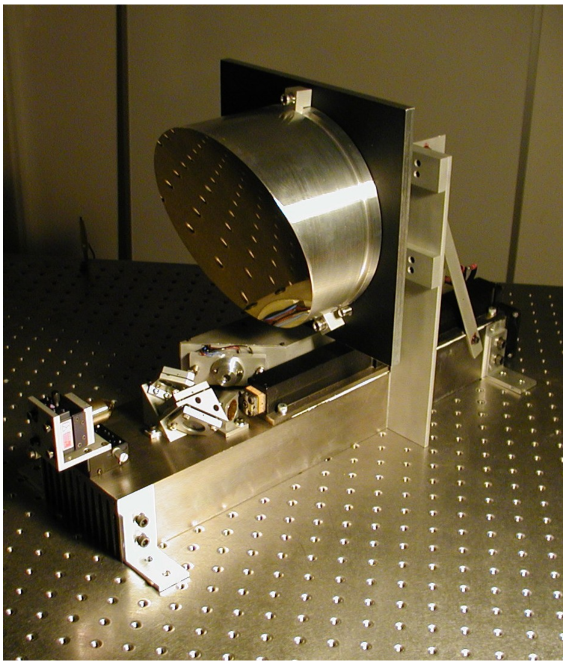

Figure 4. The whole optical assembly. The unit with the detector and amplifiers is seen mounted on the rear side of the heat sink underneath the large telescope mirror.

Figure 5. The final demonstration version of the laser anemometer.

For the outdoor measurements the optics assembly, the electronics, the power supplies and the computer are assembled in a waterproof steel box. Figure 5 is the final demonstration version of the laser anemometer.

3.2.6. Signal processing

3.2.6.1. The detector signal

Since the light is scattered from randomly distributed scatterers in the measuring volume, the optical field in front of the receiving telescope shows a stochastic behaviour, also known as laser speckles.[4] The Doppler signal will only be detected when the optical wave front of the back-scattered light is correlated across entire aperture of the telescope that means, when a speckle correlation cell covers the area of the telescope input aperture. The speckle pattern of the back-scattered light changes dynamically as new scatters enters the focus region (measuring volume) of the output beam. The statistics of the speckle intensity of the speckles entering the telescope (and the detector) is described by a negative exponential function with zero intensity as the most probable event. Due to the dynamics of the speckles, the Doppler signal measured by the detector will be consisting of bursts of signal appearing randomly in time and having various

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[4] See, for example, J. C. Dainty, "The statistics of speckle patterns" in Progress in Optics, Vol. XIV,E. Wolf, editor (North-Holland Publishing Co., Amsterdam, 1976), Chap.1. S. M. Kozel and G. R. Lokshin, "Longitudinal correlation properties of coherent radiation scattered from a rough surface," Optics and Spectroscopy, Vol. 33, No. 1, 89-90 (1972). T. Asakura and N. Takai, "Dynamic laser speckles and their application to velocity measurements of the diffuse object," Appl. Phys., 25, 179-194 (1981). T. Yoshimura, "Statistical properties of dynamic speckles", J. Opt. Soc. Am. A3, 1032-1054 (1986). B. Rose, H. Imam, S. G. Hanson, H. T. Yura, and R. S. Hansen, "Laser-speckle angular-displacement sensor: theoretical and experimental study" Appl. Opt. 37,2119-2129 (1998). T. Okamoto and T. Asakura, "The statistics of dynamic speckles," in Progress in Optics, Vol. XXXIV, E. Wolf, editor (Elsevier Science B. V., Amsterdam,1995),Chap.3. H. T. Yura, S. G. Hanson, and T. P. Grum, "Speckle: statistics and interferometric decorrelation effects in

amplitudes. The signal processor must be able to detect these bursts of Doppler signal within the frequency range from 500kHz (wind speed: 2.6m/s) to 7.5MHz (wind speed: 40m/s). When seen in the time domain, the Doppler signal from the detector has a very low signal to noise ratio (-6dB to -10dB) when having the full bandwidth, and can thus not be detected directly. Therefore the bandwidth has to be divided in a number of frequency sub-bands and ideally, the signal processor must constantly search for the bursts of Doppler signal in all sub-bands simultaneously. Two schemes for detecting the Doppler signal are implemented. The first scheme uses a burst detector as shown on Figure 3 Each time the burst detector detects a burst above the noise fluctuations, the burst detector triggers the sampling circuit. The detector signal is then digitised and transferred to the PC-computer for further analysis. The signal bursts can come from high intensity speckles arriving at the telescope or large single scattering particles entering the measuring volume. The second detection scheme is based on averaging a sufficient large number of discrete Fourier power spectra for the fluctuations of the averaged spectrum to become smaller than the signal induced changes in the spectrum. Averaging 400 spectra gives the sensitivity for the laser anemometer where the minimum acceptable volume scattering coefficient for the airborne aerosols is approximately $\beta_{min} = 5*10^{-7}\ m^{-1}\ sr^{-1}$. Test has shown that the computer is able to calculate and process approximately 80-150 spectra per second. The averaging of 400 spectra thus takes a few seconds. Only the average value of the amplitude of the Doppler signal will last during a processing time of seconds, and single burst of high amplitude will be averaged out. This processing scheme will be measuring the average signal level from the detector, the so-called aerosol background. The average power spectrum is found by using a running average algorithm.

In order to minimize the complexity and the cost prize of the instrument, a compact detection scheme that is unable to distinguish between positive and negative Doppler shifts has been chosen for the design. The laser anemometer is therefore not able to determine the direction of the measured wind velocity and do not need to when always being directed against the wind direction.

3.2.6.2. Measuring accuracy

The accuracy of the measured wind velocity is mainly determined by three factors, the angle between the laser beam and the wind velocity, the determination of the Doppler frequency in the power spectrum, and the wavelength of the laser. The laser anemometer will at any time be measuring only the component of the velocity lying along the laser beam. Any angling of the laser beam with respect to the wind direction will introduce a bias error on the measured velocity. Test measurement has shown calculated accuracies of approximately 0.2m/s at mean velocities of 3-10 m/s. In the detection scheme averaging a number of spectra, the resulting averaged spectrum will show a broad signal. The width of this spectrum is cause mainly by two factors. First, the wind velocity may change during the time needed to sample and calculate the required number of spectra. Second, turbulence in the airflow along the measuring volume will distribute the Doppler frequencies over a boarder frequency range than if all the particles where translating in a fixed formation. An accurate expression for the measurement accuracy has not been found. However, the average Doppler frequency can be determined accurately from a least squares fit of a Gaussian spectrum to the measured spectrum. This has been implemented in the software recently. The frequency bin containing most signal power is chosen as a guess for the non-linear fitting routine.

3.2.7. Data processing

The measured wind velocities are transmitted via the Internet to computers, running client software, for further use.

3.2.8. Performance verification

Comparison and test measurements are in progress. The demonstration version of the laser anemometer is mounted 4 meters above ground level and the laser beam is focused nearby a second mast equipped with a cup anemometer and a wind vane. The focusing distance is 50m. When focused in this distance, the beam diameter in the focus region (measuring volume) has the following dimensions: diameter, d_0=6mm and length $2\Delta z$=5m. Figure 6 is an example of a power spectrum obtained when a burst of Doppler signal has been captured. The spectrum shown is an average over 3 spectra, each with 512 points. The spectral peak is spread over approximately 3 frequency bins.

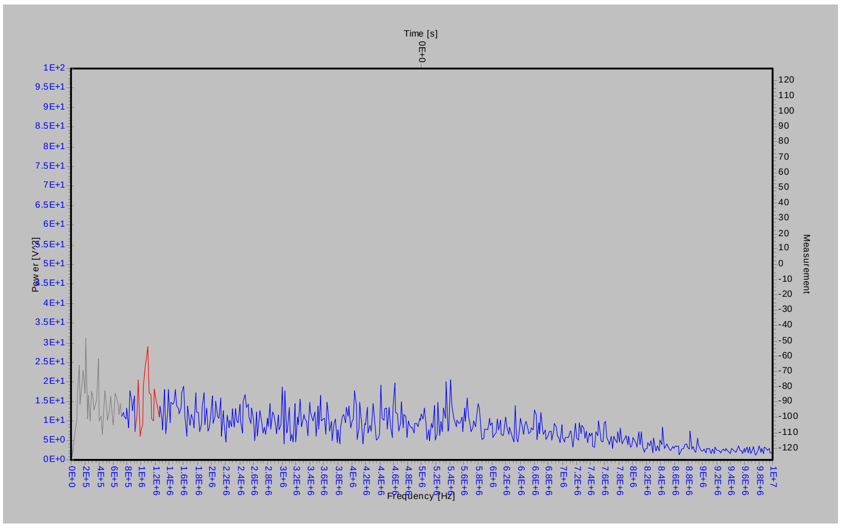

Figure 6. Example of a spectrum obtained by using the burst-detecting scheme. The units on the power axis are the raw byte values squared from the digitising card.

In Figure 7 the measured wind velocity is compared with the velocity measured by the cup anemometer. The velocity measured by the cup is corrected for the wind direction by multiplying the result with cosine to the angle with the laser beam. When using the burst detection scheme, the laser anemometer will capture strong burst signals. These measurements are seen to be arriving randomly in time. Most of the measurements are in accordance with the cup anemometer. Sometimes, if a particle with a high back scattering coefficient crosses the measuring volume, its velocity component towards the laser anemometer will be determined. Those particles might not be following the mean wind direction when crossing the measuring volume. It is believed that such particles are causing the differences seen in some measurements.

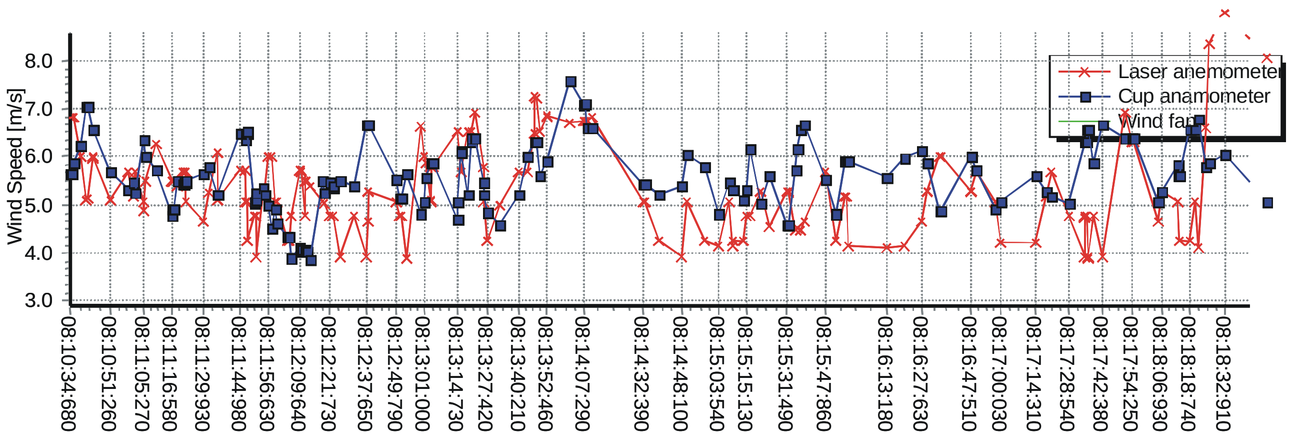

Figure 7. Comparison between the wind velocities measured by the cup anemometer (squares) and by the laser anemometer (cross).

When using the detection scheme averaging a number of power spectra, the resulting spectrum can be seen in Figure 8. Here the running average algorithm averages 400 2048-point power spectra.

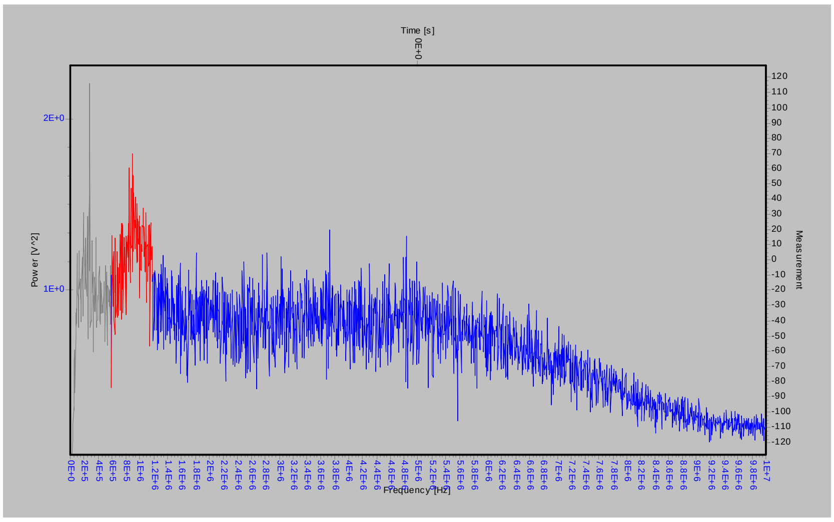

Figure 8. Example of a spectrum obtained by using the spectrum-averaging scheme. The units on the power axis are the raw byte values squared from the digitising card. The single peak at 300kHz is an external noise source entering the detector system.

Comparison between the cup and the laser anemometer running the averaging scheme is seen in Figure 9. The time averaging of the measured wind velocity is clearly seen. On the other hand, single particles are not disturbing the measurements as for the burst detection scheme.

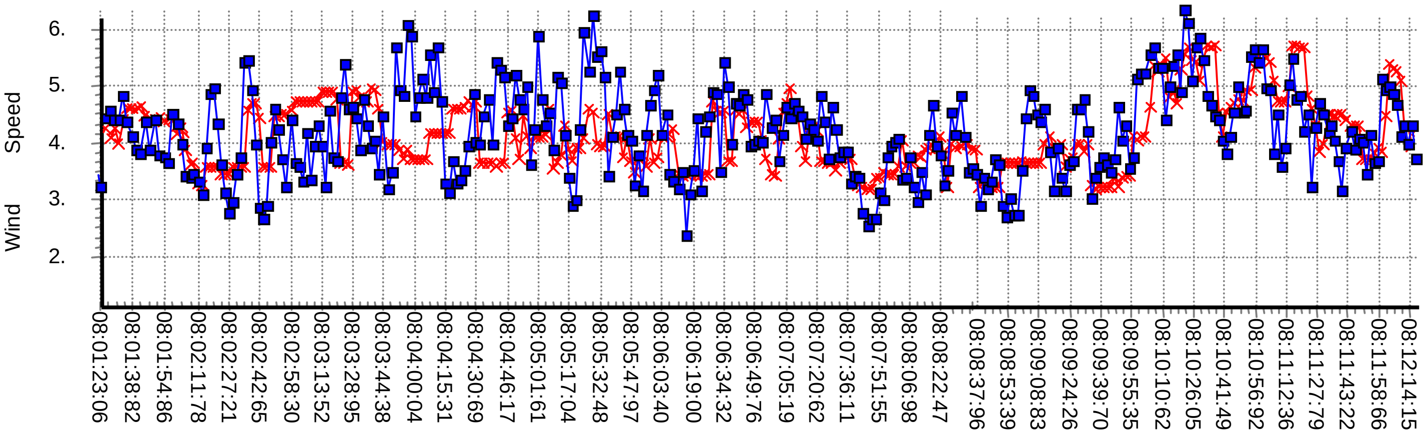

Figure 9. Comparison between the wind velocities measured by the cup anemometer (squares) and by the laser anemometer (cross) averaging 400 power spectra.

In the burst detection scheme, the instrument captures single signal bursts, and is therefore able to react fast to changes in the wind velocity and/or capture single particles entering the measuring volume. If the bursts are originating from speckles with high intensity i.e. the light is coming from the whole scattering volume or larger particles following the wind, the measured wind velocities are in good accordance with results from the cup anemometer. At some instances, signals with a frequency very different from the average Doppler frequency are captured and approved by the computer software. These signals can come from large scattering particles crossing the measuring volume in angles very different from the mean wind direction, or there is a finite possibility of detecting a noise peak as being a signal. When signals are detected and the burst detector is set for this new frequency, the possibility of detecting more bursts with this frequency is higher. Therefore the anemometer is sometimes seen to capture more signals with frequencies nearby the latest approved signal. There is a trade off when setting the threshold level for separating signals peaks from random noise peaks in the Fourier spectrum. At higher threshold level the possibility of detecting random noise decreases, but the average time between signal bursts, large enough to pass the threshold, increases. In the averaging scheme, the laser anemometer is measuring the average velocity due to the processing time needed for calculating the large number of particles are averaged out. When measuring turbulent wind fields, the averaging also causes the Doppler frequency spectrum to be broadening out thus increasing the difficulty in detecting the signal in the spectrum. Employing faster hardware for calculating the fft-spectra can make the reaction time faster and thereby minimize the averaging of the wind measurements and reducing the broadening of the turbulent Doppler frequency spectrum. Using a detector, which is cooled to liquid nitrogen temperature, will increase the signal to noise ratio and thus reducing the number of averages needed to extract the Doppler signal from the noise. However, liquid nitrogen is not a preferable detector cooling method for the applications in this report. Other schemes to obtain liquid nitrogen temperature of the detector are too expensive for the present purpose; therefore more extensive signal processing is preferred. Development of new hardware based signal processing is presently in progress.

As the temperature changes, the power of the laser varies resulting in some dropouts in the Doppler signal, and thereby the wind measurements. The laser employed in the demonstration version of the laser anemometer is not actively stabilized. If needed later, stabilisation of the laser can stabilize the Doppler signal.

3.3. Power curve measurements

3.3.1. Model of flow

It has been investigated theoretically whether it would be possible to obtain wind speed and direction at hub height by letting a Doppler-laser anemometer perform a conical scanning with the axis in the wind direction. Under the assumption that the wind velocity is horizontal and varies logarithmically with height and that the angle of the axis of the cone with the wind velocity is small and known, it is shown to be theoretically possible to obtain this information. Further, by segmentation of the conical scanning it is also possible to measure the wind speed variation with height.

The question whether it is possible to predict a downstream gust from a measured gust in the Doppler laser measuring volume relies on the one-dimensional, longitudinal velocity correlation as a function of lags in both distance r and time τ. It should be pointed out that this correlation is unity if Taylor's hypothesis for frozen turbulence is applied. This is quite unrealistic in this case and, therefore, a model with wavelength dependent decay time for turbulent eddies was developed. A simple equation for the correlation function as a function of the two variables $u_*\tau/z$ and r/z, where u_* is the friction velocity and z the height, has been derived. The model correlation will be well suited for simple numerical modelling.

Earlier it is found that it is possible to model the correlation between the upstream, wind velocity disturbance, e.g. a speed-up, and the corresponding wind velocity disturbance which will occur downstream after a flight time corresponding to the distance and the advection velocity (mean-wind speed). The correlation found above is the Eulerian correlation. The relation between the Eulerian correlation and the Lagrangian correlation is discussed in order to be able to compare the two and see which serves the purpose best. The difference between the Eulerian and the Lagrangian velocity field is that the first is the flow velocity measured at a particular point in space as a function of time while the second is the velocity of a particular velocity particle, also as a function of time. An anemometer measures the Eulerian velocity. The Lagrangian velocity can in principle not be measured.

It is discussed, the possibility of using the upwind wind fluctuations to predict when a gust or a lull crosses the plane of the rotor. If we detect a significant fluctuation upwind, we want to determine the probability density for significant excursions at the rotor, at a later time, corresponding to the travel time of a fluctuation from the measuring volume to the rotor of this fluctuation. Using a simple joint Gaussian probability density between the two velocities, we find that the most probable excursion at the rotor will be the correlation coefficient ρ times the excursion upwind. The conditional probability density is Gaussian with the width $\sqrt{2\left(1-\rho^2\right)}\sigma_0$. It should therefore in principle be possible to improve stall regulation by some kind of ``early warning´´. The difficulty is the determination of the correlation coefficient. A modelling of the second-order, space-time statistical behaviour of turbulence has been found in order to obtain the correlation coefficient $\rho(x,\tau)$ for the streamwise velocity component as a function of the displacement x and the time lag τ. The model is based on the standard methods from the theories of atmospheric turbulence. However, it most certainly will need to be tested experimentally.

The instrument is anticipated to yield a better measurement accuracy on power curve measurements than obtainable by cup anemometers on towers.

3.4. Turbine control

Introducing a device that is able to measure the wind speed up-stream in front of the turbine will naturally lead to the idea that this device can be integrated in the turbine control system.
The perspective of measuring the wind speed ahead is that if the change in the incoming wind speed is known before it reaches the turbine, the turbine control system has time to adjust itself just right in accordance with the change. This should be compared to the common way of controlling a turbine, where the control system reacts on a change measured on the turbine itself, i.e. the rotor power, meaning that the control system reacts on a situation that 'has been'.

In this project the measuring device is a laser anemometer measuring in a point upstream of the turbine. Using such a device sounds at first as an attractive and simple method for improving the wind turbine regulation, but there are however a number of difficulties and potential disadvantages that will have to be investigated in order to make an evaluation of the method.
One of the major problems is if the wind speed measured in a point ahead is not a precisely enough measure of the wind that will eventually hit the rotor. If the wind prediction is wrong, the wind turbine control system will have adjusted itself to something that will not happen, and in the severe case this inconsistency could lead to an increased loading on the turbine.

3.4.1. Controlling a wind turbine

Controlling a wind turbine is of cause many things, but in this context with relation to the laser anemometer, power and load level control and power optimisation are the main issues.
In the design of a control strategy for a wind turbine, it is necessary to choose a primary regulation signal. Dependent on the control actions possible, i.e. blade pitch and rotor speed, this signal must in a reliable manner, be able to link to the instantaneous turbine status. Most turbines today are feedback regulated according to power or a combination of power and rotor speed. The present investigation is focusing on the wind speed, because this is the type of signal that the laser anemometer will provide, trying to address the main benefits and problems involved in using this feed-forward type of control signal.

A simple way of looking at the main task's and problems when controlling a wind turbine is to divide the power curve into 3 different zones, as shown in Figure 10, that shortly can be described as follows:

Zone I:	Task: Optimise production	Main problem: Optimise production
Zone II:	Task: Optimise production	Main problem: Avoid power / load overshoot
Zone III:	Task: Stable nominal power	Main problem: Avoid power / load fluctuations

Controlling in Zone I: Optimisation of production

In general the success of the production optimisation depends on how well it is possible to estimate the instantaneous operational situation of the turbine, i.e. the wind speed, and how the turbine can respond to a change.
Looking at the pitch control system, the response time is, compared to the fluctuation frequency of the wind, quite low in the range from 0.5-3 seconds, and an adaptation to a new situation can take place without other losses than driving the pitch system itself.

For rotor speed control the response time is quite longer mainly because of the large inertia in the rotor. An attempt to make rapid changes in the rotor speed in the haunt for an optimal efficiency demands that i.e. the converter drags down the speed rapidly when the wind drops and let the rotor run rapidly up in speed when the wind rises. The penalty paid for this is increased power fluctuations on the grid and increased fatigue loading on the turbine. Choosing a very short response time could therefore result in losses larger than the possible gains, while a very long response time will decrease the benefit from the rotor speed control system.

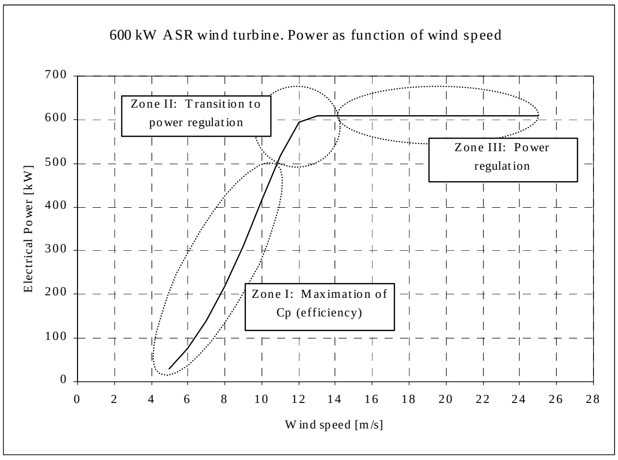

Figure 10. The power curve divided into 3 zones, each with a different control task and problem

Both of the above cases can to some extent be quantified by looking at a curve comparing power and pitch angle respectively rotor speed at a given wind speed. Looking first at the connection between power and pitch angle for fixed rotor speed and wind speeds the curves describes upside down U – curves as shown in Figure 11. Dependent on the turbine configuration the curve through the optimal points will have a more or less steep gradient. If the curve is vertical, there will be no loss if the wind speed changes, and the pitch angle do not have to be changed. With a realistic slope as shown on the figure and taking the 7 m/s curve as an example, a wrong estimation of the wind speed of 1 m/s will give a theoretical production loss in the range from 0.7 – 1.4 %. Similar a wrong estimation of the wind speed of 2 m/s will give a theoretical production loss in the range from 1.7 – 3.2 %

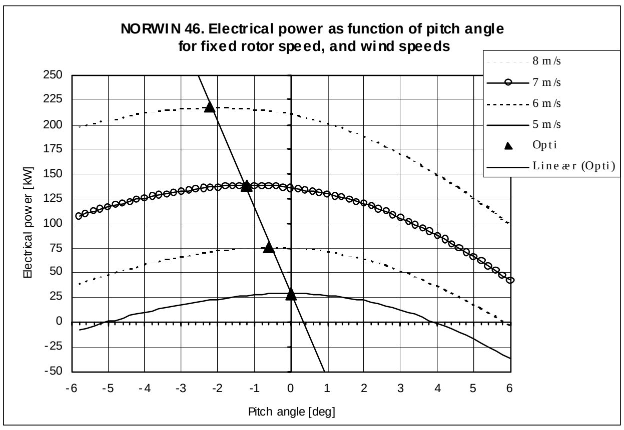

Figure 11. Connection between power and pitch angle for fixed wind speeds

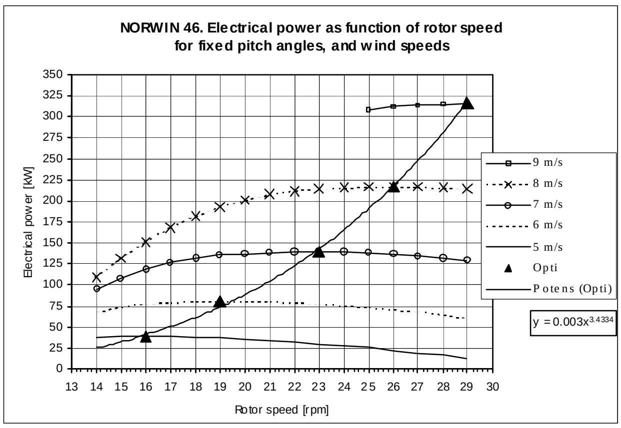

Figure 12. Connection between power and rotor speed for fixed wind speeds

Turning to the connection between power and rotor speed the same type of curve applies as shown in Figure 12. From the curve it is seen that the change in rotor speed in order to have an optimal performance is quite large compared to the pitch angle change. Further, it is observed that the loss can be quite substantial if the rotor speed setting is wrong.

Again taking 7 m/s as an example, a wrong estimation of the wind speed of 1 m/s and a rotor speed regulation according to this, will give a theoretical production loss in the range from 2.3 – 3.2 %. Similar a wrong estimation of the wind speed of 2 m/s will give a theoretical production loss in the range from 7.7 – 15.3 %
In general it is seen that an error in the rotor speed regulation will have a much more significant impact, than an error in the pitch regulation, and since the rotor speed regulation due to the rotor inertia has a longer response time a wrong regulation can not be corrected rapidly without a penalty.

If the power and/or rotor speed is used as control signal it is quite clear from the figures, that the controller sometimes will make a wrong adjustment because it evaluates the present situation based on information that is strongly influenced by the previous control history. If a precise measure of the wind speed could be provided, the error from the control history could almost be eliminated. If the prediction on the other hand is too inaccurate, the losses could be significant.

Controlling in Zone II:
Zone II, is generally described as the interval where the turbine controller should change mode of operation between optimising the production and constraining the power to the nominal level of the turbine. How this is done is dependent on the regulation type of the specific turbine, but the general problem is the same for all active regulated turbines. Looking at Figure 10, the slope of the curve in zone I, could in principle be continued in zone II and III, if the control system was adjusted for this. Constraining the power therefore needs an action, like pitching the blades, when the wind increases through zone II, and vice versa when the wind speed drops. On turbulent sites the wind speed can increase and run through zone II in few seconds, and if the control system does not react, the result will be a power and load overshoot. Dependent on the confidence in the response of the control system, a more or less conservative adjustment of the system parameters could be chosen. A conservative regulation could i.e. mean that the system would start decreasing the power output already at the entrance into zone II. This will reduce the risk of overshoot, but will on the other hand also reduce the power production in zone II.

Discussing the laser anemometer wind speed measurement as control signal, it is in general regarded that a system based on a wind speed measurement alone, is not a feasible solution. The lack of feedback control makes it impossible to make a sufficiently good power level regulation, and to correct overshoot errors. Concluding this, why would it then be worthwhile to look at using the laser anemometer in zone II?
A feedback control system using the power as control parameter will in some situations have large overshoots because it is responding to a historical situation with some delay. To avoid this a non-aggressive regulation in zone II can naturally be chosen as described earlier. It is however possible that a power regulation system extended with a wind speed 'predictor' that make control actions based on advance knowledge of incoming wind gusts, makes it possible to allow for a more aggressive regulation, and at the same time makes it possible to avoid overshoots, and thus reduce the loading on the turbine. However, if this should work, it is extremely important that the wind speeds really are a correct estimate of the rotor gust. An estimate in the wrong direction can make the problem with overshoot even worse.
A diagram roughly sketching the main outline for a pitch regulation system with wind speed feed forward measurement is shown in Figure 13. In zone II this system could typically be used in a manner where information about observed incoming wind gusts are used to change the setting of the pitch operation to a more conservative mode, or eventually if the confidence in the information is high, to respond directly to the gust.

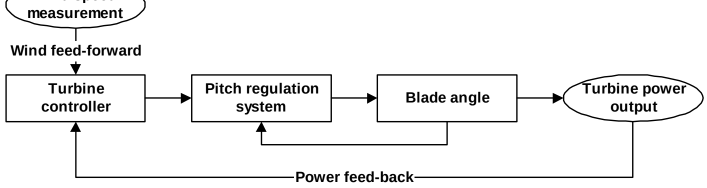

Figure 13. Power feed back system with wind speed feed-forward information

Controlling in Zone III. Power regulation
Controlling in last part of zone II and in zone III, is in this context not very different, and the main control problem with regulation according to a wind speed signal is if the wind speed is estimated with a large error. The result of such error will be a bit dependent of the type of control system in question. For an active stall regulated turbine, working on a very flat power curve, a wrong estimation of the wind speed will result in a less stable power level, but normally not in severe overloading. For a pitch-regulated turbine, working on very steep power curves and with a high regulation frequency, a wrong estimation result can lead to severe overloading.

Summing up on the findings so far the most likely use of a laser anemometer measuring the up-wind wind speed in front of the turbine will be as an addition to an existing power regulation system. The system could be used to enhance regulation by adding the possibility of feed-forward regulations to wind gusts, to the feedback regulation of power.
For the three regulation zones, the benefit of the system could be the following: Zone I – An optimisation of the power production. Zone II – An enhanced possibility to use a more aggressive regulation strategy without penalties. Zone III – A reduction of peak loads.
A potential gain in power productions in zone I using a wind speed predictor seem to be most likely for turbines with rotor speed control, because the two alternative control parameters: Power and rotor speed itself are highly influence by a setting that initially is wrong. On the other hand, a fault in the prediction will also cause a higher loss. It is assumed that to get an improvement, the average fault in wind speed predicted by the laser anemometer, should not exceed 1 m/s. For zone II and III, it has been assumed that to obtain any kind of load reduction, the maximum fault in wind speed predicted by the laser anemometer, should not exceed 3 m/s.

3.4.2. Theoretical assumptions on laser anemometer for wind turbine control.
When controlling a wind turbine according to a wind speed measured up-stream of the turbine a number of questions with respect to the method itself arises. The two major questions are, first, how good does the wind speed measured in a point represent the average wind speed perpendicular to the rotor plane? This problem is sketched in Figure 14 and relates to the turbulence eddies that are normally found in the wind field, meaning that the variance in wind speed over the rotor plane can be quite large.

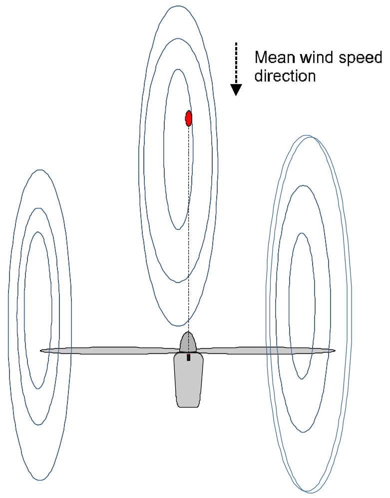

Figure 14. Measuring in front of the turbine, with different wind speed over the rotor

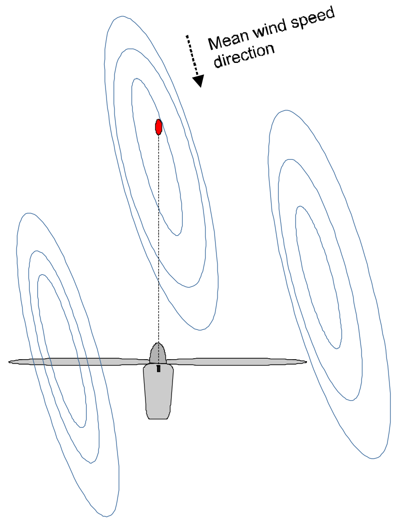

Figure 15. Measuring in front of the turbine, with a directional error on the wind speed

If the wind speed is measured in a point, even with some time averaging, the measurement is maybe, seen from a control point of view, not a sufficiently good measure of the wind speed over the rotor. Second, how good does the wind speed measured ahead actually represent the wind speed that finally hits the rotor? An example of this problem is sketched in Figure 15 showing the same situation as Figure 14, but now with a direction of the incoming wind that is not going directly from the measuring point and to the turbine, but has a certain cross wind included. This means that a quantity of the measured wind will not hit the rotor at all.

With respect to the two problems, the up-stream distance to the measuring point is quite important. Intuitively it is assumed that the longer the distance, the less correlation between measured up-stream wind speed and rotor wind speed. From this point of view the measuring distance should be short in order to make the measured wind speed a true representative of the actual wind speed that hits the rotor. To get a reliable wind speed signal, some averaging of the measured signal will have to be made in order to avoid that the controller acts on insignificant turbulence eddies. However, the averaging time should also not be so long that major wind gusts are passing through unnoticed.
The demand for a certain averaging time is clearly in contradiction to the wish for a short measuring distance. The reason is that the wind speed should be known before it reaches the turbine, and the averaging time will increase the needed up-stream measuring distance, because the measurement needs to be finalized before the measured wind volume reaches the turbine. In addition to this the response time of the turbine control system will increase the measuring distance even further, because the control system needs time to react also before i.e. the centre of the volume reaches the turbine. The situation is sketched in Figure 16 for the reasonable example where the centre of the time averaged measuring volume is supposed to be in the rotor plane at the time when the turbine control system has adapted to the correct setting. The measuring will naturally be made as a rolling average, so that the turbine controller constantly will receive updated information.

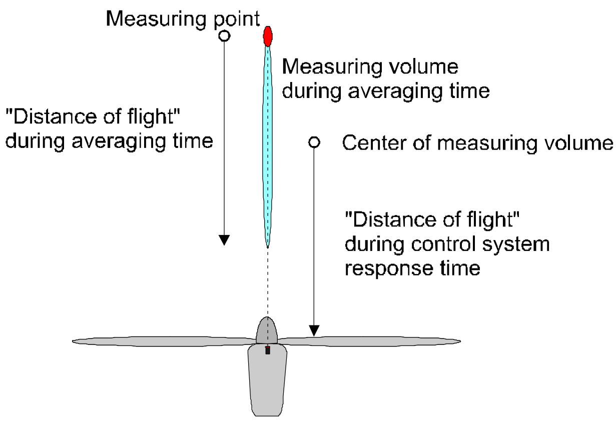

Figure 16. Up-stream measuring distance with respect to measuring average time and control system response time.

Using the simple approach as shown in Figure 16 the measuring distance can be calculated from the following formula $\Delta X := \left(\frac{t_{ave}}{2} + t_{res}\right) \cdot U$ where: t_{ave} is the averaging time in the wind speed measurement, t_{res} is the wind turbine control system response time and U is the wind speed of the incoming wind.
It is observed from the formula that the measuring distance changes proportionally with the wind speed, which will clearly be a problem if the laser anemometer is unable to change measuring distance. It is further observed that an increase in both averaging time and response time will increase the difference between smallest and largest measuring distance. If changing the measuring distance raises a big problem with respect to the measuring equipment, the alternative could be to change the averaging time of the wind speed measurement, and to some extent the response time. For a fixed measuring distance the equation will then change to: $t_{ave} := 2 \cdot \left(\frac{\Delta X}{U} - t_{res}\right)$

Using response time examples of 2 and 25 seconds, and choosing wind speed average times of i.e. 5 and 30 seconds, Figure 17 shows in accordance with the equation, the needed measuring distance as function of the wind speed. It is observed that if the measuring time and in particularly the response time is long, the measuring distance will be quite big. I.e. the case with 2 seconds response and 30 seconds averaging time will result in a final measuring distance at about 9 rotor diameters for a 600 - 750 kW class turbine.
Fixing the measuring distance instead, and choosing a response time of 2 seconds, gives in accordance with the second equation results shown in Figure 18, where the curve for three different measuring distances are shown. It is found that

the averaging time changes quite lot especially at low wind speeds, and it needs to be examined if sufficient good results can be obtained with such long averaging.

For each of the mentioned methods an equipment and data processing problem arises. Dynamically changing the measuring distance, assuming that the equipment would be capable of this, means that the distance should be changed during the on-line measuring process, which could give quite chaotic results.
Dynamically changing the averaging time is an easier process as long as the measuring distance is linked to the highest wind speed where measurements should be predicted, i.e. 25 m/s. The principle in the method is to run a number of rolling averages with different averaging times simultaneously, and then choosing the one corresponding to the instant wind speed. Using this method no measurements will be lost.
An alternative to each of the above methods is to use them in a simple combination. The benefit resulting from using this method is that the measuring distance can be made shorter if this is desired, and that the difference in averaging time with change in wind speed can be made less. Due to the overlap in wind speeds, the change in measuring distance can be made when it is uncritical to do so.

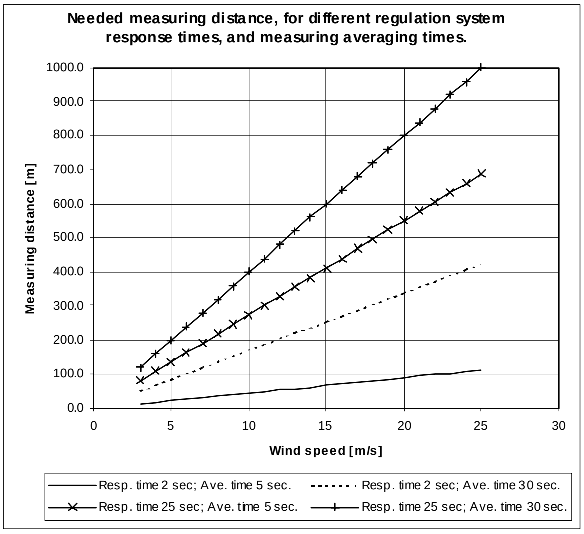

Figure 17. The needed up-stream measuring distance as function of the wind speed, for the different response and averaging times

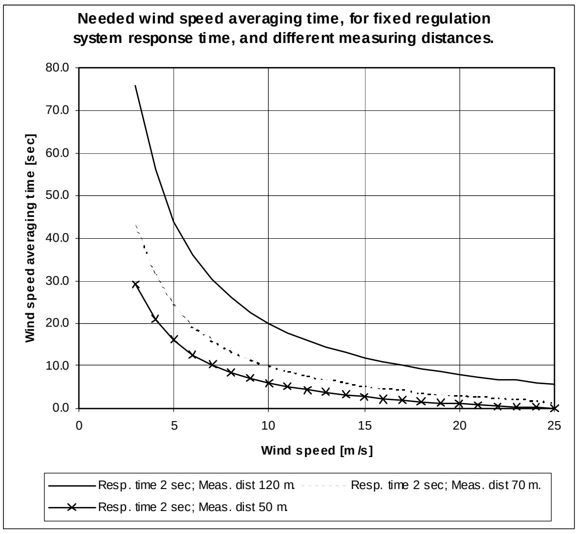

Figure 18. The needed averaging times as function of the wind speed, for a response time of 2 seconds and three fixed up-stream measuring distances

The situation described so far has mainly been with respect to single turbines standing alone. For turbines standing in a wind park the situation is quite more complicated. The turbulence in wind parks can be quite higher than for single turbines, and this is assumed to decrease the confidence in the measured wind speed. Possible wake situation both between the turbine and between turbines and measuring points could further make the measurements highly unreliable. Finally, if the measuring distance needs to be very long it will maybe even exceed the distance between the turbines, which will make measurement impossible.

3.4.3. Evaluation measurements

In the project plan the laser anemometer was supposed to be finalized for testing as control device, approximately half way through the project. This was not possible because the design and building of it turned out to be much more complicated than expected. When that became clear the decision was taken to start up measurement campaigns with other means that could provide working data with respect to investigating the possibilities of using the laser anemometer as control device.
The measurements were made at the NORWIN test site 'Ørsted' in Denmark. On the test site an NW46-ASR-600 kW, and an NW46-ASR-750 kW turbine is erected (two speed generators). Both equipped with sensors for power and load measurements. A measuring mast is further installed, placed approximately 115 m from the 600 kW turbine that were

used for these measurements. The measuring mast is equipped with anemometers in two heights and wind-vane. The anemometer in hub height is a calibrated Risø cup anemometer. In addition a second calibrated Risø cup anemometer were placed on top of the wind turbine, behind the rotor between the 2nd pair of turbine anemometer and wind-vane.
Using the described set-up, a simulation of the laser anemometer measurements was made with the anemometer on the mast. This will of cause give another type of measurement than the laser anemometer will provide. The most significant difference is that the laser anemometer will have a single directional measuring of the wind in the direction perpendicular to the rotor, while the cup-anemometer measures the horizontal wind speed in general. However, the test method will give a quite good indication of the correlation between the wind speed measured up front of the turbine, and the wind speed measured on the turbine.
Using this set-up, a representative time series of 90 minutes length collected with a sample frequency of 40 Hz were chosen for conduction of the further analysis. With this size of series, enough data for testing of long averaging times would be available, and at the same time there would not too much data for testing of short averaging times.
For the choice of data series to be used for the analysis work some characteristics were defined in order to give a straightforward evaluation process. First, there should be no significant directional error between the incoming wind speed and the horizontal plane perpendicular to the rotor, to eliminate the influence from this potential error. Second, the wind speed range should be in zone I, because the results are much easier to interpret when the connection between wind speed and power is nearly proportional. This investigation might give results that could not be directly extrapolated to zone II and III, but the results are on the other hand not expected to be better in zone II and III. Therefore, the worst-case scenario from zone I, is also as a minimum expected in zone II and III. Finally, all measurements should be made with the turbine running on a single rotor speed.

The analysis of the series was conducted in a number of steps in an attempt to pinpoint the difficulties and eventual benefits from the up-stream measuring method itself, and to link this to the turbine control system.
Investigating the potential in a new method does however not only mean looking at some criteria's that should not be exceeded if the method should be workable. It also means comparing and evaluating the method with respect to competing methods. In this case two competing methods were in particular investigated. Both are persistence methods where it is assumed that the condition in the next X seconds is equal to the condition in the last X seconds (X – persisting value). The first is based on the wind speed measured with the nacelle cup-anemometer and the second is based on the wind speed deducted from the rotor power (up to approximately 11 m/s) and the rotor power evaluated as control signal from this point and up.
In order to conduct a method evaluation, made it necessary first to define the reference wind speed measure that is assumed to be the most significant measure of the actual situation. The three possible options are:

- Mast wind speed – wind speed measured on the mast (laser anemometer substitute),
- Nacelle wind speed – wind speed measured on the wind turbine anemometer,
- Power wind speed – wind speed recalculated from the turbine power

The power wind speed is recalculated from the wind turbine power by the averaged proportional connection between wind speed and power, and is thus another expression for the turbine power. Since the turbine actually encounters and need to respond to this wind speed, and since it integrates the wind speed over the total rotor, this signal was chosen as reference.
In the analysis four different averaging times of the measured signals were worked with for convenience. Those were 5, 10 30 and 60 seconds. It was further decided to look at two control system response times: 2 seconds and 25 second, from the point of view that a broad range of control actions would then be covered.

Based on measured data an investigation was conducted with the aim of giving some indicative estimates for use of a measured up-stream wind speed as control information. The investigation was concentrated on finding the standard and maximum deviation figures for the measured wind speed, in order to evaluate those against the acceptable values. The following main influences were included: Deviation within the averaging time of the measured signal; deviation due to lack of correlation between the measured wind speed and the reference wind speed on the rotor; influence from control system response time. In Figure 19 and Figure 20 the findings with respect to the combined deviation figures are shown. The combination is made as a simple summation of the different influences.

Figure 19 shows the standard deviation between predicted and reference wind speeds for a period of time. The reference wind speed was the power wind speed as described above.
Looking at the columns with the description 'WSP mast', they describes the standard deviation between the mast wind speed and the reference wind speed, for averaging times of 5, 10, 30 and 60 seconds. I.e. assuming that the mast signal with the chosen averaging time is used for control of the turbine, the column value shows the standard deviation between the wind speed prediction that was used for control and the wind speed that the turbine actually saw. Going back to Figure 11 or Figure 12 the possible operational production loss could then be estimated from this figure.

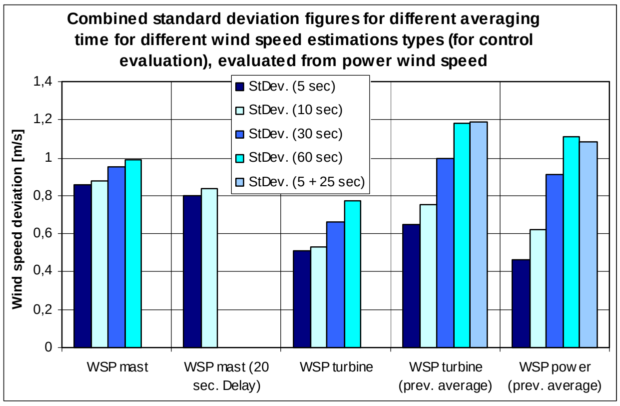

Figure 19. Combined standard deviation figures

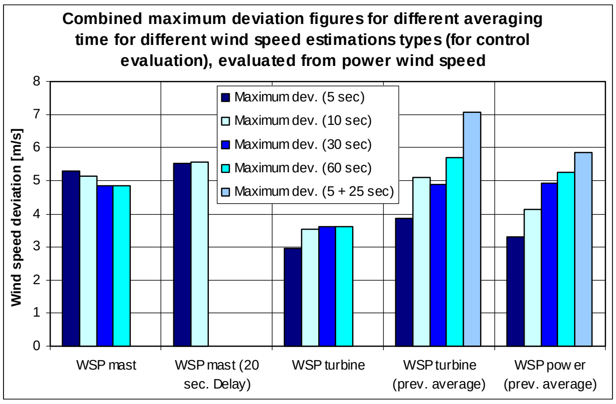

Figure 20. Combined maximum deviation figures

The columns with the description 'WSP mast (20 sec. Delay)' describes in the same manner the standard deviation between the wind speed measured on the mast and the reference wind speed. This time the measured mast wind speed was however delayed in order to account for the 'distance of flight' (Figure 16). For the measured wind speeds the delay was averaged to approximately 20 seconds, and looking at the standard deviation values, a slight improvement is found compared to the measurement directly taken from the mast.
The columns marked by 'WSP turbine' are included for reference, since they cannot be used for control evaluation, because the columns show the nacelle wind speed and the power wind speed for exactly the same time frame. They are included to demonstrate the correlation limits between the two figures and what could be called 'the best obtainable value' for the wind speed on the turbine measured with a nacelle anemometer.
In the columns with the description 'WSP turbine (prev. average)' the values for the persistency method base on the nacelle wind speed are shown. It is observed that the values at low wind speeds are fairly good, but that the value for 60 seconds averaging time exceeds the reference limit of 1 m/s.
In all the figures until now it has been assumed that the control response time was low (2 seconds) because the influence from the wind speed deviation in this case is almost negligible. If the response time is increased this is however not so, and in the persistency methods an example with a turbine control response time of 25 seconds is therefore included. The example assumes that a 5 seconds persisting value was used to predict the wind speed, but that it then takes the control system 25 seconds to reach the optimal settings according to this. It is found that the wind speed standard deviation in this case reaches approximately the same level as if the control was based on a 60 seconds averaging time.
The last columns with the description 'WSP power (prev. average)' show the values for the persistency method base on the power wind speed. Those are fairly close to the figures based on nacelle wind speed just better seen from a control point of view.
Looking at the total result for the standard deviation figures (WSP turbine not included in this) in Figure 19, both the mast and the nacelle wind speed measurement are below the critical value of 1 m/s in acceptable deviation. With regard to the persistency method, this is only the case for the short averaging times. The best value is found from the persistency method base on power wind speed and 5 seconds averaging time. For all measuring types the standard deviation is in general increasing with increased averaging time.

In the same manner as above, Figure 20 shows the maximum deviation between predicted and reference wind speeds for a period of time. It is seen that none of the methods is within the reference limit of 3 m/s, but that the power wind speed persistence method comes close. It is evaluated that this method is the best applicable for controlling in zone II and zone III (Figure 10) as well. In those zones the method are no longer a wind speed measuring method but a direct power feedback method. If controlling according to a wind speed measure is desired the nacelle wind speed persistency method is the best applicable as long as the averaging time is short. For longer averaging times, 30 seconds and up, the mast wind speed seems to be a possible solution. Choosing an averaging time this long is however not very likely for the majority of applications.

From the investigations with respect to control of wind turbines, the following was concluded for the three different investigated control signals linked to the wind speed:

The persistence method based on power wind speed:
The persistence method based on the power (power wind speed) is the best method for control of the wind turbine in zone I, since both the standard and maximum deviation values are the lowest found in the investigation. If it is demanded that the control signal is not linked to the power i.e. if the power level is sensitive to 'historical' errors in the regulations (see i.e. Figure 12), this signal is of cause not applicable.
The method is further the best applicable for controlling in zone II (Figure 10) and for most wind turbines, i.e. pitch regulated machines in zone III as well. In those zones the method are no longer a wind speed measuring method but a direct power feedback method. If controlling according to a wind speed measure is desired the nacelle wind speed persistency method is the best applicable.
It was found that this was the sole method able to be within the acceptable limits set out for the control system of 1 m/s standard deviation and 3 m/s maximum deviation. This was obtainable if the averaging time was decreased to approximately 3 seconds. Looking at the trend lines for the connection between averaging time and deviation further indicates that this method is the only one where deviation could dramatically be reduced by reducing the averaging time even further. The stability of such signal and an eventual lower limit for the averaging has not been investigated.
In zone I, a regulation based on the power signal will give a more steady (less structural fatigue) regulation. This is because the turbine acts as a combined integrator of the wind speed over the rotor and filter due to the natural response damping.

The persistence method based on nacelle wind speed:
The persistence method based on the nacelle wind speed is the most suitable method for control of the wind turbine in zone I, provided that the persistence method based on the power wind speed is not suitable. The standard deviation is within the acceptable range and the maximum deviation will most likely be acceptable for a number of applications, although outside the reference limit of 3 m/s.
The persistence method based on the nacelle wind speed could be applicable for controlling in zone II and in zone III as well provided that the turbine is designed for a relatively weak response to a change in wind speed. This is possible i.e. for an active stall regulated turbine. If controlling according to a wind speed measure is demanded the nacelle wind speed persistency method is the best applicable.

The up-stream measuring method based on mast wind speed (laser anemometer simulation):
The investigation has conclusive shown that for systems with short control response times and a similar demand for a short control signal averaging time, the up-stream measuring method is unable to compete with any of the persistence system methods, at least if the measurements takes place rather far from the turbine as required for power curve measurements.
The better correlation between the nacelle anemometer and the wind turbine power indicates, that a considerable shorter distance should be used if the laser anemometer is used for control purposes. This had not been possible to test here as the anemometer mast is fixed. Also use of the laser anemometer would not have allowed such tests because the test anemometer also is fixed to a certain distance. Pursuing tests should focus on this.
The key problem is however the relatively poor correlation between the wind speed measured in a point and the wind speed distributed over the rotor disk. An instrument allowing measurements in more points on a disk in front of the turbine (or a scanning of the wind field) would probably improve the method considerably.

A small improvement would maybe be possible for wind turbine control systems with a fairly long response time, like a very slow reacting rotational speed control, but the control system should at the same time be very robust with respect to maximum deviations in wind speed prediction, since large deviations should be expected. Large uncertainties and rough estimations are involved in this analysis, and a further and more detailed analysis can only be made if a laser anemometer instrument is used for the testing.

Other indicative findings:
Decreasing the response time of the active turbine controller will in general decrease the deviation between the control signal wind speed and the real wind speed over the total rotor at the time.
If the persistence method is used, the design response time should be chosen relatively short compared to the averaging time. A suggested, but not thoroughly investigated relation would be 3:1 so that a chosen averaging time of 3 seconds would be used in combination with a control response time of 1 second.

4. RESULTS AND CONCLUSIONS

The main objectives of the project have been accomplished. An innovative laser anemometer has been developed, built and partially tested. When mounted on the nacelle, the laser anemometer will remotely be measuring the wind velocity at a distance in front of the turbine, thus eliminating the need for metrology masts during power curve and performance measurements. Also, since the nacelle - and therefore the laser anemometer - always will be pointing against the wind direction, measurements can be obtained from all wind directions. The use of the laser anemometer thus offers better accuracy and more flexibility of the power performance measurements. Ahead of the project start, expectations on employing the laser anemometer for delivering wind forecast for controlling the turbine have been stated. During the project, it has been concluded that due to limited correlation between a measured wind velocity ahead of the turbine and the wind field entering the turbine, satisfactory control of the turbine cannot be obtained.

A demonstration version of the laser anemometer has been built. The anemometer focuses a single laser beam in some distance in front of the wind turbine. The wind velocity is measured from the Doppler shift of the coherent laser light back scattered from the airborne aerosols in the focal region of the output laser beam (the measuring volume). Due to cost considerations, a simplified detection scheme that doesn’t allow the laser anemometer to separate velocities toward the instrument from velocities away from the instrument is implemented. This feature is not needed when assuming the instrument always will be pointing against the wind direction. The Doppler shift of the back-scattered light is detected by an optically heterodyne detection scheme where the collected light from the measuring volume interferes with a reference beam extracted from the laser output. The dynamics of this interference pattern is detected by a thermoelectrically cooled Mercury-Cadmium-Telluride-detector. The laser anemometer will only measure the component of the velocity parallel with the laser beam, and only the light scattered from the elongated region where the transmitted laser beam is focused (the measuring volume) is measured.

The Doppler output signal from the detector has a very low signal to noise ratio (-6dB to -10dB) and can therefore not be detected directly. When calculating the Discrete Fourier transform of the sampled signal, it is possible to detect the Doppler signal as a signal peak in the Fourier power spectrum. Because the coherent laser beam is scattered backwards from a volume of randomly located aerosoles, the optical field returned from the measuring volume has a stochastic nature, known as speckles. Doppler signal will only be present at the detector output when a speckle correlation cell is collected by the telescope and focused onto the detector. The Doppler signal from the detector will therefore vary randomly in amplitude, and can only be detected in the Fourier space. Two detection schemes for the detection of the Doppler signal has been implemented,

a) a burst detection scheme where a narrow band amplifier is “listening” for any signals (burst detector) and the laser anemometer is capturing those single bursts of signal, having large enough amplitude to be separated from the noise, and
b) the spectrum-averaging scheme, where a large number of spectra are averaged to extract the average Doppler signal.

In the latter, the anemometer will be averaging the wind velocity over a few seconds due to processing time needed for the sampling and calculation of the large number of spectra needed. The measured wind velocities are transmitted via the Internet to receiving computers running the client software.
During test measurements, the anemometer is mounted 4m above ground and the measuring volume is focused 50m from the instrument nearby a cup anemometer and a wind vane. Initial test results show that, when using the burst detection scheme, the instrument captures single signal bursts. If these bursts are originating from speckles with high intensity i.e. the light is coming from the whole scattering volume or larger particles following the wind, the measured wind velocities are in good accordance with results from the cup anemometer. Each time a burst of Doppler signal is captured and determined by the computer not to be noise; the centre frequency of the burst detector is set the Doppler frequency just found. In this way the burst detector is tracking the Doppler frequency. At some instances, signals with a frequency very different from the average Doppler frequency are captured and accepted by the computer-software. These signals can come from large scattering particles crossing the measuring volume in angles very different from the mean wind direction, or due to the finite possibility of detecting a noise peak as being a true Doppler-signal. When relevant signals are detected and the burst detector is set for this new frequency, the possibility of detecting more bursts with this frequency is higher. Therefore the anemometer sometimes captures more signals with frequencies near the latest accepted signal. There is a trade off when setting the threshold level for separating signals peaks from random noise peaks in the Fourier spectrum. At higher threshold level the possibility of detecting random noise decreases, but the average time between signal bursts large enough to pass the threshold increases. In the wind measurements performed by using the spectra-averaging scheme, the laser anemometer is seen to average out the fast changes in the wind velocity. The averaging time is determined by the computing time of the spectra. Often, this detection scheme is capturing the average wind velocity. Bursts from single particles are averaged out. On the other hand, it is more sensitive to turbulence in the measuring volume than the burst detection scheme. The accuracy of the measured data have shown standard deviations of approximately 0.2m/s at 5m/s average wind velocity.

Theoretically, it has been investigated if it is possible to obtain wind speed and direction at hub height by letting a Doppler-laser anemometer perform a conical scan with the centre axis in the wind direction. Under the assumption that the wind velocity is horizontal and varies logarithmically with height and that the angle of the axis of the cone with the wind velocity is small and known, it is shown theoretically possible to obtain this information. Further, by segmentation of the conical scanning it is also possible to measure the wind speed variation with height.

An investigation was conducted with the aim of providing estimates for use of a measured up-stream wind speed for control purpose. Due to the lack of the laser anemometer instrument, ready for testing, the measurement were made with a mast cup-anemometer. The investigation was concentrated on finding the standard- and maximum deviation between the measured wind speed and the actual wind speed that the turbine was subjected to. In the investigation the following main themes were included: Deviation within the averaging time of the measured signal; deviation due to lack of correlation between the measured wind speed and the significant wind speed on the rotor and influence from control system response time. To provide comparison data for methods competitive to the up-stream measuring method, a persistency method based on the nacelle cup-anemometer wind speed, and the same based on the turbine power were included. From the investigations with respect to wind turbine control, the following was concluded for the three different investigated control signals linked to the wind speed.

- The persistence method based on the power (power wind speed) is the best method for control of the wind turbine, since both the standard and maximum deviation values are the lowest found in the investigation.
- The persistence method based on the nacelle wind speed is the most suitable method for control of the wind turbine, provided that the persistence method based on the power wind speed is not suitable. The standard deviation is within the acceptable range and the maximum deviation will most likely be acceptable for a number of applications.
- For systems with a short control response time and a similar demand for a short control signal averaging time, the up-stream measuring method (laser anemometer) is unable to compete with any of the persistence system methods. This is clear for the relatively long distance between point of wind measurements and the rotor (here

115m). Considerable shorter distance might give better results. This has not been possible to investigate within the scope of the project, but might be worth considering in future research.

- For systems with a long control response time a small improvement could be possible, but before drawing a final conclusions, it is necessary to test the real laser instrument.
- A laser anemometer, which could measure simultaneously in more point in front of the turbine, would probably increase the correlation between the measured wind and the wind field hitting the rotor disc considerably, and by that be a better instrument for control purposes.

A final conclusion on the use of a laser anemometer for control purposes cannot be drawn from the investigations performed so far. We are however skeptical as to the adequacy of single point measurements, but a multi-point instrument may be the way to go if such an instrument can be available in the future for a price matching the gains.

Looking at the experimental results that have been achieved with the laser anemometer, it seems to be a good candidate for measuring the wind velocity upstream for power performance and load measurements. Another possible application of the instrument is investigations of new locations for wind farms. For those two purposes, a higher selling prise of the instrument can also be tolerated. A revision of the IEC61400-12 standard on performance testing is under way; and as it is, only mast-mounted cup anemometers are allowed for measurement of reference wind speed. Participants in the laser anemometry project are engaged in the revision work of the IEC61400-12 standard and will thus seek acceptance of the application of laser anemometry in the standard.

5. EXPLOITATION PLANS AND ANTICIPATED BENEFITS

During the project period dissemination of results has followed the *guidelines for reporting* of the Commission. Conditioned by proper protection of *intellectual property rights* results the project has been described to the public by presentations in the media[5,6], at international conferences[7,8,9,10] by the European Commission, RTD info-21, February 99, and by meeting EC: Wind Energy Research Projects Contractors' Meeting 2000: "*Advances in Wind Energy RTD – From FP4 towards FP5"*. 3-5 May 2000, at the National Technical University of Athens. Stemming from such "promotion", an increasing interest in the project is shown by European laser research units and individuals that would want formal or informal connection to the project.

To our knowledge no other EU-funded projects or projects funded through other funding agencies are similar in nature or have direct links to the project in question.

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[5] René Skov Hansen, Wind turbine project turns to fusion technology, Fusion Business, Issue Ten, May 2000

[6] René Skov Hansen, Technology developed in fusion is being used to build a laser-based anemometer and control system for wind turbines, A Fusion and Industry spin off brochure entitled "Making a Difference", Edited by Umberto Finzi, Principal Advisor on Fusion to the Director General for Research, The European Commission, and Derek Robbinson FRS, Head of the Research Unit of the Fusion Association, EURATON/UKAEA

[7] Lading, L.; Hansen, R.S.; Miller, G., Long-range laser anemometry: Heterodyne versus autodyne. 8. EALA International conference on laser anemometry - advances and applications, Rome (IT), 6-9 Sep 1999.

[8] René Skov Hansen, Lars Lading and Graham Miller, Optical mixing in coherent LIDARs: comparing three schemes. IEEE International Conference on Applications of Photonic Technology, Quebec City, 12-16 June 2000.

[9] René Skov Hansen and Graham Miller, A laser anemometer for control and performance measurements on wind turbines, 11th Coherent Laser Radar Conference, Malvern, Worcestershire, UK, 1-6th July 2001

[10] René Skov Hansen and Graham Miller, A laser anemometer for control and performance measurements on wind turbines, Poster at the

6. POTENTIAL APPLICATIONS OF THE PROJECT

Three main industries, where the laser anemometer can be applied are
* wind energy: a) performance study b) regulation c) surveying of the wind fields for new wind power sites
* airports: measuring of turbulence and/or remote wind speed measurements
* vibration measurements of remote objects

However, the CO_2 laser anemometer may – if realised and marketed – be of direct importance to, e.g., standards on wind turbine testing: A revision of the IEC61400-12 standard on performance testing is under way; as it is one mast-mounted cup anemometers are allowed for measurement of reference wind speed. Participants in the laser anemometry project are engaged in the revision work of the IEC61400-12 standard and will thus seek to allow the application of laser anemometry in the standard.

Figure 21. Artificial image of the laser beam directed in front of the wind turbine.