The Stall Flag, Prior Development and First Results,
- Aiming at Visualisation of the Stalled Area on Full Scale Wind Turbines -

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Summary

Presently even the most sophisticated predictions of the stall behaviour of commercial wind turbines are often bad. Theoretical studies of this highly complex phenomenon are forced to many assumptions, and therefore result in large uncertainty. Therefore theoretical models should be improved by checking their predictions with direct experimental data. However such data hardly exist, because state of the art measuring techniques are not applicable to large commercial turbines for a reasonable budget.

Therefore a new method to visualize stall was developed. The method is based on a very thin detector, the so called 'stall flag', that provides a clearly visible signal that shows whether the flow over the stall flag is reversed (stalled) or not. The stall flags operate passively, contact less and have a fast response, they can be seen as advanced tufts. Their weight is about 1 g and they can be seen clearly from the ground. The stall flags do not limit the operational range of the turbine under study. To equip the turbine with stall flags takes only several hours, installation of a rotating camera is not required. Stall flags have the potential to visualize the complete stalled area on commercial rotors. ECN applied for a patent on the stall flag.

This report starts with the arguments to develop the stall flags. Then the design of the stall flag and the optical details on the visualisation method are presented. Also the first results of the application of stall flags on turbines in the field will be described. Among these results are high quality photographs of the area of reversed/radial flow on a 10 m diameter wind turbine and several test pictures of the Rotorline 32 rotor of the Nedwind 30 wind turbine.

Keywords: stall flag/ tuft/ full scale/ measurements/ stall/ radial flow/ separation/ flow visualisation/ wind turbine
List of Symbols

roman:

\( a \) [-] aperture
\( A_b \) \([\text{m}^2]\) area on a white blade
\( A_r \) \([\text{m}^2]\) area of a retro reflector
\( c \) \([\text{m}]\) blade chord
\( c_d \) [-] aerodynamic drag coefficient
\( d \) \([\text{m}]\) distance between camera/light source and the rotor
\( d_L \) \([\text{m}]\) diameter of the camera lens
\( E_b \) \([\text{lux}]\) illumination of the white turbine blades by the sun
\( E_R \) \([\text{lux}]\) illumination of the retro reflectors by the artificial source
\( E_l \) \([\text{lux}]\) illumination of the lens
\( EV \) [-] Exposure Value, \( EV \) = 0 = 100 ASA, 1 s, \( a=1.0 \). \( EV = \log(100 \times a^2/(\text{ASA} \times \Delta t))/\log 2 \)
\( f \) \([\text{m}]\) focal length
\( f \) \([\text{[°]}\] opening angle of the flap (0° is closed)
\( h \) \([\text{[°]}\] hinge angle (0° is in radial position with the retro reflector down stream)
\( I_R \) \([\text{cd}]\) luminous intensity of the retro reflector acting as a secondary source
\( I_s \) \([\text{cd}]\) luminous intensity of the source (60 cd = luminous intensity of 1 cm\(^2\) of a full radiator at 0°C of platinum.)
\( M \) [-] magnification
\( r \) \([\text{m}]\) radial position
\( R \) \([\text{m}]\) Rotor radius
\( S \) \([\text{m}]\) luminous flux of the source = cd sr (an isotropic point source of 1 cd has a luminous flux of 4\(\pi\) lm and the illumination at 1 m is 1 lux.)
\( S_R \) \([\text{lm}]\) reflected luminous flux
\( \Delta t_b \) \([\text{s}]\) illumination time of the blade images
\( \Delta t_R \) \([\text{s}]\) illumination time of the reflector images
\( x \) \([\text{m}]\) chordwise position

greek:

\( \alpha \) \([\text{[°]}\] angle of attack
\( \beta \) \([\text{[°]}\] pitch angle
\( \beta_t \) \([\text{[°]}\] total pitch angle
\( \delta \) \([\text{rad}]\) divergence angle of reflected light
\( e_{bi} \) \([\text{J/m}^2]\) exposure of the blade images
\( e_{ri} \) \([\text{J/m}^2]\) exposure of the reflector images
\( \eta_b \) [-] reflection efficiency of the white turbine blade area
\( \eta_t \) [-] lens transmittivity
\( \eta_R(\psi) \) [-] entrance angle dependent retro reflector efficiency
\( \theta \) \([\text{rad}]\) cone angle of the light source
\( \psi \) \([\text{rad}]\) angle between rotor axis and optical axis
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1. Introduction

Nowadays wind turbines are mainly commissioned aiming at electricity production. The kinetic energy of the wind is converted into a rotor torque, which on its turn is converted into electricity with a generator. Wind turbines need to be competitive and thus cheap. This means that models should be accurate to guarantee a turbine design with little conservativeness. However, engineering models predicting the loads on wind turbine rotors and the power produced by stall controlled rotors are often bad. In practice the produced power above the nominal wind speed can deviate with as much as 30% from the designed power. To improve the modelling, the models should be compared with practice. That means that accurate measurements on wind turbines are required to check the models. To get the most direct comparison between the prediction of models and practice, the measurements should be carried out on the large commercial wind turbines suffering from bad modelling. However no state of the art experimental method to study the stall behaviour adequately turned out to be applicable on large commercial wind turbines. Among the state of the art measuring techniques simple flow visualisation with tufts has a high potential, however tufts are bothered by bad visibility, centrifugal force dependence and flow perturbation. For this reason this study was focussed on taking away the complications of tufts. The method was to develop a kind of advanced tuft: which was called 'stall flag'. The stall flag is much better visible and is expected to be less bothered by the centrifugal force and to cause less flow perturbation. These characteristics had to be combined with the very high applicability of tufts. The stall flags enable in combination with a recording/illumination system, visualisation of areas of different flow directions on the surface of the blades. Changes in flow direction are closely related to the stall-behaviour mentioned above, therefore the new technique has the potential to yield data from experiments on large commercial wind turbines that can be used directly to validate or adapt theory. This report includes the first year of development of the new visualisation technique in detail. Starting point was the first prototype of the stall flag which incorporated the basic ideas, but was technically very primitive. The report concludes with a prototype that proved to remain operational for a few months on a commercial wind turbine. The report also includes a preliminary theoretical model of the optical part of the visualisation method, it does not include new results on the aerodynamics of wind turbines, it is only about the method to study the aerodynamics.

The Research Structure in Short

Problem Definition:
Bad aerodynamic modelling of wind turbines with respect to produced power and turbine loads. The models are hardly validated because of a lack of knowledge with respect to separated or radial and reversed flow on wind turbine blades. The list of uncertainties about separated or radial flow presented in section 1.1.3 illustrates the problem in detail.

State of the Art Problem Solving:
Several research institutes (ECN, DUT, NREL, Imperial College) carry out pressure measurements on moderate sized wind turbines (10-28m diameter) in the field. The (empirical) theories are tuned with the experimental results aiming at better aerodynamic models of wind turbines.

Discussion of State of the Art Problem Solving:
The state of the art procedure has the benefit that the pressure measurement system provides highly accurate pressures at the fixed measuring positions on the turbine.
blades. The obtained chordwise pressure distributions can be compared with the distributions predicted by the models. Comparisons between theory and practice are likely to provide better models on wind turbine aerodynamics. The state of the art procedure also has disadvantages:

- The test turbines on their fixed locations have limited analogy with the commercial turbines on other locations: The test turbines are rather small (except of the ECN turbine, which is about 28 m diameter) compared to the commercial turbines. They often are not allowed to operate above a wind speed of about 10-15 m/s, while the shortcomings of the models occur mainly at high wind speed of about > 15 m/s. Then they are not developed with the latest engineering models, while these engineering models require validation. Furthermore when a problem turns up on a commercial turbine it cannot be reproduced on the test turbines in general and therefore it can hardly be studied. Even if the problem could be ‘simulated’ on a test turbine, then it could not be concluded that the results would also be valid for the commercial turbine.

- The equipment of the test turbines is relatively inflexible and expensive: to equip a turbine takes in practice a few years and over a Mecu. Data is collected at a few (1-3) radial positions around the contour of a single blade. Therefore it is per definition impossible to study correlations between the blades. To derive integral loads of power interpolation or extrapolation of pressure data is required and will inevitably result in large uncertainties.

Two extreme approaches are possible to obtain the information, which can eliminate the discrepancies between predictions and measurements. One extreme exists of systematic wind tunnel measurements and subsequently implementation of the derived relations via scaling laws in the design codes. The other extreme exists of a direct experimental study on full scale wind turbines on which discrepancies between observed and predicted loads and power output occur.

Proposed Problem Solving
To solve urgent problems on commercial turbines measurements with the properties ‘fast result / high quality / little restrictions’ are required in close relation with theoretical analysis. Both theory and measurement should be applied as close as possible to the troubles in practice. Results of the latter approach could be included directly and reliably in the design codes. Therefore it is proposed to study directly modern commercial wind turbines with aerodynamic troubles.

Realisation
We need techniques to study stall on large commercial wind turbines with the characteristics ‘fast result / high quality / little restrictions’. In other words these characteristics mean respectively ‘low degree of complexity’, ‘obtaining valuable information’ and ‘full operational range of wind turbine maintained’. From a judgement of state of the art techniques it was concluded that flow visualisation with tufts has an exceptionally beneficial ratio between the value of the obtained information and the complexity of the technique. Therefore tufts were chosen as starting point for the development of a new technique that would provide much information on the flow for a low price and that would be applicable without restrictions to commercial wind turbines. The result is the new flow visualisation method based on ‘stall flags’, which was designed to meet the desired characteristics.

Future work
Once we have the technique to investigate the flow direction over the blades of large commercial turbines, the technique should be applied to turbines with troubles. The results should be compared with theory and theory can be validated or adapted, with
as consequence a better (aerodynamic) design of wind turbine rotors.

The information given above will be repeated in much larger detail in the remaining of the introduction.

1.1 Problem Definition

Section 1.1.1 explains the importance of the phenomenon stall for wind turbines. Then section 1.1.2 introduces the definitions of terms like 'radial flow' or 'separated flow' as they will be used in this report. Subsequently section 1.1.3 summarizes actual uncertainties about the stall phenomenon as it exists on wind turbines.

1.1.1 Importance of Stall

The torque on the rotor of a wind turbine is the result of aerodynamic lift and drag forces acting on the rotor blades. The magnitude of lift and drag are determined by a complicated interaction of the wind, the turbine and its surrounding. In this introduction only a very basic relation of the lift and drag forces is relevant: lift and drag increase with about the second power of the wind speed. Consequently below a certain wind speed, the torque will be insufficient to run the generator and above a certain wind speed, the torque could exceed the reactive torque of the drive train and generator. The latter wind speed is called the rated wind speed $V_{\text{rated}}$. At $V_{\text{rated}}$ the turbine reaches its nominal power. A cost-effective design of wind turbines requires that the turbine maintains operation far beyond $V_{\text{rated}}$, therefore the efficiency of the rotor should decrease when the wind speed exceeds the nominal speed to maintain nominal power output. The standard horizontal axis wind turbines dominantly use either pitch or stall control to maintain nominal power. This report will only deal with stall controlled wind turbines. Before continuation the definition of stall as being used in (Hoerner, 1985) will be introduced: an aerofoil is said to stall when the lift decreases with increasing angle of attack (AOA).

The stalled fraction of wind turbine blade can vary between 0 (nowhere stalled) and 1 (entire blade stalled). In two-dimensional aerodynamics, the stalled part of an aerofoil behaves as an aerodynamic object with low lift over drag ratio i.e. as a part of an aerofoil with very low efficiency. Therefore it is assumed that the power output of a wind turbine can be kept constant by increasing the stalled fraction of the rotor blades when the wind speed increases. This mechanism is used deliberately to control the power and the loads in case of the so called 'stall controlled' wind turbines.

We return to the problem again: the actual control of the power and loads of a (stall-controlled) wind turbine often turns out to be different from the designed mechanism. Both a precise quantification and the cause of these differences is hard to find, because no experimental method existed that could provide valuable information about the complete stalled area on the rotor blades of full size wind turbines. Some techniques could visualize stall on a fraction of a rotor blade, however this is not sufficient to derive for example the turbine power. Conclusively even when the actual stall behaviour of wind turbines would be very different from the modelled stall behaviour, we would not know.

The importance of the stall-phenomenon is widely recognized and therefore it is often a topic under study. Several projects deal (at least partly) with stall like the European project 'Dynamic Stall and Three Dimensional Effects' or the national project 'TIDIS: Three Dimensional Effects in Stall'. The purpose of these studies is to improve the aerodynamic understanding of rotating wind turbines, especially when bothered by the stall-phenomenon.
1.1.2 Definitions

The definition of stall presented above (an aerofoil is said to stall when the lift decreases with increasing angle of attack) does only depend on the relation between angle of attack and lift, it does not demand anything about the physical cause of for example the drop of lift. Therefore several definitions related to stall will be introduced that do describe physical effects. The term separation means that the flow does not follow the aerodynamic surface but leaves it or separates from it. In 2d-aerodynamics the location of separation corresponds to the location of zero shear stress. The flow over wind turbine blades can become separated beyond a certain position: the separation line. Both upwind as well as downwind the separation line the flow is directed towards the separation line. Upwind it has the main flow direction and downwind the flow is directed opposite to the main flow direction. The latter flow is denoted as reversed flow. Then we introduce the term radial flow, which is defined as flow which has a radial (from the turbine axis towards the tip) velocity component that cannot be neglected as in two dimensional aerodynamics. Both in the case of reversed flow and of radial flow the flow direction has changed largely. We introduce a new definition for such areas: areas of deviated flow. Deviated flow areas imply that the flow is radial or/and reversed. Both radial flow and reversed flow imply that the flow is deviated. The importance of the definition of deviated flow lies in the property that it can be measured with tufts or with stall flags. Radial flow is assumed to exist in separated areas on wind turbine blades and to significantly influence the aerodynamics. In the recent aerodynamic model of Snel (Snel, Houwink & Piers, 1992) this radial flow is assumed to be responsible for the deviations between theoretical and measured values for wind turbine loads and power.

In this report the term 'stall' will only be used furthermore in standard denotations like stall-controlled wind turbines or stall phenomenon. In most other cases the term 'stall' will be replaced by the more specific terms like 'separation', 'reversed', 'radial' or 'deviated' flow.

The relations between the definitions introduced above are presented by figure 1. If objects in the figure are connected by arrows, then the direction of the arrow corresponds to an implication. To put things very clear some of these implications (⇒) or non-implications (⇒) are explained in words:

- Stall ⇒ Separation
- Separation !⇒ Stall (laminar separation succeeded with turbulent reattachment, small scale separation)
- Separation ⇒ Flow of Changed Direction = Deviated Flow

Figure 1: Flow diagram of definitions. The direction of the arrows corresponds to the direction of implications.
1. if deviated area > tuft/ stall flag
2. radial flow does not imply separation
3. if dL/dα < 0 and dD/dα > 0 (Hoerner, 1985)
4. stall is always large scale thus detectable.
- Deviated Flow $\Rightarrow$ Reversed (2d) and or Radial Flow (3d)
- Reversed Flow $\Rightarrow$ Separation
- Radial Flow $\Rightarrow$ Separation (radial flow could occur on the surface of a rotating disk in a laminar boundary layer)
- Deviated Flow/Change of Flow Direction (over dimensions larger than/equal to the stall flags) $\iff$ Change of Stall Flag signals (if the flow direction change occurs over an area larger than/equal to the stall flag size.)

The last bidirectional implication is of special importance because it couples theory (deviated flow) with experiment (stall flag signals). Such a coupling enables validation or adaption of theory.

### 1.1.3 Uncertainties About Deviated Flow

Many uncertainties about deviated flow (which was defined as a combination of radial flow and/or reversed flow) collected from literature and from many discussions are given in the list below. This list can be seen as a thorough problem definition. To answer the questions in the list or to validate the hypotheses we would have to measure the precise pressures and flow directions everywhere along the blade on any wind turbine. It will be clear that we will be largely restricted by the availability of measuring techniques that can provide this information. Section 1.2.1 deals with this problem.

#### a. Location of deviated flow
- Do separated areas extend from the root of the blade towards the tip with increasing wind speed? (state of the art assumption)
- Are very high lift coefficients at inboard sections caused by a delay of separation (Himmelkamp, 1945)?
- The shed vorticity at the radial change over positions of annuli modelled with simple Blade Element Momentum are not independent like they are modelled, but are connected to each other. Reference: personal communication with B. Montgomery.
- Could there be an advance of separation at the tip section? At the inboard sections air moves towards the tip, which is regarded to be responsible for a delay of separation. At the tip the air moves inwards due to the tip vortex. These airflows meet each other at about 90-100% radius, therefore an advance of separation could be expected in this area.

#### b. Time Frequency Behaviour of Areas of Deviated Flow
- Do separated areas move over the blade with a certain pattern (centrifugal and coriolis effects)? (Snel, Houwink & Piers, 1992)
- Has the stall phenomenon hysteresis? (state of the art assumption)

#### c. Relation Between Noise and Separation
- How are noise production and the separated area related?
- Could the tip noise at low wind speeds be caused by a small separated tip area?

#### d. Type of Separation
- In (Hoerner, 1985) three types of separation are described: leading edge long bubble, leading edge short bubble and trailing edge. The type of separation might be dependent on 2d or 3d flow? Trailing edge separation is delayed, but leading edge short or long bubble might not be.
e. **Stall Strips and Vortex Generators**
- To force an aerofoil into stall sometimes stall strips are attached at a few blade locations. It is assumed that the few strips cause stall on the entire blade. Reference: personal communication with N. Timmer. It is not known under 3d-conditions when stall strips cause stall and when not.
- When the power yield of a turbine is less than it was designed for at high wind speeds, sometimes vortex generators are installed on aerofoils aiming at a postponement of stall.

What is effective range of the generators? Where should they be placed? What is the direction of the flow at the location of the vortex generators? (State of the art assumption)

f. **Power Control**
- Some engineering models assume that an increase of the wind speed of only 1-3 m/s is sufficient to bring an aerofoil from the just-separated situation into separation of the entire suction side (van Rooy and Timmer, 1993, a&b).
- The Bouma turbine did not show a clear power control by stall (van Rooy and Timmer, 1993 b, page 9,41-43). However the Darwin 180 turbine behaved rather good as was predicted from calculations. These conclusions were derived from the P-V curve only. Causes?
- An unexpected separated area was assumed to cause the low power output of the 44m Vestas turbines. Reference: personal communication with N. Timmer. It is also assumed that a larger than expected separated area caused the low power output of the flexhat. Reference: personal communication with J. Dekker.
- Does the complete rotor remain in attached flow until maximum power output is reached?
- Are parts of the rotor still in attached flow when the turbine power production exceeds the maximum design power of the turbine?
- Wind turbines without twist (e.g. the Lagerwey 18/80 turbines) could stall at the inboard sections before nominal power is reached and this would decrease the efficiency.

g. **Stall Induced Vibrations**
- In the study 'Stall Induced Vibrations' (Rasmussen, Petersen e.a., 1993), vibrations in the rotor of a turbine were attributed to separation. However this was concluded from blade root bending moments and power measurements, separation or radial flow was not observed directly. Validation with measurements is required.
- Lead lag motion from an unknown origin was observed on a large BONUS turbine. The cause could be an oscillating of the areas of deviated flow. Reference: personal communication with A. Brand.
- Can measured fluctuations of the size and location of separated areas explain the measured load fluctuations?

h. **Confirmation of Tuft Data**
- Sometimes tufts on rotating rotor blades suggest purely radial flow over large blade areas. The direction of the tufts could be dominated by centrifugal force in these cases (Antoniou and Pedersen, 1990).

i. **Different Power Levels / Multiple Stall**
- Several LM blades showed two or more power levels at high wind speeds (P. Grabau, 1996). The cause is unknown, however differences in separated areas are expected.
- Many rumours are heard that stall controlled windturbines show multiple stall levels corresponding to different power levels. Because manufacturers fear a bad image of their product, official information about multiple stall hardly exists or is confidential.
j. Relation between Lift/Drag and Stall
What are the quantitative consequences of separation or radial flow with respect to normal and tangential forces on the blades?

1.2 Solving the Problem

Systematic in the Wind Tunnel or Realistic in the Field?

The preceding section illustrated the lack of knowledge with respect to the stall or deviated flow on wind turbines. To improve and validate present theory, thorough experiments should be carried out. We classify all experiments on wind turbine aerodynamics in three groups: experiments in the wind tunnel, experiments with field test turbines and experiments on the commercial wind turbines that have the aerodynamic 'troubles'. This classification into three classes is discussable: for example the first class could also be divided into wind tunnel experiments with a non-rotating blade section and wind tunnel experiments with a rotating small wind turbine. The latter might correspond better to commercial wind turbines because it rotates, but a non-rotating blade section would corresponds better to the real situation regarding the Reynolds number. Another discussable part of this classification is that the difference between a commercial wind turbine and a test turbine would vanish, when the commercial one would be equipped with lots of measuring equipment: the commercial turbine would become a test turbine. In practice it takes many years and millions of guldens to transform a commercial turbine into a test turbine. The precise classification of experiments is of no importance for our purpose, we only need global acceptance about this classification. We would like to choose the type of experiment with the highest potential. Therefore the characteristics and definitions of the three classes will be explained.

Each class has pros and cons. In short wind tunnel experiments are relatively well conditioned and the influence of most physical factors on the flow can be discriminated. The understanding of stall could be improved in the wind tunnel, however the 'distance' to the actual problems is large. It is not sure that theory validated by wind tunnel experiments is applicable to the large commercial turbines in the field. For example the centrifugal number and the Reynolds numbers differ in general largely and can not correspond to the actual situation simultaneously. Figure 2 sketches the characteristics of each class. The second class is already much closer to the actual problems. The test turbines vary from about 10 m diameter for the test turbine of DUT to about 28 m diameter for the test turbine of ECN. The pro of measurements on test turbines is that they are in general closer to the practical aerodynamic troubles then wind tunnel measurements. Major cons of these measurements are that the ambient parameters (wind etc.) cannot be controlled and that the measurements are in general very expensive and take several years. Furthermore it should be noted that aerodynamic phenomena are very geometry
dependent. Because the geometry of the commercial turbines with troubles in general differs from that of the test turbines, also an (unknown) translation of the obtained data/theory is required. It is even not guaranteed that phenomena observed on the commercial turbines can be created on the test turbines. A final but severe problem of test turbines is that the sophisticated equipment in the turbine often restricts the operational range of the turbine. This is of large importance because most troubles with commercial wind turbines occur at very high wind speeds: wind speeds at which test turbines are often not permitted to operate.

The third class of experiments are carried out on the turbine that experiences the aerodynamic troubles. These experiments are maximally direct and realistic, no translations to another scale or geometry is required. The results can also be compared with the predictions from the engineering models used for the design of the turbine. These models are mostly more up to date than the models used for the design of test turbines. Validation or adaption of these models could be a direct consequence. This class of experiments requires fast and cheap applicability of measuring techniques that can provide appropriate data without limitation of the operational range of the wind turbine. Such techniques hardly exist and therefore scientific experiments are rarely carried out on large commercial wind turbines.

From the extremes 'systematic in the wind tunnel' and 'realistic in the field' the latter could not be chosen in the past, because no measuring techniques were available with characteristics like 'low complexity', 'high value of obtained information' and 'applicable in the field under most operational conditions on large commercial wind turbine'. This report presents the first results of a new technique that was developed to have the characteristics mentioned above. If the technique will become available successfully, then the option 'realistic in the field' is not bothered by practical reasons anymore. In this study we are aiming at that option, because it is judged to be of more value for the wind turbine industry: it is likely to provide faster results about actual problems.

1.2.1 Measuring Techniques to Observe Stall

If there would not be any restriction to obtaining experimental data, what kind of data would we like to have? In this theoretical case we would like to have the flow velocity and direction together with the total or static pressure at all locations around and especially on the wind turbine blades. If our demands would be a bit more modest, then it should be realised that when we have the total pressure that we can derive the static pressure if we know the flow velocity vector and vice versa. However if the velocity is derived from the difference of static pressure and total pressure, then the direction of the velocity vector is unknown. So if we have to choose, we prefer to have the flow velocity everywhere in the flow field instead of the static pressure everywhere in the flow field. Now we will return to practice again.

Many techniques exist to study the flow in one or another aspect. Some of the techniques can provide an enormous amount of accurate data. For example Particle Image Velocimetry, called PIV for short is such a technique. However this technique is also extremely complicated. Many particles are supplied to the flow and are photographed two times shortly after each other. From the displacement of the particles the local in-plane air speed can be determined. But, the optical requirements of the technique are extremely high and enormous illumination power is required to investigate large sheets. Furthermore the processing of the optical data into in plane flow velocities is a complicated procedure. Finally the particles put in the flow tend not to penetrate in the boundary layer; especially the suction side will be a region of low particle concentration. Simultaneously the suction side of the turbine blades is the region of largest interest. Altogether we conclude that rather valuable information can be obtained with PIV, but only for an extremely high price. Also the
ratio of obtained information over complexity \( i/c \) is low. The technique has proven to be successful in the wind tunnel, but with large complications. For details see (Corten, 1995a)

In table 1a we summarized many techniques to study the flow together with the obtained information and the major complications. The last column of table 1a gives a (partly subjective) judgement about the applicability of a particular technique. The meaning of the judgement is explained below the table.

Each judgement should not be seen as absolute truth. For example PIV is judged to be hardly applicable in the wind tunnel on non-rotating objects in table 1. However the study about PIV (Corten, 1995a) concluded with the statement: 'PIV can from purely technical point of view be applied to a 25 m diameter wind turbine in the field, but it will take many many man-years, millions of guilders and would harm the environment'. So the last column of table 1 should be seen as a reasonable judgement about the technique.

From table 1a it can be seen that the application of tufts has a low complexity. At the same time tufts provide important information: very well localized on the blades they point in the direction of the flow with a very fast response. Conclusively the ratio of obtained information over complexity \( i/c \) is high. This information is of large relevance for most items of the thorough problem definition listed in section 1.1.3 ‘Uncertainties about Deviated Flow’. These large benefits of tufts have been reason to use them as a starting point for the evolutionary development of ‘better’ tufts, which were designed not to be bothered by the problems of tufts. These problems are firstly the bad visibility with as consequence that only a fraction of a large rotor blade can be visualised and that the recording camera should rotate with the rotor. The last requirement implies that the technique is hardly applicable on commercial wind turbines. Other problems of tufts are the self-excited whipping motion which causes indeterministic behaviour and motion blur (Antoniou and Pedersen, 1990). Finally problems of tufts are the centrifugal force dependence and flow perturbation. The subsequent section will present the result of this study: the ‘stall flag'.
Table 1a: characteristics of state of the art flow investigation techniques

<table>
<thead>
<tr>
<th>technique</th>
<th>obtained information</th>
<th>complexity</th>
<th>app</th>
<th>i/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Image Velocim.</td>
<td>- air speed in a 2d investigation sheet</td>
<td>- complicated optics required</td>
<td>--/-</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- flow perturbation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pressure sensitive paint</td>
<td>- global pressure at high air speeds (&gt;0.5 Mach)</td>
<td>- short half life time</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- no direct response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Crystals</td>
<td>- global shear stress</td>
<td>- illumination/view angle depend.</td>
<td></td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- centrifugal force dependent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hot wire anemometer</td>
<td>- precise air speed at a one or a few locations</td>
<td>- equipment extremely delicate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- flow perturbation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- electric connections / slip rings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pressure sensors</td>
<td>- precise pressures = flow speed but not direction</td>
<td>- built inside the blade</td>
<td></td>
<td>++</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- electric connections / slip rings</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>- weather sensitive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>piëzo foils</td>
<td>- pressures changes</td>
<td>- electric connections / slip rings</td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>smoke</td>
<td>- global flow pattern</td>
<td>- production of precisely localised dense smoke</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>tufts</td>
<td>- flow direction on blade segment</td>
<td>- centrifugal force dependent</td>
<td></td>
<td>++</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- bad visibility</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 The applicability of the techniques is nominated according to the following definitions on the scale from -- to ++.

-- = Many complications even if applied in a wind tunnel.
-
= Only applicable in the wind tunnel.
+
= Applicable in the field only on test turbines.
++ = Applicable on full scale commercial wind turbines.

2 i/c = ratio of the value of obtained information over complexity. Also this value is subjectively determined. As qualitative measure the following ideas were used:

Valuable information means information with many of the following characteristics:

- accurate data on normal and shear stresses on the blade surface
- fast detector response and high sample rate
- direct measurement of the physical quantity under study
- little restrictions to the operational range of the wind turbine
- large number of measuring points
- measuring positions at all desired locations simultaneously

A low degree of complexity means for the aimed experiments:

- minimum changes to the turbine required (in practice: simple manner to fix a minimum amount of equipment on the blade surface and certainly not inside, no cables to the equipment, no slip rings and observer/camera on the ground, no restrictions to turbine operation)
- maintenance free equipment (only little and simple elements, passive operation is preferred)
- equipment durably resistant to the weather (resistant to lightning, water, ice, bright sunlight, etc.)
1.2.2 Stall Flag Method in Short

Tufts have been the starting point for the development of a new instrument that also would have a large ratio between obtained information on deviated flow and complexity. The result is the 'stall flag', which is much better visible than the tuft. A stall flag is a small instrument that provides a binary signal; it discriminates two intervals of flow directions. In one direction the stall flag is invisible, in the other direction it is clearly visible. The signals of the stall flags are so clear that they are visible for an ordinary consumer video camera observing the complete rotor plane of a large commercial wind turbine from the ground at about 100 m behind the turbine.

With these characteristics, the method of flow visualisation with stall flags has the potential to provide direct information on all uncertainties listed in section 1.1.3, except of uncertainty j. If we would add this new technique to the table of the previous section then the following result is obtained (see table 1b).

<table>
<thead>
<tr>
<th>technique</th>
<th>obtained information</th>
<th>complexity</th>
<th>app</th>
<th>i/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>stall flags</td>
<td>-area of deviated flow on complete rotor</td>
<td>-design of the stall flags</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>
2. The Stall Flag Method

During this study a method to visualise the stalled area on the blades of large (commercial) wind turbines was developed. The method has the low complexity and high applicability like flow visualisation with tufts. However, when tufts become invisible due to motion blur or by application on large objects, the newly developed detector becomes not. The method is based on an instrument that is much better visible than a tuft: the ‘stall flag’. The stall flag is a very thin detector that can be placed like a sticker on an aerodynamic object on which the flow direction needs to be measured.

Figure 3: The measuring set-up during a stall flag experiment. This pictures is not taken at the light source, therefore the retro reflectors can not be seen. See also figure 4.

Figure 4: Picture of the rotor plane taken from the position of the light source. The light bands on the pictures are caused by motion blur of the stall flag signals.

The development of the method ‘Visualisation with Stall Flags’ can be divided into two main parts: the development of the stall flag and that of the optical system to record the signals of the stall flags. The first part about the stall flag is described in section 2.1. The considerations for
the design of the optical system are presented in section 2.2.

2.1 The Stall Flag

The stall flag consists of the combination of a flap, a hinge, the support and the optically contrasting materials (see figure 5). Dependent on the direction of the flow, the stall flag shows two states, which are clearly optically distinguishable. Therefore the stall flag behaves as a detector with a binary output signal. It signals or flags a change in the direction of the flow. Because the detector was developed to flag the stalled area on large wind turbines it was called stall flag. A row of detectors is called a stall flag array (see figure 6). Each stall flag can distinguish two complementary intervals of flow direction. By using an array of stall flags placed under different angles a flow direction detector can be constructed (see figure 7). The moving part of the stall flag, the flap, is about 10 cm wide and 2 cm high. One edge of the wide side of this flap is fixed with a very flexible hinge to the support layer. In figure 5 the flap is dark grey on both sides, the support is light grey. The area of the support below the flap when it is pointing down is optically very different from the remaining of the support. In practice this area is covered with retro reflective or fluorescent material. In this report we assume that retro reflective material is used. The stall flag will be completely grey when the flap is in the downward position, but will be partly retro-reflective when the flap is in the upward position. This principle enables clear visibility of the binary output of the stall flag even from large distances.

Placement of a stall flag on a wind turbine is in short defined by the coordinates (r/R%, x/c%, h°). These three parameters respectively are the radial position, the chordwise position and the angle between the hinge and the radial direction. The last angle is defined to be zero when the hinge is oriented parallel to a radial line and when the retro reflector is located downstream with respect to the hinge, see figure 13. The hinge angle increases in direction of rotation of the wind turbine. If not noted otherwise, it is assumed that stall flags are placed on the suction side of the blade.
2.1.1 The Operating Principle of the Stall Flag

It is assumed that the flow direction determines the position of the flap, see again figure 6. Subsequently the position of the flap (open or closed) determines whether the stall flag is visible or not. During this study it was concluded that very good optical characteristics were obtained when a retro reflector was placed under the flap in one of its extreme positions. In that case a light source had to be placed close to the observer: see figures 3 and 4. When the flap would cover the retro reflector it could not be seen, when it would not cover the reflector it would retroreflect the light to the source and thus to the observer close to the source.

2.1.2 Evolutionary Development of the Stall Flags

This section reports the main work carried out during this study: the evolutionary development and testing of the successive prototypes of the stall flags. The work aimed at the design of a prototype that could be guaranteed to operate for several months on a wind turbine in the field. All constructive and optical details of the stall flag are equally important, because they all determine whether the detector will function or not, however these details would draw too much attention in the body of this report. Therefore the evolutionary development was reported in a separated report (Corten, 1997a).

In this section only the first and one of the last prototypes will be described briefly. The successive section will deal with all aspects of the stall flags that turned out to be important during the evolutionary development.

Every prototype is documented in three parts: the part 'production/construction' describes how it was made, the part 'tests/results' describes what was tested and the results of the tests and finally the part 'recommendations/conclusions' describes all new insights that should be taken into account for the successive prototypes. These insight are collected in the overall list of conclusions/recommendations, which is also given in (Corten, 1997a). This list contains the information about the design of a stall flag that is obtained during this study.

Prototype 1 (first stall flag array, drag increase tested in wind tunnel)

production/construction:
In total 33 rectangular flaps of 5 cm * 1 cm of icarex are pasted directly on the support of dacron of 180 g/m² which is 10 cm wide. The mutual distance between the flaps is 2 cm. The hinge is formed by adhesive which is smeared with a finger over the edge of the flap on the support. The stall flag array is shown by picture 8.

tests/results:
The prototype was tested in the Low Speed Tunnel of Delft University of Technology. It was placed on a perfectly smooth aerofoil. During the operation of the tunnel (1 hour) several flaps loosened. The edges of the flags were flapping and came loose first. The drag of the aerofoil with and without flags was measured. The drag coefficient $c_d$ measured with a wake rake increased from 0.009 to maximally 0.025 at 0° angle of attack and Re=10^6, see figure 9. The perturbation extended over about 20 cm width, in this area the average $c_d$ was approximately 0.022, outside this area $c_d$ was not influenced. The increase of $c_d$ per stall flag over the width of a stall flag will be estimated: $c_d$ increased with 0.013 over 20 cm width, while the flaps were only 5 cm wide. If the $c_d$ increase is assumed to be concentrated only over the width of the flaps then it would increase 20/5*0.013=0.052. Prototype 1 existed of an array of 33 flaps, so per flap the $c_d$ increase is 0.052/33 = 0.0016. To get an idea of the importance of such an increase, it can be compared to the increase of $c_d$ due to
roughness on the aerofoil, which is about 0.01. The estimation of the $c_d$ increase due to the flaps could be rather inaccurate when it is used to predict the drag increase due to stall flags in general. The increase could be too small because the first flaps probably produce much more drag than the last ones. It could also be too low for stall flags in general, because the prototype 1 flaps were very rough with flapping edges and therefore were expected to produce much drag. Furthermore the flags were located all around the leading edge, which is the most sensitive location for flow perturbation. The value of 0.0016 for the $c_d$ increase concentrated over the width of the flap can only be used as an indication, when better data are not available.

**recommendations/conclusions:**
- The rectangular shape of the flaps caused flapping edges, which probably introduced relatively large flow perturbation and drag increase. The edges of the flaps should be cut off.
- The directly pasted hinge is not strong enough, several flaps loosened after tunnel operation of 1 hour.
- The distance between the stall flags could be larger. A resolution of 25 chordwise positions is not required to study the stall behaviour.
- The increase of the drag coefficient $c_d$ due to a single stall flag is estimated to be 0.0016. For calculations it should be assumed that this increase only should be taken into account over the width of the flap.

*Figure 8: Prototype 1, which was tested in the Low Speed Tunnel of DUT.*

*Figure 9: The increase of the drag coefficient due to the prototype 1 stall flag array with 33 flaps. For calculations it is advised to increase $c_d$ with 0.0016 per flap only over the width of the flap.*
Below one of the latest prototypes is described partly. The full description can be found in (Corten, 1997a). The description here is only meant to show that many aspects that required attention turned up during the development: the stall flag became more and more perfect, many details became important.

**Prototype 12** (double PE-foil hinge and double layered flaps)

**production/construction:**

1a) White PP tape (polypropylene) of 0.5 m length and 4 cm width was taken by both ends and was pulled over sandpaper till the complete non-adhesive side was sandpapered.

1b) A piece of polyvinyl of 0.5 m length and 4 cm width was cut precisely from the black polyvinyl sheet. Then the removable layer was taken away.

2) The white PP or black polyvinyl tape was put with the non-adhesive side on a curved object (e.g. the drum of a centrifuge) to force the tape over its complete surface to the object. The tape was fixed on both ends with masking tape.

3) Glass fibre adhesive tape was put on the PE (polyethylene) foil to make the foil more manageable.

4) Pieces of 0.4 m times 1 cm were cut from the glass fibre tape with the foil. These pieces were put with an overlap of about 4 mm on both sides of the white PP tape. Afterwards the glass fibre tape was removed.

5) A piece of 3M double sided adhesive tape of 0.5 m length and 2 cm width was cut in two pieces of half width. Each piece was put precisely over the overlapping part of the PE foil over the PP tape. Then the removable layer of the double sided adhesive tape was removed.

6-20) See (Corten, 1997a).

**tests/results:**
The prototype 12 stall flags were tested with a jet of compressed air. The results were satisfactory: the hinges survived the jet at maximum speed for about 1 minute. None of the stall flags of preceding constructions could survive the maximum jet longer than a few seconds.

**recommendations/conclusions:**
The double polyethylene foil hinge of symmetric construction is much stronger than
the asymmetric single foil hinge. However, the double construction is also much more complicated.

2.1.2 Recommendations/Conclusions Concerning the Stall Flag

In this section all aspects about the stall flags that were topic of study during the evolutionary development are listed briefly. In (Corten, 1997a) the same list is given, but in larger detail.

1) flap shape -The flap shape turned out to be very important for the durability of the hinge: rectangular and trapezoidal shaped flaps came loose rapidly. Smooth flap shapes performed much better.

2) flap size -The height of the flaps should be about 1.5-2.5 cm.
- The hinge-width of the flaps, was chosen between 8 and 12 cm.

3) flap material -The flap material should be weather resistant and should be made of a material that can be pasted with adhesive.

4) flap weight -The weight should be minimal to provide maximum response speed. A pressure differences over the flap of 1-2 Pa satisfies to lift the weight of the flap.

5) adhesive -Many types of adhesives and methods to apply adhesive were tested, see (Corten, 1997a).

6) support -The support should consist of a single non-cutted piece. The support should be coloured darkly. It should be attached over its complete leading edge to the aerodynamic object to avoid puffing up. If the support extends to the pressure side flow perturbation is probably reduced. The support should be a few cm wider than the stall flags.

7) support mat. -The material should be weather resistant. Adhesive should hold on the support,

8) tape -Many tapes were tested, see (Corten, 1997a).

9) visibility -The visibility is increased by orders of magnitude when retro reflective material is used: it can be applied on the support layer under the flaps or on the flaps. The retro reflector should be as large as possible.
- At bright sunlight orange fluorescent diffuse reflective flaps in combination with a red-filter are better visible than retro reflectors.

10) hinge -The hinges has been the aspect of largest concern during this study. The hinge ‘problem’ origins from the required conflicting demands: the hinge needs to be both very flexible and strong. Beside of these requirements the hinge should also be weather resistant, durable (a few months), and it has to be attachable to the flap and support. See (Corten, 1997a).

11) reference Reference reflectors can be placed on the aerodynamic object studied with stall flags to check the recording system and for orientation. If a reference reflector is required, it should be placed further apart from the stall flags then the resolution of the video-camera. Otherwise the stall flag signals can not be distinguished from the reference signals.

12) non-adhesive For removable tape the support of address-stickers or the support of double sided adhesive or PP- or PE-foil can be
13) noise
   The flaps turned out to produce noise above certain flow speeds.

14) flap fixation
   -The foil hinges of stall flags have to be pasted unbended in
     the attached flow position to yield minimum flow perturbation
     and maximum durability.

15) flag distance
   -The chordwise resolution can be rather low because the stall
     phenomenon is very rough. About 3 to 5 chordwise positions
     will satisfy in most occasions.
   -The distance between flags should be equal to or somewhat
     larger than the resolution of the recorded images, otherwise
     the flags can not be distinguished. A video CCD is about
     600*600 pixels. If at least one CCD pixel should be in between
     the retro reflectors, an estimate for the distance between the
     stall flags is \((\text{turbine diameter} * 2) / 600\).

16) flow disturb
   -The increase of the drag coefficient \(C_d\) due to the stall flags is
     estimated to be 0.0016. This estimate is not reliable. For
     calculations it should be assumed that this increase occurs
     only over the width of the flap.
   -The flapping motion of the flaps is expected to increase flow
     perturbation.

17) flapping
   -Edges of rectangular flaps experience a strong flapping motion
   -The flapping motion is associated with Kelvin-Helmholtz
     instability.
2.2 Stall Flag Visibility

Figure 11 shows an example of the application of the technique on a wind turbine. At eight radial positions a stall flag array is placed like a sticker over the aerofoil. The applied arrays are pictured by figure 12. Each array is designed to 'flag' the stalled fraction in chordwise direction. The purpose of all stall flag arrays together is to visualize the total stalled area on the turbine blade (the dashed area on the blade in figure 11). The retro reflectors of stall flags which indicate stall, are uncovered and therefore will reflect the light from the artificial light source backwards to the source. The observer close to the artificial light source will clearly see the retro reflected light beam, because it slightly diverges.

![Stall flag arrays at 8 radial positions](image)

**Figure 11:** Stall flags on the Delft 10 m diameter test turbine.

**Figure 12:** The applied stall flag arrays.

The visibility of the binary signal of a stall flag on a wind turbine blade for a human being or for a (video) camera on the ground behind the turbine can be calculated as a function of parameters like the luminous flux of the artificial light source and the distance to the turbine. Later in this section such a calculation is presented. The calculation assumes that the visibility of the stall flag signal is based on retro reflection. The presented calculations are accompanied with rather large uncertainties: for example the spectral sensitivity of the observer or video camera is not incorporated, the usage of filters is not discussed and several more assumptions were made. In section 2.2.1.3 an estimate for the stall flag visibility is presented together with a list of applied assumptions. Due to the assumptions the absolute results of the calculations could deviate a factor 2 to 4 with practice, however for optical calculations such deviations are relatively small. During this study the visibility was not optimized by application of filters or adaption of the spectral sensitivity of the camera. For such optimizations the assumption used in this study can not be accepted, errors in the order of a factor 10 could be the consequence. In literature theoretical estimates of the visibility of retro reflectors in the field could not be found. The reason could be that many factors that are hard to include in formulas are of large importance. For example how should the formulas take the following situations into account: if the sun would shine straight into the camera lens, or if the retro reflection efficiency is changed by a thin water film over the reflectors. What about the variation of the solar spectrum during the day. For this reason the visibility of
retro reflectors is in general determined by experiments and rarely with theory. In this section an attempt was made to estimate the retro reflector visibility theoretically. To derive the equations, only state of the art optical relations were used.

### 2.2.1 Retro Reflector Visibility

Retro reflectors are visible if two demands are met:
1) The exposure of the retro reflector images should at least be more than a certain absolute minimum that depends on the sensitivity of the observer or camera.
2) The ratio of the exposure of the retro reflector images over the exposure of the remaining part of the image should at least be 2 or more.

The successive subsections deal respectively with the exposure of the retro reflector images, with the exposure of the remaining parts or the background and finally with the retro reflector visibility.

#### 2.2.1.1 Exposure of Reflector Images

As explained before the reflectors - if not covered by flaps - will be illuminated by a light source located closely to the (video)camera or observer. The reflectors will reflect the light backwards to the light source and its close neighbourhood, in which the camera is located. The reflectors will also be illuminated by background light (e.g. sun light), but most of this light will be reflected backwards to its origin (the sun) and therefore will not reach the camera. For this reason we assume that the background illumination does not contribute to the (video)camera images of the reflectors.

We use a light source with luminous flux $S$ and a bundle of isotropic intensity with cone angle $\theta$. The space angle of such a cone is equal to $2\pi(1-\cos\theta)$ sr.

Consequently the light source has luminous intensity:

\[ I_s[cd] = \frac{S[lm]}{2\pi(1-\cos\theta)[sr]} . \tag{1} \]

In this and many following equations the dimensions of the different quantities are often included between brackets to increase the comprehensibility. The illumination $E_R$ (expressed in lux) of a surface positioned under an angle $\psi$ in the bundle and located at a distance $d$ from the source is equal to:

\[ E_R[lu\text{x}] = \frac{I_s[cd] \cdot 4\pi[sr] \cdot \cos\psi}{4\pi \cdot d^2[m^2]} = \frac{I_s}{d^2} \tag{2} \]

If $d$ is also the distance between the light source and the centre of the turbine rotor then $E_R$ is the illumination of the rotor plane under an angle $\psi$. It is assumed that the turbine blades have no cone angle, that the blades are flat plates without twist and that the reflectors are fixed on these flat plates. In this case $\psi$ is approximately the average entrance angle of the light on the reflectors. It follows that the luminous flux from the artificial source on a reflector of area $A$ is $AE_R$ lm. The reflector will reflect this luminous flux with an entrance angle dependent retro reflection efficiency $\eta_R(\psi)$. The reflector can be seen as a secondary light source which returns a luminous flux $S_R$ which can be written as:

\[ S_R = \eta_R(\psi)E_RA. \tag{3} \]

The bundle of light from the reflector returns to its origin with a divergence angle $\delta$, which is a property of the reflective material (see Appendix B). The precise definition of the efficiency $\eta_R(\psi)$ used in this study is the ratio between the luminous flux from the reflector within the bundle of divergence angle $\delta$ divided by the luminous flux on the reflector (equation 3). It is assumed that the luminous intensity is isotropic within
the returned light bundle. Then it follows that the luminous intensity coming from the reflector \( I_R \) is equal to:

\[
I_R [\text{cd}] = \frac{S_R [\text{l}m]}{2\pi (1 - \cos \delta) [\text{sr}]} = \frac{S_R}{\pi \delta^2}.
\] (4)

In equation 4 the approximation is valid because typical divergence angles are 0.55° and 0.22°. The distance camera - reflector equals the distance light source - reflector, thus is also \( d \). It follows for the illumination of the camera lens \( E_L \) due to a single reflector:

\[
E_L [\text{lux}] = \frac{I_R [\text{cd}] 4\pi [\text{sr}]}{4\pi d^2 [\text{m}^2]} = \frac{I_R}{d^2}.
\] (5)

The camera lens of diameter \( d_i \) positioned in the area covered by the reflected bundle catches a luminous flux of \( \frac{4\pi}{M} d^2 E_L \). It should be noted that the optical axis of the camera lens is positioned parallel to the reflected light beam. A fraction \( \eta_L \) (the transmittivity of the lens) of this luminous flux is distributed over the reflector image. If the focal length of the lens \( f \) is much smaller than the object distance \( d \), then the magnification \( M \) equals \( \frac{f}{d} \). It follows that the reflector image has a surface area of \( M^2 \alpha \cos \psi \). It can now be derived that the illumination of the reflector image \( (E_{Ri}) \) is:

\[
E_{Ri} = \eta_L \frac{md_i^2}{4M^2 \alpha \cos \psi} E_L.
\] (6)

If we substitute the aperture value \( a = \frac{f}{d} \) and \( M = \frac{f}{d} \) in the equation above and use the derived expressions for \( E_L \), \( I_R \), \( S_R \) and \( E_{Ri} \), we can rewrite the equation into:

\[
E_{Ri} = \eta_L \eta_R(\psi) \frac{I_s}{4\pi^2 d^2 \delta^2}.
\] (7)

Finally the exposure of a reflector image \( \epsilon_{Ri} \), which determines in combination with the film or CCD sensitivity the density of the image, follows simply from the product of \( E_{Ri} \) and the exposure time of the reflector images \( \Delta t_{Ri} \):

\[
\epsilon_{Ri} = \eta_L \eta_R(\psi) \frac{I_s \Delta t_{Ri}}{4\pi^2 d^2 \delta^2}.
\] (8)

### 2.2.1.2 Exposure of the Background

Following the derivation for the exposure of reflector images, the exposure of white turbine blades will be derived. Starting point for this derivation is not the luminous flux of the sun, but the illumination of white turbine blades \( E_B \) by the background, mostly the sun. According to the law of Lambert the luminous intensity of a diffuse surface of size \( A_B \) in a direction of an angle \( \psi \) with the normal equals:

\[
I_B = \eta_B \cos \psi \frac{E_B A_B}{\pi},
\] (9)

in which \( \eta_B \) is the reflected fraction of light of the incoming light flux. Proceeding like in the previous section, it follows for the exposure of images of the blades \( \epsilon_{Bi} \):

\[
\epsilon_{Bi} = \eta_L \eta_B \frac{E_B \Delta t_{Bi}}{4 \pi^2},
\] (10)

in which \( \Delta t_{Bi} \) is the exposure time of the images of the blades.
2.2.1.3 Retro Reflector Visibility

Equation 8 presents the exposure of a reflector image, this parameter determines whether good recordings can be made when interference of background light is neglected. At night this negligence is correct, but during the day also the ratio of this absolute reflector image exposure and the exposure of the image of the turbine by the sunlight becomes important. At bright sunlight the turbine image could be brighter than the reflector images and consequently the reflectors could become invisible. To compare this exposure to the exposure of the reflector images, relation 2 is substituted in equation 8 and it follows:

\[ e_{Ri} = \eta_L \eta_R(\psi) \frac{E_R \Delta t_{Ri}}{4a^2 \delta^2 \cos \psi} . \]  

(11)

Subsequently it follows for the ratio between the exposure of the reflector images and the blade images:

\[ \frac{e_{Ri}}{e_{Bi}} = \frac{1}{\delta^2} \frac{\eta_R(\psi)}{\eta_B} \frac{E_R}{E_B \cos \psi} \frac{\Delta t_{Ri}}{\Delta t_{Bi}} . \]  

(12)

This ratio should at least be larger than about 2, otherwise the reflector images become invisible with respect to the images of the white blades. Because so many dependencies are involved, we recommend to carry out an experiment to determine the practical value for the minimum acceptable ratio for \( e_{Ri}/e_{Bi} \). The requirements for retro reflector visibility are in equation form:

\[ e_{Ri} > e_{min} , \quad \frac{e_{Ri}}{e_{Bi}} > 2 \]  

(13)

Each of the four factors on the right handed side of equation 12 needs some discussion to understand its practical meaning. The term \( 1/\delta^2 \) takes into account the 'amplification' thanks to the use of retro reflectors and has a value of about \( 2 \times 10^4 \) for \( \delta=0.40^\circ \). The next term is the ratio between the total reflection efficiencies. From appendix B it follows that the numerator is about 0.035 for the 'VIP' retro reflectors with and about 0.022 for the 'normal' reflectors. In both cases \( \psi \) is considered to be 30°. For the denominator we assume that \( \eta_R=0.8 \). The third term takes into account the ratio between the object illumination due to the background (the sun) and due to the artificial source. At total darkness this ratio is infinite in this model and therefore the visibility of the retro reflectors will be optimal. At bright sunlight the illumination of a surface perpendicular to the sun is about 1 kW/m². Because the blade surface is oriented almost vertically it is assumed that the \( E_B \) is about 10.5 kW/m². In this study a 3 kW light source was used to illuminate a turbine of 32 m diameter. The efficiency of the source was about 10% and the efficiency of the bundling on the rotor plane was about 33%. Consequently the exposure of the reflectors \( E_R \) was about 3 kW*10^-3/3.3(48m²*32² m²)=0.12 W/m². Conclusively the third term has a value of about \( 2.5 \times 10^4 \) at bright sunlight. The last term is the ratio of the exposure times. At high rotation speeds the exposure time of reflectors on the blade tips is determined by about the time it takes for a reflector to travel its own length in tangential direction. For example: if the reflector is located at radial position \( r \), the rotation speed of the turbine is \( \omega \) and the length of a reflector is \( l \) then the exposure time is maximally about \( l/(\omega r) \). A practical value for a stall flag on the tip is about \( 2 \times 10^3 \) s (\( \omega=34 \) rpm, \( r=15 \) m, \( l=2 \) cm). Thus, when the shutter time is less than \( 2 \times 10^3 \) s the ratio of the exposure times is 1 and for longer shutter times it drops rapidly. This is true when a continuous artificial light source is used, in case of stroboscopic illumination \( \Delta t_{Ri} \) is mostly determined by the duration of the flash. When an image is recorded with a normal photographic flash unit (flash duration = 0.7 ms) the ratio is about 1/3 or less.
Taken all factors into account, it is roughly estimated that for the retro reflectors of type normal (3M8850) at bright sunlight and with the 3kW artificial source illuminating a 30 m diameter wind turbine the ratio of the exposures is about 0.1. Therefore the retro reflectors will not be visible under these circumstances.

Inaccuracy of this value is about a factor 2.

Assumptions
Below a brief overview is given of all assumptions that were required to derive the exposure relations presented above:

1) The retro reflectors are only illuminated by the artificial light source.
2) The background/ turbine blades are only illuminated by background light.
3) The artificial light source has an isotropic intensity with a cone angle θ.
4) The retro-reflected light has an isotropic intensity with a cone angle δ.
5) The magnification M equals l/d.
6) Differences due to the colour of the light and related effects of filtering and colour-dependent sensitivity of photographic film/human eye or CCD-chip are neglected.
7) The lens is assumed to behave like a mathematically perfect lens without diffraction.
8) The transmittivity of air is assumed to be 1.

In a successive report about the stall flags assumptions 6 and 7 will not be used in a more thorough exposure analysis. Then it turned out that these assumptions could be of large influence.

2.2.2 Azimuthal Dependence of Stall Flag Visibility

When stall flags are placed on a rotating wind turbine blade, several geometric parameters change continuously with azimuth when the observer is not located on the produced part of the rotor axis. These parameters are the distance between the observer and the stall flags, the entrance angles which influence the retro-reflection efficiency and the uncovered retro reflector size.

These geometric changes influence the stall flag visibility largely. Systematic errors in the stall flag signals could therefore be the consequence. For example when a stall flag would be positioned at a location of reversed flow over a complete revolution, then the flag would not cover the retro reflector. However, because both the distance between observer and stall flag as the entrance angle of the incoming light change with azimuth, the retro reflector could become invisible over a fraction of the revolution. The observer would incorrectly conclude that the stall flag experienced reversed flow only over part of the revolution. This example illustrates the relevance of analysing the azimuthal dependence of the stall flag signals.

To determine precisely the azimuth dependent visibility a long list of geometric parameters has to be taken into account. The relations between the parameters are implemented in a computer program that calculated the exposure of a stall flag image as a function of the azimuth position on a linear scale. The results of simulations are presented in the next section. Here we will only explain the algorithm in words and what is included and what is neglected. The precise goniometric formulas can be derived straightforwardly and are therefore not included in this report.

Included Parameters
The turbine geometry includes the turbine height, the tilt angle, the cone angle and the angle between the surface of the blade at the position of the stall flag and the direction of motion of the blade. The latter angle is a kind of total pitch angle that includes the twist, the pitch and the profile shape, see figure 13.
The position of the observer and the light source are equal and are given by the height above the ground, the horizontal distance to the line through the rotor axis and the horizontal distance to the rotor centre of a vector in the vertical plane that includes the rotor axis. Then the position of the stall flag is given by distance from the rotor centrum to the stall flag measured along the blade, the chordwise position and the angle between the line through the hinge of the stall flag and the line through the rotor centre and the stall flag position, see figure 14. This angle is defined to be zero for a stall flag with its hinge in radial position with a covered retro reflector in attached flow. The stall flag geometry is given by a height (perpendicular to the hinge) and a width (parallel to the hinge) and the angle over which the flap has opened. This angle is 0 when the flap is completely closed and is \( \pi \) when the flap is fully opened. In the latter state the retro reflector is uncovered. Furthermore the entrance angle dependent retro reflector efficiency of the commonly used retro reflective material is included, the precise relations can be found in appendix B.

**Neglected effects**
The effects neglected in the analysis can be divided into three groups:

1) Changes of turbine geometry due to bending/torsion of the blades or tower.
2) When the uncovered size of the retro reflector is determined it is assumed that the flap is much wider than the retro reflector. So regarding the flap size, only the height of the flap determines the visible fraction of the retro reflector.
3) For the exposure calculations the relations presented in section 2.2.1 above are used, that means that the assumptions listed in section 2.2.1.3 are also applied here.

**Extreme Positions**
When the visibility of a stall flag at position \((r_e/R, \gamma/c, h_\theta)\) is studied we start with determination of the corresponding total pitch angle \(\beta_{\text{ter}}\). Then we feed as input parameters to the simulation program the coordinates \((r_e/R, \beta_{\text{ter}}, h_\theta)\). If the stall flag is
proven to be visible over the complete azimuth range of the rotor, then it is
guaranteed that any stall flag at position \((r/R, \beta, h)\) is visible over the same range
when \(r/R < r/R\) and \(|\beta| < \beta_{\text{in}}\) and \(h = h_{\text{p}}\). This statement is true because the distances to
the stall flag and the entrance angle of the light become more beneficial with
decreasing radius or total pitch angle.
Conclusively if just the visibility of stall flags at several extreme positions is proven
then the visibility of all other stall flags is guaranteed.

Figure 15 shows the shape of a thick and a thin profile for a wind turbine. The thick
profile is a typical profile that is used for the root of wind turbine blades and the thin
profile is a typical profile for the tip section. In practice stall flags are mostly placed
between 20%\(c\) and 80%\(c\) on the suction side of a profile. From the figure it follows
that the angle between the blade surface and the chord line varies between 20%\(c\)
and 80%\(c\) from +7° to -12° for the thick profile and from +9.5° to -12° for the thin
profile. Although many different profiles are used for wind turbine blades, the total
pitch angles do not vary largely if equal radial and chordwise position are compared.
The pitch angle of a typical wind turbine is about 0° at the tip and about 10° at the
root of the blade. Therefore the total pitch angles vary between +17° and -2° at the
blade root \((r/R=0.2)\) and between 9.5° and -12° at the blade tip \((r/R=1)\). In both
cases the values were given for respectively the leading edge and the trailing edge. It
follows from these values that one extreme positions is at the trailing edge of the tip
\((r/R=1, |\beta|=12^\circ, h)\). But closer to the root the total pitch angle exceeds 12°, therefore
the visibility is not guaranteed by studying only the mentioned extreme. If we assume
that the total pitch at the leading edge decreases linearly with radial position, then it
follows that for \(r/R=0.5\) the total pitch angle at the leading edge is 12°. So if we use
as second extreme \(r/R=0.5\) together with the maximum total pitch angle at the root
\(|\beta|=17^\circ\), then the position \((r/R=0.5, |\beta|=17^\circ, h)\) is a second extreme. This extreme is,
despite of the assumption about the precise radial positions and precise total pitch
angles, conservative: at \(r/R=0.5\) we use \(|\beta|=17^\circ\), while the local total pitch angle was
estimated to be only 12° and at the leading edge of the blade root we have both a
smaller radial position than in case of the second extreme and in practice the
luminous intensity of the light source increases with decreasing radius.
In short: if it is proven that stall flags on the positions \((r/R=1, |\beta|=12^\circ, h)\) and
\((r/R=0.5, |\beta|=17^\circ, h)\) are visible over the complete azimuth range, then all stall flags
on positions \((r/R<1, 0.2<\chi<0.8, h)\) are also guaranteed to be visible over their
complete azimuth range.
In this paragraph the relevance of the angle of the hinge \(h\) has not yet been taken
into account. Its relevance will be derived from simulations presented in the next
paragraph.

2.2.3 Simulation of Stall Flag Visibility

In this section the azimuthal dependence of the stall flag visibility will be presented as
a result of computer simulations. Three different dependencies are studied with the
program: the horizontal distance between the turbine and the observer, the location
of the retro reflector on the stall flag and the dependency of the visibility on the hinge
angle.

Linear Visibility:
The computer program calculates a value linear with the illumination of the retro
reflector image as a function of azimuthal position. The value will be called 'linear
visibility' and is proportional to the image illumination expressed in lux. The values
have only a meaning with respect to each other, but not in absolute sense. The main
reason for this is that the spectrum of the light source and spectral density of the
CCD-camera or photographic film should be included in the calculations to give the
results absolute validity. From experiments it was estimated that a stall flag is visible when the program calculates a linear visibility of 1 or more.

The Simulated Situation:
From the previous section it was concluded that just one or two extreme positions have to be studied with respect to visibility. We restrict ourselves to the following stall flag position \((r/R=1, |\beta|=12^\circ, h)\). For all other parameters, values were used that could be realistic for an experiment of a 30 m diameter wind turbine. The turbine is axis is chosen to be at 30 m height and 2.5° tilted. The cone angle of the rotor is also 2.5°. The observer and light source have an altitude of 1.5m and are localised at the same position. Both observer and light source are localised below the produced part of the line through the rotor axis and if not mentioned otherwise at 80 m horizontal distance from the rotor centre. The stall flag exists of a trapezoidal flap with edges cutted under 45°, see figure 12. The flap height is 2 cm and the width of the hinge is 8 cm, the flap surface is 12 cm² and can be adjusted to be retro reflective or not. The support reflector is 1.5 cm high and 7 cm wide and has an reflective surface of 7.84 cm². The location of the stall flag is given by the coordinates \((r/R=1, |\beta|=12^\circ, h)\), which corresponds to the 80%c position at the tip. If not mentioned otherwise the flap is open over an angle of 180° and the hinge angle \(h\) is 0°. The azimuth angle of the wind turbine rotor is in most cases varied from 0° to 360° with a step of 15°. At an azimuth angle of 0° the blade under study is positioned horizontal and is moving upwards, at an azimuth angle of 90° it is directed vertically in top position.

Distance Dependency:
The horizontal distance between the turbine and the observer is varied in these runs. The result is presented by figure 16. Two criteria determine which distance is the optimum. The first is that a stall flag at the worst azimuth position should be clearly visible, the second is that the variation of the visibility with azimuth position should be minimal. The criteria are conflicting. As a compromise the distance of 80 m is used furthermore in this analysis.

Figure 16: Linear Visibility as a Function of the horizontal distance between the observer and the wind turbine. At 60 m the minimum visibility has the largest value, however the visibility is largely azimuth dependent. Therefore a distance of about 80 m is regarded to be optimal.

Figure 17: Linear Visibility of the support as a function of the opening angle of the flap \(I\). When the angle exceeds 90°, then the stall flag remains visible over the complete azimuth range.
Location of the Retro Reflector:
Three possible configurations with respect to the placement of the retro reflector(s) on the stall flag are studied during these simulations: a reflector on the support below the flap only, a reflector on the flap only and reflectors on both locations. Both the flap as the area of the support under the flap -called support from now on - can be covered with retro reflective material. At first sight it might be the best option to provide both flap and support with retro reflective material, however the stall flag becomes thicker and the flap heavier in that case. A thicker stall flag might give more flow perturbation and a heavier flap will be more centrifugal force dependent and respond slower to aerodynamic changes. Thus it is preferred not to use retro reflective flaps. Figures 17 & 18 show simulation results for the linear visibility of the support only and of the flap separately. The different curves represent different values for the opening angle \( \theta \) of the flaps. From the figures it can be seen that the retro reflector on the flap becomes visible at much larger opening angles. This is another argument not to use retro reflective flaps, however at about 180° azimuth position the visibility of the support has its minimum and the visibility of the flap has a maximum. At opening angles between about 100° and 150° the visibility might double for a certain azimuth range, if both flap and support below the flap would be retro reflective. For this reason the visibilities at an opening angle 105° were compared in more detail, see figure 19. Although the figure shows that at the specific situation of an azimuth angle of about 180° and a flap opening angle of about 105° the visibility becomes less azimuth dependent. It was decided that the flaps need not to be retro reflective. The reason, from optical point of view, is that in most other situations the azimuthal dependence becomes worse. Furthermore even in case of the specific situation pictured in figure 19, the visibility is still guaranteed with just a retro reflective support.

Figure 18: Linear Visibility of the retro reflective flap as a function of the opening angle of the flap \( \theta \). This angle should at least be 135° to guarantee visibility for all azimuth positions.

Figure 19: At an opening angle of 105°, the total visibility becomes less azimuth dependent when the flap is also retro reflective.

Figure 20: Azimuthal stall flag visibility for different hinge angles at a flap angle of 30°. The stall flag is invisible for almost all situations.
Hinge Angle Dependency:
The dependency of the visibility with respect to the hinge angle is studied only for a stall flag on the extreme position at the tip at 80% chordwise position. Three series of simulations were carried out: at three different flap angles the hinge angle was varied. Figures 20, 21 & 22 present the results for flap angles of respectively 30°, 60° and 90°. seen that for flap angles below 30°, the stall flag remains invisible no matter what the azimuth position or the hinge angle are. At about 60° the visibility depends largely on the specific combination of hinge angle and azimuth angle. When the flap opens to 90° or more, then the visibility is guaranteed for all combinations of azimuth and hinge angle. From this analysis we conclude the following about the binary stall flag signal. Visible means that the flap angle is 30° or more, invisible means that the flap angle is less than 90°. conclusion in the form of a drawing.

Practical Proof for Visibility:
From the simulations above it became clear that the visibility of the stall flags depends largely on a long list of parameters. The calculations do take into account many dependencies correctly, however assumptions have been made and therefore the simulated results could be wrong or at least incomplete. The results can help with the alignment of an experiment and to calculate for example the maximum turbine size to which the method can be applied. But to be sure that stall flags will be visible if the flap is open over more than 90°, also a practical proof is advised. Therefore it is recommended to place reference retro reflectors of the same size as is used for the stall flags at the extreme positions. These reference reflectors are per definition always uncovered and therefore should be visible over the full azimuth range. Figure 23 shows an example of a stall flag pattern on a wind turbine.

Figure 21: Azimuthal stall flag visibility for different hinge angles at a flap angle of 60°. The visibility of the stall flag depends largely on the combination of azimuthal position and hinge angle.

Figure 22: Azimuthal stall flag visibility for different hinge angles at a flap angle of 90°. The stall flag is visible for almost all situations.

Figure 23: Example of a wind turbine blade with stall flags and reference reflectors at the extreme positions. The reference reflectors should always be visible.
blade with reference reflectors at the extreme positions.

2.2.4 Discussion/Conclusions/Recommendations

From the visibility analysis we conclude the following.

1) It would practically be handy if parameters like the distance between observer and wind turbine would be non-dimensionalised. It might result in an equal number for every configuration. However this is not the case. For a small turbine the observer and the light source can relatively easy be located on the produced part of the rotor axis. The amount of light will not be a restriction, and therefore the distance to the turbine can be relatively large, for example over 10 diameters. When a turbine is really big, the amount of light will be a severe restriction. In that case the source/observer will be placed as close as possible to the turbine as the entrance angle dependent reflection efficiency of the retro-reflectors permits. An estimate for the distance would be about 2 rotor diameters. The conclusions is that it does not make sense to non-dimensionalize the optical relations.

2) The presented calculations/simulations were based on several assumptions, which were listed in sections 2.2.1.3 and 2.2.2. Among the assumptions were the approximations that the lens was not bothered by diffraction and that all effects due filtering and colour sensitivity were neglected. These two neglections could influence the calculations largely, therefore it is recommended to improve the derived relations with respect to these neglections.

3) If a stall flag at the extreme position \((r_e/R, \beta^{\text{w}}, h_e)\) is proven to be visible over the complete azimuth range of the rotor, then it is guaranteed that any stall flag at position \((r/R, \beta, h)\) is visible over the same range when \(r/R<r_e/R\) and \(|\beta|<\beta^{\text{w}}\) and \(h<h_e\).

4) To guarantee the visibility in practice, reference retro reflectors should be placed at the extreme positions. These reflectors should be visible over the full azimuth range.

5) From the simulations it follows that from optical point of view there is hardly reason to use retro reflective flaps. Only retro reflective material below the flaps is sufficient. From aerodynamic point of view retro reflective flaps have only disadvantages.

6) The binary stall flag signal has the following meaning: visible means that the flap angle is 30° or more, invisible means that the flap angle is less than 90° (see figure 24).

Figure 24: Flap angle dependent visibility of the stall flag.
3. Experiments with Stall Flags on Rotors

This chapter described four experiments with stall flags, which were carried out on rotating rotors. The experiments aimed at over all tests of the visualisation technique and its possibilities. Most conclusions and recommendations are also included in the overall list of conclusions/recommendations concerning the stall flag design and production in (Corten, 1997a).

3.1 Stall Flags on the 28 m Diameter Test Turbine of ECN

setup:
The first field experiment existed of the fixation of three stall flag arrays on a blade of the 28 m diameter test turbine of ECN. Two bands with 6 stall flags each were put on the tip and one band with 12 stall flags was positioned at 60% radius, the stall flag arrays are described in (Corten, 1997a, 'Prototypes 6 a-c'). The order a to c corresponds to their positions counted from root to tip. The complete rotor plane was recorded with both a video camera and a photo camera positioned on the ground. As light source three halogen construction lamps were used (one of 1000W and two of 500W). The divergence angles of these lamps is about 90°, which is much too large for this application.

results:
The main benefits of the technique presented themselves: the experiment showed the occurrence of reversed flow clearly and the low complexity of the application of stall flags. The preparations took just a few hours. Next to these beneficial aspects the following observations were made: above certain rotor speeds a kind of flapping noise was audible. Adjacent stall flags could not be distinguished from video recordings due to the bad resolution of the video. The reference reflectors could be confused with stall flag signals. The durability and flexibility of the stall flags should be improved. The video recordings are archived in appendix D.1, the references to the pictures are f54,24a-36a and f55,23-33.

recommendations/conclusions:
This experiment proved the major benefits of visualisation with stall flags: in a few hours preparation time reversed flow could be visualised on a large wind turbine
for an observer on the ground, see figure 25.

3.2 Stall Flags on a Fast Rotating 0.45 m Diameter Propeller

setup:
Four stall flags of prototype 10 were placed at different radial position on a propeller blade. The propeller was 0.45 m diameter and rotated at about 600 rpm. In one quarter of the rotor plane a much smaller propeller of 12 cm diameter blew a jet of air through the rotor plane of the larger one. The flow directions of both propellers were opposite. The setup aimed at forcing the large propeller into stall in just about one sixth of its rotor plane.

results:
The result is shown by figure 26 (reference 158,35-36). The results is of special value for two reasons: firstly it shows that pictures with large motion blur do not bother the stall flag signals. In the contrary: the azimuthal stall distribution could be recorded on a single picture! For such recordings there exists one requirement: the stall flags shouldn't overlap each other in radial direction. The second interesting results is the fast response of the stall flags. The propeller turned around about 10 times per second and the stall flags could turn over and back in much less than one sixth of a rotation. Conclusively the stall flag can turn over and back in much less than about 16 ms.

recommendations/conclusions:
Motion blur does not harm the stall flag signals on the condition that they are placed without radial overlap. Due to this characteristic the stall flag signals can be recorded for about one rotor rotation on the same image.
The stall flags have a response time of at least less than 8 ms.
3.3 Stall Flags on the 10 m Diameter Test Turbine of IvW.

setup:
This experiment aimed at detailed visualisation of the stalled area on one blade of the 10 m test turbine in Delft. At 8 equidistant radial positions an array of 7 stall flags was placed. Prototype 8a-e stall flags have been used in the beginning of the experiment, after a few weeks they were replaced by prototype 10 stall flags which didn’t produce noise. See (Corten, 1997a, prototypes 8 & 10).

results:
Recordings of the complete rotor plane, that yielded clearly the area of reversed flow, have been made. The preparation time was very low again: all 8 stall flag arrays could be placed on about 2 hours. As light source 8 lamps of the type halogen 150W PAR 30 were used. With these lamps good quality recordings were made even at rather bright days. Figure 27 presents an example of the visualisation. For the video recordings we refer to appendix D.2. For the photographs the references are: f57,1-36.

During this experiment the stall flags yielded the first observation about the stall behaviour of a turbine: close to the blade root an area of full aerofoil stall was observed. At 10% larger radial position the aerofoil was in attached flow, so an area with only trailing edge stall was not observed, see figure 27. From the 2d-measurements we expect stall at the trailing edge for $\alpha > 16$ and full aerofoil stall when $\alpha > 25^\circ$. The ‘suction’ of the boundary layer could delay trailing edge stall, but probably would not delay leading edge stall: at the leading edge only a very thin boundary layer exists.

recommendations/conclusions:
Full aerofoil stall was observed at the blade root with stall flags. This area was limited by an area of trailing edge stall as would be expected. Could it be the case that trailing edge stall is delayed in the rotating situation and leading edge stall is not?
3.4 Stall Visualisation on the Nedwind 30 - Rotorline 32

setup:
This field experiment was meant to be the proof of concept for the new visualisation method. It has been divided in two phases: phase 1 deals with the preparation of the technique to become a standard method. Many parameters still had to be determined, and the durability of the stall flags had to be improved largely. For this experiment a light source existing of 21 150W PAR30 lamps was used. In this report only phase 1 is described briefly.

results:
Phase 1 was carried out and yielded stall flags which survived the worse conditions on a rotating wind turbine for months and were clearly visible on pictures of the complete rotor plane of the Nedwind 30 taken from a distance of 90 m. Another result of phase 1 were protocols for photographic and video recordings, which precisely described the proper combinations of shutter time/ aperture/ film sensitivity/ illumination power/ distance to the turbine etc. An overview of the measurements is given by figure 28. It should be noted that the stall flag signals cannot be observed, because the signals are only visible close to the light source (think about the retro-reflection principle). The phase 1 experiment has been reported in detail in (Corsten,1997b).

recommendations/conclusions:
The phase 1 experiments has been carried out successfully and thus phase 2 could be started. Phase 2 aimed at a thorough analysis of the stall behaviour of the Nedwind 30 - Rotorline 32 combination. Phase 2 is meant to be the proof of concept of stall visualisation with stall flags.

The placement of stall flags in chordwise direction is copied from pressure measurement sections. These sections are originally designed for 2d measurements. To study 3d-flow it is logical to place sensors both in chordwise as in radial direction. For a future experiment with stall flags it is therefore recommended to place for example a row of stall flags on the 80% c section from root to tip and a row at 20% c. This configuration enables the detection of the stall type (trailing edge/leading edge/full aerofoil) as a function of radial position.
4. Future Studies

Further research related to the stall flag method can be divided into three groups. The most important group focuses on studying the aerodynamics of large wind turbines with stall flags. The other groups focus respectively on characterising the technique in more detail and improvement of the technique. The subsequent sections summarise the items to be studied.

4.1 Studying Aerodynamics with Stall Flags

- Application of stall flags on wind turbines or other aerodynamic objects like helicopter rotors, sails, towers, propellers etc. The experiments should aim at taking away the uncertainties listed in section 1.1.3 'Uncertainties about Deviated Flow'. In particular an investigation of a series of almost equal turbines (NedWind turbines of different sizes) aiming at determination of flow direction and separation could yield valuable information for the design of a new turbine of the same series.
- Validation of state of the art engineering models for wind turbines based on 2d-aerodynamics. Do the predicted and observed stalled areas agree?
- Validation of the recent aerodynamic model of Snel that includes 3d-aerodynamics (Snel, Houwing & Piers, 1993). This model predicts implicitly the flow direction over the blades and could therefore be validated with stall flags.

4.2 Characterization of the Stall Flag method

- Estimation of the influence of stall flags to transition
- Modelling of the flutter behaviour of the stall flags.
- Modelling of the stall flag behaviour in a two dimensional separated boundary layer.
- Analysing whether the stall flag could have multi stable states.
- Wind tunnel experiments to validate the calculated effects mentioned above.
- Improvement of the Optical Modelling of the Stall Flags (effects due to filtering, spectral sensitivity and diffraction should be included).
- Estimation of the dependence of the stall flag signals on the location of the observer.

4.3 Improvement of the Stall Flag Method

- Standardization of the method (recording protocols, standard manner to fix the stall flags to the blades).
- Calibration of the stall flag signals (with pressure measurements).
- Studying the benefits of digital recording and digital image analysis of the stall flags.
- Improvement of the artificial light source.
- Improvement of the stall flag. Visibility, durability and fast response should be maximized, flow perturbation and centrifugal dependence should be minimized.
- Automation of the production of the stall flags.
5. Conclusion

A technique was developed that enables visualisation of the flow direction over the blades of almost any wind turbine. The technique is based on a newly developed detector, the so-called 'stall flag' and is characterized by the following list of pros and cons.

Pros:
- Stall flags are clearly visible, even from a large distance.
- The complete rotor of large turbines can be visualised, interactions between the blades can be observed.
- Motion blur does hardly bother the recordings.
- High reliability due to the direct visibility of the signals.
- Stall flags are placed just like stickers on the blades.
- No changes to the turbine: full operational range maintained.
- Fixable at almost any (blade) location in a very short time.
- Stall flags operate purely passively and non-electronic.
- No electric contacts/ slip rings/ power supplies required.
- Invulnerable for lightning or short circuiting due to rain or salt sedimentation.
- No electric distortion of the signals.
- Stall flags have thickness ≤ 0.4 mm and weight ≤ 2 g.
  - Low flow perturbation height.
  - Large surface/mass ratio i.e. low influence of centrifugal force.
  - No influence to the dynamics of the turbine.
  - Fast response (<8 ms).

Cons:
- A too large angle between the optical axis of the camera and the turbine axis could introduce systematic azimuth dependent deviations in the observed flagged area.
- The camera has to be replaced when the turbine yaws over large angles.
- Ice and water can restrict the motion of the flaps and can decrease the efficiency of the retro reflectors largely. However operation of the stall flag is recovered after a short dry and ice-free period.
- At bright sunlight the visibility of the stall flag can be insufficient for application on large turbines.
- Further studies are required to determine the relation between the stall flag signals and the corresponding aerodynamic forces.

From the list of pros and cons we conclude that stall flags enable 'fast result tests' of the stall behaviour of large commercial wind turbines at low cost, and that stall flags can provide information on the flow direction under most realistic circumstances. This direct type of information has the potential to improve the modelling of power output and loads of actual wind turbines.
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Rasmussen, F., Petersen, J.T., Winkelaar, D., Rawlinson-Smith, R., 'Response of Stall Regulated Wind Turbines - Stall Induced Vibrations', Risoe-R-691(EN), Denmark, June 1993.

(Snel, Houwink & Piers, 1993)
Acknowledgements

Dr. ir. A.J. Brand, dr. J.W. M. Dekker and prof. dr. ir. Th. van Holten are credited for their critical comments on the concept version of this report. Furthermore the Netherlands Energy Foundation is credited for financially supporting this work.
Appendix A. Origin/History of the Stall Flag

This section gives a short overview of the main steps in the development of flow visualisation with stall flags. Before the study about the stall flag was started much experience was obtained with another newly developed instrument: 'the stagnation flap' (Corten, 1996). This instrument was developed to visualize the stagnation line on the leading edge of rotating wind turbine blades by means of a very simple method. The assumption was that the observed stagnation line could be transformed into an angle of attack via the 2d-relation between stagnation point and angle of attack determined in the wind tunnel. Because by that time the angle of attack was seen as the most important parameter determining the pressure distribution along the chord. Thus if the angle of attack could be estimated along the full span of a blade then the integral loads and power could subsequently be derived. This theoretical background explains the purpose. The question how to reach the purpose was answered by the following two observations or conclusions. One is explained in section 1.2.1 'Measuring Techniques to Observe Stall', and was the fact that flow visualisation with tufts provides important information and is relatively simple. Even in modern industrial laboratories of Boeing and Fokker where money is of less importance tufts are still being seen as an important tool. The second observation was the view of a dog in a gale: all hairs were pointing away from the stagnation point and at the stagnation point the skin was visible. The stagnation point was visualised very simple with tufts! These observations have been reason to start the study 'Visualisation of the stagnation point', which was reported in (Corten, 1996) in 1993.

Localisation of the stagnation point on wind turbine blades was regarded to be a promising method to determine the angle of attack. On the leading edge of turbine blades a stagnation line is found instead of a stagnation point and for this reason flaps with hinges pointing in radial direction could be used instead of tufts. This change solved the problem of the centrifugal force (making the tufts point to the tip) simultaneously. The study [Corstag95] presents in detail the evolutionary development of the technique. In the successive study (Herzke & Peinelt, 1994) the first experiments on a field wind turbine with flaps to visualise the stagnation point were presented. However, it was decided to stop further development of the technique due to mainly technical problems (for details see [Corstag95]) in august '94. Long before this decision it was realized that the problems had three main causes. The stagnation flaps were positioned at the leading edge, which firstly is very sensitive for flow perturbation and is difficult to record with a video camera. Secondly the resolution requirements for precise localisation of the stagnation point were very high. Thirdly radial flow over the leading edge could influence the stagnation flap largely. In the beginning of February '94 the idea turned up to use flaps to visualize stall instead of the stagnation point. This application was not bothered by the mentioned three main problems with the visualisation of the stagnation point. Furthermore determination of the stalled area on wind turbine blade would be even more valuable than the localisation of the stagnation line.

The detector developed to visualize stall was called 'stall flag'. The stall flags were bothered by two main problems. One problem was to construct a hinge that was both extremely flexible and strong enough to survive for weeks/months on rotating wind turbine blades. The second problem was to improve the visibility of the stall flags so that the detection of stall by the detectors could be seen from large distances. This problem was mainly solved in March '95 by using retro reflectors as optical markers. Another improvement of the visibility was obtained in December '95 when one side of the flaps was provided with fluorescent material. In December '95 hinges of polyethylene and polyurethane foils were developed: high flexibility and high strength were combined. Some realistic experiments were carried out: the experiment with the 28 m diameter VERA-HAT in August '95, experiments with the 10
m diameter OARRF in October ‘95 and an experiment with a 0.45 m diameter fast rotating propeller in August ‘95. Below an overview of the major steps in the development is given.

detection of stagnation point (Corten, 1996)
- fur of the dog visualises the stagnation point
  Nov. ’93
- construction of first multi tuft
  5 Dec. ’93
- first stagnation flag
  19 Dec. ’93
- stagnation flag version 7
  24 Jan. ’94
- application on 10 m turbine
  March-July ’94


detection of stall/reverse flow
- first idea stall flag
  6 Febr. ’94
- retro reflectors improved visibility largely
  March ’95
- IDNL starts exploitability study
  May ’95
- full scale 25mHAT exp. (section 3.1)
  19 July ’95
- 10 m Delft exp. (section 3.3)
  Oct. ’95
- 0.45 m propeller experiment (section 3.2)
  Aug. ’95
- experiment on commercial NedWind 30 (sect. 3.4)
  Jan-March ’96
- application of PE and PUR-hinges
  Dec. ’95
- production of durable flags
  March ’96
- ECN applies for a patent on the stall flag
  May ’96
- poster (figure A.1) of the stall flag method at the
  EUWEC’96 becomes overall winner.
  May ’96

Figure A.1: Poster presented at the EUWEC’ 96, Göteborg, Sweden.

The Stall Flag, Prior Development and First Results 39
Appendix B. Properties of Retro Reflectors

In this appendix the results of a few tests with three types of thin film retro reflectors are presented. The three types under study are '3M diamond grade VIP' and two versions of '3M diamond grade normal' (3M8850). The difference between the two 'normal' types is that one type exists of uncovered retro reflectors (it feels like sandpaper) while the retro reflective material of the other type is embedded in a transparent layer. The relative intensities of retro reflected light normal to the reflector surfaces were measured to be 100%, 63% and 28% respectively. For that reason the third type has not been studied further in this analysis. Two important characteristics of the retro reflectors are the entrance angle dependent reflection efficiency and the divergence angle of the reflected light. Both characteristics are dealt with in detail below.

Entrance Angle Dependent Reflection Efficiency
The entrance angle dependent reflection efficiency was measured with the light meter of a professional camera which was looking to the reflector material while a LASER was fixed on the camera lens which was aligned parallel to the optical axis. The LASER illuminated the reflector. The entrance angle \( \psi \) of the reflector was adjustable. The reflection efficiency \( \eta_{\text{ref}} \) was measured for two distances between retro reflector and the camera with the LASER. The results are presented in figure B.1. The measurements at 6.5 m and 10 m distance are indicated with 6.5 and 10 respectively. The curves of the 'normal' reflector material is estimated with the curve 'fit (normal)'. From the figure it can be seen that the 'VIP' material is brighter at small entrance angles but at larger entrance angles the brightness drops more rapidly. Above about 45° the 'normal' reflectors have a larger efficiency than the 'VIP' material. For our purpose the characteristics of the 'normal' reflectors are favourite: the efficiency is more equal for \( 0^\circ < \psi < 50^\circ \) and higher for large entrance angles, which will occur incidentally. The function of the fit is \( \eta_{\text{fit}}(\psi) = \eta_{\text{ref}} \eta_{\text{max}}(1.36 - 0.022 \psi) \) for \( 15^\circ < \psi < 50^\circ \). For the purpose of visualisation of stall the entrance angles will mostly occur in the second range, therefore the function in this range can be used for calculations.

Divergence of the Retro Reflected Light
The divergence is measured by illumination of the reflectors with a LASER from a distance of 7.5 m. The normal vector of the reflective area was aligned parallel to the LASER beam. For a perfect retro reflector the LASER beam would be retro reflected exactly to the source, thus around the LASER no reflected light could be measured in that case. In practice we find around the LASER a bright spot of reflected light. The diameter of the spot is about 10.5 cm, which corresponds to a divergence angle \( \delta = 0.40^\circ \). With the photo camera it was determined that the VIP and the normal retro reflectors reflected respectively 5.0% and 3.1% of the incoming luminous flux within
this 0.40° divergence angle. These values were used for the exposure calculations presented in chapter 2.
A precise observation of the divergence angles shows that the diameters of the spots of the VIP and the normal reflectors were 14.5 and 5.8 cm respectively. In the spot the brightness is approximately homogeneous, outside the spot the brightness drops more or less rapidly. From these observations it was derived that δ=0.55° for the 'normal' reflectors and for the 'VIP' reflector δ=0.22°. The divergence angles are practically important. The reflectors return a light spot to the light source. The size of this spot is given by δ and the size of the source. The cameras have to be placed inside the spotted area, thus δ determines the maximum distance between camera and light source.

**Conclusion/Discussion**
For our experiment the reflectors have to meet several requirements. The requirements will be discussed briefly and compared with the characteristics of the reflectors summarized in table B.1. The first requirement is a large reflection efficiency for large entrance angles, the second is a low flow disturbance (low thickness). Both requirements are met better by the 'normal' reflectors than by the 'VIP' reflector.

**Table B.1: Properties of the retro reflectors**

<table>
<thead>
<tr>
<th>property</th>
<th>retro reflector</th>
<th>Diamond grade norm.-8850</th>
<th>Diamond grade VIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness [mm]</td>
<td></td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>surface</td>
<td></td>
<td>like fine sandpaper</td>
<td>smooth</td>
</tr>
<tr>
<td>fixation</td>
<td></td>
<td>self-adhesive</td>
<td>self-adhesive</td>
</tr>
<tr>
<td>δ divergence angle [°]</td>
<td></td>
<td>0.55</td>
<td>0.22</td>
</tr>
<tr>
<td>n_{max} (δ=0.40°)</td>
<td></td>
<td>3.1%</td>
<td>5.0%</td>
</tr>
</tbody>
</table>

The distance between light source and camera is determined as a function of the divergence angle. Table B.2 presents the maximum distances for a few practical distances between camera and reflectors.

**Table B.2: Maximum distance between camera and light source m.**

<table>
<thead>
<tr>
<th>distance camera-reflector [m]</th>
<th>distance camera-light source [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>reflector</td>
<td>normal (.55°)</td>
</tr>
<tr>
<td>25</td>
<td>24</td>
</tr>
<tr>
<td>50</td>
<td>48</td>
</tr>
<tr>
<td>100</td>
<td>96</td>
</tr>
<tr>
<td>200</td>
<td>192</td>
</tr>
</tbody>
</table>

**Settings/specifications of the apparatus**
6.5 m measurements:
camera: NIKON F801s, integral light measurement, f11, 100 ASA.
len: 35-135zoom at 135 mm, f8.
10 m measurements:
camera: NIKON F801s, spot light measurement, f—, 100 ASA.
len: 80-200zoom at 200 mm, f2.8 with factor 2 teleconverter.
$\eta_{\text{max}}$ measurement: NIKON F801s, integral measurement, illuminated area=area within integral circle.
LASER 5 mW, 670 nm
Appendix C. Illumination Sources

A continuous or a stroboscopic light source can be used for illumination. Both of them will be discussed below.

C.1 Stroboscopic Light Sources
A stroboscopic source needs to be synchronized with the (video) camera, but on average the power output is much less: most of the time no light is emitted. The duration of the flashes from stroboscopes can be very short < 1 ms, therefore the objects hardly have time to move during the recording and the images will be sharp. The combination of a photo camera and a flash unit gives very good results, but it should be realized that the shutter time of the camera is generally much longer than the flash duration. The consequence of this is that the background has a relative large contribution. Table C.1 presents several stroboscopic light sources.

Table C.1 Stroboscopic light sources

<table>
<thead>
<tr>
<th>source</th>
<th>power [W]</th>
<th>light yield [J]</th>
<th>bundle [°]</th>
<th>( \text{l}_{\text{relative}} ) (2)</th>
<th>price [hfl]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nikon SB24 (1)</td>
<td>50</td>
<td>0.1-100 (10 Hz)</td>
<td>25</td>
<td>1800%</td>
<td>800</td>
</tr>
<tr>
<td>Hec-Delft</td>
<td>150</td>
<td>10 (15 Hz)</td>
<td>?</td>
<td>?</td>
<td>700</td>
</tr>
<tr>
<td>Drelloscoop</td>
<td>400</td>
<td>2 (100 Hz)</td>
<td>?</td>
<td>?</td>
<td>10^4</td>
</tr>
</tbody>
</table>

(1) This flash unit for photo cameras distributes its stored flashing capacity over the series of stroboscopic flashes and has to recharge about 10 s after stroboscopic operation.
(2) The intensity of 21 PAR30 lamps of 150W each is defined as 100%.

C.2 Continuous Light Sources
Continuous sources require much more power because of their continuous light output. The benefits are that the sources are often cheaper than stroboscopes and that synchronisation is not required. When continuous light sources are used the shutter time of the (video) camera determines the illumination time and thus the sharpness of the moving stall flags. To obtain sharp images shutter times shorter than 1 ms are required. Table C.2 summarises several continuous light sources and their characteristics.

From table C.2 it can be seen that the highest luminous flux per guilder can be obtained from the lamp called 'halogen constr.', however the bundle of this lamp is very wide and therefore the luminous intensity is relatively bad. The halogen 150 W Par 30 lamp is also cheap and has higher intensity than the 500 W halogen constr. lamp, therefore this lamp will be used for the first experiments. The Par 56 lamp is relatively more expensive than the Par 30, furthermore it needs an armature and the Par 56 is much larger (d=17.5 cm) than the Par 30 (d=9.5 cm). This is a disadvantage because the distance between camera and lamps should be minimal to obtain maximum retro reflection efficiency. If the first experiments are successful, a larger investment is justified and the more expensive lamps from the table come in the picture. Their efficiency is up to 7 times higher and their bundling is also better. Illumination of large wind turbines will probably require these efficient sources. The most important column in table C.2 is the I/P column. It shows that the high pressure sodium lamp provides the highest intensity per watt. The difference with the metal halogen or high pressure mercury lamps is small but it should be mentioned that the latter lamps produce white light, while the sodium lamp gives yellow light. The relative intensity of the sodium lamp with respect to sunlight can therefore be improved with a
factor of about 2-3 by application of an optical filter. Conclusively the high pressure sodium lamp is the best option from the continuous light sources. The PAR30 lamps yield much infrared light. The video camera can be adapted by removing a special infrared filter and will become extremely sensitive for infrared. It is estimated that the sensitivity can be increased with a factor of about 4-8 in that case. The sodium lamp will be about 4 times brighter per watt with respect to sunlight compared to the PAR30 lamps. If we also take into account that the PAR30 lamps are a factor 20 cheaper per lumen it can be concluded that these lamp are a good second option. For the experiment described in section 3.4 'Stall Visualisation on the NedWind 30 - Rotorline 32' 21 PAR30 lamps have been used. Altogether the light intensity was $2.7 \times 10^5$ cd and the power was 3.2 kW.

Table C.2 Continuous light sources [6]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>halogen constr.</td>
<td>500</td>
<td>9.9</td>
<td>12 hor 35 vert</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td>halogen diapj.</td>
<td>150</td>
<td>5</td>
<td>20</td>
<td>49</td>
<td>350</td>
</tr>
<tr>
<td>halogen Par 30</td>
<td>150</td>
<td>2.6</td>
<td>10</td>
<td>87</td>
<td>20</td>
</tr>
<tr>
<td>Par 56</td>
<td>300</td>
<td>6</td>
<td>40 hor 16 vert</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>metal halogen</td>
<td>1960</td>
<td>189</td>
<td>6/-6 (adjust)</td>
<td>630</td>
<td>$4 \times 10^3$</td>
</tr>
<tr>
<td>high press. sod.</td>
<td>1000</td>
<td>130</td>
<td>6/-6 (adjust)</td>
<td>845</td>
<td>$3 \times 10^3$</td>
</tr>
<tr>
<td>low press sodium</td>
<td>180</td>
<td>33</td>
<td>60 hor 60 vert</td>
<td>58</td>
<td>$1.5 \times 10^3$</td>
</tr>
<tr>
<td>high pres. hg.</td>
<td>1800</td>
<td>150</td>
<td>6/-5 (adjust)</td>
<td>650</td>
<td>$5 \times 10^3$</td>
</tr>
</tbody>
</table>

C.3 Miscellaneous:

SB24 versus halogen
We compared the light yield of the Nikon SB24 with a 500 W halogen structure lamp. The halogen lamp gave a good picture at $d=4.0$ m, $f2.0$, 50 mm, 1/60 s. At equal settings the SB24 reaches 13 m at 24 mm. Thus the SB24 is $(13/4)^2 = 10.6$ times stronger. Zoomed to 85 mm the SB24 is 42 times stronger. The flash unit produces the light during 1/1000 s compared to 1/60 s of the halogen lamp. This difference makes the SB24 another factor of 1000/60=16.7 times more intense. We conclude that at 24 mm the SB24 produces 180 times higher intensity and at 85 mm this is 700 times more than a 500 W halogen lamp. If we compare 21 PAR 30 lamps with the SB24 then the light yield of the PAR lamps is one eighteenth of the SB24 at 85 mm.

C.4 Discussion/Conclusion
Continuous sources are simpler to use because synchronisation is not required. Furthermore they are in general cheaper than stroboscopic sources. But because stroboscopic sources are only operational during the exposure and not in between successive exposures they can be much more efficient (about a factor 10-30). Presently good recordings of a 30 m diameter wind turbine can be made with 3150 W of halogen PAR30 light, while no filtering has been used. However at bright sunlight the artificial light intensity is far too less. By optimizing the recordings with filters the relative artificial light intensity can be improved with a factor of 4 with respect to sunlight. By using high pressure sodium lamps another factor 4 can be reached at equal illumination power. Finally it is recommended to evaluate the possibility of bright LED's and of LASER light. Because these sources are monochromatic and can be used as stroboscopes, probably maximum efficiency can be obtained.
### Appendix D. Archive of Video Recordings

#### D.1 28 m diameter test turbine of ECN

<table>
<thead>
<tr>
<th>orig. time</th>
<th>rel. time</th>
<th>rot. sp.</th>
<th>pitch</th>
<th>stall</th>
<th>shutter</th>
<th>visibility</th>
<th>reflectors</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00:00</td>
<td>00:00:00</td>
<td>10-12</td>
<td>-18</td>
<td>upper half</td>
<td>yes</td>
<td>auto</td>
<td>60%</td>
<td>over-illumi++</td>
</tr>
<tr>
<td>00:19</td>
<td>00:19</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>120</td>
<td>good/best r+</td>
<td></td>
</tr>
<tr>
<td>00:33</td>
<td>00:33</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>250</td>
<td>good/best r+/-</td>
<td></td>
</tr>
<tr>
<td>00:52</td>
<td>00:52</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>1000</td>
<td>less good</td>
<td>just vis.</td>
</tr>
<tr>
<td>01:03</td>
<td>01:03</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>2000</td>
<td>bad</td>
<td>vanished</td>
</tr>
<tr>
<td>01:20</td>
<td>01:20</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>4000</td>
<td>bad, not us</td>
<td>vanished</td>
</tr>
<tr>
<td>01:35</td>
<td>01:35</td>
<td>&gt;25</td>
<td>-10?</td>
<td>trail edge</td>
<td>yes</td>
<td>auto</td>
<td>60%</td>
<td>over-illumi++</td>
</tr>
<tr>
<td>01:47</td>
<td>01:47</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>120</td>
<td>good/best r+</td>
<td></td>
</tr>
<tr>
<td>02:03</td>
<td>02:03</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>2000</td>
<td>bad</td>
<td>vanished</td>
</tr>
<tr>
<td>02:17</td>
<td>02:17</td>
<td>decreas.</td>
<td>vane</td>
<td>lead edge</td>
<td>m</td>
<td>m</td>
<td>1000</td>
<td>less good</td>
</tr>
<tr>
<td>02:28</td>
<td>02:28</td>
<td>decreas.</td>
<td>vane</td>
<td>lead edge</td>
<td>1000</td>
<td>eetc.</td>
<td>just vis.</td>
<td></td>
</tr>
<tr>
<td>03:03</td>
<td>03:03</td>
<td>decreas.</td>
<td>vane</td>
<td>lead edge</td>
<td>m</td>
<td>m</td>
<td>250</td>
<td>+</td>
</tr>
<tr>
<td>03:57</td>
<td>03:57</td>
<td>decreas.</td>
<td>vane pos.</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>04:17</td>
<td>04:17</td>
<td>&lt;10</td>
<td>&gt;0</td>
<td></td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>05:12</td>
<td>05:12</td>
<td></td>
<td>vane</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>05:21</td>
<td>05:21</td>
<td>stop</td>
<td>vane pos.</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>05:31</td>
<td>05:31</td>
<td>40</td>
<td>07</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>05:47</td>
<td>05:47</td>
<td>&gt;50</td>
<td>&quot;</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>06:00</td>
<td>06:00</td>
<td>auto stop</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>06:07</td>
<td>06:07</td>
<td>stop</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>06:25</td>
<td>06:25</td>
<td>start</td>
<td>trail edge</td>
<td>full stall</td>
<td>&quot;</td>
<td>m</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>07:00</td>
<td>07:00</td>
<td>dyn. stall</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>08:30</td>
<td>08:30</td>
<td>trail edge</td>
<td>full stall</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>10:15</td>
<td>10:15</td>
<td></td>
<td>too dark further on</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13:48</td>
<td>13:48</td>
<td>end</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### D.2 10 m diameter test turbine of 1kW

#### D.2.1 10 1955 first recordings of stall detection on the OARRE, wind 2-3 [m/s]

<table>
<thead>
<tr>
<th>Betamax</th>
<th>VHS</th>
<th>rot. sp.</th>
<th>distance</th>
<th>stall</th>
<th>visibility: file</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
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* stall starts at the leading edge and disappears from the trailing edge.

** only trailing edge stall

*** the flap in the middle of the first detector is often open

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* Flaps are located close to the 50% pressure measurement section.

# D.3
## D.3.1 31 01 96, Nedwind 30 fase1 illumination/detector tests, wind 6 [m/s]

34 [rpm], diameter 31 [m], 70% of the image height was used.

- Illumination: 3150 [W] halogen PAR30 lamps, 200V, recorded with a Sony Handycam

<table>
<thead>
<tr>
<th>Time (orig.)</th>
<th>Time (rel.)</th>
<th>Hour</th>
<th>Distance</th>
<th>Backgr.</th>
<th>Shutter</th>
<th>Visibility</th>
<th>Reflector</th>
<th>Turbine</th>
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<td>+/-</td>
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# D.3.2
## 01 02 96, Nedwind 30 fase 1 Illumination/detector tests

34 [rpm], diameter 31 [m], 100% of the image height was used, temp -8C.

- Illumination: Only sunlight, recorded directly on VHS via a Sony Handycam

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<th>Time (rel.)</th>
<th>Hour</th>
<th>Distance</th>
<th>Backgr.</th>
<th>Shutter</th>
<th>Visibility</th>
<th>Turbine</th>
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## 01 02 96 Test of the influence of the exposure

01:32:38 600? EV 13.3 10000 ++ ++ --

## 01 02 96 Test of the resolution

Only 2/3 of the turbine was recorded

01:32:56 600? EV 13.3 250-10000 ++ ++ --

01:33:44
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<th>bkgd/turb.</th>
<th>shutter</th>
<th>viability</th>
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(1) Too less light on the left side
(2) Mutual distance of 25 cm satisfies, 15 cm not.
(3) Mutual distance of 15 cm satisfies

Conclusions:
1. If EVI > 10 then no recordings are possible
2. If EVI < 4.0 high quality recordings are possible
3. Decreasing the illumination power has a negative effect under all circumstances
4. Only the shutter times 1/250, 1/1000 and 1/2000 can give good quality recordings
5. The minimum distance between the distinguishable flags is 36 cm
6. The fluorescent orange or white flags could not be visualised in any situation
7. The tripod should be made more stiff
8. The voltage drops due to the long cables to 200 V.
9. The light is rather badly distributed over the rotor plane
10. The reflected intensity is a factor 2-4 less then at 31 01 96 snow/ice on reflectors?
11. Several distances between camera and rotor should be tested.

D.3.4 21 02 96, Nedwind 30 fase l illumination/detector tests
34 [rpm], diameter 31 [m], wind speed = 6 [m/s], temp = -3 C
Illumination 3150 [W] halogen PAR30 lamps, 219V, recorded with a Sony Handycam, exposure just vis

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PAR30: 3150W, 75mm = EV3(80mm), EV3.5(200mm); PAR64, EV2.5(80mm), EV3.16(200mm) more bundled
Thus 1.27-2 times 1000W PAR64 = 1600 W would produce equal light intensity in the turbine centre. However the PAR30's illuminate the rotor plane rather homogeneously and the PAR64 illuminates mainly the centre.

Conclusions:
1. If EV1 > 9 then no recordings are possible
2. If EV1 < 7.5 high quality recordings are possible
3. Shutter times of 1/250 or 1/1000 provide optimum recordings
8. The voltage drop in the thicker cable is to 227V at 0W; 221V at 1.5kW and 219V at 3.2kW.
9. More illumination of the left side of the rotor can compensate for the larger entrance angle
10. The reflected light intensity is increased compared to the measurement of 09 02 96?
11. The horizontal distance of 75 m gives better results than 50 m.
12. The PAR64 has double intensity [cd], but is more bundled, the lamp is not an improvement.
Appendix E. Apparatus

In this section the specifications of the photo and video cameras are presented.

**Video camera** used for the measurements described in section 4.1 'Stall Flags on the 28 m Diameter Test Turbine of ECN' and in section 4.4 'Stall Visualisation on the NedWind30 - Rotorline 32:
Sony Handycam TR80SE hi-8

**Video camera** used for the measurements described in section 4.3 'Stall Flags on the 10 m Diameter Test Turbine of lvW:
-681(H) * 582(V) pixels interline CCD 5.4 mm * 7.0 mm
-2:1 interlace
-Horiz.: 15.625 kHz, vert. 50 Hz
-5 lux at f1.6
-shutter 1/50-1/10,000
lenses:
-7.5/15 and 24 mm (34°/17°/10°)

**Photo camera** used for all measurements and tests:
Nikon F801s
lenses: Nikon 50mm f1.8
    Nikon 35-135mm f3.5-4.5
    Nikon 80-200mm f2.8
flash: Nikon SB24

**LASER:**
LASER pointer 670nm, 5mW, class 3b