Technical report TR-181

KNMI

Calibration study of the K-Gill propeller vane

Marcel Bottema

Koninklijk Nederlands Meteorologisch Instituut

De Bilt, 1995

Technical report TR-181

De Bilt, 1995

Postbus 201
NL-3730 AE De Bilt

Telephone +31.30.220 69 11, telefax +31.30.221 04 07

This project has been funded by the Dutch National Programme on Global Air Pollution and Climate Change (NOP-1) as project NOP-854140.

UDC: 551.508.51.035
ISSN: 0169-1708
ISBN: 90-369-2093-0

Calibration study of the K-Gill propeller vane

Marcel Bottema

Wageningen Agricultural University
Dept. of Meteorology
Duivendaal 2
6701 AP Wageningen
The Netherlands

SUMMARY

This report presents the calibration results and dynamical properties of a K-Gill propeller vane. This instrument will be used for long term measurements of turbulent heat flux w'T' and momentum flux u'w' at the 200 m Cabauw mast of the Royal Dutch Meteorological Institute. The calibrations served as a first check on the quality of the instrument. Furthermore, some issues with regard to a field comparison experiment in Wageningen (K-Gill versus sonic anemometer) are discussed. This field comparison and the check-calibrations that follow are the final test to judge whether, and how, we can use K-vanes at the 200 m Cabauw mast.
Because of the size of the available wind tunnel, propellers and vane were tested separately. Propeller tests showed excellent agreement between individual propellers, at least for equilibrium response. Calibration constant was about $(50.0 \pm 0.3)^{-1}$ ms^{-1} Hz^{-1} for normal flow. The angular response of the tested propellers showed 'neat' behaviour. The propeller distance constant was about 2.5 m for zero angle of attack. We found that the propeller distance constant was not as constant as often assumed. For large wind speed drops, deviations from the classical first order e^{-t}-decrease were observed. Some preliminary experiments and results are reported in appendix I. Vane properties were evaluated by some preliminary static tests and were roughly 4 m (natural wavelength) and 0.4 (damping ratio). Further wind tunnel tests (including dynamic vane tests; see section 6.2 for proposals) are recommended for better evaluation of K-vane properties.

Finally, this report discusses some issues related to future application:

- The minimum measuring heights – in relation to propeller response – to assure 20% accuracy in u'w' and w'T' are about 6 and 21 m in neutral conditions, in very stable conditions the measured covariance fraction at 20 m is 68% and 50% for u'w' and w'T'. For vertical variances, height requirements are still more restrictive so that propeller response corrections are desirable for at least stable conditions.
- The maximum sample frequency that – with the required on-line computations – can be achieved with a Campbell 21X datalogger is about 5 Hz. Variances and fluxes may be affected if U is not well below 15 ms^{-1} (section 5.1), so that again corrections are desirable.
- A method of recovering wind components from K-vane output is given (section 5.2)
- 'Overspeeding' (section 5.3) may lead to up to 10% overestimation of mean wind speed U in deep, highly unstable boundary layers. The influences of overspeeding on the fluxes w'T' and u'w' remains an open question. Field comparison should yield better estimates.
- For practical purposes, field comparison tests (see section 6.2) may give a useful estimate of K-vane response properties, and an estimate of measuring errors that are difficult to evaluate theoretically.
- Section 6.3 and the appendices II and III discuss issues relevant to the Haarweg field intercomparison (K-vane versus sonic anemometer) experiment, with special attention to things that may cause errors in the final Cabauw measurements.

An overall conclusion with regard to the expected accuracy of u'w' and w'T' must be preliminary as so many, sometimes uncertain, factors come into play: e.g. tilt, propeller inertia, limited sampling frequency (due to limited datalogger speed) etc. Without corrections, the resulting errors in measured fluxes and variances may well exceed 10-20%. Suitable correction algorithms for the above effects are needed, but correction may be difficult for strongly stratified conditions, for highly transient conditions, and over strongly inhomogeneous terrain. Calibration stability and K-vane durability during normal operation seem to be satisfactory, as indicated by recent data mentioned in section 5.4.

CONTENTS

1. INTRODUCTION

This report presents the calibration results of a K-Gill propeller-vane (figure 1). By June 1994, this vane is to be used in a comparison experiment at the Haarweg-location at Wageningen. K-vane results will be compared with the output of a sonic anemometer at the same height (20 m), and the performance of the K-vane will be judged from this comparison. The results of the field comparison test are not available yet. Ultimately, 6 K-vanes will be used in a long term measurement programme for turbulent momentum and heat fluxes of the Royal Netherlands Meteorological Institute (KNMI), at the 215 m mast at Cabauw. This measurement programme is part of the TEBEX-project of KNMI.

The aim of the present calibration experiments is twofold:
- to investigate whether any problems are to be expected in the use of K-vanes. In other words, the calibration results are also used to determine whether the K-vane is a suitable instrument for the field experiments (e.g. accurate and sturdy enough)
- to determine some relevant properties, so that some expected systematic errors in K-vane-measurements can be analyzed beforehand.

More information about this K-vane project is given in the project report (Bottema, 1994).

For the long term field experiments, K-vanes were chosen for a number of reasons:
- their price (about $3000,-)
- their assumed sturdiness (indeed, K-vanes have survived some bad conditions at sea, Katsaros et al, 1993)
- their very stable calibration properties (Busch et al, 1980)

The K-vane has also some important disadvantages: a response length which is large compared to that of e.g. a sonic anemometer, and rather complicated dynamics.

2. DESCRIPTION OF INSTRUMENT AND TEST FACILITY

The K-vane has two propellers (also manufactured by R.M. Young; model/catalog nr. (0)8254) which are oriented 45° upwards and downwards (see figure 1). By adding and subtracting the propeller velocity components, the instantaneous $U_h(t)$ (horizontal) and W(t) (vertical) components can be recovered (Ataktürk and Katsaros, 1989). Meanwhile, wind direction is recorded by the vane, so that $U_h(t)$ can be decomposed into an west-east and south-north component (U_{WE}, U_{SN}). After completing a sample, the average wind direction can be computed, and the axes can be rotated in such a way that the U-component is parallel to the time averaged wind vector, and the V-component perpendicular to it.

In practice, recovering of the desired along-wind, across-wind en vertical wind components (and statistical properties of components and their combinations) is more complicated. Firstly, the propellers do not respond exactly to the axial component of wind, but yield less output for oblique flow. Secondly, both the propeller and the vane have finite response times (more exactly: response lengths) to the wind. This results in a rather complex vane-propeller interaction: both overspeeding and underspeeding are possible. The paper of MacCready and Jex (1964) and the review paper of Wyngaard (1981) can well serve as a first introduction on propeller-vanes and related anemometers. Reading the review of Busch et al (1980) requires more background knowledge. Zhang (1988) published an extensive analysis of propeller-vane interaction, and the effects on measured mean wind speed.

Figure 2 gives an impression of the dimensions of the Wageningen wind tunnel in which the propellers were calibrated. Actually, it is a copy of the KNMI wind tunnel (Monna, 1983). On the floor of the test section, a turntable is placed. There are also some facilities for mounting anemometers, and reading their position (distance to test section centre and orientation).
Figure 3 gives a closer view of the test section (without turntable). Effectively, the test section can be approximated as a cylinder with length and diameter both equal to 0.4 m. The size of the complete K-vane is very large compared to the wind tunnel. Therefore, the complete K-vane could not be tested. Only the propellers (which were mounted on their electronics housing) were tested thoroughly as the vane did hardly fit into the wind tunnel.

3. CALIBRATION RESULTS PROPELLERS

As noted above, the K-vane propellers were tested in the wind tunnel of the Group Meteorology of Wageningen Agricultural University (WAU). Each propeller – with its electronics housing – was mounted in such a way that its axis was within 10 mm of the test section centre for all wind directions. Figure 4 shows some relative wind speeds and turbulence intensities (100% x σ_u/U, Monna 1983). At the propeller location, relative wind speeds vary from about 0.99 near the propeller axis to 1.00 at 0.75 propeller radii (165 mm) from the axis, and to 1.01 near the propeller tip. Hence, the propeller will experience a wind speed which is well within 0.5% of the "reference speed".
In the following (3.1), the calibration procedures are described in somewhat more detail.

3.1 Calibration factor

First of all, the propeller calibration factors were determined. Part of the experimental set up has been described above. Some further general information (which also applies to the next sections) is given below:

Properties of both the propellers and the housing (e.g. internal friction in the photo chopper unit) could be different. Therefore, the propeller with serial number 52111 was assigned to the top-housing, and the propeller with number 52132 to the bottom-housing (both with serial number facing away from the housing). Note that the housing could be recognized by the rain screens at their axis: for the upward sensor, the rain screen was largest (widest) near the housing, for the downward sensor near the propeller.
Each propeller housing was equipped with a device to convert the voltage pulses of the photo chopper-unit to current pulses (this is necessary for the fieldwork). Outside the propeller-unit, current pulses were led over an electric resistance, and pulse rates were measured by an oscilloscope, by a counter, and by a Campbell 21X datalogger.
The computer program 'c:\wind\oud\aanloop' was used to fix the wind tunnel speed at some desired value. Usually, this was achieved within 15 seconds. Measured wind speeds are corrected for instrument blockage of the flow, and are reported. The program had an option to choose a large or a small cup anemometer. As no blockage corrections for propellers were known, propeller 52111 has been calibrated in the wind tunnel at the KNMI against a Lambrecht vane anemometer (no.1405a/1420543). Using this calibrated propeller the other propeller has been calibrated in the wind tunnel at WAU.

So far the general information. The calibration factor K and the correction U_c have been determined for wind parallel to the propeller axis. The calibration relation is:

$$U = K \times f + U_c. \qquad (1)$$

U is the 'real' wind speed (indicated by program 'aanloop'; f is the pulse rate (in Hz). Pulse rate measurements were made for 0.5, 1, 2, 3, 4, 5, 6, 8, 10,12, 15 and 18.5 ms^{-1}. Four runs were made; two for increasing tunnel speed, two for decreasing tunnel speed. These results were averaged. Then, a linear regression was made to obtain U_c and K.
For the top-unit, pulse rate was determined from counter data. It turned out that the Campbell results were in excellent agreement with the counter data. Moreover, the Campbell allows for a longer sample duration (10 sec. as long as number of counts is less than 6999) so that statistical errors could be decreased. Therefore, Campbell data were used for the second (bottom-) unit. Some control measurements were made with an oscilloscope. The resulting pulse rates were 1.8±0.2 % lower than those measured with the counter or the Campbell

datalogger.
The regression results are given below:

	top unit (counter)	bottom unit (Campbell)	manufacturer
K^{-1}	50.0±0.2 $Hz(ms^{-1})^{-1}$	50.0±0.3 $Hz(ms^{-1})^{-1}$	51.7±1.7 $Hz(ms^{-1})^{-1}$
U_c	0.20±0.03 ms^{-1}	0.21±0.06 ms^{-1}	0.2±0.6 ms^{-1}
r	0.99995	0.99996	- (2 points)

with r the correlation coefficient of the regression. Both propellers show excellent mutual agreement. Moreover, the calibration indeed shows almost perfect linearity, and a very low correction (about 0.20±0.05 ms^{-1}). The calibration results agree reasonably well with manufacturers specifications. By the way, the latter seem rather inaccurate as only two calibration points with a one digit accuracy in wind speed were available. It is reasonable to choose a K-value (eq. 1) of 1/50 in further work (error less than 1%).
The starting speed of propeller 52111 is determined at the KNMI and is about 0.21 ms^{-1}. The accuracy of this starting speed is uncertain however, since the starting speed of the Lambrecht is of the same order of magnitude.

The calibration factor of the propellers is in good agreement with the pitch of the propellers. The pitch, the column of air that has passed the propeller after one revolution of the propeller, is 0.30 m. The photo chopper unit produces 15 voltage pulses per propeller revolution. So in the absence of drag, with U = 1 ms^{-1}, the propeller unit produces 1 ms^{-1} ÷ 0.30 m $rev.^{-1}$ x 15 pulses $rev.^{-1}$ = 50 pulses per second.

3.2 Angular response

One feature of propeller anemometers is the fact that for oblique winds with angle θ, the output is generally less than cos(θ) x $U|_{\theta=0}$ (Gill, 1975; Busch et al, 1980). We can define angular response factors C(θ) by:

$$U_{meas.} = U \times \cos\theta \times C(\theta). \tag{2}$$

For the orthogonal fixed frame Gill-UVW anemometers (Gill, 1975), assuming ideal cosine response (i.e. C(θ) = 1 for all θ) can lead to 30% underestimation in e.g. the vertical velocity standard deviation σ_w (Hicks, 1972). For the present K-vane, errors by assuming ideal cosine response (C(θ) = 1) are still significant.

In the present work, response factors C(θ) have been determined largely in the same way as the calibration factor K. Measurements were made for wind speeds of 1, 2, 5, 10 and 15 ms^{-1}. Angles between wind and propeller axis were 0°, 15°, 30°, 37.5°, 45°, 52.5°, 60°,70°, 80° and 90°. Again four runs were made: an initial measurement for 0°, and all angles from -90° to + 90° (this corresponds to 270°, 180° and 360° on the wind tunnel turntable scale). One repetition of the procedure yielded the four runs. It is essential to measure response for a positive angle and its negative counterpart, and to average the results (its seems reasonable to assume that the propeller is symmetric). In this way, alignment errors (alignment within 2-3°) can be reduced by such an amount that they are negligible.

Some results are presented in table 2. As expected, both propellers show very similar behaviour with regard to cosine response. Reported error margins (table 2) are somewhat larger (too large) for the top propeller. This is because the reported errors are actually derived from coefficients of variance of the measured data. These data include alignment errors, which

are compensated when taking the average (attenuation for one measurement: $\cos\partial$ - $\sin\partial\tan\theta$; average over $\pm\theta$ only $\cos\partial$).
Figure 5 shows that cosine response is also slightly dependent on wind speed. This has mainly to do with the fact that for small wind speeds and large θ, the axial wind component approximates the starting speed U_s. For such large wind angles, the output of the other propeller is much larger. Hence the observed wind speed dependence is not very important. Around +60°, there is a small peak in cosine response. This could be due to the orientation (twisting) of the propeller blades.
Around ±90° the propeller output is not 0, as expected (except for very small wind speeds). The apparent angles ($\arccos(f/(f|_{\theta=0}))$, where f is pulse rate) for -90° and 90° were 3.4° and 2.4° for the top unit, and 3.2° and 3.1° for the bottom unit. In the top unit, the two angles differ as a result of alignment errors. Actually, the above shown difference between -90° and 90° is the best available proof of (and means of evaluating) imperfect sensor alignment.
For both propellers, the flow through the propeller was reversed, i.e. the flow was diverted around (and pointed away from) the propeller housing. One important observation was made: the propeller unit did not discriminate between different rotation directions. This can be important in convective conditions.

The next step is to model the above data in a way that is suitable for easy data processing. In the K-vane configuration, especially attack angles around 45° are of importance. Some curve fits by eye were tried, and compared with data of table 2. The best fit was:

$$C(\theta) = 1 - 0.3\sin^2\theta + 0.02\sin(6\theta). \tag{3}$$

This formula is accurate within 0.005, except for 15° and 60° where the fit is within ±0.02 of (average) experimental data. For $|\theta| > 65°$,it appears that actual response is somewhat underestimated by eq. 3. However, the uncertainty in the experimental data is larger than the difference between curve fit and actual data. This applies to both propellers.

The present results show that the angular responses of both our propellers are in good to excellent agreement. However, figure 6 shows that large differences between seemingly similar propeller types (all manufactured by R.M. Young) can still exist.
First of all, let us compare our parametrization by eq. 3 (solid line) with the manufacturers specification (filled squares;Young, 91). There is excellent agreement, except for $\theta \geq 60°$. For $\theta > 70°$, our data are smaller than manufacturers data, even for high wind speeds ($C(\theta)$-values 0.77 and 0.85). As already noted, errors for large θ do not have large implications for the final K-vane output.
Figure 6 shows also a dashed line which is a parametrization (Drinkrow, 1972) of data presented by Horst (1973). Especially around the important angle of 45°, there are significant differences with the present data. Some other data by Hicks (1972) are given as well. Hicks too, used 23 cm Gill propellers. Hicks' data correspond well with the present work, even slightly better than the manufacturers data.
Some data of figure 3 of Ataktürk et al (1989) are plotted as well, because they may shed light on the cause of the differences. In figure 6, the open squares denote results for a lightweight polystyrene propeller 23 cm diameter (catalog nr. 21281) at U =5.73 ms^{-1}. The filled triangles are for an 18 cm sturdy polypropylene propeller (cat. nr.8234) at 5.73 and 11.73 ms^{-1}. We used (0)8254 propellers. Large differences can be seen between the lightweight propellers and the sturdy propellers. However, figure 3 in Ataktürk et al (1989) shows also significant differences between the two lightweight propellers of different radius. Qualitatively, the differences are the same for our sturdy propeller of 22 cm diameter, and Ataktürk's 18 cm propeller. By considering figure 6, we can conclude that the properties of propellers of similar shape (i.e.

angular response) do at least depend significantly on the propeller material (its weight), and on the propeller dimensions.

3.3 Distance constant

The distance constant D – or at fixed wind speed the response time τ – is an important property of a propeller. Generally, a propeller is assumed to be a first order system which satisfies the following equation (Horst, 1973):

$$\tau \frac{dU_{meas.}}{dt} = -\left(U_{meas.} - U(t)\right). \tag{4}$$

where $U_{meas.}$ is the speed indicated by the propeller, and τ a time constant. The distance constant D is defined as :

$$D = U\tau . \tag{5}$$

As the name already suggests, it is – approximately – a constant. In the present work, U is always the full wind tunnel speed. As opposed to others (e.g. Busch et al, 1980) we did not choose a reference speed in axial direction. This is because we want to demonstrate clearly that a propeller on a K-vane responds slower because it is inclined to the mean flow.
It is important to note that by eq. 5, the propeller response time τ is wind speed dependent. Hence, it would appear that a propeller tends to overspeed because the time response to wind speed increases is quicker than for wind speed decreases. This is MacCready's (1966) u-error. In practice, this is not necessarily the case (Busch et al, 1980). Consequently, the 'distance constant' is not really a constant.

Measurements of distance constant D require that either an independent fast response measurement of wind speed history is available, or that – at a fixed wind speed – propeller speed can be fixed at a certain value.
The first method could not be used because the characteristic time of the wind tunnel was between 5 (low speeds) and 9 seconds (for high speeds). This large wind tunnel response time made it very difficult to estimate D for wind speed decreases (see later).
We used the second method, and simulated a step change in wind speed by imposing a steady wind, and then suddenly releasing the propeller. This was done by swiftly moving away a rod which rested on the propeller. The rod pointed through a hole in the wind tunnel ceiling, and could be held in place by some foam plastic. The propeller output (pulse rate) was measured with a Campbell 21X datalogger, and later analyzed in a spreadsheet program (example in figure 7).

Still, there were considerable practical problems to solve in the evaluation of D. The reason is that our propellers deliver only 50 pulses when a unit column of 1 meter air crosses the anemometer. For 63% speed up of the propeller, a column of D meter air has to cross the anemometer, and for an acceptable resolution in the response time (and hence D), only a column of 0.2 x D should pass the anemometer. For a fast propeller, with D = 1 m, this would – using the calibration factor of section 3.1 – result in a maximum of 10 pulses per time interval, i.e. a maximum output resolution of 10%, and a maximum time resolution of 20%! Hence, it is very difficult to estimate D for fast propellers with pulse output. Luckily, our propellers were not so fast and D was sufficiently large (2.5 m) to allow for reasonable estimates of D (see also figure 7). We used Δt = 0.1 sec. (the minimum sample time which

yielded correct results), except for 2 ms^{-1}, where we used $\Delta t = 0.2$ sec.
Figure 7 shows a typical step function response, and a curve fit according to eq. 4. In the observations for small angles of attack, there was a trend for $D_{63\%}$ to be larger than D_{LR}, where $D_{63\%}$ is estimated from the point of 63% speed up, and D_{LR} from a regression. One cause may be the time discretization: the last measurement with zero output is assigned t=time=0 (2.3 sec. in figure 7). For $\tau = D/U = 2.5/4 = 0.63$ sec., and $\Delta t = 0.1$, the average overestimation is 8%. The remaining 12% can be caused by initial (friction) effects, or by too slow a removal of the rod.
Anyway, it is important to note that D should be determined from regression of the entire propeller output (according to eq. 4), and not by simply taking the point of 63% adaptation!

With the methods described above, distance constant was determined as a function of attack angle. Figure 8 and 9 show some typical results for both propellers. For large angles, the variability is rather large (figure 8), but no significant trend with wind speed can be seen. Figure 9 shows that the bottom propeller responds slightly quicker than the top propeller. The observed angular dependence corresponds well with the formula:

$$D(\theta) = D(0°)/\sqrt{\cos\theta}. \quad (6)$$

Note that many investigators (e.g. Busch et al, 1980) prefer to refer D to the axial wind component, so that their D(θ) is proportional to $\cos^{0.5}(\theta)$ instead of $\cos^{-0.5}(\theta)$.

Table 3 gives a summary of the data. The most important results are:
D(0°) = 2.5 m
D(45°) = 3.5 m (effective D in K-vane configuration)
$D(\theta) \approx D(0°) / \cos^{0.5}(\theta)$
The symmetry of the K-vane makes it easy to derive the (effective) distance constant in a K-vane configuration: for horizontal winds it is simply the D we measured for 45° angle of attack. For non-horizontal winds, we made some rough estimates by using eq. 8 of Brook (1977), and the fact that for the K-vane $U = 0.707 \times (U_{top} + U_{bottom})$, and $W = 0.707 \times (U_{bottom} - U_{top})$. For U, only elevation angles of ±45±10° led to more than 5% increase in D (19% at 45°). For W, D decreased by 3, 6, 14 and 28% for elevation angles of ±11, 22, 33 and 45°. Significant deviations occur only for large angles so normally, we can treat D as a constant (of 3.3 m).

The manufacturer let us know (pers. comm. R.M. Young, 26-04-1994) that D(0°) = 2.1 m, and $D(\theta) \approx D(0°) / \cos(\theta)$, in fair agreement with the present work. For similar (but not identical) propellers, Ataktürk and Katsaros (1989) report D = 2.7, 3.2 and 4.4 m for θ = 0°, 45° and 60°. These results differ in two respects with ours: a larger value of D(0°) (this can be explained if they use $D_{63\%}$, see discussion above), and a much larger D(60°) (reason not known). Other references report mainly about the much lighter polystyrene Gill propellers which have a distance constant of about 1 m (e.g. Hicks, 1972; Gill, 1975).
Finally, it is important to note that due to both propeller properties and testing methods, significant differences can occur for similar propellers, as in the case of cosine response. Hence, it is important to test propellers before using them in the field. Moreover, in the case of distance constants, the testing methods should be described in sufficient detail as well.

It was thought necessary to estimate D not only for U-increases, but also for U-decreases. Some preliminary tests have been carried out which suggest that D might not be constant. This was thought to be important, so the experiments and the results are discussed in appendix I.

4. STATICAL EVALUATION OF VANE PROPERTIES

4.1 Method

In the present work, vane properties were evaluated by some static tests (see Wieringa, 1967 for basic equations to be used for dynamic testing) and a theoretical/computational method (Wieringa, 1967) as no time was available to carry out dynamic vane tests. For the present analysis, we assumed the vane to be frictionless.

Key properties of a wind vane are natural wavelength $Ut_0 = \lambda_n$ and damping ratio ζ. From ζ and λ_n, the decay distance λ_D (length of air column that has to pass before either signal or signal amplitude is below a certain threshold) and the damped wavelength λ_d can be determined (see Wieringa, 1967, 1971).
Wieringa's (1967) eq. 9 and eq. 11 yield the following formulas for λ_n and ζ:

$$U t_0 \equiv \lambda_n = U \times \frac{2\pi}{\sqrt{N/J}} \quad ; \quad \zeta = \frac{\pi r_v}{\lambda_n}. \tag{7}$$

where N is the torque per unit angle of attack ($N = r_v F_v/\beta$), r_v the distance between the aerodynamic centre (0.25 - along-wind - vane lengths from the leading edge of the fin) and the vane axis, and J the moment of inertia.
The moment of inertia can be computed, while N can be measured with some static tests in a wind tunnel.

4.2 Moment of inertia

The moment of inertia ($\int r^2\,dm$ or $\Sigma\, m_i r_i^2$) is evaluated by adding the moments of four components:
- the vane axis
- the vane blade
- the counter weight on the vane axis
- the two housings of the propeller

The moments of the propellers and of the turning part of the K-vane frame were neglected because either their weight (m_i) or their arm (r_i) is relatively small, and because this is only an approximate analysis.
The weight of the propeller housings m_{proph} could be measured straightforwardly. The total weight of blade, vane arm and counter weight could also be measured directly, as well as the volumes of each component. However, the counter weight was expected to have a greater density than the vane arm and blade. A balancing test showed that this was indeed the case: $\rho_{c.weight} \approx 7320$ kgm^{-3}, while for the other two components, $\rho \approx 2115$ kgm^{-3}. The masses of the components were: 99, 99, 209 and 2 x 191 g (axis, blade, c.weight, prop.housing). The contributions to the moment of inertia were $J_{axis} = 0.0170$, $J_{blade} = 0.0307$, $J_{c.weight} = 0.0012$ and $J_{proph} = 0.0148$ kgm^2. This yields a total moment of inertia J = 0.064 kgm^2.

4.3 Torque per unit angle

The torque per unit angle N is estimated by some static tests in the wind tunnel. The vane was mounted on the K-Gill-frame. The frame with vane could be led through an opening in the test section floor. Next, the frame was positioned vertically (checked with a water-level) so that the vane had no preferential position (checked). Comparison of figure 1 with figure 2 and 3 shows that the K-vane was actually much too large for the wind tunnel: the propeller housings were in the inflow section (there was no room for propellers), while the vane blade was in the outflow section. The latter made it easy to fix the vane in a known initial position. Finally, a rubber band served as a spring which was fixed in such a way (figure 10) that its (force moment) arm was half the arm of the wind force ($0.5 \times r_V = 0.24$ m).

In the tests, wind direction was measured (by measuring voltage over K-vane potentiometer output) for a number of tunnel speeds: 1, 2, 5, 10, 15 and 18.5 ms^{-1}. For the latter speed, wind direction was also measured without the 'spring'. It turned out (actually, it was clearly visible) that the *vane had an offset of about 3°*! In standard meteorological coordinates (N=0°,E=90° etc.), the measured wind direction might be 3° too low.

The force on the vane can be computed from (see also figure 10):

$$F_v = \frac{1}{2}F_{spring} \approx \frac{1}{2}\left[k\times\left(\frac{1}{2}r_v\sin(\theta-\theta_0)\right)\right]. \qquad (8)$$

where F_V is the wind force on the vane, F_{spring} the force on the spring, k the spring constant of the spring, r_V the 'arm' for the vane (0.47 m), θ the measured 'wind' direction, and θ_0 the 'wind' direction for zero wind speed. The spring constant k is evaluated by measuring the length of the 'spring' while various 'weights' were attached to it. Linear regression led to a $k = 92\pm13$ Nm^{-1}.
Next, torque parameter $N = r_V F_V/\beta$ could be evaluated. The angle β is defined as $\theta|_{U=\infty} - \theta$.

4.4 Results

Table 4 gives a summary of the results as obtained from the measurements described above. A striking feature is that the values N/U^2 are not independent of wind speed. This is in contradiction with results of Camp et al(1970) who found that their calibration results were almost independent on wind speed and initial angle of attack. A possible explanation is the fact that the spring suffered from strong wind induced vibrations for tunnel speeds greater than 5-10 ms^{-1}. The resonance leads to a smaller length increase of the spring and hence, the inferred force on the vane and N are also smaller. By eq. 7, this leads to an overestimation of λ_n, and an underestimation in ζ.

Because of this resonance phenomenon, the low wind speed vane properties seem to be most representative. At 1 ms^{-1} however, the vane is not likely to work very well. So the best estimate of the vane properties is probably made at 2 ms^{-1}: λ_n= 4 m, ζ = 0.4. The damped wavelength λ_d is slightly larger (≈4.3 m).
The present data correspond well to other propeller vanes (Monna & Driedonks, 1979). Ataktürk and Katsaros (1989) presented some calibration results for a K-vane. They found λ_n = 7 m and ζ = 0.40 for a square vane blade of approximately 0.225 x 0.225 m. However, our vane shape is such that a different aspect ratio is to be expected (larger vertical size at tail end; figure 1). By eq. 7, and by the definition of J and N, this results in a decrease in λ_n, and in an increase in ζ. This explains part of the observed differences. Note that – if the 'arm' r_V is kept constant – vane size is not expected to be very significant as F_V (proportional to vane blade surface S) and J increase by the same rate.

MacCready and Jex (1964) discuss the issue of phase matching of the along-wind (u) and lateral (v) component. By putting equal the asymptotic approximations for (low frequency) phase shifts for propeller and vane, they find as a requirement: $D = \lambda_n \zeta / \pi$. For the present K-vane, we have $D = 7 \times \lambda_n \zeta / \tau$; i.e. the propeller phase lag is approximately 7 times larger than the vane phase lag. This is expected to influence measurements of u'v'.

The starting speed, or the vane threshold speed, seems to be slightly above 1 ms^{-1}, but certainly well below 2 ms^{-1}. See table 4. This would be rather high, but still acceptable. However, a small positioning error of the vane and the spring could also account for the vane deflection being zero at U = 1 ms^{-1}. By extrapolation (table 4), the expected $\theta|_{U=1} - \theta|_{U=0}$ is about 0.26°. This yields a length increase of the spring of 10^{-3} m. This is of the same order as a small positioning error (i.e. by hanging up the spring a bit too loosely).

Finally, it is noted that the present results are only approximate. Busch et al(1980) state that friction effects are significant, and that gyroscopic effects by the propellers can also be significant. MacCready and Jex (1964) however, state that the latter are negligible. Still, it is desirable to carry out dynamic tests in a larger wind tunnel (cross section at least 1 m^2) for a better estimate of vane properties.

5. APPLICATION

In this section, various aspects will be discussed which can be relevant for field experiments with K-vanes. First a few operational aspects will be discussed, as well as the minimum measuring height. Furthermore, correction procedures for non cosine response will be discussed, and a few estimates of propeller overspeeding will be given.

5.1 Minimum measuring height; sampling frequency

Which measuring height do we need for a given accuracy in flux measurements with propeller vanes? The matter proved to be more complicated than estimating at which dimensionless cut off frequency f (nz/U, with n freq. in Hz) there is a certain loss in the measured variance. Horst (1973) integrated Kaimal's (1972) spectra for neutral and stable atmospheres, and accounted for spectral attenuation by the propellers.
His results are given in table 5. The minimum measuring heights – in relation to propeller response – to assure 20% (or 10%) accuracy in u'w' and w'T' are about 6 (13) and 21 (74) m in neutral conditions. In very stable conditions (Ri = 0.2) the maximum distance constant to assure 20% (10%) accuracy in u'w' at 20 m is 1.8 m (0.8 m), the measured covariance fraction at 20 m is 68% and 50% for u'w' and w'T'. Above this height the validity of Monin-Obukhov scaling becomes questionable. So it can be seen that for the desired measuring levels > 20 m, U_*^2 can be measured with sufficient accuracy, except for very stable conditions. On the other hand, vertical wind variances are strongly underestimated at 20 m. Errors in w'T' are slightly smaller than errors in σ_v^2. All these data serve as an indication, as we will measure on inhomogeneous sites, where the conventional literature spectra for homogeneous terrain have limited applicability. However, we can still conclude that for accurate flux measurements, corrections for propeller inertia (by multiplying measured spectra with reciprocal transfer functions, see section 6.2) are generally necessary.
In unstable conditions, requirements are less restrictive. In field experiments, Garratt (1975) found about 10% error for z/D ≈ 2, and Horst (1973) found no apparent error for z/D ≈ 6.

Another related issue is the sample frequency to be used. We made a rough estimate by first evaluating the response time of the propeller for given wind speed: τ = D/U. We considered sampling time intervals of 1, 0.5, 0.2 and 0.1 sec. (frequencies of 1, 2, 5 and 10 Hz). For wind speeds which are well below 3, 7, 15 and 33 ms^{-1} (i.e. D/τ, with D = 3.3 m), the propeller inertia dominates, and sample frequency is of limited importance. This is one of the reasons that we try to achieve a sampling frequency of 5 Hz (the dataloggers impose a maximum sample frequency which can be less, see section 6.2) for the 1995 Cabauw measurements. Direct estimates of desired sampling frequency are possible by integrating the relevant spectra.

5.2 Recovery of wind components from K-vane output

Ataktürk and Katsaros (1989) present an iterative scheme to recover the along-wind u-component, and the vertical w-component. They assume that propellers are pointed well (say within 15°) into the wind, so that misalignments in the horizontal plane have negligible influence on propeller attack angles.
They define ϕ_T as the attack angle for the top propeller and ϕ_B as the attack angle for the bottom propeller. Both angles are given by:

$$\phi_T = 45° + \Delta\phi - \delta \quad ; \quad \phi_B = 45° - \Delta\phi + \delta , \tag{9}$$

where $-\delta$ is the elevation angle of wind ($w(t) = -|V|\sin\delta$),and $\Delta\phi$ an error due to tilt of the instrument. The latter can be measured with a tiltsensor. Note that $\Delta\phi$ is defined positive if the K-vane is tilted forward (as in Ataktürk and Katsaros, 1989). The true top and bottom wind components U_T and U_B are given by:

$$U_{\mathrm{T}} = \frac{U_{\mathrm{T,meas.}}}{C(\phi_{\mathrm{T}})\cos(\phi_{\mathrm{T}})} \quad ; \quad U_{\mathrm{B}} = \frac{U_{\mathrm{B,meas.}}}{C(\phi_{\mathrm{B}})\cos(\phi_{\mathrm{B}})}, \qquad (10)$$

where $C(\phi)$ denotes the function that describes the non cosine response. For the present propellers, $C(\phi)$ will be: $1 - 0.3\sin^2(\phi) + 0.02\sin(6\phi)$. Note that $U_{T,meas.}$ and $U_{B,meas.}$ represent the raw measuring data, not the values of a previous iteration. Next, the magnitude of the wind vector, and the u and w-components can be computed from:

$$V = \sqrt{\left(U_{\mathrm{T}}^2 + U_{\mathrm{B}}^2\right)} \;;\quad u(t) = V\cos\delta \;;\quad w(t) = -V\sin\delta\,. \qquad (11)$$

We can find a new value of ϕ_T by:

$$\phi_{\mathrm{T,new}} = \arctan\left(\frac{U_{\mathrm{B}}}{U_{\mathrm{T}}}\right). \qquad (12)$$

The first thing we need in the above iteration process, is an initial guess of ∂. If a previous sample is available, we can take $\delta_0(t)$ as $\delta(t-1)$, else $\delta_0 = 0$. By eq. 9 we compute the propeller attack angles ϕ_T and ϕ_B. These angles are used to compute an estimate of the true components U_T and U_B from the raw measurements. These true components are used for a new estimate of ϕ_T, which yields a new δ, etc.
For 0.1° accuracy, the number of iterations needed varies from 1 for $\delta = \pm 45°$ or $\delta = 0°$, to 3 for $22° < |\delta| < 45°$, and 4 for $\delta \approx 10°$. Ataktürk reports 10 iterations for 0.01° accuracy at $\delta = 10°$, but 0.1° accuracy seems to be sufficient for our application (tilt and flow distortion are less than 0.1° in ideal experiments only). The iteration process is much quicker if we use $\delta(t-1)$ as a starting value instead of $\delta = 0°$.

On datalogger systems, there can be conflicting requirements between computing time needed (e.g. for evaluating non cosine response corrections) and desired sampling frequency. See also section 6.2. Horst (1973) proposed to use a quick correction method which is applied on the time averaged properties (means and (co)variances). For this report, it would lead too far to work out such a method for K-vanes. Suffice to say that Horst's (1973) method is based on a constant wind speed with randomly fluctuating direction and elevation.

5.3 K-vane overspeeding

An extensive analysis of propeller vane dynamics, and of propeller-vane overspeeding and underspeeding is given in Zhang (1988). Zhang's overspeeding evaluation method can also be applied to a K-vane configuration. The main assumptions of the present evaluation are the perfect cosine response that the propellers should have, and the spectra that Zhang used to evaluate propeller-vane overspeeding. Furthermore, the author of this report assumed that wind profile stability corrections ψ needed in the analysis were -4.7z/L for stable conditions, and about $(1+16z/L)^{0.25}-1$ for unstable conditions (Jensen et al, 1984).

Table 6 shows that overspeeding is only significant (>1%) for unstable conditions. The main

parameter is $-z_i/L$,where z_i is the boundary layer depth, and L the Monin-Obukhov length. Especially in deep convective boundary layers (large $-z_i/L$), overspeeding becomes significant and can well exceed 5%.
In convective conditions, the main contribution to overspeeding is from the convective part of an error of the 'data-processing' type (see MacCready,1966): the vane follows the wind fluctuations well, and the propellers tends to output the time average of the horizontal wind speed instead of the component parallel to the time averaged horizontal flow. At larger heights, this is also the main contribution for stable and neutral conditions. At lower heights, the asymmetrical response of propellers to wind speed increases and wind speed decreases becomes important: the u-error described by MacCready(1966). The combined v-error (vane is too slow to point into the wind) and data processing error can even become slightly negative in strongly stable conditions at low heights.

Finally, surface roughness length z_0 has a significant influence on overspeeding. Over smooth terrain (z_0 = 0.03 m instead of 0.1 m), overspeeding is roughly 30% lower, while over rougher terrain (z_0 = 0.3 m), overspeeding is about 70% higher at 20 m height, and about 45% higher at z = 200 m. These figures are lower for stable conditions.

The main conclusion that we should draw is that one should try to avoid the data processing error described above. This can be done by converting each sample point to an (u(t),v(t),w(t)) in a fixed coordinate system (e.g. the earth system), and by rotating the axes afterwards (so that mean wind is aligned with x-axis).

Zhang's (1988) analysis showed that for the mean properties, the combined propeller-vane response can yield a mean overspeeding up to the order of 5%. Unfortunately, analysis of the effects on turbulent fluxes is still more complicated, since both w' and u' will be influenced by the variable response lengths of the two propellers in a turbulent wind field. On the other hand, the above mentioned processing error may – by the inclusion of the v-component – lead to some overestimation of u', and of the momentum flux u'w'. An analysis of this problem should be part of the comparison experiment Haarweg.

5.4 Other considerations

The durability of the instrument, and the stability of the calibration are partly open questions. Busch et al (1980) notes that stability of the calibration is very good for propellers, but that durability can be a problem as propellers can initiate aggressive behaviour by birds. Hicks (1972) notes that in dusty environments, soiling can cause considerable friction. Finally, Ataktürk and Katsaros (1989) note that K-vanes can be used successfully for measuring programs over sea.
Clearly, literature provides no clear answer. The best way therefore, is to carry out a field experiment, and to compare wind tunnel calibrations before and after the experiment. In fact, two field experiments would be needed, one in winter to see whether the K-vane can result strong gales, and one in summer to see whether the K-vane can survive severe thunderstorms. As last thing, the K-vane should survive during transport. After transport/shipping, it turned out that our vane blade was slightly dented, and that the axis was bent by a few degrees.
Finally, recent, unpublished, data (analyzed by drs. J. Verkaik, Department of Meteorology, Wageningen Agricultural University) suggest that the calibration properties after the Haarweg comparison experiments were largely the same. This would mean that in Dutch summertime conditions, calibration remains stable for at least a few weeks.

6. FUTURE WORK

6.1 Further wind tunnel tests

Further wind tunnel tests are needed for better estimates of the K-Gill properties. Especially tests for the vane mounted on the K-Gill are needed. Such tests should be carried out in a wind tunnel which is large enough (cross section ≥ 1 m^2) to avoid effects of wall constraint and non-uniformities (wall boundary layers). Further tests are also useful in order to verify the new findings on distance constants for decreasing wind speeds.

With regard to the vane properties, wind tunnel tests provide abetter, independent estimate of the vane properties natural wavelength λ_n and the damping factor ζ. Moreover, Busch et al (1980) noted that vane properties are often wind speed dependent because of mechanical friction, and because of possible gyroscopic effects by rotating propellers. Hence, dynamic wind tunnel tests are strongly recommended.
Vane properties can be evaluated (see MacCready and Jex, 1964) by analyzing the damped oscillation of the vane after releasing the vane from some initial position. The damped oscillation period τ_d can be read directly from (a graph of) the vane output. The damped wavelength $\lambda_d = U\tau_d$. Damped wavelength, and natural wavelength are related by (also for vanes with friction):

$$\lambda_n = \lambda_d \sqrt{(1-\zeta^2)}, \qquad (13)$$

the damping factor ζ is given by:

$$\frac{h}{H} = \frac{e^{-\pi\zeta}}{\sqrt{(1-\zeta^2)}} \quad ; \quad 2\zeta^2 = 1 - \sqrt{1 - \frac{4\ln^2(H/h)}{\pi^2}}, \qquad (14)$$

where h/H is the overshoot ratio; i.e. the amplitude ratio of two successive extremes (not positive maxima) in vane deflection.
Finally, wind speeds and initial vane deflections have to be chosen, as well as a number of repetitions for accuracy. The author recommends to consider the standardized procedure proposed by Finkelstein (1981). Wieringa (1967) recommends a maximum initial vane deflection of 15° for consistent results, at angles > 15° the vane will no longer act as airfoil.

With regard to the propellers, firstly, tests are recommended for a better estimate of calibration constants and angular response of the propellers. In the present work, propellers are tested separately. In the K-vane configuration, results can be slightly different. New angular response tests require facilities to fix the vane portion at a given (azimuth) angle. Furthermore, the K-vane should be mounted in such a way that it can be inclined forward or backward. Then, angular response and calibration factors should be determined as a function of both inclination angle and azimuth angle. Needless to say that the mounting facilities should not induce significant flow distortion (they should be smaller/thinner than the K-vane frame; or they should be positioned at a larger distance from the propellers).

Distance constants for propellers on a K-vane can be determined in a way similar to that described above. Sensitivity to the configuration is expected to be small, so the results of section 3.3 are expected to be representative. However, for wind which is not in the plane of the vane blade, some calculations are needed to compute the effective angle of attack.

An 'integral' distance constant can be estimated by spectral analysis of propeller response to a turbulent signal (see next section). However, this does only partly lead to a better understanding of propeller response (the sign and magnitude of the wind speed step are not considered). Therefore, it is recommended to do several step response tests (step up and step down; and different step magnitudes), and other tests in order to judge whether the propellers behave as a first order system in practice as well. Furthermore, such tests can lead to a better understanding of propeller dynamics, and to better estimates of propeller overspeeding (MacCready's 1966 'u-error') due to a quicker response to wind speed increases. Step response tests could be carried out at fixed wind tunnel speed, e.g. by connecting the propeller axis to an axis (motor-driven) turning at fixed rate by a rubber band. The step function is simulated by quickly removing the rubber band from the motor axis, as in the present work (4th step down test in appendix I). The rotation rate of the motor axis should allow for propeller speeds significantly greater than the present 1.6 ms^{-1}. This can be achieved by an increased motor axis rotation rate or an increased radius of the motor axis.

6.2 Possibilities for field calibrations

An estimate of propeller and vane dynamic properties (propeller distance constant D; vane natural wavelength λ_n and damping factor ζ) can also be determined from spectral response in a field comparison experiment (e.g. comparison with a sonic anemometer). Both phase lag and spectral attenuation (Wieringa and Van Lindert, 1971; Horst,1973) can then be used.

MacCready and Jex (1964) give expressions for phase lag in first order and second order systems (propellers and vanes). For frequencies ω much lower than the reciprocal response times of the instrument, propeller phase lag is $\omega U/D$. Phase lag of the vane is $\zeta\omega\lambda_n/(\pi U)$. As for the vane both λ_n and ζ have to be estimated, the phase lag method gives only part of the desired results. Moreover, there are often practical problems, e.g. achieving an accurate synchronization of both instruments.

Often, it is easier to evaluate instrument properties from spectral attenuation at given frequencies. This approach is used by Wieringa and Van Lindert (1971) and by Horst (1973). The principle is as follows (Moore, 1986):

$$\overline{(u_i u_j)}_m = \int_0^\infty S_{ij}(n)\, T_{ij}(n) dn. \quad (15)$$

where $S_{ij}(n)$ is the measured(co)spectrum of the flux $(u_i u_j)_m$ ($u_i u_j$ can be u'w', w'T' etc.), and where $T_{ij}(n)$ is the so called transfer function. T_{ij} is defined as the ratio of measured and real $S_{ij}(n)$:

$$T_{ij}(n) = \left(S_{ij}(n)\right)_{meas.} / S_{ij}(n). \quad (16)$$

If we have an instrument that is quick enough, it is possible to estimate the 'real' $S_{ij}(n)$, and we can compute $T_{ij}(n)$. By averaging different runs, and by smoothing, we can finally obtain a $T_{ij}(n)$ that can be analyzed.

For first order systems like a propeller, $T_{ij}(\omega) = 1 + \omega^2\tau^2$, which can be converted to an expression with a distance constant D by using the dimensionless frequency f = 2π_z/U. The expression for $T_{ij}(f)$ is: $1 + (fD/(2\pi z))^2$. For a wave number spectrum $S_{ij}(k)$, the expression is even simpler:$T_{ij}(k) = 1 + (kD)^2$. D can be estimated most accurately by using the slope of the T_{ij}-curve for high f or k. Horst (1973) applied this concept successfully by correcting his spectra from Gill UVW measurements T_{ij}^{-1}, and showing that for the horizontal components the inferred D agreed well will manufacturers specifications (when the latter were corrected for the observed angle of attack).

For a second order system like a vane, the transfer function $T_{ij}(\omega)$

$$T_{ij}(\omega) = \left[\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + 4\zeta^2\left(\frac{\omega}{\omega_n}\right)^2\right]^{-1} . \qquad (17)$$

$T_{ij}(f)$ and $T_{ij}(k)$ follow by replacing ω/ω_n by $f\lambda_n/z$ and $k\lambda_n/(2\pi)$ respectively.
At high frequencies, the slope of T_{ij} can be used to evaluate $\zeta\lambda_n$. A second equation which allows to solve for ζ and λ_n follows by evaluating T_{ij} for one fixed ω.
In practice, the wind direction spectrum is not always available. Then, the vane transfer function can be derived by dividing the along-wind and lateral transfer functions: $T_{ij} = T_{vv}/T_{uu}$.

The 'benchmark' instrument against which K-vane results will be compared (a sonic) yields a final practical problem. A sonic too has a finite response as wind speeds are averaged over a path length p of typically 0.2 m. Moore (1986) gives an approximation for the transfer function for the w component:

$$T_{ww,sonic}(f) \approx \frac{2}{\pi f}\left(1 + \frac{e^{-2\pi f}}{2} - 3\left(1 - \frac{e^{-2\pi f}}{4\pi f}\right)\right), \qquad (18)$$

where f is np/U or $k_1 p/2$,k_1 being the along-wind wavenumber. Generalized transfer functions for the horizontal components are not available as they depend to a greater extent on instrument geometry and wind direction (Moore, 1986); case specific expressions are given by Kaimal et al. (1968). Still, some conclusions can be drawn. For the propeller $T_{ij} = 0.5$ (half power point) for kD = 1. With a D of 3.3 m this yields $k = 0.3\ m^{-1}$. For p = 0.2 m, a f = 0.03 results, and $T_{ww,sonic} \approx 1$. The half power point of $T_{ww,sonic}$ is for a much larger f ($f \approx 1$). Hence path averaging effects of the sonic are expected to be insignificant. Moreover, the present propellers will average over an area with a radius of 0.22 m, which yields similar averaging effects.

Sensor separation effects can also distort measured (co)spectra. For lateral separation (as for the two propellers) $T_{ij,latsep}(f) \approx \exp(-9.9f'^{1.5})$ where f' is ns/U, with s the lateral separation (0.4 m for the K-vane). The half power point is at $f' \approx 1.7$. Hence, the inertia of the propeller (f=np/U=0.03; and with s=2p:f'=ns/U=0.06) is still dominant. For stable conditions with L (Obukhov length)< 57 m (more exactly: for d > 0.007 x L), this should be considered only as a first approximation (Moore, 1986).
Longitudinal separation can play a role in heat flux measurements (w'T'; with thermocouple either at the junction of the K-branches, or at the fixed part of the frame). Moore (1986) suggests to use the same expressions for longitudinal separation. Hence, propeller inertia dominates also in heat flux evaluation.

So far for the suggestions for field calibration experiments. Finally, some issues about the field experiment are briefly discussed, as the planned work is not only an alternative calibration but also a test experiment. These experiments on the Wageningen Haarweg site will be described in later publications.

6.3 A few words about the Haarweg comparison experiment

The site of the Wageningen meteorological station at the Haarweg is considered a suitable site for a K-vane sonic intercomparison for a number of reasons:
- easy access and at a short distance from the university
- a 20 m mast (instruments are placed on a support on top of the mast with approximate dimensions of 1.5 x 0.2 m, and a thickness of roughly 0.05 m), computers and main supply are available. A height of 20 m corresponds to the lowest level at Cabauw, and is sufficiently high to avoid considerable signal loss in turbulent (co)variances.
- the Haarweg site offers both undisturbed and disturbed wind directions, so that the K-vane can be tested for different turbulence conditions.

A K-vane sampling frequency of 5 Hz was recommended, as for Cabauw. When the K-vane is connected to the Solent sonic anemometer and datalogger (by using a frequency-voltage converter for propeller pulses), sampling frequency is 20.8 Hz, as for the sonic. However,maximum sampling frequency is only about 2 Hz if the K-vane is connected to a Campbell datalogger. This is mainly due to the fact that several (co)variances had to be computed (about 10). In the 1995 Cabauw measurements, we plan to connect two K-vanes to the datalogger. If we measure u'w' and w'T' (as desired) and W/U (as a check on tilt and flow distortion), a sampling frequency of 3-4 Hz might just be possible. Cosine response corrections (by using eq. 3) proved to be of secondary importance as long as the number of iterations was two or less.

In the comparison, the following things should be compared/analyzed:
- output of mean variables and (co)variances; K-vane vs. sonic, by means of regression analysis.
- checks that V, W, u'v' and v'w' are sufficiently small
- checks on / comparisons of spectra

Analyses should be carried out for 6, 9 or 15 classes defined by stability ($z/L < -0.2$, $-0.01 < z/L < 0.01$, $z/L > 0.2$) and terrain properties (undisturbed: azimuth dd: 240°-280°; strongly disturbed: 200°-220°, and slightly disturbed: other wind directions). Stability should be classified because (1) in unstable conditions, the main errors are expected to be cosine response errors and overspeeding errors and (2) in stable conditions,frequency response can be insufficient.

Special attention should be given to:
- tilt (stationary and fluctuating; main indication: tilt sensor output; secondary indication: both instruments have about equal W/U)
- flow distortion by instrument and supports (instruments have a differing non-zero W/U) For some wind directions (e.g. NNW, SSE), wake effects are to be expected.
- propeller correction (estimate from x-axis intercept linear regression K-vane vs. sonic output)
- vane starting speed (for averaged output over 1 minute or longer: compare wind direction sonic and K-vane; scatter plot wind direction diff. vs. wind speed)
- propeller vane interaction and overspeeding (easily checked for mean wind speed; check also σ_u and σ_v for cases with strong overspeeding: unstable and disturbed wind direction)
- cosine response errors: the propellers suffer from rectification errors: they can not discriminate between wind components to and from the propeller housing. As a result, inclination angles θ are measured as $\pm(90°-\theta)$, and σ_u is overestimated, and σ_w is underestimated. This effect can

be significant in cases with strong convection.
- finally, both the sonic and the K-vane data can be used to estimate the effect of simplified correction algorithms for non cosine response

7. CONCLUSIONS

First the calibration results for the propellers will be discussed. Wind speed was determined as a function of propeller pulse rate. Measurements with a counter and a Campbell datalogger were in excellent agreement. The calibration relation proved to be almost perfectly linear. For both propellers, the calibration constant K (eq. 1)was $(50.0\pm0.2)^{-1}$ $ms^{-1}Hz^{-1}$. This is in good agreement with manufacturers results $(51.7\pm1.7)^{-1}$ $ms^{-1}Hz^{-1}$. Furthermore, the absence of significant differences between propellers is an indication of the quality of the instrument. The propeller correction is about 0.2 ms^{-1}.

Angular response of the propellers can be described within 2% by eq. 2 and eq. 3. Some deviations can be contributed to low testing speeds, when propeller correction becomes significant. At ±90° (flow in propeller plane) there was some flow distortion: there was reversed flow, with an angle deviation of about 3°. It is important to note that the present propeller output did not show any difference between the normal and reversed propeller rotation sense. In field measurements, this can be important in convective conditions with a high σ_w/U. For angular response, there is again excellent agreement between the two propellers. However, significant differences exist between this type of propellers and propellers of slightly different design. Calibrations before the start of a measuring campaign will always be needed.

Distance constant was determined by the classical first order response to a sudden step up in wind speed. We found that it is not correct to evaluate D from the point with 63% increase in wind speed. Instead, we recommend a regression analysis to estimate D. Then, we find D(0°) = 2.5 m, and D(45°) = 3.5 m. For other angles θ, $D(\theta)/D(0°)$ is in accordance with literature data (eq. 6).
Step-down tests that were carried out indicate that possibly the 'distance constant' is not as constant as often assumed.
From most of the above given results, we can conclude that the measured distance constants are not only dependent on instrument properties but also on testing methods! This has been noted by Busch et al (1980) as well. Additional work is needed to evaluate the appropriate corrections for instrument response and u-error (defined in MacCready, 1966). The Haarweg experiment maybe a first step to do so.

Vane properties were evaluated by Wieringa's (1967) method which uses the moment of inertia J, and the torque per unit angle N. The latter is determined by some static experiments. Remarkably, the measurements of N/U^2 turned out to be wind speed dependent. In literature (Busch et al, 1980) wind speed dependence is attributed to friction effects. In our case however, deviations at higher wind speed might be caused by resonance effects in the spring which held the vane in place. Our best – but still preliminary – estimate of vane properties is: natural wavelength $\lambda_n \approx 4$ m; damping ratio $\zeta \approx 0.4$. Starting speed is well below 2 ms^{-1}. These figures, based on measurements at low wind speeds only, are in fair agreement with data of Ataktürk and Katsaros (1989). Dynamic propeller/vane tests in a larger wind tunnel are recommended for better accuracy. Finally, we found that the vane had an offset as large as 3°! Apparently, the vane can be damaged during transport.

The minimum measuring height at which flux loss due to propeller inertia is below 20% (or 10%) varies between 6 (13) m for U_*^2, about 21 (74) m for w'T', and 64 m (170) for σ_w^2. This applies for neutral conditions. In very stable conditions at 20 m flux loss is about 2-4 times larger compared to neutral conditions. See section 5.1, table 5 and Horst (1973). Generally, corrections for propeller inertia are needed.
In some (mainly strong wind) cases, corrections for sampling frequency are also needed. We

recommend a (minimum) sample frequency of 5 Hz for the field experiments, about the maximum that – with the planned on line computations – can be achieved with the present dataloggers.

Section 5.2 presents an iteration scheme to recover wind components from K-vane output. Convergence is quick; after 4 iterations, 0.1° accuracy was achieved in evaluation angle arctan(W/U).

K-vane overspeeding is evaluated by the theoretical method of Zhang (1988). No significant overspeeding is expected in stable or neutral conditions. In unstable conditions, overspeeding can be significant. It may even reach 10% if the ratio of boundary layer height over Obukhov length ($-z_i/L$) is greater than 100. The effect on u'w' and w'T' remains an open question and should be analyzed in context of the Haarweg comparison experiment.

The durability of the instrument seems to be rather good, although damage may occur during transport. This is clearly shown by our vane, which arrived dented, while the arm was bent by a few degrees! The manufacturer will take more care with future shipments.

Finally, a result of the following sections is already mentioned here: A Campbell datalogger has in practice a maximum sample frequency of only 2 Hz, unless the number of computed means/variances is much less than 10. In the final 1995 Cabauw experiments, we should find a solution for this.

An overall conclusion with regard to the expected accuracy of measured fluxes is difficult to draw and consequently preliminary because so many – sometimes still uncertain – factors come into play: tilt (Rayment and Readings, 1971), flow distortion by the instrument and its supports (Wieringa, 1980; Wyngaard, 1981b), propeller inertia, response of the combined propeller-vane system (overspeeding), effect of sampling frequency etc. Propeller inertia, and too small a sampling frequency can lead to over 10% or even 20% error in measured fluxes and variances, so it is important to use correction algorithms for these effects. In this way, a factor 2 reduction in error level must be possible, so that the final accuracy – except for e.g. strongly stratified or highly transient conditions - should be within 10-20%. Tilt and flow distortion by the instrument and its supports are equally important (especially for u'w'), but these problems are not specific for K-vanes.
Calibration stability and K-vane durability during normal operation seem to be satisfactory, as indicated by recent data mentioned in section 5.4.

8. ACKNOWLEDGEMENT

The present work has been part of the project "K-vane observations for Cabauw flux parametrization project". This project has been funded by the Dutch National Programme on Global Air Pollution and Climate Change (NOP-1). This work has been supported by the Dutch National Institute for Public Health and Environmental Protection (RIVM).

I am grateful to Mr. S. Zwerver of NOP, and to Prof. J. Wieringa of Wageningen Agricultural University, who offered the possibility of 6 months part time work on this project. Also many thanks to the technical staff of the Group Meteorology who have done a lot of preparations for the experiments. Many thanks to drs. J. Verkaik for providing me his new insights with regard to the WAU wind tunnel calibration, and also for having carried out part of the revision of this report. Dr. H.A.R. de Bruin asked me to supervise the students practical training "micrometeorology / field measurements" during the month of May. He allowed me to combine it with some K-vane work, a combination which proved to be fruitful! Finally, I wish to acknowledge my other colleagues of the Group Meteorology, who contributed to a very pleasant time in Wageningen.

The Royal Netherlands Meteorological Institute (KNMI) accepted this paper for publication in the series of Technical Reports. F.C. Bosveld and W.A.A. Monna of KNMI contributed to the final version of this report.

9. LITERATURE

S.S. Ataktürk, K.B. Katsaros, 1989, The K-Gill: A twin propeller-vane anemometer for measurements of atmospheric turbulence, J. of Atmospheric and Oceanic Techn. 6, p. 509-515

M. Bottema, K-vane observations for Cabauw flux parametrization project;results of a feasibility study, project report, Wageningen Agricultural University, Group Meteorology, 1994, 5 pp.

R.R. Brook, 1977, Effective dynamic response of paired Gill anemometers, Bound.-Layer Meteor. 11, p. 33-37

N. Busch, O. Christensen, L Lading, S.E. Larsen, Cups, vanes,propellers and laser anemometer, Air Sea Interaction: Instruments and methods (eds. F. Dobson,L. Hasse, R. Davids), Plenum Press, NY, 1980, 11-46

D.W. Camp, R.E. Turner, L.P. Gilchrist, 1970, Response tests of cup,vane and propeller wind sensors, J. of Geoph. Res. 75, p. 5265-5270

R. Drinkrow, 1972, A solution to the paired Gill-anemometer response function, J. of Applied Meteor. 11, p. 76-80

P.L. Finkelstein, 1981, Measuring the dynamic performance of wind vanes, J. of Applied Meteor. 20, p. 588-594

J.R. Garratt, 1975, Limitations of the eddy correlation technique for the determination of turbulent fluxes near the surface, Bound.-Layer Meteor. 8, p. 255-259

G.C. Gill, 1975, Development and use of the Gill UVW anemometer,Bound. Layer Meteor. 8, p. 475-495

B.B. Hicks, 1972, Propeller anemometers as sensors of atmospheric turbulence, Bound.-Layer Meteor. 3, p. 214-228

T.W. Horst, 1973, Corrections for response errors in a three-component propeller anemometer, J. of Applied Meteor. 12, p. 716-725

N.O. Jensen, E.L. Petersen, I. Troen, 1984, Extrapolation of mean wind statistics with special regard to wind energy applications, WMO World Climate Applications Programme,TD-No. 15, 85 pp.

J.C. Kaimal, J.C. Wyngaard, D.A. Haugen, 1968, Deriving powerspectra from a three-component sonic anemometer, J. of Applied Meteor. 7, p.827-837

J.C. Kaimal, J.C. Wyngaard, Y. Izumi, O.R. Coté, 1972, Spectral characteristics of surface layer turbulence, Quart. J. Royal Meteor. Soc. 98, p. 563-589

K.B. Katsaros, M.A. Donelan, W.M. Drennan, 1993, Flux measurements from a SWATH ship in SWADE, J. of Marine Systems 4, p. 117-132

P.B. MacCready, H.R. Jex, 1964, Response characteristics and meteorological utilization of propeller and wind vane sensors, J. of Applied Meteor. 3, p.182-193

P.B. MacCready, 1966, Mean wind speed measurements in turbulence, J. of Applied Meteor. 5, p. 219-225

W.A.A. Monna, A.G.M. Driedonks, 1979, Experimental data on the dynamic properties of several propeller vanes, J. of Applied Meteor. 18, p.699-702

W.A.A. Monna, De KNMI windtunnel (the KNMI wind tunnel, in Dutch),KNMI Technical reports TR-32, KNMI, De Bilt, NL, 1983, 34 pp.

C.J. Moore, 1986, Frequency response corrections for eddy flux correlation systems, Bound. Layer Meteor. 37, p. 17-35

R. Rayment, C.J. Readings, 1971, The importance of instrumental tilt on measurements of atmospheric turbulence, 97, Quart. J. Royal Meteor. Soc., p.124-130

J. Wieringa, 1967, Evaluation and design of wind vanes, J. of Applied Meteor. 6, p. 1114-1122

J. Wieringa, F.X.C.M. van Lindert, 1971, Application limits of double-fin and coupled vanes, J. of Applied Meteor. 10, p. 137-146

J. Wieringa, 1980, A revaluation of the Kansas mast influence on measurements of stress and cup anemometer overspeeding, Bound. Layer Meteor. 18, p. 411-430;discussion and reply in vol. 22, p. 245-250

J.C. Wyngaard, 1981, Cup, propeller-vane and sonic anemometers in turbulence research, Ann. Rev. Fluid Mech. 13, p. 399-423

J.C. Wyngaard, 1981b, The effects of probe induced flow distortion on atmospheric turbulence measurements, J. of Applied Meteor. 20, p.784-794

R.M. Young, april 1994, personal communication

R.M. Young, 1991, specifications of K-Gill propeller vane model 35301, R.M. Young Company, Traverse City, MI 49684, USA

S.F. Zhang, A critical evaluation of the von Karman constant from a new atmospheric surface layer experiment, PhD thesis, University of Washington, Dept. Atm. Sciences, AK-40, Seattle, Washington 98195, USA, 1988,133 p.

10. TABLES AND FIGURES

	top unit (counter)	bottom unit (Campbell)	manufacturer
K^{-1}	50.0±0.2 $Hz(ms^{-1})^{-1}$	50.0±0.3 $Hz(ms^{-1})^{-1}$	51.7±1.7 $Hz(ms^{-1})^{-1}$
U_s	0.20±0.03 ms^{-1}	0.21±0.06 ms^{-1}	0.2±0.6 ms^{-1}
r	0.99995	0.99996	- (2 points)

Table 1: Estimation of calibration factor K and correction U_s (see eq. 1); regression results. r is the correlation coefficient.

angle $\|\theta\|$	TOP all U	TOP U >= 5 ms^{-1}	BOTTOM all U	BOTTOM U >= 5 ms^{-1}
80°	0.72±0.10	0.76±0.06	0.74±0.06	0.78±0.01
70°	0.75±0.03	0.77±0.02	0.75±0.02	0.76±0.01
60°	0.79±0.02	0.80±0.02	0.80±0.01	0.80±0.00
52.5°	0.80±0.02	0.81±0.01	0.80±0.01	0.81±0.00
45°	0.83±0.01	0.83±0.01	0.83±0.01	0.83±0.00
37.5°	0.88±0.01	0.88±0.01	0.88±0.00	0.88±0.00
30°	0.93±0.01	0.93±0.01	0.93±0.01	0.93±0.00
15°	0.98±0.01	0.98±0.01	0.98±0.01	0.98±0.00
0°	1	1	1	1

Table 2: Summary of cosine response factors C(θ) for both propellers as a function of the absolute value of the wind angle |θ|. Results are averaged over 1, 2, 5,10, 15 ms^{-1}, and 5, 10, 15 ms^{-1} respectively (if only high wind speeds are considered). Eq. 3 gives an approximation of the C(θ) of this table. See also figure 5 and figure 6.

TOP

angle $\|\phi\|$	$D_{63\%}$	D/D(0°)	D_{LR}	D/D(0°)	$\cos^{-0.5}(\phi)$ (lit.)
0°	3.4	1	2.6	1	1
30°	3.5	1.03	2.9	1.12	1.07
45°	3.8	1.13	3.6	1.36	1.19
60°	3.6	1.06	3.9	1.48	1.41
75°	4.9	1.47	5.3	2.04	1.97

BOTTOM

angle ϕ	$D_{63\%}$	D/D(0°)	D_{LR}	D/D(0°)	$\cos^{-0.5}(\phi)$(lit.)
0°	2.9	1	2.4	1	1
30°	3.4	1.14	2.9	1.22	1.07
45°	3.4	1.14	3.5	1.43	1.19
60°	3.6	1.21	3.7	1.52	1.41
75°	4.4	1.50	4.8	2.00	1.97

Table 3: Distance constants for both propellers as a function of attack angle ϕ. $D_{63\%}$ is determined from the point of 63% adaptation (incorrect method, see text), D_{LR} from a regression according to eq. 4. Relative uncertainties in D_{LR} vary from about 3% for small ϕ to 6% for ϕ = 60° and 12% for ϕ = 75°;uncertainties in $D_{63\%}$ are about twice as large.

U	$\theta-\theta\|_{U=0}$	β	F_v	N	N/U^2	λ_n	ζ
1 ms^{-1}	0°	6.19°	0 N	0	0	-	-
2.1	0.72	5.47	0.137	0.68	0.154	4.04 m	0.369
5.2	2.45	3.74	0.47	3.38	0.123	4.53	0.329
10.5	3.45	2.74	0.66	6.51	0.059	6.53	0.229
15.7	4.17	2.02	0.80	10.7	0.044	7.64	0.195
19.4	4.61	1.58	0.88	15.1	0.040	7.92	0.188

Table 4: Results of static tests for K-Gill vane. U is wind tunnel speed; $\theta-\theta|_{U=0}$ is angle from which length increase of rubber band is evaluated (figure 12), $\beta = \phi-\phi|_{U=\infty}$ is effective attack angle of wind; F_v is wind force on vane; N is force moment per unit angle of attack; $8,23_n$ and ζ are vane natural wavelength and vane damping ratio which had to be evaluated

	minimum height neutral		covariance fraction at z = 20 m	
			neutral	very stable
error level (co)variance:	10%	20%		
u_*^2	13	6	93%	68%
σ_u^2	≈16	≈7	≈92%	≈65%
σ_v^2	74	27	77%	40%
σ_w^2	170	64	61%	25%
w'T'	≈74	≈21	≈78%	50%

Table 5: Estimate of minimum measuring height for propellers with effective distance constant D = 3.5 m, in order to guarantee a given accuracy (a maximum underestimation) in a (co)variance measurement, based figure 8 of Horst (1973). The two left columns are for neutral conditions and the two middle columns for very stable conditions (Ri = 0.2). The two right columns denote the (co)variance fraction that will be measured at the Haarweg site (z = 20 m; D = 3.5 m). Errors in w'T' are estimated to be 50% of errors in σ_w^2.

	z/L	$-z_i/L$	∂_{20}	∂_{200}
stable....	1.0		0.3%	0.2%
	0.1		0.8%	0.6%
neutral....	0		0.4%	0.5%
unstable....	-0.1/-1	5	1.1%	1.0%
	-1/-10	25	2.9%	3.7%
	-1/-10	50	4.6%	5.5%
	-1/-10	100	7.5%	8.4%

Table 6 Relative overspeeding ∂ at 20 and 200 m height for the present K-vane propellers for different values of z/L (stable) and z_i/L (unstable), where z_i is boundary layer (inversion) height, and L Obukhov length. Method: Zhang,1988. Parameters: z_o = 0.1 m, D = 3.3 m, λ_n = 4 m, ζ = 0.4.

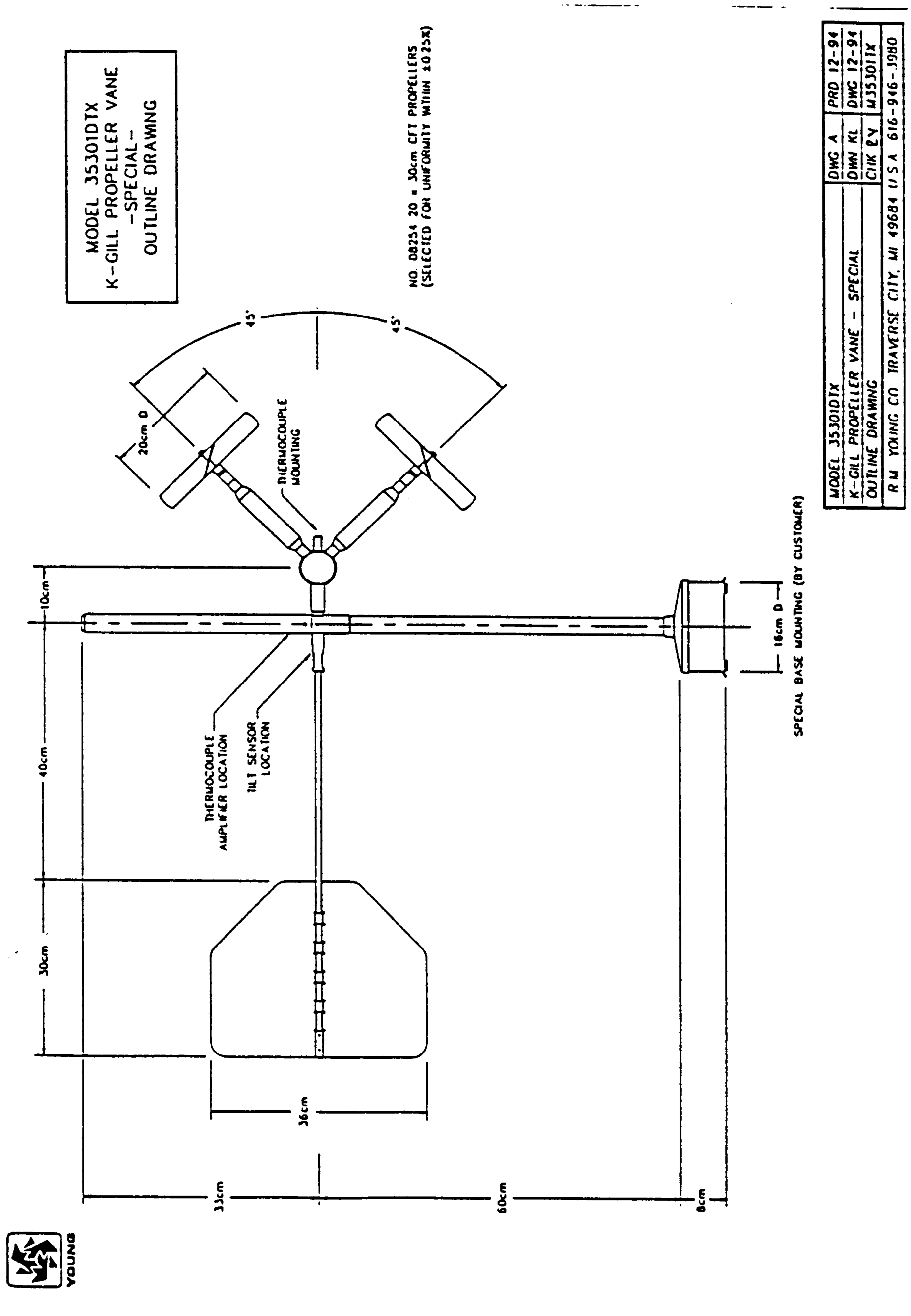


Figure 1 Outline drawing of the K-Gill propeller-vane (K-vane).

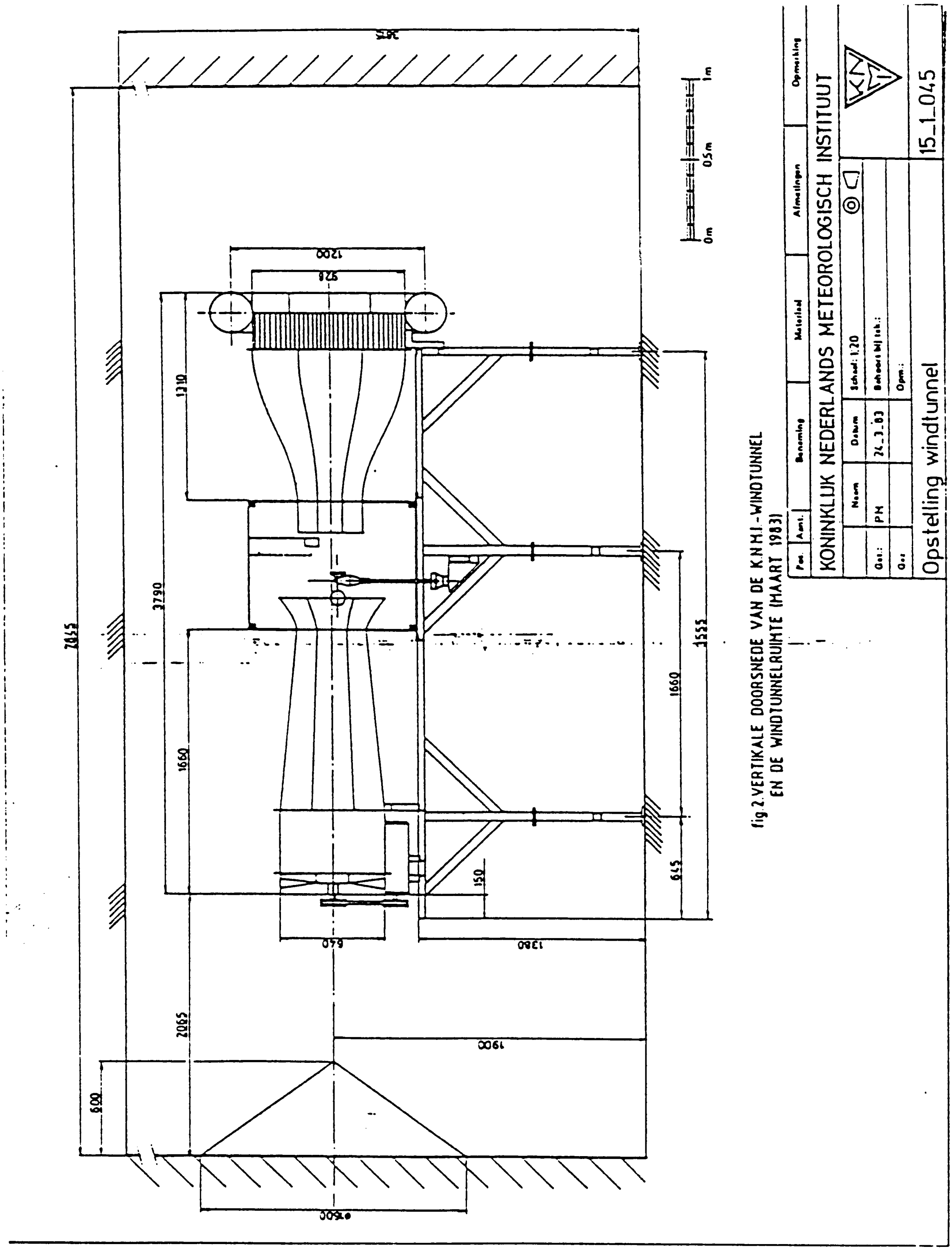


Figure 2 Outline drawing of wind tunnel used (Monna, 1983). Note that flow is from the right to the left. Both inflow and outflow ('bell mouth') are of octagonal shape.

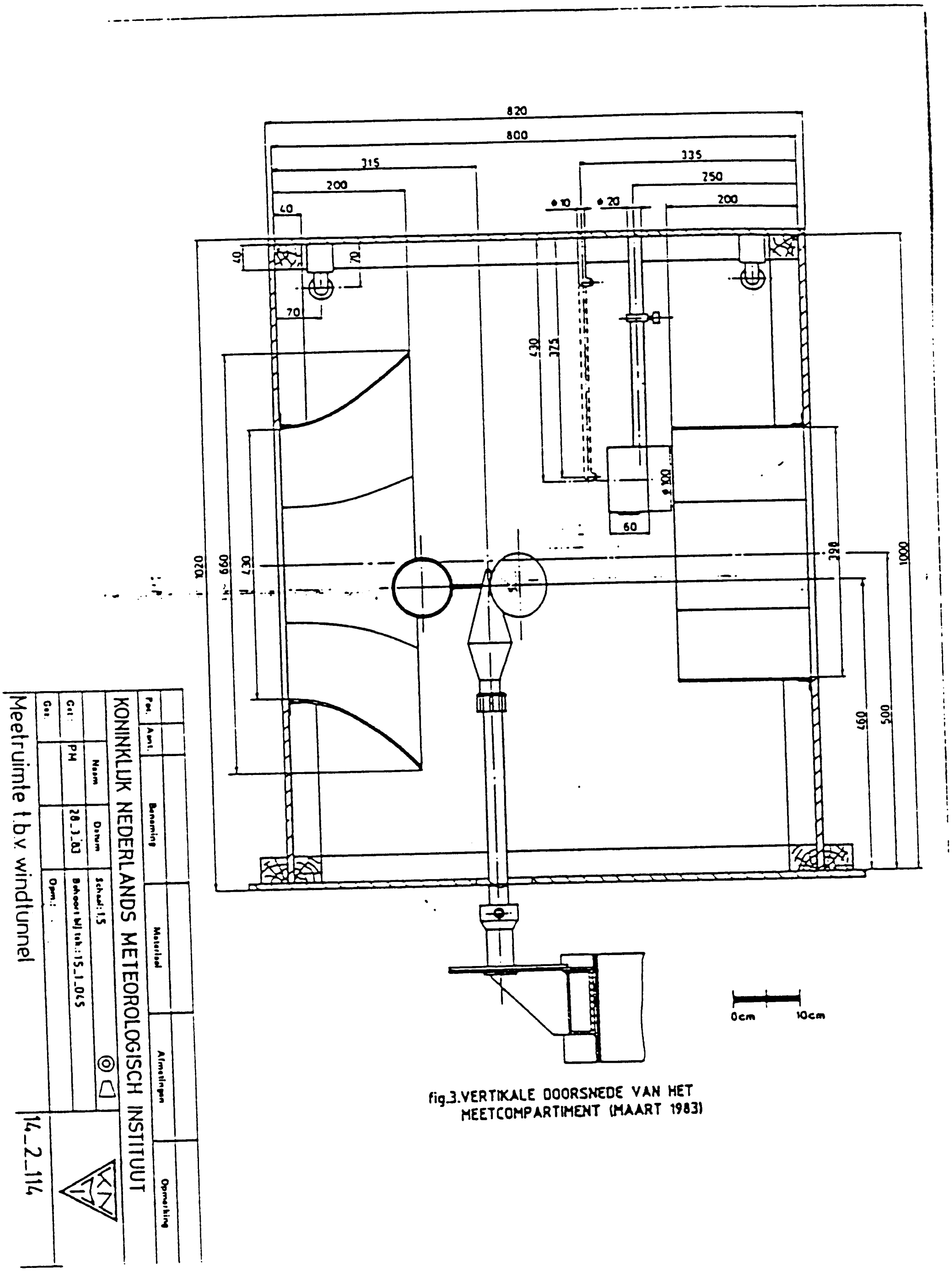


Figure 3 Enlarged view of wind tunnel test section (Monna, 1983). Note that in the present experiments, all drawn instruments were absent.

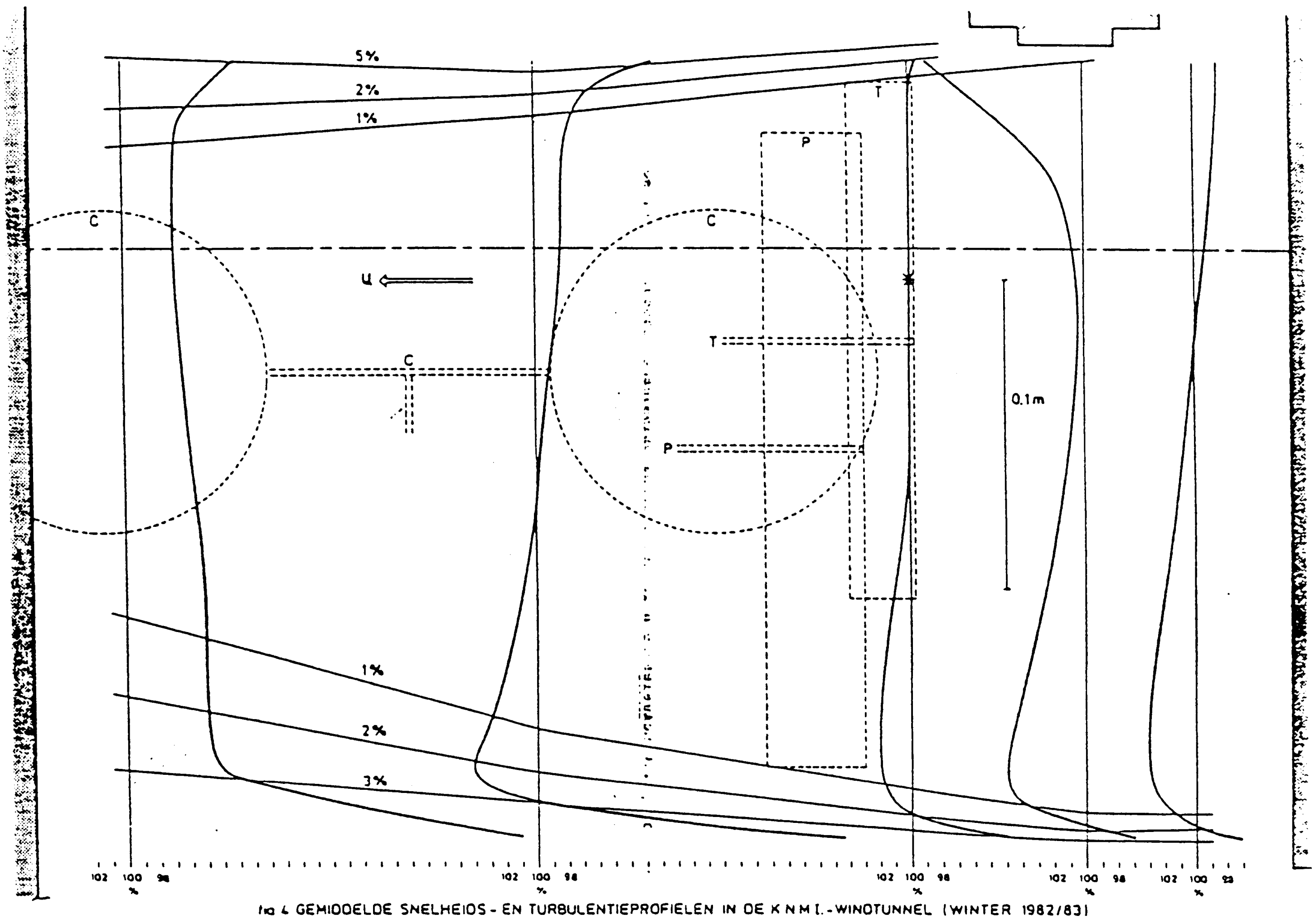
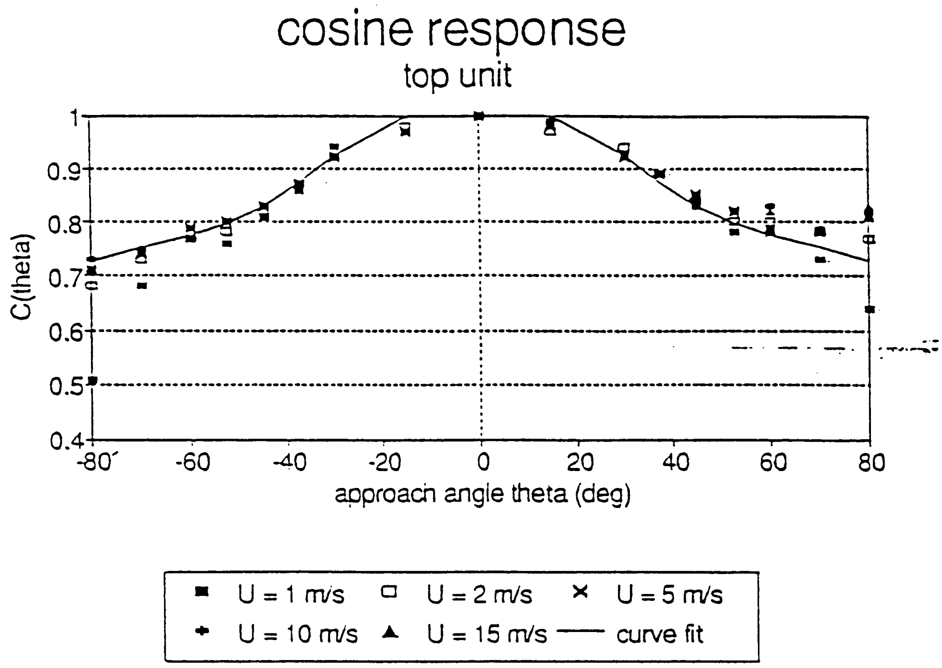


Figure 4 KNMI wind tunnel. Relative mean wind speeds U/U_o, where U_o is wind speed at reference location: (indicated by star *; x = 120 mm, z = 190 mm or 10 mm below symmetry axis of tunnel). Turbulence intensities(100% x σ_u/U) are also indicated. The dashed-dotted horizontal line represents the wind tunnel symmetry axis. Note that only the data below this line should be used;as KNMI has some reference anemometer in the upper part of the tunnel. Flow is from right to left. (Monna, 1983)



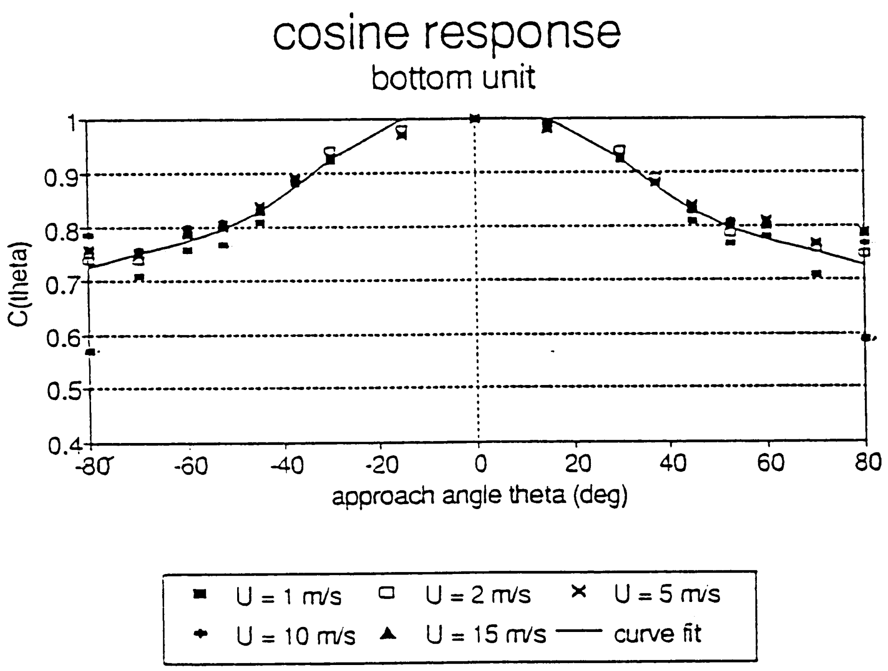


Figure 5 Cosine response factors C(θ) as a function of wind angle (0° is parallel to propeller axis) for a number of wind speeds. Asymmetry is mainly caused by imperfect alignment of the sensor. The curve fit (eq. 3) is chosen for maximum accuracy around ±45°.

a) top unit

b) bottom unit

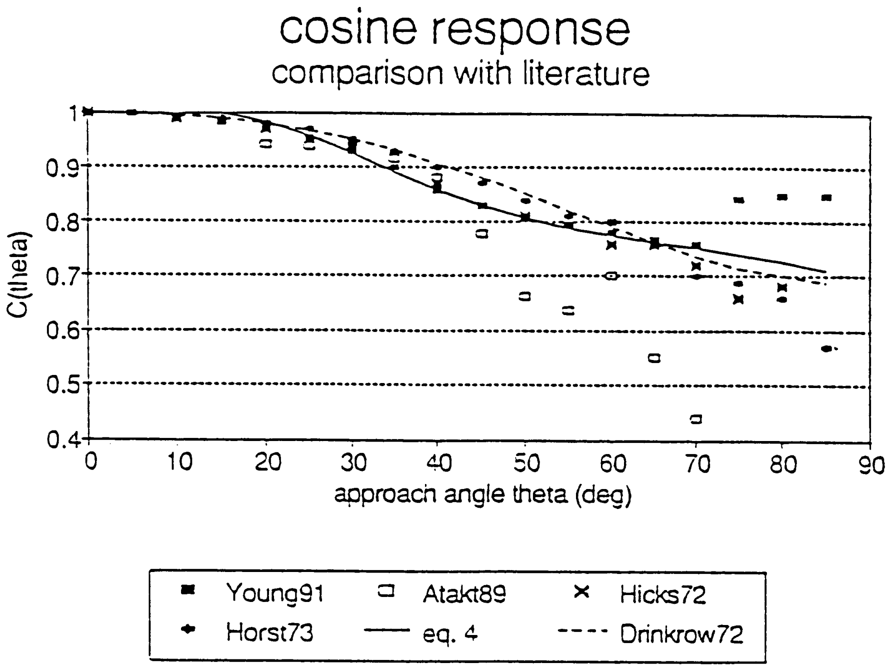


Figure 6 Cosine response factors C(θ) for the present propellers(eq. 3 and Young91), and for similar Gill propellers.

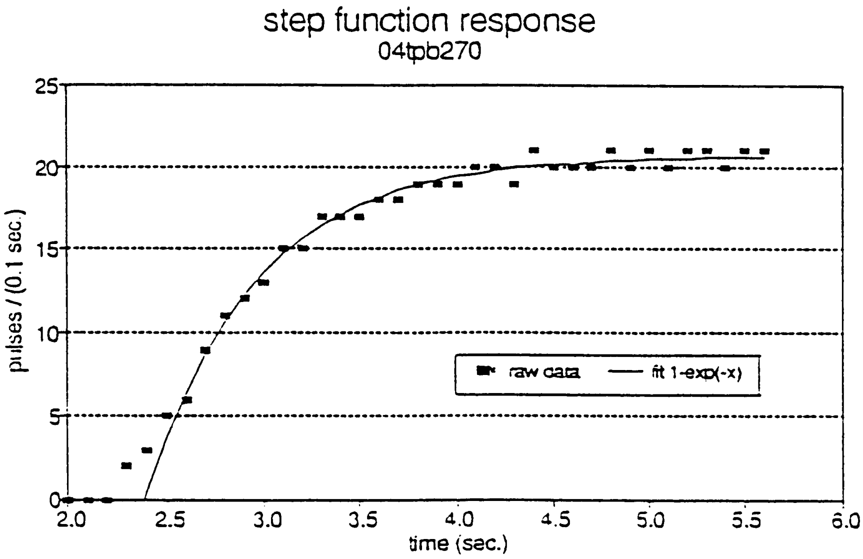


Figure 7 Example of step response registration when propeller is suddenly released. Output is number of pulses per 0.1 sec. time interval; x-axis gives time. The solid line gives a curve fit according to eq. 4.
Further data: tunnel wind speed: 4 ms^{-1}; angle of attack: 0° (270° in wind tunnel coordinates)

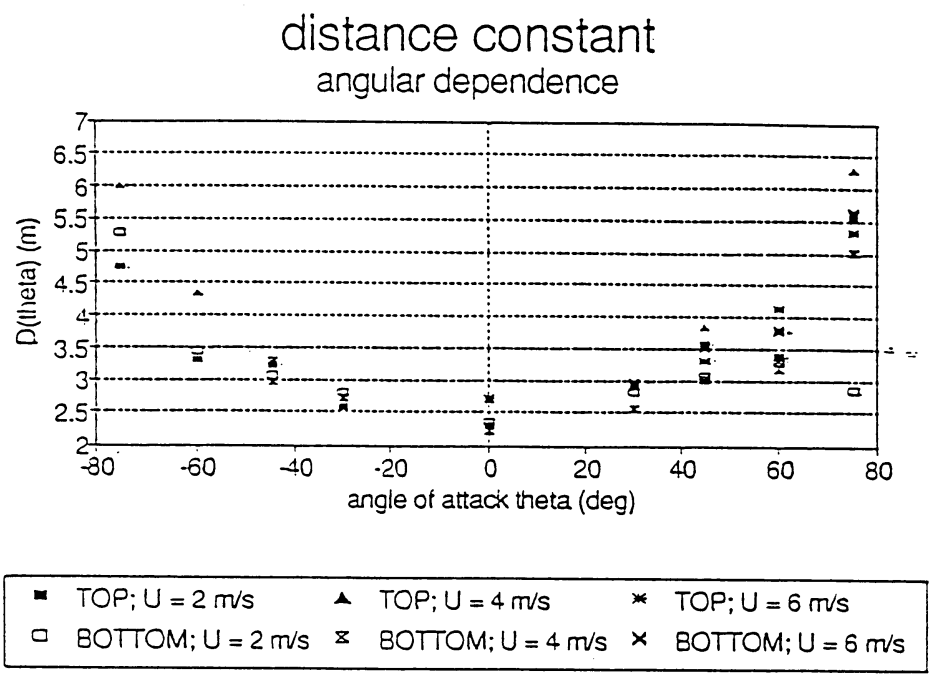


Figure 8 Distance constant D as a function of attack angle θ. D is defined as $U\tau$, with the response time according to eq. 4, and U the wind tunnel speed. Data are given for different wind speeds, and for top and bottom propeller. Relative errors (standard dev./D) are about 7% for 0-45°, 15% for 60° and 25% for 75°..

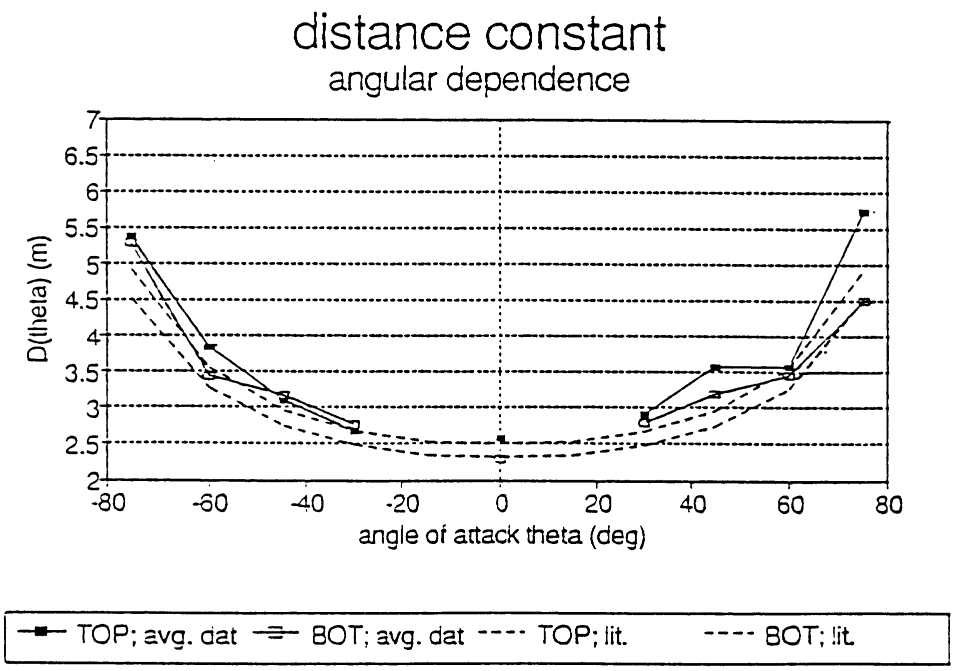


Figure 9 Distance constants averaged over all wind speeds as a function of attack angle. Dashed lines denote literature parametrization $D(\theta) = D(0°)/\cos^{-0.5}(\theta)$. Relative uncertainties in present data vary from about 3% for 0-45° to 7% for 60° and 12% for 75°

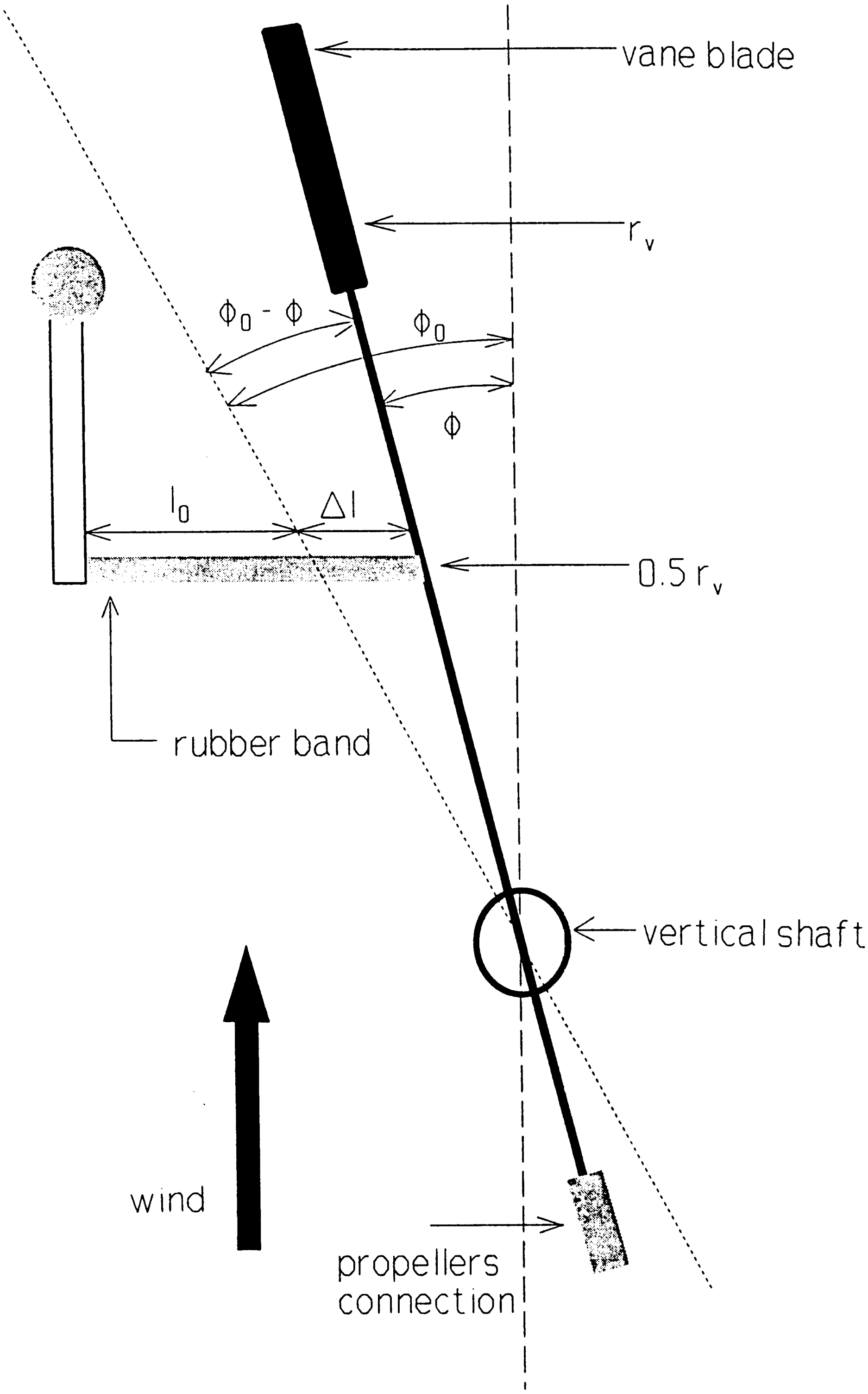


Figure 10 Sketch of test arrangement and geometry for evaluation of vane torque parameter N.

APPENDIX I Propeller response to a decrease in wind speed

Generally, it is assumed that for a step down in wind speed, eq. 4 and 5 (section 3.3) apply as well so that wind speed decreases exponentially with time constant $\tau = D/(U|_{t>0})$.
It is not easy to verify this assumption, and this is probably the reason that no data are found in the open literature (although Busch et al, 1980 note that D is not as constant as its name suggests). Three tests were made for a sudden wind speed decrease of about 70% from 5, 10 or 15 ms^{-1}. This was achieved by quickly opening the wind tunnel door, as the response time of the wind tunnel was over 5 seconds. Figure 10 shows that this does not cause any irregularities in the registration. In a fourth test, we connected the propeller with a motor driven rotating axis by using a rubber band. By suddenly pushing the rubber band away from the motor axis (by the same rod as in the step-up experiments), a wind speed step down of 1.6 ms^{-1} to zero was simulated. Time constraints and wind tunnel availability made it impossible to carry out tests for a range of small wind speed changes (say of ±10, 25 and 50%), although this would have been desirable. In future experiments the flow field during the 'open door' tests should also be investigated, e.g. by using hot wires.

For the step-down cases, two types of functions were tested: an e^{-x} function and a $(1+x)^{-1}$ function (see later). The best type of function was determined from correlation coefficients of the regressions, and by comparing the time constants for the middle part (20-70% adaptation) and the tail of the function(70%-90% adaptation). In the following – and in table A1.1 – only data for the middle part are given.
For the 70% wind speed decreases (the first three experiments; see figure 10), the best fit is given by the exponential function mentioned above, and response lengths are about constant. However, the response lengths differ from the distance constants of section 3.3! Table A1.1 shows that $D = U|_{t=0}\tau$ yields a larger D than in the step-up experiments, while $D = U|_{t=\infty}\tau$ yields a much lower D. Note that $D = U|_{t=0}\tau$ is the only variant (of $U|_{t=0}\tau$, $U|_{t=\infty}\tau$ and $D = |\Delta U|\tau$) which yields a constant 'D'. The present results suggest that $D = U\tau = D_{step\text{-}up}$ if $U \approx 0.5U|_{t=0}$, which is reached after t/τ = 1.47, 1.14 and 0.84. These data should be considered valid for the present case only.

In the fourth experiment (step down to zero wind speed with closed wind tunnel door as described above; figure 11), the $(1+x)^{-1}$ function proved to be a much better fit. In the absence of wind, let us assume that the instantaneous propeller speed determines D (i.e. let us assume that the propeller is forced by the wind generated by the 'ventilator' effect of the propeller), or that the decrease in propeller speed is proportional to the drag forces on the propellers. In both cases, eq. A1.1 follows:

$$\frac{dU_{meas.}}{dt} = -\frac{U^2_{meas.}}{\lambda}. \qquad \textbf{(A1.1)}$$

where λ is some length scale. In the first case ('ventilatoreffect'), $\lambda \sim D$. In the second case (drag effect), $\lambda = L \times C_D$, with L some propeller length scale ($0.5 \times \lambda_{air} \times A_{prop}/m_{prop}$), and C_D a drag coefficient, and A_{prop} the propeller area facing the wind. Integration of eq. A1.1 with respect to time for a wind speed step down from an initial wind speed U_o to 0 yields:

$$U_{\text{meas.}} = \frac{U_0}{1 + U_0 t/\lambda}. \qquad \text{(A1.2)}$$

The present experiment results in a λ of 4.5 m. More experiments are needed to judge whether it is coincidence that $\lambda = D_{\text{step-down}}$ (see table A1.1).

We can conclude from the above data that for decreasing wind speed, generally a conventional e^{-x} decrease can be observed. However, the step-up relation $D = U\tau$ does only apply if U is some wind speed between $U|_{t=0}$ and $U_{t=\infty}$. Behaviour like $(1+x)^{-1}$ is only to be expected for very large wind speed drops: $U|_{t=0}/U_{t=\infty} >> 1$, and is therefore merely of academic interest. Finally, the following can be concluded.
Equation 5 suggests that propellers may overspeed because response time to a wind speed increase ($\tau = D/U|_{t>0}$) is smaller than for a wind speed decrease. The resulting error is the same as the u-error described by MacCready (1966). The present results suggest that $\tau = D/U_1$, with $U|_{t=0} < U_1 < U_{t=\infty}$. However, the present results were obtained for large jumps in wind speed only. Verification for small wind speed changes is still needed, so further experiments are recommended.

U	τ	U_∞	$U_0\tau$	$U_\infty\tau$	best fit
15.7 ms^{-1}	0.28 s	4.4 ms^{-1}	4.4 m	1.24 m	e^{-x}
10.5	0.38	2.9	4.0	1.51	e^{-x}
5.2	0.82	1.4	4.3	1.12	e^{-x}
1.7	2.7	0	4.5	0	1/(1+x)

Table A1.1: Time constants and 'distance constants' from regressions of best fitting functions (right column) for sudden decreases in wind speed. U_0: before step down; U_∞ after step down. Relative uncertainties in data are 6% for the fourth experiment, and 2-3% for the others.

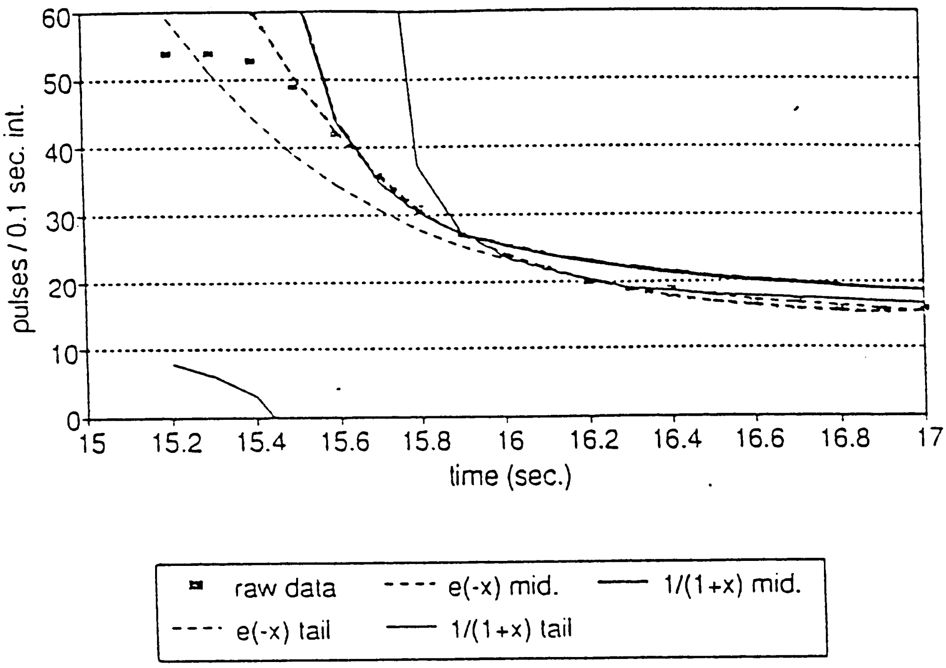


Figure A1.1 Example of step response registration when wind tunnel door is suddenly opened(wind speed step down from 10 to 2.8 ms^{-1}). Output is number of pulses per 0.1 sec. time interval; x-axis gives time. Curve fits are given according to eq. 4 and eq. A1.1. Note that the overall e^{-x} curve (bold dashed line) fits almost all data.

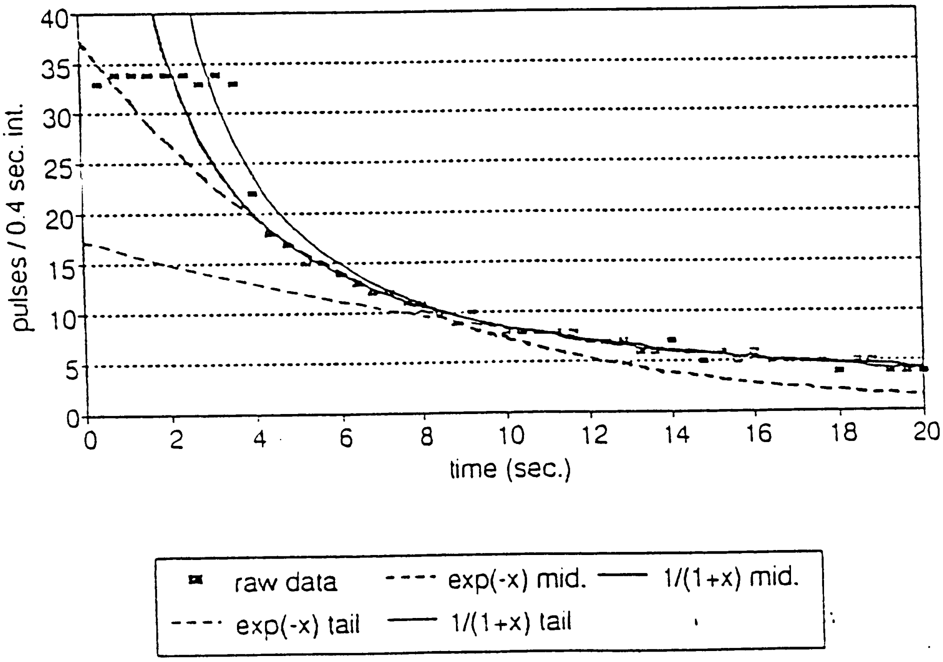


Figure A1.2 Step response registration for a step-down in wind speed from 1.6 ms^{-1} to zero. Output is number of pulses per 0.4 sec. time interval; x-axis gives time. Curve fits are given according to eq. 4 and eq. A1.1. Note for this full step down, both $(1+x)^{-1}$ curves (even the tail curve) fit all data well.

APPENDIX II Description of the Haarweg site

The field comparison between the K-vane and a sonic anemometer is carried out at a 20 m mast at the meteorological site of Wageningen Agricultural University. The site matches WMO standards (10 m measuring height, large fetch over short grass with z_0 = 0.03 m) fairly well, and is used as a standard meteorological station.

Figure A1.1 shows the location of the measuring site. The site which consists of shortly mown grass, is about 140 x 140 m large. The 20 m mast is about 20-30 m from the southwestern corner of the field. The standard 10 m masts are at the northern side of the field (the middle one is used for the roughness analysis). In the middle of the field, some low masts (up to 4 m) were used for students practical training. There is a small building in the southeastern corner of the field.
The field was surrounded by somewhat longer grass, low crops and a few scattered trees. At larger distances there were some rows of trees in the north, some orchards in the southwest, and the town of Wageningen in the southeast. See also figure A2.1.

A site evaluation was carried out by estimating the angle of obstruction (at ground level), and evaluating the ratio of fetch over obstacle height x/H. For the 20 m mast, we found:

wind direction	obstruction angle	x/H	classification
0°	5°	11	disturbed
30°	3°	19	slightly dist.
60°	2.5°	23	"
90°	3°	19	"
120°	3°	19	"
150°	2°	29	"
180°	1.5°	38	undisturbed
210°	18°	3.1	strongly disturbed (trees)
240°	1.5°	38	undisturbed
270°	1°	57	undisturbed
300°	2.5°	23	slightly disturbed
330°	5°	11	disturbed

Table A2.1: Obstacles around the Haarweg comparison site. Obstruction angle arctan(x/H) and fetch over obstacle height ratio x/H as a function of wind direction(azimuth).

For the comparison tests, we can make the following terrain classification:

undisturbed:	240-280°
slightly disturbed:	15-180° and 280-315°
disturbed:	315-15° (around N)
strongly disturbed:	200-220°

For the comparison experiment, the undisturbed sector 240-280°, and the strongly disturbed sector 200-220° are the most interesting. Two 20° sectors around the strongly disturbed (tree wake) sector are not incorporated as strong lateral gradients will hamper interpretation of measuring results.

Finally, figure A2.2 shows the results of a roughness evaluation for the southwesterly sector.

This evaluation is made from routine data (sample freq. 0.33 Hz) from the standard 10 m meteorological mast (many thanks to Mr. C.L.A.M. van den Dries for preparing the data). From 21 June 1994 12 GMT to 22 June 10 GMT, there was a strong wind period with 10 min. wind speeds between 6 and 12 ms^{-1}, and magnitude of Obukhov length above 200 m (daytime) and 2000 m (nighttime). Roughness length z_0 was evaluated from turbulence intensity $T_u = \sigma_u/U$, and from gust factor analysis (Wieringa, 1973). The number of 10 min. samples for each 10° wind direction interval is 7, 21, 1, 5, 34 and 2 for unstable conditions, and 0, 1, 6, 13, 27, 0 for stable conditions.
Turbulence intensity analysis is based on a constant standard deviation $\sigma_u = 2.4U_*$, and on the logarithmic wind profile which yields:

$$T_u = \frac{0.96}{\ln(z/z_0)}. \qquad \textbf{(A2.1)}$$

Gust factor analysis for 10 min. sample duration is based on (Wieringa, 1973):

$$G = 1 + \frac{1.42 + 0.3\ln\left(\frac{1000}{Ut} - 4\right)}{\ln(z/z_0)}, \qquad \textbf{(A2.2)}$$

where G is the gust factor ($U_{max,t}/U$);$U_{max,t}$ is the maximum (median) gust that is measured with equipment with a characteristic time t (in our case 3 seconds).
Both methods yield a z_0 that is representative of surrounding terrain within a few kilometres distance. Local z_0 of the measuring field should be derived from mean wind profiles.

Figure A2.2 shows that typical roughness lengths for the Haarweg site vary between 0.1 and 0.01 m, with a typical relative uncertainty of 50%. Data are less reliable near 215° because of tree wakes. Furthermore, the unstable data tend to predict too low a z_0. Hence, we must assure that for roughness evaluation, not only mean wind but also turbulence behaves as in the neutral case. On average, there is little difference between the two methods.

Reference:

J. Wieringa, 1973, Gust factors over open water and built-upcountry, Bound. Layer Meteor. 3, p. 424-441.

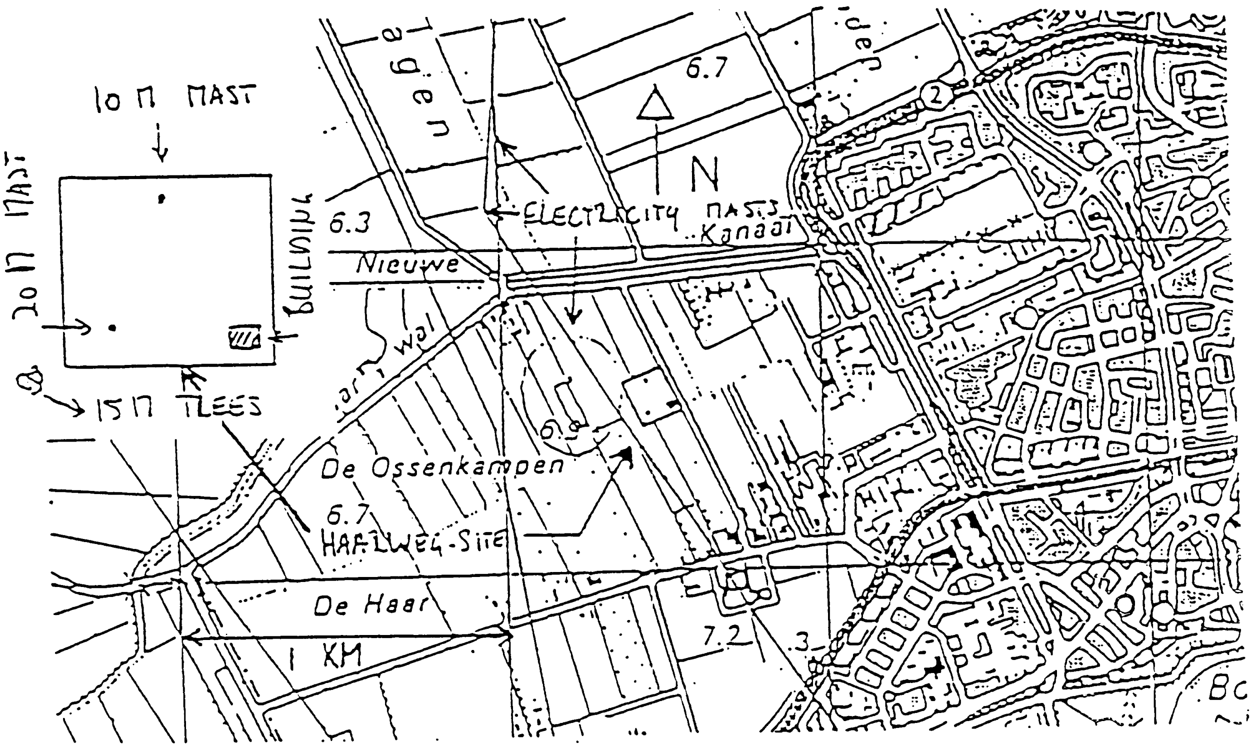


Figure A2.1 Map showing location of Haarweg site and surroundings. Our 20 m mast is near SW-corner of field. Regional roughness is evaluated from northern 10 m mast. A small group of trees is near the SW-corner.

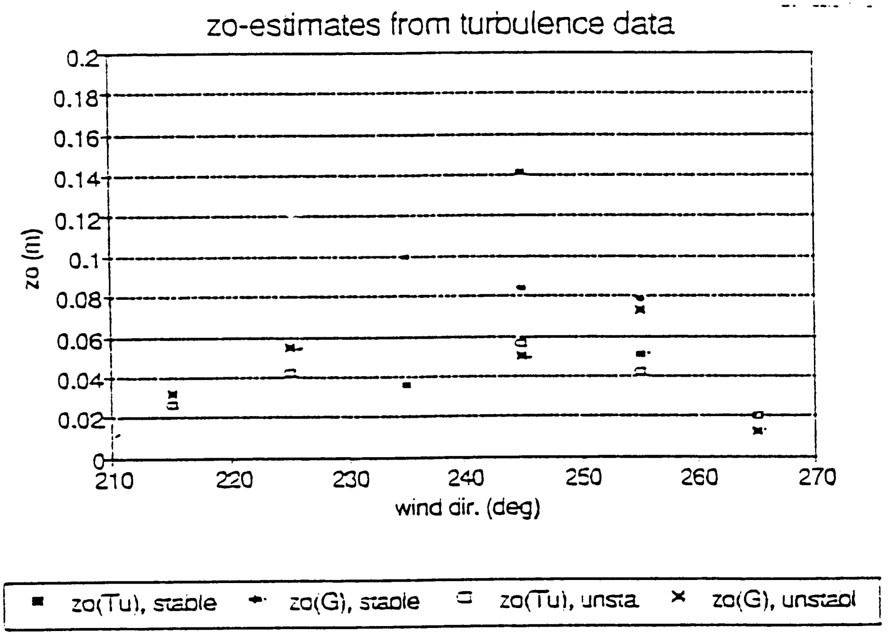


Figure A2.2 Estimates of aerodynamic roughness length z_0 as evaluated by eq. A2.1 and A2.2. Estimates near 215° are less reliable because of tree wakes. Relative uncertainty in z_0: about 50%. Number of samples for each 10° wind direction interval is 7, 21, 1, 5, 34 and 2 (unstable), and 0, 1, 6, 13, 27, 0 (stable).

APPENDIX III Classification of stability and terrain properties

In section 6.4, the following classification was proposed to analyze the data of the Haarweg comparison experiment:

Terrain conditions	Undisturbed	Intermediate	(strongly) Disturbed
dd:	240-280°	15-180°; 280-315°	200-220°; also 315-15°
Stability:			
$z/L < -0.2$	TU/SVU	TI/SVU	TD/SVU
$-0.2 < z/L < -0.01$	TU/SU	TI/SU	TD/SU
$\|z/L\| < 0.01$	TU/SNN	TI/SNN	TD/SNN
$0.2 > z/L > 0.01$	TU/SS	TI/SS	TD/SS
$z/L > 0.2$	TU/SVS	TI/SVS	TD/SVS

Table A3.1 Classification of terrain and stability conditions to be used in analysis of Haarweg comparison experiment where T? stands for terrain undisturbed, intermediate and disturbed,and S* for very unstable, unstable, near neutral, stable and very stable.

Terrain conditions were easily determined by the terrain evaluation of the previous section. It is not that easy to get the wind direction, and especially to get a quick (and preferably independent) stability estimate.

The most accurate way is to use the output of the sonic anemometer. We choose our sample size in such a way that we have a sample duration of slightly less than half an hour (at 20.8 Hz). By processing our sonic anemometer output, we can obtain a time averaged wind direction and heat flux (w'T'). Obukhov length L can then be evaluated if we know U_*. U_* can be evaluated from:

$$U(z) = \frac{U_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \Psi\left(\frac{z}{L}\right)\right]. \qquad \textbf{(A3.1)}$$

The roughness length z_0 is estimated in the appendix A2. U(z) is measured by the sonic, and the Von Karman constant $\kappa = 0.4$. The stability correction function can be taken as -5z/L for stable conditions, and as (approximation) $(1-16z/L)^{0.25}-1$ for unstable conditions (Jensen et al, 1984). The parameter z/L can simply be taken from the table (class boundaries; e.g. -0.2, -0.01, 0.1 or 0.2).

This approach has one important disadvantage: we have to analyze all our measured data, before we can judge which would be the most interesting cases.

A better approach would be to use the data which were gathered for the students practical training in micrometeorology / field measurements. These data consist of 10 minute averages of radiation, ventilated dry and wet bulb temperatures (1 and 2 m), wind speeds (0.5, 1, 2 and 3.7 m; measured with cup anemometers with $D \approx 2$ m) and wind direction (light vane).

The data were originally split into two files, e.g. pract29a.dat (temperatures) and pract29b.dat (other) but combined files in Quattro Pro format (prac???c.wq1 where the first digit indicates the month and the last two the day) are available. At present, the files are stored in drs. J. Verkaik's directory 'w:\practdat.d'. Subdirectories for the raw (*.dat) data indicate the month. These raw data files should not be interchanged between subdirectories!

For computations of Obukhov length, we have to import the pract??c.wq1 file (use command tools/combine) in the file claszldd.wq1. Then, the row BW gives a good estimate of Obukhov length L.
The spreadsheet estimate of L is based on the following two approximate equations (De Bruin, 1994):

$$L \approx \frac{T}{g} \frac{\left(U(z_2) - U(z_1)\right)^2}{(\theta_2 - \theta_1)\ln(z_2/z_1)}, \quad \textbf{(A3.2)}$$

for unstable conditions, and

$$L \approx \frac{T}{g} \frac{\left(U(z_2) - U(z_1)\right)^2}{(\theta_2 - \theta_1)\ln(z_2/z_1)} - \frac{z_2 - z_1}{\ln(z_2/z_1)}, \quad \textbf{(A3.3)}$$

for stable conditions. In this appendix, θ will denote potential temperature!

An even simpler method is to use the daily standard output of the Haarweg meteorological station. Mean wind speed, mean wind direction, temperatures, and some radiation components are given for 6 hour blocks. The blocks from 6-12 GMT and from 12-18 GMT (they will be named B and C) can be assumed representative for daytime unstable conditions, whereas the block from 18-24 GMT can be assumed representative for nighttime (stable) conditions.

A disadvantage of the Haarweg data is that we have not got an estimate of Obukhov length. In a number of cases however, we can convert a z/L requirement into a wind speed requirement.
Let us first consider the unstable case. The required Obukhov length follows from 20/L = z/L from table A3.1. The Obukhov length L is defined as:
Note that L is most sensitive to U_*, and that the other main parameter is w'T' (kinematic heat flux; sometimes also defined with w'θ', or with a virtual temperature: $w'\theta_v'$, $w'T_v'$). Mean temperature T can be fixed at 290 K without much loss of accuracy.
U_* can be easily estimated from eq. A3.1, where we approximate $\Psi(z/L)$ as $(1+16z/L)^{0.25}-1$. Note that here, we should use z = 10 m (standard meteor. station). Now we only have to estimate the sensible heat flux $H = \rho c_p w'T' \approx 1250 \times w'T'$. Sensible heat flux is estimated from incoming short wave radiation K_{in} ('global radiation') by using an approximation in the evaporation formula by Makkink (De Bruin, 1994): $H \approx 0.5 \times K_{in}$. On sunny days (summer) total global radiation is about 2700 J/cm^2 (average w'T': 0.38 Kms^{-1}), on mainly cloudy days (<10% sun) this is about 1000 Jcm^{-2} (average w'T': 0.14 Kms^{-1}). For z/L > -0.2 and z/L > -0.01 we have minimum wind speeds of 9 and 25 ms^{-1} for the sunny case, and 7 and 19 ms^{-1} for the cloudy case. This would mean that near neutral or even slightly unstable conditions are almost absent during summer.

For stable conditions, we assume rather arbitrarily a that H = -50 Wm^{-2} for moderate and strong winds and clear sky. This yields a w'T' of 0.04 Kms^{-1}. For z/L < 0.2 and z/L < 0.01 this yields 10 m wind speeds of 5.6 and 13 ms^{-1}. Again, near neutral conditions seem to be rare (except in transition periods). As for the unstable conditions, we should use these estimates only as very rough indications.

The above requirements for neutral conditions do seem very restrictive. However, they are confirmed by the spreadsheet data mentioned above. These data show very few measurements for which the computed $|z/L| < 0.1$ (with $z = 20$ m), even when $U(2m) \geq 5\ ms^{-1}$. Now that these spreadsheet data are worked out (graphs of stability and wind direction as a function of time are available from drs. J. Verkaik) it is recommended to use these data for a first selection of suitable measuring periods.

References:

H.A.R. de Bruin, 1994, Reader Micrometeorology (in Dutch), Department of Meteorology, Wageningen Agricultural University.

N.O. Jensen, E.L. Petersen, I. Troen, 1984, Extrapolation of mean wind statistics with special regard to wind energy applications, WMO World Climate Applications Programme,TD-No. 15, 85 pp.