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K-Gill propeller vane observations for the Cabauw parametrization experiment

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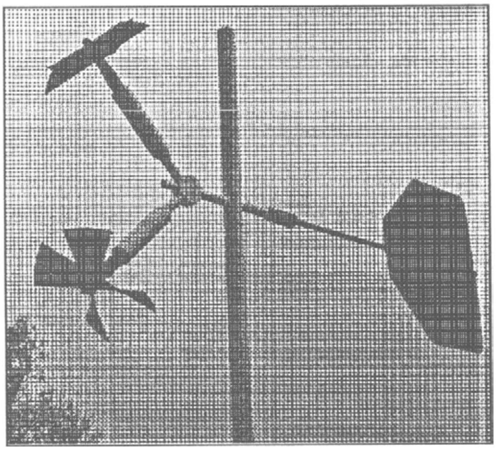
Abstract

Some calibration results of the K-Gill propeller vane are discussed. The propellers static and dynamic response were determined. The two propellers show perfect linearity in calibration factor. Starting speed is found less than 0.18 ms^{-1}. Response lengths of the propellers is 2.5 m. Effective response length in K-Gill configuration is 3.3 m. A new function for propeller response to a drop to zero in wind speed is suggested.

1. Introduction

In the TEBEX mesoscale project K-Gill propeller vanes[1] will be used at the 215 m mast of the Royal Netherlands Meteorological Institute (KNMI) at Cabauw. Measurements of turbulent heat and momentum fluxes over inhomogeneous terrain will be made in all weather situations. TEBEX will provide valuable data for e.g. validation of k-ε-models.



Picture of the K-Gill propeller vane.

K-Gills are chosen for a number of reasons: K-Gills can be used to measure fluxes in all weather situations[2], K-Gills have stable calibration[3] and are less expensive than e.g. a sonic anemometer. Major disadvantages are the large response length (compared to e.g. a sonic) and the rather complicated dynamics of the K-Gill.

This summer wind tunnel tests as well as field comparison tests, using the K-Gill and a sonic anemometer at the 20 m mast at the Haarweg test site in Wageningen, were carried out to measure the K-Gills static and dynamic response. Vane properties have been determined by the method of Wieringa[4]. The vane was too large to do wind tunnel tests so the vane properties will not be discussed now.

An extensive report of this project is written by Bottema[5].

2. Description of the instrument

The K-Gill (manufactured by R.M. Young; model 35301) consists of two propellers, which are oriented 45° upwards and downwards, and a vane. (see picture on the previous page) From the propeller velocities the horizontal wind (U_h) and the vertical wind can be computed[1]. Meanwhile the wind direction is recorded by the vane, so that U_h can be decomposed into an west-east and south-north component.

Complications arise in recovering the desired along-wind, across-wind and vertical wind components as a results of non-perfect cosine response of the propellers and of the inertia of the propellers and vane. In this rather complex propeller-vane interaction both overspeeding and underspeeding are possible. An extensive analysis of propeller-vane interaction is given by Zhang[6].

3. Static propeller response

The K-Gill propellers were tested in the wind tunnel of the Group Meteorology of Wageningen Agricultural University (WAU). The test section of this wind tunnel is too small for the K-Gill to fit in it, but the propellers could be tested separately.

3.1 Calibration factor

The calibration factor K and the starting speed U_s were determined for wind parallel to the propeller axis. The calibration relation is:

$$U = K*f + U_s \tag{1}$$

U is the 'real' wind speed (ms^{-1}); f is the pulse rate (Hz). Pulse rates measurements were made with U from 0.1 ms^{-1} to 18.5 ms^{-1}. After averaging several runs K and U_s were determined from linear regression. The calibration measurements were repeated after two months of duty on the 20 m mast of the Haarweg test site in Wageningen this summer.

Both propellers showed excellent agreement and almost perfect linearity and stability in calibration. Differences between propellers were less than 0.4%, the accuracy to which K was determined. The repeated calibrations after the field experiments did not show any significant deviations either. The starting speed however remains uncertain, because the flow blockage correction for propellers was not known. We could only conclude that $U_s \leq 0.18$ ms^{-1} for both propellers.

3.2 Angular response

The output of propeller anemometers for oblique flow with angle θ is generally less than $\cos(\theta)U|_{\theta=0}$. The angular response C(θ) is defined by:

$$U_{measured} = U*\cos(\theta) * C(\theta) \tag{2}$$

From literature it can be concluded that angular response of propellers of similar shape at least depends on the propeller material and on its dimensions[1,7,8,9].

C(θ) has been determined with U from 1 ms^{-1} to 15 ms^{-1} at angles between the wind and the propellers axis from 0° to 90°. As expected, both propellers showed similar behaviour with regard to cosine response. A slight dependence of cosine response on wind speed was probably caused by the fact that for small wind speeds and large θ, the axial wind component approximates the starting speed. The propeller units now used do not discriminate between flows with angle 90+δ° and 90-δ°, which may be important in convective conditions. The best fit to the measured C(θ) 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.

4. Dynamic response

Generally, a propeller is assumed to be first-order system which satisfies the following equation:

$$\frac{dU(t)}{dt} = \frac{1}{\tau}(U_\infty - U(t)) \tag{4}$$

where U_∞ is the full wind tunnel speed and τ a time constant. Usually τ is written as

$$\tau = D / U_\infty \tag{5}$$

where D is the distance constant. Solution to eq. 4 is a exponential function:

$$U(t) = (U_0 - U_\infty)e^{-t/\tau} + U_\infty \tag{6}$$

where U_0 is the wind speed at t = 0 s.

4.1 Wind speed increase and angular dependence of D

D can be determined from the length of the air column after 63% speed up of the propeller ($D_{63\%}$) or from linear regression (D_{LR}). In all our observations, there was a trend for $D_{63\%}$ to be larger than D_{LR} (largest overestimation of 20%). One cause is the time discretization. With $\tau = 0.63$ s and $\Delta t = 0.1$ s the average overestimation is 8%. The remaining 12% must be caused by initial friction. We used linear regression when calculating D. All regressions were taken at the interval from 20% to 70% adaption.

For flow parallel with the propellers axis, we found for both propellers D = 2.5 ± 0.2 m. Repeated measurements after the field experiment did not show any significant differences.

A propeller responds slower when it is inclined to the mean flow. The angular dependence we observed corresponds well with the formula:

$$D(\theta) = D(0°)/\sqrt{\cos(\theta)} \tag{7}$$

Effective D in K-Gill configuration corresponds to the measured D at 45°: 3.3 m.

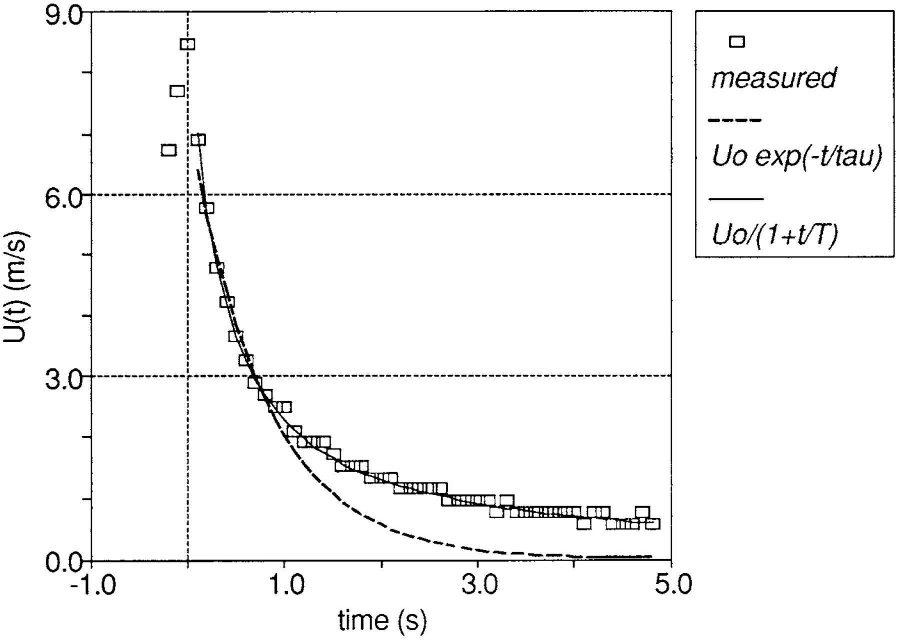


Figure 1 Propeller response to a drop to zero in wind speed.

4.2 Wind speed decrease

Propellers deceleration is usually described by eq. 4. In case $U_\infty = 0$ ms^{-1}, τ can not be defined as in eq. 5. Now let us assume the propellers deceleration is proportional to the drag forces on the propellers, so

$$\frac{dU(t)}{dt} = -\frac{1}{\lambda}\,(U_\infty - U(t))^2 \qquad (8)$$

where λ is some length scale. Instead of an exponential function, eq. 6 yields a hyperbola:

$$U(t) = \frac{U_0 - U_\infty}{1 + t/T} + U_\infty \qquad (9)$$

where T is a new time constant:

$$T = \lambda/(U_0 - U_\infty) \qquad (10)$$

Measurements were carried out in a wind tunnel with fixed wind speed at $U_\infty \approx 0$, 1, 2 and 3 ms^{-1}. The propeller was speeded up like a top, using a cotton wire. This way U_0's were reached from 6.5 to 9.0 ms^{-1}. The best type of function was determined from correlations coefficients of the regression.

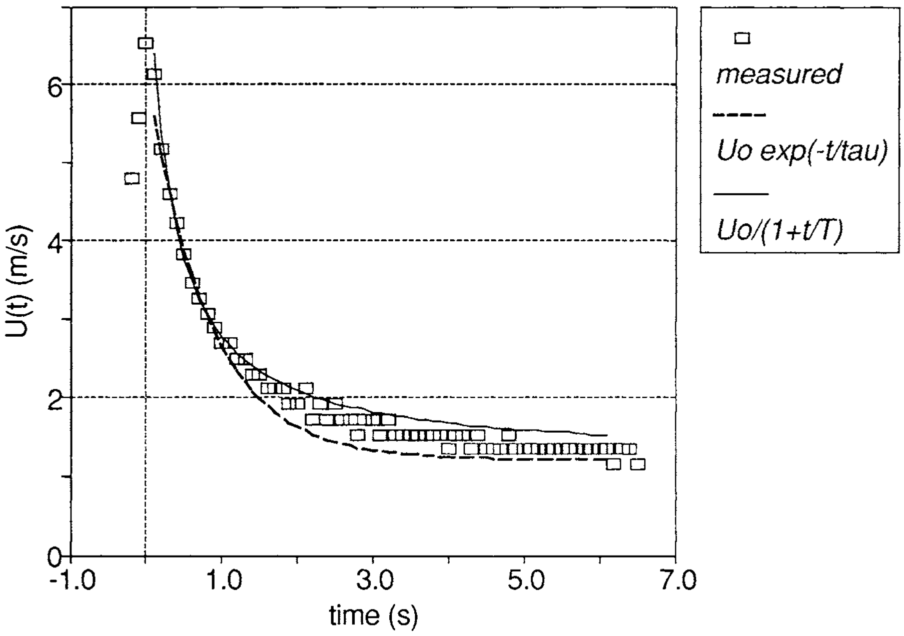


Figure 2 Propeller response to a drop to 1.2 ms^{-1} in wind speed.

Some results are summarized in table 1. The values of D, τ, λ and T are averaged over several runs and the average and standard deviation for several values of U_∞ are printed. In the bottom row the ratio of the of the standard deviation and the mean values for D, τ, λ and T for all U_∞'s are printed. Clearly D is not constant but increases with U_∞. From the bottom row it can be seen that in this wind speed range the relative differences in D are larger than those in τ, so rather τ than D should be called a constant.

Table 1
D, τ, λ and T for several U_∞'s

U_∞ (ms^{-1})	D = τU_∞ (m)	τ (s)	λ (m)	T (s)
.0	.0 ± .0	.84 ± .04	3.17 ± .07	.37 ± .01
1.2	.92 ± .05	.76 ± .04	2.2 ± .2	.35 ± .03
2.0	1.32 ± .08	.65 ± .04	1.6 ± .1	.29 ± .02
3.0	1.59 ± .04	.54 ± .02	1.27 ± .07	.23 ± .02
std./avg.	.22	.17	.35	.17

The ratio T/τ is 0.44 for all U_∞'s. This is a result from the chosen regression interval. From the correlation coefficients of regression it could be concluded that equation 9 provides a much better fit than the exponential function only in case U_∞ = 0 ms^{-1}. (fig. 1 and 2) For small U_∞ the exponential function is equally well or better. The value for λ found this way decrease from 3.17 m at U_∞ = 0 ms^{-1} to 1.27 m at U_∞ = 3.0 ms^{-1}.

5. References

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