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EVALUATION OF DISTANCE CONSTANTS FOR VARIOUS CUP ANEMOMETERS AND MEASUREMENT OF THE VERTICAL SENSITIVITY OF A 'VECTOR' TYPE A100 CUP ANEMOMETER

for

Commission of the European Communities DGXVII
CEC Contract No 87-B-7010-11-7-17

Report No. EUEC/25

February 1989

NATIONAL ENGINEERING LABORATORY

DEPARTMENT OF TRADE & INDUSTRY

National Engineering Laboratory East Kilbride Glasgow G75 OQU

NATIONAL WIND TURBINE CENTRE,
POWER SYSTEMS ENGINEERING DIVISION

Report On

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S U M M A R Y

This report describes experimental investigations undertaken by the National Wind Turbine Centre into factors affecting the dynamic response of cup anemometers. Experiments involving step changes in incident wind speed and varying angles of attack are described.

The work is dealt with in two parts. The first describes the effect a step change in wind speed (either increasing or decreasing) has on the output of a cup anemometer. The responsiveness of an instrument to such changes can be described numerically by its 'distance constant'. Results are given for five cup anemometers of various rotor sizes and cup profiles.

The second part of the report discusses the sensitivity of a 'Vector' type A100 cup anemometer to changing angles of incident wind flow. Comparisons with the ideal cosine response are made.

Date February 1989

For Dr DA Bell
Director

Reference EUEC/25
SB

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PROJECT OUTLINE

The objective of the Joint Wind Turbine Test Station Programme, being sponsored by DGXVII of the Commission of the European Communities, is the development of common standards and certification procedures for wind turbines throughout the Community.

The objective of this project on 'Accuracy of Wind Speed Measurement' is to derive recommendations on how the test stations should measure wind speed, the single most important parameter, particularly with regard to power performance testing of wind turbines. The project is being led by the National Wind Turbine Centre (NWTC) with contributions from the following organisations:

Vrije University Brussels, Belgium,
Riso National Laboratory, Denmark,
DFVLR, Germany,
ECN, Netherlands, and
Rutherford Appleton Laboratory, UK.

At present cup anemometry is used by all test stations as the means of determining wind speed. However different test stations use different instruments of differing size, type and manufacture. Additionally anemometer calibration techniques vary throughout the Community.

Cup anemometers have limitations. In particular they suffer from overspeeding effects of varying magnitudes. The difference between the drag on the convex and concave faces of the cups makes the instrument more responsive to increases than to decreases in the horizontal wind speed. In addition cup anemometers tend to follow a non-cosine response to angle of attack in the vertical plane.

In a turbulent wind regime, such as occurs in the free atmosphere, cup anemometers are therefore prone to inherent error.

This report forms part of the basic information which, by discussion and agreement, will lead to recommendations for the European test stations on the use, acceptable accuracy and method of calibration for cup anemometers. The report describes the measurement of response coefficients for a variety of cup anemometers currently in use at a number of the test stations, and looks at the sensitivity to angle of attack of the anemometer type currently favoured by the UK National Wind Turbine Centre (NWTC).

PART 1: EVALUATION OF DISTANCE CONSTANTS FOR CUP ANEMOMETERS

1.1 INTRODUCTION

The response of a cup anemometer to a step change in wind speed can be described by its 'distance constant'. This is defined as the length of air column which passes horizontally through an anemometer rotor during the time taken for the anemometer to respond to $\{1 - (1/e)\}$ or 63.2 per cent of the step change applied. The equation of motion of a cup anemometer can be written (Reference 1) by approximation as follows:

$$dn/dt = -avn + bv^2 \qquad (1)$$

where n is the angular speed of the rotor in revolutions per second,

t is the time in seconds,

v is the horizontal wind speed in meters per second, and

a,b are constants dependent on the instrument and the air density.

Solution of this equation for a step change of Δv in speed v at time t = 0 yields the rotational speed of the cup, n(t), given by

$$n(t) = C[v_i + \Delta v\{1 - \exp(-t/\tau)\}] \qquad (2)$$

where C = b/a,

v_i is the initial wind speed,

Δv is the step change in wind speed, and

$\tau = 1/\{a(v_i + \Delta v)\}$ is the time constant, defined as the time taken for the anemometer to respond to $\{1 - (1/e)\}$ or 63.2 per cent of the step change in wind speed, Δv.

The length of air column which passes the anemometer in the time interval τ is simply the area under the speed-time graph of the anemometer response, between the time limits t = 0 and t = τ. Calculation of the distance constant, d, therefore involves integration of the speed function n(t) from t = 0 to t = τ.

$$d = \int_{t=0}^{t=\tau} n(t)dt. \qquad (3)$$

Substitution of equation (2) into equation (3) followed by integration over the specified limits yields the following expression for the distance constant, d.

$$d = \{v_i + (1/e)\Delta v\}\tau. \qquad (4)$$

Equation (4) shows the dependence of the distance constant on both the initial wind speed, v_i, and the step change experienced, Δv.

It should be noted that the time constant, τ, is inversely proportional to both initial wind speed, v_i, and the step change, Δv. As a result a cup

ERRATUM

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The distance constant of an anemometer is defined as the length of air column which passes horizontally through an anemometer rotor during the time, τ, taken for the anemometer to respond to $\{1 - (1/e)\}$ or 63.2 per cent of the step change applied.

The length of this air column should be calculated from the real wind speed at the anemometer which is given by

$$v_f = v_i + \Delta v \qquad \text{(i)}$$

where v_f, v_i and Δv are as defined in the report.

The distance constant is then

$$d = (v_i + \Delta v)\tau \qquad \text{(ii)}$$

Equation (4) has been derived by assuming the air column length is calculated from the apparent wind speed as indicated by the anemometer, and should be replaced by equation (ii) above.

Table 2 should be replaced by the attached table of recalculated distance constants.

TABLE 2

RECALCULATED DISTANCE CONSTANTS

Anemometer	Increasing step			Decreasing step		
	Actual m	Mean m	Error %	Actual m	Mean m	Error %
Schiltknecht	3.8 3.6 3.7	3.7	3	2.4 2.6 2.6	2.5	4
Vector A100	3.1 3.5 3.1	3.2	4	2.5 2.5 2.6	2.5	4
Riso	2.4 3.0 3.0	2.8	4	2.1 2.1 2.1	2.1	4
Thies	5.5 5.2 5.0	5.2	2	5.3 5.4 5.3	5.3	2
Lambrecht	3.9 5.5 3.4	4.3	3	6.9 6.4 5.6 4.4 6.7	6.0*	2

*This test was repeated five times in order to improve the accuracy of the mean.

anemometer will tend to respond more quickly to an increasing step change than to a decreasing step change of the same magnitude.

1.2 METHOD OF INVESTIGATION

1.2.1 The Anemometers

The five anemometers used in this study were typical of the instruments currently preferred by each of the European wind turbine test stations participating in the present project.

Fig. 1 shows these anemometers and their relative sizes, while Table 1 contains a description of rotor geometry and electrical output for each instrument.

1.2.2 Specialised Equipment

In order to evaluate the distance constant, d, of an anemometer using equation (4) it was necessary to create a finite step change, Δv, in the mean horizontal wind speed incident on the anemometer rotor. This was achieved using the NWTC's free jet wind tunnel and a purpose-designed retractable friction drive shaft, Fig. 2.

The principal components of the retractable friction drive shaft are listed below and are also shown in Fig. 3:

a variable speed d.c. motor,

b drive shaft,

c friction head, and

d retaining catch and release trigger.

To generate a step change in wind speed at an anemometer, the variable speed d.c. motor was used to control the initial speed of the rotor. This was achieved via the retractable drive shaft and friction head arrangement mounted vertically above the anemometer. On release of the retaining catch the motor, drive shaft and friction head were rapidly withdrawn from the wind tunnel free jet enabling the anemometer to respond instantly to the pre-set wind tunnel free jet air speed.

1.2.3 Experimental Procedure

Anemometer output was monitored using either a digital voltmeter or a pulse counter, depending upon the nature of the signal.

The rotational speed of the anemometer rotor under test was adjusted, via the retractable friction drive shaft, until the anemometer output corresponding to the desired starting speed was steady. The frictional force between the friction head and the anemometer rotor was adjusted until there was no slippage between the two. Care was also taken to ensure that the drive shaft arrangement would not affect the rotor performance on subsequent release.

Having set the anemometer to rotate steadily at the chosen initial speed, the air speed of the free jet impinging upon the rotor was adjusted to the desired final wind speed value. This was achieved via a reference pitot-static tube.

To obtain an increasing step change, the wind tunnel was set to give a nominal outlet speed of 10 m/s while the retractable friction drive shaft was adjusted until the anemometer output corresponded to that produced by the instrument rotating in a nominal 6 m/s wind. After a short period of time in which the entire system was in a steady state the release trigger was activated allowing rapid disengagement of the friction drive shaft from the rotor head and retraction from the free jet. Upon release, the anemometer was then instantly free to respond to the higher wind speed.

A decreasing step change in incident wind speed was achieved in a similar fashion but with the tunnel outlet speed set to a nominal 6 m/s and the anemometer driven at a nominal 10 m/s.

In addition to monitoring the anemometer output on the DVM, or pulse counter, the signal was connected to a fast responding Brush pen chart recorder in the case of analogue anemometers and to a Medelec For-4 M-scope u.v. recording oscilloscope for pulse output instruments. This produced a hard copy of the anemometer response from which the initial and final wind speeds, and hence the distance constant, could be calculated. Initial calibration of the pen chart recorder was required for each analogue anemometer tested in order to set reference voltage levels. Subsequent measurement of the initial and final speeds was based on these fixed voltage levels.

Six tests were carried out for each anemometer, three for increasing and three for decreasing steps. Sufficient time was allowed prior to and following release of the retractable friction drive shaft mechanism to ensure that the initial and final speeds of rotation were well-defined.

1.3 RESULTS

1.3.1 Analogue Output Anemometers

For each analogue output anemometer tested the initial and final wind speeds, v_i and v_f respectively, were calculated from the chart recordings using the set voltage levels and the instrument's known sensitivity. From this the actual step change in wind speed, Δv, experienced by the anemometer rotor was found, positive for an increasing step, negative for a decreasing step.

The definition of distance constant, d, requires the time, τ, taken for the anemometer to respond to 63.2 per cent of the speed change experienced. Therefore the speed v_2 defined as follows was calculated

$$v_2 = v_i + 0.632\Delta v. \tag{5}$$

The time, τ, taken for the anemometer rotor speed to change from v_i to v_2 was then evaluated from the recorded anemometer response, and hence the distance constant, d, was calculated from equation (4).

1.3.2 Pulse Output Anemometer

In the case of the pulse output instrument, successive average frequencies of pulsing over sets of five adjacent pulses were calculated and converted to wind speed via the anemometer sensitivity. Thereafter the measured data were plotted as average speed against time for each five-pulse section of the recorded response. This resulted in a 'histogram' showing the speed-time dependence for each step change. Initial and final speeds were then read off from the histogram and calculation of the distance constant proceeded as for the analogue output anemometers.

Results for both analogue and pulse output anemometers are shown in Table 2.

1.3.3 Errors

Test results were combined to give mean values of distance constants, increasing and decreasing, for each anemometer. The errors shown for the quoted mean distance constants were derived from the reading errors associated with the interpretation of each contributory pen chart or oscilloscope recording. They represent the estimated maximum error on each mean value. Test results were combined to give mean values of distance constants, increasing and decreasing, for each anemometer.

Errors calculated for the pulse output anemometer for a decreasing step were found to be significantly higher than for all other instruments, due to large errors associated with determining the exact time of rotor release by the retractable friction drive shaft. This test was therefore repeated five times to improve the accuracy of the mean value for the distance constant.

1.3.4 Consistency of the Distance Constant

The assumed equation of motion given in equation (1) leads to the conclusion that an anemometer's responsiveness can be described by its distance constant. To check on the consistency of this index, a particular response recording was examined. Rather than taking the starting rotational speed as the only initial speed, a number of other locations along the curve were also selected, as shown in Fig. 4. Each starting point enabled a distance constant to be calculated.

This was done both for increasing and decreasing step changes. If 'distance constant' is indeed constant then, for a given response curve, it should be independent of initial speed. Results showed that for both conical and hemispherical cup profiles reacting to an increasing step change the distance constant, d, was indeed independent of starting speed, confirming that the quantity d is a true constant. However for these same anemometers it was found that d was not independent of initial speed for decreasing step changes as shown in Table 3. The distance constants given in Table 2 have therefore been derived using the full range of the step change for each test.

This difference in response to increasing and decreasing step changes implies that there is some physical difference in the way that a cup anemometer reacts to the two situations.

1.4 DISCUSSION

Five cup anemometers of various rotor geometries were examined to determine their response characteristics in conditions of increasing and decreasing wind speeds.

The responsiveness of each anemometer was quantified by its 'distance constant'. Measured data showed that cup anemometers are more responsive to increasing than to decreasing winds, as expected. As a consequence cup anemometers in a turbulent environment tend to overpredict the prevailing mean wind speed level.

It was expected that the smaller, lighter rotors would be more responsive with smaller distance constants. In general this was found to be the case, with the large rotors of the Thies and Lambrecht anemometers having the largest distance constants. The most responsive anemometer overall was found to be the Riso instrument and not the smaller Vector or Schiltknecht anemometers.

PART 2: EVALUATION OF THE VERTICAL SENSITIVITY OF A CUP ANEMOMETER

2.1 INTRODUCTION

Ideally wind flow measuring devices should exhibit a cosine response to varying angles of incident air flow, θ, as shown in Fig. 5. In the case of a cup anemometer this implies maximum wind speed should be recorded when the air flow is perpendicular to the axis of rotation of the rotor. Thereafter as the angle of incidence, θ, is increased the measured air speed should decrease in proportion to the cosine function until θ = 90, at which point the indicated air speed should be zero.

However for real cup anemometers this is not the case and deviations from a true cosine response are observed.

The NWTC has investigated experimentally the sensitivity of a cup anemometer to variations in angle of attack, θ, using its free jet anemometer calibration wind tunnel.

2.2 METHOD OF INVESTIGATION

2.2.1 The Anemometer

A 'Vector' three cup anemometer of manufacturer's designation A100 was used for the study. The cups of this instrument have a conical profile. Other geometric data is given in Table 1.

2.2.2 Specialised Equipment

The study required the angle of incidence between the free jet and the rotor axes to be varied from 0-90°. This was achieved using a specially designed pitching rig into which the anemometer was securely clamped, Fig. 6. The rig was designed in order that the anemometer could pitch about the centre of its rotor. Consequently the relative position of the rotor centre in the free jet was not affected by pitch angle, only the inclination of the rotor within the air flow was changed.

2.2.3 Experimental Procedure

In order to accurately determine the anemometer response to pitch angle, θ, data were sampled at the following angular values:

0, 1, 2 ... 30°, ie 1° intervals,

35, 40, 45 ... 70°, ie 5° intervals,

72, 74, 76 ... 80°, ie 2° intervals,

and 85°,

giving a total of 45 data points.

High resolution of the response curve was required in the range 0-30° since these are the angles of attack most likely to be encountered in the free atmosphere and consequently 1° intervals were chosen for measurement. Thereafter 5° intervals were used to show the trend in output. It was anticipated that any unusual rotor behaviour would occur at larger angles of incidence and therefore 2° settings were used in the range 72-80°.

At each angular setting raw data values of reference differential pressure (Pa), anemometer output (V), atmospheric pressure (mbar) and ambient air temperature (°C) were sampled continuously over a 30-second period.

Measurement of the prevailing air pressure and temperature allowed the air density of the free jet during each 30-second sampling period to be calculated. An initial correlation between the dynamic pressure head measured at a fixed reference position and that measured at the centre of the anemometer rotor had previously been carried out using two ellipsoidal head pitot-static tubes. This allowed the true dynamic head at the anemometer to be derived for every pressure value recorded at the reference location during each 30-second sampling period. The true air speed at the anemometer for each sampled pressure value was then calculated from each of the known dynamic head values and the prevailing air density. Thereafter mean and standard deviation values were calculated for each of the four data channels.

A low head differential pressure transducer was used to monitor dynamic pressure. To minimise the effect of drift in the transducer and signal conditioning, the system offsets were adjusted, prior to the test, to less than ±0.05 mV, which represents ±0.02 Pa in dynamic head at the anemometer rotor. Checks on the electrical stability of all data sampling instrumentation were carried out before and after data acquisition.

The free jet wind tunnel was adjusted to give a nominal wind speed of 10 m/s at the anemometer. This setting was fixed throughout the test period.

2.3 RESULTS

Due to the large number of angular settings used in the study some drift in rig conditions over the entire test period was experienced. To remove the effect of these time-dependent fluctuations on the free jet speed at the rotor, the quotient

$$\frac{\text{mean anemometer output (V)}}{\text{mean free jet speed (m/s)}}$$

was formed for each measurement position. Dividing all the quotients produced in this way by the corresponding value at 0° allowed the measured data to be compared directly with the true cosine response as shown in Fig. 5.

Fig. 5 clearly shows that the cup anemometer did not exhibit true cosine response except in the narrow range 0-5°.

Unusual rotor behaviour including rocking motion, reverse rotation and hesitancy in rotor movement was observed at attack angles above 70°. These effects are summarised in Table 4 which shows clearly that vertical (or near vertical) turbulent wind field components have highly undesirable consequences for rotor performance and corresponding anemometer output.

The effect of reverse rotation at high pitch angles on anemometer output is not immediately apparent. The anemometer used in this study is fundamentally a digital device, generating pulses the frequency of which depends solely on the rotational speed of the rotor and not on the direction of rotation. An internal frequency-to-voltage converter generates the final anemometer output which must necessarily be a positive voltage. If, however, the anemometer contained a tacho-generator device, reverse rotation would produce a negative output voltage. Consequently for the purpose of this study the sign of the anemometer output has been taken to be the sign of rotation, ie positive for forward rotation, negative for backward rotation.

To quantify the relative error in anemometer output produced by varying the angle of incident air flow, the difference between the true cosine curve and the measured normalized response curve has been plotted in percentage terms in Fig. 7. This graph shows that the measured output can differ by up to 65 per cent from the true cosine response, for angles of attack in the range 20-70°.

The measured output shows good agreement with cosine behaviour only for angles of attack of 0-5°. In the range 5-20° the cup anemometer output is up to 3 per cent less than that expected from a true cosine response.

Further increases in the attack angle yield overprediction errors with a maximum value of 65 per cent for an attack angle of 65°. Thereafter the magnitude of overprediction decreases with increasing angle of attack, to 0 per cent at approximately 73°. For attack angles greater than 73° the measured response is significantly lower than that expected from true cosine behaviour and cup anemometers experiencing wind flows from these extreme angles will underpredict the prevailing wind.

2.4 DISCUSSION

The cup anemometer used in this study was a 'Vector' instrument of manufacturer's designation A100. The cup profile was conical. Output from the instrument was monitored for 45 angles of attack in a steady air flow of nominal 10 m/s and compared with the ideal cosine response. Differences of up to 65 per cent were measured for angles of attack in the range 20-70°. Deviations for wind velocities with small vertical components were of much smaller magnitude. However attack angles in the range 5-20° which are not unusual in a turbulent wind climate will result in underprediction of the horizontal wind speed by up to 3 per cent. This corresponds to a 9 per cent underprediction of the available wind power and has obvious implications when carrying out a wind survey to establish the economics of a proposed wind turbine development. Additionally for wind turbine power performance evaluation a significant potential source of error has been identified.

The results of this study for a conical type, three cup anemometer clearly show the necessity for accurate mounting of cup anemometers which are to be used for wind resource or wind turbine power performance assessments. Deviations from the true vertical of more than 5° will lead to serious errors in estimating the magnitude of the available wind resource.

Careful site selection and cup anemometer mounting arrangements are therefore necessary in order to reduce errors.

It should be noted that the instrument used in this study has conical cup profiles. Drag forces acting on conical and hemispherical cups will differ and consequently the behaviour observed here may not typify the response of an anemometer with different cup profiles. It is also likely that the ratio of cup diameter to rotor diameter will influence the nature of the sensitivity to non-horizontal winds.

CONCLUSIONS

The dynamic responses of various cup anemometers in conditions of changing wind strength and direction have been studied. Parts 1 and 2 of this report detail the methodology used to investigate each of these effects.

Cup anemometer response to an increasing step change in wind speed can be described by a 'distance constant', d, which for each instrument studied was found to be independent of initial wind speed and magnitude of step change. This confirms that the quantity, d, is a constant for a particular instrument. For decreasing step changes however this was found not to be the case. This was true for both conical and hemispherical cup profiles.

In general smaller, lighter rotors were more responsive, ie had smaller distance constants than larger, heavier rotors. Inertia is therefore the most important quantity affecting an anemometer's responsiveness.

Varying the angle of attack in the vertical plane produces deviations from the ideal cosine response of up to 65 per cent. Consequently alignment of the anemometer is crucial to accurate wind measurement, as angles of only 5-10° from the horizontal will cause underestimation of the wind strength by up to 3 per cent.

This study has highlighted the need for careful use of cup anemometers both for wind resource assessment and for wind turbine power performance evaluation. Mean wind speeds in highly turbulent wind regimes will be inherently overestimated due to the asymmetric response to positive and negative fluctuations in wind speed, while large vertical components in the wind field may either enhance or offset this overestimation. Cup anemometers should only be used, therefore, with a good appreciation of their intrinsic dynamic limitations.

REFERENCE

1 METEOROLOGY OFFICE. Handbook of meteorological instruments. Part 4: Measurement of surface wind. 2nd edition, HMSO, 1981.

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TABLE 1

DESCRIPTION OF EUROPEAN TEST STATION ANEMOMETER ROTORS

Anemometer	Output	Rotor dia. mm	Cup dia. mm	Cup profile	Test Station
Schiltknecht	Analogue	100	38	Hemispherical	VUB
Vector A100	Analogue	152	50	Conical	NWTC
RISO	Analogue	190	70	Conical	RISO
Thies	Analogue	315	75	Hemispherical	DFVLR
Lambrecht	Pulse	315	75	Hemispherical	ECN

Note: Key to test station abbreviations:

VUB - Vrije University Brussels, Belgium

NWTC - National Wind Turbine Centre, United Kingdom

RISO - Riso National Laboratory, Denmark

DFVLR - German Aerospace Research Establishment, Germany

ECN - Netherlands Energy Research Foundation, Netherlands.

TABLE 2

MEASURED DISTANCE CONSTANTS

Anemometer	Increasing step			Decreasing step		
	Actual m	Mean m	Error %	Actual m	Mean m	Error %
Schiltknecht	2.6 2.5 2.6	2.6	3	3.4 3.6 3.6	3.5	3
Vector A100	2.4 2.6 2.4	2.5	3	3.9 4.0 4.2	4.0	2
Riso	1.9 2.2 2.3	2.1	5	3.1 3.1 3.0	3.1	3
Thies	4.1 4.1 3.8	4.0	2	8.5 8.8 8.7	8.7	1
Lambrecht	3.0 3.2 2.9	3.0	3	9.9 14.0 10.6 10.4 11.3	11.2*	6

*This test was repeated five times in order to improve the accuracy of the mean

T A B L E   3

EFFECT ON MEASURED DISTANCE CONSTANT OF VARYING INITIAL SPEED ON A GIVEN RESPONSE CURVE

Test station		Increasing step				Decreasing step				
Vrije	v_i (m/s)	5.9	6.8	7.7	8.5	10.4	9.2	8.5	7.7	7.0
	v_f (m/s)	11.8	11.8	11.8	11.8	6.2	6.2	6.2	6.2	6.2
	d (m)	2.6	2.5	2.6	2.8	3.4	3.6	3.2	2.6	2.0
NWTC	v_i (m/s)	5.8	6.2	7.0	7.7	10.2	9.2	8.5	7.7	
	v_f (m/s	9.4	9.4	9.4	9.4	5.3	5.3	5.3	5.3	
	d (m)	2.6	2.4	2.3	2.6	3.9	3.3	2.8	2.6	
RISO	v_i (m/s)	6.0	6.7	7.3	8.05	10.5	9.4	8.05		
	v_f (m/s)	9.3	9.3	9.3	9.3	6.0	6.0	6.0		
	d (m)	1.9	1.8	2.0	1.9	3.1	2.0	1.8		
DFVLR	v_i (m/s)	6.35	7.11	7.73		10.19	9.81	9.07	8.46	
	v_f (m/s)	9.23	9.23	9.23		5.19	5.19	5.19	5.19	
	d (m)	4.00	3.98	4.04		8.35	7.54	6.80	5.98	
ECN	v_i (m/s)	2.5	4.00	6.00	7.00	13.05	12.00	10.00	8.00	
	v_f (m/s)	11.24	11.24	11.24	11.24	4.55	4.55	4.55	4.55	
	d (m)	3.65	3.20	3.49	4.11	13.99	10.00	8.63	6.93	

NB v_i: chosen initial speed
v_f: actual final speed
d : measured distance constant

TABLE 4

ROTOR BEHAVIOUR AT LARGE ANGLES OF ATTACK

Angle degrees	Notes
72	Normal rotation
74	Hesitancy observed in rotor, ie non-uniform rotational speeds
76	Hesitancy observed in rotor, ie non-uniform rotational speeds. Rotor came to rest at certain positions. Some backward rotation of up to ½ turn observed. Rocking motion observed.
78	Behaviour as for 76° with the following degradation: • less forward motion. • more rocking. • more backward rotation. • few complete revolutions in either direction. • appeared to show same amount of backward and forward rotation.
80	Mostly backward rotation observed. Hesitancy observed in rotor. Rocking motion observed.
85	Steady backward rotation with only slight hesitancy. The rotor did not come to rest at any position.

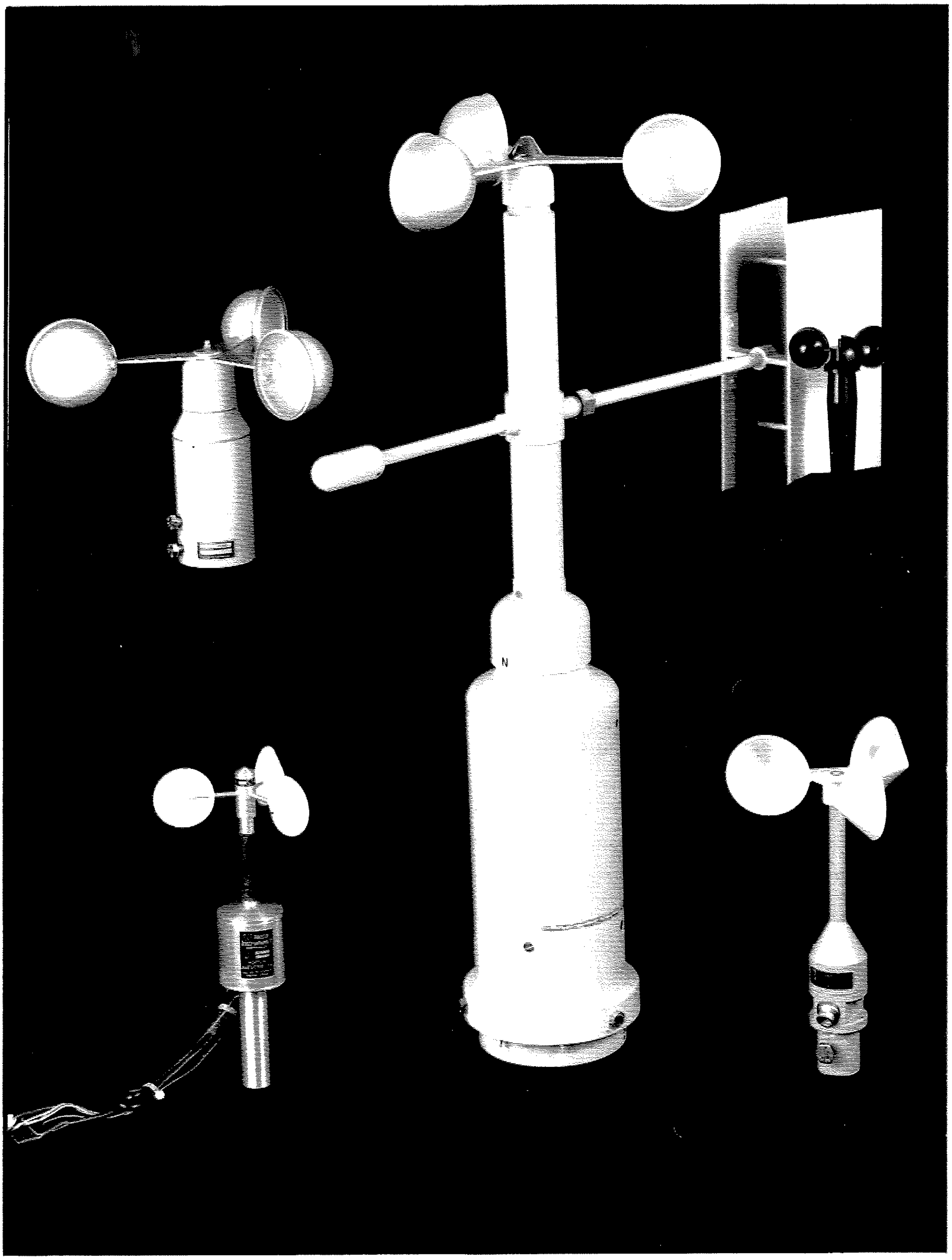


Fig 1 The European Test Station Anemometers

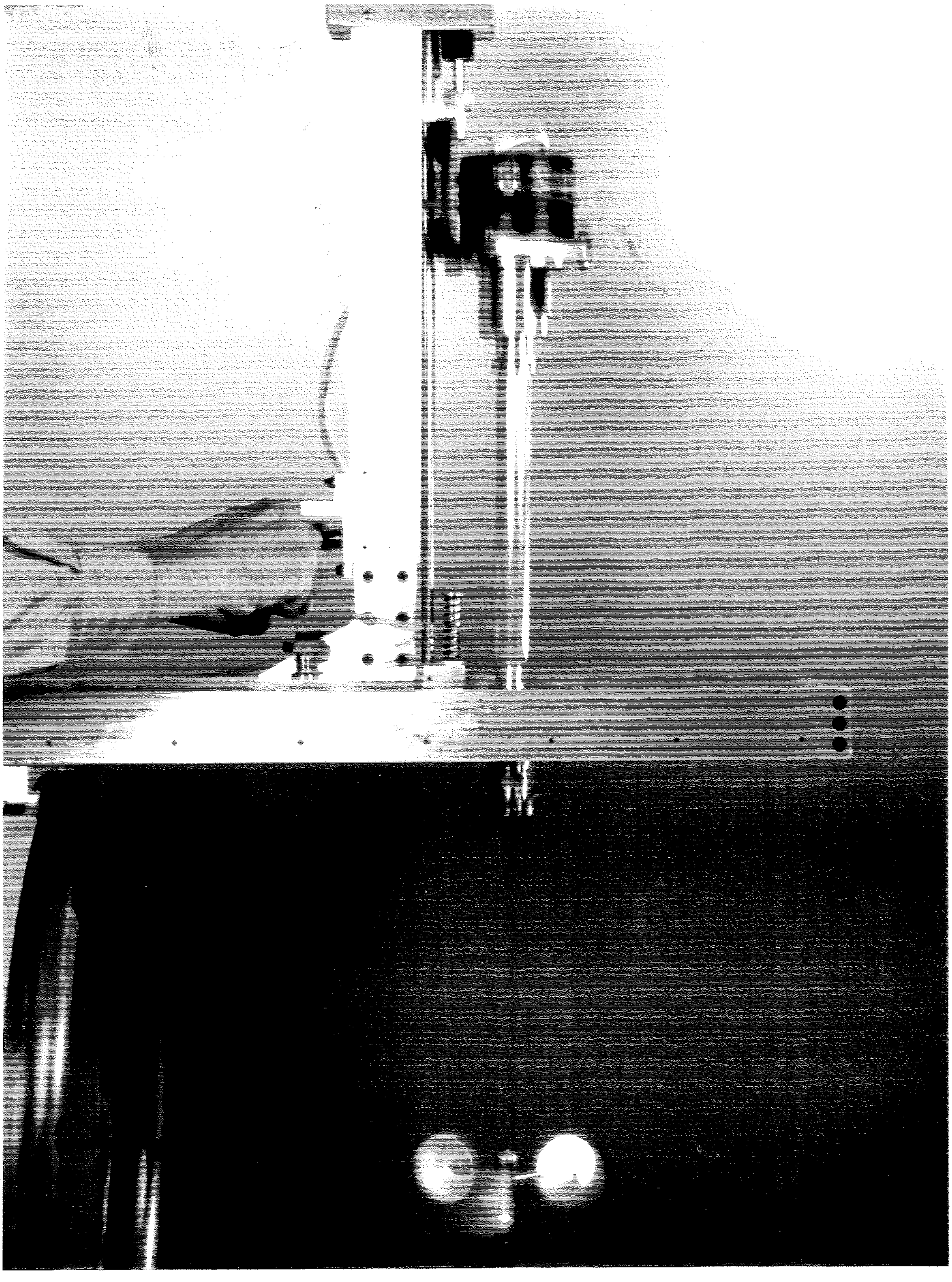


Fig 2 NWTC Retractable Friction Drive Shaft

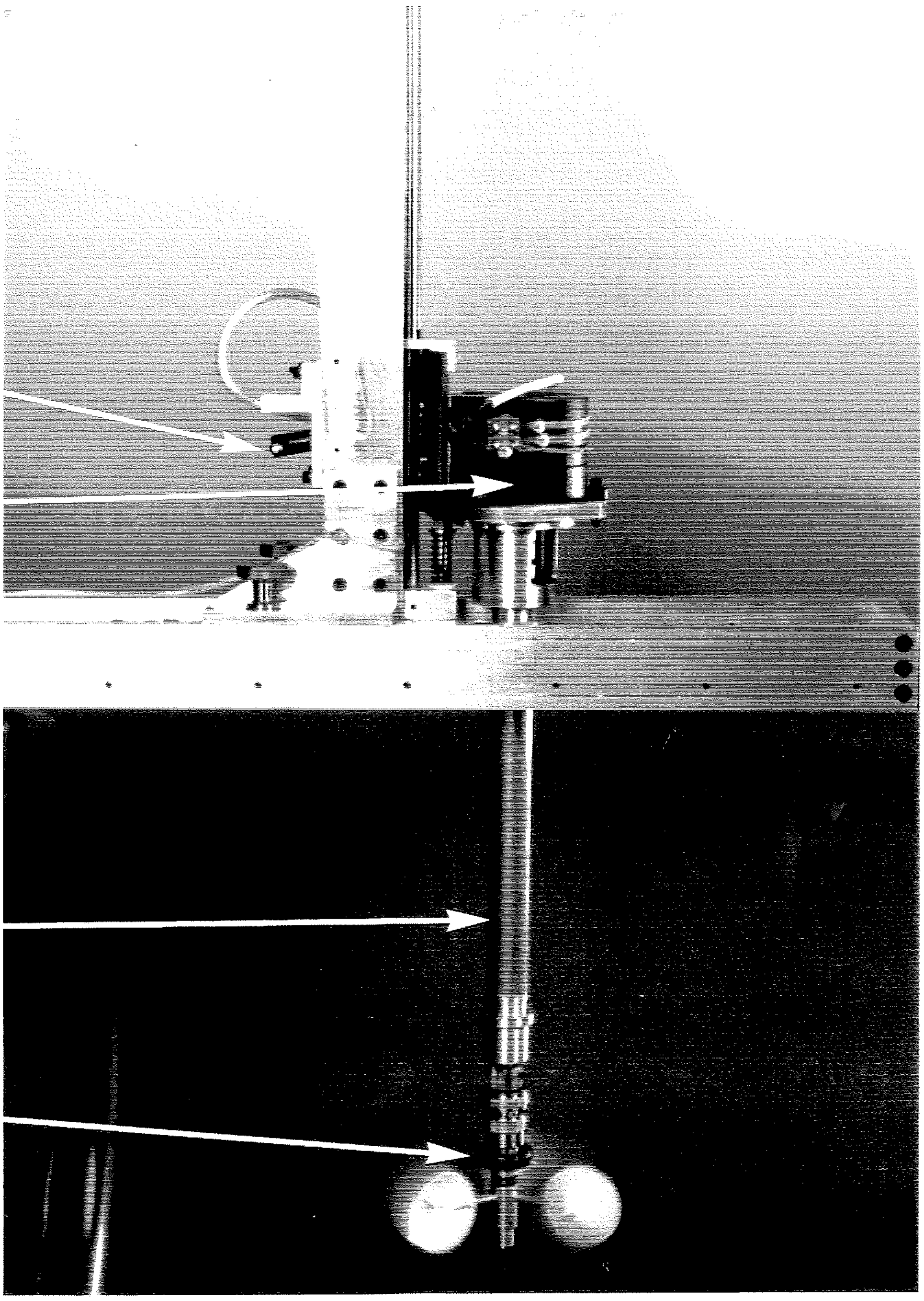


Fig 3 NWTC Retractable Friction Drive Shaft Principal Components

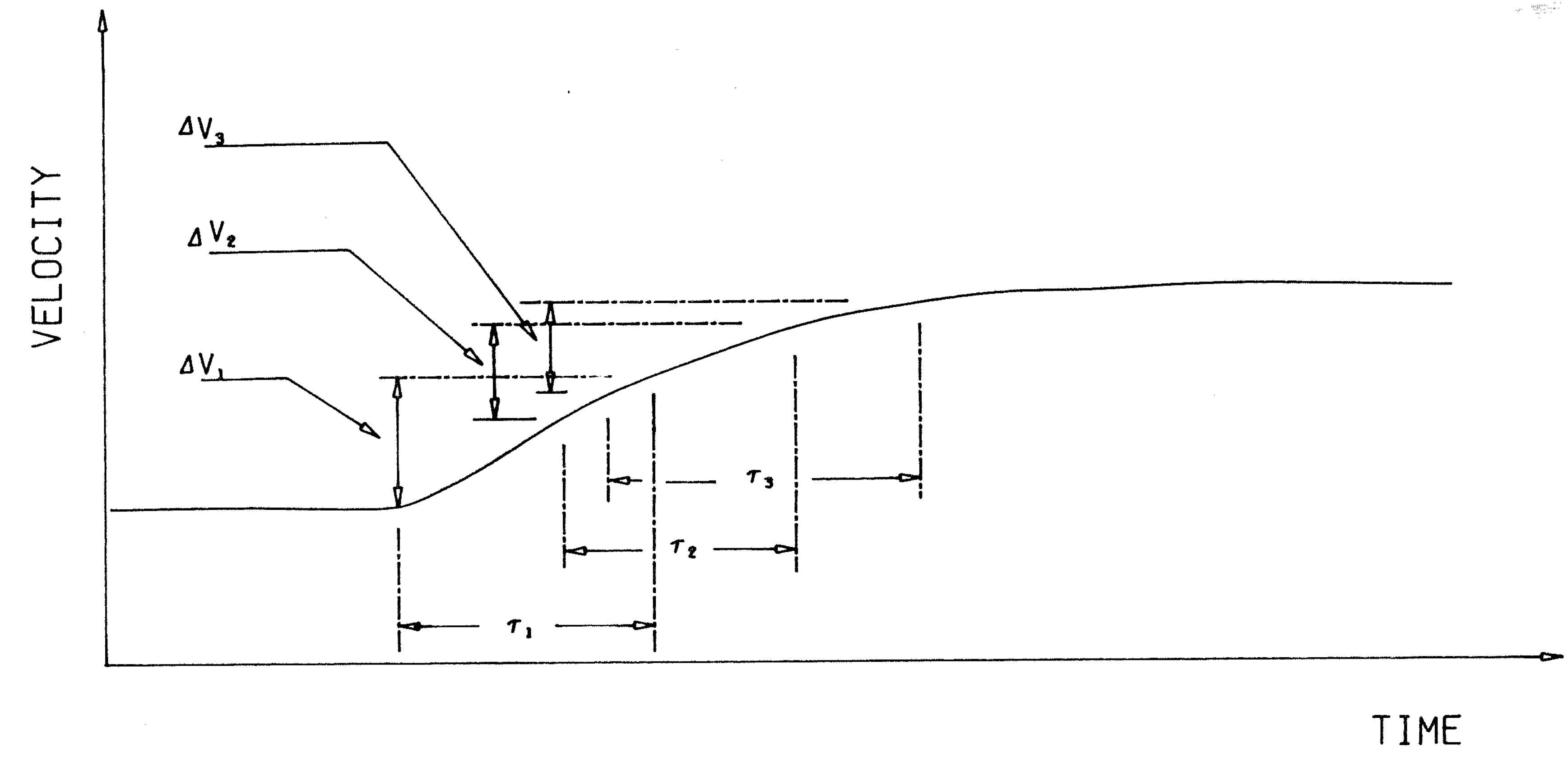
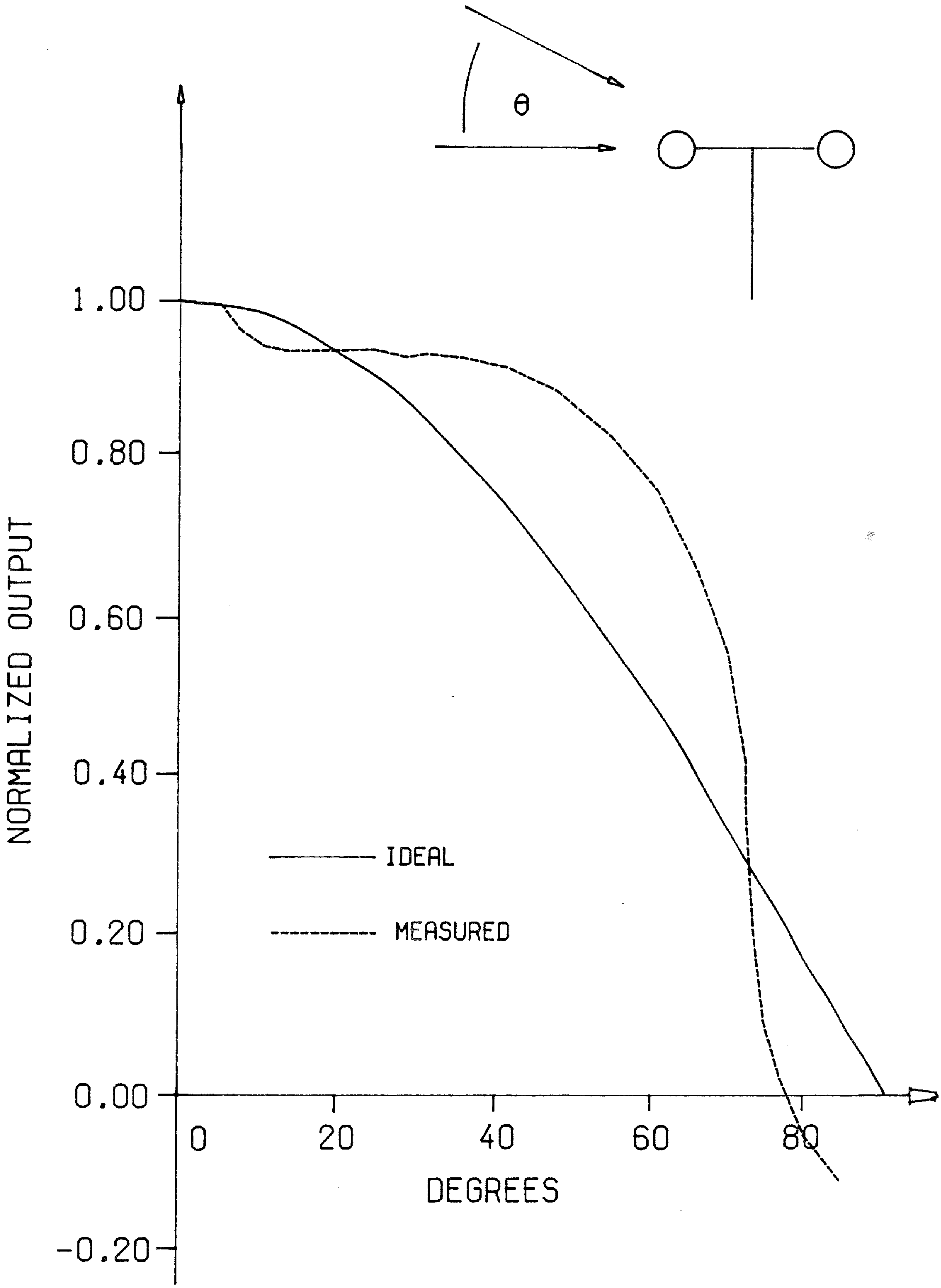


FIGURE 4 VARIATION IN INITIAL SPEED ON A RESPONSE CURVE

FIGURE 5 IDEAL AND MEASURED RESPONSE OF A CUP ANEMOMETER TO ANGLE OF ATTACK



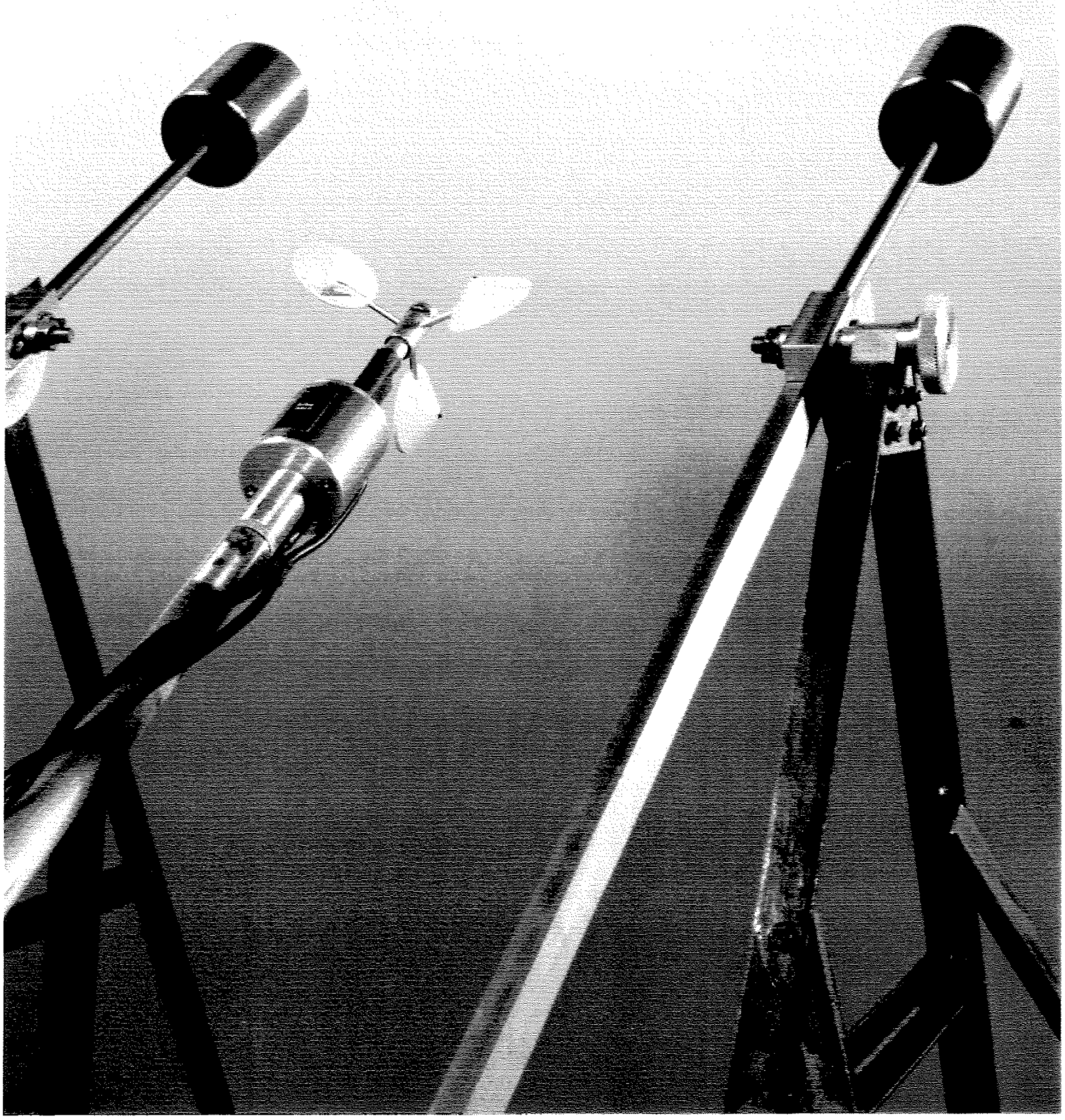


Fig 6 NWTC Anemometer Pitching Rig

FIGURE 7 PERCENTAGE DEVIATION OF MEASURED RESPONSE FROM IDEAL RESPONSE TO ATTACK ANGLE IN THE RANGE 0-70 DEGREES