Chapter 4 Measurement of Surface Wind

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4.1　Definitions and Units

Natural wind in the open air is a three-dimensional vector that has the directions of north, south, east and west in addition to vertical components and magnitude (i.e., wind speed). As the vertical component is ignored for most operational meteorological purposes, surface wind is practically considered as a two-dimensional vector.

Wind blowing over the earth's surface is turbulent, and is characterized by random fluctuations of speed and direction. This can be seen in smoke drifting from a chimney, for example, as it fluctuates from quick to slow and backward, right, left, up and down. This rapid fluctuation is called gusting.

Wind speed is classified into instantaneous and average types. The average wind speed is the average of the instantaneous wind speed over a ten-minute period. As described above, however, wind speed fluctuates continuously, and measured values of instantaneous wind speed are affected by anemometer response characteristics. Defined below are some basic terms and units used in wind measurement, with a focus on those related to response characteristics that affect anemometer performance.

4.1.1　Definitions

1) **Wind passage (L (m))**: The distance that wind (air mass) covers over a given period of time (t).

2) **Instantaneous wind speed (V_i (m/s))**: Wind speeds change very quickly, and the numerical expression for instantaneous wind speed (V_i) at time (t) is expressed as follows:

$$Vi = \lim_{\Delta t \to 0} \frac{\Delta L}{\Delta t} = \frac{dL}{dt}$$

where ΔL is the distance the wind travels from one time (t) to another (t +Δt) (m) and Δt is the short period since the initial time (t) (s). The maximum instantaneous wind speed (peak gust) is the maximum observed instantaneous wind speed over a specified period of time.

3) **Average wind speed (V_m (m/s))**: The numerical expression for the average wind speed (V_m) at time (t), in m/s, is defined as follows:

$$Vm = \int_{t_0}^{t_0+t} Vi \frac{dt}{t} = \frac{L}{t}$$

where L is the distance the wind travels from one time (t_0) to another (t_0 + t) (m), Vi is the instantaneous wind speed (m/s), and t is the measurement period since the initial time (t_0) (s).

4) **Starting threshold speed (V_0 (m/s)):** The lowest wind speed at which a rotating anemometer mounted in its normal position starts to turn continuously.

5) **Response length (L_d (m)):** The distance that an air mass moving through a rotating

anemometer travels in a given time period (time constant) required for the output of an anemometer's sensor to reach 63% of the equilibrium wind speed after a step change. The numerical expression for the response length L_d is defined as follows:

$$L_d = V \times \tau \, (m)$$

where V is the final indicated wind speed and τ is the constant of the instrument.

6) **Critical damping:** The damping actuated when the direction of a wind vane changed stepwise reaches equilibrium with the fastest transient response without overshoot.

7) **Overshoot (θ):** The amplitude of a wind vane's deflection when it oscillates after release from the initial displacement.

8) **Overshoot ratio (Ω):** The ratio of two successive overshoots as expressed by the following equation:

$$\Omega = \theta_{(n+1)} / \theta_n$$

where θ_n and $\theta_{(n+1)}$ are the nth and n + 1th overshoots, respectively.

In practice, since deflections after the first overshoot are usually small, the overshoot ratio is determined by the deflection of the initial release point (n = 0) and the first deflection after release (n = 1)(Figure 4.1).

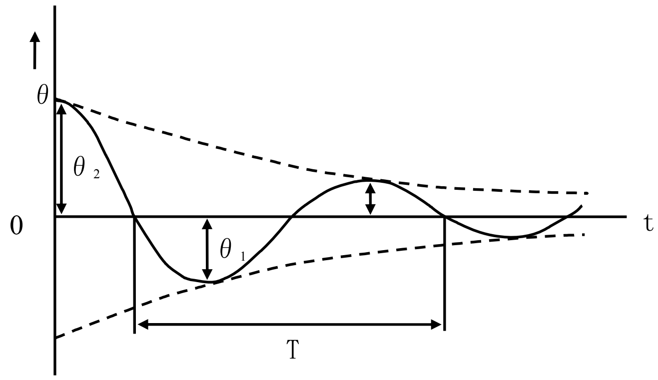


Figure 4.1 Overshoot of damping oscillation

9) **Damping ratio (ξ):** The ratio of actual damping to critical damping as expressed by the following equation:

$$\xi = \frac{\ln(1/\Omega)}{\left(\pi^2 + [\ln(1/\Omega)]^2\right)^{1/2}}$$

where Ω is the overshoot ratio.

WMO recommends a damping ratio in the range of 0.3 to 0.7. Figure 4.2 shows wind vane response according to ξ.

If ξ< 1, underdamping occurs, and if ξ= 0, single harmonic motion with no resistance at all is seen.

If ξ= 1, critical damping occurs.

If ξ> 1, the wind vane does not oscillate; the time until equilibrium is long, and it is sometimes unclear whether equilibrium has been reached. This is called overdamping.

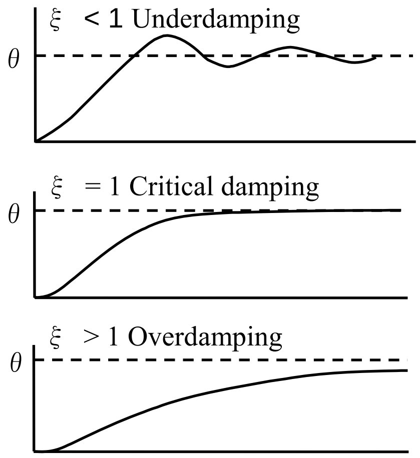


Figure 4.2 Oscillation changes by damping ratio

4.1.2 Units

A number of different units are used to indicate wind speed, including meters per second (m/s), kilometers per hour (km/h), miles per hour (mph), feet per second (ft/s) and knots (kt). In synoptic reports, the average wind speed measured over a period of 10 minutes is reported every 0.5 meters per second (m/s) or in knots (kt). Table 4.1 shows the conversion for these units.

Table 4.1 Speed conversion table

kt	m/s	km/h	mph	ft/s
1.000	0.515	1.853	1.152	1.689
1.943	1.000	3.600	2.237	3.281
0.868	0.447	1.609	1.000	1.467
0.540	0.278	1.000	0.621	0.911
0.592	0.305	1.097	0.682	1.000

Wind is described in terms of the direction from which it blows, and is given as compass-point expressions graduated into 8 or 16 directions clockwise from true north (Figure 4.3).

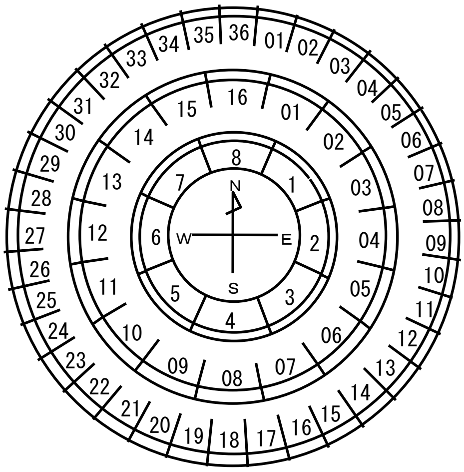


Figure 4.3 Wind-direction scale

In synoptic reports, the average wind direction over 10 minutes is reported in the same way as for wind speed in degrees to the nearest 10 degrees using a code number from 01 to 36. By way of example, 02 means that the wind direction is between 15° and 25°. Wind with an average speed of less than 1 kt is termed calm, and its direction and speed are both reported as “00.”

4.2 Principles of Measuring Instruments

Surface wind is usually measured using a wind vane and a cup or propeller anemometer.

When a measuring instrument malfunctions, or when no such instrument is available, the wind direction and speed may be estimated subjectively.

This section mainly describes the principles of measurement using vanes and rotating anemometers (cup and propeller types) and the response characteristics of these instruments.

4.2.1 Wind Estimation

If a measuring instrument becomes faulty or is not available, wind can be estimated by visual means such as observing smoke as a guide to wind speed and using the Beaufort Scale(Table 4.2).

It is also possible to estimate wind direction by observing the flow of smoke or the movement of a flag. Streamers at airports can also be used when the wind speed is high enough.

When wind is monitored visually, the following points should be noted:

* Stand directly under the indicator to eliminate any perspective-related errors.
* Do not mistake local eddies resulting from the surrounding conditions (buildings, for example) for the general wind direction.
* Do not use the direction of cloud movement as an indicator even if their altitude seems low.

Table 4.2 Beaufort Scale

Beaufort Scale number and description	Wind speed equivalent at a standard height of 10 meters above open flat ground (kt)	(m/s)	(km/h)	(mph)	Specifications for estimating speed over land
0 Calm	< 1	0 – 0.2	< 1	< 1	Calm; smoke rises vertically.
1 Light air	1 – 3	0.3 – 1.5	1 – 5	1 – 3	Direction of wind shown by smoke-drift but not by wind vanes.
2 Light breeze	4 – 6	1.6 – 3.3	6 – 11	4 – 7	Wind felt on face; leaves rustle; ordinary vanes moved by wind.
3 Gentle breeze	7 – 10	3.4 – 5.4	12 – 19	8 – 12	Leaves and small twigs in constant motion; wind extends light flags.
4 Moderate breeze	11 – 16	5.5 – 7.9	20 – 28	13 – 18	Raises dust and loose paper; small branches are moved.
5 Fresh breeze	17 – 21	8.0 – 10.7	29 – 38	19 – 24	Small trees in leaf begin to sway, crested wavelets form on inland waters.
6 Strong breeze	22 – 27	10.8 – 13.8	39 – 49	25 – 31	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.
7 Near gale	28 – 33	13.9 – 17.1	50 – 61	32 – 38	Whole trees in motion; inconvenience felt when walking against the wind.
8 Gale	34 – 40	17.2 – 20.7	62 – 74	39 – 46	Breaks twigs off trees; generally impedes progress.
9 Strong gale	41 – 47	20.8 – 24.4	75 – 88	47 – 54	Slight structural damage occurs (chimney-ports and slates removed).
10 Storm	48 – 55	24.5 – 28.4	89 – 102	55 – 63	Seldom experienced inland; trees uprooted; considerable structural damage occurs.
11 Violent storm	56 – 63	28.5 – 32.6	103 – 117	64 – 72	Very rarely experienced; accompanied by widespread damage.
12 Hurricane	64 and over	32.7 and over	118 and over	73 and over	-

4.2.2 Vanes

Vanes are classified into wind vane and aero vane types. Wind vanes are used alone, while aero vanes are used with a propeller anemometer and a wind direction plate, which looks like the vertical tail part of an airplane.

4.2.2.1 Wind Vanes

A one-vane weathercock is the most basic wind vane; various types of vanes have been developed, as shown in Figure 4.4.

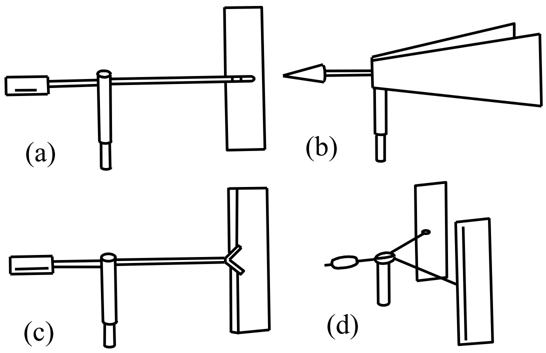


Figure 4.4 Types of wind vane

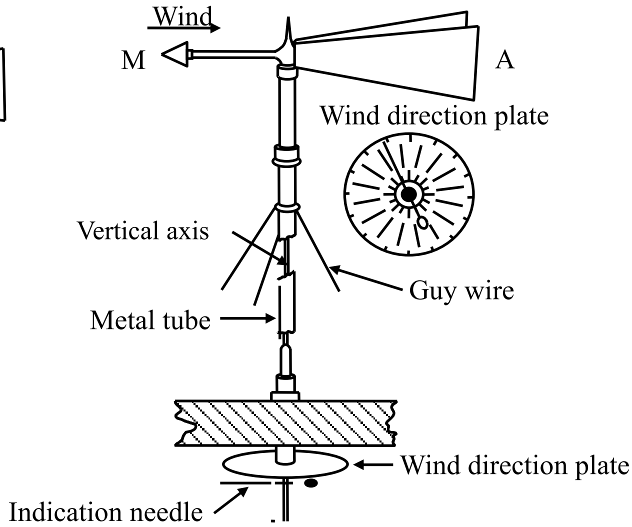


Figure 4.5 Wind vane

In the case of wind vane (b) shown in Figure 4.4, the Y-shaped vane shown in Figure 4.5 is fitted in such a way that the two metal plates A are positioned to form an angle of about 20 degrees. A weight, M, is attached to the top of the vane for balance. A steel pipe passes through the top and is attached to the roof, and the axis is fitted through the steel. To indicate the rotation angle of the vane, a compass is directly mounted on the rotation axis. To enable remote indication of the vane's angle of rotation, a potentiometer or selsyn motor is mounted on the rotation axis.

4.2.2.2 Wind Direction Signal Converters

A wind direction transmitter is a device used to convert the angle of the wind direction axis into an electrical signal. Equipment including a potentiometer, a selsyn motor and an encoder system is used for this purpose. This section describes the principles of vanes using these converters.

[Principles of Vanes with a Potentiometer]

A vane with a potentiometer is designed to generate a voltage proportional to the change in the angle of the potentiometer's sliding contactor mounted in the wind direction.

Figure 4.6 shows a ring potentiometer, which consists of a transmitter and a receiver. The transmitter has three taps, and the receiver consists of a rotor encompassing a permanent magnet and a stator with three 120° coil windings. This rotor has a pointer that indicates the wind direction.

A 12-volt direct voltage is fed to the potentiometer through a sliding contactor that has a pair of contact points directly coupled to the wind direction axis. A current from the position of the sliding contactor (slide rheostats) is applied to the three coils of the stator in the receiver through the three taps of the potentiometer that generates the magnetic field of the stator. A pointer fastened to the rotor indicates the angle proportional to the sliding-contactor position, namely the wind direction.

The three taps of the potentiometer are usually connected to the receiver with cables to enable observation of the wind direction from remote locations.

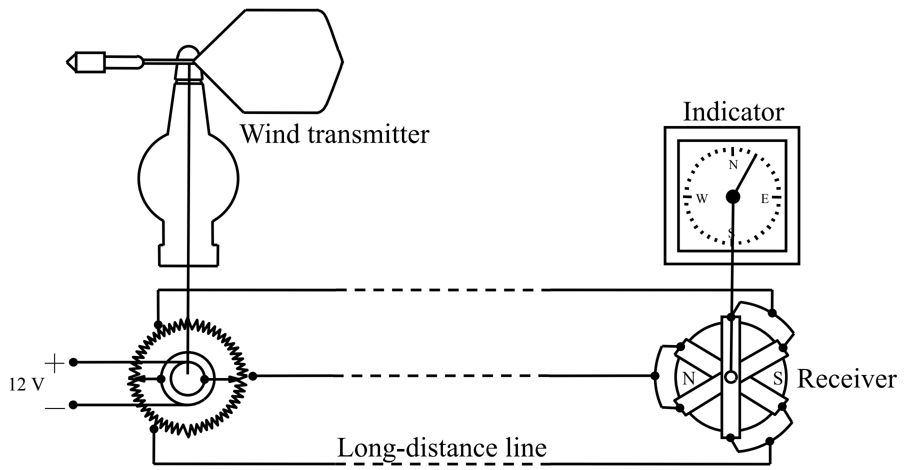


Figure 4.6 Ring-potentiometer assembly

The advantages of this type of indicator are that it is simply designed and can be installed easily as a signal converter. Its disadvantages are that the sliding contactors wear quite rapidly and that the torque of the receiver to move the indicator pointer is small. In addition, the electrical resistance of the cables between the potentiometer and the receiver is greatly affected by the distance between the vane and the indicating device. Large wind-direction errors may also appear if the connection of the three cable leads is not tight.

[Principles of Vanes with a Selsyn Motor System]

These vanes have two selsyn (self-synchronous) motors with the same structure – one mounted on the vane (the transmitter) and the other on an indicating device (the receiver). Torque generated in the motor on the vane in response to changes in the vane's angle of rotation is electrically transmitted to the recorder or indicator so that the wind direction can be ascertained.

Selsyn motors are used to electrically transmit the angle of rotation of the transmitter's axis to the receiver so that the angle of rotation of the receiver's axis can be made to match it. A selsyn motor consists of a stator with three windings set 120 degrees apart and a rotor with a bi-polar winding.

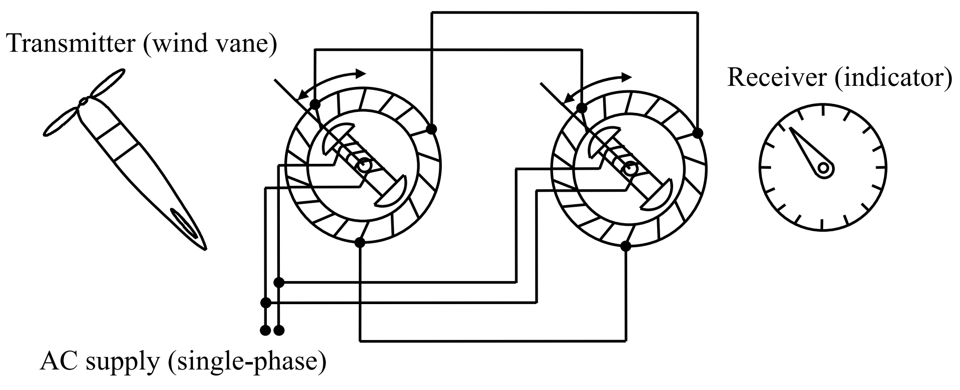


Figure 4.7 Selsyn motor

One selsyn motor is connected to the other as shown in Figure 4.7. If the position of the transmitter's rotor does not correspond to that of the receiver, the voltage induced in each of the transmitter's three windings does not correspond to that in each of the receiver's three windings. A current consequently flows that generates torque to make the receiver's angle follow the transmitter's rotation. The same torque also acts on the transmitter, but the transmitter is restrained by wind pressure. Consequently, the axis of the receiver, which has a very light pointer, rotates until its angle corresponds to that of the transmitter.

The selsyn system is capable of synchronizing the rotation angle of one selsyn motor with that of the other.

[Principles of Vanes with an Optical Pulse Encoder]

As shown in Figure 4.8, an optical pulse encoder consists of a disk featuring a special pattern of concentrically cut slits with light-emitting diodes (light transmitters) and phototransistors (light receivers).

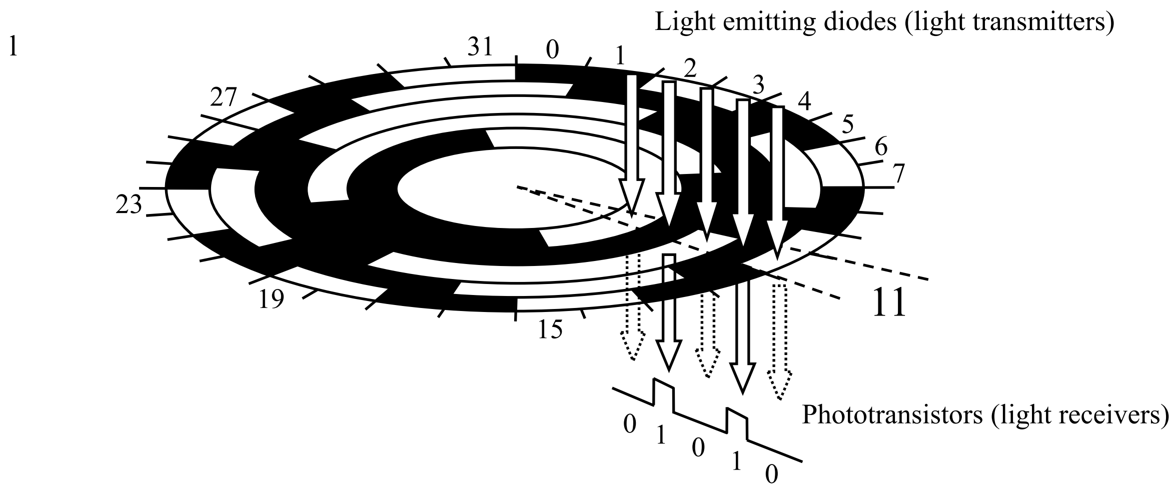


Figure 4.8 Digital angle-encoder disk (5-bit)

The pulse encoder used with the vane is designed to have a specific number of bits that meets the required angle resolution. If the angle is represented with five or eight bits, its resolution is as follows:

$$360° \div 2^5 = 360 / 32 = 11.25°$$
$$360° \div 2^8 = 360 / 256 = 1.4°$$

If a beam of light from a light transmitter passes through the circular disk and reaches the light receiver, a signal of "1" is output. If the beam is reflected by the disk and does not reach the receiver, a signal of "0" is output. The principle of wind direction measurement with a five-bit encoder is shown in Figure 4.8. When the beams of light pass through the disk in the manner shown, a signal of 01010 is generated. The 11th segment shown in the figure corresponds to an angle between 11th ×11.25° and 12th ×11.25°, namely between 123.75° and 135.00°.

Optical pulse encoders have two advantages: they are free of mechanical friction because they have no contacting parts, and superior response characteristics can be achieved by making the unit small and lightweight. In addition, they are suitable for data processing with a computer because the output can be processed as digital signals.

4.2.2.3 Vane Response Characteristics

Propeller anemometers and wind vanes cannot respond to rapid changes in wind direction. Delayed response to such changes significantly affects errors in wind speed observation, especially with propeller anemometers.

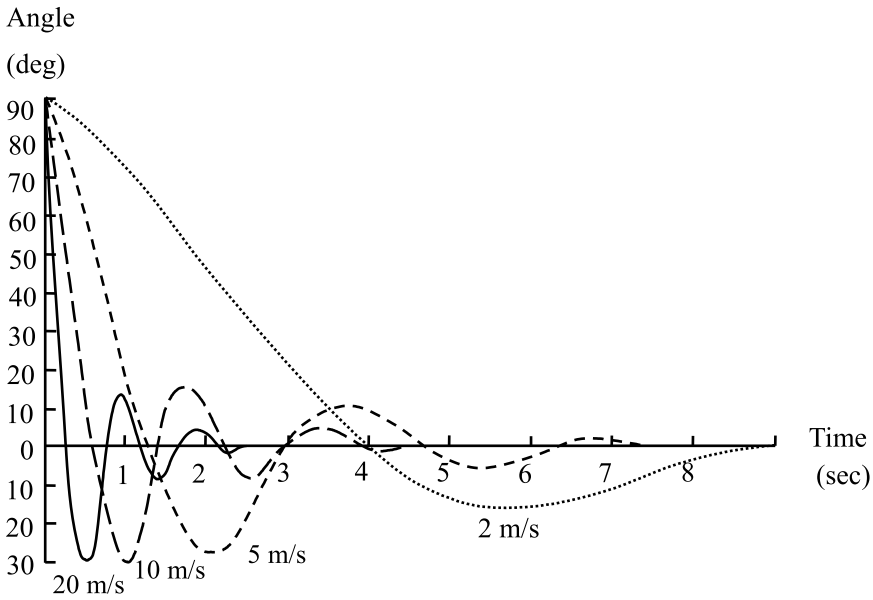


Figure 4.9 Wind-vane response characteristics

Figure 4.9 shows the response characteristics of a propeller anemometer upon exposure to wind speeds of 2, 5, 10 and 20 m/s in a wind tunnel when the propeller axis is oriented at 90° away from the air flow at a constant speed and released. The way it gradually changed direction with oscillation and faced the wind flow directly was observed. As is apparent from the figure, the higher the wind speed, the more quickly the propeller axis faced the airflow directly.

If the wind direction changes within the time the propeller axis takes to face the wind direction directly, the response will be delayed and wind speed cannot be measured accurately. A high-performance propeller anemometer should reduce its amplitude quickly and have a short oscillation period.

4.2.3 Rotating Anemometers

There are two types of rotating anemometer: the cup anemometer, which has three or four cup wheels attached to the rotating axis, and the propeller anemometer, which has propeller blades. Both types rely on the principle that the revolution speed of the cup or propeller rotor is proportional to the wind speed.

Rotating anemometers can be classified as the generator type or the pulse generator type according to the type of signal generator used. The generator type is a kind of wind power generator whose cup or propeller axis is directly coupled to the axis of a generator that generates voltage from their rotation. As the generated voltage is proportional to the revolution speed of the cup or propeller rotor and thus to the wind speed, the wind speed can be measured. The two types of generator are the AC (alternating current) and the DC (direct current) kinds. As a DC generator requires a commutator (i.e., a collector and brushes) and has a more complicated structure than an AC generator, the AC generator type is widely used.

Rotating anemometers with a pulse generator come in several different types, including one that generates electrical pulse signals using an electrical contact-breaker and one that generates optical pulses using an optical light-chopper converter. The latter consists of a light-emitting diode, a perforated disk fixed to the axis of the rotation sensor and a phototransistor. The number of pulses, which is proportional to the number of anemometer revolutions (and thus to the wind speed) is counted to ascertain the wind speed.

These anemometers measure instantaneous wind speed. The average wind speed is obtained using either the pulse-of-wind-passage method or with a CR integrated circuit (a combination of capacitors and resistors), or alternatively with a microprocessor. These measurement principles are explained in the following sections.

4.2.3.1 Cup Anemometers

A cup anemometer has three or four cups mounted symmetrically around a freewheeling vertical axis. The difference in the wind pressure between the concave side and the convex side of the cup causes it to turn in the direction from the convex side to the concave side of next cup. The revolution speed is proportional to the wind speed irrespective of wind direction. Wind speed signals are generated with either a generator or a pulse generator.

A cup anemometer has three or four cups mounted symmetrically around a freewheeling vertical axis. The difference in the wind pressure between the concave side and the convex side of the cup causes it to turn in the direction from the convex side to the concave side of next cup. The revolution speed is proportional to the wind speed irrespective of wind direction. Wind speed signals are generated with either a generator or a pulse generator.

The cups were conventionally made of brass for its qualities of rigidity and rust resistance. In recent years, however, cups made of light alloy or carbon fiber thermo-plastic have become the mainstream, allowing significant reductions in weight. Beads are set at the edges of the cups to add rigidity and deformation resistance. They also help the cup to avoid the effects of turbulence, allowing the stable measurement of a wide range of wind speeds.

[Principles of Wind Speed Measurement]

1) Generator-type Cup Anemometers

This type has a small AC generator coupled to its axis. The wind turns the cups and the generator to generate a voltage proportional to the instantaneous wind speed, and the signal is transmitted to the indicator(Figure 4.10). The CR integrated circuit calculates the average wind speed as the circuit charges and discharges the capacitor over a certain period. This type of anemometer is located in an exposed position on a tower and is connected to an indicator through cables, and observation from remote locations is possible. The greatest distance between the anemometer and the indicator depends on the electrical resistance of the cable and the design (a model allows a maximum distance of 1,500 m). This type of anemometer does not require a power supply for the main unit, but the counter takes 3-volt dry-cell batteries (Figure 4.11).

Recent models are equipped with an A/D (analog to digital) converter to allow computer processing of data tasks.

The generator-type cup anemometer generates wind speed signals by itself, and can be used without an electrical supply.

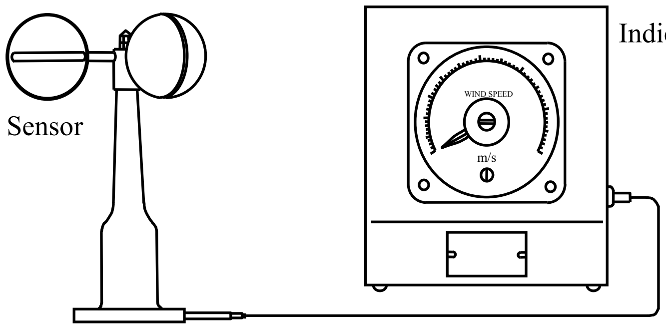


Figure 4.10 Generator-type cup anemometer

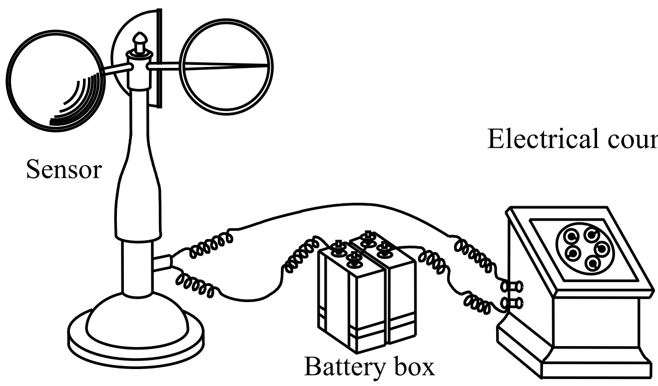


Figure 4.11 Connection of lead cables

2) Pulse Generator-type Cup Anemometers

A pulse generator-type cup anemometer counts the number of cup-wheel rotations, which is proportional to the wind passage. The number of rotations in a particular period (such as ten minutes) is counted, and the wind passage is obtained by multiplying the factor specified for the anemometer (e.g., 54 rotations for a wind passage of 100 m) by this number. The wind speed is obtained by dividing the wind passage by the number of time units in this period.

The optical pulse generator type is mainly used now, having replaced the electrical contact breaker type. An optical pulse generator consists of a perforated disk (called a chopper disk) directly fixed to the rotating axis of the cup wheel and a photocoupler. As the cup wheel rotates, the chopper disk turns and either allows the passage of or interrupts a beam of light between the light transmitter and the light receiver of the photocoupler, creating pulse signals with a frequency proportional to wind speed. After P/A (pulse-analog) conversion, a DC voltage proportional to the number of pulses in a specific period is generated. This voltage is then converted to give an instantaneous wind speed. Some cup anemometers with a pulse generator digitize signals and indicate the instantaneous wind speed with a microprocessor.

A CR integrated circuit or a microprocessor are used to obtain the average wind speed. For details of these methods, refer to the next section regarding pulse generator-type propellers.

The chopper disk and photocoupler of a pulse generator-type cup anemometer can be made small. The weight of a pulse generator-type cup anemometer can be less than that of the generator in a generator-type cup anemometer, allowing improved starting threshold speed and response characteristics.

3) Mechanical-type Cup Anemometers

A much simpler method for measurement of wind speed using a cup anemometer is to count the number of cup revolutions. A mechanical-type cup anemometer indicates the number of cup rotations through gears connected to the sensor axis. Specifically, the increment (wind passage) of indication over a period of ten minutes before the observation is read and the average wind speed are obtained by dividing the wind passage by 10 minutes (600 seconds) (Figure 4.12).

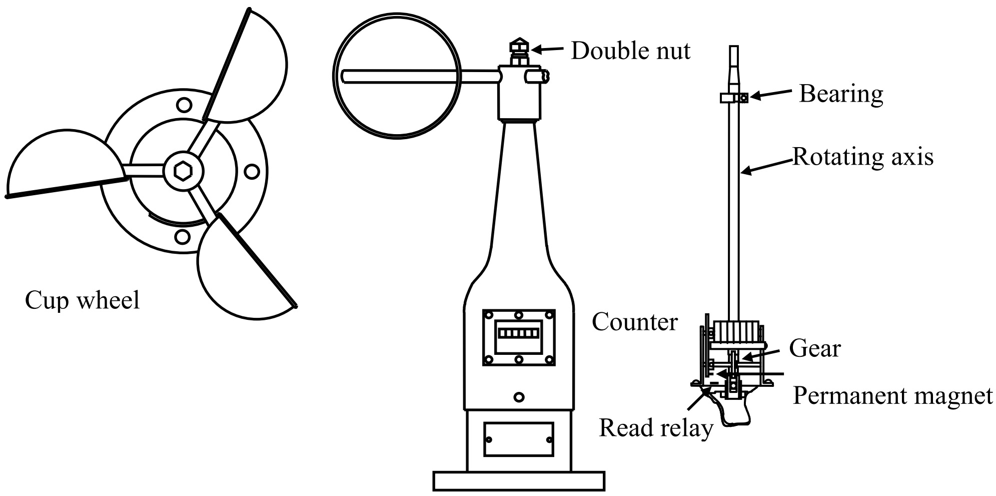


Figure 4.12 Three-cup-wheel wind-path anemometer

This type of anemometer has a number of advantages: it does not require a power supply, its structure is simple, and it remains relatively problem-free. However, its body is connected to the counter, and it is necessary to go outdoors to read the counter for each instance of observation. A type of anemometer with a reed-relay directly connected to the counter is available to eliminate the need to go outside to obtain readings, as the generated contact signals are counted with an electric counter indoors. In such cases, a DC 3V power supply is required for the electric counter.

4.2.3.2 Propeller Anemometers

A propeller anemometer has a sensor with a streamlined body and a vertical tail to detect wind direction and a sensor in the form of a propeller to measure wind speed integrated into a single structure. It measures wind direction and wind speed, and can indicate/record the instantaneous wind direction and wind speed in remote locations. It also measures the average wind speed using wind-passage contacts or by calculating the number of optical pulses. This type is used as the standard anemometer of the Japan Meteorological Agency (JMA).

There are generator-type and optical pulse generator-type propeller anemometers. At present, the optical pulse generator type is mainly used because its contact resistance is small over a wide range of wind speeds from weak to strong, and its measurement system can be made small and lightweight. Some anemometers are capable of measuring wind speeds from 0.4 to 90 m/s.

[Principles of Wind Speed Measurement]

1) Generator-type Propeller Anemometers

Figure 4.13 shows the main part of a generator-type propeller anemometer's transmitter sensor. It includes a propeller that reacts to wind pressure and turns at a rate corresponding to the wind speed, an AC generator, a tail assembly and a selsyn motor to generate wind direction signals.

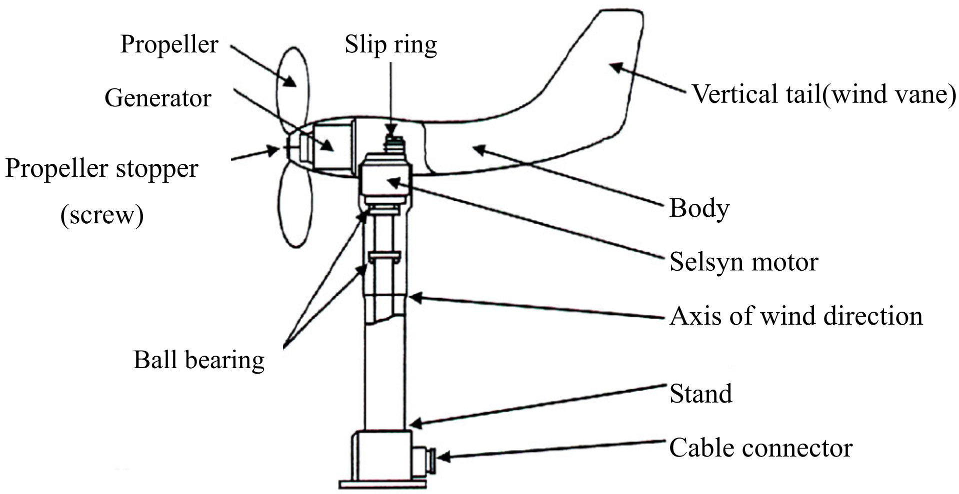


Figure 4.13 Generator-type propeller anemometer

To detect the wind direction and measure the wind speed accurately, the tail assembly of a propeller anemometer is designed so that the propeller always faces the wind. An AC generator connected to the propeller shaft generates induced voltages proportional to the wind speed. As shown in Figure 4.14, these AC voltage signals are rectified to a DC voltage and output as an analogue voltage signal proportional to the wind speed. The analogue voltage signal is transmitted to a wind speed indicator or a recorder in which a voltmeter is assembled, and the instantaneous wind speed is ascertained.

There is another type of propeller anemometer that uses a different method. As the propeller shaft undergoes a certain number of revolutions for a wind passage of 60 m or 100 m, for example, worm gears (i.e., a gear-reducing mechanism) coupled to the axis of the generator rotate the reduced gear once; a microswitch linked to the reduced gear generates electrical pulses, which are then counted to calculate the average wind speed over a ten-minute time period. This is a combination of the generator type and the pulse generator type.

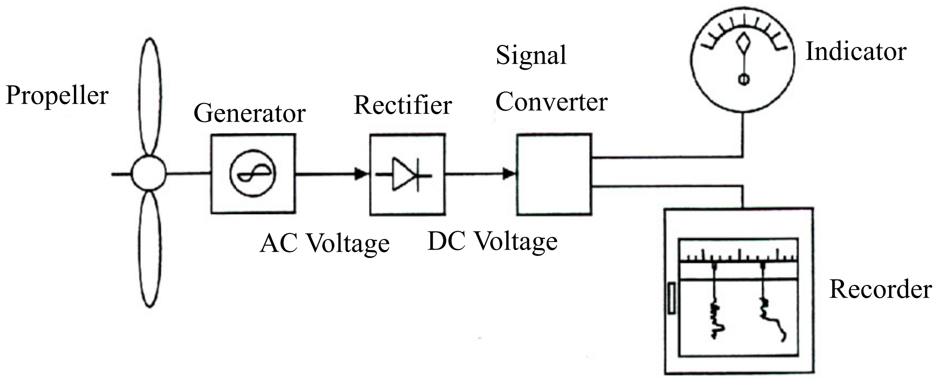


Figure 4.14 Diagram of signal flow

This type of anemometer, called a wind-passage propeller anemometer, ascertains wind speed by dividing the wind passage by the number of time units in a certain period. It is advantageous in that that the average wind speed can be measured even in very weak wind conditions when the propeller rotates only intermittently and it is difficult to obtain the average wind speed from the instantaneous wind speed.

Wind speed signals are output through the slip rings, the brushes and the terminal at the bottom of the stand. These slip rings send electrical signals from the rotor through the brushes. If there is a contact fault between the slip rings and the brushes due to contamination or wear, pulse-shaped noises will occur and the wind speed measurement may have errors. Extra care must therefore be taken with maintenance for the slip rings and brushes.

2) Pulse Generator-type Propeller Anemometers

A pulse generator-type propeller anemometer basically has the same external appearance as a generator-type propeller anemometer. The optical pulse generator type generates voltage pulses using a chopper disk that is directly coupled to the propeller shaft and a photocoupler.

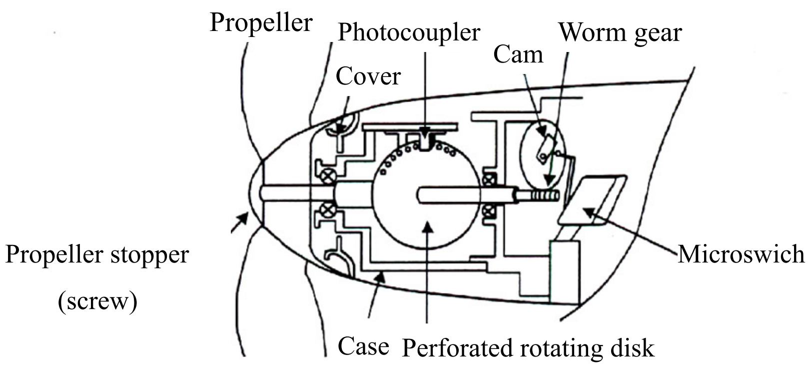


Figure 4.15 Pulse generator-type propeller anemometer

As shown in Figure 4.15, the wind speed sensor consists of a chopper disk and a photocoupler (i.e., a semiconductor device to convert light to electrical signals). It is essentially a light-emitting diode and a phototransistor situated facing each other, placed inside a mold and sealed.

The chopper disk is positioned so as to interrupt the optical axis of the photocoupler. A number of holes are made along the periphery of the disk so that it allows the passage of or interrupts a beam of light between the emitting and receiving devices of the photocoupler. When the phototransistor receives the beam of light, a voltage pulse is generated. The number of pulses for each unit time depends on the number of holes (24, 48, 60, etc., per revolution), and a number of pulse signals proportional to the wind speed is output. These pulse signals are sampled every 0.25 seconds, and the average value of the samples over a 3-second period (12 samples) is taken as the instantaneous wind speed.

The average wind speed over a ten-minute period is obtained using the wind-passage method or the CR integrated-circuit method of calculating generated pulses in real time with a microprocessor. In the case of the method with the microprocessor, pulse signals sampled every 0.25 seconds are processed to obtain the average value over a 1-minute period (20 instantaneous values are sampled), and this value is further averaged to obtain an overlapping average for a 10-minute period.

As the pulse signals output from the optical pulse generator type are digital, they are suitable for computer processing. They are converted to DC analogue signals using a D/A converter for indication or recording on analogue devices.

Another method of signal transmission is to use optical fibers to transmit pulse signals. A beam of light is emitted onto the chopper disk, and the optical pulses chopped by it are directly transmitted to the converter and the recorder through optical fiber. This method uses the same principle of wind-speed signal generation as the pulse generator type; the difference is in how the generated signals are transmitted.

[Comparison between the generator and pulse generator types]

The pulse generator type has the advantage of a lower starting threshold speed than the generator type. This stems from the fact that the weight of the chopper disk and other parts directly connected to the propeller shaft of the former can be made lighter than those of the latter type. By way of example, the starting threshold speed of the former type can be as low as about 0.5 m/s, while that of the latter type is about 1 m/s.

The overall weight of the propeller shaft in the pulse generator type can be made light, and consequently the moment of inertia becomes small. This makes it superior to the generator type in terms of its response to wind speed.

Furthermore, in the case of the generator type, the resistance of the signal cable may cause measurement errors because an AC current is carried from the anemometer to the indicator/recorder. The measurement accuracy of the pulse generator type, however, is not affected as long as a pulse frequency is detected. This applies even when the pulse amplitude becomes small due to the resistance of the signal cable.

While both the generator type and the pulse generator type use a generator, signal cables and electrical circuits (all of which are electrical conductors), another pulse generator type uses optical fiber, which does not conduct electricity. This type is resistant to lightning, and is suited for use in areas that need to be explosion-proof such as high-voltage substations and petroleum industrial complexes.

4.2.3.3 Response Characteristics of Rotating Anemometers

The response characteristics of an anemometer are determined by its starting threshold and its damping oscillation properties. An anemometer that immediately starts to rotate when the wind starts blowing and immediately halts when the wind stops is said to have good response characteristics. In the case of rotating anemometers, however, the mechanism does not allow the frictional force of the rotating axis to be reduced and the moment of inertia cannot be zero; accordingly, delayed response to changes in wind speed occurs. This delay is a source of errors in wind speed measurement.

The response characteristics differ between cases when the wind speed increases and when it decreases; for increases, the response time is shorter than for decreases. Graph 1 in Figure 4.16 shows the response when the wind speed suddenly increases from V_1 to V_2. There is a delay of t_1 in Curve ① until the indication reaches the level of V_2, while Curve ② indicates a delay of t_2. If the wind speed suddenly decreases from V_2 to V_1 as shown in Graph 2, the rotating axis does not stop immediately because of the moment of inertia and the dynamic friction of the rotating axis. As a result, delays of t_3 and t_4 occur. In both graphs 1 and 2, the response characteristics of Curve ① are better than those of Curve ②. The curves in Graph 1 are called acceleration curves, and those in Graph 2 are called deceleration curves.

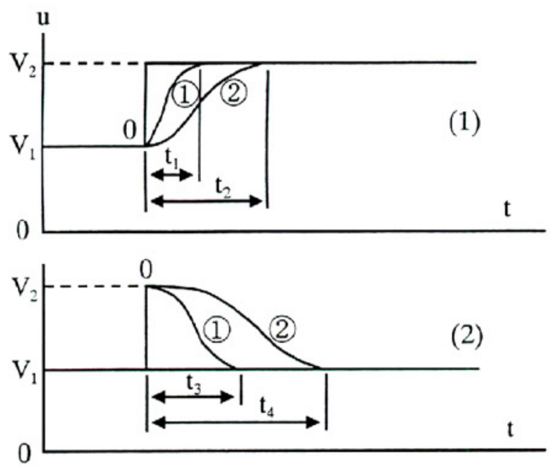


Figure 4.16 Acceleration and deceleration curves

A rotating anemometer has response characteristics such as t_1 (or t_2) < t_3 (or t_4) in the acceleration and deceleration curves shown in Figure 4.16. As its response is faster when the wind speed increases than when it decreases, the average wind speed it measures is a little higher than the true average.

The response characteristics of anemometers examined in a wind tunnel are shown in Figure 4.17, in which the solid lines show acceleration curves and the broken lines show deceleration curves at 5 m/s, 10m/s and 20 m/s, respectively. τ_1 and τ_2 are the time constants for each wind speed when the speed increases and decreases, respectively. As described above, τ_1 is generally smaller then τ_2. Provided that the wind speed is v and the time delay coefficient is the time constant τ, the value ($v \times \tau$) remains almost constant, and is termed the response length. As the time constant of a rotating anemometer varies with the wind speed and whether it increases or decreases, the response characteristics cannot be evaluated from the time constant alone. Accordingly, the response length is used as a measure to determine these characteristics. The smaller the response length, the better the response characteristics of the anemometer.

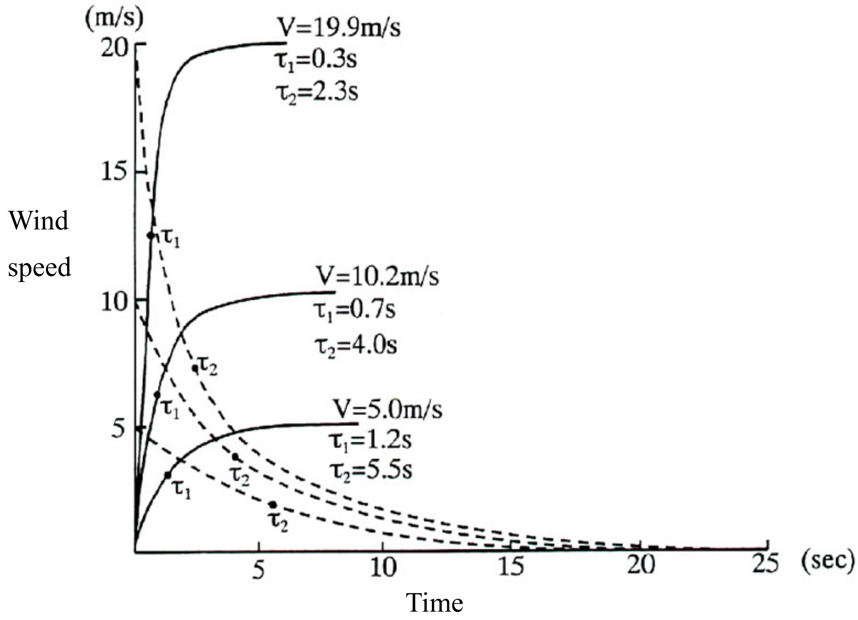


Figure 4.17 Anemometer response characteristics

4.2.3.4 Off-axis Response Characteristics of Rotating Anemometers

In wind speed measurement, it is assumed that the anemometer is exposed in a flat, open location and that it measures horizontal wind. This section describes the off-axis response characteristics of propeller and cup anemometers in relation to an exposed place with changes in the wind direction.

Figure 4.18 shows the off-axis response characteristics of propeller and cup anemometers examined in a wind tunnel. The vertical axis shows the ratio of measured speed when an anemometer is set laterally to the value at its normal position to the wind; the ratio is 1 when it is positioned facing the wind flow directly (i.e., when the angle is zero). The solid line shows the propeller anemometer’s off-axis response, and the dotted line shows that of the cup anemometer.

When an updraft or a downdraft (oblique flow) blows against the cup anemometer, vertical velocity fluctuations can cause overspeeding of the equipment as a result of reduced cup interference from the oblique flow. It is reported that the total overspeed can be as much as 10 per cent with some designs and wind conditions (cup anemometers at a height of 10 m with a response length of 5 m over very rough terrain).

On the other hand, when a propeller anemometer is exposed in oblique flow, the vane does not respond to the vertical component of wind. The indicated wind speed therefore decreases in proportion to the cosine of the oblique flow's angle. When observations are made with a propeller anemometer in oblique winds, only their horizontal component is measured. Accordingly, a propeller anemometer has virtually no vertical-component overspeed.

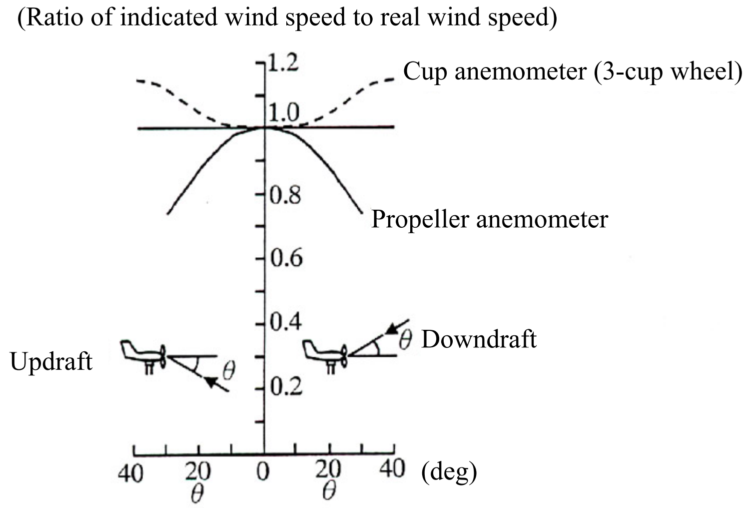


Figure 4.18 Off-axis response

4.2.4 Other Anemometers

In addition to the rotating anemometers (propeller and cup anemometers) described in the previous sections, there are other types that use different measurement methods, principles and ranges of wind speed. Figure 4.19 shows some examples, including the wind pressure anemometer and the sonic anemometer. This section gives an outline of the measurement principles and features of these devices.

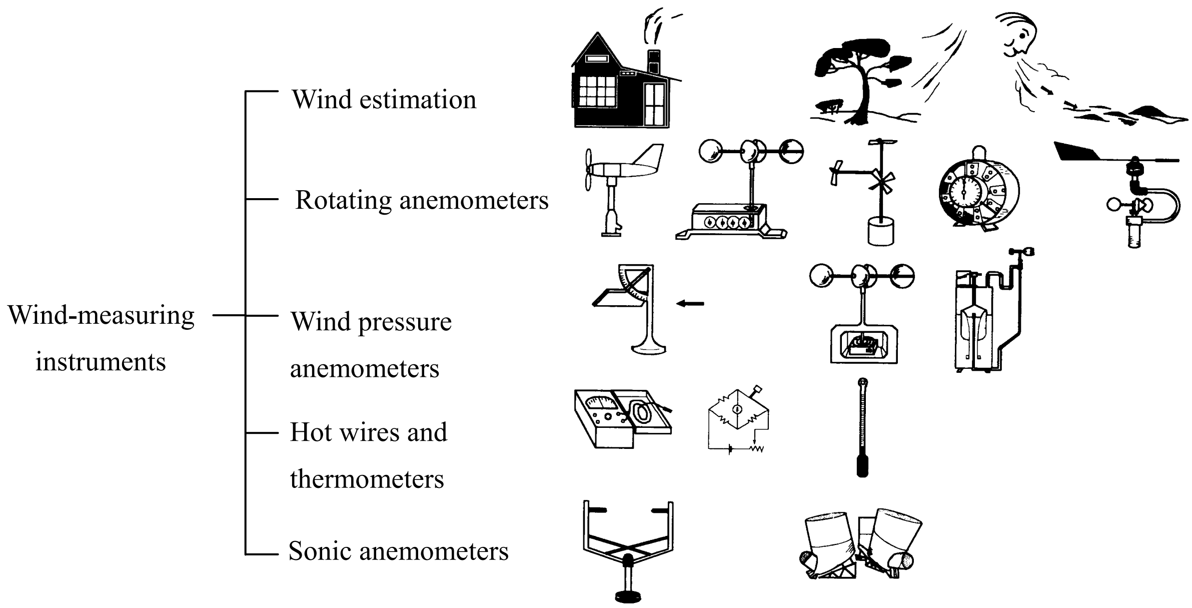


Figure 4.19 Wind-measuring instruments

4.2.4.1 Method Using Wind Pressure Measurement

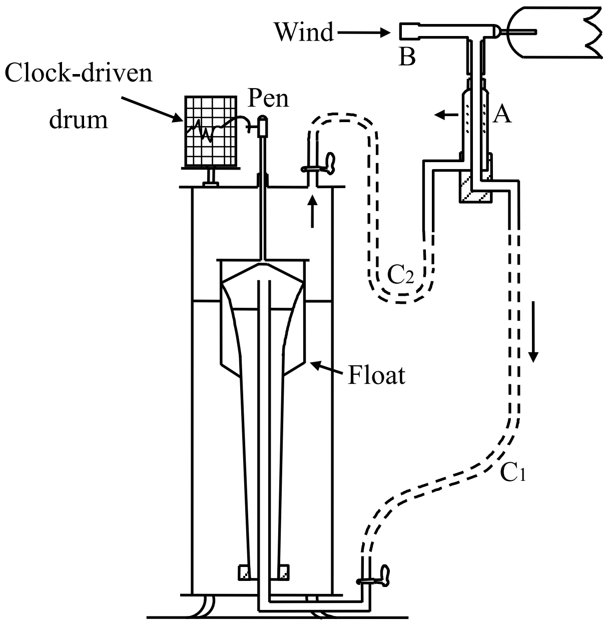
(1) Dines Anemographs

A Dines anemograph measures wind pressure to ascertain instantaneous wind speed. A single-plate vane is fixed to a pitot tube to allow its sensor to face the wind directly at all times as shown in Figure 4.20. There is an inlet hole B at the end of the pitot tube to measure dynamic pressure and a row of small holes A along the periphery of the tube at equal intervals to measure static pressure. The pressure values at B (dynamic pressure) and A (static pressure) caused by wind are induced through two pipes C_1 and C_2 into the inside and outside of a uniquely shaped float in a column of water. The upward and downward movement of the float is recorded on a clock-driven drum to represent instantaneous wind speeds.

This instrument has poor response to very weak wind conditions and rapid wind fluctuations. Additionally, because the difference between dynamic and static pressure is affected by air density, it is necessary to compensate changes in temperature. It is also necessary to prevent the water from freezing and exclude vibration to ensure that the float functions as intended in the water.

Measurement range: 0 to 60 m/s

Measurement accuracy: ±0.5 m/s



A: static pressure

B: dynamic pressure

C_1: dynamic-pressure tube

C_2: static-pressure tube

Figure 4.20
Dines (pressure-tube) anemograph

4.2.4.2 Method Using Heat Radiation

(1) Hot-wire Anemometers/Thermistor Anemometers

A hot-wire anemometer measures wind speed based on the theory that when a hot metal wire is exposed to wind and then cooled, its electrical resistance changes (Figure 4.21). Platinum wire is generally the type used for this purpose. As these anemometers have a small sensor part, they are suitable for wind speed measurement in confined environments.

This type of anemometer has a bridge circuit with a hot wire (the sensor) fitted on one side of the bridge. As wind blows against it, its temperature decreases and its electrical resistance changes; this creates an imbalance in the bridge and causes an electrical current to flow. The relationship between the current and the wind speed is predefined, and the current is converted to a wind speed value.

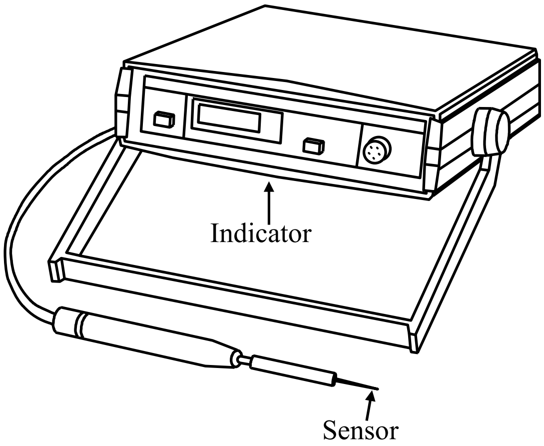


Figure 4.21 Thermistor anemometer

Another type of hot-wire anemometer that uses a thermistor device rather than a platinum wire has recently been introduced. The advantage of this new type is that it features superior sensitivity and response characteristics even in weak-wind conditions. However, if rain, snow or mist touch the sensor, large measurement errors may arise; it is therefore not suitable for outdoor use and cannot be used as a meteorological measuring instrument.

Measurement range: 0 to 1 m/s, 0 to 10 m/s, 0 to 50 m/s and various other ranges

Measurement accuracy: ±2% to ±3% in each respective measurement range

4.2.4.3 Method Using Sound Propagation

(1) Sonic Anemometers

Ultrasonic waves of more than 20 kHz that are inaudible to humans propagate at a speed of about 340 m/s in wind-free conditions. Sonic speed changes slightly in wind; sound waves propagate at a higher (lower) speed in the same (opposite) direction as its movement. A sonic anemometer leverages this relationship between wind and sound-wave propagation (Figure 4.22).

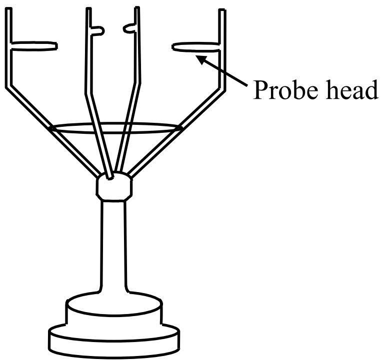


Figure 4.22
Sonic anemometer

A sonic anemometer has two pairs of sonic transmitting/receiving devices (heads) fixed facing each other across a specified span. Ultrasonic wave pulse signals are repeatedly emitted alternately from each pair of heads at certain time intervals. The propagation times of the ultrasonic pulses in opposite directions are measured; the wind speed is calculated in each direction, and the wind direction and speed are derived through vector synthesis. As the speed of sound in air depends on the temperature, measuring techniques have been developed to minimize this influence.

Because sonic anemometers have no moving parts to be actuated by wind force, the concept of a starting threshold speed is not applicable; such devices provide wind speed measurement from calm conditions upward. They also respond much more quickly to changes in wind direction and speed than rotating anemometers.

Measurement range: 0 to 60 m/s

Measurement accuracy: ±0.2 m/s

(2)SODAR (Sound Detection and Ranging)

The pitch of an ambulance siren or a train sounds higher when approaching the listener than when moving away from him or her. The phenomenon whereby sounds appear to have a higher or lower pitch than their actual frequency is known as the Doppler effect.

A SODAR device uses sound-wave deviation to measure upper-air wind speeds (Figure 4.23). It emits audible sounds (in a range from 1 to 6 kHz) from its transmitter in three directions (vertical, obliquely upward in a north-south direction and obliquely upward in an east-west direction) and monitors their return as they are scattered by air-mass density fluctuations. By detecting the difference between the frequency of the emitted sound waves and that of the ones that return (known as Doppler shift), the average movement of an air mass (i.e., the three directional components of wind) can be measured.

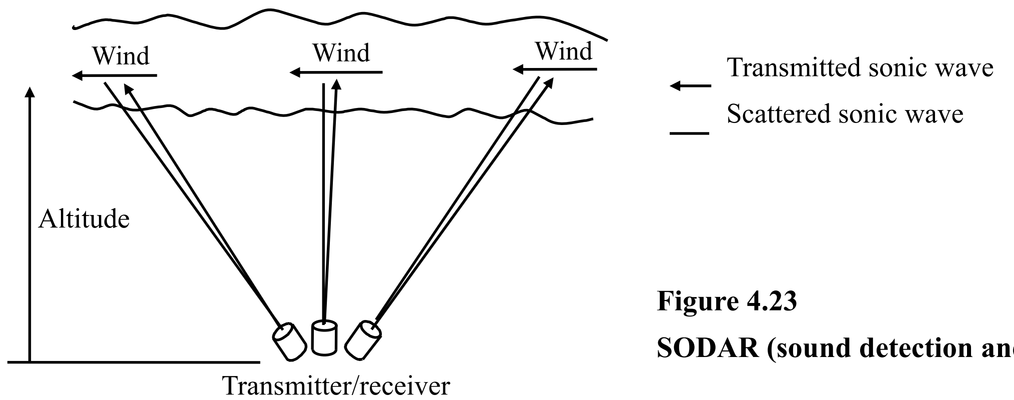


Figure 4.23
SODAR (sound detection and ranging)

This instrument is advantageous in that it can continuously measure winds at altitudes of 500 to 600 meters.

4.2.4.4 Method Using Radio Waves

(1) Wind Profilers

While SODAR uses the Doppler effect of sound waves, a wind profiler uses the Doppler effect of radio waves. As shown in Figure 4.24, it emits radio waves from its transmitter in three directions upward into the air and monitors their return as they become scattered by fluctuations in the refractive index caused by turbulent flow in the air. By detecting the difference between the frequency of the emitted radio waves and that of the ones that return, it can measure wind components in three directions.

The altitude to which a wind profiler can measure depends on the frequency of the radio waves used. In the 400-MHz band, winds at altitudes from 0.5 to about 16 km can be measured continuously.

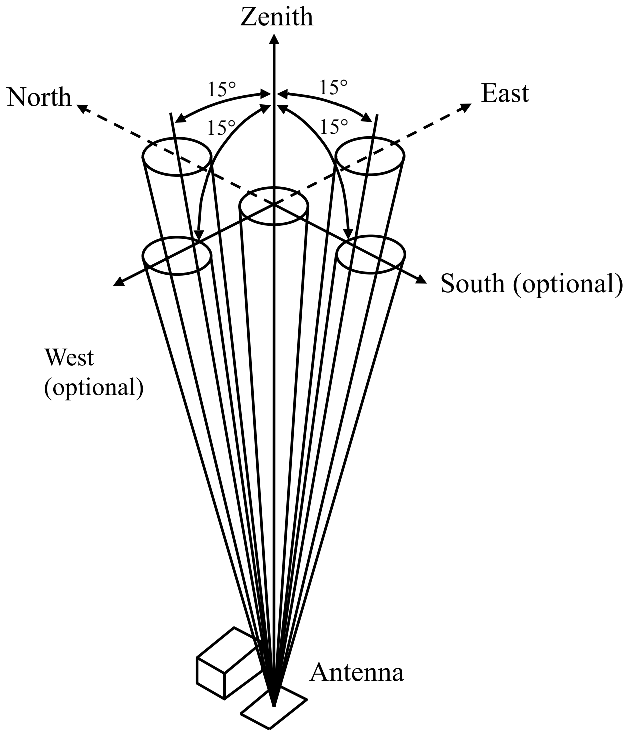


Figure 4.24 Wind profiler

(2) Doppler Radars

A function to measure Doppler shift in radio waves is added to a meteorological radar to create a weather Doppler radar. As shown in Figure 4.25, this device emits radio waves and monitors their return as they are reflected by precipitating particles such as raindrops or snowflakes. By detecting the difference between the frequency of the emitted radio waves and that of the ones that return, it can measure the distribution of wind speed elements such as divergence and convergence. In Doppler radar usage, the movement speeds of precipitating particles are considered to be equal to the wind speed in the air.

SODAR and wind profilers measure wind speeds by capturing echoes reflected as a result of upper-air density fluctuations. While they can make measurements continuously, Doppler radars have the disadvantage of not being able to take measurements where there are no precipitating particles.

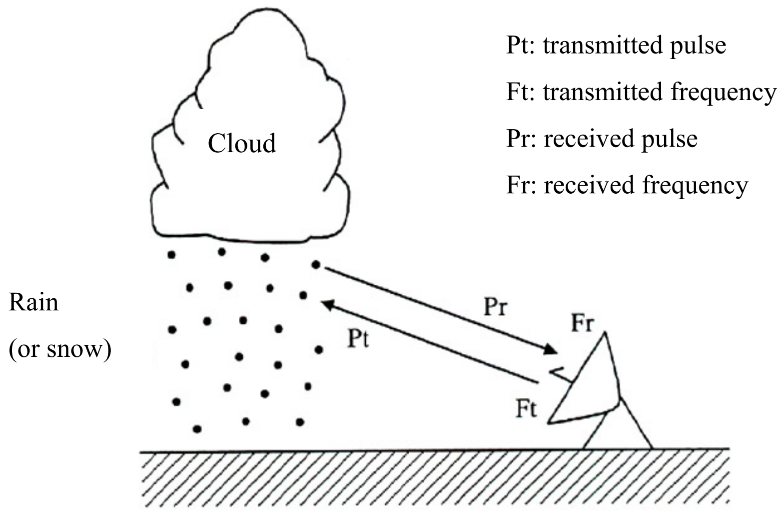


Figure 4.25 Doppler radar

4.3 Maintenance and Repair

As anemometer sensors operate in outdoor environments and are exposed to severe weather conditions, they deteriorate relatively quickly. To ensure stable, high-accuracy observation, anemometer maintenance should be carried out periodically.

This section describes general points to note when performing maintenance and repairing the sensors of anemometers. Strictly speaking, it is not possible to repair anemometers on site. If cups, propellers or bearings that may affect rotation characteristics are serviced or repaired, the device must be recalibrated. In principle, repairs and calibrations must be carried out by the manufacturer or a Meteorological Instrument Center in the relevant country, where the various standard instruments and calibration/testing equipment necessary are available.

4.3.1 Maintenance and Repair of Rotating Anemometers

Check item	Problem	Repair
External appearance	* Cup dents, arm deformation * Propeller deformation, wind-direction plate damage	* Badly deformed parts must be replaced. Slightly deformed parts can be repaired, but must be subjected to a rotational balance test. * It is not possible to repair such parts on site. Replacement is necessary.
Setup conditions	* Out-of-level mount * Wind-direction deviation	* Restore level status using a spirit level. * Orient the anemometer to the reference direction (usually north).
Unusual sounds	* Creaking sounds from rotary parts or lack of rotation at low wind speeds	* Bearings may be out of oil, worn or badly deformed. Dismantle the anemometer, clean bearings with gasoline and lubricate them. Bearings with significant wear must be replaced. * Overhaul the anemometer, clean all parts and lubricate them once a year.
Deterioration in sensitivity	* Wear on generator brushes or slip-ring contamination	* When overhauling an anemometer as described above, clean the brushes and slip rings.

4.3.2 Other Points to Note

(1) Cable Damage Caused by Small Animals

On agricultural land such as forests and fields, small animals including field mice, rabbits and squirrels may damage cable coverings or even break cables. Accordingly, it is advisable to string cables high above the ground. If buried in the ground, they should be placed at a depth of 30 cm or more to avoid the leaf mold layer. In buildings too, the same precautions should be taken to guard against damage caused by mice.

(2) Clearing Snow and Ice

Snow and ice may adhere to anemometers in cold climates. If exposed to snow or low temperatures with no wind, rotating parts may become frozen. As anemometers may also be deformed by the weight of snow or ice, such build-up must be cleared periodically.

It is advisable to provide artificial heating for anemometers operating in such environments.

4.4 Calibration

Accurate anemometer calibration can only be performed in a wind tunnel. However, the installation of such a facility involves tremendous investment, and its setup and maintenance are not easy tasks. This section describes some simple methods of checking anemometer operation to achieve the minimum required level of performance. An outline of the wind tunnel used by the Japan Meteorological Agency is also given.

4.4.1 Comparison by Beaufort Scale Observation

Comparing wind speeds measured with an anemometer to Beaufort Scale observation is the simplest method. However, as it provides only a rough estimation, its accuracy cannot be guaranteed.

4.4.2 Starting-threshold Torque Measurement

The torque of the starting threshold for a wind vane or anemometer is determined at the design and manufacture stages of each model. When a new instrument is introduced, its torque value should be checked with the manufacturer, or the torque at the starting threshold for the wind speed and the wind direction should be measured. The relevant data should be kept for reference, and subsequent instrument checks should be carried out with reference to these values. A tension gauge is used to measure the starting-threshold torque. Take several measurements and use the average as this torque value.

Another simple method of measuring starting-threshold torque is to use a weight equivalent to this torque value.

(1) Starting-threshold torque measurement using a tension-gauge

a. Place a cup anemometer horizontally in a wind-free indoor environment and connect it to a tension gauge with a string of about 50 cm in length as shown in Figure 4.26.

b. Slowly pull the tension gauge horizontally in the direction of the cup anemometer's rotation. Record the reading on the meter when the cup starts rotating.

c. After repeating Step b several times, average the measured values to obtain the starting-threshold torque.

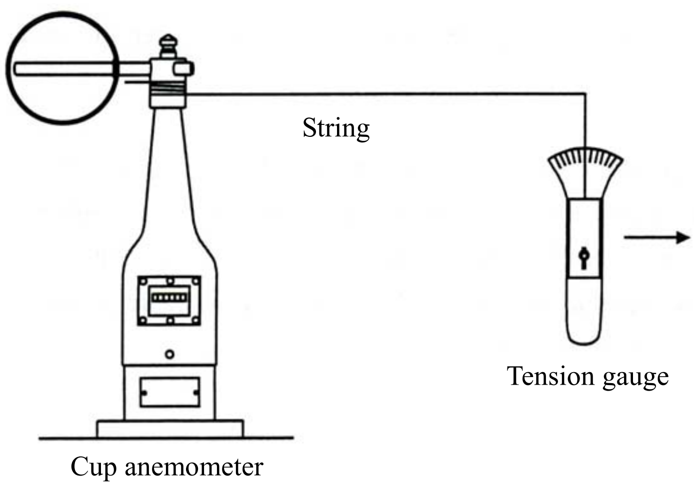


Figure 4.26 Measurement of starting threshold torque (wind speed axis) with a tension gauge

(2) Testing of wind-direction measurement initiation using a weight

a. Prepare a piece of string measuring about 1 m in length and a weight of about 35 g.

b As shown in Figure 4.27, set the anemometer horizontally, wind the string several times around the supporting shaft and hang the weight at the end of the string. Check the wind-direction axis to ensure that rotation starts smoothly in all directions.

(3) Testing of wind-speed measurement initiation using a small weight

a. Prepare a piece of string measuring about 1 m in length and a weight of about 7 g.

b. As shown in Figure 4.28, set the anemometer vertically. Detach the propeller and wind the string around its shaft. Hang the weight at the end of the string and check that the shaft rotates smoothly.

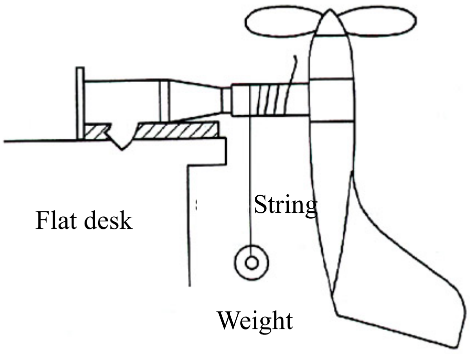


Figure 4.27
Propeller anemometer starting-threshold torque test (wind direction axis)

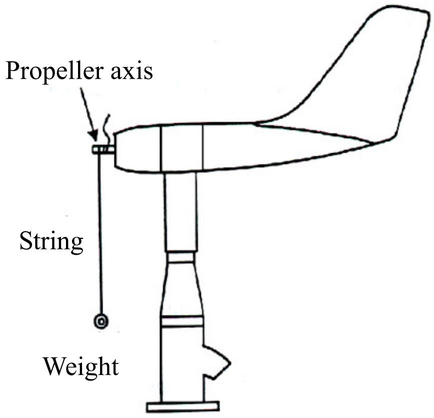


Figure 4.28
Propeller anemometer starting-threshold torque test (wind speed axis)

Starting-threshold torque measurements and tests conducted using weights to check wind direction and wind-speed measurement initiation are solely for the purpose of verifying smooth start-up in anemometers. They are not intended to guarantee the accuracy of calibration performed at individual wind speeds.

This section describes the measurement of starting-threshold torque and wind-direction/wind-speed measurement initiation for FF-6-type propeller anemometers, which are designed based on JMA's specifications. The torque required for wind-speed measurement initiation naturally varies with the size of the wind direction axis and the propeller shaft.

[Japan Meteorological Agency Wind Tunnel]

A wind tunnel is a piece of wind-generating equipment used to verify the performance of anemometers and calibrate them. In 1943, the Japan Meteorological Agency installed the first wind tunnel of the Gottingen type. The diameter of its exit cone was 1 m, and the drive motor had a power of 75 kW. The wind speed range was from 1 to 75 m/s, and its body was made of wood. This wind tunnel was used until it was replaced in 1964 when the main building of JMA was rebuilt.

The current wind tunnel is made of steel and installed in the basement of the JMA building (Figure 4.29).

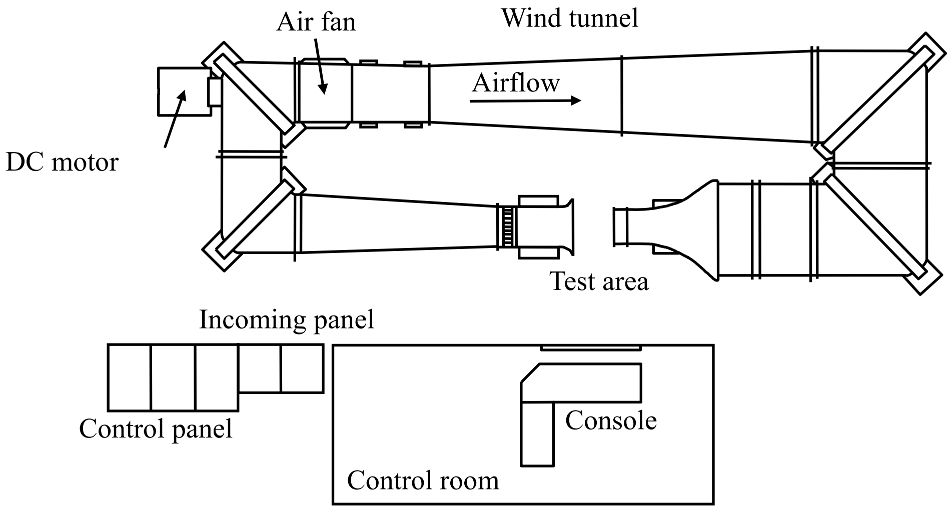


Figure 4.29 JMA wind tunnel layout

Main specifications

1) Type: Gottingen
2) Wind speed range: 0.35 to 90 m/s
3) Exit-cone diameter: 1.0 m
4) Air duct overall length: 47 m (including the working section of 1.2 m)
5) Air capacity: 230 to 4,240 m^3/min.
6) Fan: propeller-type single-stage axial fan (diameter: 1.7 m)
7) Rotation speed: 8.5 to 1,800 rpm
8) Motor: DC 440 V
9) Power: 200 kW
10) Control system: Thyristor Leonard

<u>Control from the console</u>

The console has various switches and gauges that the operator can use to select one of four operation modes: manual, automatic, step and fluctuating.

In automatic mode, 19 values can be set, allowing the operator to implement wind speeds automatically. In step mode, the wind speed is changed stepwise over selected speeds. Fluctuating mode implements speed changes with an amplitude around a given speed selectable within a range of 1 to 5 m/s and a period within a range of 5 to 15 seconds.

<u>Power supply and controller</u>

Three-phase 3,000 V, 50 Hz power is stepped down to 460 V using a distribution transformer. A Thyristor Leonard unit converts the AC voltage to a DC voltage to drive the DC motor. The feedback mechanism of a rotary encoder culed with the DC motor can adjust the motor’s rotation for any selected wind speed.

Fan-driving motor

The DC motor is directly connected to the 10-blade fan, which rotates in a range from 8.5 to 1,800 rpm and generates wind speeds from 0.35 m/s to 90 m/s.

Working section

The anemometer to be examined is mounted on the pedestal. A sonic anemometer is the standard instrument for wind speeds of less than 6 m/s. For wind speeds of more than 6 m/s, the pressure difference between the exit cone and the maximum diameter section is measured with a crystal pressure sensor, and is corrected using the ambient atmospheric pressure and air temperature at the exit cone as measured with a platinum-resistance thermometer. The signals from all the sensors are transmitted to the control console.

Data processing

Reference wind speeds are indicated on the gauges of the control console, and are simultaneously fed to a computer. The operator inputs the values measured with the anemometer to the computer, and the calibration results are printed out.

4.5 Others

4.5.1 Wind Instrument Exposure

Wind instruments are installed on open terrain 10 m above the ground. Open terrain is defined as an area where the distance between the anemometer and any obstruction is at least ten times the height of the obstruction.

In practice, however, it is often difficult to find ideal or even acceptable locations for wind measurements. Usually, wind sensors are exposed on a measuring tower or anemometer mast erected on the roof of a meteorological station or in its vicinity (Figure 4.30).

Even in locations where the standard exposure is not achieved, it is necessary to select a place where the environment meets the specified requirements (i.e., a flat, open location and a height of 10 m above the ground) as far as possible. The anemometer mast should be vertical to the ground, and the true north value of the wind-vane's sensor must be adjusted properly to the indicator or the recorder.

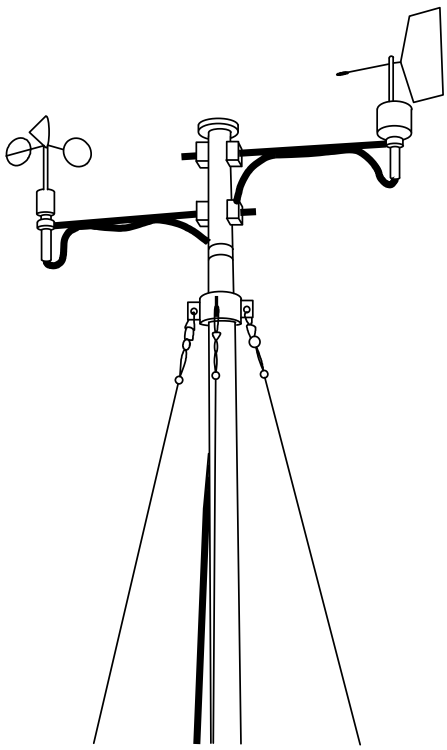


Figure 4.30 Anemometer mast

4.5.2 Wind Instrument Transportation

Regarding the transportation of instruments, refer to Chapter 1's Introduction to Meteorological Measuring Instruments and Transportation of Measuring Instruments.

4.6 Practical Training (Outline)

Disassembly and cleaning of a cup anemometer

Verifying the structure and working principles of a three-cup anemometer and performing disassembly and maintenance work

[Subjects to be covered in practical work]

(1) Checking of external appearance (presence of damage – cup dents, arm deformation, etc.)

(2) How to check the balance of cup wheels

(3) How to measure and check the starting-threshold torque

(4) How to check the overall condition and wear condition of bearings and replace them

(See the attached practical training manual.)