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Structure and characterization of a new instrument measuring wind speed and direction simultaneously

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Abstract
In this paper, a mechatronic-based structure that can simultaneously measure the wind speed and direction is presented. This mechanism consists of a sphere subjected to wind shear, a connecting cantilever to transmit this force, and a deformation diaphragm in which eight strain sensors are uniformly distributed around connecting cantilever. This instrument is structurally safe and can achieve high accuracy over a wide range of measurements by applying a specially designed single crystal silicon strain sensor. The experimental results and analysis confirmed that wind speed can be measured with an accuracy of ±0.2 m/s in the range 1-50 m/s and wind direction with ±2° resolution in the range 0-360°.

Keywords: MEMS, wind speed, pressure sensor, cylindrical cantilever

Introduction
Gas flow characteristics are very important in many fields including manufacturing process control, mechanical engineering, air conditioning system, environmental detection, medical field measurement, meteorological forecasting system, etc. Flow sensing by micro-electromechanical system (MEMS) technologies, have many advantages compared with their conventional large-scale counterparts, such as anemometers, turbines, Pitot- tubes, etc. These sensors have many advantages including lower power consumption, higher precision. Rapid response, lower manufacturing cost, improved portability, and improved portability. The main objective of the measurement of fluids, including wind, is the determination of flow velocity and direction of flow. The most commonly used methods in this case are the turbo-rotary method, the heat transfer effect, the electromagnetic properties of fluids such as ultrasound, the measurement of the fluid displacement force, and the use of differential pressure. Among them, the method of using fluid displacement force and heat transfer effect has been extensively studied. With the recent development of MEMS technology, micro-precision measuring instruments have been developed and used in various forms [1-4, 6-14].
The manufacturing process uses the established technology of integrated circuit manufacturing.
In references [1, 2], a thin cross-shaped cantilever was fabricated using MEMS technology as a silicon material to measure the wind speed and direction.
The drag force of the wind deforms the cantilever and changes the platinum film resistance that is placed on this cantilever. From these four resistance changes, the wind direction is determined. The wind speed is reduced by installing a circular platinum resistance heater and resistors and measuring the change in resistance due to heat convection phenomena with speed.
In reference [6], using MEMS technology, eight cantilevers are mounted on the disk, and the change in the platinum film resistance on the cantilever is measured by the wind, reducing the wind speed and converting the wind direction to the difference of the eight values. This measuring instrument does not use heaters.
In reference [7] measures the wind speed by installing one or two windshield plates and acquiring a signal in the bridge circuit to change the resistance due to the deformation of the resistor mounted on a thin cantilever attached to the plate by the wind. And the heating resistance wire is mounted on it to measure the velocity as a function of the resistance change with the speed of the wind.

In this work, the low wind speed is determined by the hot wire structure, the relatively high wind speed is obtained by the mechanical structure, and the same two instruments are installed vertically to each other to obtain the wind direction.

In reference [8], a meteorological measuring instrument was fabricated on a silicon diaphragm made by MEMS technology to comprehensively measure pressure, temperature, humidity, wind speed and direction. Eight resistance sensors and heaters were placed to measure the wind speed and direction.

In reference [11] determined the wind speed and direction by setting four thermal resistors and four heaters in groups, respectively, at the corner of a rectangular substrate and calculating the relationship between the respective varying resistance values using the wind-induced convection phenomenon.

In reference [10.14.3] measures air flow through a cylindrical rod mounted vertically in the middle of a micro machined diaphragm. When air flows, a vertical rod is forced to displace the diaphragm under the inclined line. Depending on the magnitude of the deformation, the resistance value of the piezo resistive film changes, and this value is reduced to determine the strength and direction of the air flow.

In reference [4], fabricated a mechanical flow sensor based on MEMS technology to measure the wind speed and direction.The instrument is designed to provide a connecting channel within a cylinder, to install multiple flow sensors in it, to form a network, to act on the sensors in which the wind from the impingement of the cylinder flows through the corresponding channel, and to measure the wind speed over a wide range.

In reference [12], determine the wind speed by determining the direction with the encoder plate and photodiode and measuring the speed of the wind blade by measuring the oscillation signal in a motor connected to the shaft.

In reference [9], a new mechatronic structure was designed to measure the wind speed and direction using the wind shear force. In this study, a sphere placed in the wind was placed vertically in the center of the diaphragm with a silicon strain sensor, and the velocity and direction of the wind were determined by sensing the position of the sphere by the drag force of the wind. And a prototype was built and compared with various anemometers and characteristics, obtaining accuracy of ±3% and ±5% in the range of velocity measurement 1-25.2 m/s and orientation measurement 0-360°, respectively.

This paper presents a novel wind speed and wind direction measurement instrument structure that is mechanically safe, sensitive, accurate and wind-ranging, by combining a semiconductor strain sensor with a wind-induced mechanical strain structure. The optimal modeling is carried out by design using numerical methods and the results of the analysis and test resultare compared for wind speed and direction.

2. New structure and principle of operation

2.1. Structure of Instrument

The structural model of the new measuring instrument is shown in Fig. 1.

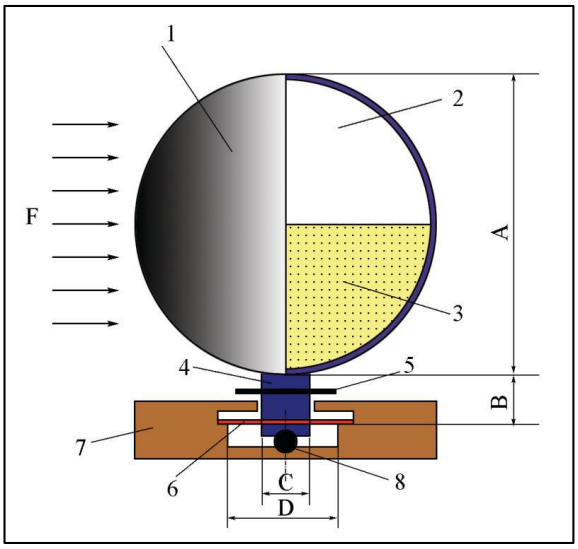

Fig 1: New measuring structure model

Where,

1. Surface of a cylindrical sphere under wind shear.
2. The inner cavity of a cylindrical sphere subjected to the thrust of the wind.
3. Metal materials made of balanced structure.
4. Connecting cantilever that transmit the thrust of the wind.
5. Overload limit
6. Strain diaphragm (0.2 mm thickness).
7. Support body
8. Ball metal

A. The diameter of the sphere (100 mm).
B. The height of the cantilever (20 mm).
C. Diameter of cantilever (10 mm)
D. Diameter of deformation diaphragm (30 mm).

The new structure consists of a single-crystal silicon semiconductor strain-sensitive resistor mounted on a deformable membrane, a centrally cantilevered deformation diaphragm, and a connecting cantilever that transmits the motion of sphere of tumbler-type to diaphragm in the flow of wind.

2.2. Structure and operation of measuring instrument

The main part of the sensor presented here, which simultaneously measures wind speed and wind direction, consists of a cylindrical cantilever carrying the thrust force due to wind, as shown in Fig. 1, and a metal diaphragm with eight resistive stress sensors based on MEMS technology.

The cylindrical cantilever is mounted vertically at the center of the metal diaphragm and is forced to generate a torque at the metal diaphragm center by transferring the thrust force generated by the wind flow.

Fig. 2 shows the model for the deformation of the diaphragm when the connecting cantilever is tilted by the force of the wind.

As can be seen in the figure, the deformation and stress of the diaphragm are concentrated at the largest value around the connecting cantilever.

Thus, this is the right place for the sensor to install.

Here, the detailed deformation of the diaphragm was obtained from ANSYS 19.2 calculation tool.

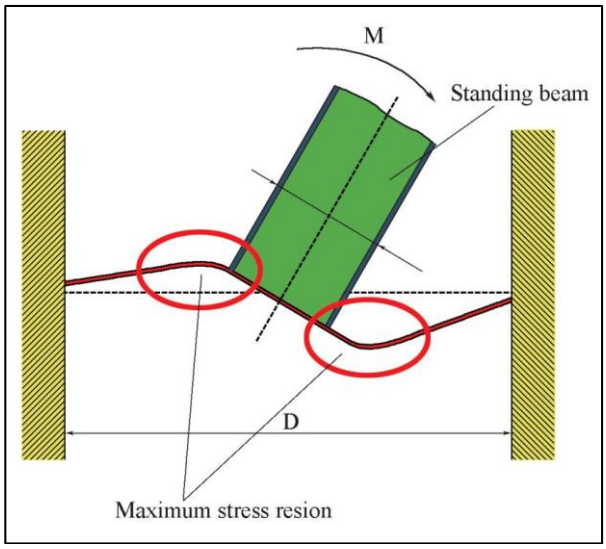

Fig 2: The model for the deformation of the diaphragm

The cylindrical cantilever is made of light and hard plastic material or thin metal sheets, so it only is inclined by the gas flow thrust force, but it does not cause deformation. The edges of metal diaphragm structure are fixed to the measuring device board. The metal diaphragm is circular and eight diffused silicon single crystal piezo resistive stress sensors are arranged as shown in Fig.3.

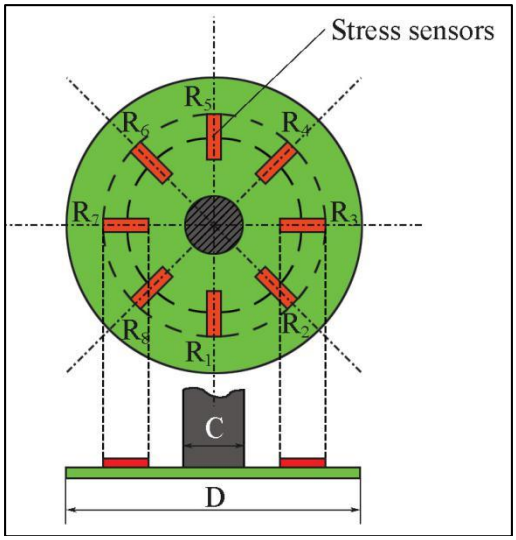

Fig 3: Arrangement of eight diffused silicon single crystal piezor resistive stress sensors

These eight resistive sensors are located at 45° intervals from each other and are located in the region of greatest stress located near the center of the deformation diaphragm. The strain behavior of the diffusion-type single-crystal piezo resistive stress sensor, as illustrated in Fig. 4, is presented in detail.

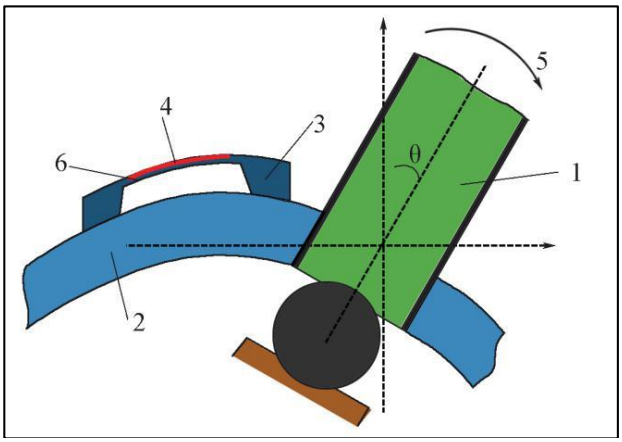

Fig 4: Structure and deformation behavior of a silicon single crystal piezo resistive stress sensor

Where,
1. Connecting cantilever.
2. Strain diaphragm.
3. Thin-Film Support of a Single-Crystal Stress Sensor
4. Diffusion resistance formed on silicon thin membranes.
5. The direction of wind deformation.
6. Si thin membrane

Since the thickness of the silicon sensor is very small compared to the thickness of the membrane, it was not taken into account in the deformation analysis of the membrane, and the strain of the sensor was considered to be identical to that of the membrane and used for stress calculation. The silicon sensor is composed of single crystal silicon with a thin membrane fixed on both sides in the radial direction, so that the change in diffusion resistance due to deformation is very large. These sensors are connected to an electronic circuit that amplifies and processes the piezor resistive change signal formed by the tilting of a cylindrical cantilever under the drag force caused by wind.

2.3 Principle of operation

In this paper, a new mechatronic structure for measuring the wind speed and direction is presented.

As can be seen in Fig. 1, the structure consists of a tumbler-type sphere connecting rod that is placed in the wind and a circular diaphragm that is deformed by rod. The sphere was made of a light hollow plastic material, and the lower half of the hollow sphere was filled with a high-density lead metal material to form a tumble structure. This structure is a tumble structure that performs the action to recover to the central position faster when the sphere is tilted by the wind and then the wind is released. The connecting rod is a cantilever that is tilted by sphere as sphere moves by wind and transfers the drag force by wind to the diaphragm. The deflection of the diaphragm when the connecting cantilever is tilted is shown in Fig. 2. When the connecting cantilever is tilted, the diaphragm is split into two parts and symmetrically deformed by compression and stretching forces. The line perpendicular to the direction of the wind is a symmetrical line for deformation into compressive stress and deformation into tensile stress. The stress distribution during the deformation of the flat diaphragm due to the inclination of the connecting cantilever is shown in Fig.5.

As can be seen, the stress is inversely symmetrical and appears most strongly in the direction of the wind and gradually weakens symmetrically towards the edge from the center of this direction. Therefore, a larger sensing signal is generated for the strain sensor located at a high stress location. This phenomenon occurs equally in all directions of the wind because the balloon structure is designed to be circular symmetry.

2.4. Determination of wind velocity

The wind speed is determined by the magnitude of the stress sensor considered previously. When the sphere is placed in the wind stream, the thrust force experienced by the sphere is expressed as

$$F_2 = 0.5 \times C_D \times \rho_a \times \upsilon_a^2 \times A \quad (1)$$

Where,
C_D - Fluid flow coefficient
ρ_a - Air density
υ_a - The speed of the wind
A - Cross-section of the sphere

As can be seen from this equation, the force exerted by the sphere from the wind is proportional to the square of the wind speed.

The next important factor is the fluid flow coefficient C_D.

C_D is a function of the Reynolds number hydro dynamically. The Reynolds number is related to velocity of wind In Pig.5, the Relation of Reynolds number and velocity is showed [5].

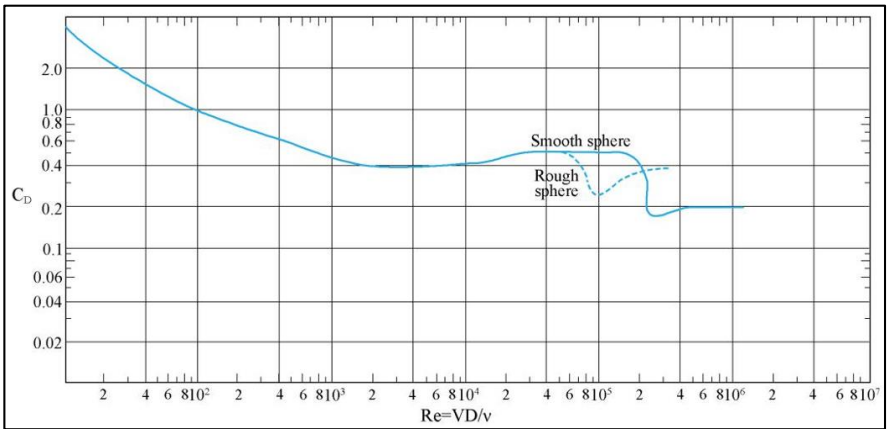

Fig 5: The Relation of Reynolds number and velocity [5].

We design a measurable instrument between 1 m/s and 50 m/s of wind speed. In this speed region, the Reynolds number ranges from 2000 to 100000, and the CD value in this region is considered to be constant at about 0.42. Therefore, since the air density depends on temperature, the force exerted by the sphere around 10 °C can be roughly expressed as

$$F = 0.22 \times A \times \upsilon_a^2 \quad (2)$$

The force exerted on the sphere by the wind is transferred to the deformation cantilever, and this force immediately causes the deformation of the circular diaphragm. Under the condition that the circular diaphragm operates within the elastic limit, the strain is directly proportional to the force. Thus, a quadratic relationship is maintained between the wind speed and the magnitude of the diaphragm deformation.

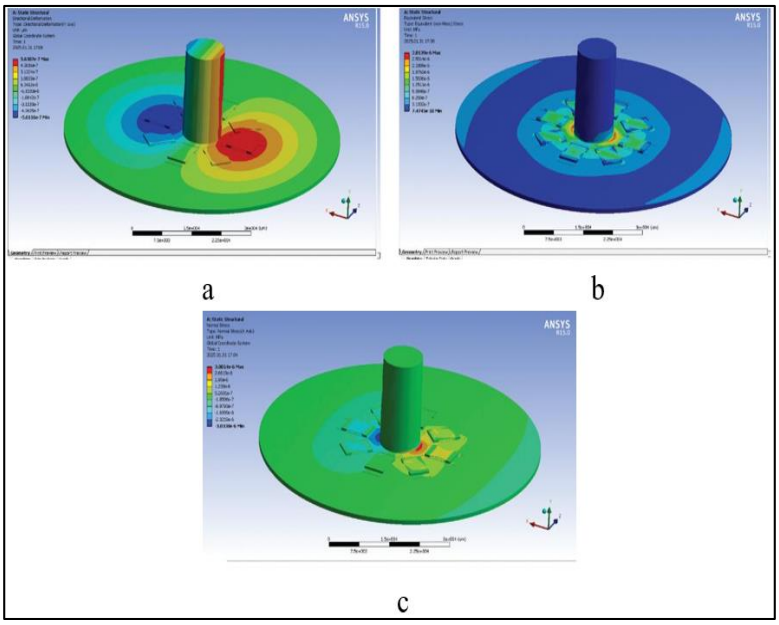

Fig 6: The configuration of the stress sensors mounted on the diaphragm Where, a) Verticality strain b) Bon mises stress c) Horzontality stress

The membrane sensing structure presented in this paper is equipped with eight single-crystal silicon strain sensors in the region where the stress is most concentrated in the strain membrane to enhance the sensitivity. Since the configuration of this strain sensor is symmetric from the membrane center, the stress acting on the sensor is also symmetric. Thus, the wind speed is in a corresponding relationship to the stresses in the diaphragm, so it can be determined by the sum of the stresses or the sum of the stresses acting on the sensing element.

Fig.6 shows the configuration of the stress sensors mounted on the diaphragm. As can be seen in fig.6, the stress sensing resistances are divided into three to four by center lines of any diameter between 0 and 360° of the diaphragm. Thus, the wind speed can be determined by the sum of the signals generated by three or four sensors. Figure 7 shows the structural model and fabrication process of a single-crystal silicon stress sensor placed on a deformation membrane.

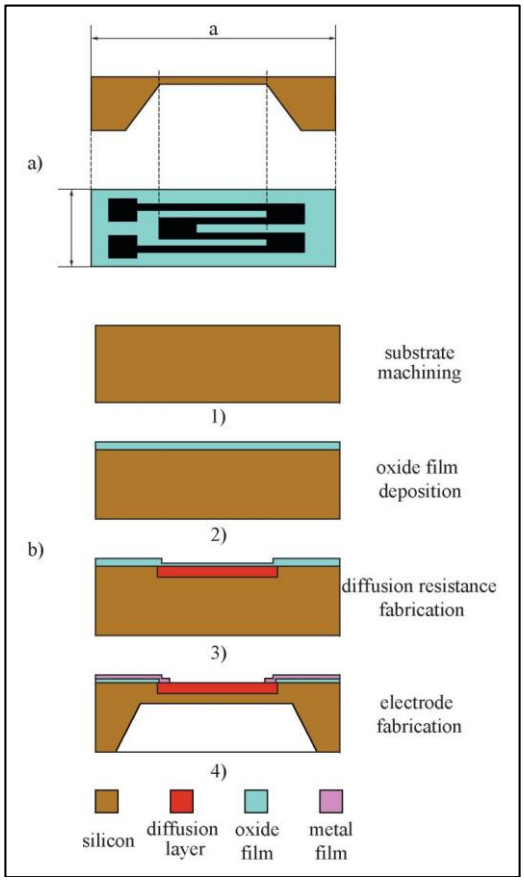

Fig 7: Structural model and fabrication process of a single-crystal silicon stress sensor placed on a deformation membrane

Where
a) Structural model of single-crystal silicon stress sensor
b) fabrication process of single-crystal silicon stress sensor

The sensing element selectively formed a 30 mm thick thin membrane by chemical etching of a silicon wafer with a (100) side of 500 mm thick.
A solution of 30-35% KOH was used as the etching solution.
Using a silicon oxide film on a thin silicon stress diaphragm, bended resist pattern is printed as shown in Fig. 1, and boron diffuses to create a diffusion resistance. The diffusion resistance was adjusted to the concentration of boron to make the total resistance value 5 kΩ. The fabrication process flow model is shown in Fig. 7(b). This fabrication process is similar to the conventional standard pressure sensor fabrication process using MEMS technology.
Fig. 8 shows the relationship between the wind speed and the sum of the drag signals by the drag stress at the designed dimensions, obtained using the wind tunnel (X5606, Druck DPI 520).
(With in the elastic limit, a linear relationship is established between Stress by drag force and resistance change of sensors)

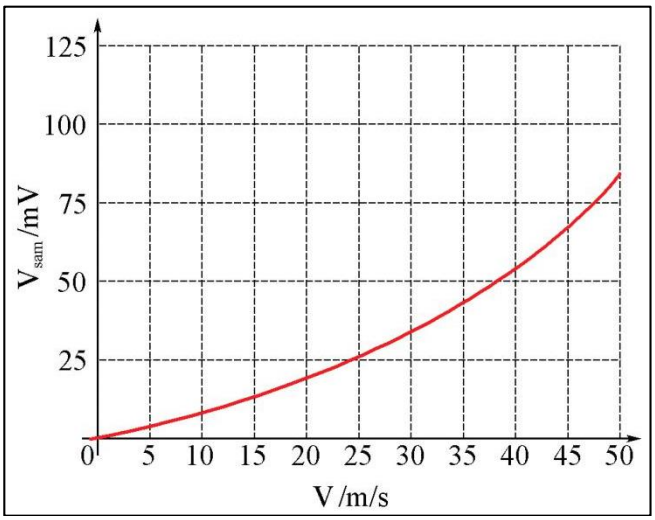

Fig 8: Relationship between the wind speed and the sum of signals by drag stress

As above, the membrane is asymmetrically deformed against corresponding diameter line, and the resistance signal located in corresponding region is also reversed. Therefore, if we find only the sum of the signals of either side, we can reduce the velocity.

2.5. Determination of wind direction

Fig.9. shows the configuration of piezoresistive sensors and wind direction.
The direction of the wind can be determined very accurately for the 24 directions shown in Fig. 9.

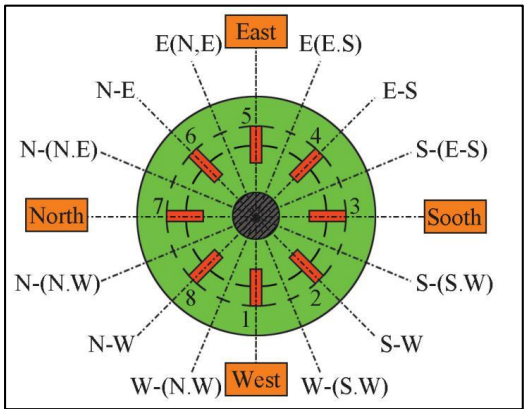

Fig 9: The wind direction arrangement on deformation diaphragm

In detail, if the values of R3 and R7 at the distance of 90° and R3, which are opposite to the east direction, are the largest in the total value, the resistance direction can be determined west, south and north, respectively. Next, if the R2, R4, R6, and R8 resistance signals are the largest, respectively, these resistance directions can be determined in the west-south, south-west, west-north, and north-east directions. On the other hand, if two adjacent resistances are identified, the wind direction lies in the middle of the two resistances. For example, if resistances R2 and R3 have the same value, the wind direction will lie between these angles, since the angle between resistances R2 and R3 is 22.5°, so the wind direction lies between about 45° of R2 and 90° of R3. On the other hand, except for the special case mentioned above, the method of determining the any direction of the wind with a more accurate resolution is to perform vector calculations.
Figure 10 shows a two-vector composite model for determining the any direction of the wind.

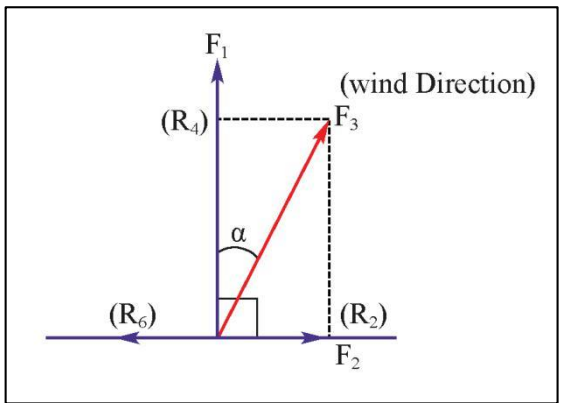

Fig 10: Two-vector composite model for determining the any direction of the wind

If we perform a vector synthesis with the largest value of the eight resistance signals measured at any wind speed and the larger value of the resistance signal between the two resistors at 90° intervals and the two at 90° intervals, this resultant vector direction can be determined in the correct direction of the wind. For example, if the R4 resistance is the largest signal resistance, R6 and resistance, R2 is arranged in left and right respectively. IF signal value of R2 is larger than resistance, R6, the direction of wind can be determined by performing combination of the resistance, R4 and resistance, R2.

In Fig. 10, the angle between the two vectors is expressed as

$$Q = arctan\frac{VR2}{VR4} \quad (3)$$

Where,

VR2-signal value in resistance R2

VR4- signal value in resistance R4

Q-Angle between maximum signal value vector of sensor and direction value vector of wind

This way, the orientation of wind can be determined precisely with a resolution up to ±2° taking into account the measurement error of the resistance value.

2.6. Effect of tumbler structure operation

In the paper, the experiment accomplished for Effect of tumbler structure operation.

The wind speed was chosen to be 50 m/s for the wind direction test stand, and the time was measured until the resistance signal value was zero, after immediately cut off with the wind shield. The recovery time was determined by averaging the several replicate measurements values. The measurement values did not exceed 2 s since the Effect of tumbler structure operation whereas the recovery time of no tumbler structure was about 3.5s.

3. Conclusion

In this paper, we have presented a mechanism that can simultaneously measure mechatronic wind direction and speed in real time, with less power consumption and more structural robustness. The instrument consists of a sphere in the wind that senses the wind shear force between 0 and 360°, a connecting cantilever that transfers this thrust to the deformation circular diaphragm, a single crystal silicon strain resistor that can sense deformation with high sensitivity, and a deformation diaphragm with eight uniformly spaced. This mechanism can enhance the sensitivity even at low wind speeds by placing a single crystal strain sensor in the location where the membrane stress is most concentrated. For higher sensitivity, the sensitivity increases in proportion to the length of the connecting cantilever as long as possible. The results confirmed that wind speed can be measured with an accuracy of ±0.2 m/s between 1 and 50 m/s and wind direction can be measured with a resolution of ±2° between 0 and 360°. The zero recovery time is about down 2s

A special point in this mechanism is the increased structural stability by increasing the thickness of the strain-sensitive diaphragm, while the sensitivity is enhanced by applying a high performance single-crystal silicon semiconductor strain sensor.

References

1. Lee CY, Wang YH, Hsueh TH, Ma RH, Fu LM, Chon PC. A smart Flow Sensor for Flow Direction Measurement. Advanced Materials Research. 2008;47-50:189-192.
2. Ma RH, Wang DA, Hsueh TH, Lee CY. A MEMS-Based Flow Rate and Flow Direction Sensing Platform with Integrated Temperature Compensation Scheme. Sensors. 2009;9:5460-5476.
3. Ma RH, Chon PC, Wang YH, Hsueh TH, Fu LM, Lee CY. A micro cantilever based gas flow sensor for flow rate and direction detection. Micro sys. Technol. 2009;15:1201-1205.
4. Bruschi P, Dei M, Piotto M. A low-power 2-D Wind sensor based on Integrated Flow Meters. IEEE sensors Journal. 2009;9(12):1916-1923.
5. Lee CY, Wen CU, Hou HH, Yang RJ, Tsai CH, Fu LM. Design and characterization of MEMS-based Flow-rate and Flow-direction micro sensor. Micro fluid Nano fluid. 2009;6:363-371.
6. Du L, Zhau Z, Fang I, Xu J, Geng D, Liu Y. A micro-wind sensor based on mechanical drag and thermal effects. Sensors and Actuators A. 2009;155:66-72.
7. Ma RH, Wang YH, Lee CY. Wireless Remote Weather Monitoring System Based on MEMS Technologies. Sensors. 2011;11:2715-2727.
8. Daldaban F, Karagoz F, Genc MS. A drag force anemometer using finite length cylinder with direction measurement capability. Measurement. Available from: http//dx.doi.org/10.1016/j.measurement.2017.02.006.
9. Jing XM, Miao JM, Xu T, Olfatnia M, Norford L. Vibration characteristics of micro machined piezoelectric diaphragms with a standing beam subjected to airflow. Sensors and Actuators A. 2010;164:22-27.
10. Russell RA, Kennedy S. A novel airflow sensor for miniature mobile robots. Mechatronics. 2000;10:935-942.
11. Rose SE, Moody CB, James DL, Barhorst AA. Drag measurement and dynamic simulation of martian wind-driven sensor platform concepts. Journal of Fluids Structures. 2006;22:21-43.
12. Wang YH, Lee CY, Chiang CM. A MEMS-based on flow sensor with a free-standing micro cantilever structure. Sensors. 2007;7:2389-2407.