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Application of Multidimensional Force Sensor in Measuring Breeze Speed

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Abstract

For the measurement of the micro wind speed, the size, accuracy and sensitivity of the measurement device have higher requirements, so most wind speed measurement instruments are difficult to achieve the wind speed measurement standards in the market. Based on the principle of wind load, the method of measuring wind speed using MEMS multidimensional force sensor is studied. Through the wind the ball, the sensor sensitive beam with sensitive strain measure pressure from X, Y, Z direction. Effective synthetic velocity and resultant wind direction can be obtained, through the relationship between pressure and wind velocity. Compared with the conventional mechanical wind speed measuring instruments on the market, it has the characteristics of simple structure and fast responding, and has no traditional mechanical components.

Key words: MEMS; Micro wind speed; Multidimensional sensor; Strain gauge.

1. Introduction

In many fields such as environmental monitoring, meteorology, industrial equipment, biomedicine, the gas velocity and flow direction are important parameters. At present, there are many kinds of instruments for measuring wind speed, but most of the velocity measurements cannot measure the wind speed. In the wind speed measurement of 0-2m/s, the size, precision and sensitivity of the equipment are high. The usual measuring equipment is: hot-wire anemometer, ultrasonic velocimeter, laser doppler velocimeter and tracer velocity meter.

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The multi dimensional force sensor has the characteristics of high accuracy, quick response, multi-complex environment and simple structure. Using the multidimensional force sensor to measure the breeze speed can solve the problem that the traditional equipment is too large, the response time is long and the environmental requirement is higher. By the multidimensional force sensor to measure wind load, wind load can be used to measure the breeze speed. Contact surface conducted the wind - force conversion and the Four elastic sensitive beams conducted the force -strain value conversion. We can get wind loads by sensitive strain resistance，To measure wind speed and wind direction measurements. The traditional Multidimensional force sensor is the main measure of the wind speed on the plane, such as H.Liu and his colleagues wind speed in the cylinder around the probe labeled MEMS hot film, the 0.1 ~ 10m/s range 3.6% plane on the accuracy of wind speed monitoring [4]. MEMS micro force probe sensor designed by Wang Weizhong and his colleagues 3uN resolution, 0.94% nonlinear error is better than the full range of the sensor, but using probe sensors to measure wind speed, the Z axis sensitivity is smaller because the wind area is too small. In view of the above problems, the traditional probe sensor is changed into a spherical shell sensor to increase the area of the receiving air body. In this paper, we mainly study the performance of the spherical shell sensor structure.

2. Wind speed measurement principle of multidimensional force sensor

The wind pressure is the pressure of the wind which is perpendicular to the direction of the air flow. According to the Bernoulli equation, the formula of wind speed and pressure is obtained:

$$Wp = \frac{r_0 * v^2}{2} \qquad (1)$$

In Formula (1), Wp is the air pressure （kN/m^2）; r_0 is the air density（kg/m^3）; v is the wind speed （m/s）。Because the density of air is related to the air gravity, therefore, the formula of standard wind pressure can be obtained according to formula (1):

$$Wp = \frac{r * v^2}{2g} \qquad (2)$$

In the standard wind pressure formula, in the standard state (air pressure is 101.325 kPa, temperature is 15 ^{o}C), air gravity ($r = 0.012018$ kN/m^3), At latitude of 45°, the acceleration of gravity at sea level ($g = 9.8m/s^2$), bring them into equation (2):

$$Wp = \frac{v^2}{1630}(kN/m^2) \qquad (3)$$

Because of $F = Wp * S$, When the cross sectional area (S)is known, the wind speed (v)can be obtained as long as the force(F)is measured:

$$v = \sqrt{\frac{1.63F}{S}}\left(\frac{m}{s}\right) \quad (4)$$

3. The structure and working principle of the sensor

3.1. sensor structure

The overall structure of the sensor is shown in Figure 1, outside a spherical shell, the shell through a sensor rod and the sensor center connector, the shell can function in the bottom of the cantilever beam sensor under external force. The bottom of the elastic body sensor selection of strain gauge, high precision technology is mature, and can reduce the production cost of the sensor, cross elastic body can effectively reduce the X, Y, Z axis coupling, simple structure, can adapt to the environment.

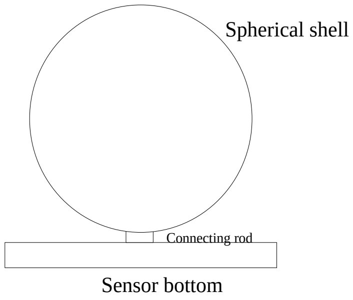

Figure 1: overall structure of the sensor

The basic model at the bottom of the sensor is shown in Figure 2; a connecting structure is arranged at the center of the bottom of the sensor, and the connecting structure is supported by a cantilever beam with a cross structure; four cantilever integrated 12 strain resistance strain, specific resistance distribution in Figure 2. Each four resistors form a full bridge circuit, and the resistance of the four cantilevers is output in the form of voltage through the Wheatstone bridge. They are used to detect the force on the Y axis of the X axis and the Z axis respectively:

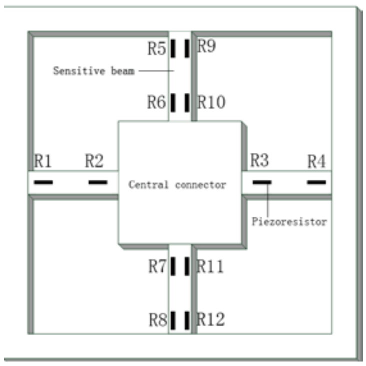

Figure 2: model of bottom of sensor and distribution of strain resistance

The MEMS micro force probe sensor designed by Wang Wei-zhong and his colleagues has been simulated by

ANSYS software. The stress distribution at the bottom of the sensor is shown in Figure 3 and figure 4; the proposed ball sensor is simulated to obtain the stress distribution at the bottom of the sphere sensor, as shown in figures 5 and 6.

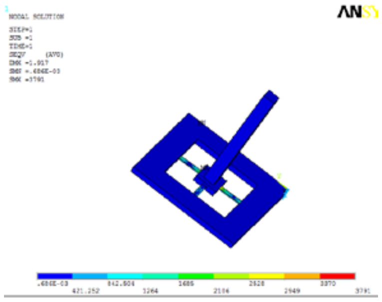

Figure 3: stress distribution in the direction of X axis of probe sensor

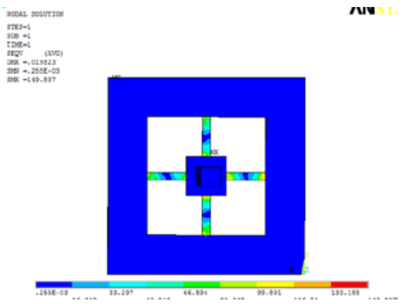

Figure 4: stress distribution in the direction of Z axis of probe sensor

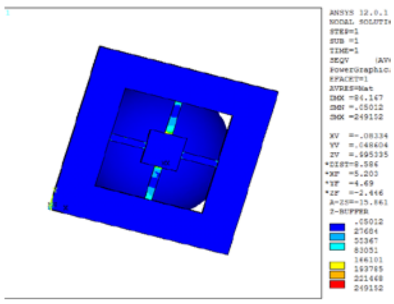

Figure 5: stress distribution in the direction of the X axis of the ball sensor

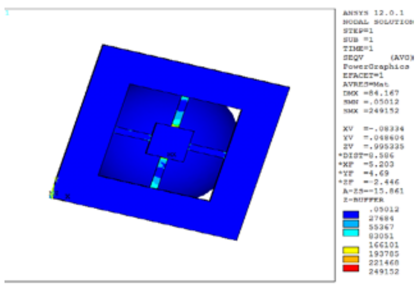

Figure 6: stress distribution in the direction of the Z axis of the ball sensor

Under the same conditions, it can be seen clearly from Figure 6 and Figure 7 that the sphere sensor has a wider measuring range than the probe sensor, and that the outer shell increases the area of the receiving air and is more sensitive to the measurement of the wind speed.

3.2. sensor work principle

In Figure 2, resistors R1 to R4 are arranged along the axis of the X axis and connected to form the Wheastone bridge detection circuit, as shown in figure 7-A. When the F_x force acts, the resistance R1 and R3 are subjected to tensile strain, and the resistance increases; the resistance R2 and R4 are subjected to compressive strain, and the resistance is reduced; then the bridge output voltage is detected. When the F_y force acts, the resistance R1 to R4 is approximately distributed on the neutral layer, and the strain is approximately zero. When the action is used, because of the symmetry of structure, the resistance of R2 and R3 changes the same, and the resistance of R1 and R4 changes the same, so there is no change in detecting the output of the bridge. When the F_z force acts, because of the symmetry of structure, the resistance of R2 and R3 changes the same, and the resistance of R1 and R4 changes the same, so there is no change in detecting the output of the bridge. To sum up, the X direction detection circuit is sensitive to force in the F_x direction only. The resistance R5 to R8 is arranged along the Y axis and connected to the full bridge circuit, as shown in figure 7-B. According to the same analysis method, the detection circuit of Y direction can be introduced only sensitive. The resistance R9 to R12 is also arranged in the direction of the Y axis, and is symmetrical with the axis of the Y axis from R5 to R8, so the direction force has little influence on it and can be neglected. And because of the particularity of its bridge connection, as shown in figure 7-C, the force acting on the direction, although the direction of the force will cause the bridge C has a certain voltage output, the output voltage is very small. In the measurement result, different direction detection circuit output voltage will be small; according to different circumstances can choose to omit or eliminate data fitting, in order to measure the accuracy of our calculation in structural analysis, using least square method to fit the data, eliminate the influence of the other direction of the output voltage.

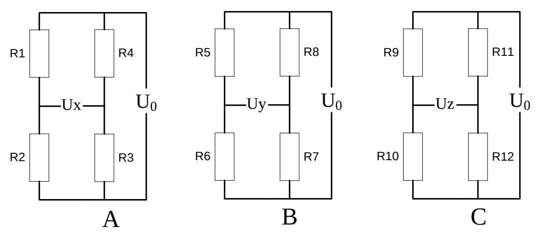

Figure 7: X, Y and Z on the axis of the Wheatstone bridge

Because the sensor probe sensor and sensor sphere model at the bottom is the same, when the F_x force acts, the resistance R1 and R3 stretched, the resistance R2 and R4 compressed, R5, R6, R7, and R8 are subjected to shear stress. When the length of the beam is much larger than the thickness of the beam, the resistance value from R5 to R8 is zero, because the strain formula of the foil strain gauge is:

$$\frac{\Delta R}{R} = K_0 \varepsilon \qquad (5)$$

So the U_x output is:

$$U_x = \frac{\Delta R}{R} * U_0 = K_0 \varepsilon_x * U_0 \qquad (6)$$

The formula (6), K_0 is the strain coefficient of metal material; ΔR and R are respectively the strain value of resistance strain resistance of bridge arm variation and bridge arm; K_0 is the strain coefficient of metal materials.

The length of the cantilever beam is L, the width is B, the thickness is t, the half width of the center connecting body is a, and the height of the rigid body is h. The relationship between the horizontal force of a single elastic sensitive beam and the stress at any point in the cross section is:

$$\sigma = \pm \frac{L^2 + 3aL - 3x(a+L)}{\frac{2}{3} bt^2 (L^2 + 3aL + 3a^2)} F\,h \pm \frac{F}{bt} \qquad (7)$$

By the formula (7), the horizontal force of cantilever beam and the output voltage of a linear relationship can be obtained.

From the formula $\sigma = \varepsilon E$, it can be seen that the voltage output Ux , Uy , Uz is linearly related to the force F_x 、 F_y 、 F_z, so the whole sensor system can be regarded as a linear system. When the force acting on the sphere sensor, the deformation occurs not only in one direction, the other direction will produce small strain, so the sensor can not be used as 3 single force sensor, should consider the deformation coordination function, coupling the direction of force. Therefore, the linear relationship between the output of the sensor channel and the three-dimensional force acting on the sensor coordinate origin is considered. The relation is described as $U = CF$ and C as the decoupling matrix.

It is known by $U = CF$ that the decoupling matrix C is obtained by decoupling the algorithm through the given force matrix F and the acquisition of the output voltage matrix U. In actual monitoring, the output voltage matrix U of the bridge can be obtained, and the force values in three directions can be obtained by $F = C^{-1}U$.

According to formula (4), v_x , v_y , v_z can be obtained. According to the parallelogram law, can get the synthesis speed and direction angle, such as formula (8) and the formula (9) (10) (11). The formula (9) (10) (11) represents the angle between the resultant velocity and the plane.

$$v = \sqrt{{v_x}^2 + {v_y}^2 + {v_z}^2} \quad (8)$$

$$\alpha_{xy} = \tan^{-1}\left(\frac{v_z}{\sqrt{{v_x}^2 + {v_y}^2}}\right) \quad (9)$$

$$\alpha_{xz} = \tan^{-1}\left(\frac{v_y}{\sqrt{{v_x}^2 + {v_z}^2}}\right) \quad (10)$$

$$\alpha_{yz} = \tan^{-1}\left(\frac{v_x}{\sqrt{{v_z}^2 + {v_y}^2}}\right) \quad (11)$$

4. Sensor performance test

4.1. Establish the relationship between the sensor load and the output voltage

According to $F = C^{-1}U$, we need to establish the relationship between the sensor load and the output voltage. Through many experimental data, the decoupling matrix is obtained by using MATLAB. The following tables 1, 2 and 3 are the measured data.

Table 1: Output voltage Ux , Uy , Uz for unidirectional loading of X axis

F_x Directional force / uN	Ux / mV	Uy / mV	Uz / mV
50	8.433	0.030	0.004
100	16.830	0.059	0.009
150	25.231	0.093	0.014
200	33.632	0.125	0.019
250	42.033	0.157	0.022

Table 2: Output voltage Ux , Uy , Uz for unidirectional loading of Y axis

F_x Directional force / uN	Ux / mV	Uy / mV	Uz / mV
50	0.032	8.334	0.004
100	0.065	16.635	0.009
150	0.098	24.937	0.013
200	0.130	33.236	0.019
250	0.160	41.635	0.023

Table 3: Output voltage Ux , Uy , Uz for unidirectional loading of Z axis

F_x Directional force / uN	Ux / mV	Uy / mV	Uz / mV
z	0.005	0.003	8.832
100	0.011	0.007	17.702
150	0.016	0.010	26.896
200	0.021	0.014	35.589
250	0.027	0.018	44.209

According to the test results, the test data are analyzed by using MATLAB software, and the decoupling matrix $U = CF$ is obtained.

Using the least square method to fit the data in the table can be obtained:

$$C = \begin{bmatrix} 0.16830 & 0.00065 & 0.00009 \\ 0.00062 & 0.16635 & 0.00009 \\ 0.00012 & 0.00007 & 0.17768 \end{bmatrix}$$

The relationship between the voltage and the X axis, the Y axis, and the Z axes is obtained:

$$Ux = 0.16830Fx + 0.00065Fy + 0.00009Fz$$

$$Uy = 0.00062Fx + 0.16635Fy + 0.00009Fz$$

$$Ux = 0.00012Fx + 0.00007Fy + 0.17768Fz$$

Use formula $F = C^{-1}U$ to get:

$$Fx = 5.9419Ux - 0.0232Uy - 0.0030Uz$$

$$Fy = -0.0221Ux + 6.0115Uy - 0.0030Uz$$

$$Fz = -0.0040Ux - 0.0024Uy + 5.6281Uz$$

Using formula (4), the wind speed v_x , v_y , v_z in the direction of Fx , Fy , Fz can be calculated, in which S is known. The resultant wind speed and direction can be calculated by formula (8) and formula (9) (10) (11).

4.2. Experimental data are validated

Test the wind speed data as shown in table 4:

Table 4: The output of the Ux，Uy，Uz when given wind speed

wind speed（v_x，v_y，v_z）	Ux/mV	Uy/mV	Uz/mV
1，0，0	10.368	0.037	0.005
0，1，0	0.038	10.203	0.005
0，0，1	0.007	0.007	10.946

The wind speed corresponding to each set of data in Table 4 is calculated according to the voltage, as shown in table 5:

Table 5: The output of the v_x, v_y, v_z when given voltage

Ux/mV	Uy/mV	Uz/mV	wind speed（v_x，v_y，v_z）
10.368	0.037	0.005	1.02，0，0.02
0.038	10.203	0.005	0，1.01， 0.02
0.007	0.007	10.946	0， 0.01，1.02

In the test results, the velocity is directional; the velocity in Table 5 is negative, representing the velocity direction opposite to the axis. We can obtain by calculation that the corresponding synthetic rate in Table 5 is 1.02 m/s，1.01 m/s，1.02 m/s, and the synthetic velocity direction is 1 degrees different from the given wind speed. By comparing the calculation results, the wind speed is measured by the multidimensional force sensor. Compared with the calculation, the average wind speed is 0.01 m/s, and the average error of synthesis angle is 1°, although there is a certain error, but it is within the acceptable range.

5. Conclusion

Using the principle of wind load, the use of multidimensional force sensors to measure wind speed, compared to the previous wind speed sensor, do not need to use mechanical moving components, without the complexity of traditional machinery, suitable for working in a variety of places. The probe sensor is changed into a sphere sensor to increase the contact area between the wind and the sensor, and the sensitivity of the ball sensor is 0.01 m/s. In the process of measuring wind speed by multidimensional force sensor, the least square method is used to process the data, which reduces the error of mutual influence between sensors, and improves the sensitivity of the wind speed measured by the sensor. By formula (1) and formula (2), it can be seen that when measuring wind speed, the sensor is affected by the humidity and pressure of the measured environment.

Because of the environmental humidity and atmospheric pressure is normal data measurement, so in different environments in order to eliminate the influence of environmental factors on the data, so the measurement of wind speed, the need for measuring wind speed data amount correction.

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