Design of Hot-bulb Probe Low-Pressure Wind Speed Calibration System

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Abstract. In order to measure the wind speed in Mars rover thermal vacuum test correctly, a low-pressure wind speed calibration system need to be developed. The purpose of this paper is to establish a low pressure-wind speed calibration system, and give an error analysis of it. In this paper, the Hot-bulb Probe calibration scheme, calibration conditions are introduced. The errors caused by length measurement and speed measurement, disturbance of low field, measuring instrument are fully analyzed.

1. Introduction

In the first Mars exploration mission development support condition construction project, in order to verify the correctness of the thermal control design, the rover vehicle needs to carry out the thermal test on the ground, and the real-time measurement of the wind speed under low air pressure is needed during the thermal test of the Mars Rover. [1] Therefore, it is proposed to support the construction of a low-pressure wind speed measurement system by the first-time Mars exploration mission development support condition construction project. [2]

2. Hot-bulb Probe measurement program

The core of the Hot-bulb Probe anemometer is a Hot-bulb Probe and looks like this; [3]

As seen in the figure, the Hot-bulb Probe is a ceramic package sphere with a diameter of less than 1 mm, the inside contains the hot end of the thermocouple and a heating wire, and the cold end of the thermocouple is externally mounted. In the test, a constant current is applied to the heating wire to generate a constant power. At this time, the temperature of the cold junction of the thermocouple can be regarded as the temperature of the fluid, and the temperature of the hot end is the temperature of the Hot-bulb Probe. At this time, the surface is different with the wind speed. The difference of convective heat transfer coefficient leads to the difference of the temperature of the spherical surface, which in turn leads to the difference of thermocouple temperature difference and electromotive force. The surface wind speed can be obtained by measuring the electromotive force. [4] [5]

The Hot-bulb Probe...
models used in the test are all QDF-6 Hot-bulb Probe anemometers. Due to different batches, there are two diameters, 0.6 and 0.8 mm respectively.

Since the thermoelectric potential of the thermocouple needs to be measured, and considering the rotating method is used, a millivolt signal transmitter is required to collect the signal before it passes through the slip ring and transmit it out of the container to prevent transmission in the transmission link. Introduced a third material, after several tests, selected KBM309G millivolt transmitter, all internal capacitors are tantalum capacitors, with working ability under low pressure and discharge area, the minimum test working temperature is reached. At -60 °C. The transmitter consists of 6 wires: two wires for power supply (12V), two wires for 485 communication, and two wires for millivolt signal input. The signal is transmitted out of the container through 485, and is collected outside the container by RS232-RS485 converter on the computer.

The system connection is as shown in Figure 2.

As seen in the figure, there are 6 sets of wind speed measurement modules and 1 backup available. Due to the difference of batches, the size of the sensor and the resistance of the heating wire are different. There are two driving methods in calibration and use: Method 1: All sensors apply the same current and record the output of each sensor; Mode 2: The current of each sensor is different, but the output mv value is the same when the wind speed is guaranteed to be zero. Since the latter applies different currents to the sensors, there is a possibility of manual entry errors in the test. Drive by mode 1, all 0.8mm probes input 56mA current, and 0.6mm probes input 40mA current. The Agilent 5750 power supply delivers constant current with a current resolution of 0.1mA.

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Figure 2 Hot-bulb Probe wind speed measuring system

2.1 Hot-bulb Probe calibration scheme
The following picture shows the actual calibration system:
As seen in the figure, the calibration test was carried out in the KM6F. The turret was used to simulate the wind speed. A 12-channel brush slip ring was installed on the top of the turntable, and four Hot-bulb Probe wind speed sensors were calibrated each time. According to the test, the Hot-bulb Probe wind speed sensor is not sensitive to temperature, and the following calibration conditions are selected:

| Condition number | Pressure (Pa) | Temperature (°C) | Gas composition |
|------------------|---------------|------------------|-----------------|
| 1                | 1400 Pa       | -85              | CO₂             |
| 2                | 1400 Pa       | -80              | CO₂             |
| 3                | 1400 Pa       | -75              | CO₂             |
| 4                | 1400 Pa       | -65              | CO₂             |

At the same time, taking into account some special requirements, the following special conditions are added for commissioning, only for 3-4 sensors in one calibration. Wind tunnel debugging may need to be tested in a 1400Pa environment.

| Condition number | Pressure (Pa) | Temperature (°C) | Gas composition |
|------------------|---------------|------------------|-----------------|
| 1                | 1400          | 22               | air             |
| 2                | 1400          | 22               | CO₂             |
| 3                | 1400          | -55              | CO₂             |

Each working condition is calibrated according to the following list (corresponding to a change in wind speed of about 0.5 m/s per working condition), and each working condition is stable and records 20 seconds of data:

| Condition number | Wind speed (m/s) | Calculation speed (RPM) | Setting rotate speed (RPM) | Real speed (m/s) |
|------------------|------------------|--------------------------|-----------------------------|-----------------|
| 1                | 0                | 0                        | 0                           | 0.000           |
| 2                | 0.5              | 3.485145                 | 3                           | 0.430           |
| 3                | 1                | 6.97029                  | 7                           | 1.004           |
| 4                | 1.5              | 10.45543                 | 10                          | 1.435           |
| 5                | 2                | 13.94058                 | 14                          | 2.009           |
| 6                | 2.5              | 17.42572                 | 17                          | 2.439           |
| 7                | 3                | 20.91087                 | 21                          | 3.013           |
| 8                | 3.5              | 24.39601                 | 24                          | 3.443           |
2.2 Calibration system error analysis

2.2.1 Errors caused by length measurement and speed measurement

After the cantilever is installed, the length measurement is 2.6m using a tape measure. Since the minimum scale is 1mm, the maximum length measurement error is 0.5mm. The rotary table uses a resolver to give the rotation speed. In the calibration, the rotation speed deviation can be controlled within 1RPM due to the wind speed (Line speed) can be expressed as:

\[ V = \frac{RPM \cdot \pi R}{60} = \frac{\pi}{60} \cdot RPM \cdot R \]

The error for speed is
\[ dV = \frac{\pi}{60} \cdot \left[ d(RPM) \cdot R + RPM \cdot d(R) \right] \]

Brought into the calculation table, you can get the error under each calibration wind speed:

| Wind Speed Error (m/s) | Target Wind Speed (m/s) |
|------------------------|-------------------------|
| 0.060                  | 0 5 10 15 20            |
| 0.065                  |                         |
| 0.070                  |                         |
| 0.075                  |                         |
| 0.080                  |                         |

Figure 4 Absolute error

As can be seen from the figure, the error caused by the length measurement and the rotational speed measurement is always about 0.07 m/s, and when the wind speed is higher than 6 m/s, the relative error is always less than 1%.

2.2.2 Error due to disturbance of flow field

When the cantilever rotates inside the space environment simulation device, it will agitate the flow field inside the container, so that there is a deviation between the speed of the probe relative to the wind field and the calibration speed. For this error, the CFD simulation method is used to analyze and establish the grid. The grid of 100,000 is divided into an internal rotation calculation domain and an external fixed calculation domain, as shown in the following figure:

Figure 6 Rotating computing domain
The cantilever motion is simulated by Fluent's mesh connection function, and the transient simulation is performed using the unsteady calculation function until the residual of each period is within the allowable range:

After the calculation is stable, the flow field around the cantilever is as shown below:

As shown in the figure, when the cantilever rotates, it will disturb the flow field in the container. In order to evaluate the influence of the disturbance, draw the flow field velocity curve along the cantilever direction, as shown in the following figure:
According to the calculation, in the limit case, when the wind speed is 15 m/s, when the wind speed sensor is installed more than 0.2 m outside the cantilever, the disturbance of the flow field can be less than 0.5 m/s. The flow velocity distribution on the concentric circles along the center of rotation is shown in the following figure:

![Figure 10 cantilever direction speed distribution](image)

Figure 10 cantilever direction speed distribution

As seen in the figure, when the distance is 1.5 m, the perturbation of the cantilever field is already small.

### 2.2.3 Error due to measuring instrument

According to the measurement instrument description, the measurement accuracy is ±0.2 %F·S when measuring at 0-75 mV, that is, the maximum measurement voltage error is 0.15 mV. According to the sensitivity of different wind speed sensors in different calibration speeds, the measurement error can be calculated. The impact is shown as below:

![Figure 11 the influence of device measurement to wind speed](image)

Figure 11 the influence of device measurement to wind speed

![Figure 12 the influence of device measurement to wind speed](image)

Figure 12 the influence of device measurement to wind speed

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As can be seen from the figure, the maximum error of the measuring instrument is less than 1 m/s in the range of 1 to 15 m/s. However, since the sensor and the transmitter are installed, calibrated and used one-to-one in the test, this part of the error has been minimized in the calibration.

3. Conclusion
This paper achieves the purpose of design of Hot-bulb Probe low-pressure wind speed calibration system. Introduces the composition and structure of the Hot-bulb Probe low-pressure wind speed calibration system. Choose the QDF-6 Hot-bulb Probe anemometers for test. Design the Hot-bulb Probe calibration scheme, calibration conditions. Analyze the calibration system error, including errors caused by length measurement and speed measurement, error due to disturbance of flow field, error due to measuring instrument.

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