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# Hanghua CTA-04 Hotwire Anemometry User Guide


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# Contents

# 1 Introduction

## 1.1 Purpose

The constant-temperature hot-wire anemometer is a scientific instrument widely used in fluid dynamics research. It utilizes a tiny tungsten-wire probe placed in a Wheatstone bridge to measure air velocity, featuring very fine temporal resolution. The system principle is illustrated in the schematic diagram Fig. 1. This article focuses on the usage of the Hanghua hot-wire anemometer, explaining each operational step and providing examples.

## 1.2 Characteristics and Advantages of the Hot-Wire Anemometer

The main functional features of the CTA-04 hot-wire anemometer are as follows:

(1) The CTA-04 hot-wire anemometer is available in two models: dual-channel and four-channel. The dual-channel model can simultaneously use 2 single-wire hot-wire probes or 1 two-wire probe; the four-channel model can simultaneously use 4 single-wire hot-wire probes or 2 two-wire probes.

(2) Through a 485 network, the system can integrate multiple CTA-04 units into a single system, supporting up to 256 channels working simultaneously.

(3) The probe operating resistance range is 1-199 ohms, with a setting precision of 0.1 ohms.

(4) The output modulation circuit features a bias function, allowing the output voltage to be shifted.

(5) The output modulation circuit includes a gain function, offering 5 gain settings: 1, 2, 4, 8, and 16.

(6) The output modulation circuit has a built-in low-pass filter with 7 switchable cutoff frequencies: 10kHz, 5kHz, 1kHz, 500Hz, 100Hz, 10Hz, and 1Hz. The low-pass filter can be turned off.

(7) The device includes a built-in square wave generator for testing frequency response. The square wave frequency ranges from 1-5000Hz, with a default value of 500Hz.

With the support of the DAQ16 data acquisition unit, CR series hot-wire calibrator, and CTALab software, the CTA-04 system can:

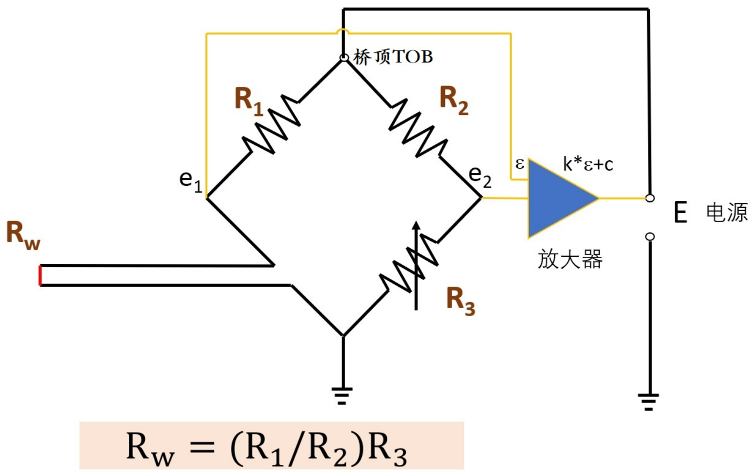



**Figure 1: A schematic of the CTA bridge.**

(1) Set the cold resistance and operating temperature of the hot-wire anemometer;

(2) Adjust the dynamic balance parameters of the hot-wire system;

(3) Adjust post-processing parameters for the output signal, such as signal amplification, bias, and low-pass filtering;

(4) Automatically calibrate the functional relationship between wind speed and output voltage;

(5) Set parameters such as sampling rate, sample count, data storage directory, and file name;

(6) Enable advanced functions such as analyzing measurements from X-type double-wire probes and triple-wire probes.

### 1.2.1 Comparison with Multi-Hole Probes

Compared to traditional techniques such as Pitot tubes and multi-hole probes, which measure velocity based on pressure, the hot-wire anemometer offers the following advantages:

(1) Dynamic Measurement Capability The hot-wire anemometer possesses exceptional dynamic measurement capabilities. It can not only measure average velocity but also resolve velocity fluctuations exceeding 100 kHz. This enables accurate analysis of velocity variations caused by vortices of various scales, as well as the measurement of critical turbulence parameters such as kinetic energy spectra, length scales, and time scales.

(2) Near-Wall Measurement Capability Due to the small geometric size of the probe, it can closely approach wall surfaces to resolve velocity distributions in near-wall regions. This allows for the acquisition of important information, such as velocity distributions in the viscous sub-layer of turbulent boundary layers, and the capture of various dynamic events occurring within the boundary layer.

Compared to Pitot tubes and multi-hole probes, the hot-wire anemometer also has weaknesses that the user should be aware of:

(1) Higher Investment Cost

The price of a hot-wire anemometer is significantly higher than that of pressure-based velocity measurement instruments such as Pitot tubes.

(2) Complexity

A complete hot-wire anemometer system consists of multiple components, including the main unit, data acquisition card, calibrator, and probes. Compared to Pitot tube systems, it is larger and more complex.

(3) Fragile Probes

The core component of a hot-wire probe is an exposed metal wire with a diameter of 5 micrometers, which is prone to oxidation and can be easily damaged even by light contact.

(4) Sensitivity to Environmental Changes

Hot-wire measurements are highly sensitive to temperature variations (a 2% change in velocity measurement per degree Celsius), requiring complex compensation algorithms for correction, with limited effectiveness.

(5) Frequent Calibration and Poor Convenience

The hot-wire anemometer requires setting parameters such as cold resistance, overheat ratio, and system balance. Additionally, square-wave testing is needed to achieve optimal frequency response. It relies on other velocity measurement instruments (e.g., Pitot tubes) for calibration. Hot-wire measurements are susceptible to various factors such as temperature and humidity, and calibration results are often valid only for a limited time.

Despite these weaknesses, the hot-wire anemometer is still widely adopted due to its advantages in dynamic measurement capabilities.

### 1.2.2 Comparison with LDA and PIV

Compared to laser-based velocity measurement methods such as Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV), the hot-wire anemometer offers the following advantages:

(1) Lower Investment Cost:

LDA and PIV systems are significantly more expensive.

(2) No Need for Tracer Particles:

Suitable for environments with high cleanliness requirements.

(3) Better Accuracy in Low Turbulence Scenarios:

In low turbulence environments, optical measurement methods often overestimate turbulence due to uneven scattering of light, making them unsuitable for critical tasks such as determining turbulence levels in wind tunnel test sections. The hot-wire anemometer, however, excels in such scenarios.

(4) Continuous Output Signal:

LDA provides discrete and discontinuous output signals, while the hot-wire anemometer offers continuous signals with better temporal resolution.

(5) Superior Temporal Resolution:

PIV has poor temporal resolution (up to 1 kHz), significantly inferior to the hot-wire anemometer, which can achieve resolutions above 200 kHz.

Despite these advantages, the hot-wire anemometer also has some disadvantages compared to LDA and PIV:

(1) Invasive Measurement:

The hot-wire anemometer is an intrusive measurement method, which may disturb the flow field. In contrast, PIV and LDA are non-invasive.

(2) Temperature Sensitivity:

The hot-wire anemometer requires a constant and spatially uniform flow field temperature. PIV and LDA are unaffected by temperature variations.

(3) Frequent Calibration:

LDA does not require calibration, and PIV only needs calibration before initial use. The hot-wire anemometer, however, requires frequent calibration.

## 1.3 Features and Advantages of Hanghua Hot-Wire Anemometer

Compared to internationally leading brands, the Dalian Hanghua hot-wire anemometer offers the following features:

(1) Late-Mover Advantage: Incorporating newer electronic technologies, making the system more reliable.

(2) New technologies such as "factory calibration" improving ease of use.

(3) Reliable after-sales service.

(4) Free software upgrade services.

(5) Better cost-effectiveness.

# 2 System Composition

## 2.1 Basic Components

A typical hot-wire anemometer system is illustrated in Fig. 2. Descriptions of each component are provided in Table 1. Among them:

(1) CTA04 Hot-Wire Anemometer Main Unit: The hot-wire anemometer main unit is available in dual-channel and four-channel configurations, as shown in Fig. 2a or 2b. A single computer can connect to multiple main units via a RS485 network. For example, a six-channel system can be composed of one four-channel main unit and one dual-channel main unit, while a twelve-channel system can be formed by three four-channel main units.

(2) DAQ16 Data Acquisition Unit: The data acquisition unit includes a built-in NI USB6211 data acquisition card, as shown in Fig. 2c. Specific parameters are listed in Table 3. In addition to the acquisition card, the unit also includes a differential pressure sensor with a measurement range of $\pm 2.1kPa$ and an accuracy of $\pm 0.1\%$ of the full scale.

(3) USB-Serial Cable (Serial Cable): An accessory to the main unit, shown in Fig. 2d, used to connect the computer to the hot-wire anemometer main unit. The computer sends text-format commands through this USB-RS485 converter to the anemometer via the cable to set operating parameters and read the anemometer's status.

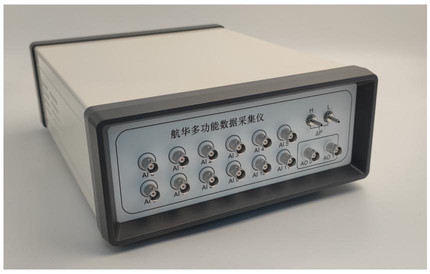
| |
|---|
| This cable contains a USB-to-serial converter chip (FT232) and requires driver installation for proper use. The installation method is detailed in Section B. |

(4) CB02A Probe Connection Cable: An accessory to the main unit, shown in Fig. 2e. One end of the cable features a two-pin LEMO connector (aviation plug), and the other end has two mini-banana female connectors. This cable is specifically designed to connect the Probe port on the front panel of the Hanghua hot-wire anemometer to the Hanghua hot-wire probe.

| |
|---|
| If the user plans to use probes from other companies with the Hanghua hot-wire anemometer, a CB02C cable should be used. If the user plans to use Hanghua probes with other hot-wire anemometers, a CB02B cable should be used. The maximum recommended length of this cable is 5 meters. Exceeding this length will require the usage of a 10kHz low-pass filter, and may affect the dynamic performance of the hot-wire measurements. |

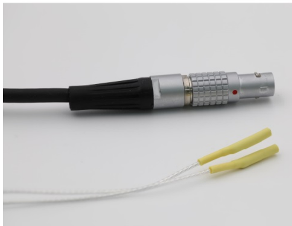
(a) Four-Channel Main Unit

(b) Dual-Channel Main Unit



(c) DAQ16 Signal Acquisition Unit

(d) USB-Serial Cable (Serial Cable)



(e) CB02A Hot-Wire Probe Cable

(f) TS02 Temperature (PT100) Sensor

(g) CB01 Data Cable (BNC Signal Cable)

(h) TypeC Data Cable

(i) HW1A Single-Wire Probe

(j) HW2A Dual-Wire X-Probe

(k) Power Cord

**Figure 2: Four-Channel Hot-Wire Anemometer Main Unit and Standard Accessories**

(5) TS02 Temperature Sensor: An accessory to the main unit, shown in Fig. 2f. The TS02 sensor is a PT100 platinum resistance temperature sensor. One end features a four-pin LEMO connector, which connects to the "Temperature Probe" interface of the hot-wire anemometer to measure temperature.

(6) CB01 Data Cable: An accessory to the main unit, shown in Fig. 2g. Both ends of this cable have BNC connectors, and it is compatible with standard "double-male BNC cables" available on the market. This cable is used to connect the output of the hot-wire anemometer to the analog input of the data acquisition card, as well as the output of the temperature sensor to the input of the data acquisition card.

(7) TypeC-USB Cable:

An accessory to the main unit, as shown in Fig. 2h. This cable is compatible with standard phone TypeC data cables (but not TypeC power cables) and is used to connect the DAQ16 data acquisition unit to the computer. Data is transmitted from the acquisition card to the computer via this cable.

(8) HW1A Single-Wire Probe:

An accessory to the main unit, shown in Fig. 2i. The sensing element of this probe is a tungsten wire with a diameter of $5\mu m$ and a length of approximately $1.5mm$. The total length of the probe is about 90mm, with a dual-prong head length of about 11mm, a main body length of 80mm, and a diameter of 2.6mm (also available in 2.4mm, upon request). The sensing element is spot-welded to the tips of the two prongs and faces the incoming flow. The tail of the probe has two flexible wires, each about 20cm long, ending with mini-banana male connectors that connect to the Probe port of the hot-wire anemometer via a CB02A cable. The geometric dimensions are shown in Fig. A.2a.

(9) HW2A Dual-Wire X-Probe:

An accessory to the main unit, shown in Fig. 2j. The sensing elements of this probe are two independent tungsten wires, each with a diameter of $5\mu m$ and a length of about $2mm$, angled at $45^o$ and $-45^o$ relative to the probe's main axis. The angle between the two wires is $90 \pm 1.0^o$. The total length of the probe is about 90mm, with a main body length of 80mm and a diameter of 3.7mm. The geometric dimensions are shown in Fig. A.2c. The head has four prongs, two long and two short, with lengths of 11mm and 10mm, respectively. One long and one short prong form a pair, and each tungsten wire is welded to the tips of a pair of prongs. To distinguish between the two wires, the prongs and connectors of one set are painted red, while the other set is black. The two sets of connectors are connected to two different Probe ports on the hot-wire anemometer using CB02A cables.

(10) HW3A Tripple-Wire X-Probe:

An accessory to the main unit. The sensing elements of this probe are three independent tungsten wires, each with a diameter of $5\mu m$ and a length of about $2.5mm$. These three wires are positioned orthogonally. The angle between the two wires is $90 \pm 1.0^o$. The total length of the probe is about 90mm, with a main body length of 80mm and a diameter of 4.5mm.

Table 1: Standard Configuration of a CTA04 Hanghua Hot-Wire Anemometer System

| No. | Item | Quantity[1] | Function |
|---|---|---|---|
| 1 | CTA04 Hot-Wire Anemometer Main Unit, Fig. 2a or 2b | 1 | Contains a constant-temperature hot-wire bridge, supplies current to the hot-wire probe, and maintains its resistance constant; outputs analog voltage signals related to wind speed. |
| 2 | DAQ16 Data Acquisition Unit, Fig. 2c | 1 | Collects voltage signals output by the anemometer. Additionally, the unit includes a built-in pressure sensor for measuring the outlet velocity of the calibrator. |
| 3 | USB-Serial Cable (Serial Cable), Fig. 2d | 1 | Connects the "Serial Port 1" on the rear panel of the hot-wire anemometer to the computer's serial port for setting and debugging parameters. |
| 4 | CB02A Probe Connection Cable, Fig. 2e | 2/4 | Connects the Probe port of the hot-wire anemometer to the hot-wire probe. |
| 5 | TS02 Temperature Sensor (PT100 Platinum Resistor), Fig. 2f | 1 | Connects to the "Temperature Probe" interface of the hot-wire anemometer to measure temperature. |
| 6 | CB01 Data Cable (BNC Data Cable), Fig. 2g | 3/5 | Connects the output of the hot-wire anemometer, the output of the temperature sensor, and the input of the data acquisition card (DAQ16). |
| 7 | TypeC-USB Cable, Fig. 2h | 1 | Compatible with standard phone Type-C cables, used to connect the DAQ16 data acquisition unit to a computer. |
| 8 | HW1A Single-Wire Probe, Fig. 2i | 2/4 | Tungsten wire with a diameter of $5\mu m$, approximately $1.5mm$ in length, facing the incoming flow, measures changes in velocity magnitude. |
| 9 | HW2A Dual-Wire X-Probe, Fig. 2j | 1/2 | Tungsten wire with a diameter of $5\mu m$, measures two-dimensional velocity components in a plane. |
| 10 | Power Cord, Fig. 2k | 2 | |

[1] The numbers on either side of the "/" symbol represent the quantities for the dual-channel and four-channel systems, respectively.

Table 2: Parameters of the CTA04 Hot-Wire Anemometer Main Unit

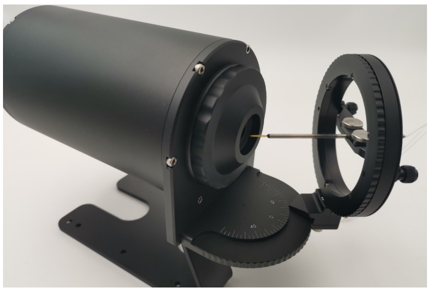
| | CTA04-Pro | CTA04-Edu |
|---|---|---|
| Medium | Air | Air |
| Velocity Measurement Range ($m/s$) | 0.1 – 300 | 0.1 – 150 |
| Frequency Response (kHz) | $\leq 200$ | $\leq 50$ |
| Probe Operating Resistance ($\Omega$) | $1 \sim 199$ | $1 \sim 199$ |
| Number of Channels per Unit | 2, 4 | 2, 4 |
| Dimensions (Width x Height x Length) (mm) | 255x155x330 (4-channel), 185x155x330 (2-channel) | 255x155x330 (4-channel), 185x155x330 (2-channel) |
| Weight (kg) | 2.8 (4-channel), 1.9 (2-channel) | 2.8 (4-channel), 1.9 (2-channel) |
| Output (V) | $\pm 5.0$ | $\pm 5.0$ |

Table 3: Parameters of the DAQ16 Data Acquisition Unit

| | Parameters |
|---|---|
| Manufacturer | National Instrument |
| Model | USB 6211 |
| Number of Analog Input Channels | 16 (single-ended, including 4 occupied channels) |
| Sampling Resolution | 16-bit |
| Input Range | $\pm 10$ V |
| Maximum Sampling Frequency | 250 kHz |
| Number of Analog Output Channels | 2 |
| Dimensions | 213*127*48 mm |
| Weight | 300 g |
| Power Supply | 12V DC, 10 W |
| Pressure Sensor Range | $\pm 2.1kPa$ |
| Pressure Sensor Accuracy | $0.1\%F.S.$ (i.e., $\pm 2.1Pa$) |

## 2.2 Optional: CR04 Manual Calibrator

The output of a hot-wire anemometer is analog voltages, which require a calibration process to convert the voltage signal into flow velocity. Calibration involves recording the mean voltage output in a series of environments with known flow velocities. Typically, the calibration environment should have low turbulence, meaning the flow velocity should not vary significantly over time.



**(a) CR04 Calibrator and Manual Rotating Table**

**(b) Frequency Drive for the Blower**

**(c) Blower**

**(d) Corrugated Hose**


**(e) Blower Power Cable**

**(f) Frequency Drive Speed Control Cable**

**(g) Pressure Measurement Tubing**

**Figure 3: Components of the CR04 Calibrator**

The components of the CR04 manual calibrator are shown in Figure 3, with details provided in Table 4. It mainly consists of the following parts:

(1) CR04M Manual Calibrator, Figure 3a

The calibrator is a jet device with an outlet diameter of 10 mm, an outlet velocity range of 2-60 m/s, and a turbulence intensity less than 0.5%. The back panel of the jet device is the air inlet, connected to the blower outlet via a plastic corrugated hose (Figure 3d). The static pressure chamber upstream of the nozzle is equipped with a total pressure collection port, connected to the calibrator pressure port (H port) of the DAQ16 data acquisition unit (Figure

2c) using flexible tubing (Figure 3g, silicone tubing with an inner diameter of 2 mm). The jet device includes a flow conditioning device, with a contraction ratio of 100:1 in the contraction section.

(2) Manual Rotating Table, Figure 3a

A manual angle adjustment mechanism integrated with the jet device. The roll angle (Roll) range between the probe axis and the jet flow direction is $\pm 90°$, and the cone angle (Cone) range for probe rotation around the axis is $0 - 360°$. The adjustment resolution is $5°$. The angle definitions are detailed in Section K.

(3) Blower, Figure 3c

A high-pressure blower with a power supply of 220 VAC, 500 W.

(4) Frequency Drive, Figure 3b

Used to control the blower speed. It can operate in both automatic and manual fixed-speed modes. The setup method is detailed in Appendix Section G.

(5) Power Cable, Figure 3e

Connects the blower, frequency drive, and power supply. One end has a four-pin connector for the blower (the long yellow-green wire is grounded, and the other red, green, and black wires connect to the motor's three-phase terminals, usually pre-connected). The other end has a six-pin connector for the frequency drive (details in Section 3.3).

(6) Frequency Drive Control Cable, Figure 3f

This cable has a BNC connector on one end and bare wires on the other. It connects the frequency drive (FV, GND ports) to the analog voltage output (AO) port of the data acquisition unit to control the blower speed. The software can send analog voltage signals (0-10 V) through the AO port to adjust the speed, enabling automatic calibration with automatic wind speed adjustment. The frequency drive can also be set to manual mode, where the speed is adjusted using the potentiometer on the front panel. Specific operations are detailed in Appendix Section G.

## 2.3 Optional: CR05 Automatic Calibrator

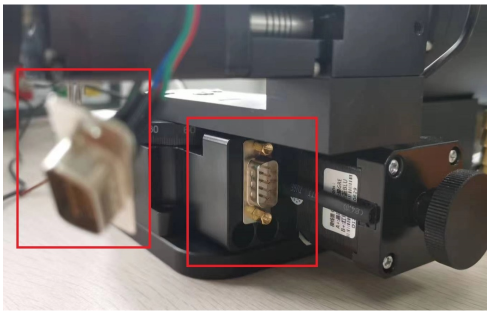
The CR05 automatic calibrator builds on the CR04 by adding automatic angle adjustment capabilities. Driven by two stepper motors, the probe's pitch and yaw angles

Table 4: Components of the CR04 Manual Calibrator

| No. | Item | Quantity | Function |
|---|---|---|---|
| 1 | CR04 Jet Device, Figure 3a | 1 | Jet device with a 10 mm outlet diameter, outlet velocity range of 2-60 m/s, turbulence intensity less than 0.5%, and a total pressure collection port in the static pressure chamber. |
| 2 | Manual Rotating Table, Figure 3a | 1 | Manual angle adjustment mechanism. Roll angle (Roll) range: $\pm 90°$, Cone angle (Cone) range: $0 - 360°$. |
| 3 | Blower, Figure 3c | 1 | 220 V, 500 W, single-phase. |
| 4 | Frequency Drive, Figure 3b | 1 | 220 V, 1 kW, controls blower speed. |
| 5 | Custom Power Cable, Figure 3e | 1 | Connects the blower, frequency drive, and power supply. |
| 6 | Frequency Drive Control Cable, Figure 3f | 1 | Connects the frequency drive to the analog voltage output port of the data acquisition unit to control blower speed. |
| 7 | Plastic Corrugated Hose, Figure 3d | 1 | Connects the blower outlet to the calibrator inlet. |
| 8 | Pressure Measurement Tubing, Figure 3g | 1 | Silicone tubing with an inner diameter of 2 mm, connects the pressure measurement hole on the calibrator to the pressure port on the DAQ data acquisition unit. |

relative to the incoming flow can be continuously adjusted within ±50°. The adjustment accuracy is better than 0.1°. The angle definitions are detailed in Appendix Section K. The components required for the CR05 are listed in Table 5, with some components overlapping with the CR04 (see Table 4). The non-overlapping components are shown in Figure 4.

(a) CR05 Automatic Calibrator



(b) Stepper Motor Cable Interface

(c) Stepper Motor Control Cable

(d) Rear Panel of the Motion Controller

(e) Front Panel of the Motion Controller

**Figure 4: Components of the CR05 Calibrator. Other required components are shown in Figure 3.**

The main components of the CR05 automatic calibrator are as follows:

(1) CR05 Jet Device, Figure 4a

The jet device has an outlet diameter of 15 mm, an outlet velocity range of 2-60 m/s, and turbulence intensity less than 0.5%. The static pressure chamber is equipped with a total pressure collection port. The back panel of the jet device is the air inlet, connected to the blower outlet via a plastic corrugated hose (Figure 3d). The jet device has a pressure measurement hole at the bottom, connected to the calibrator pressure port (H port) of the DAQ16 data acquisition unit (Figure 2c) using pressure measurement tubing (Figure 3g,

Table 5: Components of the CR05 Automatic Calibrator

| No. | Item | Quan. | Function |
|---|---|---|---|
| 1 | CR05 Jet Device, Figure 4a | 1 | Jet device with a 15 mm outlet diameter, outlet velocity range of 2-60 m/s, turbulence intensity less than 0.5%, and a total pressure collection port in the static pressure chamber. |
| 2 | Automatic Rotating Table, Figure 4b | 1 | Automatic angle adjustment mechanism. Adjusts the probe's pitch angle (Pitch) range: ±50°, yaw angle (Yaw) range: ±50°, powered by stepper motors. |
| 3 | Motion Controller, Figures 4e and 4d | 1 | Controls the stepper motors. |
| 4 | Stepper Motor Control Cable, Figure 4c | 2 | Connects the rotating table to the motion controller. |
| 5 | TypeC Data Cable, Figure 2h | 1 | Connects the computer to the controller. |
| 6 | Blower, Figure 3c | 1 | 220 V, 500 W, single-phase. |
| 7 | Frequency Drive, Figure 3b | 1 | 220 V, 1 kW, controls blower speed. |
| 8 | Custom Power Cable, Figure 3e | 1 | Connects the blower, frequency drive, and power supply. |
| 9 | Frequency Drive Control Cable, Figure 3f | 1 | Connects the frequency drive to the analog voltage output port of the data acquisition unit to control blower speed. |
| 10 | Plastic Corrugated Hose, Figure 3d | 1 | Connects the blower outlet to the calibrator inlet. |
| 11 | Pressure Measurement Tubing, Figure 3g | 1 | Silicone tubing with an inner diameter of 2 mm, connects the pressure measurement hole on the jet device to the pressure port on the DAQ16 data acquisition unit. |

silicone tubing with an inner diameter of 2 mm). The jet device includes a flow rectifier, with a contraction ratio of 100:1. The blower, frequency drive, and other components are the same as those in the CR04 calibrator.

(2) Automatic Rotating Table, Figure 4b

This automatic angle adjustment mechanism includes two stepper motors, which adjust the probe's pitch angle (Pitch) and yaw angle (Yaw), respectively, both within a range of ±50°. The angle definitions are detailed in Appendix Section K.

(3) Motion Controller, Figures 4e and 4d

Contains three independently operating stepper motor controllers. The motion controller connects to the computer via a TypeC data cable (Figure 2h) and to the stepper motors via stepper motor control cables (Figure 4c). The motion controller receives commands from the computer via the serial port (COM port) and controls the stepper motors accordingly. The specific port can be checked through the "Device Manager."

## 2.4 Optional: TM02 Traverse System

The TM02 traverse system (Figure 5) is a tool for precisely controlling the probe position to assist in measuring flow field velocity distributions. Its components are listed in Table 6.

(1) Sliding Module

The Hanghua TM02 module uses a dual linear rail and lead screw sliding table design. The travel range is 200-500 mm, with a positioning accuracy of 0.1 mm/500 mm. The horizontal load capacity is 10 kg, and the vertical load capacity is 5 kg. Users can choose 1 to 3 modules based on their needs.

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|---|
| Hanghua only provides the modules and basic connectors and is not responsible for the design and implementation of on-site installation solutions. |

(2) Motion Controller, Figures 4e and 4d

Contains three independently operating stepper motor controllers. It is compatible with the CR05 automatic calibrator (only one unit needs to be purchased). The motion controller connects to the computer via a TypeC data cable (Figure 2h) and to the stepper motors via stepper motor control cables (Figure 4c). The motion controller receives commands from the computer via the serial port and controls the stepper motors accordingly.

**Figure 5: A typical traverse system consists of 1 controller, 3 modules, cables, and connectors.**

Table 6: Components of the TM02 Traverse System

| No. | Item | Quantity | Function |
|---|---|---|---|
| 1 | TM02 Linear Sliding Module and Connectors, Figure 5 | 1-3 | Travel range: 200-500 mm, positioning accuracy: 0.2 mm/m, load capacity: horizontal 10 kg, vertical 5 kg. |
| 2 | Motion Controller, Figures 4d and 4e | 1 | Controls the stepper motors. |
| 3 | Stepper Motor Control Cable, Figure 4c | 1-3 | Connects the rotating table to the motion controller. Some products have this cable integrated with the sliding module. |
| 4 | TypeC Data Cable, Figure 2h | 1 | Connects the computer to the controller. |

# 3 Hardware Connections

## 3.1 Connecting the Main Unit and Data Acquisition Unit

The main unit requires connections for the power cable, serial cable, temperature probe, temperature probe output cable, hot-wire probe cable, and hot-wire probe output cable. The specific steps are as follows:

Step 1: Connect the power cables of the anemometer and the data acquisition unit (Figure 2k).

Step 2: Use the serial cable (Figure 2d) to connect the computer's USB port to the main unit's rear panel serial port PORT1, as shown in Figure 6.

Step 3: Connect the TS02 temperature sensor (PT100 platinum resistor, Figure 2f) to the "Temperature" port on the front panel of the main unit. Ensure that the red marker on the LEMO connector (aviation plug) aligns with the red marker on the port, and the red dot on the plug, as shown in Figure 7. Note: If you do not feel a clear "click" sound when inserting, do not push in using force. Remove the connector and check the condition of the internal copper pins to ensure they are not bent. Additionally, **search for "how to plug and unplug LEMO connectors"** in google for guidance.

Alternatively, users can connect the TS02 temperature sensor to the "Temp Measurement" port on the rear panel of the data acquisition unit, which directly connects the temperature sensor output to the AI12 port of the data acquisition card.

Step 4: If the user uses the "Temperature Probe" interface on the front panel of the hot-wire anemometer to measure temperature, use the CB01 cable (with BNC connectors on both ends, Figure 2g) to connect the "Temperature Output" interface on the front panel of the main unit to any analog voltage input (AI) port on the front panel of the data acquisition unit, such as the AI6 port in the second row.

If the user chooses to use the "Temp Measurement" port on the rear panel of the data acquisition unit to measure temperature, no CB01 cable is needed, as the data acquisition unit internally connects the temperature output to the AI12 port.

Step 5: Connect the LEMO connector of the CB02A cable (Figure 2e) to the "Hot-wire Probe" interface on the front panel of the main unit. Ensure that the red markers on the plug and socket align (the red dot on the plug should point to the 3 o'clock position). LEMO connectors have a self-locking mechanism, so do not force them during insertion or removal.

Step 6: Use the CB01 cable (Figure 2g) to connect the "Hot-wire Output" interface on the front panel of the main unit to any AI port on the front panel of the data acquisition unit, such as connecting Channel A output to AI0 and Channel B output to AI1.

Step 7: Use the TypeC cable (Figure 2h) to connect the computer to the data acquisition unit.

## 3.2 Using a Self-Provided Data Acquisition Card

If the user does not use the Hanghua multifunctional data acquisition unit but instead chooses his/her own National Instrument(NI) data acquisition (daq) unit, they can follow the method described in the previous section to connect the analog voltage output of the hot-wire to AI0 and AI1 in their daq card, and connect the temperature voltage output to any other available AI port.

If the user uses a data acquisition unit from another company (not NI), they will not be able to use the CTALab software for data acquisition.

> The Hanghua DAQ16 data acquisition unit includes a built-in pressure sensor. If the user does not purchase the DAQ16, they will need to prepare an NI data acquisition card and a pressure sensor to use the automatic calibration function of the CTALab software.

## 3.3 Connecting the CR04 Calibrator

If the user uses the Hanghua CR04 manual calibrator, follow the connections shown in Figure 8. Specific steps include:

Step 1: Connect the 4-pin end of the custom power cable (Figure 3e) to the blower (black, red, and green wires connect to U, V, and W, respectively, and yellow connects to ground). This step is usually completed in factory.

Step 2: Connect the blue, brown, and yellow wires from the 6-pin connector to the left side of the frequency drive terminal box (blue to R, brown to T, yellow to Ground), as shown in Figure 8.

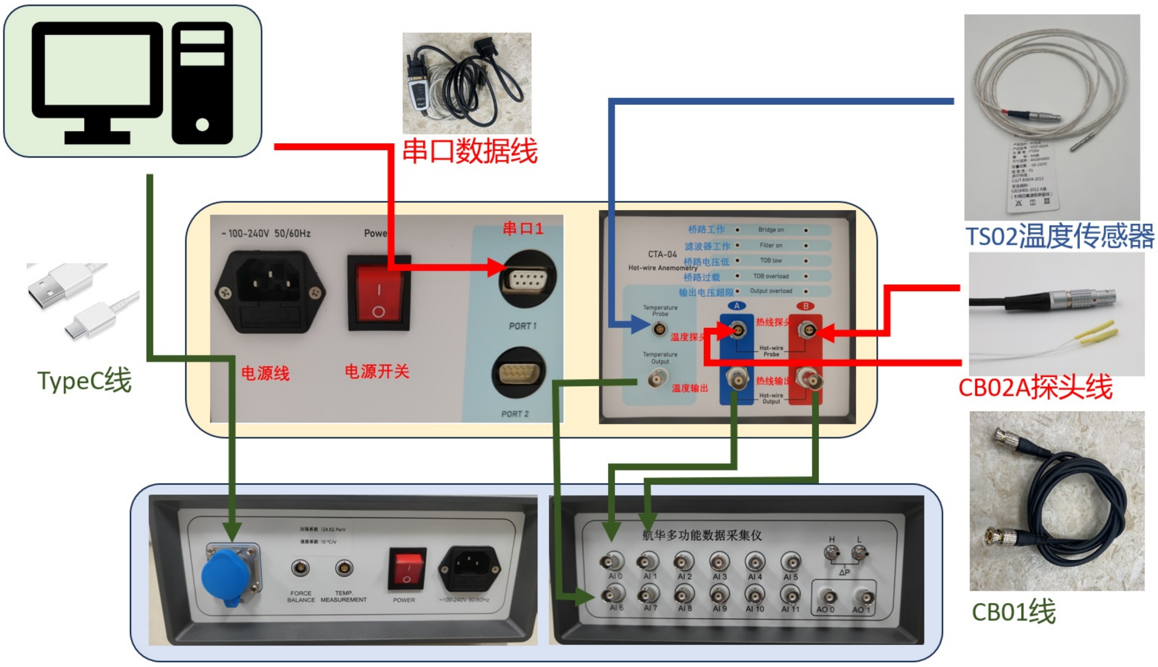



**Figure 6: Connection method between the main unit, data acquisition unit, and computer**


**(a) "Temperature Sensor" port on the front panel of the main unit**

**(b) TS02 temperature sensor plug**

**Figure 7: Usage of the LEMO connector for the temperature sensor**

Step 3: Connect the red, green, and black wires from the 6-pin connector to the U, V, and W terminals on the right side of the frequency drive terminal box, as shown in Figure 8.

| |
|---|
| If the flow velocity is found to be much lower than expected, it may be due to reverse rotation of the blower. Swap any two of the red, green, and black wires in the 6-pin connector to correct the blower's rotation. Make sure to disconnect power cable before making any change. |

Step 4: Connect the bare wire end of the BNC cable (Figure 3f) to the frequency drive input (red to FV, black to GND), and connect the BNC connector to the analog output port AO-0 of the data acquisition unit. The software adjusts the wind speed through this connection. If the user prefers manual wind speed adjustment, refer to the "Manual Wind Speed Adjustment" section (Appendix Section G).

Step 5: Connect the flexible tubing (Figure 3g) from the total pressure measurement port on the calibrator (bottom left of Figure 8) to the "H" pressure port on the upper right of the front panel of the multifunctional data acquisition unit (inside the DAQ16, the analog voltage output of the pressure sensor is connected to the AI-13 port of the data acquisition card).

Step 6: Use the corrugated hose (Figure 3d) to connect the calibrator inlet to the blower outlet.

## 3.4 Connecting the CR05 Calibrator

The installation of the blower, frequency drive, corrugated hose, and pressure tubing for the CR05 calibrator is the same as for the CR04 (see Steps 1-6 in Section 3.3). The difference is that the CR05 calibrator's angle adjustment mechanism is controlled by stepper motors, requiring the connection of the motor controller as shown in Figure 9. Specific steps are as follows:

Step 1: Use the stepper motor cable (Figure 4c) to connect the yaw motor interface to the X interface on the motion controller (Figure 4d). Ensure the LEMO connector aligns with the red marker.

Step 2: Use the stepper motor cable to connect the pitch motor interface to the Y interface on the motion controller (Figure 4d).

Step 3: Use the TypeC cable to connect the computer to the motion controller (Figure 4e).

| |
|---|
| The specific port number for communication between the computer and the motion controller can be found under the "Ports" option in the computer's "Device Manager." |

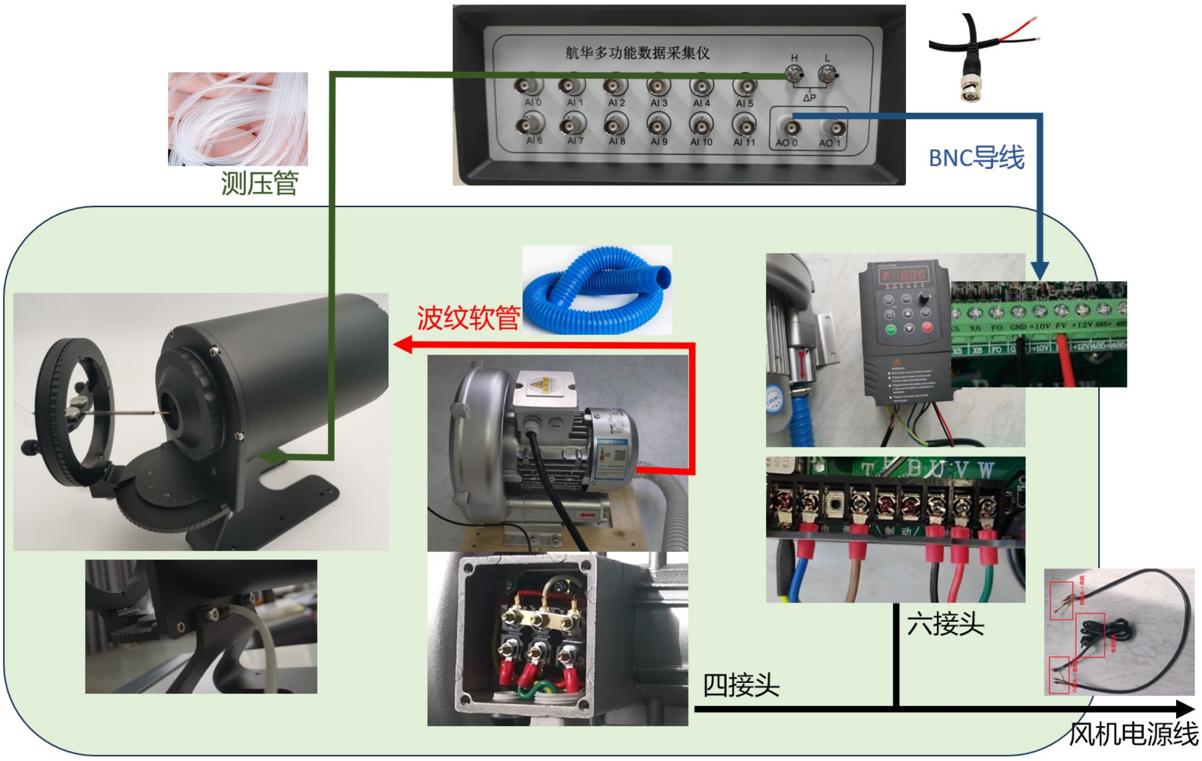



Figure 8: Wiring method for the CR04 manual calibrator

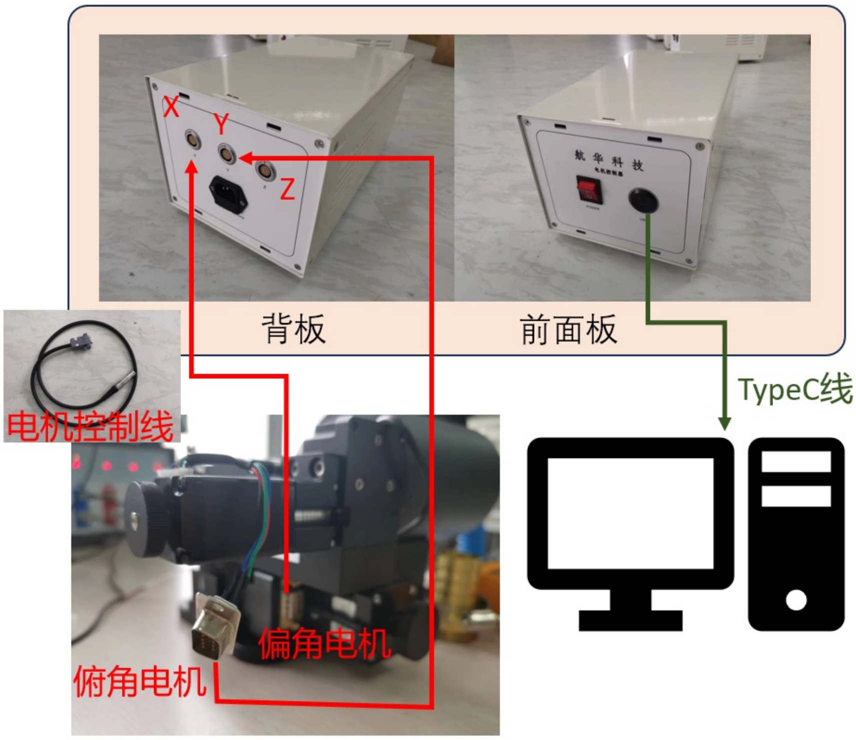



Figure 9: Wiring method for the CR05 automatic calibrator

## 3.5 Powering On

After completing the wiring tasks described in the previous section, proceed with the following steps:

Step 1: Turn on the power switches of the anemometer and data acquisition unit (switch from O to I).

Step 2: Plug the blower power cable into the socket.

Step 3: If applicable, turn on the motion controller switch.

### 3.5.1 Power-On Check

After powering on, perform the following checks:

(1) The power switch light on the rear panel of the anemometer main unit is on.

(2) The power switch light on the rear panel of the data acquisition unit is on.

(3) The front panel of the blower frequency drive is lit, with a digital display.

(4) The power switch light on the motion controller panel is on.

(5) The stepper motors are locked and require significant force to rotate.

If all these conditions are confirmed, the system is correctly powered and ready for the next steps.

### 3.5.2 Main Unit Status Lights

In addition to the system indicator lights described in the previous section, the front panel of the hot-wire anemometer main unit has a series of status indicator lights, as shown in Figure 10. These lights (from top to bottom) and the recommended user responses are:

(1) If the bridge circuit is working, the "Bridge on" indicator light is on.

(2) If a low-pass filter is working, the "Filter on" yellow light is on.

- In the CTALab software "Settings" tab, selecting "No Filter" for the low-pass filter cutoff frequency will turn off this light.

(3) The internal bridge circuit operates within a voltage range of 0.5V-9V. If the bridge top voltage (TOB, see Figure 1) is below 0.5V, the "TOB low" indicator light will turn on.

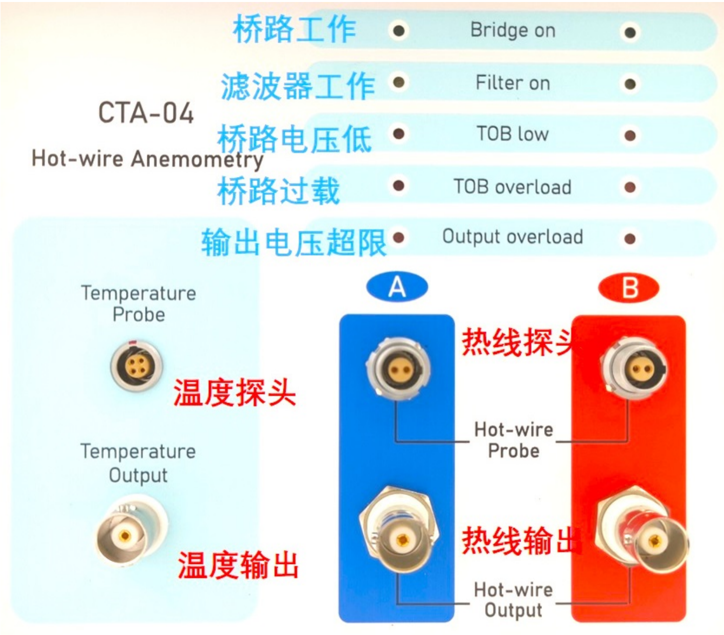



**Figure 10: Front panel photo**

- Typically, this light indicates that the hot-wire probe or cable is damaged. Please check the probe resistance after powering off.
- In some cases, the bridge may be unbalanced, causing this light to turn on. Adjust the "Balance" parameter in the CTALab software "Settings" tab.

(4) If the bridge top voltage required to maintain the hot-wire probe at a constant temperature exceeds 9V, the "TOB overload" red indicator light will turn on.

- Due to the bridge circuit's voltage range limitation of 0.5-9V, the circuit cannot provide more current to heat the probe. It is recommended to reduce the overheat ratio to lower the hot-wire operating temperature.

(5) The effective output voltage range is -5V to +5V. If the bridge circuit and output circuit settings are unreasonable, causing the actual voltage to exceed this range, the "Output overload" red indicator light will turn on.

- In the CTALab software "Settings" tab, set the "Gain" to 1 and adjust the "Offset Voltage" to keep the output within $\pm 5V$.

In practice, other situations may arise, including:

(1) Both the "TOB low" and "TOB overload" lights are faintly lit. This indicates that the system is oscillating and not stable. The balance parameter (Balance)

needs to be reset.

(2) All lights are off: Check if internal components of the anemometer have shifted in position. Severe impacts may cause internal parts to loose and to move with in case, blocking the front panel LED lights. In this case, the system can still be used normally, but the front panel LED lights will not be visible.

## 3.6 Probe Resistance Measurement

If using the probe for the first time, keep it in the box and do not remove the seal. First, measure the resistance. The cold resistance of Hanghua hot-wire probes is approximately:

- HW1A: 4-6 Ω
- HW1AH: 2-3 Ω
- HW2A: 5-8 Ω
- HW2AH: 3-4 Ω
- HW3A: 7-11 Ω.

| If the probe seal remains intact, Hanghua provides free repair services for damaged probes. |
|---|

The cold resistance, $R_{20}$, is the probe resistance at a room temperature of 20°C. This is an important parameter for the operation of the hot-wire anemometer and must be accurately provided to the anemometer software. We recommend measuring it after each probe connection or disconnection. The specific method is:

Step 1: Use a thermometer to measure the current room temperature $T$.

Step 2: Use a resistance meter (or multimeter) to measure the resistance $R$ between the mini-banana connectors at the end of the probe cable, as shown in Figure 11.

| Do not directly touch the probe tip to measure resistance, as the probe may be damaged! |
|---|

Step 3: Calculate $R_{20}$ using the metal resistance change formula:

$$R/R_{20} = 1 + \alpha_t(T - 20) \tag{1}$$

where the temperature coefficient of tungsten is $\alpha_t = 0.0045°C^{-1}$. Example: If $T = 30°C$ and the measured value is $R = 5.0\Omega$, the cold resistance of the probe should be:

$$R_{20} = \frac{R}{1 + \alpha_t(T - 20)} = \frac{5.0\Omega}{1 + 0.0045(30 - 20)} = 4.785\Omega \tag{2}$$

Note: The resistance of new probes may change during initial period of use. Therefore, new probes need to undergo annealing before measurement: operate continuously at an overheat ratio of 1.8 for more than 12 hours to stabilize the probe resistance. Cooling with air is not necessary during annealing.

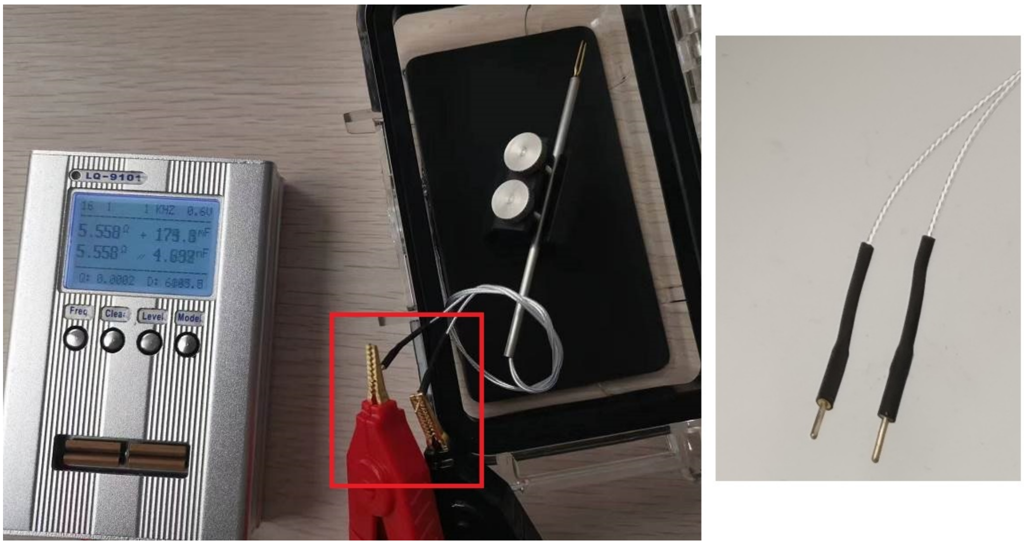


**Figure 11: Cold resistance measurement**

## 3.7 Connecting the Probe

After measuring the probe resistance, remove the probe from the box, install it on the experimental setup, and connect the cables. Note that the connection method for Hanghua probes differs from Dantec probes in the following ways:

(1) The tail of the Hanghua probe has a pair of wires connected to mini-banana plugs, while Dantec probes have pin-type connectors (a pair of needles).

(2) Hanghua probes are directly connected to the anemometer via the CB02A cable, while Dantec probes are connected to a Dantec stem, which is then connected to the anemometer via a cable.

(3) The probe cable interface on the Hanghua anemometer is a two-pin LEMO connector, while Dantec uses a BNC connector.

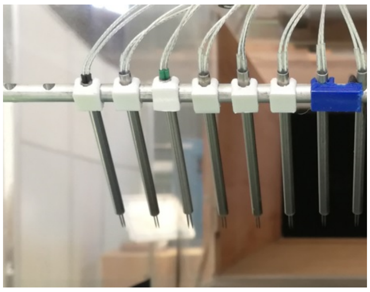
### 3.7.1 Removing the Probe

**The tip of the hot-wire probe is extremely fragile and must not be touched.** Any form of light contact can damage the probe. Therefore, users should pay attention to the following points:

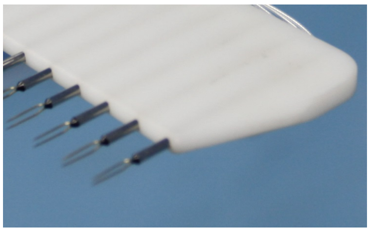
(1) During operation, always keep your eyes on the probe tip, and ensure your view is not obstructed.

(2) Use both hands and operate slowly.

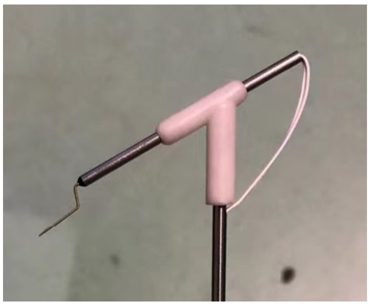
(3) Users are advised to refer to the following video for guidance:
https://www.bilibili.com/video/BV1nk4y1p7RB/



(a) Fixture 1



(b) Fixture 2



(c) Fixture 3

(d) CR04 Calibrator Fixture

**Figure 12: Several Typical Fixtures**

### 3.7.2 Installing the Probe

After removing the probe, users need to install it on the fixture of the experimental setup. The fixture is not supplied by Hanghua, and shall be designed and fabricated by the user. The dimensions of the probe required for designing the fixture are provided in Appendix Section A. We do not recommend using tape, nylon ties, or similar methods unless for temporary measurements.

When installing the probe, the axis of the probe body should be as parallel as possible to the flow direction to minimize interference with the flow. When using the single-wire HW1 series probes, the sensing element (tungsten wire) must be perpendicular to the flow direction. If the experimental setup has limited space and the HW1A probe cannot be directly aligned with the flow, users may consider using right-angle probes (HW1E, HW1F) or 45-degree angled probes (HW1G) to meet the requirements. Relevant probe information can be found in Appendix Section A.

When using the CR04 calibrator for calibration, the probe must be installed on the CR04 calibrator fixture. Users should first loosen the two silver nuts (see Figure 12d), push the clamp plate backward to fully open it, place the probe body in the middle slot, slowly push the clamp plate back, gently tighten the silver nuts (do not fully tighten yet), and adjust the probe so that the tungsten wire is approximately 1 cm away from the jet outlet. Finally, tighten the silver nuts. After installation, users need to rotate the calibrator fixture to align the probe body axis with the flow direction.

### 3.7.3 Connecting the Probe

The two mini-banana plugs at the tail of the probe (Figure 10) are connected to the two mini-banana sockets at one end of the CB02A probe cable (Figure 2e). The sensing element (tungsten wire) has no polarity, so the banana plug connections can be paired arbitrarily. The mini-banana plugs fit tightly initially and may require some force to insert or remove. Over time, they may loosen due to wear. If the connection becomes loose, the connectors need to be replaced.

| |
|---|
| Always ensure the bridge circuit is turned off when inserting or removing the probe to avoid damaging by the electric current surge. |

# 4 Software

## 4.1 Preparation

### 4.1.1 Obtaining the Software

Users can download the latest CTALab 1.0 series software for free from the Hanghua official website:

http://www.hanghualab.com/nd.jsp?id=95&fromMid=468

If you purchased the anemometer main unit and the accompanying DAQ16 data acquisition and CR04 calibration equipment, you need to install:

(1) FTDI driver, Section 4.1.3. The FTDI chip driver enables USB-to-serial conversion.

(2) CTALab 1.0 Hanghua Anemometer Application, Section 4.1.4. This software is specifically designed for the Hanghua CTA04 series hot-wire anemometer, DAQ16 data acquisition unit, CR series calibrator, and TM series traverse system. The CTALab software for Hanghua hot-wire anemometers has the following basic functions:

- Communicating with the main unit to switch the bridge, set cold resistance, set overheat ratio, and set balance parameters;
- Setting acquisition parameters and storing data;
- Communicating with other Hanghua devices, driving the calibrator for automatic calibration, and driving the traverse system for measurements at different positions.

If you only have the anemometer main unit, we recommend installing:

(1) FTDI driver, see Section 4.1.3 and Appendix B;

(2) Serial communication assistant (or any other Serial Port Utility software, there are plenty of this type of software), see Appendix Section D.

### 4.1.2 System Requirements and Basic Functions

The CTALab software has certain requirements for the computer's processing power. We recommend the following computer configuration:

- Intel I5 or higher CPU; 8GB or more RAM; 500GB or larger hard drive;
- Windows 10 or Windows 11, 64-bit system;

☞ A display resolution of at least 1280*960. Resolutions lower than this may cause parts of the software interface to be outside the display area, requiring frequent scrolling.

### 4.1.3 Installing the FTDI Driver

The FTDI driver is essential for the USB-to-serial cable's built-in chip and is a mandatory installation for the Hanghua hot-wire anemometer. The installation process is detailed in Appendix B.

### 4.1.4 Installing the Hanghua CTA04 Application Software: CTALab

Users can:

- Locate the 'setup.exe' file on the system installation disk (or download it from the URL provided in the previous section, then extract and find the 'setup.exe' file), and click to run it (Figure C.1a);
- Follow the prompts to complete the installation of the Hanghua hot-wire anemometer control program (steps are detailed in Appendix C);

  | Avoid installing the program on the C drive to minimize permission-related issues. |
  |---|

- The program will automatically install hardware drivers such as NI DAQmx and NI VISA:
  - NI DAQmx is a free data acquisition card driver software provided by National Instruments. The CTALab application software calls NI DAQmx's built-in functions to set acquisition parameters, collect data, and save it;
  - NI VISA is a free serial communication programming driver software provided by National Instruments. The CTALab application software calls NI VISA to generate control commands, which are then modulated by the FTDI program installed in Section 4.1.3 and sent to the USB port to read and control the hot-wire anemometer's operating parameters.
  - The installation process may take some time, so please be patient.

After the installation is complete:

- A CTALab application icon will appear on the Windows desktop (if it does not appear, navigate to the installation directory and locate the executable '.exe' file).

- After successful installation, a 'data' directory will appear in the installation directory. This directory contains probe calibration information and default device parameter files in text format. The software will call files from this directory, so users should not directly modify the files in this directory to avoid runtime errors.

### 4.1.5 Data Acquisition Cards

The driver software for data acquisition cards varies depending on the user's situation. If the user:

- Purchased the Hanghua DAQ16 data acquisition card:

  The device drivers NI-DAQmx and NI-VISA have already been installed in Section 4.1.4. Users can proceed directly to the next section (Section 4.1.6) to use the CTALab software;

- Did not purchase the DAQ16 but has other similar devices from National Instruments (NI USB6210, 6211):

  Users can use the Hanghua CTALab software. The device drivers included in this software can drive all computer-based data acquisition hardware from National Instruments (note that PXI and CompactRIO systems are not supported). Refer to the following link for details:

  https://www.ni.com/en/shop/pc-based-measurement-and-control-system.html

- Did not purchase the DAQ16 but has a NI acquisition card with specific operating methods (e.g. only differential) and sampling frequency limitations. Users should refer to Section 4.4.4 for configuration;

- Did not purchase the Hanghua DAQ16 but has data acquisition equipment from other companies (non-NI):

  - We recommend that users do not use the CTALab software but instead use a serial port utility software to control the hot-wire anemometer. Procedures are detailed in Appendix D;
  - Users can also consider using the Hanghua CTALab software, but only for system parameter settings, balance parameter adjustments, and manual calibration functions. To avoid program errors, users should refer to Section 4.4.4 to disable the "Collect output after sending parameters" option.

### 4.1.6 Running the CTALab Software

- Locate and run the executable file in the Windows shortcuts, desktop, or installation directory.

☞ Right-click the software icon and select "Run as Administrator" to avoid permission issues that may prevent the program from saving user-defined measurement parameters.

## 4.2 CTALab Framework

### 4.2.1 ① Program Control

The upper-left area of the software interface is the program control area (see Figure 13), which serves as the "switch" for the software:

- This function area has two buttons, from left to right: Run (arrow) and Stop (circle button). A click on these two buttons will run and stop the program, respectively. Note, the program will automatically run when loaded.
- After the program runs, the button states are shown in Figure 14a.
- Users can press the red button to stop the program at any time.
- The system will also stop running if an error occurs. Users need to click "Run" to restart the program.
- Each time the program restarts, it reads previously saved parameters from the hard drive. Users are advised to click the "Save Parameters" button after changing parameter settings; otherwise, the settings will be overwritten by the saved information (text files in the 'data' directory under the installation directory) upon restarting.
- If users want to restore the original settings after changing parameters (without saving), they can stop and restart the program to reload the saved parameters from the hard drive.

### 4.2.2 ② Function Tabs

The software has six function tabs. Users should use them in order from left to right. These six tabs are:

- Parameter Settings
  - Set the probe type for each channel: single-wire, double-wire, or triple-wire.
  - Set the data acquisition card channel corresponding to each hot-wire channel.
  - Set the COM port for communication with the hot-wire main unit.
  - Set the signal acquisition channels for temperature and pressure sensors.
  - Set the number of channels used in the experiment.
  - Set the communication ports for the angle adjustment mechanism and traverse system.

- Set the output voltage channel (for frequency drive speed control).

- System tuning
  - Set the probe cold resistance and overheat ratio for each channel.
  - Set balance parameters.
  - Set signal post-processing, including gain, offset, and low-pass filter cutoff frequency.
  - Turn the bridge circuit on/off and enable/disable square wave testing.
  - Observe square-wave test results.
  - Monitor the status of each channel.
- Calibration
  - Select the calibration method: automatic/manual speed adjustment, automatic/manual speed measurement.
  - For automatic speed adjustment: Set the maximum output voltage and the number of calibration points.
  - For automatic speed measurement: Set the sensitivity coefficient of the pressure sensor.
  - Observe the calibration process.
  - Check calibration results.
- Devices
  - Generate or read coordinate files for the traverse system.
  - Adjust the blower speed of the calibrator.
  - Move the coordinate system.
  - Control the automatic calibrator turntable.
- Measurement
  - Set acquisition parameters, data storage folder, and file name.
  - Select measurement channels.
  - Observe real-time acquisition data and spectrum.
  - Observe statistical data such as mean and standard deviation.
  - Save measurement data.

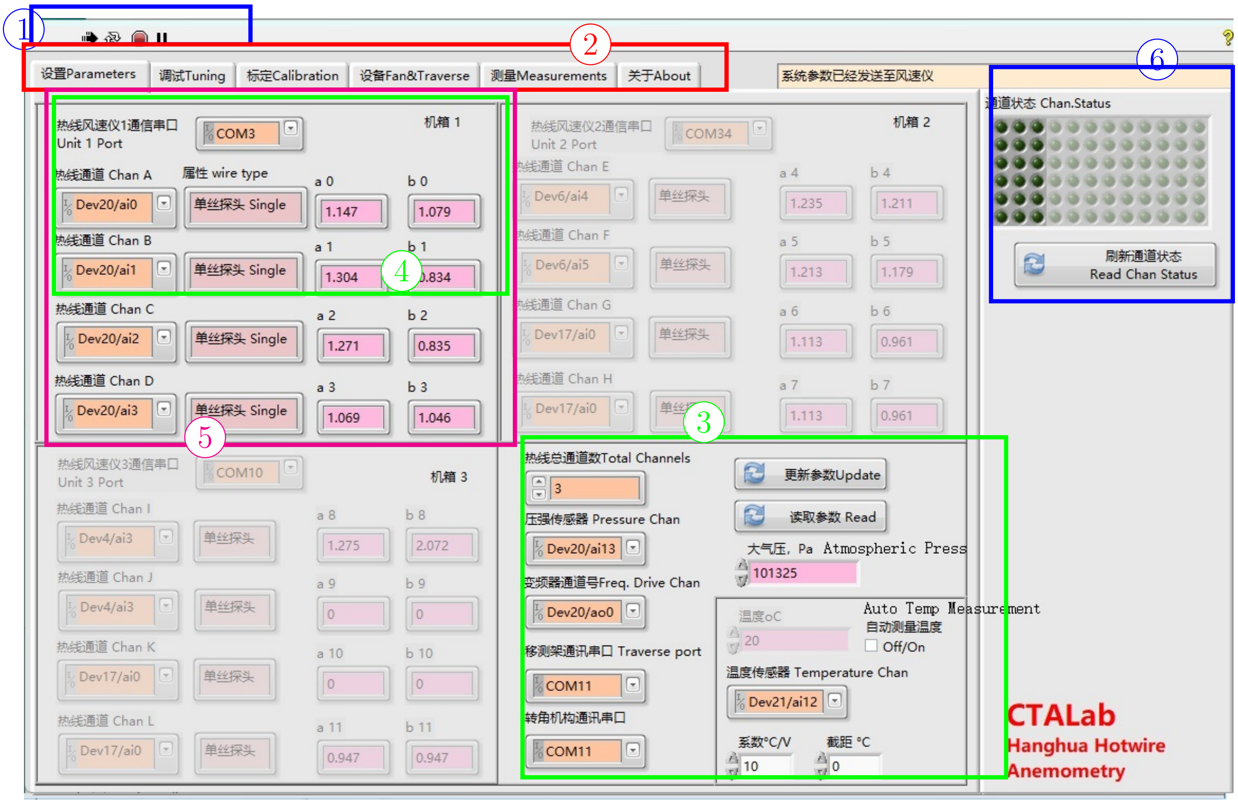
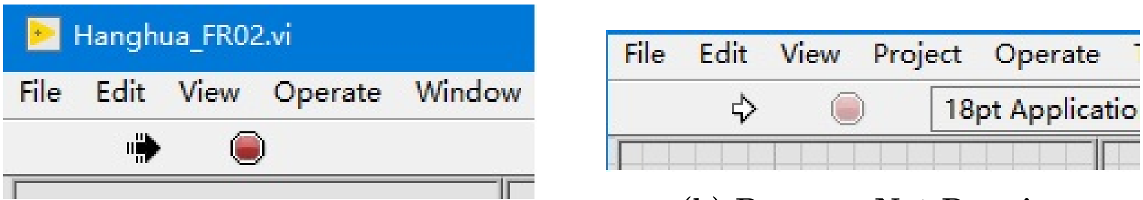



Figure 13: The main interface of the software is divided into multiple functional tabs. Within the Parameter Settings tab, it is further divided into several functional areas, including: ③ Global parameter settings, ④ Hot-wire channel settings for the two-channel system, ⑤ Hot-wire channel settings for the four-channel system, and ⑥ Channel status refresh and display area.




(a) Program Running

(b) Program Not Running

Figure 14: Software Functional Area ①: Program Control Area

- About

  Contains information such as the software version number.

## 4.3 CTALab Tab 1: Data Acquisition Parameter Settings

| Users are advised to watch the following video first: https://www.bilibili.com/video/BV16u411Y7vW/ |
|---|

Under the "Settings" tab, users can configure some basic properties of the hot-wire. Users first set the data in area ③ of Figure 13. Specific steps include:

(1) Set the total number of system channels. If using a 2-channel system, select 2; if using a 6-channel system, select 6. After the user makes a selection, some components on the front panel will be grayed out, leaving only the components for the specified channels available for configuration.

(2) "Automatically Measure Temperature": If this option is not checked, users can enter the current ambient temperature in the temperature field. The software calculates air density based on the temperature. If this option is checked, the temperature field will be grayed out, and the "Temperature Sensor Corresponding Data Acquisition Input Channel" field will become active.

The data acquisition input channel corresponding to the temperature sensor is the port selected by the user in Step 4 of Section 3.1. If using the temperature sensor interface on the front panel of the hot-wire anemometer, users need to connect the Temperature Output port to an AI port on the data acquisition unit using the CB01 cable and input the port number in the software. If using the temperature sensor interface on the rear panel of the data acquisition unit, no additional cables are needed, and users can directly input the channel number: AI12.

If using the TS02 temperature sensor, its sensitivity coefficient is $10°C/V$, and the intercept is $0°C$. These constants can be modified below.

If using a cold-wire sensor (not a standard part of a hotwire anemometry, please consult with Hanghua for this instrument) as a temperature measurement tool, first input the data acquisition channel connected to the cold-wire output, then input its sensitivity coefficient and intercept. These parameters can be obtained by calibrating the cold-wire.

(3) Pressure Sensor Channel

- If using the Hanghua DAQ16 data acquisition unit, this channel is pre-configured as Dev*/AI13 (* is the device number, which can be viewed by clicking the dropdown symbol on the right side of the control). Users need to select the channel number AI13 from the dropdown;

- If using a self-provided pressure sensor, connect the sensor's analog voltage output signal to an AI channel and input the channel number here;
- Additionally, users need to input the sensor's sensitivity coefficient, as detailed in Section 4.5.1.

(4) Select the data acquisition analog output channel number connected to the frequency drive control cable;

(5) Set the communication port for the traverse system. Users can check the "Device Manager" and "Ports" information and determine the specific port number by temporarily unplugging the traverse system control cable;

(6) (For automatic calibrators) Set the communication port number for the angle adjustment mechanism. Users can determine this using the method described above;

(7) Set the atmospheric pressure. Atmospheric pressure is used to calculate air density. Adjust this setting for cities at different altitudes to obtain the correct density value.

(8) After setting the above parameters, click the "Update Parameters" button. The system will update the parameters in memory and save them. The program will automatically read these parameters upon restart.

| Note: If a "No permission to modify file" message appears, or if the file is not successfully saved (e.g., the "Config-Channels.txt" and "Configuration File.txt" files in the "data" directory are not updated), close the program, right-click the shortcut, and select "Run as Administrator" from the drop-down menu. |
|---|

After setting the content in area ③, users need to assign the data acquisition channel numbers for the hot-wire output signals of each channel.

- If the user selects 2 channels in area ③, they need to set the corresponding parameters for the 2 channels in area ④ of Figure 13;
- If the user selects 4 channels in area ③, they need to set the corresponding parameters for the 4 channels in area ⑤.

The specific parameters for each channel include:

(1) The AI channel number of the data acquisition card corresponding to the hot-wire output. This is selected by the user during hardware connection, as described in Section 3.1.

(2) The type of probe connected to the hot-wire channel:

- If it is connected to a single-wire probe (e.g., HW1A or HW1D), select "Single-Wire Probe";
- If it is one wire of an HW2A dual-wire probe, select "X-Type Dual-Wire Probe 1". The channel connected to the other wire (e.g., Channel B) should also select "X-Type Dual-Wire Probe 1", so the system can correlate the signals from these two channels to calculate the velocity vector;
- Similarly, if it is connected to an HW3A triple-wire probe, select "Triple-Wire Probe 1".

(3) Calibration parameters a and b. These parameters are the results of the exponential calibration for each channel (see Section 4.5). After each calibration, the program will fit a set of slop and intercept (a and b, respectively) based on the test results for each channel and automatically update the information displayed in area ④. The exponential calibration results typically do not change with environmental parameters such as room temperature or air pressure, so users can also consider using the factory calibration results[2].

The far-right area of Figure 13 is area ⑥. This area displays the current status of the hot-wire anemometer. This area does not refresh automatically. After each software restart, users need to click "Refresh Channel Status" to communicate with the anemometer and obtain the latest information, such as the channel switch status.

[2]Factory annealing and calibration require extra fee


Figure 15: The Tunning tab is divided into different functional areas: ① Channel selection, ② Setting channel operating parameters, ③ Sending parameters, switching the bridge on and off, and square wave testing, ④ Current channel status indicator, ⑤ Current channel voltage output waveform, and ⑥ Status indicators for all channels.

## 4.4 CTALab Tab 2: Hot-Wire Operating Parameter Debugging

| |
|---|
| Users are advised to start watching the following video from 5:28: https://www.bilibili.com/video/BV16u411Y7vW/ |

In the "Debugging" tab (Figure 15), users send the hot-wire anemometer operating parameters, perform bridge on/off actions, and test the hot-wire operating status. The specific process is as follows.

### 4.4.1 Functional Area①: Channel Selection

First, users select the channel for parameter adjustment operations in area ①. After selection, all operations in this tab will only apply to that channel.

### 4.4.2 Functional Area ②: Input Hot-Wire Operating Parameters

(1) Overheat Ratio

Typically between 1.4 and 2.0, with a recommended value of 1.6. A higher overheat ratio results in a higher operating temperature of the probe, increased sensitivity, and better resistance to environmental temperature changes. However, it reduces the probe's lifespan.

(2) Cold Resistance.

The cold resistance is the measured resistance of the probe before installation. Record the ambient temperature during measurement and input it into the software. The software will calculate the probe's resistance at 20C based on the ambient temperature and measured resistance.

(3) Wire Resistance

If using a 2-meter-long Hanghua CB02A cable, the wire resistance is approximately 0.15 ohms; if using a 5-meter-long Hanghua CB02A cable, the wire resistance is approximately 0.25 ohms; if using a 20-meter-long cable, the resistance is about 1.2 ohms. Based on the cold resistance, overheat ratio, and wire resistance, the software will calculate the resistance of the variable resistor $R_3$ in the bridge circuit and make corresponding adjustments.

(4) Balance Parameter

- The balance parameter is a dimensionless value between 0 and 5. A higher value increases damping, making the system more stable. However, an excessively high value can degrade the system's dynamic performance;

- The optimal value depends on factors such as probe resistance and flow velocity and needs to be determined through a square-wave testing;
- The recommended balance parameter is between 0.5 and 1.5 (suggested value: 1.0) for a Hanghua hot-wire probe, ensuring normal operation for probes with resistances of 3.5-10 ohms at speeds below 50 m/s. The method for selecting this parameter during operation can be found in Section 4.4.3, item (7), and Appendix F;
- The balance parameter only needs to be adjusted once before initial use;
- The balance parameter needs to be readjusted after replacing the probe.

(5) Signal Modulation

In some cases, the output bridge voltage needs to be modulated for accurate acquisition. Modulation includes amplification (gain), offset, and low-pass filtering:

- Output Signal Gain (Gain)

  Typically, the hot-wire output signal is large enough to ensure a reasonably good signal-to-noise ratio, and no amplification is needed. However, in special cases where the bridge output signal is weak (e.g. in a low-density air flow), amplification may be required to reduce sampling errors. Available gain options include 1 (original signal, no amplification), 2, 4, 8, and 16. It is generally recommended to keep it at 1.
- Output Signal Offset (Offset)
  - The offset voltage adjusts the output voltage when the bridge is balanced, bringing it closer to the midpoint of the output range (-5∼5V). This ensures that voltage fluctuations caused by flow velocity changes during measurement do not exceed the output range;
  - The offset voltage range is 0-5 V. When the offset voltage is not zero, the output voltage equals the bridge voltage minus the offset voltage;
  - Example: If the bridge voltage is 4.2 V when the offset voltage is 0 V, setting the offset voltage to 3.0 V will reduce the bridge voltage to 1.2 V.
  - adding an offset will have no effect on precisions
  - it is recommended to use an offset of 4.0V for all measurement, because in most cases with a gain of 1, the output voltage will be around 2V, so it is nice to pull this down to -2V, so we can use most of the measurement range of daq card

- Low-Pass Filter Cutoff Frequency (Low-pass filter).

  The anemometer has built-in low-pass filters with cutoff frequencies of 1, 10, 100, 1k, and 10k Hz. Users can select "filter off" to disable the filter. It is recommended to turn it off at the beginning and only used it when there are unbearable amount of high-frequency noise.

### 4.4.3 Functional Area ③: Bridge and Square Wave Switch

(1) After setting the parameters in area ②, users need to click "Send Parameters" to send the parameters to the anemometer before turning on the "Bridge Switch."

| |
|---|
| If new parameters are not sent and the bridge switch is turned on directly, the bridge will use the old settings for the probe's operating resistance, risking probe damage. |

(2) After clicking "Send," the prompt bar in the upper right corner will display "Information successfully sent to the anemometer." A slight relay switching sound (tita) can also be heard from the anemometer during the process.

(3) After successfully sending the information to the system, click the "Bridge Switch" to turn on the bridge.

(4) After the bridge is successfully turned on:

   (a) The "Bridge On-Off" button on the software will light up;

   (b) The "Bridge On" light in area ④ will light up;

   (c) One of the lights in the first row of the "Channel Status" in the upper right corner of the software will light up (e.g., the first column for Channel A);

   (d) The corresponding "Bridge On" light on the front panel of the anemometer will light up.

(5) If the system is operating normally:

   (a) The "Bridge Status" light in area ④ will light up;

   (b) The corresponding light in the second row of the "Channel Status" in the upper right corner of the software will light up.

(6) If the following lights are on, it indicates that the bridge voltage of the anemometer is too low. This is most likely due to a broken probe or probe cable. The probe resistance needs to be remeasured to determine if it is damaged:

(a) The third light (TOB Low) on the front panel of the anemometer for the corresponding channel will light up;

(b) The third light (TOB Low) in area ④ of the software will light up;

(c) The corresponding light in the third row of the "Channel Status" in the upper right corner of the software will light up.

(7) Square Wave Test

*The square wave test is a method to determine the system's frequency response by introducing a square wave signal that disrupts the bridge balance and observing how the system restores balance.* This method evaluates the system's ability to restore balance and calculates the characteristic response time of the bridge based on the recovery curve. For details, see Appendix F. The operation process is as follows:

(a) Expose the probe to the maximum flow velocity used in the experimental study;

(b) Click "Square-Wave On-Off" to turn on the built-in square wave signal generator, which produces a 500 Hz, 100 mV square wave signal applied to the $e_1$ position of the bridge (Figure 1), periodically disrupting the bridge balance;

(c) After turning on the square wave, **users need to click "Send Parameters" again**. The system will send the parameters and then collect the output voltage, displaying it in the graph in area ⑤. The upward spikes represent the system restoring balance after being pushed away from the equilibrium point by the rising edge of the square wave, while the downward spikes are caused by the falling edge;

(d) Appendix F provides a diagram of the bridge restoring balance after being disrupted. This process is closely related to the system's response capability: a higher frequency response results in faster recovery. The time taken for the system to restore balance is called the characteristic time. **Appendix F also explains how to evaluate whether the system is balanced and the system's characteristic time constant.**

(8) After completing the square-wave test, click the "Square Wave On-Off" to turn off the test signal.

(9) The square-wave test is only required when using a new probe for the first time. It is not necessary to perform the test for every experiment.

(10) After sending parameters, turning on the bridge, and performing the square wave test, users can select the next channel in area ① for configuration.

(11) After completing the setup for all channels, proceed to the next tab, "Calibration."

### 4.4.4 Functional Area ⑥: Custom Data Acquisition Card Settings

Each time the user clicks "Send Parameters," the software uses the data acquisition card to collect a certain amount of hot-wire output signals for reference in parameter adjustment. If the user uses a data acquisition card from another company, the software cannot support this function. Please click the "Collect Signal After Sending Parameters" option in area ⑥ to disable this function.

If the user uses a National Instruments (NI) data acquisition card, the "Collect Signal After Sending Parameters" option can remain enabled. However, the user needs to refer to the specifications of their own acquisition card to select the "Sampling Frequency" and "Acquisition Card Operation Mode." For example:

- The standard NI USB6211 acquisition card has a maximum sampling frequency of 250,000 Hz, and the "Acquisition Card Operation Mode" is RSE (Referenced Single-Ended).
- The budget-friendly NI USB6009 has a maximum sampling frequency of 48,000 Hz, and the "Acquisition Card Operation Mode" varies depending on the wiring method.
- The NI USB4431 has a maximum sampling frequency of 100,000 Hz, and the "Acquisition Card Operation Mode" is Pseudo-differential.

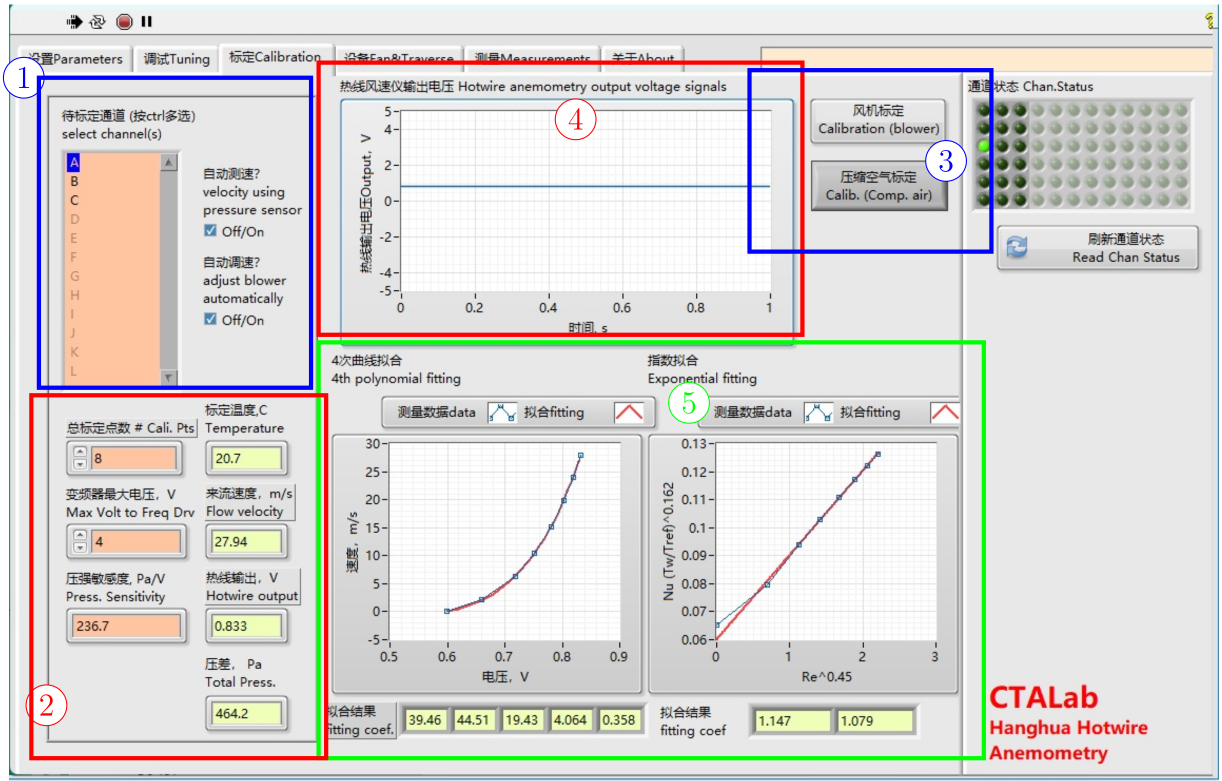



**Figure 16: The calibration interface is divided into different functional areas: ① Channel selection and calibration method, ② Setting calibration parameters and observing the mean output during calibration, ③ Start calibration button, ④ Real-time hot-wire data during calibration, ⑤ Two different calibration results.**

## 4.5 CTALab Tab 3: Calibration

After users complete parameter settings, enable the hot-wire channels, and perform Tunning, the next step is to calibrate the probe. *The calibration process determines the functional relationship between the output voltage of the hot-wire anemometer and the airflow velocity.* The calibration tab interface is shown in Figure 16. Depending on the accessories purchased and user requirements, Hanghua CTA04 offers various calibration methods (see Table 7), including:

(1) Fully Automatic Calibration: The software automatically adjusts the blower speed, measures the flow velocity, records the mean output voltage of the hot-wire anemometer, fits the curve, and saves the results. This method is suitable for low-speed (velocity less than 120 m/s) measurement users who have purchased the full set of Hanghua equipment. A detailed description is provided in Section 4.5.1;

(2) Compressed Air Calibration: This method is suitable for medium- and high-speed (velocity greater than 120 m/s) measurement users who have purchased the full set of Hanghua equipment. A detailed description is provided in Section 4.5.2. This method uses compressed air as the air source to obtain high-speed airflow for a short duration (usually in seconds depending the volume of the tank used). As the outlet velocity of the calibrator decreases, the software automatically measures the flow velocity, records the mean output voltage of the hot-wire anemometer, fits the curve, and saves the results; Note, that the compressed air calibration unit is not a standard product. It is also note that a pressure transducer with a large measurement range is needed for this calibration.

(3) Manual Speed Adjustment, Automatic flow velocity Measurement, Automatic Voltage Measurement: Users manually adjust the blower speed (or the valve opening of the compressed air pipeline) to expose the probe to a series of different flow velocity conditions. The software automatically measures the flow velocity, fits the relationship between flow velocity and output, and saves the results. This method is suitable for customers who have not purchased the Hanghua calibrator. A detailed description is provided in Section 4.5.3;

(4) Manual Speed Adjustment, Manual flow velocity Measurement, Software Voltage Measurement: Users manually adjust the flow velocity and use their own instruments to measure the flow velocity and input the results into the computer. The software fits the calibration curve based on the anemometer's voltage

output and the user-input flow velocity data. This method is suitable for customers who have not purchased the Hanghua calibrator. A detailed description is provided in Section 4.5.4;

(5) Manual Speed Measurement, Manual flow velocity Input, Manual Voltage Measurement: Users manually adjust the flow velocity, use their own instruments to measure the flow velocity and input the results into the computer software, and use their own instruments to measure the time-averaged output voltage of the anemometer. Finally, users fit the voltage and flow velocity data to obtain the calibration curve. This method is suitable for users who only have the Hanghua hot-wire main unit. A detailed description is provided in Section 4.5.5;

The software fits the relationship between the measured (or user-input) flow velocity $U$ and the output voltage $E$. CTALab software provides two different fitting methods:

(1) Fourth-Order Polynomial Calibration

The software fits the $U - E$ relationship using a fourth-order polynomial, obtaining five constants, which are saved as a text file. During actual use, these constants are used to convert voltage to airflow velocity. For details, see Appendix H;

(2) Exponential Calibration

The software does not directly fit the voltage and speed but uses the output voltage $E$ to calculate the heat transfer rate, obtaining the Nusselt number ($Nu$) that characterizes the heat transfer intensity. It then fits the linear relationship between $Nu$ and the Reynolds number ($Re$). For details, see Appendix I;

(3) Both methods have their advantages and disadvantages, as detailed in Appendix I.2.

The calibration process is divided into the following schemes based on the user's equipment, with each scheme described in a separate subsection. The operation interface is shown in Figure 16.

### 4.5.1 Automatic Calibration

| |
|---|
| Users are advised to watch the following video:<br>https://www.bilibili.com/video/BV14N411k7D3/ |

Table 7: Recommended Calibration Methods for Different User Groups (✔: Purchased, ✖: Not Purchased)

| User Group | CTA04 Main Unit | DAQ16 or NI Card | CR04 Calibrator | Air Source | Calibration Method | Section |
|---|---|---|---|---|---|---|
| 1 | ✔ | ✔ | ✔ | Blower | Fully Automatic Calibration | 4.5.1 |
| 2 | ✔ | ✔ | ✔ | Air Compressor | Compressed Air Calibration | 4.5.2 |
| 3 | ✔ | ✔ | ✖ | Blower | Manual Speed Adjustment, Automatic flow velocity and Voltage Measurement | 4.5.3 |
| 4 | ✔ | ✔ | ✖ | User-Provided Facilities | Manual Speed Adjustment, Manual Speed Input, Automatic Voltage Measurement | 4.5.4 |
| 5 | ✔ | ✖ | ✖ | User-Provided Facilities | Fully Manual Calibration | 4.5.5 |
| 6 | ✔ | ✖ | ✖ | Not Required | Calibration-Free Measurement Method | 4.5.6 |

Automatic calibration refers to the process where the software system automatically adjusts the blower rotation speed, measures the flow velocity and the mean output voltage of the hot-wire, fits the calibration results, and saves the results after receiving the "Start Calibration" command. Users need to make the following selections in area ① of Figure 16:

- Select the channel to be calibrated. If users plan to calibrate multiple probes at once, they can hold the Ctrl key and click on the next channel with the mouse;
- Click the "Automatic Speed Measurement" and "Automatic Speed Adjustment" check boxes to turn both on.

  The "Automatic Speed Measurement" and "Automatic Speed Adjustment" round lights are buttons.

In the orange area of ②, users need to input:

(1) The number of calibration points planned, typically 8-12;

(2) The maximum voltage of the frequency drive, in volts (V), recommended to be 4-5. For the Hanghua CR04 calibrator with a 10 mm jet nozzle, 4 V corresponds to a speed of 30 m/s, 5 V corresponds to approximately 40 m/s, and 10 V corresponds to around 120 m/s.

    Note: Exceeding 5 V may damage the pressure sensor. Proceed with caution.

(3) The pressure sensitivity coefficient, in $[Pa/V]$. The software uses this coefficient to convert the pressure sensor's output voltage into pressure. The software system uses the pressure to calculate the outlet flow velocity of the calibrator.

    - If using the Hanghua DAQ16 data acquisition unit, read this coefficient from the front panel label.
    - If using a self-provided pressure sensor, calibrate it first and input the calibration results here.

(4) The yellow area in ② displays the measured flow temperature, flow speed, hot-wire output voltage, and the total pressure used to calculate the flow speed during the calibration process. The data is updated after each flow velocity measurement during calibration.

After completing the above settings, users need to check if the hardware is ready for calibration, including:

(1) Whether the pressure input port H on the front panel of the DAQ16 data acquisition unit is connected to the total pressure tube of the calibrator via pressure tubing;

(2) Whether the AO port on the front panel of the DAQ16 is connected to the Fv and Gnd terminals of the frequency drive via a BNC cable, as shown in Figure 8;

(3) Whether the parameter P-003 of the frequency drive is set to 002 and whether the RUN key on the frequency drive is pressed (a green light will flash at the bottom of the front panel when pressed). For details, see Appendix G;

After passing the above checks, users can click "Blower Calibration" in area ③. The system will pause for a few seconds, then start sending analog voltage signals to the specified AO port to control the blower speed and gradually change the flow velocity. After each flow velocity adjustment, the software collects the output voltage from the pressure sensor and the hot-wire anemometer. After completing the collection at all set flow velocitys, the software turns off the blower and calculates the calibration curve. During the calibration process:

(1) The hot-wire output voltage signals collected by the system are displayed in area ④;

(2) The yellow display box in area ② shows the measured flow temperature, flow speed, hot-wire output voltage, and total pressure during calibration;

(3) The status bar in the upper right corner reports the current calibration progress.

After calibration, the blower stops. The software calculates the calibration curve for each selected channel based on the speed-output voltage data:

(1) The original speed-output voltage data for each channel is displayed in the left graph of area ⑤, with the fourth-order fitting curve shown as a solid line. The fitting results (five constants) are displayed below the graph;

(2) The corrected $Nu$ and $Re^{0.45}$ data points calculated from the original data are displayed as squares in the right graph of area ⑤, with the linear fitting results (a and b) displayed below the graph;

(3) The linear fitting results (a and b) are also displayed in the corresponding a and b fields of the "Settings" tab for that channel. For an introduction to these coefficients, see Section 4.3;

(4) Both calibration results are saved as text files in the 'data' directory under the installation directory. They will be automatically loaded when the software is run again and the channel is selected.

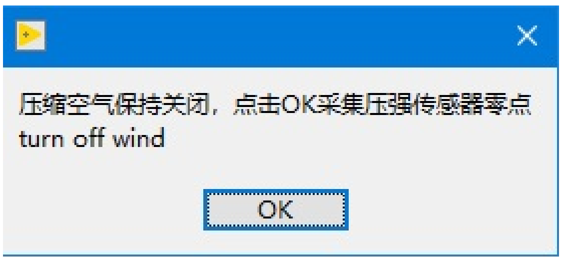
(5) If the current calibration is for Channel A:

- The fourth-order polynomial calibration results are saved in the 'coef1.txt' file;
- The average flow temperature during calibration is saved in the 'coef1-temp.txt' file;
- If the calibration is for Channel B, the numbers in the above filenames will be 2;
- The exponential calibration results (a and b) are saved in the second column of the 'power-coef.txt' file.

### 4.5.2 Compressed Air Calibration

The compressed air calibration method is a fully automatic calibration method, but unlike Section 4.5.1, which uses a blower as the air source, this method uses compressed air as the air source. This method primarily serves customers who have purchased the DAQ16 data acquisition unit, the CR04 calibrator, and require high-speed measurements (speeds greater than 120 m/s). The operation method is as follows:

(1) First, replace the end plate of the CR04 calibrator that connects to the corrugated hose with the end plate that connects to the compressed air cylinder. Use




**(a) Prompt to keep the valve closed**


**(b) Prompt to open the valve. After opening the valve, click OK to start acquisition**

**Figure 17: Prompt boxes during compressed air calibration**

a compressed air hose to connect the compressed air cylinder to the air inlet of the calibrator. Close the valve (a manual shut-off valve should be installed between the cylinder and the calibrator) to ensure no connection between the cylinder and the calibrator;

(2) Pressurize the compressor tank to the required pressure. Keep the valve closed during pressurization, and turn off the air compressor (or close the valve between the air compressor and the cylinder) after pressurization is complete;

(3) Check if the maximum range of the built-in pressure sensor in the DAQ16 data acquisition unit is within a reasonable range. The maximum range of the pressure sensor is generally divided into three types: 1 kPa, 2.1 kPa, and 5.5 kPa. If users need to calibrate compressed air, it is recommended to use a self-provided pressure sensor with a range above 50 kPa;

(4) Check the CTALab software to ensure all channels are turned on;

(5) Click the "Compressed Air Calibration" button in area ③. The software will prompt to keep the valve closed and collect the zero point of the pressure sensor (voltage for zero loading), as shown in Figure 17a. After confirming the valve is closed, click OK to continue;

(6) The prompt in Figure 17b will appear. Open the valve to form a high-speed jet at the outlet of the calibrator. After the jet is formed, click OK to continue;

(7) The software starts collecting the total pressure of the calibrator and the output voltage of the anemometer. It collects one set of data per second and calculates the time-averaged value;

(8) As the tank pressure decreases, the outlet speed of the calibrator gradually decreases over time. When the pressure is less than 1 Pa, the calibration automatically ends;

(9) The software fits the relationship between the time-averaged flow velocity and the time-averaged voltage, provides the calibration results, and saves them.

### 4.5.3 Manual Speed Adjustment and Automatic Speed Measurement Calibration

The manual speed adjustment function is suitable for customers who have purchased the Hanghua DAQ16 acquisition unit, plan to use existing calibration facilities, and have not purchased the Hanghua CR04 calibrator. In this case, there is no need to connect the AO port of the acquisition unit to the frequency drive of the customer's wind tunnel facility. Customers need to perform the following operations:

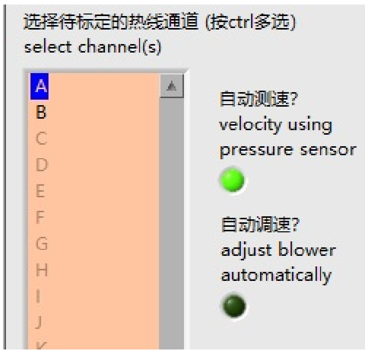
(1) Connect the pressure tubes of the existing wind tunnel system (before and after the contraction section) to the pressure input ports H and L on the front panel of the DAQ16 acquisition unit;

(2) Click the "Automatic Speed Adjustment" round button in area ① to turn it off, while ensuring the "Automatic Speed Measurement" light is on, as shown in Figure 18a;

(3) After completing other settings as described in the previous section (Section 4.5.1), click the "Blower Calibration" button to start calibration.

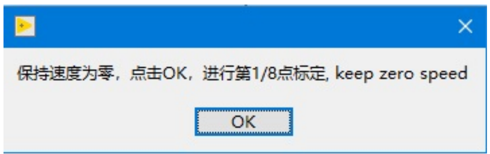
After starting calibration:

(1) The blower will not automatically adjust the speed. The software will pop up a prompt window to guide the user to manually adjust the speed, as shown in




(a) Select channel number and speed adjustment/measurement method

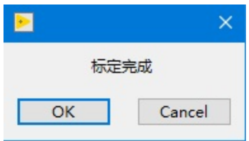

(b) Prompt to turn off the blower




(c) Prompt to keep the blower off


(d) Prompt to increase flow velocity


(e) Prompt to continue increasing flow velocity




(f) Prompt indicating calibration is complete

**Figure 18: Prompt boxes during manual speed adjustment and automatic speed measurement calibration**

Figure 18c;

(2) Under the guidance of the software, the user can first turn off the blower, keep the flow velocity at zero, and gradually increase the flow velocity until the calibration is complete, as shown in Figures 18d-18f;

(3) After collecting all data, the anemometer performs fitting, provides the calibration results, and saves them. The saving method is consistent with Section 4.5.1.

### 4.5.4 Manual Speed Adjustment, Manual Speed Measurement, and Software Voltage Acquisition Calibration

Users are advised to watch the following video:
https://www.bilibili.com/video/BV1Dk4y1p7VP/

This calibration method is suitable for customers who have not purchased the Hanghua CR04 calibrator and DAQ16 data acquisition unit. Customers need to place the hot-wire probe in a self-provided test environment for calibration. The flow velocity in this environment can be varied, and the local flow velocity at the probe location can be measured using methods such as a Pitot tube. Customers can:

(1) Place the Pitot tube near the probe, preferably side by side, without interference. The closer the distance, the better, while ensuring the probe is not damaged.

(2) Consider using a handheld pressure gauge to directly read the flow velocity from the Pitot tube.

(3) In the "Calibration" tab of the software, click the "Automatic Speed Adjustment" and "Automatic Speed Measurement" check boxes to turn both off, as shown in Figure 19a;

(4) The blower will not automatically adjust the speed. The software will pop up a prompt window to guide the user to manually adjust the speed, as shown in Figures 19b and 19c.

(5) After adjusting the flow velocity, the software will not automatically measure the speed but will pop up a window prompting the user to input the speed, as shown in Figure 19d.

(6) Under the guidance of the software, the user can first turn off the blower, keep the flow velocity at zero, and gradually increase the flow velocity until the calibration is complete.

(7) After collecting all data, the anemometer performs fitting and provides the calibration results.

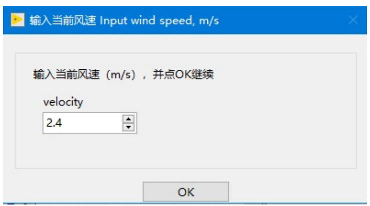
(8) The minimum number of calibration points varies depending on the calibration method:

- Exponential calibration: At least 3 data points1 zero flow velocity, 1 low speed, and 1 high speed.
- Fourth-order polynomial calibration: At least 8 data points1 zero flow velocity and 7 flow velocitys from low to high.


(a) Select channel number and speed adjustment/measurement method

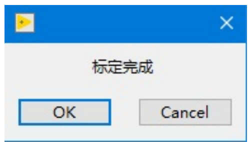

(b) Prompt to turn off the blower


(c) Prompt to increase flow velocity




(d) Prompt to input flow velocity


(e) Prompt to continue increasing flow velocity




(f) Prompt indicating calibration is complete

**Figure 19: Prompt boxes during manual speed adjustment and manual speed measurement calibration**

### 4.5.5 Fully Manual Calibration: Manual Speed Adjustment, Manual Speed Measurement, and Manual Voltage Acquisition

Using existing tools in the laboratory, manually measure and record the mean flow velocity and voltage output, and input them into an Excel sheet for manual fitting. We recommend using a multimeter, oscilloscope, or data acquisition cards. Appendix H provides a specific example.

### 4.5.6 Calibration-Free Measurement

When users do not have calibration equipment or find it difficult to perform frequent calibrations (e.g., when the probe is installed in a pipeline or other inaccessible areas), they can consider using the calibration-free measurement technique. The principle of this technique is detailed in Appendix I, and the key points are as follows:

(1) The probe and cables used for this method must be original products from Hanghua. The probe must have undergone a 24-hour annealing process and calibration before leaving the factory. The calibration report should clearly provide the calibration results: a pair of constants $a$ and $b$;

> Note: The annealing process and calibration before leaving the factory are chargeable services.

(2) The TS02 temperature sensor must be used during experiments to monitor the flow temperature;

(3) Before use, input the constants $a$ and $b$ provided in the factory calibration report in the "Parameter Settings" tab;

(4) Select "Exponential Calibration" during the measurement process.

## 4.6 CTALab Tab 4: Devices

The device tab interface is shown in Figure 20. This interface includes the following functions:

### 4.6.1 ① Area: Create Traverse Coordinate File

(1) TM02 Traverse System

The traverse system consists of a motion controller and several stepper motor-driven moving modules. Users set the coordinate grid for the moving modules in area ①;

(2) The coordinate grid set here is orthogonal and equidistant. Users specify the start and end coordinates for the x, y, and z axes and define the spacing. After clicking "Generate," the software creates a 2D array of size [3, N] (i.e., 3 rows and N columns), where N is the number of measurement points. This array is saved in the ‘motor-positions.txt‘ file in the ‘data‘ directory under the installation directory.

(3) During flow velocity acquisition, when the user selects the "Traverse System" acquisition method, the system reads the coordinate file and automatically sets the number of measurement points based on the number of columns in the array. The traverse system starts from the [0,0,0] position and moves sequentially to the coordinate positions formed by the three numbers in each column of the file. It waits for the hot-wire anemometer to measure the flow velocity, with the measurement duration set as "Sampling Duration per Point." After all measurements are completed, the traverse system returns to the initial position.

(4) If the user wants to measure an xy plane first and then move to the next xy plane, select the measurement order as x-y-z. If measuring each xz plane step by step, select the measurement order as x-z-y.

(5) If the user only measures one 2D plane, set the start and end coordinates of the third dimension to 0 (set the spacing to any non-zero value), as shown in Figure 20, area 1.

(6) The traverse coordinate file is only read under the following condition: when the user selects "Traverse System" in the "Next Block Activation Method" dropdown in the "Measurement" tab. If "Automatic" or "Manual" is selected, the software will not read the traverse coordinate file.

(7) Users can also create the traverse coordinate file using other tools:

- If using Matlab, set the coordinate file as a 3*N array 'pos' and save it to the 'motor-positions.txt' file using the following command:

  ```
  dlmwrite('motor-positions.txt', pos, 'delimiter', '\t')
  ```

- If using Excel, set the coordinate file as 3 rows and N columns of data, with the 3 rows representing the x, y, and z position data. After creating the data file, save it as a "Tab-Separated Text File."
- After creating the file, click "Import Table File" to import the coordinates. The process is detailed in Appendix J.
- Users can also directly drag their coordinate file into the 'data' directory under the installation directory and overwrite the original file.

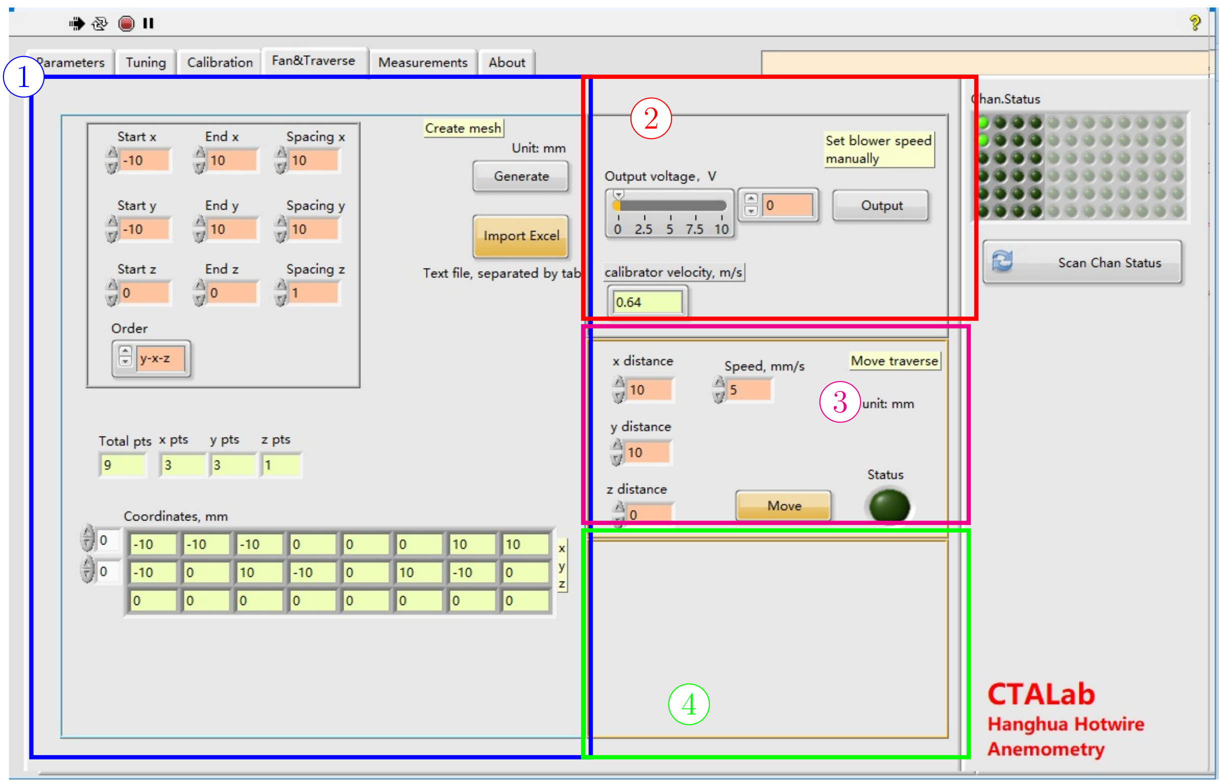



**Figure 20: The Devices tab is divided into different functional areas: ① Traverse coordinate generation area, ② Blower speed setting area, ③ Traverse system movement area, ④ Angle adjustment mechanism rotation area.**

#### 4.6.2 ② Area: Manually Adjust the Blower Speed of the CR04/CR05 Calibrator

To meet customer needs during system tunning, the software includes a manual blower speed adjustment function. Users can change the jet outlet speed of the calibrator by manually setting the output voltage of the AO port (specific port settings are in the "Settings" tab, see Section 4.3).

Users can input a voltage between 0-10V in the "Frequency Drive Output Voltage" field by dragging or entering a number. For the CR04 calibrator, 5V corresponds to approximately 40 m/s. It is recommended to keep the voltage below 5V to avoid damaging the pressure sensor. After setting, click "Output" to start the blower.

Note that the frequency drive must be set to "Automatic" mode. For specific setup instructions, see Appendix G.

| |
|---|
| If precise flow velocity measurement is required, it is recommended to click "Pressure Sensor Zeroing" before clicking "Output." Wait for zeroing to complete before clicking "Output." |

#### 4.6.3 ③ Area: Manually Adjust the Position of the TM02 Traverse System

Users can set the movement distance for the x, y, and z axes in area ③ and click "Move Traverse" to change the position of the traverse slider. The unit is millimeters. The recommended movement speed is between 5-20 mm/s, depending on the load.

The port number for the traverse system controller (specific port settings are in the "Settings" tab, see Section 4.3) must be correctly configured. After the movement is complete, the "Traverse Indicator Light" will turn on.

| |
|---|
| The traverse system does not have limit switches. Users must always monitor the slider position. |

#### 4.6.4 ④ Area: Manually Adjust the Angle of the CR05 Calibrator's Rotation Mechanism

If the user is using the CR05 calibrator, they can set the rotation angle of the pitch mechanism in area ④ to directly change the probe orientation. The unit is degrees. The recommended rotation speed is 5 degrees per second. The port number for the controller (specific port settings are in the "Settings" tab, see Section 4.3) must be correctly configured. After setting the rotation angle and speed, click "Rotate Probe." After the movement is complete, the "Traverse Indicator Light" will turn on.

| |
|---|
| The traverse system does not have limit switches. Users must always monitor the slider position. |

## 4.7 CTALab Tab 5: Measurement

The measurement tab is shown in Figure 21. Through operations in this tab, users can set measurement parameters, perform measurements, and save data.

### 4.7.1 ① Area: Select Measurement Channels and Set Acquisition Method

| |
|---|
| Users are advised to watch the following video:<br>https://www.bilibili.com/video/BV1gz4y1u7yy/ |

Users must first select the channels. The selection method is to click on the desired channel with the mouse. If more than one channel is to be measured simultaneously, hold the Ctrl key and click on the next channel. After selecting the channels, users need to set the sampling parameters. These parameters include:

**Sampling Rate** The sampling frequency is the number of samples collected per second,

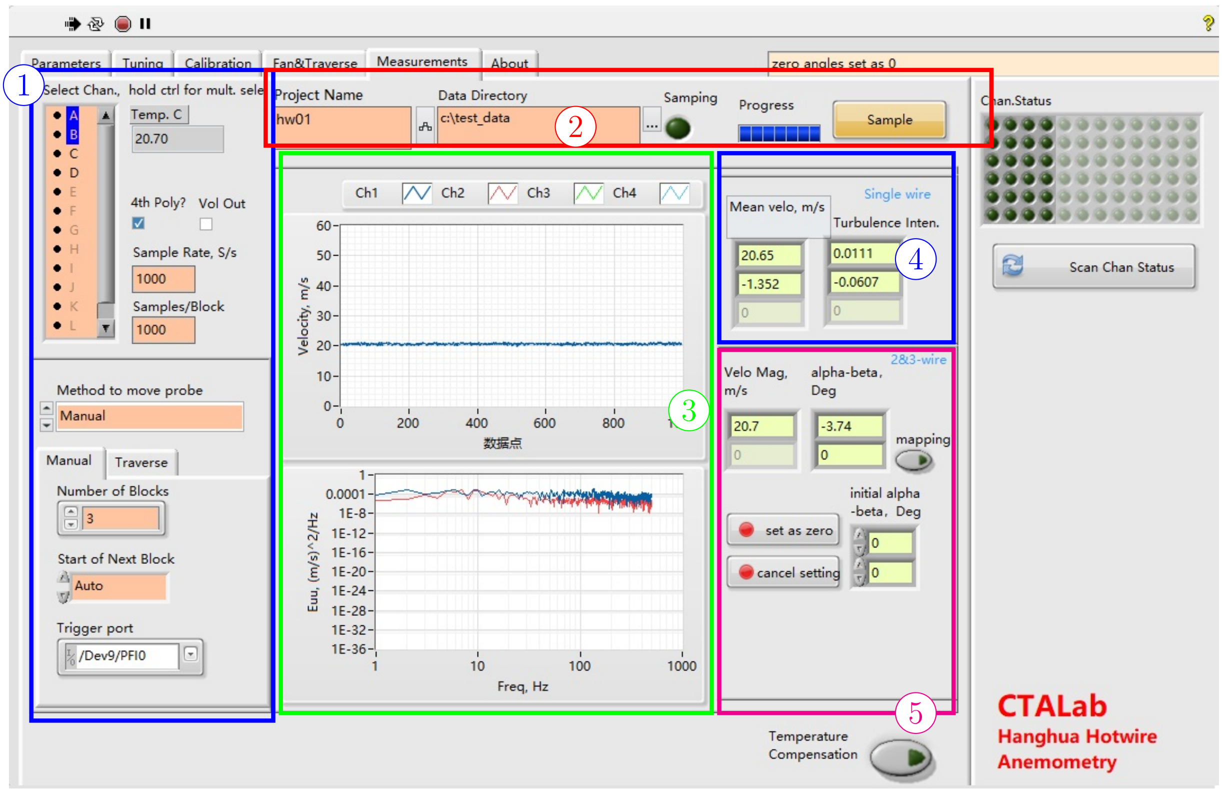



**Figure 21: The measurement tab interface is divided into different functional areas: ① Set acquisition parameters, ② Set data file parameters and acquisition operations, status display area, ③ Real-time data and power spectrum display area, ④ Single-wire probe measurement results display area, ⑤ Multi-wire probe measurement results display area.**

in Hertz (Hz) or samples per second (Sample/s). The sampling rate is closely related to the research objectives, for examples:

- If studying the development of large-scale vortices in cylinder wake flow, the sampling frequency should be at least 10 times the vortex shedding frequency.
- If studying the Kolmogorov scale under high Reynolds number conditions, a sampling frequency of 20 kHz or higher is recommended. Users can determine whether a higher sampling frequency is needed by observing if a turning point of slope in the spectrum appears.
- Note that the DAQ16 has a total sampling frequency of 250 kHz. If using 6 channels simultaneously, the maximum frequency per channel is $250/6 = 41.6$ kHz. The sampling frequency setting cannot exceed this value.
- Additionally, to improve spectral analysis efficiency, the sampling frequency is usually a power of 2, with common values being 1024, 2048, 4096, 8192, etc.

**Samples per Block** To enhance the safety of long period samplings (avoiding memory issues), the total sampling duration is usually divided into several equal-length data blocks, which are collected and saved separately. Samples per block = Sampling rate * Sampling duration per block. For example, if the sampling duration per block is 1 second and the sampling frequency is 8192 Hz, the total samples per block should be set to 8192.

**Number of Sample Blocks** The number of sample blocks and the sampling duration per block together determine the total sampling duration: Total sampling duration = Number of blocks * Sampling duration per block. For example, if the sampling duration per block is 1 second and the number of blocks is 64, the total duration is 64 seconds.

Below, we use a sampling frequency of 8192 Hz, a sampling duration of 1 second per block, and 64 sampling blocks as an example to explain the differences between different "sampling methods":

(1) The user selects the "Normal" method in "Sampling Method" and chooses "Automatic" in the "Next block Activation" option under the "Normal" tab (Figures 22a and 22b):

After collecting and saving each block of 1-second data (8192 samples per channel), the system pauses for about 0.1 seconds, then automatically starts collecting the next block of data. This cycle repeats until all 64 blocks of data are collected. During the process, the progress is displayed in the text area in the upper right corner.

(2) The user selects the "Normal" method in "Acquisition Method" and chooses "Manual" in the "Next block Activation" option:

Before starting to collect each block of data, the system pops up a notification window (Figure 22c). After the user clicks OK, the system starts collecting data (8192 samples per channel) until all 64 blocks of data are collected. During the process, the progress is displayed in the text area in the upper right corner.

> Before each click of OK, the user can use the waiting time to manually move the probe.

(3) The user selects the "Normal" method in "Sample Method" and chooses "External Trigger" in the "Next Block Activation" option (Figure 22d):

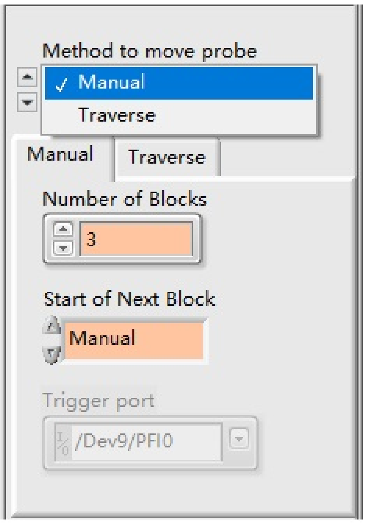
Before starting to collect each block of data, the system scans the input signal from the PFI0 digital input port of the acquisition card (some DAQ16 acquisition units have the PFI0 port connected to the BNC interface at the bottom right of the front panel, labeled "PFI0"). Once a rising edge of a TTL square wave signal is detected, the system immediately starts collecting data (8192 samples per channel). After collecting and saving the data, it waits for the next rising edge of the square wave signal until all 64 blocks of data are collected. During the process, the text area in the upper right corner displays "waiting trigger signal."

(4) The user selects the "Traverse System" method in "Acquisition Method" (Figure 22e):

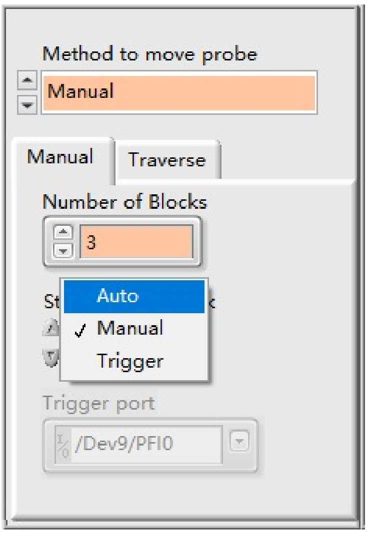
After collecting each block of data (8192 samples per channel), the system moves the position step by step according to the user-set traverse coordinates. After the movement is complete, it automatically starts collecting the next block of data (8192 samples per channel) until all positions are collected. If the coordinate file contains 9 coordinate points and the sampling duration per position is 1 second, the total sampling duration is 9 * 1 = 9 seconds. During the process, the progress is displayed in the text area in the upper right corner.

> For more information on using the traverse system, users can refer to the following video:
> `https://www.bilibili.com/video/BV1594y1r7ig/`

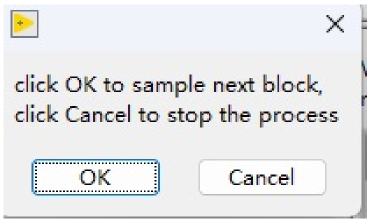
Another important parameter in the ① functional area is the two options: "**Hot-Film**" and "**Fourth-Order Curve**". These options determine the method used to convert the output voltage to flow velocity. If the user enables the "**Hot-Film**" option, the software will not perform any conversion and will directly display and save the output voltage from the hot-wire anemometer. If the "**Hot-Film**" option is disabled and the user enables the "**Fourth-Order Curve**" option, the system will use the fourth-order calibration curve to convert voltage to velocity; otherwise, it will use the exponential calibration results.



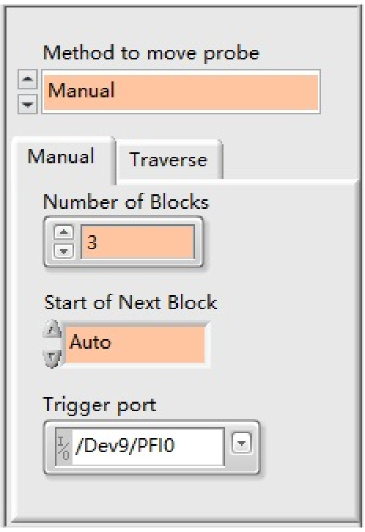

(a) The user selects "Normal" in the acquisition method.



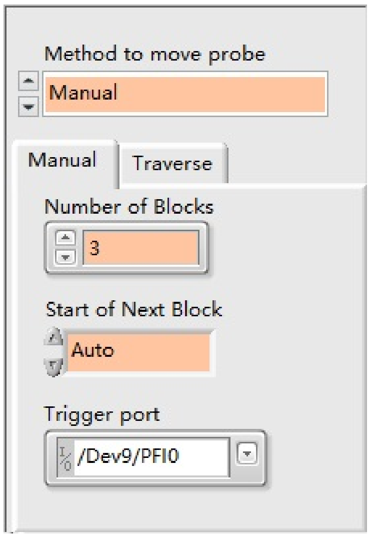

(b) The user selects "Automatic" in the "Normal" tab.




(c) In "Manual" mode, a pop-up reminds the user to proceed to the next set of measurements.




(d) The user selects "External Trigger" in the "Normal" tab.




(e) The user selects "Moving Probe" in the acquisition method.

Figure 22: Area 1 in the "Measurement" tab: Measurement parameter settings.

The advantages, disadvantages, and selection recommendations for these two methods are detailed in Appendix I.2. For guidance on choosing between the "**Hot-Film**" and "**Fourth-Order Curve**" options, users are advised to watch the following video:

https://www.bilibili.com/video/BV1T44y1F7au/

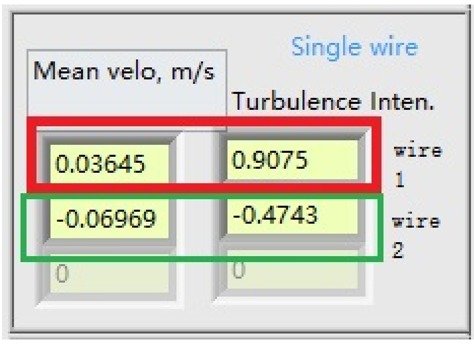
### 4.7.2 Starting Measurements

When the user clicks "Start Acquisition," the system enters the measurement state. The "Collecting" light in the left area of ② illuminates, and the progress table updates after each set of samples.

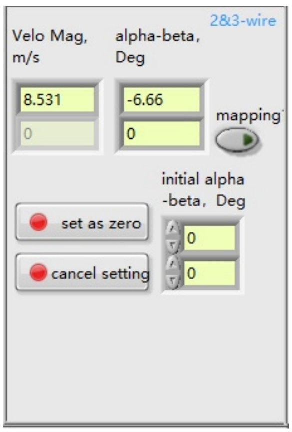
### 4.7.3 Real-Time Data and Spectrum Display

The upper part of the ③ functional area in Figure 21 displays the real-time data collected by the system, which updates after each set of measurements:

- If the user uses a single-wire hot-wire probe, the figure shows the measured data for each probe $u_1(t), ..., u_n(t)$ in units of $[m/s]$.
- The horizontal axis on the left represents time $t$ in units of $[s]$.
- If the user uses a dual-wire hot-wire probe, the figure shows the two components of the real-time velocity in the measurement plane, $u(t), v(t)$, in units of $[m/s]$. The velocity decomposition method is detailed in Appendix K.




**(a) Statistical results of single-wire hot-wire probe measurements.**




**(b) Statistical results of dual-wire and multi-wire probe measurements.**

**Figure 23: Statistical results of measurements.**

- If the user uses a triple-wire hot-wire probe, the figure shows the three components of the real-time velocity, $u(t), v(t), w(t)$, in units of $[m/s]$. The velocity decomposition method is detailed in Appendix K.

The lower part of the ④ functional area in Figure 21 displays the Power Spectral Density (PSD) distribution of the real-time data:

- The lower part shows the PSD of the velocity component $u$, $E_{uu}$, in units of $[(m/s)^2/Hz]$:
$$E_{uu} = |fft(u - U)|^2/N \tag{3}$$
Here, $fft$ is the Fast Fourier Transform, $N$ is the number of samples, and $U$ is the time-averaged value of $u$: $U = \bar{u}$.

- The horizontal axis below represents frequency $f$ in units of $[Hz]$.

The ④ and ⑤ functional areas in Figure 21 display statistical data (see also Figure 23):

- If the user uses a single-wire hot-wire probe, the mean (left) and standard deviation (right) of each set of measurement results are displayed in the ④ functional area. The data is shown for Channel 1, 2, 3, etc., from top to bottom, as illustrated in Figure 23a.

- If the user uses a dual-wire hot-wire probe, the mean velocity magnitude $|\vec{V}|$ (left) and the angle between the incoming flow velocity and the probe axis are displayed in the ⑤ functional area (top-right), as shown in Figure 23b.

- use of the 'Set as Zero' button will assign the current measured pitch and yaw to the initial (reference) pitch $\alpha_o$ and the initial yaw $\beta_o$. The reported pitch and yaw (what show above) become $\alpha - \alpha_o$ and $\beta - \beta_o$, respectively. See Fig. 24.

- use of the 'Cancel Setting' button will assign $\alpha_o = 0$ and $\beta_o = 0$

- the use of 'Mapping' option (by clicking the button named Mapping to lighten it up) with evoke the mapping option of the multiple wire. If not lighten up, a model is used to convert the voltages to velocity and angles. If the wire was calibrated individually, mapping gives better precision.

- If the user uses a triple-wire hot-wire probe, the mean velocity magnitude $|\vec{V}|$ (left) and the alpha-beta angles between the incoming flow velocity and the probe axis are displayed in the ⑤ functional area (top-right), while the theta and psi angles are displayed in the bottom-right. The definitions of these angles are detailed in Appendix K.

### 4.7.4 Selecting File Saving Method

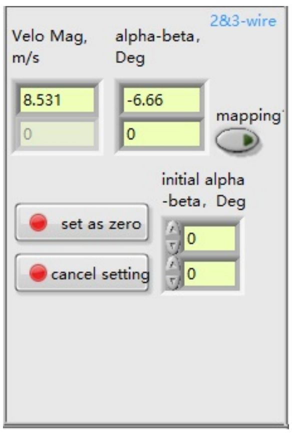
It is recommended that users watch the following video:
https://www.bilibili.com/video/BV13j411z7MU/

In the ② area, users can set the directory for saving data files in the "Data Directory." If the directory does not exist, the system will prompt the user with a pop-up before starting the acquisition. If the user agrees, the software will automatically create the directory. Users can also set a prefix for the data file names in the "Project Name" field to ensure that each acquisition generates files with unique names. See the following example for details:

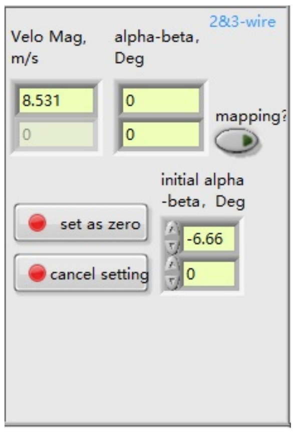
a) Data is stored in the user-specified directory, e.g., c:\test_data, as shown in Figure 21. All files use the project name as the filename prefix (in this case, hw01).

b) Two types of files are saved: statistical data files (filename = project name_stats.txt, hereafter referred to as "stat files") and real-time data files (filename = project name + measurement point number.txt, hereafter referred to as "data files"), as shown in Figure 25. Below is a detailed description of these two types of files.

c) Stat Files




**(a) Measurements when the initial (reference) pitch and yaw angle is $\alpha_o = 0$ and $\beta_o = 0$, respectively.**




**(b) Press 'Set as Zero' button will assign measured angles (show above) as the initial angles and show below. The reported $\alpha$ and $\beta$ become 0 as they are the measured value minus the initial value.**

**Figure 24: Use 'Set as Zero' and 'Cancel Setting' buttons to set and unset and the initial (zero) angles for multi-wire measurement.**

(a) For single-channel measurements, the statistical data contains a 2D array of size [number of measurement points, 8]. Only the first 4 columns of the 8 columns are valid, corresponding to the serial number, average flow velocity [m/s], standard deviation of flow velocity [m/s], and temperature during measurement [C]. The last four columns are invalid numbers.

(b) For dual-channel (A and B) measurements, where both channels use HW1A single-wire probes (not HW2A dual-wire probes), the statistical data contains a 2D array of size [number of measurement points, 10]. The 10 columns correspond to the serial number, average flow velocity for Channel A [m/s], average flow velocity for Channel B [m/s], standard deviation of flow velocity for Channel A [m/s], standard deviation of flow velocity for Channel B [m/s], and temperature during measurement [C]. The last four columns are invalid numbers.

(c) For dual-channel (A and B) measurements, where the two channels are connected to the two tungsten wires of an HW2A dual-wire probe, the statistical data contains a 2D array of size [number of measurement points, 10]. The 10 columns correspond to the serial number, average horizontal flow velocity component U [m/s], average vertical flow velocity component V [m/s], standard deviation of the horizontal flow velocity component [m/s], standard deviation of the vertical flow velocity component [m/s], and temperature during mea-

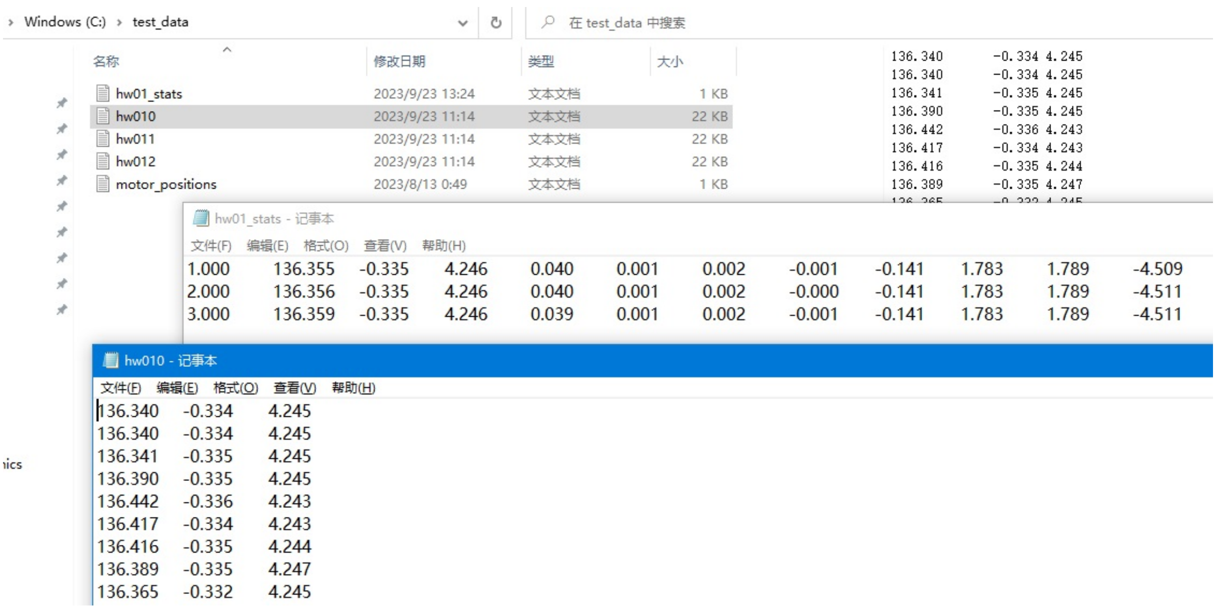



**Figure 25: Data files collected by the triple-wire probe at three measurement points are saved in the user-specified directory.**

surement [C]. Among the last four columns, the 1st and 3rd columns are the same, representing the angle of inclination, while the 2nd and 4th columns are invalid.

(d) For triple-channel (A, B, and C) measurements, where the three channels are connected to the three tungsten wires of an HW3A triple-wire probe, the statistical data contains a 2D array of size [number of measurement points, 12]. The first 8 columns correspond to the serial number, average horizontal flow velocity component U [m/s], average vertical flow velocity component V [m/s], average spanwise flow velocity component W [m/s], standard deviation of the horizontal flow velocity component [m/s], standard deviation of the vertical flow velocity component [m/s], standard deviation of the spanwise flow velocity component [m/s], and temperature during measurement [C]. The last 4 columns represent the alpha and beta angles (1st and 2nd columns) and the theta and psi angles (3rd and 4th columns), as shown in Figure 25. The definitions of these angles are detailed in Appendix K.

(e) If the user does not change the project name and runs the program again, the new statistical information will be appended to the end of the existing file without overwriting the previous data.

d) Data Files

(a) Real-time data collected at each measurement point is saved separately. If the number of sample blocks is 10, there will be 10 independent text files, with filenames = project name + block number.txt.

(b) For single-channel measurements, each data file contains a 1D array of size [N, 1] (i.e., N rows and 1 column, where N is the number of samples per block). The data represents the hot-wire measurement results in units of $[m/s]$. Note that if the user enables the "Hot-Film" option in the measurement tab, the saved values are the raw measurement voltages in units of $[V]$.

(c) The system does not save time files. If needed, users can generate them based on the sampling frequency of 1024 Hz. For example, if the number of samples per block is 2048 and the sampling rate is 1024 Hz, the time variable $t$ can be generated in MATLAB using the following command:

```
t=[1:2048]*(1/1024)
```

(d) For dual-channel (A and B) measurements, the real-time data file contains a 2D array of size [N, 2]. If both channels use HW1A single-wire probes (not HW2A dual-wire probes), the two columns correspond to the sampled speeds of the two channels [m/s]. If the two channels are connected to the two tungsten wires of an HW2A dual-wire probe, the two columns correspond to the horizontal and vertical components of the flow velocity, $u$ and $v$ [m/s].

(e) For triple-channel (A, B, and C) measurements, the real-time data file contains a 2D array of size [N, 3]. If all three channels use HW1A single-wire probes, the three columns correspond to the sampled speeds of the three channels [m/s]. If the three channels are connected to the three tungsten wires of an HW3A triple-wire probe, the three columns correspond to the horizontal, vertical, and spanwise components of the flow velocity, $u$, $v$, and $w$ [m/s].

(f) If the user does not change the project name and runs the program again, the information in the real-time data files will be overwritten.

### 4.7.5 Reading and Using Data Files

Users can employ various methods to read data files and statistical files for further processing and plotting. We recommend using Matlab or Python for processing. If users need to use Matlab to read and process the data, they can directly navigate to the data directory and run the following commands:

```
cd C:\measurements
t=[1:1024]*(1/1024);
data=load('Cobra_probe1_data1.txt');
figure,plot(t,data(1:1024,1))
```

For Python, users can run the following commands:

```
import numpy as np
import matplotlib.pyplot as plt
data = np.loadtxt("C:\measurements\Cobra_probe1_data1.txt", delimiter="\t")
fig, ax1 = plt.subplots(1, 1, sharey=True, figsize=(8, 6))
ax1.plot(data[range(1,1024),1])
```

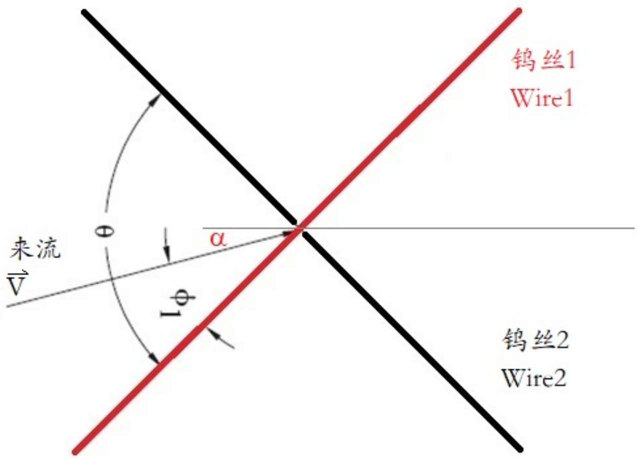
## 4.8 Multi-wire probes

A single-wire probe can only measure changes in the magnitude of velocity. To measure both the magnitude and direction of velocity, a multi-wire probe is required. This section introduces the usage of the two-wire HW2A and three-wire HW3A probes.

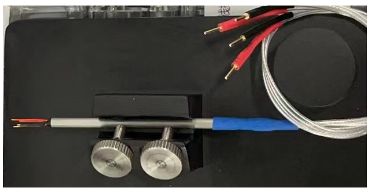
### 4.8.1 Dual-Wire X-Probe

The X-type dual-wire probe consists of two tungsten wires and four prongs:

- The four prongs are divided into two pairs, each pair painted in different colors, one pair in red and the other in black, as shown in Figure K.1;
- One tungsten wire is soldered to the top of the two red-painted prongs, referred




(a) Schematic of the X-probe



(b) Photo of the HW2A Dual-Wire X-Probe


(c) Property selection for the X-probe

**Figure 26: Usage of the HW2A Dual-Wire X-Probe**

to as the red wire, highlighted in red in Figure 26a. The ends of the prongs are connected to two red mini-banana plugs;

- The other tungsten wire is soldered to the two black-painted prongs, referred to as the black wire, highlighted in black in Figure 26a. The ends of the prongs are connected to two black mini-banana plugs;

- Each pair of prongs includes one long and one short prong. The length difference ensures that the tungsten wire forms a $45^o$ angle with the prongs, with no polarity distinction between the long and short prongs. The two pairs of prongs and wires form two parallel planes (i.e., the red plane and the black plane). The distance between the two planes is approximately 1mm.

- The measurement plane is shown in Figure 26a. In the figure, the red plane is in front, and the black plane is behind. Due to the small distance, the red and black planes can be considered as the same plane, i.e., the measurement plane. The X-type dual-wire probe can resolve the velocity vector within this plane.

The operation method of the X-type dual-wire probe is as follows:

| Users can refer to the following video for setting up the dual-wire probe: `https://www.bilibili.com/video/BV1Xu4y1v7kj/` |
|---|

- First, measure the cold resistance of the red and black wires.

- Connect the black wire to channel A (or any channel specified by the user) of the hot-wire anemometer, and the red wire to channel B (or any channel different from the red one).

- In the "Settings" tab, select the property for both channels as "Dual-Wire Probe 1" (or "Dual-Wire Probe 2", etc.), as shown in Figure 26c.

- Follow the single-wire probe procedure to set the cold resistance, overheat ratio, balance parameters, and signal modulation parameters for channels A and B, then turn on the bridge.

- Rotate the CR04 calibrator turntable to align the black wire with the incoming flow, turn on the bridge, and perform a square wave test.

- Refer to Section 4.5.1 to calibrate channel A and the black wire (the process is the same as for a single-wire probe).

- After calibrating the red wire, rotate the turntable 90 degrees in the opposite direction to align the red wire with the incoming flow, and calibrate channel B and the red wire.

| |
|---|
| Note: When adjusting and testing each channel, the corresponding tungsten wire must be perpendicular to the incoming flow. |

After setup, you can start the measurement under the "Measurement" tab. Please note:

| |
|---|
| Users can refer to the following video for using the dual-wire probe: https://www.bilibili.com/video/BV12P411s7Wi/ |

- Select both channels A and B for measurement. When selecting channel B, hold the Ctrl key and click on channel B.
- The ④ functional area in Figure 21 displays the velocity components u and v. For details, refer to Section 4.7.3.
- The ⑤ functional area in Figure 21 displays the velocity magnitude $|\vec{V}|$ and the angle of attack (alpha).

### 4.8.2 Triple-Wire Probe

The triple-wire probe can measure the three-dimensional components of the velocity at a point in the flow field. The Hanghua HW3A probe is designed based on the TSI-1299 probe and consists of three orthogonal tungsten wires:

- The three tungsten wires are soldered to three pairs of prongs, painted in black, red, and yellow, respectively, and connected via mini-banana plugs of the corresponding colors. The three wires are referred to as the black wire, red wire, and yellow wire.
- Measure the resistance of each wire and connect the black, red, and yellow wires to channels A, B, and C, respectively.
- Calibration of the triple-wire probe requires calibrating each wire separately, treating each wire as a single-wire probe.
- Mount the probe on the CR04 calibrator and tilt the angle device 35 degrees to the left (or right).
- Move the probe forward or backward so that the tungsten wire is about 1 cm from the jet outlet.

- Adjust the angle so that the black wire is perpendicular to the incoming flow (visually aligned, within ±5 degrees, as the hot-wire output will not vary by more than 0.5%).

- In the "Settings" tab of the software, set the property for all channels to "Triple-Wire Probe 1" (or "Triple-Wire Probe 2", etc., ensuring consistency across all three wires).

- Follow the single-wire probe procedure (Section 4.4) to set the cold resistance, overheat ratio, balance parameters, and signal modulation parameters for channels A, B, and C, then turn on the bridge and perform a square wave test.

- If this is not the first use and the probe has not been replaced since the last calibration, simply turn on the bridge.

- Refer to the single-wire calibration process (Section 4.5.1) to calibrate channel A and the black wire.

- Adjust the angle by 120 degrees to align the red wire with the incoming flow and calibrate channel B and the red wire.

- Adjust the angle by another 120 degrees to align the yellow wire with the incoming flow and calibrate channel C and the yellow wire.

After calibration, the usage is as follows: Arrange the probe position as shown in Figure 30. In the top view, the red long prong is centered (each color prong has one long and one short) and aligned with the incoming flow. The yellow long prong is on the right, and the black long prong is on the left. Only with this arrangement will the software report the u, v, and w components correctly according to the coordinate system.

After setup, you can start the measurement under the "Measurement" tab. Please note:

- Select channels A, B, and C for measurement. When selecting channels B and C, hold the Ctrl key and click on the respective channels.

- The ④ functional area in Figure 21 displays the velocity components u, v, and w. For details, refer to Appendix K.

- The ⑤ functional area in Figure 21 displays the velocity magnitude $|\vec{V}|$, the angle of attack, and the pitch angle $(\alpha - \beta)$. The angle of attack and pitch angle can be converted to roll-cone coordinates $(\theta - \psi)$. For definitions and conversion methods, refer to Appendix K.

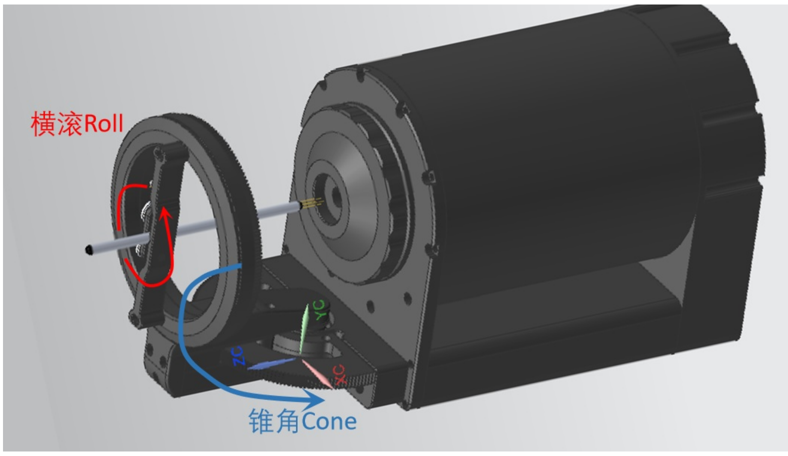



**Figure 27: Schematic of the CR04 Calibrator Jet Table Angle Mechanism for Cone and Roll Angles**

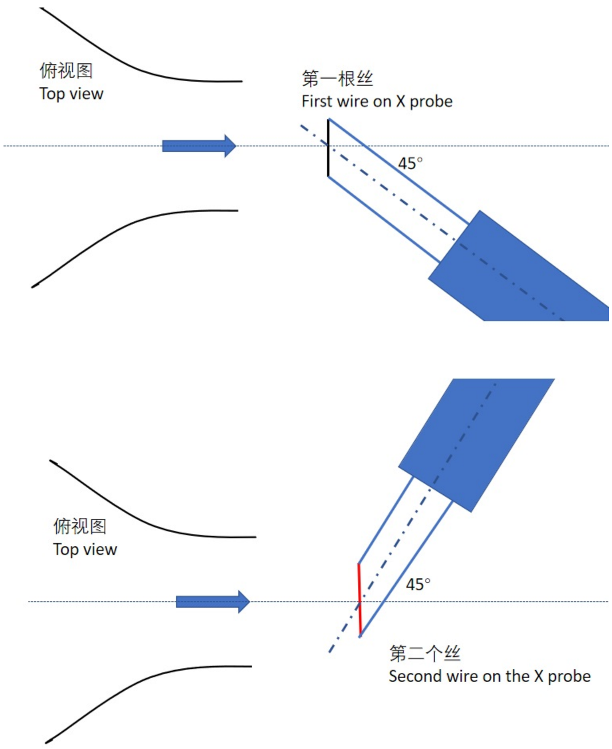



**Figure 28: Calibration Schematic of the X-Type Dual-Wire Probe. Top: First step, calibrating the black wire (prongs painted red); Bottom: Second step, calibrating the red wire.**

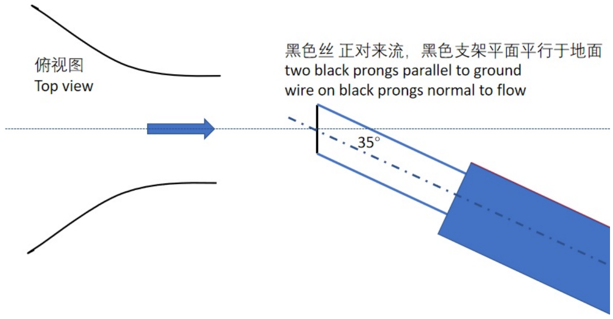



**Figure 29: First Step of Triple-Wire Probe Calibration Schematic**

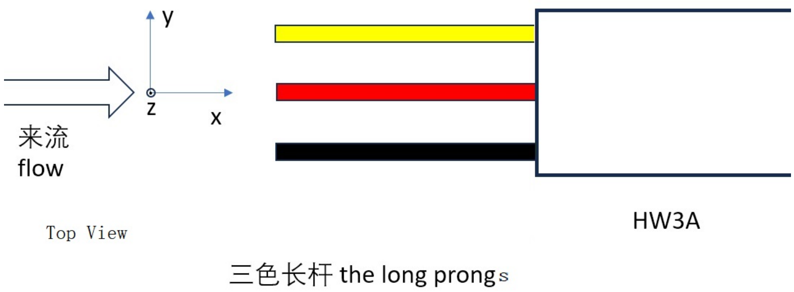



**Figure 30: HW3A Probe, Top View**

# 5 Operation Workflow Examples

Users can refer to the following video:
http://www.hanghualab.com/nd.jsp?id=123&fromMid=470

## 5.1 I Have the Main Unit, Data Acquisition Device, and Calibrator

### 5.1.1 Example with a Single-Wire Probe

Step 1: Measure the cold resistance, $R_o = 5\,\Omega$.

Step 2: Measure the room temperature and calculate the cold resistance using Equation 1.

Step 3: Connect the probe to Channel A and connect the output of Channel A to AI0 on the data acquisition device.

Step 4: Check the temperature probe and connect its output to AI5 on the data acquisition device.

Step 5: Connect the AO0 channel of the data acquisition device to the control line of the frequency converter.

Step 6: Use a pressure tube to connect the H port on the front panel of the data acquisition device to the pressure port of the CR04 calibrator.

Step 7: Check the frequency converter settings. Ensure that parameter P003 is set to 2. Press Run and check if the indicator light is flashing.

Step 8: In the "Settings" tab of the software, set the communication port of the hot-wire anemometer main unit 1 to COM3, the hot-wire channel to Dev1/AI0, the property to "Single-Wire," the total number of channels to 2, the temperature sensor acquisition channel to Dev1/AI5, and the pressure sensor to Dev1/AI13. Click "Save Parameters."

Step 9: In the "Debug" tab, select Channel A, enter the cold resistance, overheat ratio: 1.6, balance parameter: 1.5, gain: 1, offset: 0V, low-pass filter cutoff frequency: none, and click "Send Parameters."

Step 10: Turn on the fan. In the "Debug" tab, click "Square Wave Switch," then click "Send Parameters" again, and observe the acquired signal. Refer to Appendix F to adjust the balance parameter. After adjustment, turn off the "Square Wave Switch."

Step 11: In the "Calibration" tab, select Channel A, choose automatic speed adjustment, automatic speed measurement, total calibration points: 12, and maximum voltage: 5V.

Step 12: Select the pressure sensitivity coefficient from the front panel of the data acquisition device and enter it in the table.

Step 13: Click "Fan Calibration." After completion, begin measurements.

Step 14: In the "Measurement" tab, select Channel A, sampling rate: 10000, samples per group: 2000, acquisition method: normal, number of sample groups: 10, method to proceed to the next group: automatic; project name: hw_, data directory: specify as desired.

Step 15: Click "Start Acquisition" and observe the real-time signal and time-averaged values.

Step 16: Check the data files. The experiment is complete.

### 5.1.2 Example with an X-Type Dual-Wire Probe

Step 1: Measure the cold resistance: black wire $R_{o1} = 7\,\Omega$, red wire $R_{o2} = 8\,\Omega$.

Step 2: Measure the room temperature and calculate the cold resistance using Equation 1.

Step 3: Connect the red wire to Channel A and connect the output of Channel A to AI0 on the data acquisition device.

Step 4: Connect the black wire to Channel B and connect the output of Channel B to AI1 on the data acquisition device.

Step 5: Check the temperature probe and connect its output to AI5 on the data acquisition device.

Step 6: Connect the AO0 channel of the data acquisition device to the control line of the frequency converter.

Step 7: Use a pressure tube to connect the H port on the front panel of the data acquisition device to the pressure port of the CR04 calibrator.

Step 8: Check the frequency converter settings. Ensure that parameter P003 is set to 2. Press Run and check if the indicator light is flashing.

Step 9: In the "Settings" tab of the software, set the communication port of the hot-wire anemometer main unit 1 to COM3, the hot-wire channel to Dev1/AI0, the property to "Single-Wire," the hot-wire channel to Dev1/AI1, the property to "Single-Wire," the total number of channels to 2, the temperature sensor acquisition channel to Dev1/AI5, and the pressure sensor to Dev1/AI13. Click "Save Parameters."

Step 10: In the "Debug" tab, select Channel A, enter the cold resistance, overheat ratio: 1.6, balance parameter: 1.5, gain: 1, offset: 0V, low-pass filter cutoff frequency: none, and click "Send Parameters."

Step 11: Turn on the fan. In the "Debug" tab, click "Square Wave Switch," then click "Send Parameters" again, and observe the acquired signal. Refer to Appendix F to adjust the balance parameter. After adjustment, turn off the "Square Wave Switch."

Step 12: Repeat the above two steps to configure Channel B and perform a square wave test to adjust the balance.

Step 13: In the "Calibration" tab, select the pressure sensitivity coefficient from the front panel of the data acquisition device and enter it in the table.

Step 14: In the "Calibration" tab, select Channel A, choose automatic speed adjustment, automatic speed measurement, total calibration points: 12, and maximum voltage: 5V. Click "Fan Calibration." After completion, begin measurements.

Step 15: Select Channel B, choose automatic speed adjustment, automatic speed measurement, total calibration points: 12, and maximum voltage: 5V. Click "Fan Calibration." After completion, begin measurements.

Step 16: In the "Measurement" tab, select Channels A and B, sampling rate: 10000, samples per group: 2000, acquisition method: normal, number of sample groups: 10, method to proceed to the next group: automatic; project name: hw_, data directory: specify as desired.

Step 17: Click "Start Acquisition" and observe the real-time signal and time-averaged values.

Step 18: Check the data files. The experiment is complete.

## 5.2 I Have the Main Unit and Data Acquisition Device but No Calibrator

If you have other calibration facilities or a wind field where the wind speed can be varied and measured, such as a wind tunnel, you can consider using the manual calibration method (see Section 4.5.5). If you do not plan to calibrate and instead choose the calibration-free measurement method (see Section 4.5.6), the following is the workflow:

Step 1: Measure the cold resistance, $R_o = 5\,\Omega$.

Step 2: Measure the room temperature and calculate the cold resistance using Equation 1.

Step 3: Connect the probe to Channel A and connect the output of Channel A to AI0 on the data acquisition device.

Step 4: Check the temperature probe and connect its output to AI5 on the data acquisition device.

Step 5: Connect the AO0 channel of the data acquisition device to the control line of the frequency converter.

Step 6: Use a pressure tube to connect the H port on the front panel of the data acquisition device to the pressure port of the CR04 calibrator.

Step 7: Check the frequency converter settings. Ensure that parameter P003 is set to 2. Press Run and check if the indicator light is flashing.

Step 8: In the "Settings" tab of the software, set the communication port of the hot-wire anemometer main unit 1 to COM3, the hot-wire channel to Dev1/AI0, the property to "Single-Wire," the total number of channels to 2, the temperature sensor acquisition channel to Dev1/AI5, and the pressure sensor to Dev1/AI13.

Step 9: In the "Settings" tab, enter the factory calibration values for parameters $a$ and $b$ for Channel A. Note: Factory annealing and calibration is a paid service, with costs similar to the price of the probe itself. Please consider this option carefully.

Step 10: In the "Debug" tab, select Channel A, enter the cold resistance, overheat ratio: 1.6, balance parameter: 1.5, gain: 1, offset: 0V, low-pass filter cutoff frequency: none, and click "Send Parameters."

Step 11: Turn on the fan. In the "Debug" tab, click "Square Wave Switch," then click "Send Parameters" again, and observe the acquired signal. Refer to Appendix F to adjust the balance parameter. After adjustment, turn off the "Square Wave Switch."

Step 12: In the "Measurement" tab, select Channel A, sampling rate: 10000, samples per group: 2000, acquisition method: normal, number of sample groups: 10, method to proceed to the next group: automatic; project name: hw_, data directory: specify as desired.

Step 13: Click "Start Acquisition" and observe the real-time signal and time-averaged values.

Step 14: Check the data files. The experiment is complete.

## 5.3 I Only Have the Main Unit

If the user has only purchased the main unit, they can still conduct teaching and research work. The user needs:

a) A computer with serial communication capability. Use the serial port to send text commands to the hot-wire anemometer to turn the bridge on/off, set the overheat ratio, adjust the balance parameters, and enable/disable the square wave test. Users can refer to Section D to install a serial communication assistant and directly control the anemometer via command lines. Users can also choose other serial communication tools. The basic syntax is provided in the appendix.

b) A data acquisition device. This can be any functional data acquisition card, an oscilloscope, or a multimeter.

c) The user also needs to prepare a facility to adjust and measure wind speed, such as a wind tunnel.

After installing the serial debugging assistant, the user can follow the example below to operate a single-wire probe:

Step 1: Use a multimeter to measure the probe resistance (ensure to measure the resistance through the mini-banana plugs at the probe's tail; do not directly touch the top of the probe). Below, we assume:

Step 2: Measure the room temperature and calculate the cold resistance using Equation 1. Below, we assume $R_{wo} = 6\,\Omega$.

Step 3: Install the hot-wire probe on the experimental setup (e.g., wind tunnel) and connect the wires to Channel A.

Step 4: Turn on the anemometer power.

Step 5: Run the serial debugging program.

Step 6: Set the overheat ratio. For example, with an overheat ratio $OR = 1.5$:

$$R_3 = (OR \times R_{wo}) \times 10 = (1.5 \times 6.0\,\Omega) \times 10 = 90\,\Omega \tag{4}$$

Write the following command via the serial debugging program:

```
cta 1 overheat 90
```

Step 7: Turn on the bridge:

- Write the following command via the serial debugging program:

  ```
  cta 1 bridge_on
  ```

- Observe the Channel A indicator lights: If the top two lights are on, it is correct; if the third light is on, it is incorrect, and the probe may be damaged.

Step 8: Adjust the wind tunnel flow rate to the maximum flow rate expected in the experiment.

Step 9: Perform a square wave test and observe the results to analyze the system's frequency response:

- Write the following command via the serial debugging program:

  ```
  cta 1 square_wave_on
  ```

- Use an oscilloscope or data acquisition card to observe the output signal. Adjust the balance value to adjust the system's response characteristics. A higher value increases the system's internal damping, which helps stabilize the system but reduces its fast response capability.
- Use an oscilloscope to capture the signal and estimate the system's frequency response.
- Turn off the square wave by writing the following command via the serial debugging program:

  ```
  cta 1 square_wave_off
  ```

Step 10: Place the hot-wire probe in the experimental setup of the wind tunnel and prepare a Pitot tube or other instruments to measure the incoming flow velocity.

Step 11: Increase the wind speed in ten steps from low to high. At each wind speed, record the flow velocity in the wind tunnel test section and the output voltage of the hot-wire anemometer.

Step 12: Use a fourth-order curve to fit the wind speed and voltage data to form a calibration curve. For specific methods, refer to Appendix ***.

Step 13: Turn off the bridge by writing the following command via the serial debugging program:

```
cta 1 bridge_off
```

## 5.4 I Need to Perform Measurements at Medium and High Speeds Exceeding 120 m/s

The CTA04 Pro system can provide currents above 1.0 A, making it suitable for measuring compressible flows with Mach numbers exceeding 1. However, users should note:

- The tungsten wire of a standard Hanghua HW1A probe is approximately 1.5 mm long and is not strong enough for stable measurements above 120 m/s, making it prone to damage. Customers should contact us to customize probes with shorter tungsten wires.
- High-speed measurements require the use of compressed air as the gas source for calibration (for low-speed measurements below 120 m/s, a fan can be used as the gas source for calibration).
- High-speed measurements require changing the bridge ratio (Scale) to 100:1. Only then can the anemometer provide sufficient current.

The specific operation workflow is as follows (overlapping with Section 4.5.2, "Compressed Air Calibration"):

(1) Replace the end plate of the CR04 calibrator and connect the compressed air tube to the hand valve and gas cylinder.

(2) Mount the probe at the jet outlet.

(3) Use an air compressor to pressurize the gas cylinder to the required pressure (if calibrating at 1 M, considering pipeline losses, typically 0.5 MPa or higher is required). Keep the valve closed during pressurization, and turn off the air compressor (or close the valve between the air compressor and the gas cylinder) after pressurization.

(4) Check if the maximum range of the built-in pressure sensor in the DAQ16 data acquisition device is within a reasonable range: it is recommended to be above 50 kPa.

(5) Check the CTALab software to ensure all channels are open.

(6) Set the bridge ratio (Scale) to 100:1 (Figure ??) and send it to the anemometer.

(7) Open the valve to create a high-speed jet at the calibrator outlet.

(8) Click the "Compressed Air Calibration" button (Figure 16). The software will start collecting the total pressure from the calibrator and the output voltage from the anemometer. After completion, the software will provide the calibration results.

(9) You can now begin measurements.

# 6 Glossary

**Cold Resistance** $R_{wo}$ The cold resistance refers to the resistance of the probe measured with a multimeter at room temperature, in ohms.

**Overheat Ratio (OR)** The overheat ratio is the ratio of the probe's operating resistance to its cold resistance:

$$OR = R_w/R_{wo}, \tag{5}$$

Typically, the OR value ranges between 1.5 and 1.8. Based on the temperature-resistance characteristics of tungsten, the operating temperature of the probe is approximately 110-180°C higher than room temperature. In this experiment, we set the probe's operating resistance by adjusting the value of the variable resistor $R_3$ in the bridge circuit (see Figure 1), thereby setting the overheat ratio. When the bridge is balanced, the resistances in the bridge circuit should satisfy:

$$R_2/R_1 = R_3/R_w \tag{6}$$

Therefore,

$$R_w = (R_1/R_2)R_3 \tag{7}$$

Since the Hanghua CTA04 anemometer has $R_2/R_1 = 10$ (this ratio is called the bridge ratio, see Figure 1), $R_w = R_3/10$. Because $R_w = OR \times R_{wo}$, it follows that $R_3 = 10(OR \times R_{wo})$.

In this experiment, we will directly command the hot-wire anemometer to change the value of the overheat parameter, which corresponds to the resistance value of $R_3$.

**Bridge Ratio (Scale)** The bridge ratio is the ratio of the resistances of two key resistors in the anemometer's bridge circuit: $R_2/R_1$ (this ratio is called the bridge ratio, see Figure 1). The default value is 10, suitable for low-speed measurements (less than 120 m/s). For medium and high-speed measurements, this value should be adjusted to 100, as described in Section 4.4.1.

**Balance Parameter** The balance parameter is a critical parameter for the feedback balance amplifier in the circuit. It determines whether the feedback system can operate under reasonable conditions. When using a serial port assistant to control the hot-wire anemometer main unit, the balance parameter is a unitless value ranging from 0 to 65536. A higher value increases the damping in the feedback system. The default value is 37500. When using the CTALab software to control the main unit, the balance parameter ranges from 0 to 5, and we recommend setting it between 0.5 and 1.5.

**Square Wave Test** The square wave test is a tool to observe the system's response by applying a small disturbance to the bridge, thereby determining whether the balance parameter is appropriate. If using a serial debugging assistant to operate the anemometer, the commands 'square_wave_on' and 'square_wave_off' can be used to enable and disable the square wave, respectively.

**Bridge Top Voltage** The bridge top (TOB) voltage $E_t$ is the voltage applied to the bridge by the power supply. This voltage corresponds directly to the wind speed. If the bridge top voltage is below 0.4 V (TOB Low), the probe may be damaged. If the bridge top voltage exceeds 9 V, the system has overflowed.

**Signal Post-Processing** Also known as **output signal modulation**. In some cases, the bridge top voltage output may pose challenges for data acquisition. We can consider modulating the bridge top voltage. Modulation includes amplification (gain), offset, and low-pass filtering (filter). When the bridge output signal is weak, the user can set the gain to 2-16. When the bridge top voltage exceeds 5 V, some data acquisition devices may not function properly. The user can consider setting a positive offset value, ranging from 0 to 5 V. Additionally, the user can set a low-pass filter with a cutoff frequency of 1 Hz to 10 kHz.

**Sampling Frequency** The sampling frequency is the number of samples acquired per second per channel, in samples per second (Sample/s) or Hz.

**Samples per Group** The number of samples contained in each data group.

**Number of Sample Groups** The number of independent data groups acquired in a single measurement session. If the number of sample groups is 10, the user will save the data after acquiring the specified number of samples per group and then proceed to the next data group.

**Traversing Mechanism** A motion control system consisting of a stepper motor controller and a stepper motor slide, used to move the hot-wire probe to different positions in the flow field for measurements.

**Communication Port** The computer's serial port number. The software sends text commands to the hot-wire anemometer main unit through the serial port and also reads the main unit's status through the serial port. Additionally, the software controls the traversing mechanism through the serial port. The specific port number can be checked in the computer's "Device Manager."

**Hot-Wire Probe** Also known as a **hot-wire sensor**. It consists of a tungsten wire, prongs, the probe body, wires, and mini-banana plugs. The hot-wire probe is connected to the hot-wire anemometer main unit via wires (CB02A) and senses velocity changes through variations in the tungsten wire's heating.

**Hot Film** In flow measurements, hot-film sensors appear in two different contexts. The first is a metal coating (usually nickel or platinum) on a flexible substrate, often attached to the surface being measured to infer wall shear stress based on current changes. The second is a metal film coated on a cylindrical polymer surface with a diameter of about 100 micrometers. The cylinder is mounted on a pair of prongs like a tungsten wire. Due to its sturdier structure, this type of hot-film sensor is used as a replacement for tungsten wire hot-wire probes to measure flow velocity changes. The second type of sensor is often used in water.

**Frequency Response** Short for frequency response characteristics, it describes how an instrument responds to signals of different frequencies. An ideal instrument should respond equally to signals of all frequencies. Typically, instruments respond better to low-frequency signals and worse to high-frequency signals. When the amplitude of high-frequency signals gradually decreases and becomes 3 dB or more lower than that of low-frequency signals, this frequency is usually considered the upper limit of the instrument's frequency response. In engineering practice, engineers often refer to this upper limit as the instrument's frequency response.

# Appendices

## A Hanghua Hot-Wire Probes

Hanghua offers a variety of hot-wire probes to meet different measurement needs of customers. Descriptions of the most commonly used HW1A and HW2A probes are provided in Table 1. The vast majority of customers choose these two probes. All available probes are listed in Table A.1. Some photos are shown in Figure A.1.

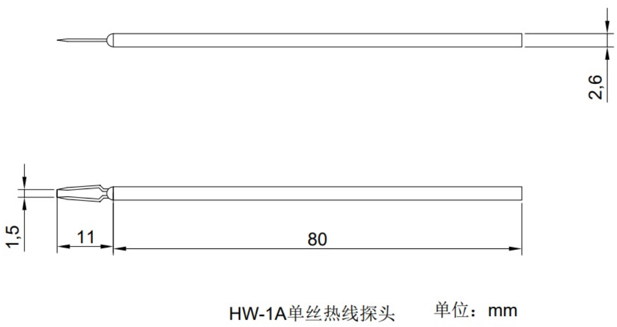
Some commonly used probes can be purchased directly from Hanghua's Taobao store at:

`https://shop184358989.taobao.com/`

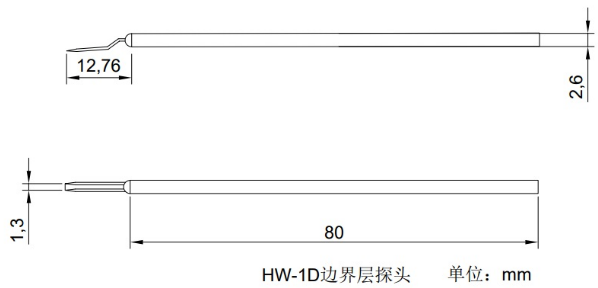

**Figure A.1: Photos of some Hanghua probes.**

Table A.1: Several commonly used Hanghua probes.

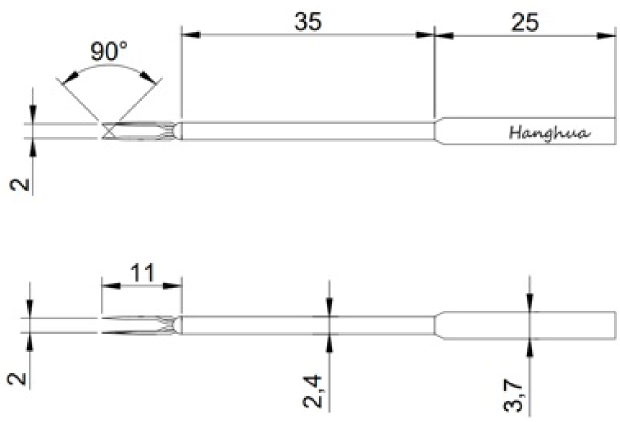
| No. | Product Name | Quantity | Function |
|---|---|---|---|
| 1 | HW1A Single-Wire Probe | Standard | Tungsten wire with a diameter of 5 $\mu m$, approximately 1.5 mm wide. The tungsten wire must face the incoming flow to measure velocity changes. Suitable for most research and teaching applications. See Figure A.2a. |
| 2 | HW1B Single-Wire Probe | Optional | Tungsten wire with a diameter of 2.5 $\mu m$, approximately 0.5 mm wide. High frequency response, mainly for customers studying small-scale turbulence structures. |
| 3 | HW1C Bent Single-Wire Probe | Optional | Tungsten wire with a diameter of 5 $\mu m$, 1.2-1.5 mm wide, with a 90-degree bend at the tip. |
| 4 | HW1D Boundary Layer Single-Wire Probe | Optional | Tungsten wire with a diameter of 5 $\mu m$, 1.2-1.5 mm wide, for measuring velocity changes in the near-wall region. See Figure A.2b. |
| 5 | HW1E Right-Angle Single-Wire Probe | Optional | Tungsten wire with a diameter of 5 $\mu m$, 1.2-1.5 mm wide, with the tungsten wire perpendicular to the probe axis. Suitable for scenarios where space is limited and HW1A cannot be accommodated. |
| 6 | HW1G Angled Single-Wire Probe | Optional | Tungsten wire with a diameter of 5 $\mu m$, approximately 2 mm wide, with a 45-degree angle. Mainly for customers in the power engineering field. |
| 7 | HW1H High-Speed Single-Wire Probe | Optional | Tungsten wire with a diameter of 5 $\mu m$, approximately 0.5 mm wide, for measuring velocity changes in compressible flows. |
| 8 | HW2A Dual-Wire X-Probe | Optional | Tungsten wire with a diameter of 5 $\mu m$, approximately 2 mm wide, for measuring two-dimensional velocity components in a plane. See Figure A.2c. |
| 8 | HW2B Parallel Dual-Wire Probe | Optional | Tungsten wire with a diameter of 5 $\mu m$, 1.2-1.5 mm wide, with a spacing of $0.5 \pm 0.02\,mm$. For measuring velocity gradients. |
| 10 | HW2H High-Speed | Optional | Tungsten wire with a diameter of 5 $\mu m$, |




(a) HW1A




(b) HW1D




(c) HW2A

**Figure A.2: Geometric dimensions of the main types of probes.**

# B FTDI Software: Serial Port Driver

The FTDI software is essential for driving the USB-to-serial communication line. Users can download it from the following URL:

`http://www.hanghualab.com/nd.jsp?id=95&fromMid=468`

After downloading, extract the files and run the ‘CDM v2.23.00 WHQL Certified.exe‘ file. You will see the following prompts in sequence: Select Extract, Confirm, Run Program, Extract, Next, I Accept, Next, and Finish.

After installing the FTDI driver, connect the USB-to-serial cable and open the computer's **Device Manager**. You can see the **serial port** device number COM3 corresponding to the hot-wire anemometer main unit (this number will not change after the first setup). See Figure B.1.

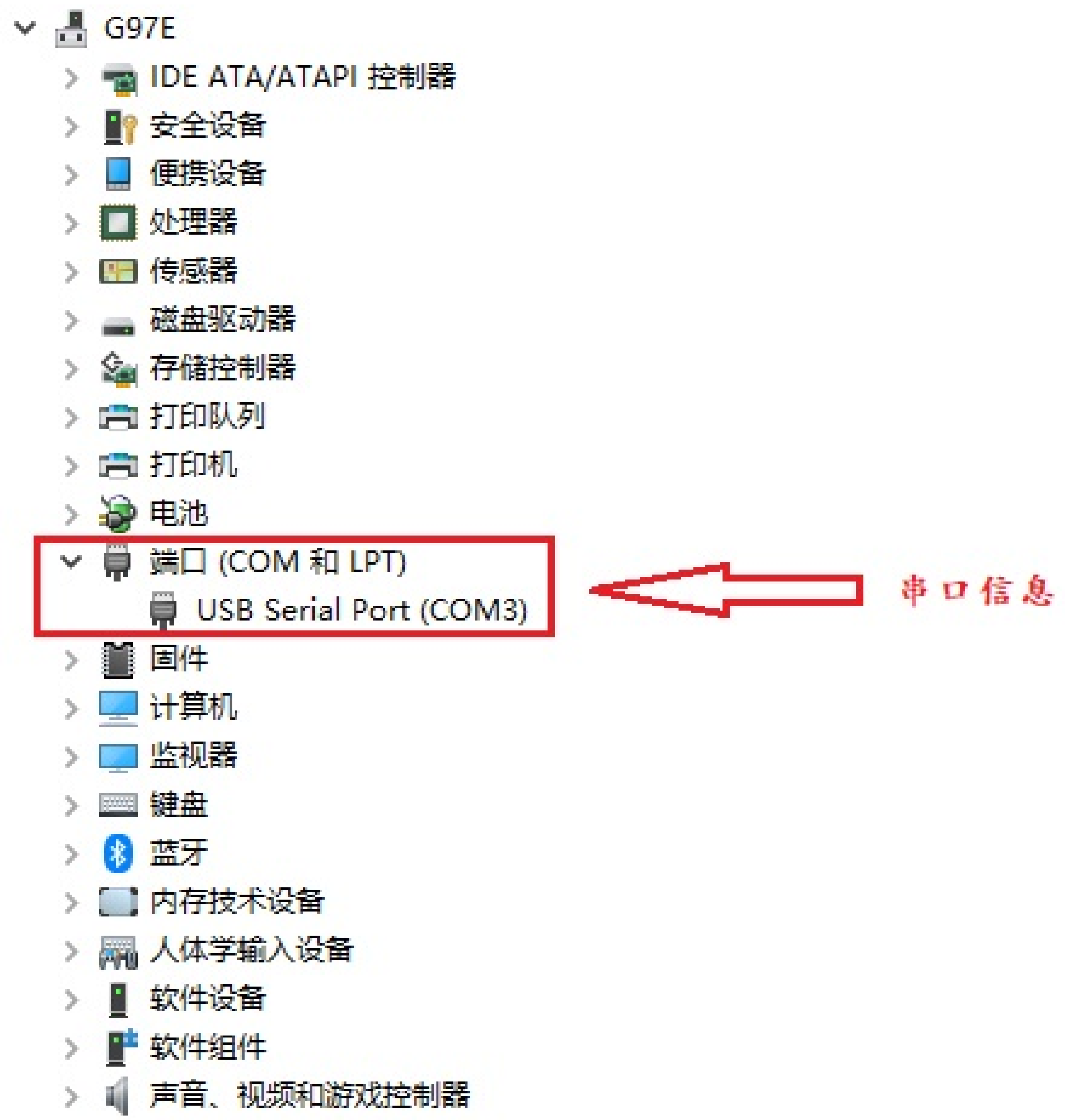


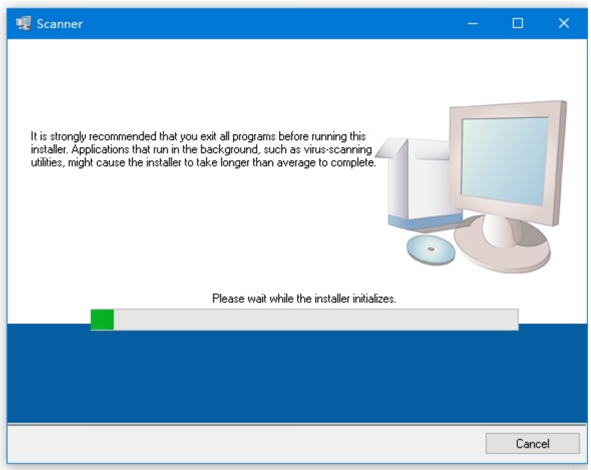

**Figure B.1: Check the COM port number in the Device Manager after installing the FTDI software.**

# C CTALab Software Installation

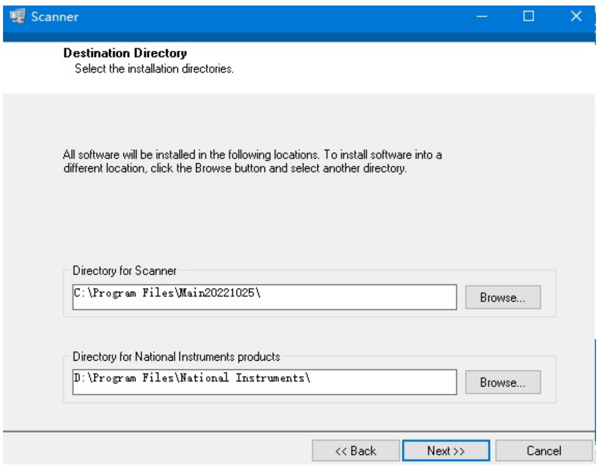
The CTALab software is an essential component of the hot-wire anemometer. Its installation process is shown in Figure C.1. The main functions of the software include:

- Communicating with the hot-wire anemometer main unit via the serial port to set working parameters, turn the bridge on/off, and read the main unit's status.
- Directing the calibrator to calibrate the hot-wire probe and hot-wire channel.
- Communicating with the data acquisition device to set acquisition parameters, collect and save data, and display key statistics.
- Communicating with the traversing mechanism and angle adjustment device to control the position of the traversing mechanism and the angle of the angle adjustment device.

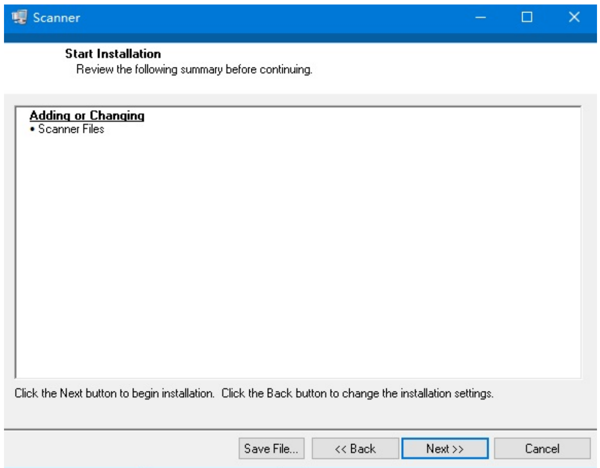

**(a) Installation file directory.**




**(b) Start installation.**




**(c) Select installation directory.**




**(d) Installation complete.**

**Figure C.1: Example of software installation.**

# D Serial Port Debugging Assistant Installation and Usage

## D.1 Serial Port Debugging Assistant Installation

The Serial Port Debugging Assistant is an essential tool for sending serial port commands and reading the status of serial port devices. Users can choose to use this tool to control the hot-wire anemometer. The installation program for the Serial Port Debugging Assistant can be obtained from the following URL:

`http://www.hanghualab.com/nd.jsp?id=95&fromMid=468`

Refer to Figure **??** for the installation process of the Serial Port Debugging Assistant.

## D.2 Setting Communication Parameters

After installing the Serial Port Debugging Assistant, set the communication parameters as follows:

**Serial Port Number** Select the corresponding serial port number.

**Baud Rate** 57600.

**Data Bits** 8.

**Parity** None.

**Stop Bits** 1.

**Flow Control** None.

**Receive Settings** ASCII.

**Send Settings** ASCII.

After setting, the Serial Port Debugging Assistant interface will look like Figure D.1. At this point, the bottom left corner of the interface will display COM3 CLOSED, indicating that the serial port is closed.

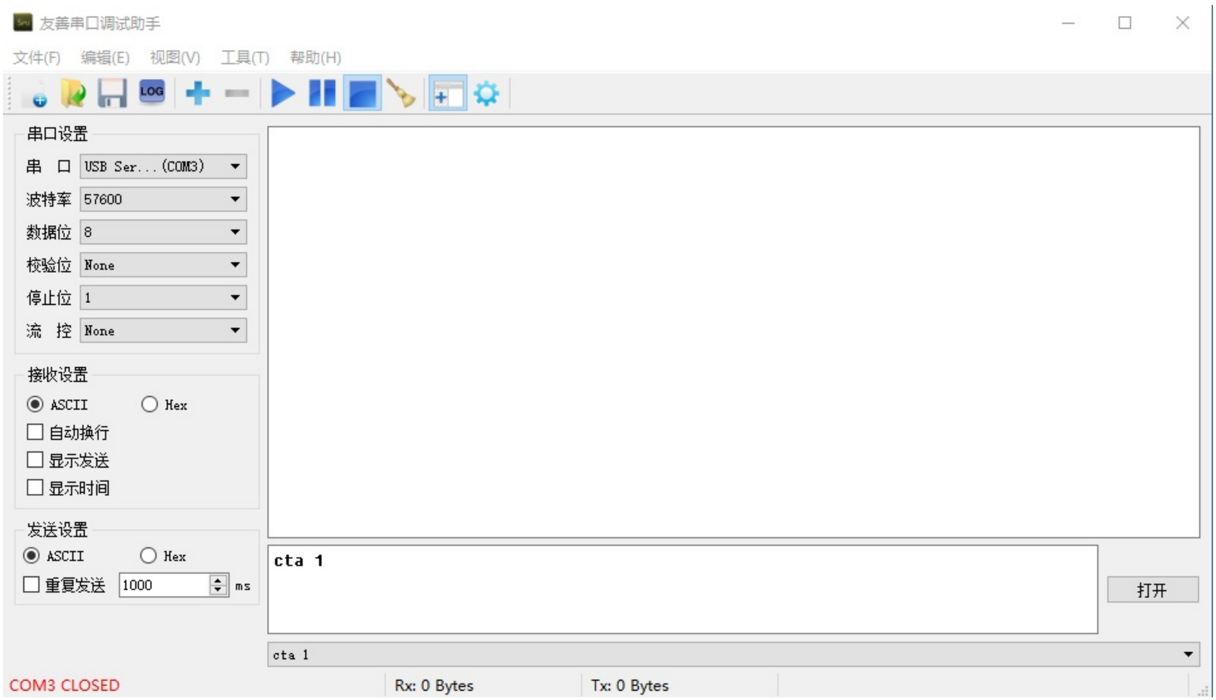



**Figure D.1: Serial port information set up.**

## D.3 Opening the Communication Channel

Open the serial port (click the play button in the Serial Port Debugging Assistant, as shown in Figure D.1). At this point, you can see the prompt indicating that the serial port is open and the related communication parameter settings.

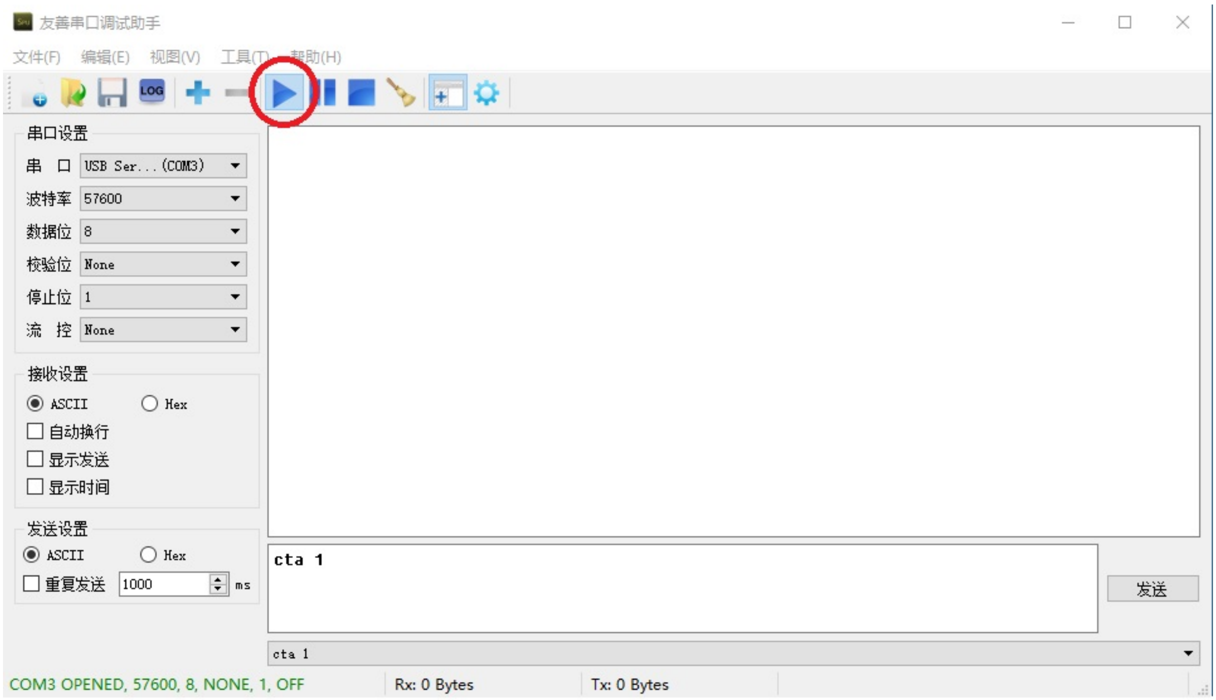



**Figure D.2: Click the "Play" button to connect the serial port.**

## D.4 Sending Commands

After establishing the serial port connection, you can send commands to the hot-wire anemometer to query information or set parameters. To send a command, enter the relevant command in the input box of the Serial Port Debugging Assistant and click Send. The received data will be displayed in the receive data box above.

| Note: Do not leave spaces or press Enter after writing the command. |
|---|

The command syntax and parameters are listed in Table D.1. There are three types of commands, formatted as follows:

a) Query command: 'cta [anemometer channel number]'. Use a space to separate 'cta' and the channel number. The anemometer will immediately reply with all parameters via the serial port. The channel number is a number from 1 to 4. The returned data includes the current settings of the anemometer for that channel. The specific meaning is shown in Figure D.3, which shows an example of querying information for Channel 1.


**Figure D.3: After entering the "cta 1" command, the system displays the status query result for Channel A.**

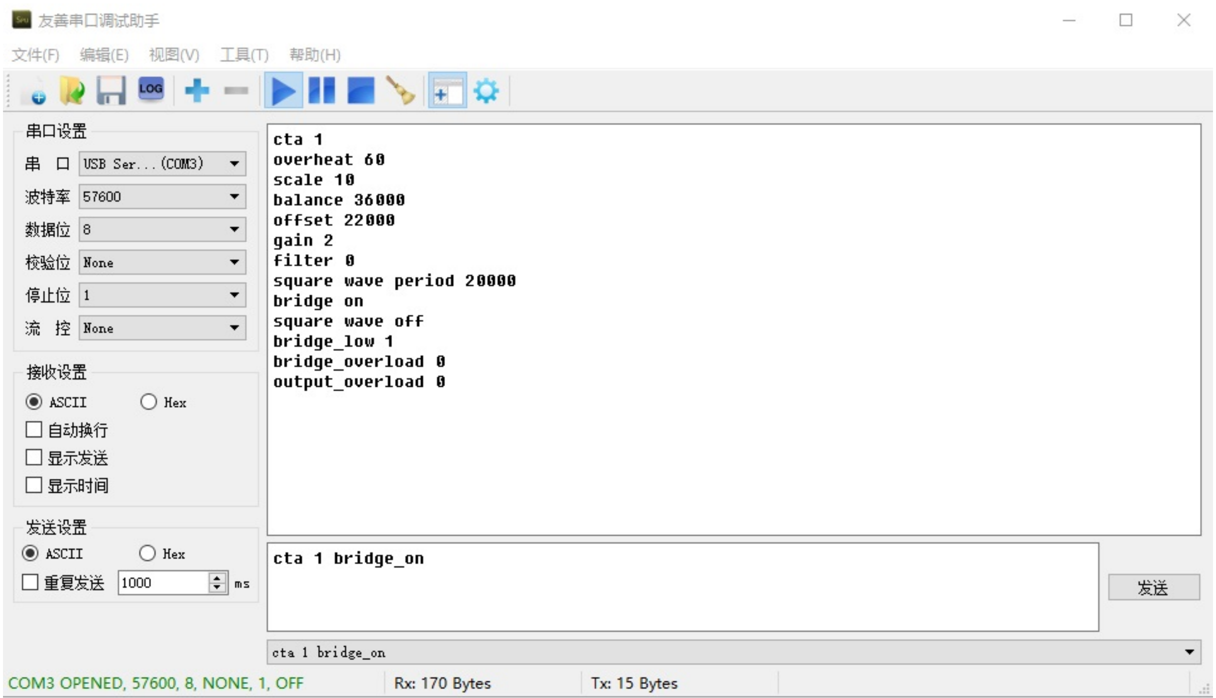



**Figure D.4: Using the bridge switch command to turn on Channel A.**

b) Commands to turn the bridge or square wave on/off (see Figure D.4). The anemometer will immediately reply with all parameters after receiving the command.

```
cta [anemometer channel number] bridge_on
cta [anemometer channel number] bridge_off
```

The above commands are used to turn the anemometer bridge on/off. Use spaces to separate ‘cta‘, the channel number, and ‘$bridge_off$‘. The connection and disconnection of the probe must be done with the bridge turned off to prevent damage from current surges.

```
cta [anemometer channel number] square_wave_on
cta [anemometer channel number] square_wave_off
```

The above commands are used to control whether the square wave test signal is connected.

c) Commands to modify parameters. The anemometer will immediately reply with all parameters and save the modified parameters. Saving parameters takes about one second, and the anemometer will reply with "parameter saved" once the parameters are saved. ‘cta [anemometer channel number] [parameter name] [parameter value]‘ (use spaces to separate the components).

Table D.1: Summary of Serial Port Command Syntax and Parameters

| Parameter Name | Parameter Value Range (all integers) |
|---|---|
| overheat | 0-1999. Divide by 10 to get the probe's operating resistance. Dividing this by the probe's cold resistance gives the overheat ratio. Example: If the probe resistance is 4.8 ohms and the overheat ratio is set to 1.4, the overheat value should be $4.8 \times 1.4 \times 10 = 67$. |
| balance | 0-65535, typically between 30000-40000. Conversion to the CTALab software balance parameter $B$ is: $6553.4 \times B + 32767$. |
| offset | 0-65535, typically around 20000. Conversion to the CTALab software offset voltage $E_o$ is: $E_o \times 13107$. |
| gain | 1, 2, 4, 8, 16 (five levels). |
| filter | 0-7, where 0 means no low-pass filter is used. 1 corresponds to 10 kHz, 2 to 5 kHz, 3 to 1 kHz, 4 to 500 Hz, 5 to 100 Hz, 6 to 10 Hz, and 7 to 1 Hz. |
| square_wave_period | 1-20000, in microseconds. Typically set to 2000, corresponding to a square wave frequency of 500 Hz. |
| scale | 10 or 100. Use 10 for measurements below 120 m/s, and 100 for others. |

# E Overheat Ratio Setting

The overheat ratio (OR) of a hot-wire probe is the ratio of the probe's operating resistance $R_w$ to its cold resistance $R_{20}$ when powered:

$$OR = R_w/R_{20} = 1 + \alpha_t(T_w - 20). \tag{8}$$

Here, $T_w$ is the operating temperature, and $\alpha_t = 0.0045\,°C^{-1}$ is the temperature-resistance coefficient of tungsten. The cold resistance $R_{20}$ is the probe's resistance at $20\,°C$, measured before the experiment. Based on the above equation, we can derive the relationship between the overheat ratio and the operating temperature, as shown in Table E.1.

| Overheat Ratio, OR | Probe Temperature $T_w$, $°C$ |
|---|---|
| 1.2 | 64 |
| 1.4 | 109 |
| 1.6 | 153 |
| 1.8 | 198 |
| 2 | 242 |

Table E.1: Comparison of Overheat Ratio and Probe Temperature for Hot-Wire Anemometers

Recommendations for selecting the overheat ratio:

- High overheat ratio: Greater heat transfer between the probe and the fluid, resulting in higher sensitivity and better frequency response.
- High overheat ratio: Higher current, smaller velocity measurement range, and shorter probe lifespan.
- Typically, 1.5-1.8:
  - For turbulence research below 30 m/s, choose 1.8.
  - For applied research around 100 m/s, choose 1.5.

# F Square Wave Test and System Balance

## F.1 System Balance Judgment

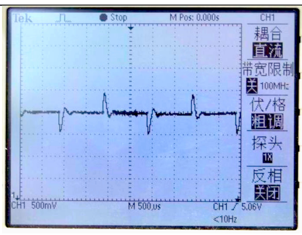
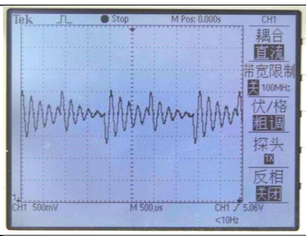
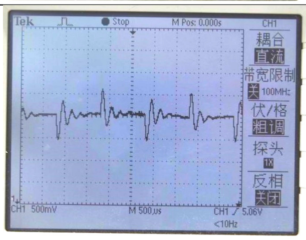
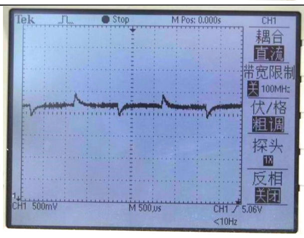
Before starting an experiment, we typically need to test whether the hot-wire anemometer system has entered a stable working state. The Hanghua hot-wire anemometer has a built-in square wave test function. When the system enters the test state, the built-in square wave signal generator produces a square wave signal with an amplitude of 100 mV, which is applied to the bridge at position $e_1$ (Figure 1), disrupting the bridge balance ($e_1 - e_2 \neq 0$). If the system can quickly restore the balanced state ($e_1 - e_2 = 0$) after the balance is disrupted, it indicates that the system is operating in a stable state and experiments can proceed. Table F.1 provides typical bridge top voltage response diagrams for stable working conditions and non-ideal conditions.

## F.2 System Frequency Response Measurement

By observing the bridge top voltage signal, the process of the system restoring balance can be monitored. Additionally, based on the curve of the system restoring balance, the frequency response of the bridge can be estimated. There are currently several methods for determining the frequency response. Below is the method provided in Lomas' book (C.G. Lomas, Fundamentals of Hot Wire Anemometry, Cambridge University Press; Reissue edition, 2011): The system characteristic time $\tau$ is the time it takes for the deviation voltage to recover to 37% of the maximum deviation voltage ($V_{max}$) after reaching its peak (the amount by which the output voltage deviates from the balanced voltage). The system frequency response is the reciprocal of the characteristic time, $1/\tau$. For example, in Figure F.1, for a HW1A probe with a 5-micron diameter tungsten wire under a flow of 20 m/s, $\tau \approx 32\,\mu s$, and the frequency response is 32.3 kHz.

Compared to the Lomas method, another commonly used method, the Bruun method, is more conservative (H.H. Bruun, Hot-Wire Anemometry: Principles and Signal Analysis, Oxford University Press, 1995). This method considers $\tau$ as the time from the rising edge of the square wave until the deviation voltage recovers to 3% of the peak value, multiplied by a safety factor of 1.3. Using the data in Figure F.1 as an example, the characteristic time determined by the Bruun method is $\tau \approx 65\,\mu s$, and the frequency response is 15.4 kHz.

Table F.1: Method for Adjusting System Balance Parameters

| | |
|---|---|
|  | After adjusting the wind speed to the maximum value used in the actual experiment, send the command "cta 1 square_wave_on" to enable the square wave test (if using CTALab software, click the "Bridge Switch" in Figure 15). Use an oscilloscope or data acquisition card to observe the bridge top voltage waveform. The ideal waveform is shown on the left, indicating the system is working stably. |
|  | Problem: The bridge is unbalanced and cannot be used. Consider significantly increasing or decreasing the balance value and then observe the waveform again. |
|  | Problem: The bridge is unstable, and the internal resistance of the system is too low. Consider increasing the balance value. |
|  | Problem: The damping is slightly low. Consider slightly increasing the balance value. |
|  | Problem: The damping is too high, the bridge is overly stable, and the anemometer's frequency response is low. Consider appropriately reducing the balance value. |

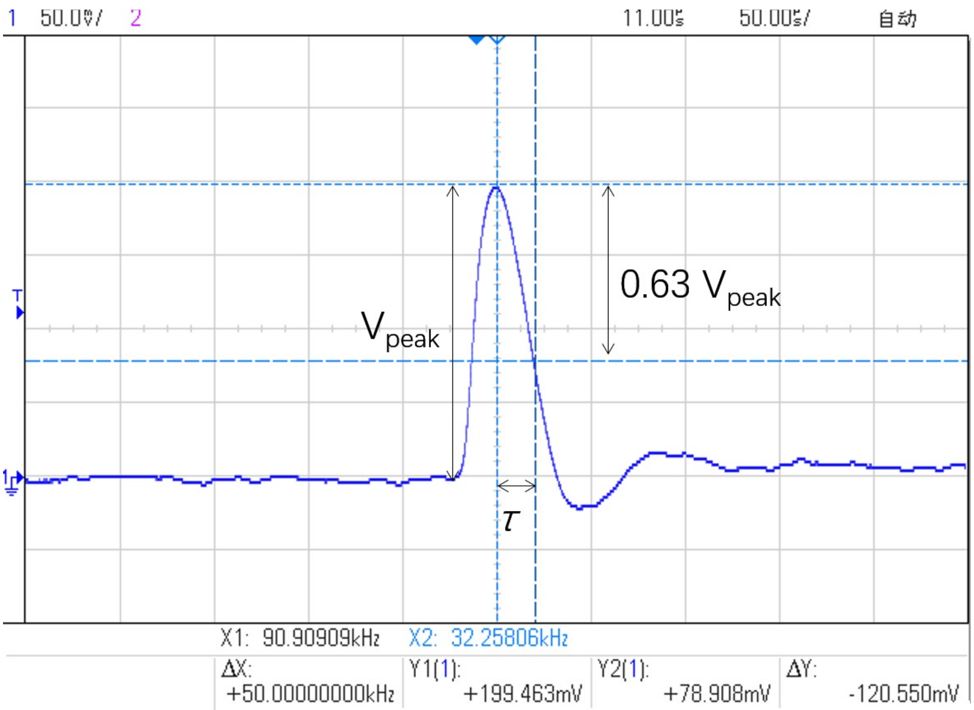
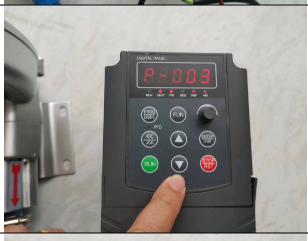



**Figure F.1: A typical square wave test result, where $\tau$ is the system characteristic time.**

# G Setting up the frequency drive

Table G.1: Method for Setting the Calibrator Frequency Converter to "Automatic" and "Manual" Speed Adjustment

| | |
|---|---|
|  | Press PROG button (up left) a few second, until P001 blinks, Frequency drive enters setting mode |
|   | Press UP and DOWN button, until P-003 shows up. Press ENTER button |
|   | Press UP and DOWN button, until the value becomes 002. Press Enter button. Frequency drive enters the 'Auto' mode: it runs according to the voltage applied to the BNC cable |
|   | Press UP and DOWN button, until the value becomes 001. Press Enter button. Frequency drive enters the 'Manual' mode: it runs according to the setting of the potentiometer in the front panel |
|   | Press PROG button a few second, until frequency drive comes out of the setting mode and enters back to the working mode |
| | Run Press RUN button, a green LED blinks, frequency drive is ready to work |

# H Example of Fully Manual, Fourth-Order Curve Calibration Method

This method is primarily aimed at customers who only have the Hanghua hot-wire anemometer main unit and no additional functional accessories.

The output of the hot-wire anemometer is an analog voltage signal within the range of $\pm 5.0\,V$. This signal needs to be calibrated to obtain the flow velocity. Calibration requires placing the probe in an environment with a known flow velocity, which should also have low turbulence. Generally, a wind tunnel test section or a jet with a converging outlet is a suitable calibration environment. During calibration, the tungsten wire of a 1D probe should be placed perpendicular to the incoming flow. At a specific fan speed of the wind tunnel (or other calibration setup where the speed can be manually adjusted), the hot-wire output signal is collected, and a Pitot tube is used in conjunction with a pressure sensor to measure the time-averaged flow velocity $U$. The average value $E$ of the hot-wire output signal is then calculated. The specific steps are as follows:

Step 1: Set the fan speed to 0;

Step 2: Read the anemometer output voltage value, with a sampling time of more than 10 seconds and a sampling count of more than 10,000, and calculate the average value $E_1$;

Step 3: Read the velocity value $U_1$ measured by the Pitot tube;

Step 4: Adjust the fan speed, wait for the flow to stabilize, and repeat steps b and c to obtain the second set of voltage $E_2$ and the corresponding velocity $U_2$;

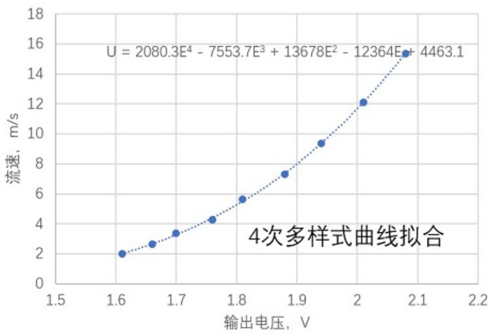
Step 5: Gradually increase the fan speed and measure the system voltage output values corresponding to more than ten different velocities;

Step 6: Use a fourth-order polynomial curve to fit the relationship between voltage $E$ and flow velocity $U$ in software such as Excel or MATLAB;

$$U = a_4 E^4 + a_3 E^3 + a_2 E^2 + a_1 E + a_0 \tag{9}$$

Step 7: After calibration, start the experiment. During the experiment, collect and save the anemometer voltage value $E$, and use Equation 9 to calculate $U$.

| 数据点 | U速度 m/s | E输出 Volts |
|---|---|---|
| 1 | 2.02 | 1.61 |
| 2 | 2.62 | 1.66 |
| 3 | 2.36 | 1.7 |
| 4 | 4.26 | 1.76 |
| 5 | 5.62 | 1.81 |
| 6 | 7.32 | 1.88 |
| 7 | 9.38 | 1.94 |
| 8 | 12.12 | 2.01 |
| 9 | 15.36 | 2.08 |




标定结果:

$$U = 2080.3E^4 - 7553.7E^3 + 13678E^2 - 12364E + 4463.1$$

**Figure H.1: Example of the fourth-order curve fitting calibration method.**

# I Exponential Calibration Method and Pre-calibration Method

## I.1 Exponential Calibration Method

The exponential calibration method is based on an exponential relationship between the heat generation $Q$ of the hot-wire probe and the flow velocity $u$. The principle of this method is as follows:

A small cylinder of length $l$ and diameter $d$ is placed perpendicular to the incoming flow, as shown in Figure I.1. When electrically heated, the dimensionless Nusselt number describing convective heat transfer can be expressed as:

$$Nu = \frac{hd}{k}. \tag{10}$$

Here, $k$ is the thermal conductivity of air, and $h$ is the convective heat transfer coefficient:

$$h = \frac{Q}{(T_w - T_o)A}. \tag{11}$$

The surface area of the tungsten wire $A = \pi dl$, where $T_w$ and $T_o$ are the probe operating temperature and the incoming flow temperature, respectively. $Q$ is the heat transfer between the wire and the air, which can be calculated using the bridge top voltage $E_t$ and the resistances in the bridge circuit:

$$Q = \left(\frac{E_t}{R_w + R_L + R_1}\right)^2 R_w. \tag{12}$$

Here, $R_w$ is the operating resistance of the probe, $R_L$ is the wire resistance (typically less than 0.1 ohms), and $R_1$ is a fixed resistor in the bridge circuit (see Figure 1).

The experimental results in Figure I.2 show that when $Nu$ is corrected for temperature $(T_m/T_{ref})^{0.16}$, it exhibits a linear relationship with $Re^{0.45}$, and the fitting results are unaffected by environmental temperature, operating temperature, and other factors, depending only on the geometric characteristics of the probe:

$$Nu\left(\frac{T_m}{T_{ref}}\right)^{0.16} = aRe^{0.45} + b. \tag{13}$$

Here, $T_m = (T_w + T_o)/2$ is the average temperature of the probe and the ambient air, $T_{ref}$ is the reference temperature (20C), $Re = Ud/\nu$ is the Reynolds number, $\nu$ is the kinematic viscosity of air, and $U$ is the time-averaged velocity. The air properties $\nu$, $k$, and $c$ are all determined based on $T_m$.

Thus, we can use calibration experimental data, a series of corresponding time-averaged $E_t$ and time-averaged velocity $U$, to fit Equation 13 and obtain the exponential calibration results $a$ and $b$.

## I.2 Comparison of Fourth-Order Curve Method and Exponential Method

The fourth-order curve calibration method and the exponential calibration method are two ways the software converts the voltage signal output by the hot-wire anemometer into a velocity signal. Each method has its advantages and disadvantages, and users can choose based on their conditions and needs. The specific explanations are as follows:

**Fourth-Order Curve Method** The system uses the fourth-order curve calibration results (five constants, see Section 4.5.1) to convert the voltage $e(t)$ into velocity $u(t)$. The advantages of this method are:

- The relationship between the output voltage and the time-averaged velocity, $E$ and $U$, is directly correlated, simple, and intuitive, without needing to consider the influence of channel settings, gas properties, and other parameters;
- Under constant environmental conditions, the fourth-order curve conversion method has very high accuracy.

The limitations of the fourth-order curve method are also significant:

- The calibration results are affected by channel settings, wire contact resistance, environmental temperature, and other factors. Slight changes in these parameters can significantly impact the calibration results, potentially rendering them invalid.

We recommend users *calibrate and use immediately*: perform measurements right after calibration. Additionally, try to:

- Maintain a constant environmental temperature.

  If the experimental environmental temperature $T_o$ differs from the calibration temperature $T_c$ by more than 1C but less than 3C, consider applying a temperature correction to the measurement results. If the temperature difference exceeds 3C, stop the experiment immediately and recalibrate;
- Do not disconnect or reconnect the probe and anemometer wires (whether powered or not), and avoid touching them to minimize changes in contact resistance;
- Do not change any parameters after calibration. Modifying the cold resistance, overheat ratio, or signal modulation parameters will alter the output results;

  If accidentally modified, revert to the original values; recalibration is not necessary.

- For long-duration experiments (e.g., over 2 hours), perform calibration at both the start and end of the experiment and compare the results. If the differences are significant, consider using the average of the two calibration curves. If the differences are too large, discard the experimental results;
- If a reliable measurement environment cannot be guaranteed, consider using the exponential calibration results for voltage-to-velocity conversion.

**Exponential Method** The system converts the voltage $e(t)$ into the probe's heat generation $Q(t)$, calculates the convective heat transfer Nusselt number $Nu$, and uses the exponential calibration results (calibration constants $a$ and $b$) to calculate the Reynolds number $Re$, from which the velocity $u(t)$ is derived. For details, see Appendix I. The advantages of this method are:

- It is insensitive to changes in environmental temperature and probe parameters, making it particularly suitable for situations where frequent calibration is not possible, environmental temperature varies significantly, or probe parameter settings have changed.

The limitations of this method include:

- It uses air property models and tungsten wire property models to calculate $Nu$ and $Re$, each introducing errors;
- It performs poorly in the low-speed region (less than $1\,m/s$) due to deviations from the linear region (affected by natural convection).

## I.3 Calibration-Free Measurement Method

"Calibration-free" refers to not requiring user calibration, as the calibration is performed before leaving the factory. The so-called calibration-free measurement method uses the measured bridge top voltage $E_t$ to calculate $Nu$, and then uses the factory calibration results $a$ and $b$ to calculate $Re$, thereby obtaining the flow velocity $u$.

Because the heat transfer and flow velocity relationship described by Equation 13 is insensitive to changes in environmental temperature, operating temperature, and other factors, and depends only on the geometric characteristics of the probe, the calibration results are highly reproducible across different environments, as shown in Figure I.2. Therefore, only factory calibration is necessary, and customers can directly use the factory calibration results after receiving them. The specific usage method is described in Section 4.5.6.

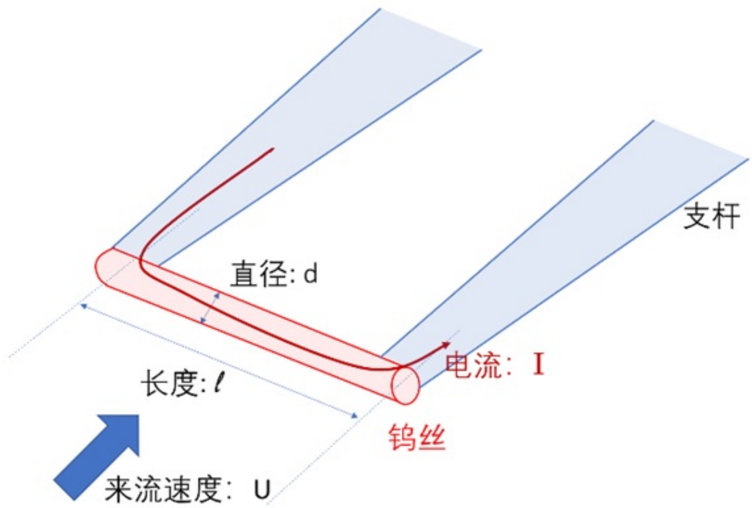



**Figure I.1: Schematic of heat transfer for a single-wire hot-wire probe.**

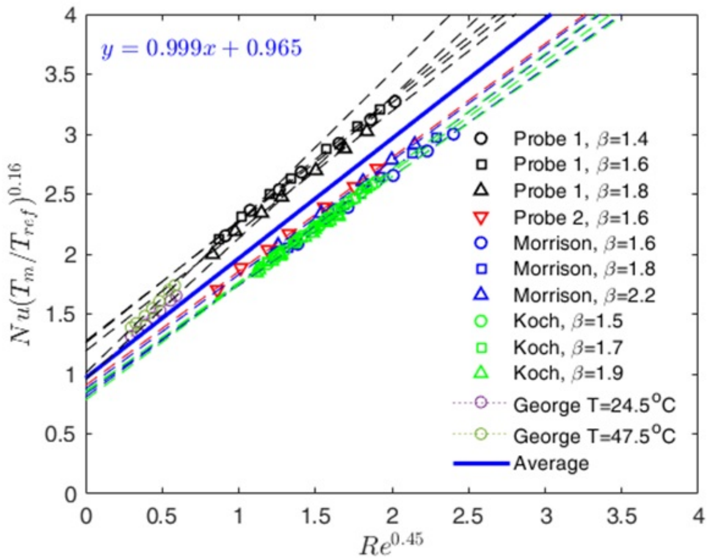
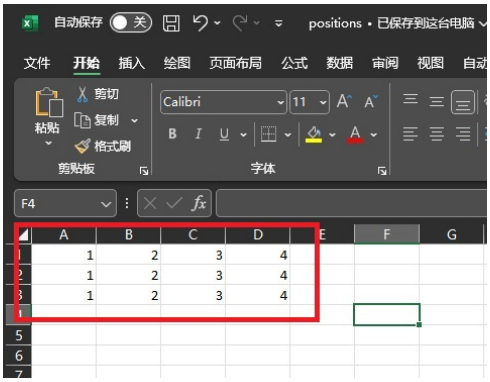


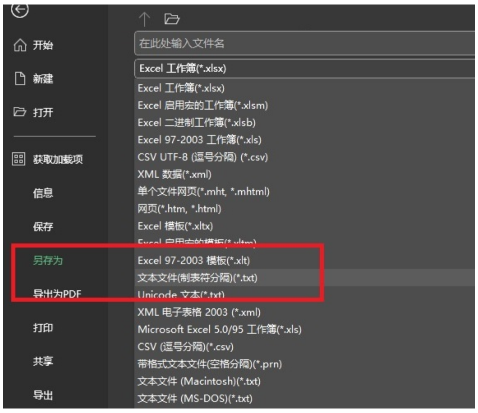

**Figure I.2: Basis of the calibration-free measurement method.**

# J Importing Traverse Position Files

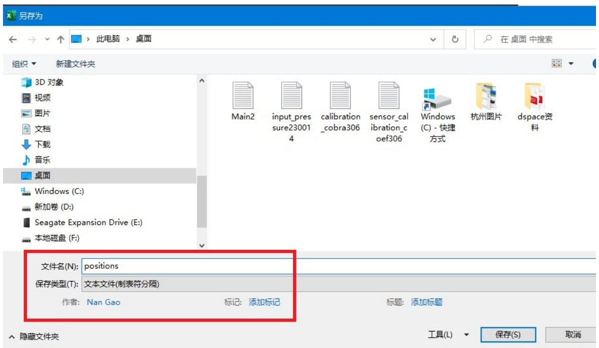
Users can use the "Import" function to import traverse position files generated by other Excel files into CTALab. The specific process is shown in Figure J.1.



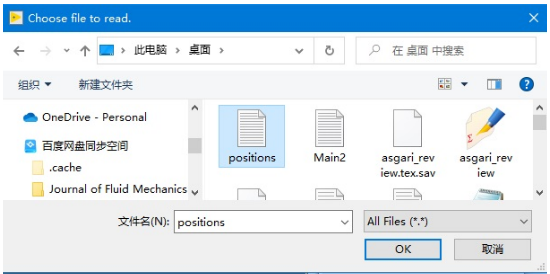

(e) Create a 2*N 2D array in Excel.




(f) Save as a tab-delimited text file.




(g) Save to any directory.




(h) Click "Import Table File" in the "Devices" tab and select the file.


(i) Check the imported coordinate data.

Figure J.1: Using Excel to create a traverse position file and import it into CTALab.

# K Calculation of Two- and Three-Dimensional Velocity Components

## K.1 Calculation of Velocity Components for a 2D X-Probe

If the user uses a dual-wire hot-wire probe, the figure displays the two components of the real-time velocity in the measurement plane, $u(t)$ and $v(t)$, in units of $[m/s]$. The decomposition method is as follows (see Figure K.1):

$$u = |\vec{V}|\cos(\alpha) \tag{14}$$

$$v = |\vec{V}|\sin(\alpha) \tag{15}$$

Here, the real-time velocity vector is $\vec{V} = u\vec{i}+v\vec{j}$, and $|\vec{V}|$ is the magnitude of the real-time velocity.

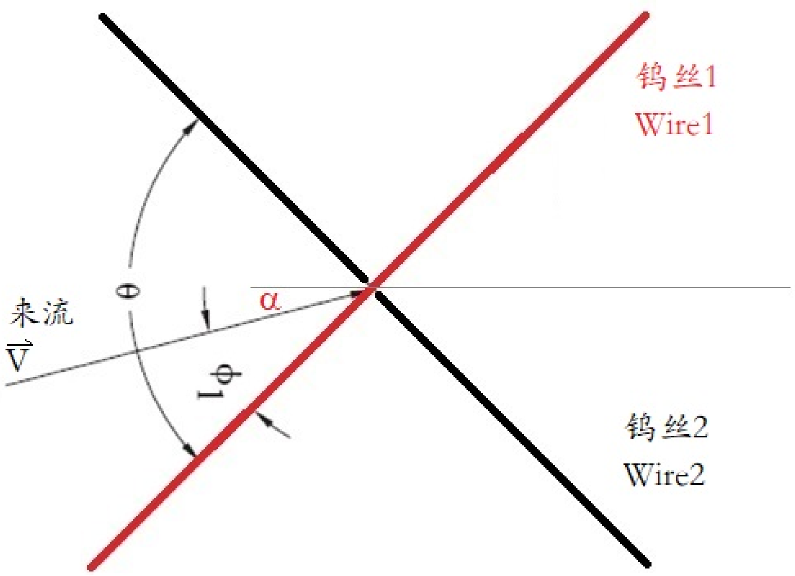



**Figure K.1: Schematic of an X-probe.**

## K.2 Calculation of Velocity Components for a Triple-Wire Probe

If the user uses a triple-wire hot-wire probe, the figure displays the three components of the real-time velocity, $u(t)$, $v(t)$, and $w(t)$, in units of $[m/s]$. The velocity decomposition method is shown in Figure K.2 and is as follows:

$$u = |\vec{V}| \cos(\beta) \cos(\alpha) \tag{16}$$
$$v = |\vec{V}| \sin(\beta) \tag{17}$$
$$w = |\vec{V}| \cos(\beta) \sin(\alpha) \tag{18}$$

Here, the real-time velocity vector is $\vec{V} = u\vec{i} + v\vec{j} + w\vec{k}$, and $|\vec{V}|$ is the magnitude of the real-time velocity. For more details, see Section 4.8.2.

The angle conversion method is:

$$\theta = \cos^{-1}(\cos\alpha \cos\beta) \tag{19}$$
$$\phi = \tan^{-1}\left(\frac{\sin\alpha}{\tan\beta}\right) \tag{20}$$

and

$$\alpha = \tan^{-1}(\tan\theta \sin\phi) \tag{21}$$
$$\beta = \sin^{-1}(\sin\theta \cos\phi) \tag{22}$$

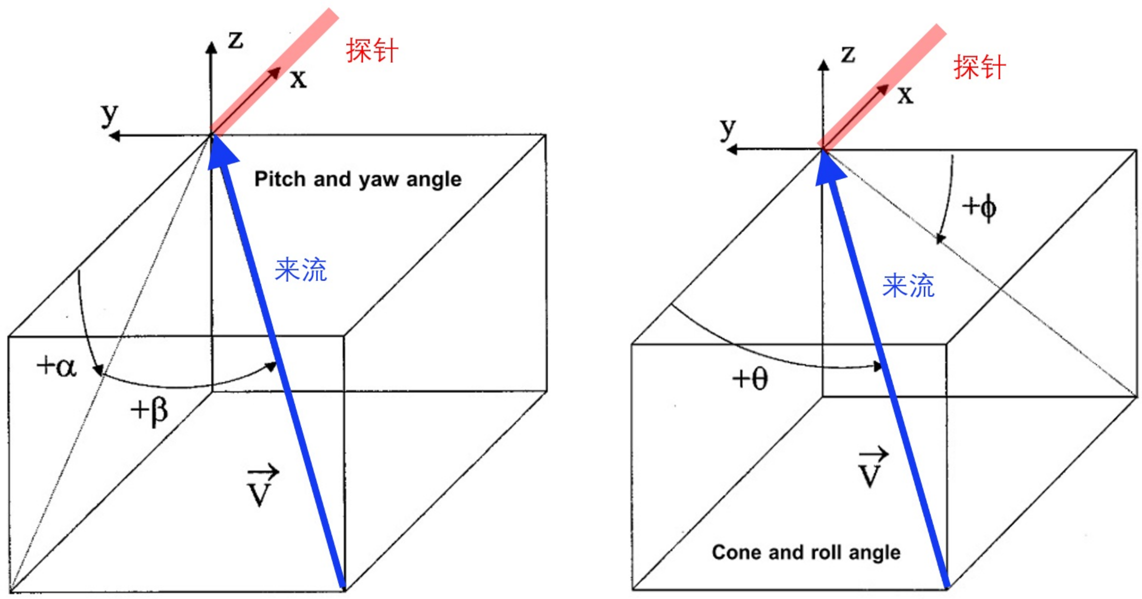



**Figure K.2: Schematic of the relationship between velocity components and angles in a 3D flow field.**

# L Traverse System Wiring

Hanghua provides a serial port-controlled traverse system. It is pre-configured before leaving the factory, and users can use it directly. If issues such as loose wires occur, please refer to the following wiring diagram for repair.

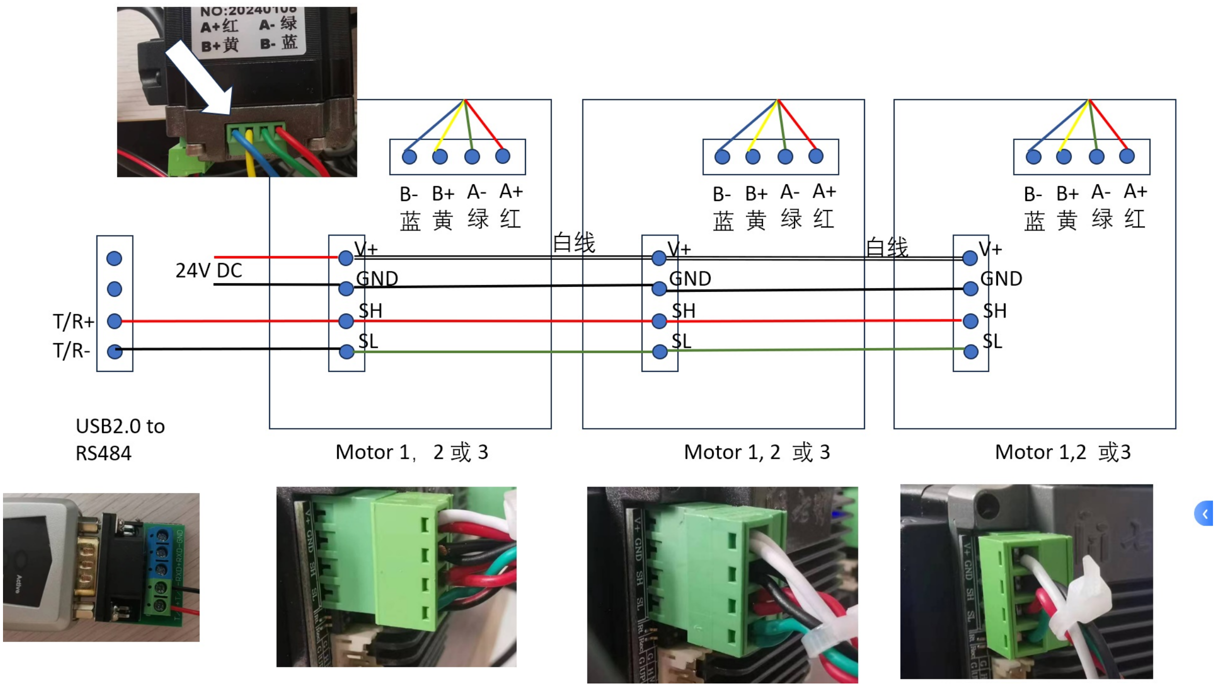



Figure L.1: Schematic and photo of the traverse system wiring.

# M lvanlys.dll Error

When using the software on a computer with an AMD processor, the following error may occur: "LabView: Resource not found lvanlys.dll". This is due to insufficient support for AMD processors by the development platform of this software. The repair method is as follows:

- Add a new environment variable. The specific method is: "Control Panel" - "System" - "Advanced System Settings" - "Advanced" - "Environment Variables" - "System variables" (the bottom part of the dialog) - "New".
- Enter $MKL\_DEBUG\_CPU\_TYPE$ as the variable name.
- Enter 4 or 5 as the variable value.
- Confirm OK multiple times to close all dialogs.
- Restart Windows.


**Figure M.1: "Control Panel" - "System" - "Advanced System Settings", or directly search for "Advanced System Settings".**

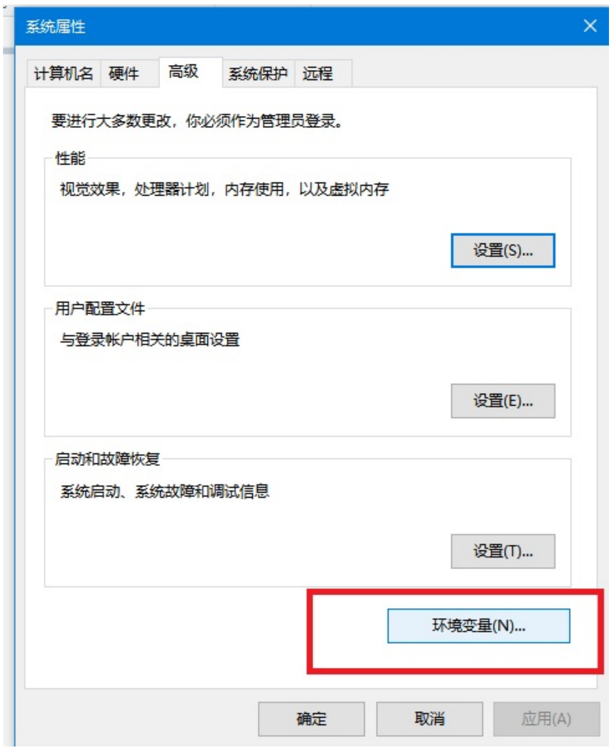



Figure M.2: "User Profiles" - "Advanced" - "Environment Variables".

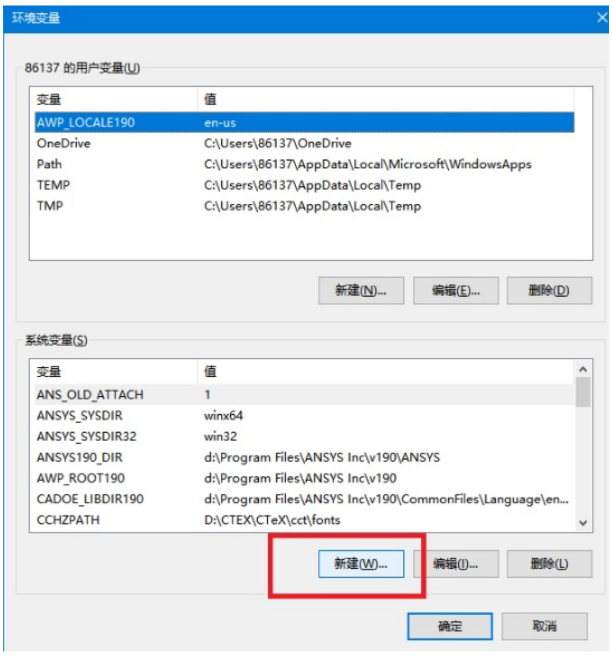



Figure M.3: "New" system variable.

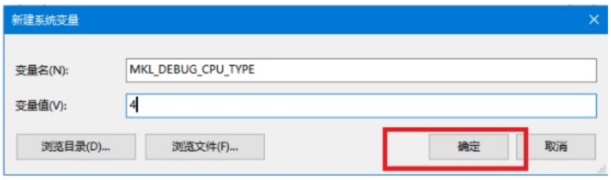



**Figure M.4: Enter $MKL\_DEBUG\_CPU\_TYPE$ as the variable name, then enter 4 or 5 as the variable value.**