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Low speed calibration of hot-wire anemometers

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Abstract

A device for calibration of hot-wire anemometers at low velocities is described. The calibration technique is based on moving hot-wire probes in stagnant air. The device is relatively small, highly mobile and consists of a horizontal swing arm rotated by a DC motor. The motor speed can be adjusted to obtain the desired velocity range. Calibration procedures and data acquisition techniques used in this calibration are described. Results of calibration are discussed and the calibration constants are determined and compared with previous studies.

Keywords: Calibration; Hot-wire anemometer; Low speed

1. Introduction

Hot wire anemometers have provided one of the most important sources for data in turbulent flow investigations. In recent years, increasing interests in micro-machined jets for propulsion of miniature Micro Airborne Platforms (MAPs), microchip cooling devices and micro pumps have highlighted the need for low velocity calibration of hot-wire anemometers to characterize the flow field as well as aerodynamic coefficients of micro-devices. In the past, an accurate calibration of hot-wire anemometer at low velocity (0–1 m/s) has been a major problem. Typically, hot-wire probes have been calibrated using a wind tunnel or calibration nozzle. The velocity is evaluated from the pressure difference using pitot-static tube in the wind tunnel or the pressure drop across the calibration nozzle. However, when the velocity becomes smaller than about 2 m/s, the pressure drop in airflow becomes so small that it is difficult to obtain accurate velocity measurements using these methods [1]. Several methods for calibration of hot-wire anemometers at low velocities have been proposed and investigated. The most popular method is based on a gravitationally driven mechanism [2–6]. Another method of calibrating hot-wire anemometers at low velocities is by utilizing fully developed laminar pipe flow [1,7,8]. Lee and Budwig [7] used a shedding-frequency method in which the reference velocity is obtained from a continuous Strouhal–Reynolds number relationship. Tsanis [9] and Chua et al. [10] mounted hot-wire probes on a traversing mechanism that is driven by a servo motor and travels at constant speed.

One issue that arises when calibrating hot-wire anemometers is the correlation between the velocity, U, and the voltage across the hot wire, E. The most commonly used relationship is the modified King's Law

$$E^2 = A + BU^n \tag{1}$$

where A, B and n are constants. The exponent n is found to be strongly dependent on the velocity regime and varies from 0.4 to 1.3 [6,10]. Few studies have been reported on calibration of hot-wire anemometers at low velocities and therefore additional independent calibrations at low velocities are required. This paper describes a device for calibration of hot-wire anemometers at low velocities. The method is based on moving hot-wire probe in stagnant air. Results of the calibration are presented and constants of the modified King's Law are determined and compared with previous studies.

2. Calibration setup and procedure

2.1. Calibration device

A device for calibration of hot-wire anemometers at low velocities is shown in Fig. 1. The calibration method is based

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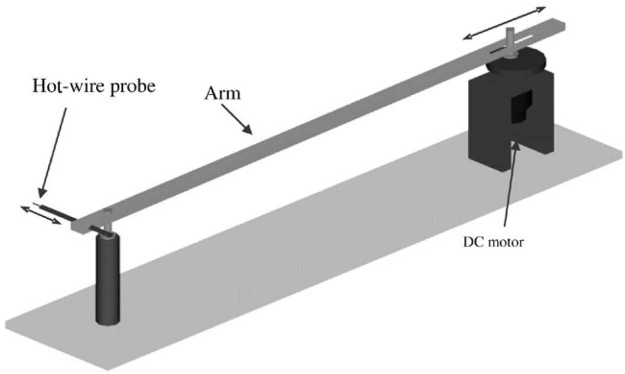

Fig. 1. 3D view of the calibration device.

on moving hot-wire probe in stagnant air. As a result, one must make sure that the following criteria are satisfied: (i) the velocity of the probe and the related anemometer signal must be measured accurately, (ii) the fluid must be stagnant, and (iii) the motion of the probe must be virtually free of vibrations [11]. This device is made of aluminum and consists of a 76.2 cm arm (henceforth arm). The arm is pivoted at one end and driven by a vertically mounted, variable-speed dc motor (12 V, 60 mA) at the other end. The motor's maximum speed is 160 RPM and is attached to a disk by a standard coupling. A nylon shoulder bushing was used as a sliding roller. Moreover, a miniature sensor was attached to the sliding roller in order to determine the angular position of the roller. The sensor minimum and maximum values correspond to $\theta = 0°$ and 180°, respectively. As the motor rotates, the arm swings back and forth around a pivoted point. The hot wire holder is attached to the arm by means of 2 set screws as shown in Fig. 1. The motor was connected to a DC power supply that can be adjusted to obtain the required velocity range. Alternatively, the arm length may be changed. This calibration device is relatively small and highly mobile.

2.2. Procedure of calibration

The above calibration device can be represented by a 3-linkage mechanism as shown in Fig. 2. The motion of the arm is governed by

$$R_0 + R_1 e^{j\theta_1} = R_2 e^{j\theta_2}. \tag{2}$$

Eq. (2) can be differentiated in time and split into real and imaginary parts to give the angular velocity of the arm, ω_2, as a function of the angular velocity of the motor, ω_1,

$$\omega_2 = \frac{\omega_1 R_1 \cos(\theta_1 - \theta_2)}{R_2} \tag{3}$$

where $\omega_1 = \mathrm{d}\theta_1/\mathrm{d}t$ and $\omega_2 = \mathrm{d}\theta_2/\mathrm{d}t$. The arm length, R_2, and angular position, θ_2, are determined from the geometry as

$$R_2^2 = \sqrt{R_0^2 + R_1^2 + 2R_0R_1\cos\theta_1} \tag{4}$$

and

$$\theta_2 = \sin^{-1}\left(\frac{R_1\sin\theta_1}{R_2}\right). \tag{5}$$

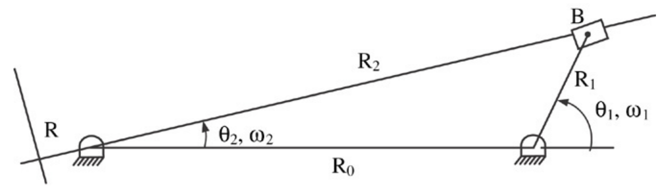

Fig. 2. A representation of the calibration device by 3-linkage mechanism.

Substituting Eqs. (4) and (5) into Eq. (3) and multiplying by the radial distance gives the hot wire velocity

$$U = \frac{\omega_1 R \cos\left[\theta_1 - \sin^{-1}\left(\frac{R_1\sin\theta_1}{R_2}\right)\right]}{\sqrt{1 + \frac{R_0}{R_1}\left(2\cos\theta_1 + \frac{R_0}{R_1}\right)}}. \tag{6}$$

Hence, to calculate the hot wire velocity, the exact arm length, R_2, as well as the roller angular position (point B in Fig. 2) should be determined. The sensor attached to the roller provides its angular position as a function of time, $\theta_1(t)$, and consequently the arm length, R_2, is calculated using Eq. (4). The output of the sensor ranges from 1.4 V at $\theta_1 = 0°$ to 3.24 V at $\theta_1 = 180°$. Note that a full rotation of the motor is determined from the sensor output i.e. from $e_{\min}$ to $e_{\min}$. In this measurement, the sensor provides 376 readings of θ_1 in each rotation resulting in a resolution of ∼1°.

2.3. Data acquisition

The calibration has been performed using a single hot-wire probe made of platinum and connected to a constant temperature anemometer. The analog output from the anemometer was conditioned (offset, gain and filter), simultaneously acquired with the sensor output using a computer equipped with a 12 bit National Instruments PCI-6023E data acquisition board (DAQ). The input range of this board is −10 to +10 V and the board is capable of acquiring voltage data at 200 kHz. In this calibration, a sampling frequency of 1 kHz was used for data acquisition resulting in a time resolution of 0.001 s. The calibration device was isolated in a box so that the air around the hot wire is stagnant. In addition, the motor was wrapped with a grounded copper tape in order to prevent noise pick up by the hot wire.

3. Results and discussion

A calibration of hot-wire probe has been conducted at low velocities ranging from 0 to 15 cm/s. The DAQ was set to take 100,000 readings at a rate of 1000 Hz. In order to improve the resolution of the measurements, a dc offset of the hot wire signal was performed resulting in a resolution of the hot-wire output of approximately 0.586 mV. Moreover, the maximum uncertainty in the measurements obtained was about 4.1% based on a 95% confidence level.

Fig. 3 shows the sensor output and the hot-wire velocity computed using Eq. (6) as a function of the angular position, θ_1. The sensor output and consequently the hot-wire velocity follow a cosine curve. As mentioned above the output of the

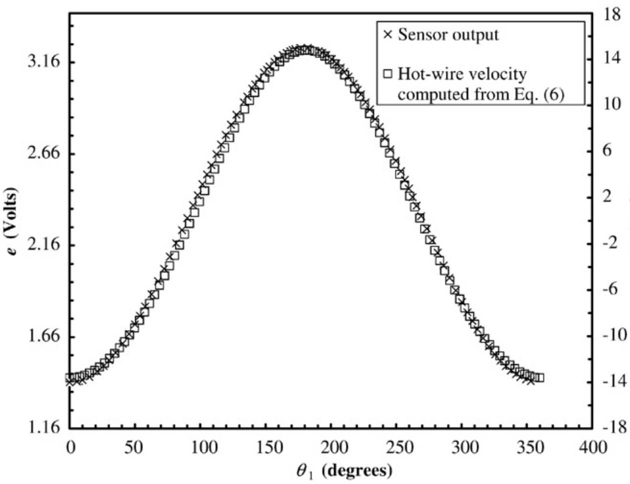

Fig. 3. Sensor output and the corresponding hot wire velocity computed from Eq. (6).

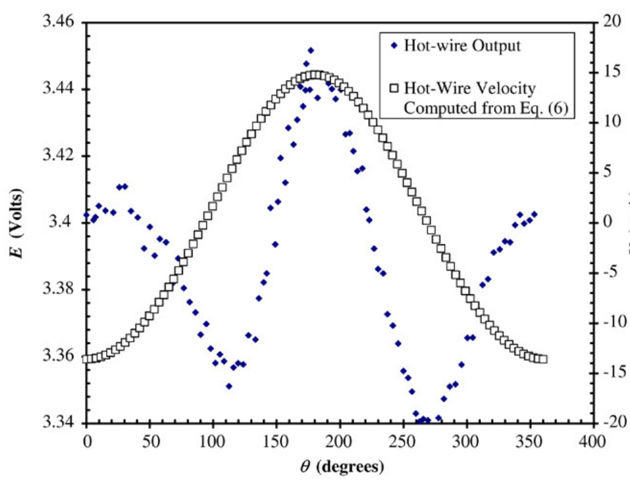

Fig. 4. Hot-wire output and velocity computed from Eq. (6).

sensor is used to measure the angular position of point B (Fig. 2) and ranges from 1.4 V at $\theta_1 = 0°$ to 3.24 V at $\theta_1 = 180°$. The motor angular velocity, ω_1, is determined from the sensor output and the time period required by the motor to complete one rotation. The figure also shows that the hot wire moves forward between $90° < \theta_1 < 270°$ and backward between $0° \leq \theta_1 < 90°$ and $270° < \theta_1 \leq 360°$. The maximum velocity of the hot wire is 14.8 cm/s and occurs at $\theta_1 = 180°$.

Fig. 4 shows the hot wire output, E, as a function of θ_1. Also shown in the figure is the hot wire velocity as a function of θ_1 to illustrate the effect of changing the direction of motion of the hot wire on the wire output. The output of the wire ranges from 3.35 V at $U = 0$ to 3.47 V at $U = +15$ cm/s. As expected the wire output is maximum at $\theta_1 = 180°$ which corresponds to the maximum velocity, $U = +15$ cm/s. On the other hand, the wire output is minimum when $\theta_1 \sim 90°$ and 270° at which the hot-wire velocity is approximately zero. In addition, when the wire moves backward ($U < 0$), the maximum output of the wire is 3.42 V at $\theta_1 = 0°$ and 360° which is less than that when the wire moves forward (3.47 V at $U = +15$ cm/s). This can be attributed to the wake effects of the probe holder and moving arm.

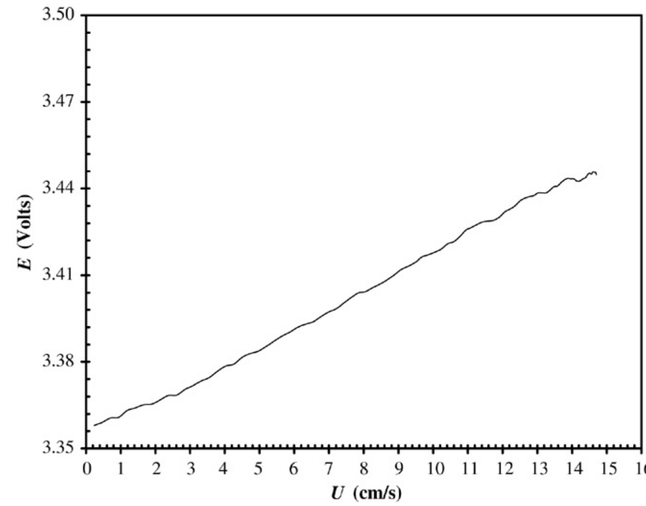

Fig. 5. Hot-wire calibration curve.

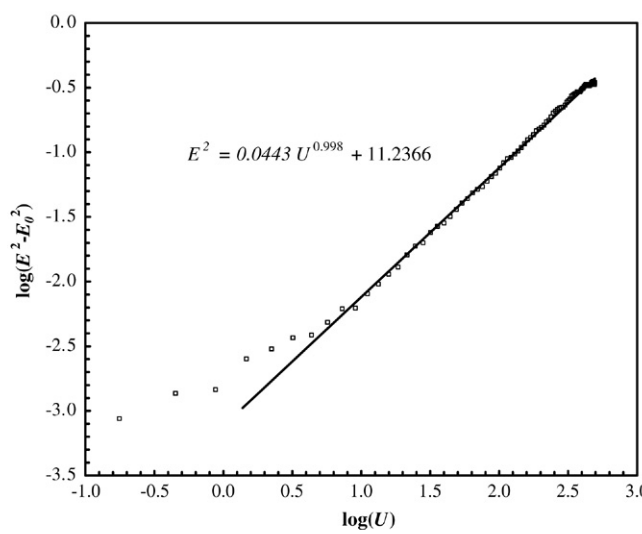

Fig. 6. Least-square fitting of calibration data to the modified King's law.

Fig. 5 illustrates the calibration curve of the hot wire probe in the range between $U = 0$–15 cm/s. The figure shows that the calibration curve is linear in this range. The best fit of the linear portion of the data to the modified King's law was determined using a least square fitting. The result of the fit is shown in Fig. 6. One can observe that the relationship between E^2 and U^n is linear in the range between $U \approx 3$–15 cm/s. However, as U decreases below 3 cm/s this relationship starts to depart from linearity. Similar observations were documented by Zabat et al. [4] and Tsanis [9] where the data follows the King's law in the range between $U \approx 5$–22 cm/s and $U \approx 4$–20 cm/s, respectively. The King's law constants A, B and n are 0.0438, 11.2365 and 0.998, respectively. As mentioned above, the value of n is found to be strongly dependent on the velocity regime and varies from 0.4 to 1.30. While some investigators proposed a value of n between 0.4 and 0.5 for $U \geq 1$ m/s, others found that this value increases as the velocity falls to a few centimeters per second [2,6,12]. The value of n determined in this calibration (0.998) is comparable to the value reported by Tsanis [9] using a different calibration technique for a velocity range of $U = 4$–20 cm/s ($n = 1$). A higher value of $n = 1.2282$ was reported by Chua et al. [10] for a very low velocity range ($U = 1$–5 cm/s), which is much smaller than the velocity range considered in this calibration.

4. Conclusion

A device for the calibration of hot-wire anemometers at low velocity regime has been described. The calibration method is based on moving hot-wire probes in stagnant air. The device is relatively small and highly mobile. The results show that the relationship between E^2 and U^n is linear in the range of $U \approx 3$–15 cm/s when fitted to the modified King's law. However, as U decreases below 3 cm/s this relationship starts to depart from linearity. These observations were documented by Zabat et al. [4] and Tsanis [9] where the data follows the King's law in the range between $U \approx 5$–22 cm/s and $U \approx 4$–20 cm/s, respectively. The value of n determined in this calibration is 0.998 which is comparable to the value reported by Tsanis [9] using a different calibration technique ($n = 1$).

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