Module 3: Velocity Measurement

Lecture 13: Two wire hotwire measurement

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Hotwire anemometry

A two channel hotwire anemometer (DANTEC) was used for the present investigation. Hotwire anemometry (HWA) is based on the principle of compensation of the rate of heat loss $\dot{Q}$ of a small heated metallic wire exposed to flow. The probe responds primarily to the magnitude of the velocity vector. The anemometer output voltage then undergoes signal conditioning to filter out noise and improve the signal-to-noise ratio. The operating temperature of the hotwire is usually much higher than the room temperature, typically 150-250^0C in air flow measurements. In the present experiments, the probe operated at a temperature of around 150^oC; this minimized mixed convection and radiation errors, without appreciable loss of sensitivity. Higher temperatures enhance the sensitivity of wire but make the wire fragile. Additionally, to avoid oxidization it is essential that the wire temperature at any point along the wire element is kept well below 350^0C.To illustrate these points, consider a typical hotwire probe (DANTEC 55P11) for which the electrical properties are $R_{20} = 3.5\Omega$ and $\alpha_{20} = 0.0036^oC^{-1}$. For an overheat ratio of 1.5, the operational resistance of the wire will be $1.5 \times 3.5\Omega$. The corresponding mean wire temperature can be evaluated from the equation

$$R = R_{20} + \alpha_{20}R_{20}(T_{sensor} - T_{20})$$

as being equal to about 150^oC which is well below the oxidation temperature. On the front panel of the anemometer, the parameter fixed is the operating resistance of the wire.

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The output of the feedback circuit of the anemometer is a measure of the fluid velocity. After proper calibration of the probe, it is possible to measure fluid velocities with an accuracy of 0:05% or better, depending upon the measurement range and the quality of calibration. In view of the high frequency response of the hotwire anemometer it can follow transients in the flow field without practically any time delay. The hot-wire has a limitation that it is insensitive to the flow direction. For an X-probe, the velocity measured by each wire is different from the component of velocity in the laboratory coordinates. The velocity sensed by each wire is known as the effective cooling velocity.The minimum velocity that can be measured by the HWA is determined by the velocities associated with natural convection from the heated wire. If a probe is calibrated and used under the same orientation with respect to the gravity field, it may be used at low velocities. The limit is then reached when natural convection dominates forced convection. In dimensionless form, this limit is expressed in terms of Reynolds number Re and Grashof number Gr as

$$Re < 2 \times Gr^{\frac{1}{8}}$$

where $Re = U \times \frac{D}{v}$ and $Gr = \ gD^3\,\beta\ (T_w - T_o)/v^2$ The notation used is: *U* is the fluid velocity, *D* is the sensor diameter, v is the kinematicviscosity of the fluid, β is the coefficient of thermal expansion (equal to *1/T* for an ideal gas) and *(Tw - To)* is the excess sensor temperature over the ambient. For the present experimental conditions, the minimum.Reynolds number for which forced convection dominated natural convection was estimated as Re=23, which corresponds to an air velocity of 0.12 m/s.

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The hotwire anemometer accompanied by a feedback circuit is referred to as the constant temperature anemometer(CTA), Figure 3.17 - 3.18. The CTA consists of a Wheatstone bridge and a servo amplifier. One arm of the Wheatstone bridge is the probe sensor. As the flow condition varies, the sensor tends to cool appropriately with a resulting change in resistance.The change in resistance leads to an error voltage $e_2 - e_1$.These two voltages form the input to the operational amplifier. The selected amplifier has an output current, which is inversely proportional to the change in the resistance of the hot-wire sensor. Feeding this current back to the top of the bridge will restore the sensor's resistance to its original value. The feedback circuit plays an important role in improving the frequency response of the hotwire, typically from 10-20 Hz to several kHz.

The temporal flow feild has been mapped in the present work using an X-probe for obtaining the u and v components of velocity. In two-dimensional measurements, calculation of velocity components involves solving a pair of non-linear, simultaneous equations. Thus, the accuracy of hotwire measurements is affected by the accuracy of the calibration procedure. In addition, the accuracy of the numerical solution that is used to solve the nonlinear simultaneous equations is relevant. Two approaches were applied for data reduction and are discussed in Chapter 15. Both approaches yielded nearly identical velocities, thus showing that numerical aspect of data reduction was satisfactory.

The X-probe supplied by DANTEC has been used in the present research, which mostly satisfies all the above- stated criteria. Additionally, some of recommended electronic tests by the manufacturer have also been carried out to optimize the response of the anemometer's output voltage.

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Hotwire Probes

Two platinum-coated tungsten wires forming an X-probe in the vertical plane (normal to the cylinder axis) have been used in the present work. The probe was supplied by DANTEC. The wire properties are: $\alpha_{20} = 0.0036\Omega/\Omega^{o}\mathrm{C}$, diameter $= 5\mu\mathrm{m}$, length=1.25 mm. The measurements of two components of velocity and velocity fluctuations were carried out by using X-probes, type-55P61, (Figure 3.19-b) and Type-55P11 (Figure 3.19(a)), operating at constant temperature.

Fig 3.17: Picture of the hotwire anemometer

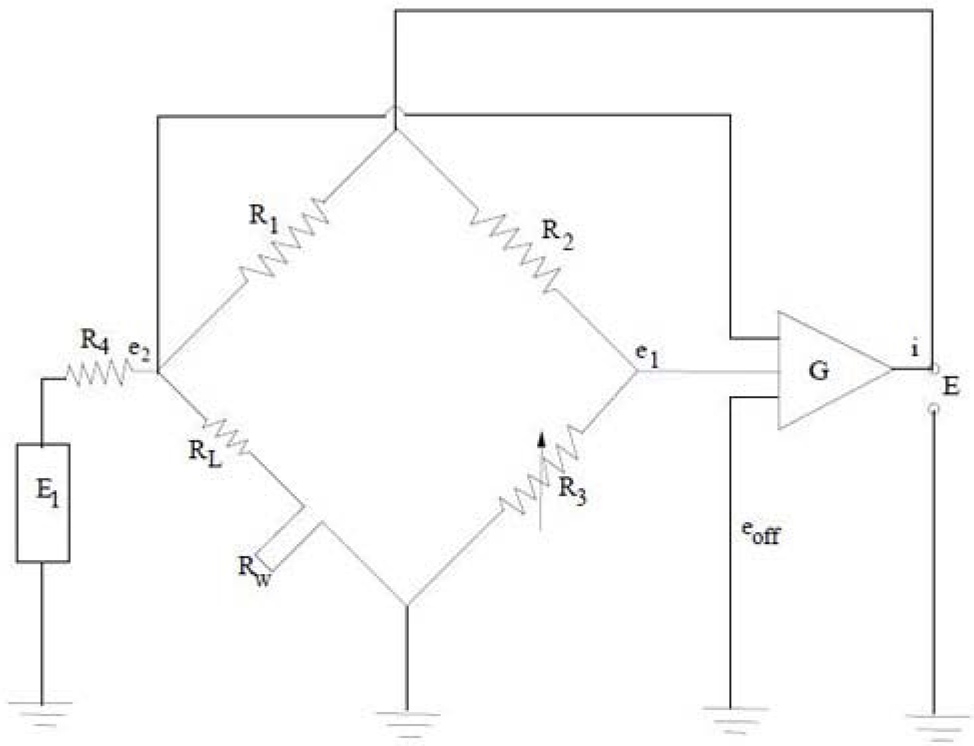

Fig 3.18: Circuit diagram of a Constant Temprature Anemometer (CTA)

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CTA Bridge and Accessories

The hotwire probes were driven by the commercially available DANTEC 56C17 constant temperature Wheatstone bridge circuits. The 56C17 CTA bridge is supplied as a plugin module for an existing 56C01 CTA system. The main unit 56C01 CTA delivers the servo-voltage as the output of the instrument. This voltage is a measure of fluid velocity. The 56C01 circuits contain servo amplifiers, filters, protective circuits, and a square-wave generator for dynamic balancing of the bridge.

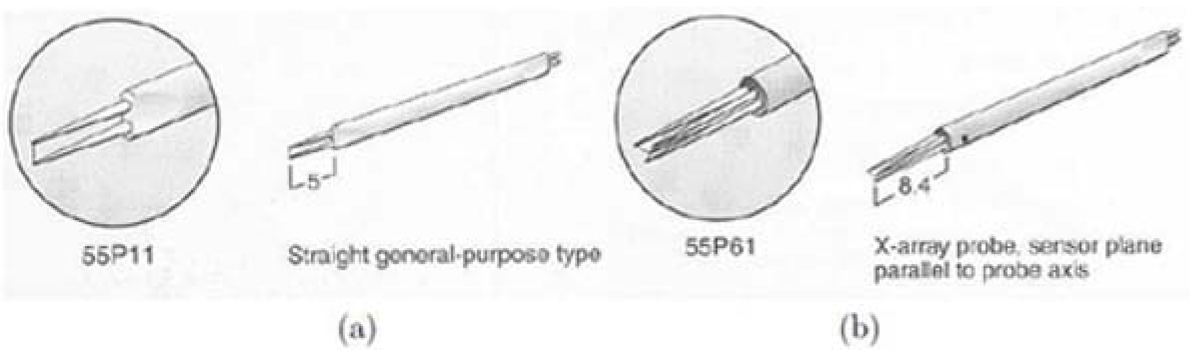

Fig 3.19: Miniature Wire Probes { 5μm diameter, platinum-plated tungsten wire, welded at the ends of prongs to provide active sensor length of 1.25 mm.

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The 56C01 CTA contains a function switch with three modes for operation, namely TEMP, STD.BY and FLOW. In TEMP position the resistance of the connected probe can be measured in terms of a current supplied to it. In STD.BY position no current flows through the bridge. In FLOW setting the CTA starts operating with the function of the servo amplifier. If the function switch is shifted quickly from position TEMP to FLOW, the square-wave generator is activated. A setting named BRIDGE ADJ enables the adjustment of bridge balance for measurement of probe resistance and setting of the desired overheat resistance. BRIDGE ADJ has a switch pair for coarser adjustment of overheat resistance and a screw for fine adjustment. Resistance settings ranging from 0-30Ω in steps of 0.001 Ω are possible. This adjustment is crucial for adjusting the overheat resistance for the calibration procedure. CTA in TEMP mode produces a voltage proportional to resistance of wire. From the wire resistance, the instantaneous temperature attained by the wire at a given location in the flow field can be determined.

The main-frame of the anemometer unit is fitted with the 56N20 signal conditioner unit, which is designed to amplify the AC signals up to a level suitable for PC-based data acquisition. The signal conditioner can selectively amplify the input signals with gain factors ranging from 1 to 900. The filter circuit comprises high-pass and low-pass filters as well as an amplifier. The filter settings were determined in the present work by examining the complete power spectrum of the velocity components. For the present investigations, voltage signals from the CTA were low-pass filtered at 3.0 kHz and highpass filtered at 0.1 Hz. The mean-value unit 56N22 is a 5.5 digit display voltmeter, and the primary purpose of this module is to measure the DC component of the output signal from 56C01 CTA. This module has a $100\mu V$resolution, 1-1000 seconds integration time and switch selectable 14 inputs.

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Data Acquisition System

The HWA output is a continuous analog voltage signal; it has been sampled as a time series consisting of discrete values by an analog-to-digital converter (A/D board). The accuracy of the analog output signal is determined by the quality of the anemometer hardware. The accuracy of the reduced time series depends on the choice of the A/D board, the selection of sampling intervals, number of samples, N, and the extent of digitization. The values for sampling rate, SR and N depend primarily on the specific experiment, the required data analysis (time-averaged or spectral analysis), the available computer memory and the acceptable level of uncertainty. The level of digitization is specified as m-bit, indicating a resolution of the ratio of the full-scale reading and 2^m.The full scale reading is in the range of 0-10 V. Smaller voltages can be measured by using a gain of upto 1000. The final accuracy is thus a product of instrument specifications and data acquisition set-up related to the actual flow.

The full scale reading is in the range of 0-10 V. Smaller voltages can be measured by using a gain of upto 1000. The final accuracy is thus a product of instrument specifications and data acquisition set-up related to the actual flow. Time-averaged analysis, such as the determination of the time-averaged velocity and of velocity fluctuations requires uncorrelated samples. It can be achieved when the time elapsed between individual samples is at least two times larger than the integral time scale of the velocity fluctuations. On the other hand, spectral analysis requires the sampling rate to be at least twice the highest frequency in the flow oscillations. In the present experiments, a long signal, typically of 20 seconds duration with a sampling frequency of 1000 Hz was recorded from the hot-wire anemometer. A band pass filter (0:1 Hz- 1 kHz) and a gain setting (10) were additionally used. The A/D card was configured in the differential mode to avoid unwanted noise in the measured signal. The signal is amplified prior to digitization. The gain, ranges and resolution are selected on the basis of the characteristics (amplitude and spectral) of the input signal. The instantaneous voltage signals have been recorded by using a DAQ card (Keithley Instruments, KPCI-3108) of 16 bit resolution. The advent of graphical programming concept introduces the possibility of creating a new type instrumentation, not in hardware but in software. This new approach is called Virtual Instrumentation, (VI).In the present investigation, LabVIEW software has been used for programming the Keithley A/D card. LabVIEW (Laboratory Virtual Instrument Engineering Workbench) delivers a powerful graphical development environment for signal acquisition, measurements, analysis, and data presentation. It gives the flexibility of a programming language without the complexity of traditional development tools. Both data acquisition as well as cylinder actuation have been conducted in the LabVIEW environment.

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Electromagnetic Actuator

The arrangement of the cylinder in the test section and the apparatus used for achieving forced in-plane oscillations of the cylinder are shown in Figure 3.20. A dual channel power oscillator with two electromagnetic drive units was used to generate controlled movement of the cylinder. The actuator assembly was procured from Spanktronics. The electromagnetic actuator consists of the yoke, magnet and pole tip, and the moving coil assembly. It works by virtue of the interaction between the magnetic field and an oscillating current flowing in the coil of the moving assembly. Under such circumstances, a force is generated at right angles to the line of flux and the conductor carrying the current. This force is proportional to the product of instantaneous current and the magnetic flux density. The useful frequency range of the actuator is equal to 1-200 Hz. The maximum amplitude is 1.5 mm, corresponding to 50% of the cylinder size.

The cylinder was mounted horizontally and fixed on the two electromagnetic drive units on each side of the test cell. Proper care was taken to ensure that no leakage occurred at the junctions of the test cell and the cylinder. During experiments, the shedding frequency of a stationary cylinder was first measured using a hotwire. The cylinder was subsequently excited at various harmonics around the shedding frequency in the streamwise direction. The amplitude of excitation was set by the voltage input to the electromagnetic actuator. Both actuators operated from a single power source and thus ensuring identical phase. In an open loop arrangement, the activation signal was generated from a built-in signal generator in the power oscillator. With feedback, the activation signal was generated from the hotwire output with suitable amplication and phase inversion to the drive unit. Here, the feedback signal was low pass-ltered and sent to the digital-to-analog converter. The amplitude of the cylinder displacement was measured from magnified images of the cylinder oscillation using the CCD camera.

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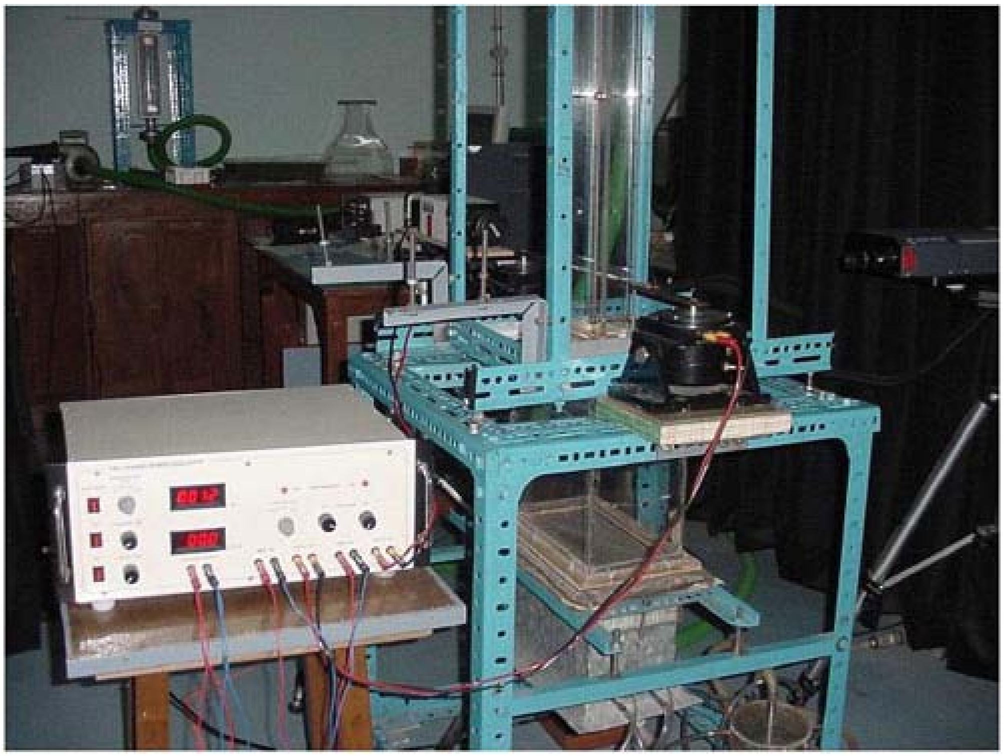

Fig 3.20: Experiments with an electromagnetic actuator

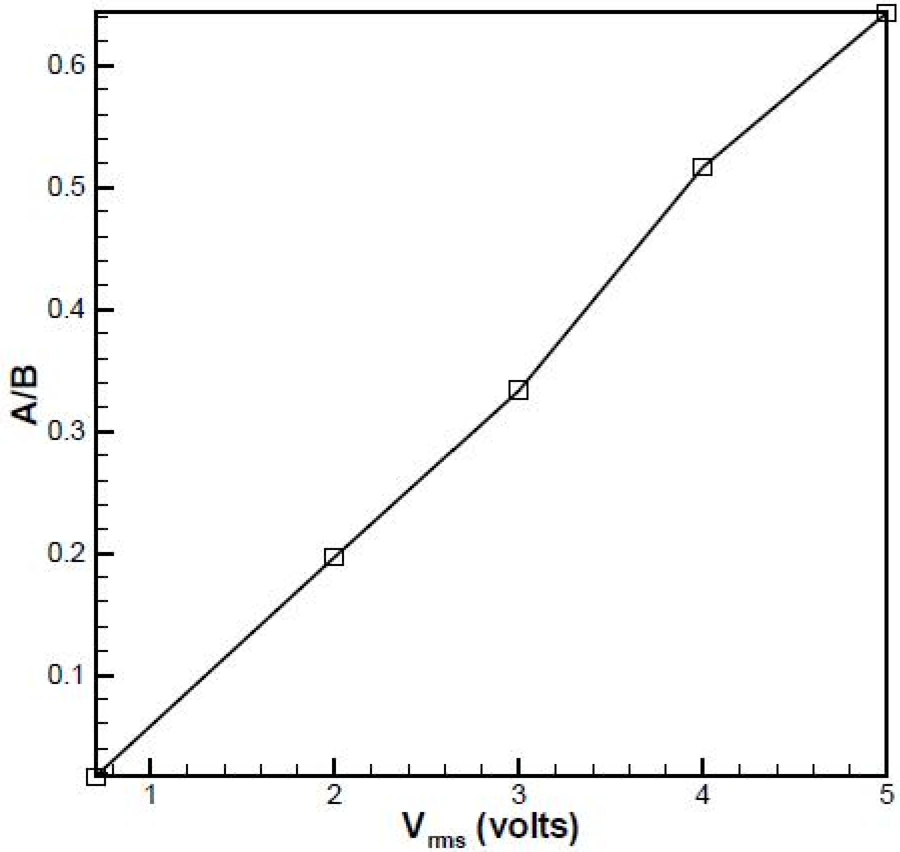

Fig 3.21: Variation of cylinder displacement with voltage supplied to the actuator.

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Auxiliary instruments

Starting from the initial validation of the vertical test cell to the final measurements of the cylinder wake, various instruments, other than HWA and PIV have been used. A brief introduction to these instruments is presented below.

Digital Micromanometer

The pitot-static tube was used for velocity measurements in the undisturbed flow. It was connected to a high quality differential pressure micromanometer (model FC012, Furness Controls) with a pre-calibrated velocity output and a digital display. The micromanometer uses a capacitance-type differential pressure transducer. It measures differential pressures upto 1.99 mm H_2O with a resolution of 0.01 mm H_2O. It is equipped with a temperature correction chart to account for changes in the room temperature. The maximum measurable velocity with this manometer is equal to 5:6 m/s. The pitot-static tube and digital manometer combination have been used for calibration experiments of the hotwire anemometer.

Fig 3.22: Picture of the micromanometer (left) and pitot static tube (right) used during the experiment

Digital Multimeter

The HP 3457A is a versatile digital multimeter. It can measure DC voltage, AC voltage, AC and DC currents and the resistance over a wide range of values. The math operation facility can manipulate or modify a set of measurements before display. The STAT operation can perform up to five running calculations on the present series of measurements and stores the results. It evaluates the standard deviation, time-mean, number of samples, upper reading and lower reading. These facilities can be used to measure mean temperature and the RMS value of the temperature fluctuations with the constant current mode of the hotwire anemometer.

Spectrum Analyzer

The digital spectrum analyzer used in the present work (Advantest R9211E) employs the Fast Fourier transform (FFT) algorithm for determining the signal statistics. Wide band as well as high sensitivity measurements can be performed in the frequency range of 10 mHz-100 kHz and input voltages of 1 Vrms-31:6 Vrms. The analyzer has four different modes of operation. The waveform and spectrum modes are important ones generally used in turbulence measurement. In waveform mode the spectrum analyzer does on-line measurement of the time signal, followed by calculations of the histogram (PDF), autocorrelation and cross-correlation functions. In the spectrum mode, it measures power spectrum and the complex spectrum. It has various options such as Math, Setup, Device and Copy. The Math menu does arithmetic operations between two arrays and integration and differentiation of an array. This facility can be used for the measurement of average of product of two-wire signals. All traces shown on the screen can be stored on a floppy and processed whenever required. These facilities have helped in standardizing the measuring procedures linked to the HWA.

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Digital Oscilloscope

A two channel digital storage oscilloscope (Gould 1602) with a sampling speed of 20 Ms/sec and an operating frequency range of 0 – 20 MHz has been used. The Gould 1602 can operate in storage as well as non-storage mode. In the former, it has a sampling speed of 2 MHz. The oscilloscope has been used for square wave testing of the hotwire anemometer.

Fig 3.23: Picture of the storage digital oscilloscope

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