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Modifications to a Constant-Temperature Hot-Wire Anemometer System to Measure Higher-Order Turbulence Terms Using Digital Signal Processing

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DSTO-TR-0506

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ABSTRACT

An existing constant-temperature hot-wire anemometer system that enabled broadband-turbulence quantities to be determined using a hybrid analog/digital measurement technique has been modified so that turbulence quantities can now be determined using a purely digital technique. With the new system, higher-degree turbulence terms, such as $\overline{u^3}$, $\overline{v^3}$, $\overline{w^3}$, $\overline{u^2v}$, $\overline{uv^2}$, $\overline{u^4}$, $\overline{v^4}$ and $\overline{w^4}$, can now be obtained. These terms are used to calculate turbulent-kinetic-energy and Reynolds-shear-stress balances, and skewness and flatness factors, that could not be calculated previously. In this report the new equipment is described and the procedures and computer programs used to take measurements and process the data are detailed.

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Executive Summary

Turbulence plays a significant role in many fluid-flow studies, including testing of models of aircraft and ships in wind tunnels, and a knowledge of the behaviour of turbulent flows is of fundamental importance. Such flows can be studied using a hot-wire anemometer, which is an electronic instrument used to measure fluctuating velocities in a turbulent flow field, thereby enabling turbulence quantities to be determined.

In the past, the constant-temperature hot-wire anemometer system at AMRL used a combination of analog and digital measurement techniques to determine some turbulence quantities. This hybrid system had limited capabilities due to the restrictions imposed by the analog circuits, and it was only possible to measure mean velocities and Reynolds stresses. This range of terms is not sufficient for in-depth studies of turbulent flows.

The anemometer system has been modified so that turbulence quantities can now be determined using a purely digital measurement technique. The new digital system samples and processes the data using a desktop computer that replaces the analog circuits used in the hybrid system. As well as measuring mean velocities and Reynolds stresses, it is now possible to measure more-complicated turbulence terms which could not be determined previously.

In this report, the new digital hot-wire anemometer system is described and details of the hot-wire anemometers, the probes, the dynamic calibrator for calibrating the wires, and the computer programs used for calibration, data sampling and data processing, are given. The procedures for using the equipment and the programs are also presented.

Since more-complicated turbulence terms can be measured with the new system, it will be possible to provide a greater range of flow measurements. With the availability of a wider range of data, a more in-depth understanding of the physics of flow behaviour will be possible to meet ADF and associated Defence Industry requirements.

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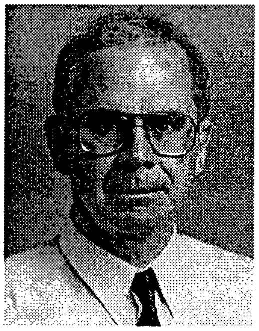

Lincoln Erm obtained a Bachelor of Engineering (Mechanical) degree in 1967 and a Master of Engineering Science degree in 1969, both from the University of Melbourne. His Master's degree was concerned with the yielding of aluminium alloy when subjected to both tensile and torsional loading. He joined Aeronautical Research Laboratories (now called Aeronautical and Maritime Research Laboratory) in 1970 and has worked on a wide range of research projects, including the prediction of the performance of gas turbines under conditions of pulsating flow, parametric studies of ramrocket performance, flow instability in aircraft intakes and problems associated with the landing of a helicopter on the flight deck of a ship. Concurrently with some of the above work, he studied at the University of Melbourne and in 1988 obtained his Doctor of Philosophy degree for work on low-Reynolds-number turbulent boundary layers. Lincoln is currently employed as a Research Scientist in the Air Operations Division and is undertaking a research investigation to improve the quality of the flow in the test section of the low speed wind tunnel as well as conducting flow-visualization experiments in the water tunnel to determine ways of modifying vortical flows over aircraft to improve aircraft performance at extreme flight attitudes.

Contents

NOTATION

DISTRIBUTION LIST

DOCUMENT CONTROL DATA

Notation

A	Constant used in calibration law
A_0 to A_3	Coefficients used in calibration equation for U
B	Constant used in calibration law
B_0 to B_4	Coefficients used in calibration equation for V
E_U	Output voltage of matching box (see Figure 6)
$\overline{E}_U$	Average value of E_U for each of the 120 positions of the chopper disk (averaging applies to a specified number of cycles of the calibrator), (volt)
$\overline{\overline{E}}_U$	Average value of the 120 values of $\overline{E}_U$, (volt)
$E_{U_{rms}}$	Root-mean-square value of $(\overline{E}_{U_n} - \overline{\overline{E}}_U)$, (volt)
E_V	Output voltage of matching box (see Figure 6)
$\overline{E}_V$	Average value of E_V for each of the 120 positions of the chopper disk (averaging applies to a specified number of cycles of the calibrator), (volt)
$\overline{\overline{E}}_V$	Average value of the 120 values of $\overline{E}_V$, (volt)
$E_{V_{rms}}$	Root-mean-square value of $(\overline{E}_{V_n} - \overline{\overline{E}}_V)$, (volt)
E_0	Output voltage of a hot-wire anemometer
E_1	Output voltage of hot-wire anemometer number 1 (see Figure 6)
E_2	Output voltage of hot-wire anemometer number 2 (see Figure 6)
E_{01}	Voltage at top of bridge for hot-wire anemometer number 1 (see Figure 6)
E_{02}	Voltage at top of bridge for hot-wire anemometer number 2 (see Figure 6)
f	Average calibrator frequency at a particular free-stream velocity, (Hz)
n	Index used in calibration law (n varies between 0.4 and 0.5)
N	Number of pairs of sampled voltages, E_U and E_V, or number of pairs of velocities, U and V
R	Radius of calibrator motion ($R = 0.0381$ m)
u	Fluctuating component of velocity in x direction, (m/s)
U	Velocity in the x direction ($U = \overline{U} + u$), (m/s)
$\overline{U}$	Mean velocity in the x direction, (m/s)
U_{rms}	Root-mean-square value of the x-component perturbations in fluid velocity as seen by an oscillating probe, (m/s)
v	Fluctuating component of velocity in the y direction, (m/s)
V	Velocity in the y direction ($V = \overline{V} + v$), (m/s)
$\overline{V}$	Mean velocity in the y direction, (m/s)
V_{rms}	Root-mean-square value of the y-component perturbations in fluid velocity as seen by an oscillating probe, (m/s)
w	Fluctuating component of velocity in the z direction, (m/s)
W	Velocity in the z direction, (m/s)

x	Coordinate in streamwise direction (positive in direction of flow)
y	Coordinate in transverse direction
z	Coordinate in transverse direction
	Note that x, y and z form a right-handed coordinate system (see Figure 2)

Subscript

n	denotes the value of a variable in a data set

1. Introduction

A hot-wire anemometer is used to measure instantaneous velocities or temperatures at a point in a turbulent flow field by monitoring the change in resistance of a thin wire that is heated electrically and attached to a small probe placed in the flow. The wire is sensitive and has a high frequency response to small fluctuations in velocity or temperature in the flow. This makes hot-wire anemometers ideal for studies of turbulent flows. For velocity measurements, different components of turbulent flows can be measured simultaneously by fitting more than one wire to a probe. There are two modes of operation of hot-wire anemometers: constant wire current and constant wire temperature. The constant-current anemometer is used to measure temperature fluctuations, and it can be used to measure velocity fluctuations although this is rarely done these days. A major disadvantage of the constant-current device is that the wire can burn out if the flow stops, and nowadays the constant-temperature anemometer is used almost universally. Only constant-temperature anemometers will be considered in this report.

To determine broadband-turbulence terms, fluctuating output voltage signals from hot-wire anemometers are sampled and processed using either analog or digital techniques. With analog techniques, fluctuating voltage signals are sampled continuously for a specified sampling period and processed by analog circuits to yield output voltages that correspond to the required turbulence terms. With digital techniques, the fluctuating voltage signals are sampled at specified uniform time intervals to yield discrete voltages which are stored for subsequent processing. Turbulence terms can then be readily evaluated from the measured voltages. The choice between analog and digital processing of hot-wire signals involves a trade off between the increased accuracy of analog systems which results from the continuous measurement (very high bandwidth) of a turbulence signal, and the increased range of turbulence terms that can be measured using digital systems.

The previous constant-temperature hot-wire anemometer system at the Aeronautical and Maritime Research Laboratory (AMRL) used a combination of analog and digital techniques to determine broadband-turbulence terms. Details of this hybrid system are given by Watmuff (1986). With this system, unscaled mean and root-mean-square quantities were determined from fluctuating voltage signals using analog techniques, but digital techniques were used when performing a dynamic calibration (Sections 3.3 and 5.1). Also, a digital computer was used to supervise a microprocessor-based data acquisition system which sampled, monitored and controlled the analog circuits. The range of terms that could be measured with the hybrid system was fixed by the setup of the analog circuits. Quantities that could be measured were mean velocities, U, V and W, but turbulence quantities were limited to the Reynolds stresses, $\overline{u^2}$, $\overline{v^2}$, $\overline{w^2}$ and $\overline{uv}$.

Early digital systems, particularly those based on desktop computers, suffered from unacceptably low rates of data transfer to memory. The normal solution was to use a large amount of memory locally on the analog-to-digital card and then to transfer data slowly from this local memory to the main memory, or even more slowly to the disk, after the particular measuring run. Digital measurement techniques have become increasingly popular over the years as a result of the continuous improvement in the speed and storage capacity of digital computers and the equipment and method used to determine broadband-turbulence terms have recently been modified at AMRL so that all sampling and data reduction is now done digitally. An MS-DOS®[1]-based desktop computer with an inbuilt analog-to-digital converter (Section 4) is now used to sample the fluctuating voltages (Section 5.2) and process the data (Section 5.3). The use of digital processing techniques in the new system enables turbulence terms of any complexity to be evaluated (e.g. $\overline{u^6}$, $\overline{u^7v^8}$ –see Section 5.3 for an explanation of turbulence terms), as required. It is now possible to measure mean velocities, U, V and W, Reynolds stresses, $\overline{u^2}$, $\overline{v^2}$, $\overline{w^2}$ and $\overline{uv}$, triple products, $\overline{u^3}$, $\overline{v^3}$, $\overline{w^3}$, $\overline{u^2v}$ and $\overline{uv^2}$, as well as fourth-degree terms, $\overline{u^4}$, $\overline{v^4}$ and $\overline{w^4}$ –see Hinze (1959). These turbulence terms can be used to obtain balances of both turbulent kinetic energy and Reynolds shear stress, as well as for determining skewness and flatness factors, none of which could be measured previously (for the u component of the turbulence, skewness is given by $\overline{u^3}/[\overline{u^2}^{1.5}]$ and flatness is given by $\overline{u^4}/[\overline{u^2}^{2}]$. With the new system, turbulence terms comprised of combinations of v and w (such as $\overline{vw}$ and $\overline{vw^2}$) are still not measurable using a conventional crossed wire probe, as with the previous system.

For the new system, it is possible to sample 1 channel at up to 25 kHz, 2 channels at up to about 20.8 kHz, 3 channels at up to about 14.3 kHz and 4 channels at up to about 10.9 kHz (see equation 16). Up to 32 channels can be used and the maximum number of data points which can be sampled for all channels combined is fixed at 252000 in any given run and the data occupies about 3.5 Mb of memory. The maximum number of data points for each channel is given by 252000/[number of channels chosen] (Section 5.2). It is possible to increase the number of data points sampled by increasing the memory of the computer. The sampled data are written straight to the main memory in the time interval between successive samples and the new system has sufficient memory and acceptable data transfer rates to meet present requirements.

In this report, the new digital hot-wire system used to take broadband-turbulence measurements is described. Features of the hot-wire anemometers, probes, matching box, dynamic calibrator and the computer are discussed in detail, and the computer programs, including those used for dynamic calibration, data sampling and data reduction, are described. Procedures for using the system, including the method of adjusting the hot-wire anemometers and the matching box, the procedure for dynamic calibration, and the method of using the computer programs, are also presented.

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[1] MS-DOS is a registered trademark of Microsoft Corporation.
In this report, the use of trade names for products is for descriptive purposes only and is not an endorsement of the products by AMRL.

2. Hot-Wire Anemometers and Probes

2.1 Hot-Wire Anemometers

The constant-temperature hot-wire anemometers are based upon those at the University of Melbourne initially developed by Perry & Morrison (1971a). The operation of these anemometers is described briefly in the following. A hot-wire filament and the associated leads form one arm of a wheatstone bridge. An electric current is passed through the filament which may be located in a turbulent flow. As the velocity fluctuates, the heat transfer from the filament varies which causes the temperature and resistance of the filament to vary. The filament is connected to a feedback circuit which attempts to keep the wheatstone bridge balanced so that the filament has a constant resistance and hence constant temperature. An offset voltage is applied to cause the bridge to be slightly out of balance as this gives better stability and frequency response. The changes in the resistance of the wire are monitored and the anemometer gives fluctuating output voltage signals related to the variations in flow velocity. The output voltage signals are sampled as specified by a user (Section 5.2) and velocities are determined using predetermined calibration equations. Further details of constant-temperature hot-wire anemometers are given by Perry (1982).

The AMRL anemometers comprise two double-channel units, constructed by Watmuff (1986) who followed the recommendations of Perry (1982). A diagrammatic representation of the front panel of an anemometer and a photograph of the anemometers are given in Figure 1. The wire sensing element is connected to the anemometer bridge via the terminal labeled "WIRE". The thumb wheel switches labeled "HOT RESIST" are used to set the hot-wire resistance ratio (Section 2.3.1) by altering the resistance in one of the arms of the bridge. The terminal labeled "SQ WAVE" is used to apply a square wave voltage perturbation from an external source to the offset voltage when setting the anemometer's frequency response. The offset voltage is adjusted using the potentiometer labeled "OFFSET" and the balance inductance labeled "INDUCT" is also adjusted until the desired frequency response of the anemometer is obtained (Section 2.3.2). The fluctuating voltage at the top of the bridge has a large DC component and the signal can be "bucked", i.e. the DC component removed, using the potentiometer labeled "BUCK" (see Section 3.3 for further details of "bucking" procedure). The resultant signal is amplified by the gain factor set on the switch labeled "GAIN" to yield the anemometer output voltage at the terminal labeled "AMPL OUT" (Section 3.3). The ammeter indicates the wire current and has a full-scale reading of 1.0 mA.

2.2 Hot-Wire Probes

2.2.1 Types of Probes

For turbulence measurements at AMRL, DANTEC[2] (DISA) single-wire probes (e.g. type 55P01) and crossed-wire probes (e.g. type 55P51) and corresponding leads are

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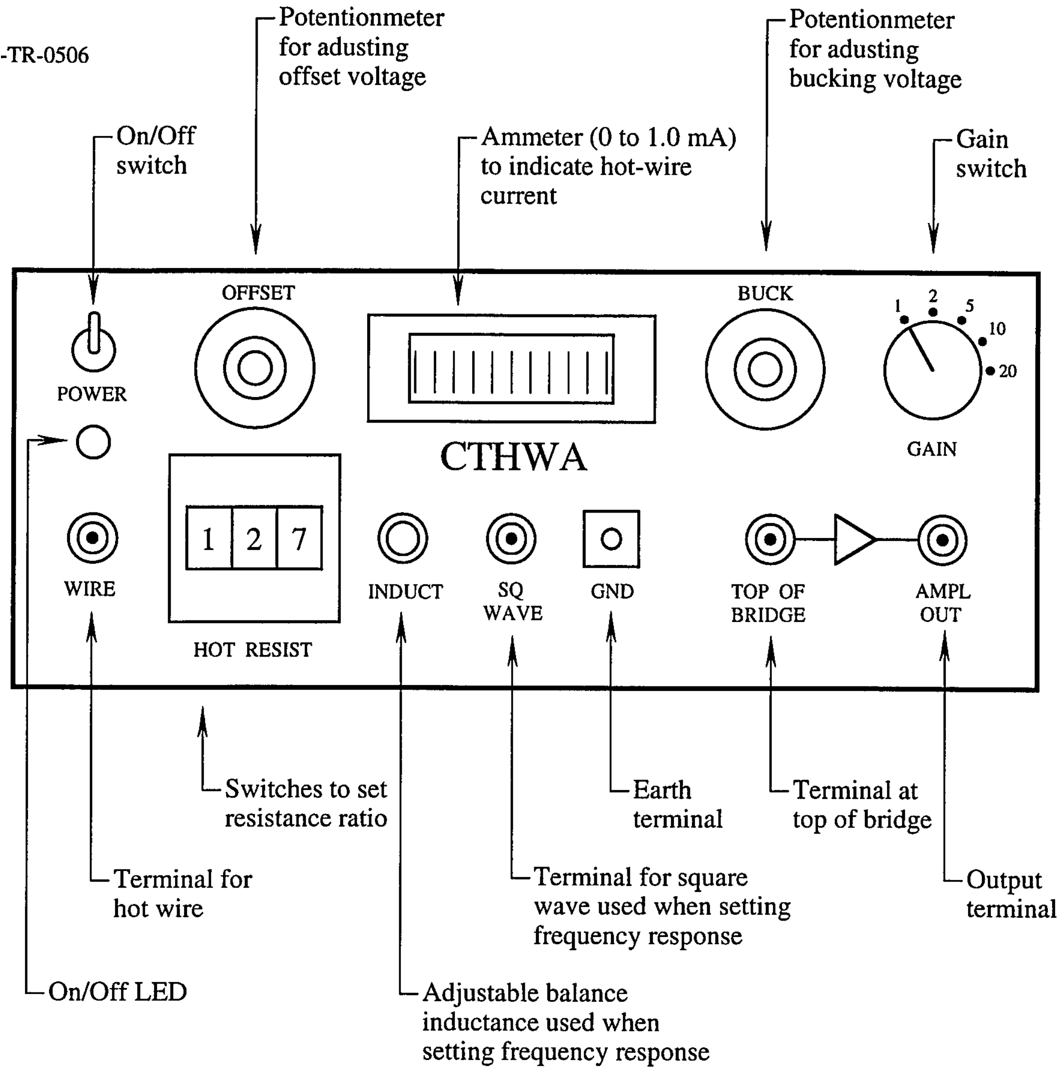
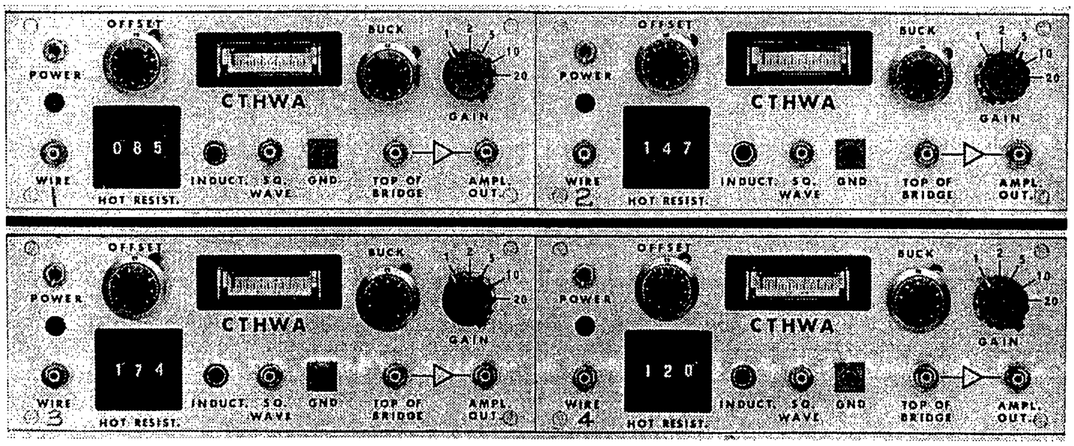
[2] DANTEC Elektronic, Tonsbakken 16-18, DK-2740, Skovlunde, Denmark.



(a) front panel of anemometer.



(b) photograph of two double-channel anemometers.

Figure 1 Constant-temperature hot-wire anemometers.

used, but the platinum-plated tungsten wires on these probes are replaced with Wollaston wires (Section 2.2.3). Single-wire probes are used to measure u turbulence terms only (such as $\overline{u^2}$ and $\overline{u^3}$) and crossed-wire probes are used to measure uv terms (such as $\overline{u^2}$, $\overline{v^2}$, $\overline{uv}$ and $\overline{u^2v}$), or alternatively, uw terms (such as $\overline{u^2}$, $\overline{w^2}$ and $\overline{w^3}$). For u measurements with a single-wire probe, the axis of the filament must be oriented at 90° to the x or streamwise direction. For both uv and uw measurements with a crossed-wire probe, the orientation of the two filaments is shown diagrammatically in Figure 2. For uv measurements, the wire axes are oriented at 0° to the xy plane and for uw measurements, the wire axes are oriented at 0° to the xz plane. The probe is converted from uv mode to uw mode by simply rotating the plane of the crossed wires through 90° about the probe longitudinal axis. As indicated in Section 1, vw turbulence terms are not measured with this anemometer system.

2.2.2 Types of Sensing Filaments

Platinum and tungsten are two of the more common materials used as sensing filaments on hot-wire probes. Wollaston wire has a cylindrical platinum core (core diameters of 2.5, 5, 10 and 15 μm are available) with a silver coating that is etched away over about one-third of its length to allow the platinum to act as the sensing filament. Uncoated tungsten wire is also available in a range of sizes and copper stubs are usually electroplated onto the ends of the wire to facilitate the soldering of the tungsten to the prongs of a probe.

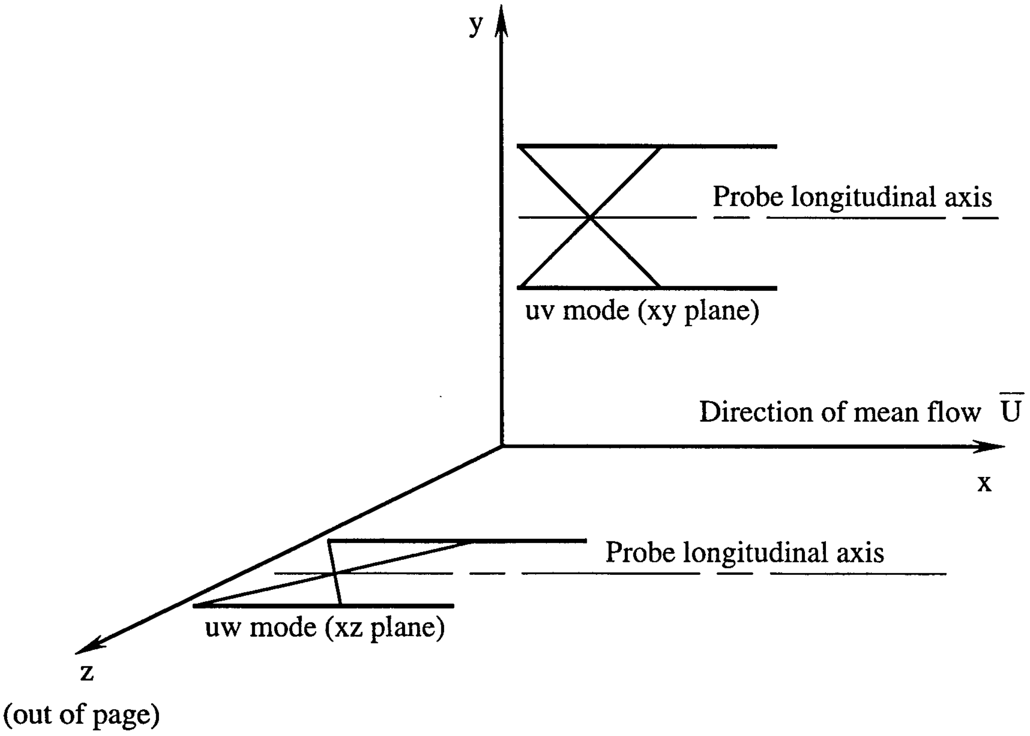


Figure 2 Orientation of crossed-wire probe for both uv and uw measurements.

Tungsten wire has a very ragged surface which can collect dust and debris quickly and the surface of tungsten wire may oxidize if resistance ratios in excess of about 1.6 are used (Perry, 1982). The calibration coefficients of tungsten wire tend to drift with time and this can cause significant errors in the quantities being measured. Wollaston wire has more stable calibration coefficients provided the platinum core has been annealed or aged correctly, which is accomplished by setting the resistance ratio of the wire to a value of about 2.2 for about 24 hours before resetting it to the normal operating value of 2.0 (Perry, 1982). However, tungsten wire is stronger than Wollaston wire and it is better able to survive impacts from dust particles and other debris that may be in the airstream. The wires on the DANTEC probes used at AMRL, mentioned previously in Section 2.2.1, have a platinum-plated tungsten core (5 μm core diameter) with a copper and gold coating for the stubs, so that the sensing filaments incorporate advantages of both tungsten and platinum, i.e. a smooth surface, no oxidation problems and high strength. Unfortunately, the calibration coefficients for these wires can still drift more than the calibration coefficients for platinum wires as the ambient air temperature changes slightly throughout the course of an experiment. Tungsten has a resistivity of 5.4×10^{-8} Ωm and a temperature coefficient of resistance of 4.8×10^{-3} K^{-1}. Corresponding figures for platinum are 10.58×10^{-8} Ωm and 3.92×10^{-3} K^{-1} (Fink & Christiansen, 1989).

The choice of which wire material to use is not straightforward and is based upon many conflicting requirements. The choice is usually governed by the required accuracy of the results, the availability of material and the ease of soldering new wires onto probes. Cost is also an important consideration (Section 2.2.3). AMRL currently has a supply of Wollaston wire, with core diameters of 2.5, 5, 10 and 15 μm and corresponding external diameters of 19, 72, 100 and 145 μm respectively. To obtain the most accurate results and minimize the cost of operation with the constant-temperature anemometer system now available, Wollaston wires are soldered onto DANTEC probes after the existing (platinum-plated tungsten core) wires have been removed. The anemometers have been optimized for use with Wollaston wires but tungsten wire can be used if necessary.

The anemometer system was tested using wires of diameter 5 and 10 μm (core diameters) to determine wire diameter/maximum air velocity limits. The 10 μm wire can only be used up to about 4 m/s before components of the anemometers reach their current (amperes) operating limits, but the 5 μm wire can be used without problems up to about 90 m/s and this wire size is normally used in the low-speed wind tunnel (LSWT). The 5 μm wire was tested at this velocity for at least 5 minutes and did not break. Wire of diameter 2.5 μm can be used satisfactorily with the anemometer system for all velocities but as it is much thinner than the 5 μm wire it is more likely to break.

2.2.3 Replacement of Hot Wires

Wollaston wire is soldered onto the prongs of a DANTEC probe and the silver is etched away using the equipment shown in Figure 3. Before soldering a wire onto the prongs

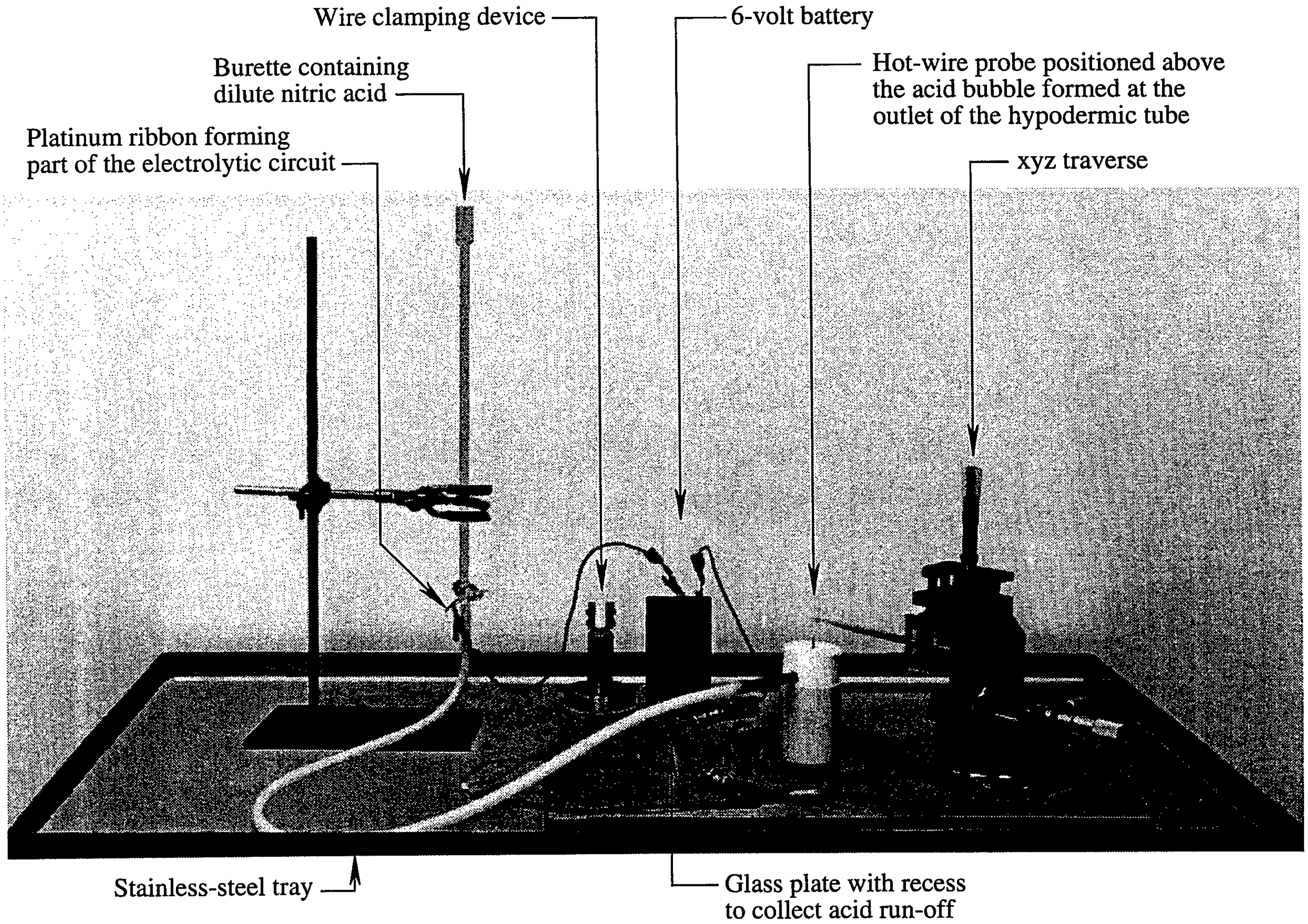


Figure 3 Equipment for replacing hot wires.

of a probe it is necessary to check that the open-circuit resistance of the probe is greater than 30 MΩ, since a lower resistance could cause electrical instability and wire burn-out. The wire is aligned with the prongs of a probe using the wire clamping device and the xyz traverse shown in Figure 3. Phosphoric acid is placed on the tips of the prongs and the Wollaston wire is soldered to the prongs using a small soldering iron. Excess wire is removed using a scalpel. The length of the wire on the probe is about 3 mm and its resistance (5.0 μm core diameter) prior to etching should be about 0.3 Ω (after allowing for the resistance of connecting leads). A much higher resistance of the wire and leads usually indicates a poorly soldered joint. The wire is positioned in the acid bubble formed at the outlet of the hypodermic tube using the xyz traverse shown in Figure 3, and the silver coating is etched away electrolytically using nitric acid of 15% concentration to expose the platinum core. For safety reasons the etching should be done in a fume cupboard. For a wire of 5.0 μm core diameter, the etched length is typically 1.0 mm, giving a length-to-diameter ratio of 200. After etching, the prongs and wire are gently washed with distilled water to remove any acid. The resistance of the wire after etching should be about 6 Ω (after allowing for the resistance of connecting leads which should be measured before attaching the wire).

New DANTEC wires (already etched) can be welded onto DANTEC probes using DANTEC spot-welding equipment, but this is an expensive process. The equipment needed consists of a micromanipulator (55A13, cost ≈ $19 800), and a welding power generator (55A12, cost ≈ $4000), which are not available at AMRL. In addition, the cost of each filament is about $120. The cost of the equipment shown in Figure 3 for replacing Wollaston-wire filaments is about 10% of the cost of the equipment just mentioned. The cost of a 10 m spool of Wollaston wire is about $3000 (1997 prices quoted above).

2.3 Initial Adjustments to Hot-Wire Anemometers

2.3.1 Setting the Filament Operating Resistance

For Wollaston wire, the resistance of a filament when it is operating should be about twice the resistance of the filament when it is at the temperature of the fluid in which measurements are being taken (Perry, 1982). The factor of 2 is termed the resistance ratio. The increased resistance of the filament when it is operating causes an increase in filament temperature. The filament is operated at an elevated temperature to improve sensitivity, but the filament can burn out very easily if the temperature becomes too high. A resistance ratio of 2 for Wollaston wire provides a good compromise. If the filament has a resistance of say 6 Ω at ambient temperature in still air and the resistance of the two leads combined is say 0.7 Ω, then the total resistance (filament plus leads) when the filament is operating is (6 x 2) + 0.7, i.e. 12.7 Ω. To balance the wheatstone bridge, it is necessary to adjust a balance resistance in another arm of the bridge and this is done using thumb wheel switches on the front panel of the anemometer (Figure 1). The balance resistance is set at 10 times the above total resistance, i.e. 127 Ω, because the resistances of the other two arms of the bridge are 100 Ω and 1000 Ω, i.e. the ratio of resistances is 10:1.

2.3.2 Setting the Frequency Response

To set the frequency response of an anemometer, a hot-wire probe is first placed in the tunnel free-stream and the air velocity is set to the lowest value likely to be encountered during subsequent measurements. The anemometer is then perturbed electrically by superimposing on the offset voltage a square wave of frequency 1 kHz and amplitude 100 mV peak to peak. The square wave is applied to the anemometer from an external source via the terminal labeled "SQ WAVE" (Figure 1). The anemometer output voltage at the terminal labeled "AMPL OUT" is observed on an oscilloscope and the offset voltage potentiometer, labeled "OFFSET", and the balance inductance, labeled "INDUCT", are adjusted until the frequency response has the form shown in Figure 4 (Perry, 1982).

For wires having a platinum core or a platinum-plated tungsten core (DANTEC probes), the AMRL anemometers have sufficient range of adjustment of the offset voltage and the balance inductance to obtain optimum performance with respect to system stability and frequency response.

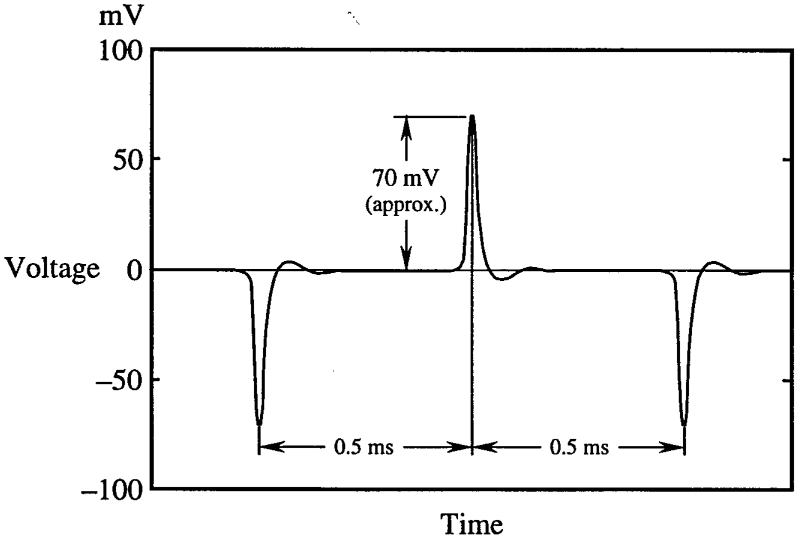


Figure 4 Waveform required for anemometer output voltage when setting the frequency response.

3. Hot-Wire Calibration

3.1 Static Calibration Method

The conventional hot-wire static calibration method used when determining broadband-turbulence terms with a constant-temperature hot-wire anemometer involves measuring values of E_0, the output voltage of the hot-wire anemometer, for a number of values of U, the velocity in the longitudinal direction. A calibration law which is extensively used (Perry, 1982) is

$$E_0^2 = A + BU^n \tag{1}$$

where A and B are constant for a given fluid, hot wire, electronic circuit and hot-wire resistance ratio. The value of the index, n, depends upon the form of the heat-transfer law used. The quoted values of n vary significantly, but generally n has been taken to lie in the range 0.4 to 0.5 (Perry & Morrison, 1971b).

The small-perturbation longitudinal sensitivity, $\partial E_0/\partial U$, derived by differentiating equation 1 and required for the measurement of turbulence terms, is given by equation 2.

$$\frac{\partial E_0}{\partial U} = \frac{nBU^{n-1}}{2E_0} \tag{2}$$

The conventional method for determining $\partial E_0/\partial U$ is to choose a value of n and plot the calibration data using non-linear coordinates of E_0^2 vs U^n, as suggested by the form of equation 1. The straight line of best fit is then determined either graphically or numerically and this gives the constant B, which is equal to the slope of the straight line. A major shortcoming of the method is that calculated values of sensitivity depend upon the value of n chosen.

Perry & Morrison (1971b) investigated the above static calibration procedure for a single wire and found that serious errors could occur in the calculated values of sensitivity. They developed an alternative calibration procedure which avoided the need to specify the functional form of the heat-transfer law and the need to fit a straight line to the calibration data. This alternative procedure, known as dynamic calibration, involves oscillating the hot wire at low frequencies (up to 2.5 Hz) in a uniform flow to produce a sinusoidal velocity perturbation at the wire. Provided the maximum perturbation velocity of the wire is not too large (less than 10% of the free-stream velocity), the wire sensitivity can be determined accurately using the dynamic calibration technique. Perry & Morrison compared sensitivities determined using static and dynamic calibration techniques and found that a static calibration could lead to errors of more than 20% in sensitivity. Dynamic calibration is discussed in detail in Section 3.3.

3.2 Dynamic Calibrator

A dynamic calibrator is a device used to impart accurately known sinusoidal velocity perturbations to a hot-wire probe. The original calibrator used by Perry & Morrison (1971b) was based on the Scotch yoke principle (a Scotch yoke is a device which converts rotary motion into reciprocating motion), but more-recent calibrators developed by Perry & Watmuff (1981), Watmuff (1986) and Erm & Joubert (1991) have been based on the Murray cycloidal drive (Lavery & Henshaw, 1972). This drive produces simple harmonic motion at its output when the input shaft is driven at constant speed. Balance weights can be incorporated in the drive mechanism so that it can be dynamically balanced with the probe attached. The dynamic calibrator developed at AMRL by Watmuff (1986) is shown in Figure 5. The calibrator has a stroke of 76.2 mm (total travel) and is capable of oscillating the probe at frequencies in excess of 10 Hz, giving a maximum probe velocity of about 2.4 m/s, but a frequency of about 2.5 Hz is generally adequate for most calibrations. A chopper disk with 120 slots, one of which is elongated, is mounted on the cycloidal drive and two LED/phototransistor pairs are mounted so that they straddle the slots in the chopper disk to produce 120 pulses and 1 pulse per calibrator cycle. These pulses are passed to the data acquisition system (Section 4) to enable the velocity of the probe and the phase of its motion to be determined accurately.

In the calibration procedure used at AMRL, the calibrator is mounted on the outside of the roof of the working section of the 2.7 m × 2.1 m LSWT with the calibrator sting protruding through the roof into the free-stream. A hot-wire probe is attached to the sting which can be oscillated at either 0^o, 45^o or 90^o to the free-stream direction depending on how the calibrator is adjusted. Side views of the setup of the calibrator and the sting for these three cases are shown in Figures 5(b-d). To adjust the calibrator for different modes of operation, it is necessary to rotate it on its mountings and simultaneously rotate the sting in the opposite direction. Pins are used to lock the calibrator and sting into position for operation at each of the three angles. In all cases, the calibrator sting remains vertical during oscillation. After calibrating a hot wire, it is necessary to transfer the probe from the calibrator sting to the probe traverse on the measurement rig and considerable care is needed to ensure that the longitudinal axis of the probe has the same orientation to the mean flow for both situations.

3.3 Dynamic Calibrator Method

The dynamic calibration method originally developed by Perry & Morrison (1971b) was only applicable to single-wire probes with filaments at 90^o to the mean-flow direction.

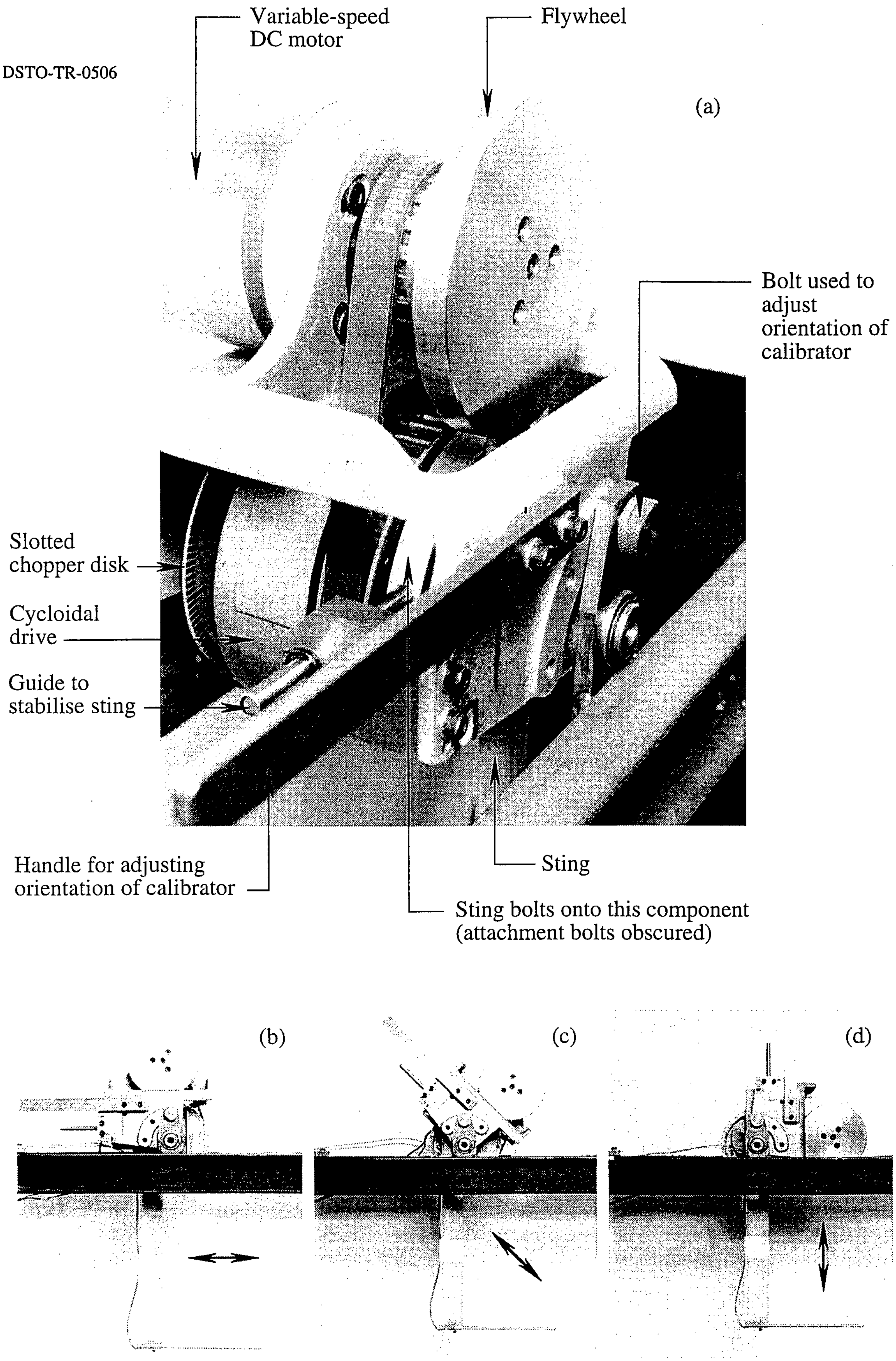


Figure 5 Dynamic calibrator: (a) view showing mechanical details; (b)-(d) setup of calibrator when oscillating the sting at 0°, 45° and 90° respectively to the free-stream direction (Watmuff, 1986).

The method was extended by Morrison, Perry & Samuel (1972) to apply to single-wire probes having inclined filaments and also to crossed-wire probes. Since then a new dynamic calibration technique has been developed (Perry, 1982). The main features of the dynamic calibration procedure used at AMRL, which is based on the technique given by Perry (1982), are given briefly in the following paragraphs for a crossed-wire probe. The technique is also applicable in a simplified form to a single-wire probe.

A diagrammatic representation of the circuit used for crossed-wire signal processing, which is connected to the data acquisition system, is given in Figure 6.

Before dynamically calibrating the crossed wires, it is necessary to make some adjustments to the potentiometers and amplifiers in the circuit shown in Figure 6. The hot-wire probe is placed on the calibrator sting with the probe oriented in uv mode as shown in Figure 2. This probe orientation is used when making the adjustments and when doing the calibration irrespective of whether uv or uw turbulence measurements are to be taken subsequently The probe is oscillated horizontally (Figure 5b) in a steady air stream having a mean velocity, $\overline{U}$, close to the midpoint of the two extremes expected to be measured. The fluctuating output voltage signals E_U and E_V are observed on an oscilloscope and the potentiometer P_4 is adjusted until the voltage signal E_V remains virtually constant, which means that E_V is insensitive to longitudinal velocity fluctuations caused by the calibrator motion. Similarly, the probe is then oscillated vertically (Figure 5d) and the potentiometer P_3 is adjusted until E_U is virtually insensitive to vertical velocity fluctuations. This process is termed "electronic matching" of the hot wires. The calibrator is then stopped and potentiometers P_1 and P_2 are adjusted until voltages E_U and E_V are both approximately zero (E_1 and E_2 are also approximately zero). This process is termed "bucking" the voltages and it does not affect the matching. The "bucking" process removes unwanted DC voltage components from E_U and E_V. To improve resolution, voltage signals E_U and E_V are then amplified by adjusting the gains on each hot-wire anemometer. Finally, checks must be made to ensure that the voltages sampled by the data acquisition system (Section 4) during the subsequent processes of calibration and measurement of turbulence terms will not exceed ±5.0 V, the limits imposed by the data acquisition system. The checks are done by subjecting the hot-wire probe to a range of velocities similar to the range subsequently expected and noting the variations in E_U and E_V.

During calibration, the hot-wire probe is oscillated in the tunnel free-stream and the only fluctuating hot-wire voltages of interest are those caused by the movement of the wire. The calibrator oscillates at up to 2.5 Hz during calibration (see below) and voltages E_U and E_V are low-pass filtered at 30 Hz prior to being sampled by the data acquisition system to remove unwanted high-frequency noise emanating from the calibrator and its sting.

When dynamically calibrating a crossed-wire probe, it is necessary to take calibration measurements in the tunnel free-stream at typically 8 different mean-flow velocities and the following description of events applies to each of these velocities. The chosen

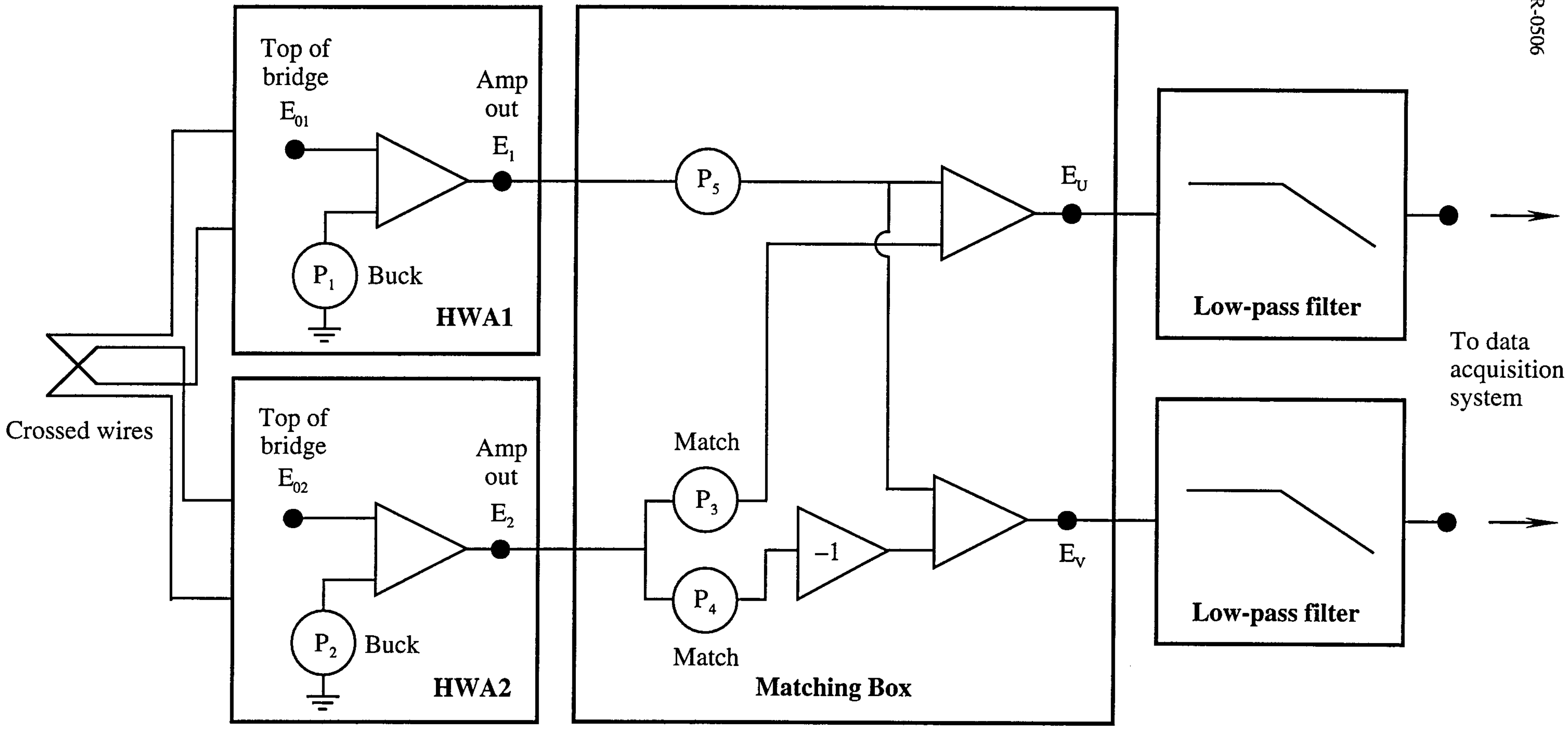


Figure 6 Hot-wire circuit showing anemometers, matching box and adjustable low-pass filters.

tunnel mean-flow velocity, $\overline{U}$, is measured using a Pitot-static probe which is located close to the hot-wire probe and the hot-wire probe is oscillated in the free-stream at 45° to the mean-flow direction (Figure 5c). To avoid the effects of hot-wire non-linearity, the maximum x-component velocity perturbation given to the probe by the calibrator should be small, being about 10% of the particular mean-flow velocity. The rotational frequency of the dynamic calibrator must be adjusted for the different mean-flow velocities to satisfy this requirement. The calibrator rotational frequencies are always kept below about 2.5 Hz to avoid filament damage, even though the velocity perturbations may still remain within the above 10% limit at higher rotational frequencies. The 2.5 Hz limit is imposed to avoid excessive dynamic (shock) loads on the hot-wire filaments. The crossed wire probe is shown diagrammatically in Figure 7 together with the mean-flow and perturbation velocities. For the DANTEC crossed-wire probes, the wires are nominally at ±45° to the mean-flow direction. It is not essential that the wires cross at 90° and Perry, Lim & Henbest (1987) used the dynamic calibration technique for wires that were at ±60° to the mean-flow direction for some of their measurements.

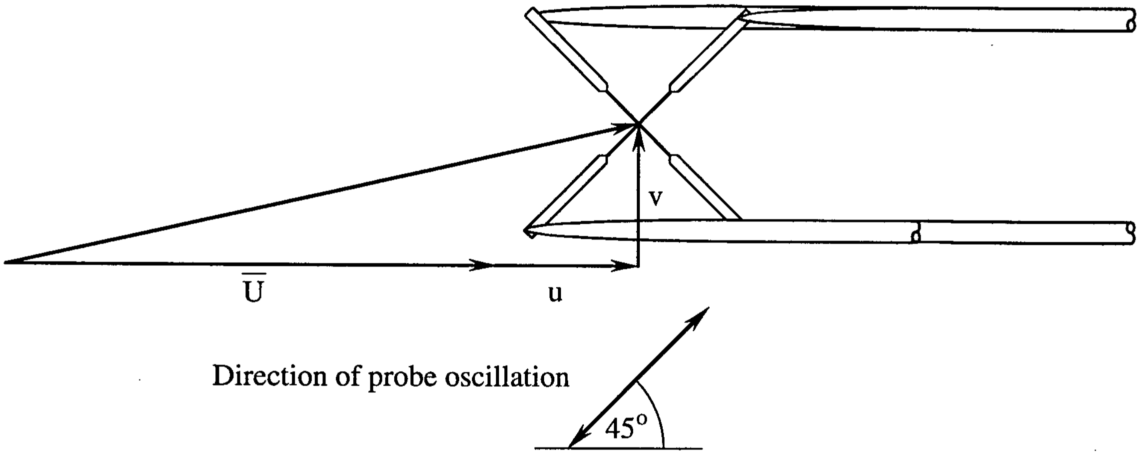


Figure 7 Diagrammatic representation of mean-flow and perturbation velocities for a crossed-wire probe.

Voltage sampling is controlled by the chopper disk referred to previously. Voltage pulses emanating from the single elongated slot are used by the data acquisition system to indicate the start and finish of a sampling cycle (revolution of the chopper disk) and to start and stop an internal clock which is used to determine the frequency of oscillation of the calibrator. Voltage pulses emanating from the 120 slots are used by the data acquisition system to initiate the analog-to-digital conversion of voltages E_U and E_V which are then transferred to arrays in memory where they are added to those recorded during previous cycles. Sampling is performed for a specified number of revolutions of the chopper disk, typically 50 or more. Values of E_U and E_V corresponding to each of the 120 disk positions are then averaged over the specified number of cycles (typically 50) to give $\overline{E}_{U_n}$ and $\overline{E}_{V_n}$ respectively, where the subscript n varies between 1 and 120. This averaging removes the effects of background turbulence and means that the hot-wire signals are averaged on the basis of the phase of the calibrator motion. The calibrator frequency is also averaged over the specified number of cycles (typically 50) to give the average calibrator frequency, f. The values of $\overline{E}_{U_n}$ and $\overline{E}_{V_n}$ are then averaged over the 120 disk positions to give $\overline{\overline{E}}_U$ and $\overline{\overline{E}}_V$ respectively. The voltage perturbations denoted by $(\overline{E}_{U_n} - \overline{\overline{E}}_U)$ and $(\overline{E}_{V_n} - \overline{\overline{E}}_V)$ for each of the 120 disk positions are then determined and the corresponding root-mean-square values of these quantities, given by

$$E_{U_{rms}} = \left[\frac{\sum_{n=1}^{120} \left(\overline{E}_{U_n} - \overline{\overline{E}}_U \right)^2}{120} \right]^{0.5} \tag{3}$$

and

$$E_{V_{rms}} = \left[\frac{\sum_{n=1}^{120} \left(\overline{E}_{V_n} - \overline{\overline{E}}_V \right)^2}{120} \right]^{0.5} \tag{4}$$

respectively, are then calculated. The perturbations in fluid velocity, as seen by the oscillating probe, are determined from the frequency and phase of the calibrator motion and their root-mean-square values are determined using the average calibrator frequency, f, at the given mean-flow velocity assuming pure sinusoidal motion. The relevant equations for the root-mean-square velocity in the horizontal and vertical directions are

$$U_{rms} = \frac{2\pi Rf}{\sqrt{2}} \cos 45 \tag{5}$$

and

$$V_{rms} = \frac{2\pi Rf}{\sqrt{2}} \sin 45 \tag{6}$$

respectively, where R is the radius of the calibrator motion (R = 0.0381 m). The small perturbation sensitivities are defined as ratios of the above quantities and the respective equations for the horizontal and vertical directions are

$$\frac{\partial U}{\partial E_U} = \frac{U_{rms}}{E_{U_{rms}}} \tag{7}$$

and

$$\frac{\partial V}{\partial E_V} = \frac{V_{rms}}{E_{V_{rms}}} \tag{8}$$

Calibration measurements are taken at typically 8 different mean-flow velocities to give 8 values of each of $\partial U/\partial E_U$, $\partial V/\partial E_V$, E_U, E_V and U (determined using the Pitot-static probe). These data are used when determining coefficients in the calibration equations given below.

Perry (1982) showed that the calibration equations relating velocities to voltages could be expressed by the following non-linear cubic form:

$$U = A_0 + A_1E_U + A_2E_U^2 + A_3E_U^3 + \ldots \tag{9}$$

and

$$V = B_0 + B_1E_U + B_2E_V + B_3E_UE_V + B_4E_U^2E_V + \ldots \tag{10}$$

where U and V are the instantaneous velocities at a point in the flow in the longitudinal and vertical directions respectively and the A and B coefficients are constants. Differentiating equations 9 and 10 gives

$$\frac{\partial U}{\partial E_U} = A_1 + 2A_2E_U + 3A_3E_U^2 + \ldots \tag{11}$$

and

$$\frac{\partial V}{\partial E_V} = B_2 + B_3E_U + B_4E_U^2 + \ldots \tag{12}$$

The coefficients A_1, A_2 and A_3 are obtained by fitting the data for $\partial U/\partial E_U$ vs E_U from the dynamic calibration to equation 11 using a second-order polynomial curve fit. The remaining coefficient, A_0, in equation 9 is determined by fitting the data for U vs E_U from the dynamic calibration to equation 9 using a third-order polynomial curve fit. Similarly, B_2, B_3 and B_4 are obtained by fitting the data for $\partial V/\partial E_V$ vs E_U to equation 12 using a second-order polynomial curve fit. The mean value of V at each calibration point is 0 so that equation 10 becomes

$$0 = B_0 + B_1E_U + B_2E_V + B_3E_UE_V + B_4E_U^2E_V + \ldots \tag{13}$$

The remaining coefficients, B_0 and B_1, in equation 10 can be determined by fitting the data for E_U vs E_V to equation 13. B_0 and B_1 are usually small.

The above description of the calibration procedure applies to a crossed-wire probe. To calibrate a single-wire probe, the probe is placed on the calibrator sting so that the filament is oriented at 90^o to the direction of the mean flow and the only adjustments that have to be made in the circuit shown in Figure 6 are to "buck" and amplify the voltages. During calibration, the single-wire probe is oscillated at 0^o to the mean-flow direction (Figure 5b). For a single-wire probe, equation 10 for V is not applicable and only equation 9 for U is relevant.

If the root-mean-square turbulence intensity is less than about 10% of the mean velocity at a given location in the flow, then turbulence terms at that point can be evaluated using hot-wire sensitivities at that point and it is not necessary to carry out a full dynamic calibration. Under these circumstances, hot-wire non-linearity can be neglected and turbulence terms can be evaluated by processing measured hot-wire voltages rather than processing velocities determined from voltages (Watmuff, 1986). The measurement of turbulence intensities in the free-stream of a wind tunnel is an example of the use of this simplified measurement technique.

4. Data Acquisition System

A new improved higher-capability data acquisition system has been developed for the measurement of turbulence quantities which replaces the system used by Watmuff (1986). The new system is based on an MS-DOS®-based desktop computer which incorporates a special multifunction analog/digital input/output board with a multiplexer expansion kit to enable the computer to operate as a data acquisition system. The system is a general purpose one that can be used for a wide range of measurements when interfaced with instruments that give output voltages normally varying from -5.0 V to +5.0 V. Although the computer has been set up to be used as a data acquisition system, it is still possible to use it on a day-to-day basis for other work. The main features of the system are:

Desktop Computer:

486 Microprocessor; 125 Mb Hard Disk Drive; 8 Mb RAM

3.5 inch, 1.44 Mb Floppy Disk Drive; 5.25 inch, 1.2 Mb Floppy Disk Drive

14 inch VGA High Resolution Colour Monitor

Data Acquisition Board:

RTI-815F Multifunction Analog/Digital Input/Output Board
(made by Analog Devices[3])

0A10 Multiplexer Expansion Kit (made by Analog Devices)
(The expansion kit uses 2 Harris Semiconductors Model 508 multiplexer chips.)

32 Analog Inputs: –5.0 to +5.0 V (can set at 0.0 to +10.0 V or –10.0 to +10.0 V)
(sample rates: 1 channel at 80 kHz, 2 channels at 40 kHz, 4 channels at 20 kHz, etc., up to 32 channels at 2.5 kHz)

2 Analog Outputs: –10.0 to +10.0 V (can set at –5.0 to +5.0 V)

8 Digital Inputs: 0.0 to +5.0 V

8 Digital Outputs: 8 bits at TTL levels

The data acquisition system is a stand-alone system and contains all the necessary software to calibrate hot wires, take turbulence measurements, and calculate mean velocities and turbulence terms from sampled voltages stored on the system.

5. Measurement of Turbulence Quantities

The following discussion on the measurement of turbulence quantities is for a crossed-wire probe but it is also applicable in a simplified form to a single-wire probe. The same computer programs are used for both the single-wire and the crossed-wire measurements. The names of the programs and their location on the computer are given in Figure 8.

5.1 Determination of Calibration Coefficients

Before the dynamic calibration method described in Section 3.3 is used to determine hot-wire calibration coefficients, it is necessary to check that the LED/photo-sensitive transistor system on the dynamic calibrator (Section 3.2) is operating correctly and that the data acquisition system is receiving 120 voltage pulses per revolution of the chopper disk. This check is done by running program NUMPULSE while the dynamic calibrator is in motion and noting the number of pulses counted per revolution, which are listed on the monitor.

To carry out a dynamic calibration, it is necessary to run programs CAL and CALCOEFF. The following description on how to use the programs should be read in conjunction with Section 3.3 which describes the dynamic calibration method.

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[3] Australian distributor: ADM Systems Pty Ltd, 27 Cumberland Dr, Seaford, Victoria, 3198.

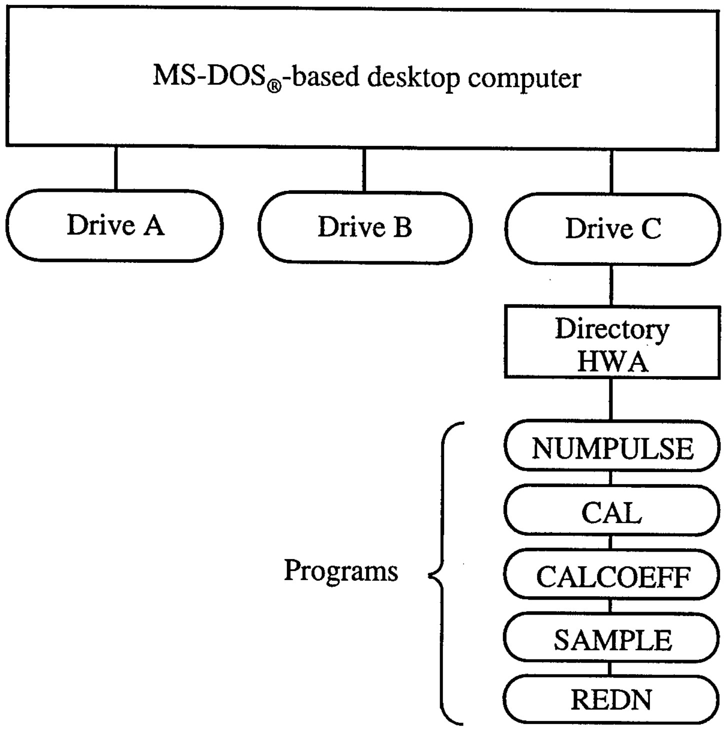

Figure 8 Names and location of programs on desktop computer.

The tunnel mean-flow velocity, which is measured using a Pitot-static probe, is set at its initial value. With the calibrator oscillating a crossed-wire probe at 45° to the mean-flow direction (Figure 5c), program CAL asks the user to specify the number of revolutions of the chopper disk for which hot-wire voltages E_U and E_V are to be sampled. Typically 50 revolutions, corresponding to 6000 pairs of voltages, is chosen. This number of sampling parameters has been found to produce acceptable convergence of calculated values of calibration variables. After sampling has been completed, the program evaluates the calibration variables which include the average calibrator frequency, f, root-mean-square voltages, $E_{U_{rms}}$ and $E_{V_{rms}}$, root-mean-square velocities, U_{rms} and V_{rms}, and sensitivities $\partial U/\partial E_U$ and $\partial V/\partial E_V$, given by equations 3 to 8. The variables are displayed on the monitor and the user has the option of writing the data to two files, designated FILE1.DAT and FILE2.DAT (typical names as chosen by the user), or else repeating measurements for the particular mean-flow velocity. FILE1.DAT is for the horizontal component of the probe oscillation and FILE2.DAT is for the vertical component. After data have been written to the files, the user instructs program CAL to continue the calibration. The mean-flow velocity and the calibrator angular velocity are set at their next values and the above procedure is repeated typically 8 times until the calibration is completed.

Before the calibration coefficients can be determined, it is necessary to create manually an additional file, designated FILE3.DAT (typical name), which contains the 8 calibration mean-flow velocities measured with a Pitot-static probe.

The calibration coefficients, A_0, A_1, A_2, A_3, B_0, B_1, B_2, B_3 and B_4, in equations 9 and 10, are determined and written to a file named FILE4.DAT (typical name) using program CALCOEFF. This program asks the user to specify the names of the files created when running CAL, such as FILE1.DAT and FILE2.DAT, as well as the name of the file containing the mean-flow velocities, FILE3.DAT, whose data are used when calculating the coefficients.

After the calibration coefficients have been obtained, it is necessary to check their accuracy, since the coefficients may have drifted during the calibration process. The check on the coefficients is a two-stage process. Firstly, with the crossed-wire probe mounted on the calibrator sting, which is stationary, mean velocities, $\overline{U}$, are measured with the crossed-wire probe. These velocities are obtained using the calibration coefficients being tested and the data sampling and data processing programs described in Sections 5.2 and 5.3 respectively. The velocities determined with the hot wire are then compared with those measured using a Pitot-static probe, located near the crossed-wire probe. The checks should be done for mean velocities close to the extremes of those used in the calibration as well as for a mean velocity close to the midpoint of these extremes. Secondly, with the crossed-wire probe still mounted on the calibrator sting, the probe is oscillated at 45° to the mean-flow direction and Reynolds stresses, $\overline{u^2}$, $\overline{v^2}$ and $\overline{uv}$, are measured with the crossed-wire probe using the data sampling and data processing programs as well as the calibration coefficients being tested. These Reynolds stresses are compared with those computed using the following theoretical relationship,

$$\overline{u^2} = \overline{v^2} = -\overline{uv} = \pi^2 R^2 f^2 \tag{14}$$

where R is the radius of the calibrator motion and f is the average calibrator frequency, which is determined by rerunning program CAL. Equation 14 is obtained by integrating the product of two sine waves of amplitude $\sqrt{2}\pi Rf$ and taking the average. The sine waves are in phase for $\overline{u^2}$ and $\overline{v^2}$ but have a phase difference of π radians for $-\overline{uv}$. It is assumed that the motion of the probe is sinusoidal, that the oscillations are at 45° to the mean-flow direction, that the two wires are at 45° to the mean-flow direction and that the free-stream turbulence intensity is negligible compared with the intensity computed using the velocity perturbations resulting from the probe motion. The checks on the Reynolds stresses should be done for the same three free-stream velocities used when checking mean velocities.

If the above comparisons show unacceptable discrepancies between the mean velocities and/or between the Reynolds stresses (variations up to 1.5% for mean velocities and up to 3% for Reynolds stresses are usually acceptable), then the calibration would need to be repeated until acceptable agreement is obtained or it may even be necessary to solder new filaments onto the crossed-wire probe if the discrepancies are due to the wires not being at 45° to the mean-flow velocity.

When determining the calibration coefficients for a single-wire probe, the probe is oscillated at 0° to the mean-flow direction and in this case the theoretical relationship to use when checking the accuracy of the coefficients is

$$\overline{u^2} = 2\pi^2 R^2 f^2 \qquad (15)$$

Equation 15 is also obtained by integrating the product of two sine waves and taking the average. In this case, the sine waves have an amplitude of $2\pi Rf$ and are in phase.

5.2 Data Sampling

Once the calibration has been verified, actual turbulence measurements can be taken. Before this can be done, it is necessary to transfer the hot-wire probe from the calibrator to the traversing mechanism to be used for the measurements. Extreme care must be taken to ensure that the wires are not broken by touching them or that they are not subjected to any mechanical shocks. Although small shocks may not actually break the wires, they could alter the calibration. To check that the calibration still holds after the hot-wire probe has been transferred, the probe should be moved into the free-stream and a few mean-flow velocities should be measured with the probe, using the data sampling and data reduction programs described in Sections 5.2 and 5.3 respectively, and compared with velocities obtained using a Pitot-static probe. Discrepancies up to 1.5% are tolerable.

The user instructs the program to start sampling (see Section 5.2.1) and when sampling is completed, the user is notified on the monitor. Sampled voltages are written to a file, designated FILE5.DAT (typical name), for subsequent processing. The hot-wire probe is moved to the next measurement location and the process repeated.

When sampling at all locations has been completed, the hot-wire probe should be moved into the free-stream once again and mean-flow velocities checked, as described previously. If the calibration has drifted by an unacceptable amount, then it is necessary to re-calibrate the probe and repeat the data sampling.

Normally, the sampled voltages are not processed immediately into velocities so that the test can be completed in a shorter time. This minimizes the errors from calibration drift which is caused predominantly by small temperature changes in the fluid throughout a test. The risk of wire breakage is also reduced significantly due to their reduced exposure time.

5.2.1 Sampling Rate and Length of Data Stream

The sampling of voltages E_U and E_V is done using program SAMPLE. For the current system, the lower sampling frequency has been arbitrarily set at 40 Hz but the maximum sampling frequency obtainable depends upon the number of channels being sampled. A sampling frequency of 25 kHz has been set as the upper limit when sampling 1 channel and this frequency is close to the maximum obtainable with the current system. There are time delays of 22 μs between the sampling of consecutive channels (see Section 5.2.2) and the maximum number of channels that can be used at other sampling rates is determined using the following relationship.

$$\text{Maximum Number of Channels} = \frac{\text{Sampling Period } (\mu\text{s}) - 4\ (\mu\text{s})}{22\ (\mu\text{s})} \tag{16}$$

The 4 μs factor is included in the relationship as a precautionary measure to keep the system operating satisfactorily within its limits. Thus, it is possible to sample 1 channel at up to 25 kHz, 2 channels at up to about 20.8 kHz, 3 channels at up to about 14.3 kHz and 4 channels at up to about 10.9 kHz. When using the sampling program, the user specifies the required sampling frequency and the program then indicates the maximum number of channels it is permissible to use for the chosen frequency. The user then indicates the actual number of channels which are to be sampled. A limitation of the sampling program is that the time interval between consecutive samples must correspond to an integer number of microseconds, which means that the program may not sample at exactly the specified frequency. The program determines the actual sampling frequency by first calculating the interval, in microseconds, between consecutive samples for the chosen frequency. For a chosen frequency of say 2222 Hz, the interval is given by $10^6/2222 = 450.045$ μs. This number is then truncated so that actual sampling is at intervals of 450 μs, which corresponds to a frequency of $1/(450 \times 10^{-6}) = 2222.222$ Hz. In any given run, the maximum number of data points which can be sampled for all channels combined is limited by the computer memory. The limit has been fixed at 252000 data points, which is close to the maximum obtainable with the current system, and the sampled data file occupies about 3.5 Mb of memory. Up to 32 channels can be used and the maximum number of data points for each channel is given by 252000/(number of channels chosen).

To measure broadband-turbulence quantities in a turbulent boundary layer, typically 30000 to 40000 samples need be taken at a sampling frequency of 200 Hz and the low-pass filters are set at 10 kHz. This filter setting is used since velocity fluctuations above 10 kHz in a turbulent boundary layer have negligible energy, as determined from spectral studies, and make an insignificant contribution to the magnitudes of broadband-turbulence terms. With this filter setting, frequencies of interest are passed but high-frequency noise above 10 kHz in the turbulence signal is attenuated. The number of samples is chosen from experience and must be sufficient to produce convergence of the broadband-turbulence terms after the data have been processed. It is acceptable to use the above sampling frequency and filter setting when taking broadband-turbulence measurements. A fluctuating turbulent signal does not have to be resolved into components of frequency, as when measuring spectra, and if the number of samples taken is sufficient to produce convergence, then broadband-turbulence quantities will not depend upon the sampling frequency used. A simple test was carried out in which a crossed-wire probe was placed in the tunnel free-stream and turbulence intensities, $\overline{u^2}^{0.5}/\overline{U}$ and $\overline{w^2}^{0.5}/\overline{U}$, were measured using different sampling rates. In each case 30000 samples were taken for both channels, and the sampling rates chosen were 200, 400, 800, 1600, 3200, 6400 and 12800 Hz. The filters were set at 10 kHz. Despite the large variation in sampling rates, the variation in measured intensities was small. For the 7 sampling rates used, the u-component intensities varied between 0.30% and 0.31% and the w-component intensities varied between 0.50% and 0.52%. If spectra are measured using a sampling rate of 200 Hz and a low-pass filter setting of 10 kHz, then aliasing will be a problem and the maximum frequency that can be resolved is 100 Hz, which is far too low for wind tunnel flows. When u, v or w spectra are measured (see Section 5.2.2 for the measurement of uv spectra), the sampling frequency used is typically 20 kHz and the low-pass filters are set at 10 kHz. The maximum frequency that can be resolved is 10 kHz, which is about the upper limit of frequencies of interest in turbulent boundary layers, as explained above. The sampled spectral data are processed using a fast-Fourier-transform routine, but details of this routine are not given here since spectral measurements are not the subject of this report.

5.2.2 Time Skew Between Channels

There is a time delay of 22 μs between the sampling of consecutive channels. Obviously broadband-turbulence terms comprised of products of only u or only v, such as $\overline{u^2}$, $\overline{v^2}$, and $\overline{u^3}$, or spectra for the u or the v component of the turbulence are not affected by the time delay, but it will have some effect on broadband-turbulence terms comprised of products of u and v, such as $\overline{uv}$, $\overline{u^2v}$ and $\overline{uv^2}$, and on uv spectra. The problem of a time delay was investigated at the University of Melbourne by Li (1989) for low-speed flows. Li studied errors in Reynolds stresses, $\overline{uv}$, measured using a system having a delay of 95 μs, and found that errors caused by the delay increased with sampling frequency. He showed that the delay caused an error of only about 0.5% in values of $\overline{uv}$ when the sampling was at 200 Hz (5000 μs between samples), but that meaningless results were obtained when the sampling was at 10 kHz (100 μs between samples). The time delay is disregarded when processing data at AMRL. However, the foregoing suggests that errors will be small for broadband-turbulence terms such as $\overline{uv}$, $\overline{u^2v}$ and $\overline{uv^2}$, obtained using a sampling frequency of up to 200 Hz, but uv spectra obtained using a sampling frequency of 20 kHz (50 μs between samples) will be meaningless and these must be measured by another method, such as a spectrum analyser.

5.3 Data Reduction

The reduction of the sampled voltages is done using program REDN. The program asks the user to specify the name of the file (such as FILE5.DAT) containing the voltages sampled. For each measurement location, there is a number, N, of pairs of sampled voltages, E_U and E_V. For each pair of voltages, program REDN computes velocities using equations 9 and 10 to give values of U_n and V_n, where the subscript n varies between 1 and N. The N values of U_n and V_n are averaged to give mean values denoted by $\overline{U}$ and $\overline{V}$ respectively.

The fluctuating velocities corresponding to a typical turbulent flow are shown diagrammatically in Figure 9. For each value of U_n, the velocity perturbation, u_n, about the mean value is given by

$$u_n = U_n - \overline{U} \tag{17}$$

and the corresponding value of v_n is given by

$$v_n = V_n - \overline{V} \tag{18}$$

Turbulence terms are computed by multiplying combinations of u_n and v_n terms, summing the products and taking the average. For example, $\overline{u^2v}$ is determined using

$$\overline{u^2v} = \frac{\sum_{n=1}^{N} (u_n u_n v_n)}{N} \tag{19}$$

The turbulence terms obtained using program REDN are $\overline{u^2}$, $\overline{u^3}$ and $\overline{u^4}$ for a single-wire probe. For a crossed-wire probe in uv mode (Figure 2), the turbulence terms obtained are Reynolds stresses, $\overline{u^2}$, $\overline{v^2}$ and $\overline{uv}$, triple products, $\overline{u^3}$, $\overline{v^3}$, $\overline{u^2v}$, and $\overline{uv^2}$, as well as fourth-degree terms, $\overline{u^4}$ and $\overline{v^4}$. If the measurements had been made with the probe in uw mode (Figure 2), then v is replaced by w in the above terms. The reduced data are written to a file, designated FILE6.DAT (typical name), for subsequent analysis.

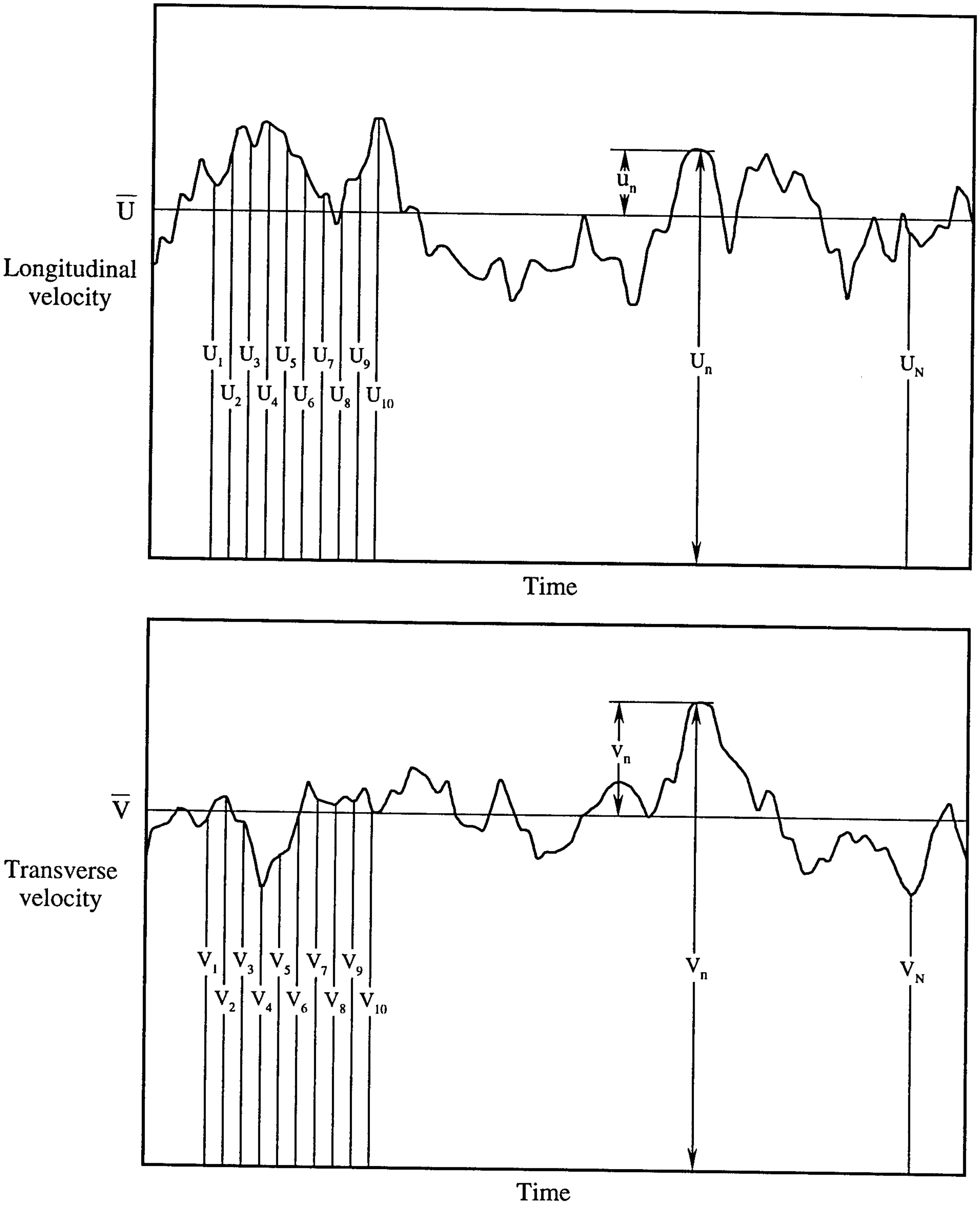

Figure 9 Diagrammatic representation of velocities for a typical turbulent flow.

5.4 Summary of Turbulence Measurement Technique

The technique for calibrating a hot-wire probe and for taking turbulence measurements is summarized in the following.

1. Set the thumb wheel switches on the console of the hot-wire anemometers (Figure 1) to correspond to the resistances of the filaments and leads and the chosen hot-wire resistance ratio (typically 2).
2. Set the frequency response of the hot-wire anemometers.
3. For a crossed-wire probe, oscillate the probe in both the longitudinal and the vertical directions and adjust the potentiometers on the matching box so that the system is "electronically matched". This is not applicable for a single-wire probe.
4. Adjust the potentiometers on the hot-wire anemometers so that the system is "bucked".
5. Adjust the gains on the hot-wire anemometers to maximize resolution and then ensure that the voltages measured by the data acquisition system will not exceed ±5.0 V when calibrating and taking turbulence measurements.
6. Mount the hot-wire probe on the calibrator sting and oscillate the sting. For a single-wire probe the oscillations are in the direction of the mean-flow and for a crossed-wire probe the oscillations are at 45° to the mean-flow direction.
7. Run program NUMPULSE to check that 120 voltage pulses per revolution of the slotted chopper disk are being received by the data acquisition system.
8. Dynamically calibrate the probe. Run program CAL to create two calibration files, one for the horizontal and one for the vertical component of oscillation. Create a file containing the mean-flow velocities used in the calibration. Run program CALCOEFF to determine the calibration coefficients.
9. At the completion of the calibration, do several spot checks to verify its accuracy. If unacceptable discrepancies are found in the measurements, then repeat Step 8.
10. Transfer the hot-wire probe from the calibrator sting to the measurement rig (probe traverse).
11. Do several spot checks to verify that the calibration is still valid. If the calibration has changed by an unacceptable amount, then repeat from Step 8.
12. Take turbulence measurements by running program SAMPLE.
13. Do several spot checks to verify that the calibration still holds. If the calibration has changed by an unacceptable amount, then repeat from Step 8.
14. Run program REDN and process the sampled voltages to obtain the required turbulence terms.

6. Concluding Remarks

An existing constant-temperature hot-wire anemometer system that used a hybrid analog/digital measurement technique for determining broadband-turbulence quantities has been modified so that turbulence quantities are now determined using a purely digital technique. The new digital system utilizes the improved speed and storage capacity of a desktop computer. Quantities that could be measured with the hybrid system were mean velocities, U, V and W, as well as Reynolds stresses, $\overline{u^2}$, $\overline{v^2}$, $\overline{w^2}$ and $\overline{uv}$. The new digital system can be used to measure all of these quantities and in addition it can also be used to measure triple products, $\overline{u^3}$, $\overline{v^3}$, $\overline{w^3}$, $\overline{u^2v}$ and $\overline{uv^2}$, and fourth-degree terms, $\overline{u^4}$, $\overline{v^4}$ and $\overline{w^4}$. These additional turbulence terms can be used to obtain turbulent-kinetic-energy and Reynolds-shear-stress balances, as well as skewness and flatness factors, which could not be determined previously. The new system is described in this report together with the computer programs and the procedure used to take turbulence measurements.

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19. ABSTRACT

An existing constant-temperature hot-wire anemometer system that enabled broadband-turbulence quantities to be determined using a hybrid analog/digital measurement technique has been modified so that turbulence quantities can now be determined using a purely digital technique. With the new system, higher-degree turbulence terms, such as $\overline{u^3}$, $\overline{v^3}$, $\overline{w^3}$, $\overline{u^2v}$, $\overline{uv^2}$, $\overline{u^4}$, $\overline{v^4}$ and $\overline{w^4}$, can now be obtained. These terms are used to calculate turbulent-kinetic-energy and Reynolds-shear-stress balances, and skewness and flatness factors, that could not be calculated previously. In this report the new equipment is described and the procedures and computer programs used to take measurements and process the data are detailed.