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Acquisition of Turbulence Data Using the DST Group Constant-Temperature Hot-Wire Anemometer System

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ABSTRACT

This report gives details of how to use the constant-temperature hot-wire-anemometer system at DST Group to measure mean velocities, broadband turbulence terms and spectra of velocity fluctuations in the low-speed wind tunnel at DST Group. The use of both single-wire and crossed-wire (2 wire) probes is described. Areas covered include a description of the anemometers and probes, soldering hot-wire filaments onto the prongs of a probe, etching the filaments, setting up of instrumentation, setting resistance ratios of hot wires, setting the frequency response of anemometers, calibration of hot wires, acquisition of data, reduction of data to obtain turbulence quantities, and use of associated software. The report is not highly technical and can be used as an operator's manual, so that experimentalists at DST Group that have some knowledge of hot-wire anemometry will be able to use the system to obtain reliable turbulence data. References are given that will enable personnel to gain an in-depth understanding of different technical aspects of the use of hot-wire anemometers, if required.

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Executive Summary

Turbulence plays a significant role in many fluid-flow studies, including testing of models of aircraft, ships and submarines in wind and water tunnels. Hot-wire anemometers and associated hot-wire probes are used to measure instantaneous fluctuating velocities in a turbulent flow field, thereby enabling turbulence quantities such as Reynolds stresses to be calculated.

It is important to have a sound understanding of the behaviour of turbulent flows over vehicles. For example, turbulent flow in boundary layers over vehicles increases the drag on the vehicles, compared with laminar flow, adding to fuel costs to propel them. Turbulent flow in boundary layers on submarines is a source of unwanted noise, making it more difficult for sonars within a submarine to pick up external noise signals through a noisy turbulent boundary layer.

Although Pitot-static probes and particle-image-velocimetry (PIV) systems are often used in research establishments to measure flow parameters in tunnels, hot-wire-anemometer systems are the preferred measurement option in some flow situations. For example, Pitot-static probes are unsuitable for measuring fluctuating velocities in a turbulent flow. PIV systems are not particularly suitable for measuring turbulence intensities and they are unsuitable for measuring spectra, although they may be the preferred option for measuring mean velocities in a wake or reversed flow. It is important for DST Group to have available a high-quality hot-wire-anemometer system and to be knowledgeable in its use. Such a system complements other measurement techniques.

A constant-temperature hot-wire-anemometer system has recently been commissioned at DST Group. This report gives details of how to use the anemometer system to measure mean velocities, broadband-turbulence terms and spectra of velocity fluctuations in the low-speed wind tunnel at DST Group. The use of both single-wire and crossed-wire (2 wires) probes is described. Areas covered include a description of the anemometers and probes, soldering hot wires onto the prongs of a probe, etching the wires, setting up of instrumentation, calibration of hot wires, reduction of fluctuating voltages in a turbulent flow to obtain turbulence quantities, and use of associated software. For a crossed-wire probe, different methods of calibrating the hot wires and reducing data have been compared for a typical test turbulent flow in the low-speed wind tunnel at DST Group. The report can be used by experimental staff with limited knowledge of the procedures involved in carrying out experiments with hot wires, enabling them to acquire meaningful turbulence data.

Author

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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 the Aeronautical Research Laboratories (now called the Defence Science and Technology Group) in 1970 and has worked on a wide range of research projects, including the prediction of the performance of gas-turbine engines 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. Since this time, he has undertaken research investigations in the low-speed wind tunnel and the water tunnel. He has extended the testing capabilities of the water tunnel, including developing a two-component strain-gauge-balance load-measurement system for the tunnel and developing a dynamic-testing capability for the tunnel, enabling aerodynamic derivatives to be measured on models. Recent work has been concerned with studying the flow around submarine models in the low-speed wind tunnel at DST Group.

Contents

Notation

a_n, b_n, c_n, d_n	Coefficients used in calibration laws, n = 0, 1, 2, 3...
E_A, E_B	Anemometer output voltages, associated with effective angles of an inclined hot wire, (V).
E_1, E_2	Anemometer output voltages from anemometers 1 and 2 respectively, (V).
k	Coefficient that accounts for the cooling effect of the velocity component along a hot wire. k^2 has a value between about 0.0 and 0.04.
n	Index used in King's calibration law (n typically varies between 0.45 and 0.5).
T	Time interval, (s).
t	Time, (s).
U, V, W	Instantaneous velocities in the x_T, y_T and z_T directions respectively, (m·s^{-1}). $U = \overline{U} + u$, $V = \overline{V} + v$, $W = \overline{W} + w$.
u, v, w	Instantaneous velocity deviations from the mean value in the x_T, y_T and z_T directions respectively, (m·s^{-1}).
U_A, U_B	Flow velocities associated with effective angles of an inclined hot wire, (m·s^{-1}).
U_{cal}	Calibration velocity, (m·s^{-1}).
U_{eff}	Effective velocity of the flow over a hot wire, (m·s^{-1}).
$\overline{U}$, $\overline{V}$, $\overline{W}$	Mean velocities in the x_T, y_T and z_T directions respectively, (m·s^{-1}).
$\overline{u^2}$, $\overline{v^2}$, $\overline{w^2}$	Turbulence intensities.
$\overline{uv}$, $\overline{uw}$	Reynolds stresses.
x_P, y_P, z_P	Probe body coordinate system (right-handed). For a single-wire probe, the x_P axis is positive in the direction of the probe longitudinal axis, looking from the rear of a probe to the wire, the y_P axis is perpendicular to the longitudinal axis of the wire and the z_P axis is parallel to the longitudinal axis of the wire (see Figure 8). For a X-wire probe, the x_P axis is positive in the direction of the probe longitudinal axis, looking from the rear of a probe to the wires, the y_P axis is in a plane parallel to the planes containing prongs and a wire and the z_P axis is perpendicular to the planes containing prongs and a wire (see Figure 8).
x_T, y_T, z_T	Tunnel coordinate system (right-handed). The x_T axis is horizontal and positive in the downstream direction, the y_T axis is horizontal and is positive to port, and the z_T axis is positive vertically downwards (see Figure 8).
z	Distance vertically downwards from origin of coordinate system used for turbulence measurements (see Figure 27).

Greek Letters

θ_{eff}	Effective angle of the flow over a hot wire, (degree).
θ_{probe}	Pitch angle of hot-wire probe. $\theta_{probe} = 0°$ when the longitudinal axis of a probe is aligned in the x_T direction, (degree). θ_{probe} is positive when nose of probe is pitched up.

Subscripts

1, 2	Subscripts denote that variables are associated with wires 1 and 2 respectively on a hot-wire probe.
–	Overbars denote mean values of quantities.

Acronyms

DST Group	Defence Science and Technology Group
LSWT	Low-speed wind tunnel.

1. Introduction

The flow over models of aircraft, ships and submarines has been studied extensively in wind tunnels by researchers at the Defence Science and Technology Group (DST Group). Hot-wire-anemometer systems have routinely been used to measure mean velocities, broadband-turbulence quantities (such as intensities and Reynolds stresses), as well as spectra of velocity fluctuations. Pitot-static probes are unsuitable for measuring turbulence quantities and spectra, due to experimental difficulties associated with measuring rapidly-changing static and total pressures, used when calculating instantaneous velocities, near the nose of a probe. Although particle-image-velocimetry (PIV) systems are often used to measure spatial variations of flow parameters in tunnels, they are not particularly suitable for point measurements of turbulence quantities and spectra. PIV systems may, however, be better suited to measuring mean velocities in a wake or reversed flow. Hot wires are the preferred option for measuring turbulence terms and spectra, and it is important for DST Group to have available a high-quality hot-wire-anemometer system and to be knowledgeable in its use.

Recently, four new constant-temperature hot-wire anemometers have been built at DST Group, that are based on the design originally developed by Watmuff (1994). This report gives details of how to use the anemometers and the associated hardware and software to acquire turbulence data in the low-speed wind tunnel (LSWT) at DST Group. Areas covered include a description of the anemometers, soldering hot-wire filaments onto the prongs of a probe, etching the filaments, preliminary setting up of instrumentation, calibration of hot wires, acquisition of data, reduction of data to obtain turbulence quantities, and use of associated software. The report can be used as a guide by experimental staff at DST Group that have limited knowledge on the procedures involved in carrying out experiments with hot wires, enabling them to acquire meaningful turbulence data. References are given that will enable personnel to gain an in-depth understanding of different technical aspects of the use of hot-wire anemometers, if required.

2. Velocities in a Turbulent Flow

Turbulent flows are commonly encountered in wind-tunnel testing, including in boundary layers, separated flows, wakes of flows over vehicles and, to a lesser extent, in the free-stream flow.

Instantaneous velocities, U, in the longitudinal direction at a fixed location in a turbulent flow are shown diagrammatically as a time history in Figure 1. Values of U can be averaged to give a mean value, $\overline{U}$, as shown. Instantaneous velocity deviations from the mean value, u, which can be positive or negative, can be determined using

$$U = \overline{U} + u \tag{1}$$

and similarly for instantaneous velocities V and W, in the lateral horizontal direction and the lateral vertical direction respectively (see coordinate systems shown in Figure 8), i.e.

$$V = \overline{V} + v \tag{2}$$

and

$$W = \overline{W} + w \tag{3}$$

Turbulence terms such as $\overline{u^2}$, $\overline{v^2}$, $\overline{w^2}$, $\overline{uv}$ and $\overline{uw}$ can then be calculated using the instantaneous velocity deviations u, v and w associated with a given time interval, T. For example, $\overline{u^2}$ can be determined using

$$\overline{u^2} = \frac{1}{T}\int_0^T u^2 dt \tag{4}$$

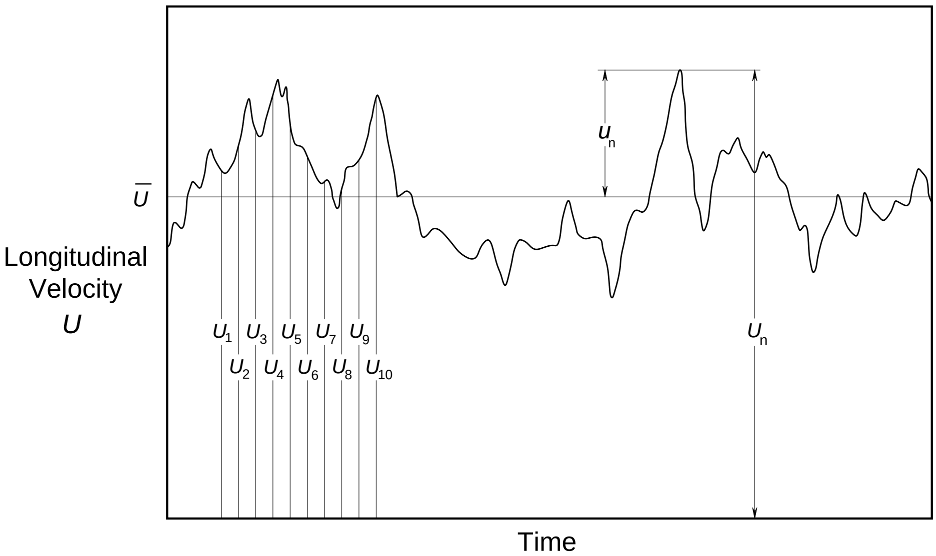

Figure 1 Time history of longitudinal velocities in a turbulent flow.

3. Hot-Wire Anemometers and Probes

Hot-wire anemometers are widely used to measure instantaneous velocities in a turbulent flow field. There are two modes of operation of hot-wire anemometers, (1) constant wire current and (2) constant wire temperature. Only constant-temperature devices are considered in this report.

3.1 Principle of Operation of a Constant-Temperature Anemometer

The operation of a constant-temperature anemometer will be described for a single-wire probe, but is also applicable to a crossed-wire probe (crossed-wire is often abbreviated to X-wire). A small probe (see Section 3.3.2) containing a hot-wire filament is placed in a turbulent flow. The wire and the associated leads form one arm of a Wheatstone bridge. The wire, which is heated by passing an electric current through it, has a high frequency response and is sensitive to rapidly changing fluctuations in velocity. As the velocity changes, the heat transfer from the wire varies which causes the temperature and resistance of the wire to also vary. The wire is connected to a feedback circuit which attempts to keep the Wheatstone bridge balanced, so that the wire 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 anemometer gives an output voltage that can be related to the feedback current required to maintain a constant wire resistance. Hence the output voltage is a function of the flow velocity. The functional relationship between voltage and velocity is determined by calibrating the wire. When the wire is placed in a turbulent flow, instantaneous anemometer output voltages are sampled as specified by a user and instantaneous velocities are determined using the calibration equations. Mean velocities and turbulence terms can then be calculated from the instantaneous velocities. Different components of velocity can be measured simultaneously by fitting more than one hot-wire filament to a probe. Details of the operation of constant-temperature hot-wire anemometers are given by Perry (1982), Lomas (1986) and Bruun (1995).

3.2 Anemometers Used at DST Group

Details of the front panel of the anemometers used at DST Group are given in Figure 2. One anemometer is needed for measurements with a normal-wire probe and two units are needed for measurements with a X-wire probe. Details of how to set up and operate the anemometers is given in the appropriate sections below.

3.3 Hot-Wire Probes

3.3.1 Wires Used on Probes

The sensing filaments or cores of hot-wires are generally comprised of platinum-plated tungsten, platinum or platinum-rhodium alloys. Cores are typically 5 μm in diameter, although larger and smaller diameters are available. Tungsten wire has a very ragged surface which can become contaminated by particles in the flow and the surface may oxidize if resistance ratios (see Section 3.4) in excess of about 1.6 are used (Perry, 1982). Wollaston wire has a cylindrical platinum core 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. Platinum wire has a smoother surface and oxidation is not a problem compared with tungsten wire. The calibration coefficients of uncoated 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 (see Section 3.4) for about 24 hours, before resetting it to the normal operating value of 2.0 (Perry, 1982). Tungsten wire is stronger than Wollaston wire and it is better able to survive impacts from particles in the flow. The wires on new DANTEC (formerly known as DISA) probes have a platinum-plated tungsten core with a copper and gold coating at the ends of the wire, which are attached to the prongs, so that the sensing filaments incorporate advantages of both tungsten and platinum, i.e. a smooth surface, no oxidation problems and high strength. However, the calibration coefficients for these wires can still drift more than the calibration coefficients for Wollaston wires as the temperature of the ambient air changes throughout the course of an experiment. For this reason, the platinum-plated tungsten wires on DANTEC probes are often replaced with Wollaston wires at DST Group (see Section 3.3.4).

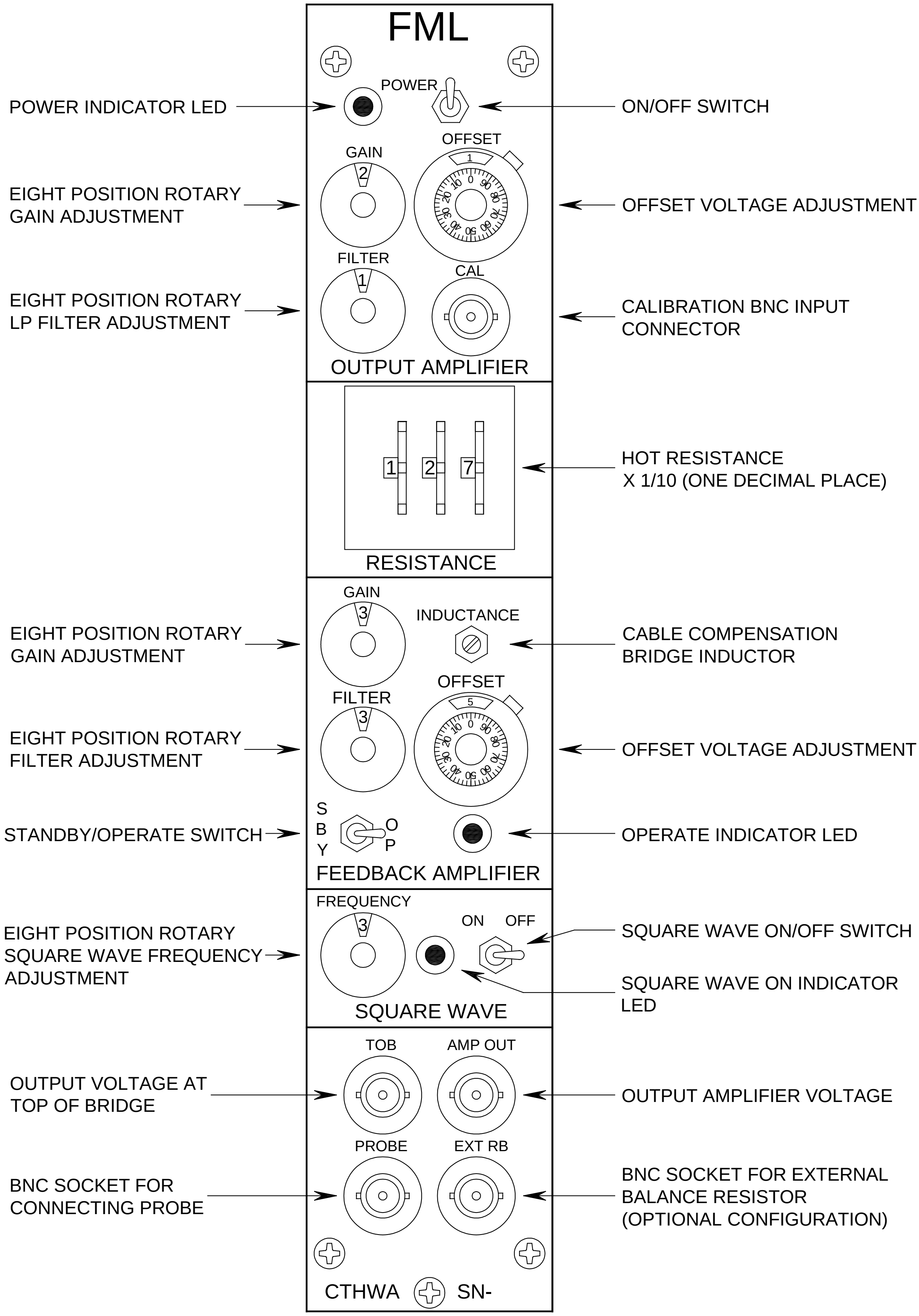

Figure 2 Front panel of a hot-wire anemometer at DST Group, based on Watmuff's (1994) design.

3.3.2 Single-Wire Probes

DANTEC standard-size normal-wire probes, Model 55P01 (general-purpose probe), and Model 55P05 (boundary-layer probe), with the platinum-plated tungsten wires replaced with Wollaston wires, are shown in Figures 3a and 3b respectively. For these probes, the sensor is located at right angles to the probe axis. Corresponding miniature normal-wire probes used at DST Group, Models 55P11 and 55P15, are not shown. Normal-wire probes are used to measure instantaneous longitudinal velocities as well as associated turbulence terms.

For a boundary-layer probe, it is preferable to attach a wire to the lower side of the prongs, as shown in Figure 3b, so that the wire is adjacent to a surface when using the probe to measure a velocity profile. If the wire is positioned on the opposite side of the prongs, then it is not possible to measure velocities close to the wall, where the velocity gradient is large.

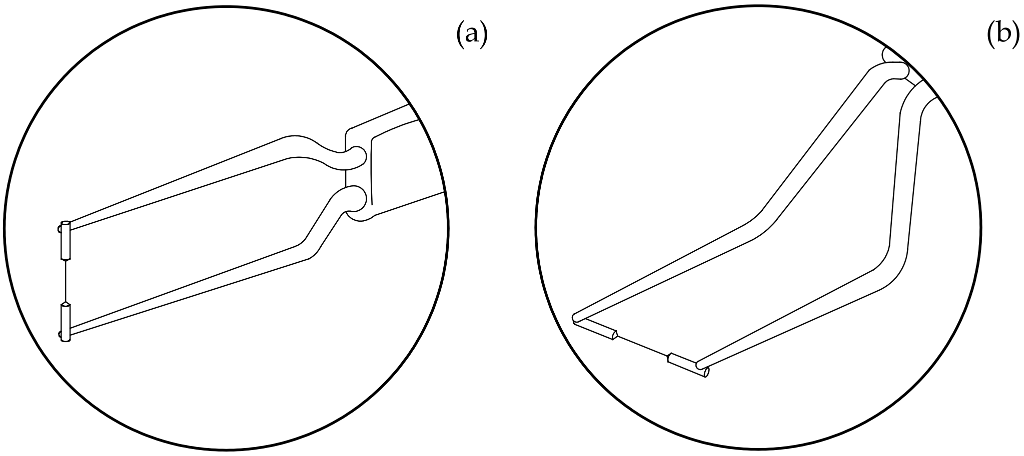

Figure 3 DANTEC standard-size normal-wire probes, (a) Model 55P01, general-purpose probe, (b) Model 55P05, boundary-layer probe. Platinum-plated tungsten wires have been replaced with Wollaston wires.

3.3.3 X-wire Probes

A DANTEC standard-size X-wire probe, Model 55P51, is shown in Figure 4. For this probe the sensors are located at ±45° to the probe longitudinal axis and at right angles to each other. A corresponding miniature wire probe used at DST Group, Model 55P61, is not shown. X-wire probes are used to measure instantaneous longitudinal and lateral velocities as well as associated turbulence terms.

For a X-wire probe, it is preferable to attach wires to the inside of the prongs, as shown in Figure 4, so that the wires are located as close as possible to each other for the given prong arrangement. Ideally, the mid points of both wires should be located at the same location, so that they are both measuring velocities at the same point in the flow, but of course this is not possible. A practical consideration is that if the wires are too close to each other, then the heat generated by each of the wires may affect the reading of the other wire. Tests by Erm at DST Group (unpublished) have shown that measured turbulence intensities at a given location in the flow are noticeably different depending on whether the wires are soldered onto the inside or the outside of the prongs of a X-wire probe. The effects of spatial resolution could be a contributing factor to such behaviour.

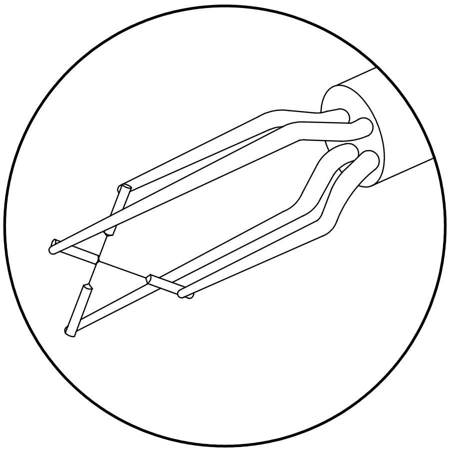

Figure 4 DANTEC standard-size X-wire probe, Model 55P51. Platinum-plated tungsten wires have been replaced with Wollaston wires.

3.3.4 Attaching Wires to the Prongs of a Probe and Etching of Wires

For measurements in the transonic wind tunnel at DST Group, DANTEC probes are generally used as purchased, i.e. the platinum-plated tungsten wires on the probes are not removed. The main reason for this is the high strength of the wires. For measurements in the LSWT at DST Group, the wires on new DANTEC probes are often removed and replaced with Wollaston wires, which are soldered onto the prongs and etched using the equipment shown in Figure 5. Before soldering a wire onto the prongs, it is first 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 (Perry, 1982). The wire is supported using a wire clamping device (not shown in Figure 5) and positioned against the prongs of a probe supported by an *xyz* traverse. A very small amount of phosphoric acid can be 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 (standard-size probe) and its resistance (5 µm core diameter) prior to etching should be about 0.3 Ω (after allowing for the resistance of connecting leads, which should be measured before attaching the wire). A much higher resistance of the wire and leads usually indicates a poorly soldered joint. Using the *xyz* traverse, the unetched wire is then positioned in the acid bubble formed at the outlet of the hypodermic tube, as shown in Figure 6, and the silver coating is etched away electrolytically using dilute nitric acid of 15% concentration to expose the platinum core. The voltage output from the variable DC power supply, which forms part of the electrolytic circuit, can be adjusted to obtain the required etch rate of the wire, as observed under a microscope. For safety reasons the etching must be done in a fume cupboard. For a wire of 5 µm core diameter, the maximum 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).

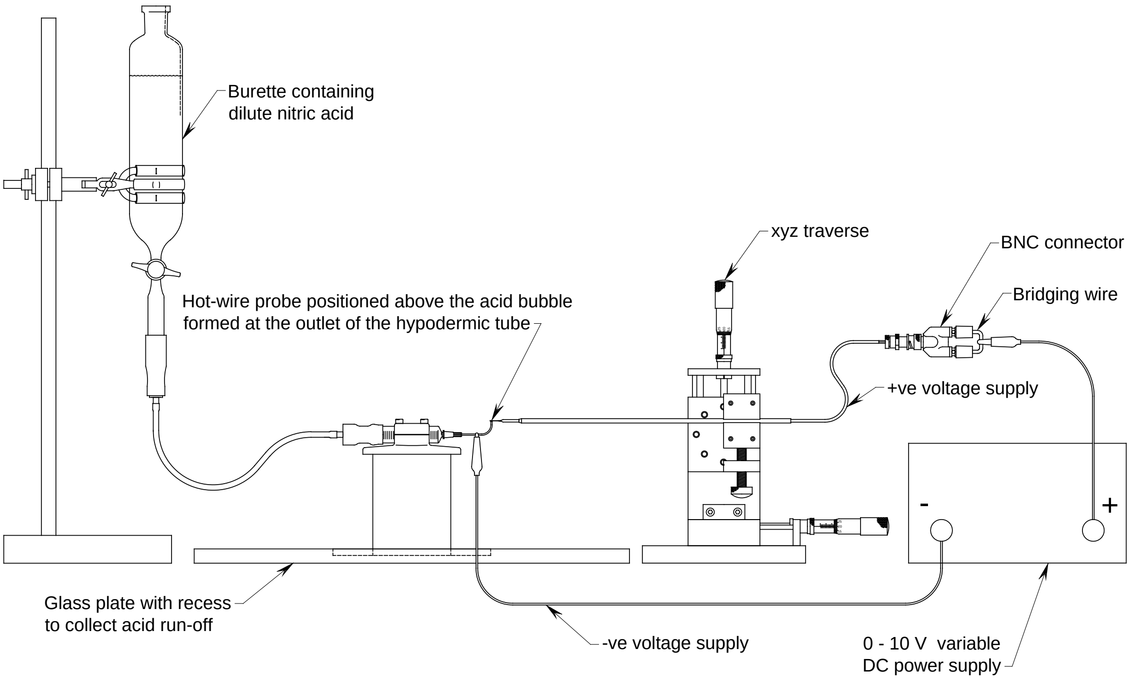

Figure.5 Equipment used to etch Wollaston-wire filaments.

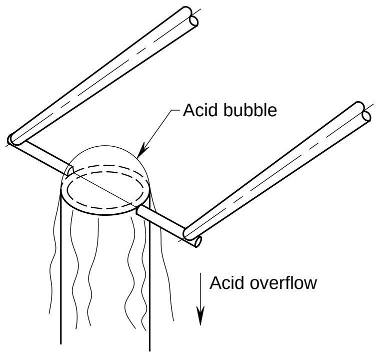

Figure 6 Etching a hot-wire filament in an acid bubble.

3.4 Setting of Wire Operating Resistance

The operating resistance of a wire is set with the wire disconnected from an anemometer. Depending on the type of wire used, the operating resistance of the wire should be 1.6 to 2.2 times the resistance of the wire when it is at the temperature of the fluid in which measurements are being taken – see Perry (1982). The number actually used when testing is termed the resistance ratio. The increased resistance of the wire when it is operating causes an increase in wire temperature, which improves wire sensitivity. At lower resistance ratios, measurements are more susceptible to variations in the tunnel ambient operating temperature than they are at higher resistance ratios. It is therefore desirable to increase the resistance ratio if testing in a tunnel in which the ambient temperature varies markedly. A wire can burn out if the temperature becomes too high. A resistance ratio of 2 is generally used for Wollaston wire. The resistance of the wire and the leads combined, plus the resistance of the leads by themselves, both have to be measured. If the wire 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 (wire plus leads) when the wire is operating will be (6 x 2) + 0.7, i.e. 12.7 Ω. To balance the Wheatstone bridge, it is necessary to adjust balance resistors in another arm of the bridge and this is done by adjusting the thumb-wheel switches on the RESISTANCE panel of the anemometer, shown in Figure 2. 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. In general, the setting of the thumb-wheel resistance, RTW (Ω), is given by RTW = [(RCW×RR)+RL]x10, where RCW is the resistance of a cold probe wire at ambient temperature in still air, RR is the resistance ratio, RL is the resistance of the two leads combined (including probe prongs) between the wire and a hot-wire anemometer.

It is important that the resistance ratio of the wire is not changed, i.e. the thumb wheel switches are not adjusted, when the hot wire is operating, since adjusting the switches can create an open circuit on the bridge, resulting in an infinite resistance ratio, leading to instant wire burnout.

After the operating resistance of a wire has been set, then the wire can be connected to an anemometer via the terminal labelled PROBE. Before connecting the wire, it is advisable to first switch on power to the anemometer using the On/Off Switch, so that the Power Indicator LED glows, and to set the Standby/Operate Switch to SBY on the FEEDBACK AMPLIFIER panel. The SBY position should always be used whenever a wire is connected or disconnected from an anemometer to prevent wire burn out.

3.5 Setting of 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 885 Hz (approximately), corresponding to a setting of 3 on the FREQUENCY dial on the SQUARE WAVE panel of the anemometer (see Figure 2). The square wave is applied to the anemometer from an internal source. The anemometer output voltage at the terminal labelled AMP OUT is observed on an oscilloscope and the offset voltage and the cable compensation bridge inductance are both adjusted using the controls labelled OFFSET and INDUCTANCE respectively, in the FEEDBACK AMPLIFIER panel, until the frequency response is optimally damped. For a DANTEC probe incorporating an original platinum-plated tungsten filament, the frequency response is as shown in Figure 7. For such a probe, an OFFSET reading of about 5 was found to be satisfactory and optimum frequency response was found to occur when controls labelled GAIN and FILTER in the FEEDBACK AMPLIFIER panel were set to 3 and 3 respectively. Using the above settings, the frequency response of the anemometer can be seen to be about 6.0 kHz. For a Wollaston wire, it may be necessary to use different anemometer settings to obtain an optimum frequency response, which would most likely be different from that shown in Figure 7. Researchers often aim to adjust their anemometers so that the frequency response is about 20 kHz, but such a response could not be achieved when DANTEC probes with platinum-plated tungsten filaments were connected to the anemometers at DST Group.

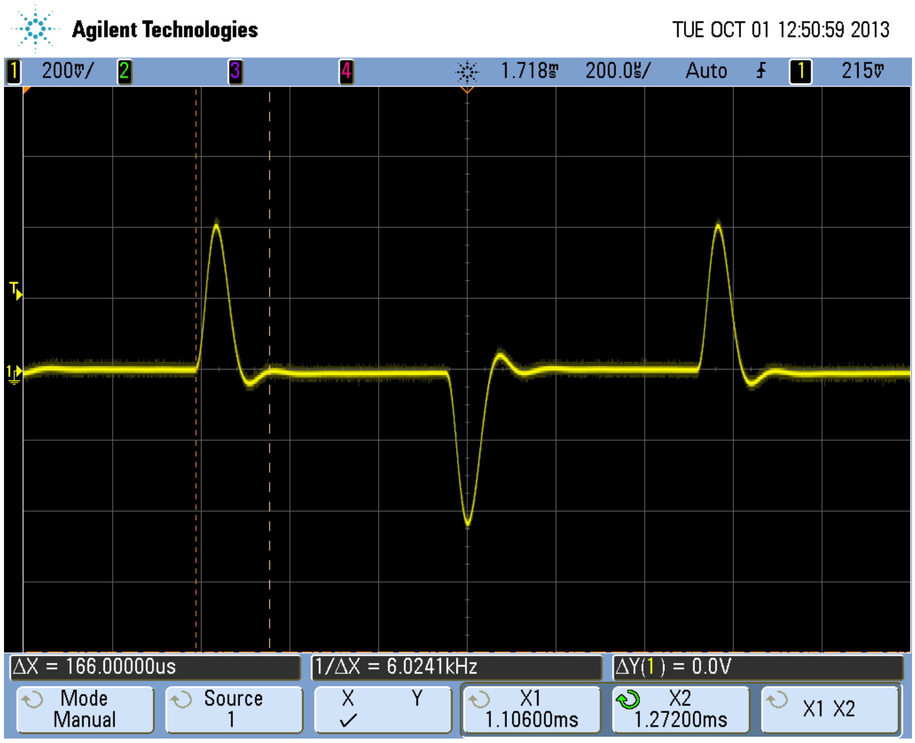

Figure 7 Waveform obtained for anemometer output voltage when setting the frequency response, for a DANTEC probe incorporating an original platinum-plated tungsten filament.

3.6 Setting the Filters, Offset Voltage and Gain

The filter dial on the FEEDBACK AMPLIFIER panel is set to 3, corresponding to a frequency of 56 kHz, and the filter dial on the OUTPUT AMPLIFIER panel is set to 1, corresponding to a frequency of 13.6 kHz (both frequencies are as given by Watmuff, 1994). To adjust the offset voltage of an anemometer, a hot-wire probe is first placed in the tunnel free-stream and the velocity is set close to the midpoint of the two extremes of velocity likely to be encountered during subsequent measurements. The OFFSET potentiometer on the OUTPUT AMPLIFIER panel, shown in Figure 2, is then adjusted until the anemometer output voltage at the terminal labelled AMP OUT is approximately zero. This process is termed "bucking" and removes unwanted DC voltages from the output signal. To improve resolution of the output voltage, the output voltage is then amplified by adjusting the setting on the GAIN dial on the OUTPUT AMPLIFIER panel. Checks must be made to ensure that voltages sampled by the data-acquisition system during subsequent calibration and measurement of turbulence terms will not exceed ±10.0 V, the limits imposed by the data-acquisition system. The checks are done by subjecting the wire to a range of velocities subsequently expected and noting the variations in the output voltage. It may be necessary to adjust the setting on the GAIN dial and repeat the checking process until output voltages are within acceptable limits.

3.7 Coordinate Systems for LSWT and Hot-Wire Probes

The right-handed coordinate systems for the LSWT at DST Group, x_T, y_T, z_T , and for the single and X-wire probes, x_P, y_P, z_P, are shown in Figure 8.

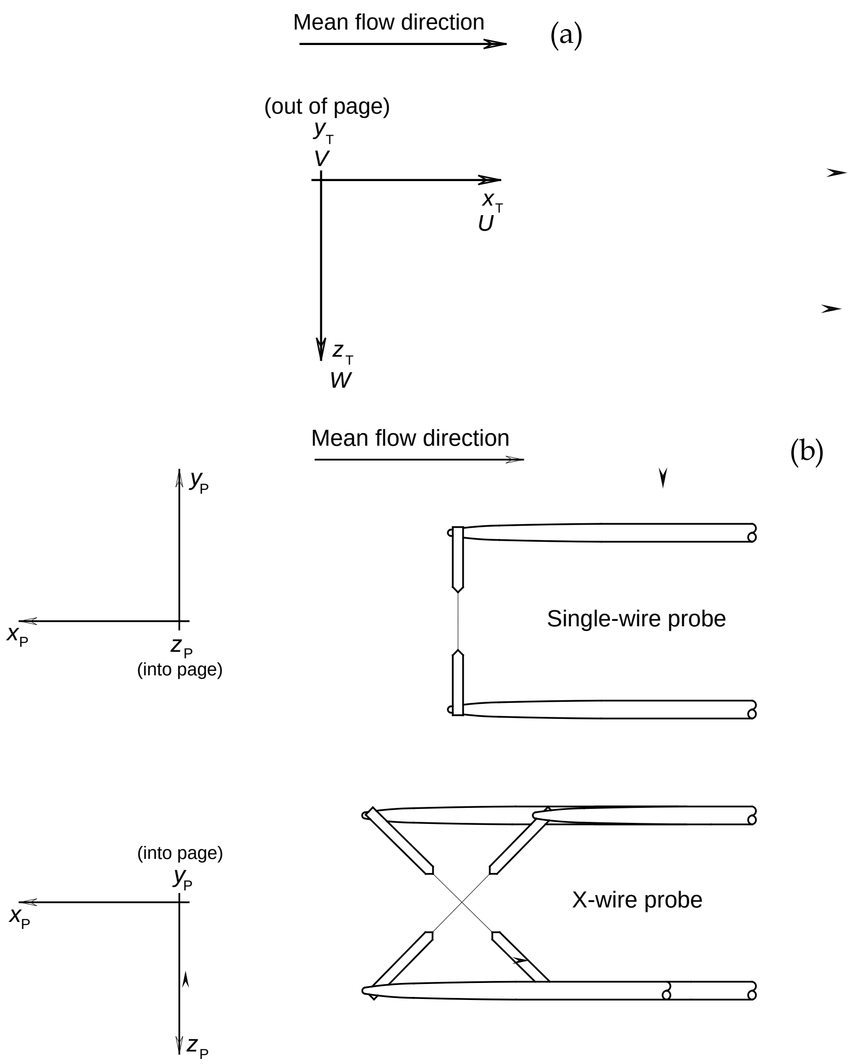

Figure 8   Coordinate systems for (a) the tunnel and (b) the single- and X-wire probes.

4. Ancillary Equipment Used for Hot-Wire Measurements

4.1 Desktop Computer

A Hewlett-Packard® HP Z400 workstation was used for the experiments. The computer incorporated an Intel® Xeon Central Processing Unit, specification W3520, operating at 2.666 GHz (4 Cores, 8 threads with hyperthreading). The hard disk drive had a capacity of 500 GB, and there was 3 GB of RAM.

4.2 Data-Acquisition System

Data were acquired using a Microstar Labs® data acquisition system. The system is controlled by a board, designated DAP4000a/212 Microstar Labs® Data Acquisition

Processor, installed in the host PC. The Data Acquisition Processor is a computer, separate from the PC, with its own central processing unit and operating system. This board can be used to provide analog and digital input/output functions, but for the current tests the system is configured so that all analog input and output functions are controlled by expansion boards, designated MSXB080-01-E3E8-B and MSXB075-01-E3E-B respectively. The expansion boards are installed remote from the PC. The Data Acquisition Processor communicates with the expansion boards using digital input/output.

The current setup incorporates 2 MSXB080-01-E3E8-B input boards. Each board has 8 isolated 16-bit analog input channels for sampling voltages. The maximum sampling rate is 333 k samples per second for each channel, i.e. 2 M samples per second· total. The input voltage range is ±10 V, and input gains can be selected to be 1, 2, 5, or 10. There is 1 MSXB075-01-E3E-B output board. The board has 4 isolated 16-bit analog output channels. The output voltage range is ±5 V or ±10 V. The analog output channels were not required for the current tests.

For the MSXB080-01-E3E8-B input boards, there is simultaneous sampling for each of the channels, i.e. there is no time lag between sampling voltages. This is a necessary requirement when computing turbulence terms which depend on voltages sampled from 2 different channels, such as Reynolds stresses, $\overline{uv}$. If there is a significant time delay between sampling different channels, then errors will occur in computed turbulence terms since measured voltages will be associated with different regions of turbulent flow.

4.3 Electronic Manometer

An electronic manometer is used to measure pressures from a Pitot-static probe, enabling tunnel velocities to be calculated when calibrating a hot wire or when using the wire to take turbulence measurements. Suitable manometers available for use in the LSWT at DST Group include:
(1) Baratron® model number 220CD-00100A2B, having a range of 100 torr = 100/760 atmosphere = 13332.2 Pa (≈ 100 mm Hg), and an output voltage range of 0-10 V DC. The model number of the corresponding power supply/readout unit is PDR-C-1C.
(2) Baratron® model number 120AD-00100RDB, having a range of 100 torr = 13332.2 Pa and an output voltage range of 0-10 V DC. The model number of the corresponding power supply/readout unit is PR4000B.

4.4 Overhead Traversing Mechanism

An overhead traversing mechanism, shown in Figure 9, is mounted on guide rails above the test section of the LSWT. The main body of the mechanism, which is outside the test section, incorporates a PC-controlled linear actuator that moves in the vertical direction. A vertical sting, attached to the actuator, protrudes into the test section. A rotatable sting is attached to the lower end of the vertical sting and a hot-wire probe is attached to the lower end of the rotatable sting. This arrangement is used to move a probe to specified vertical locations. A PC-controlled stepper motor is located at the upper end of the rotatable sting and the motor is used to pitch X-wire probes to specified angles when calibrating X wires.

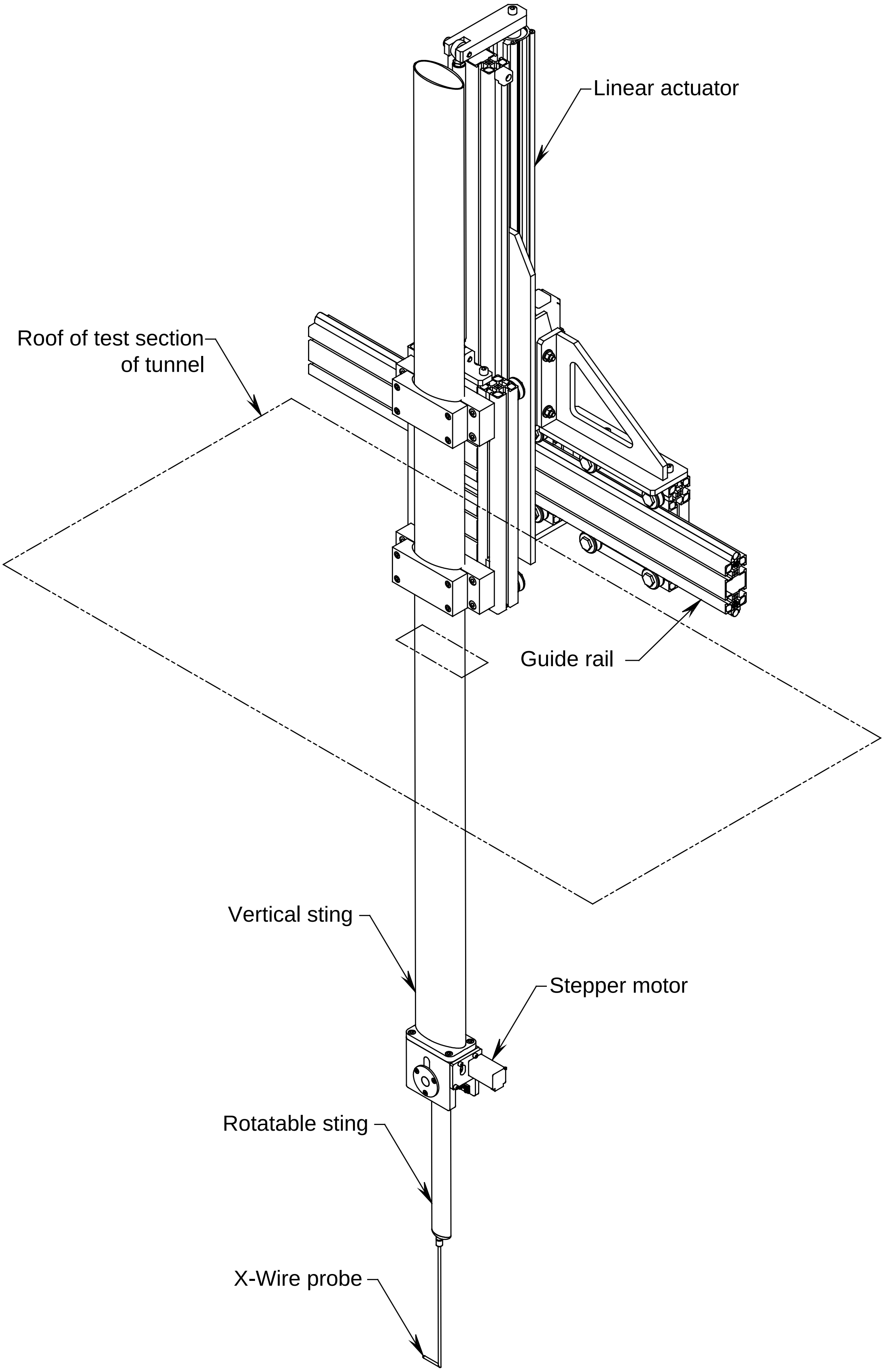

Figure 9 Overhead traversing mechanism used for tests in LSWT at DST Group.

5. Setup of Anemometers and Ancillary Equipment

The setup of the anemometers and the ancillary equipment used when calibrating hot wires and taking turbulence measurements is shown in Figure 10. Anemometer output voltages are denoted by E_1 and E_2. A graphical-user interface on the PC is used to control all tests. The interface is used to set the probe pitch angles and sampling parameters during calibration, to set the probe vertical positions and sampling parameters during acquisition of turbulence measurements, and to enter file names associated with a given test.

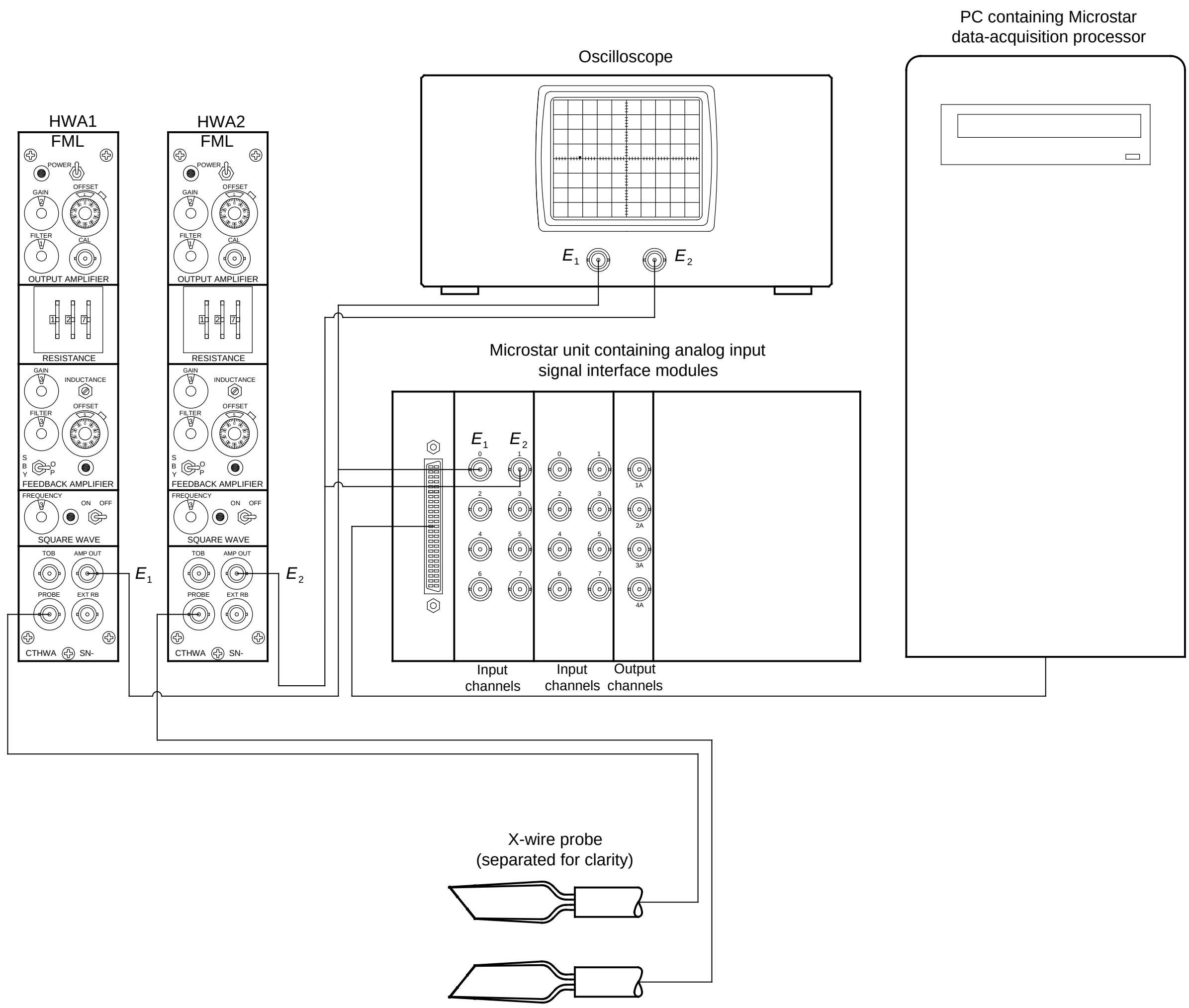

Figure 10 Setup of anemometers and ancillary equipment, used when calibrating X wires and when taking turbulence measurements.

6. Calibration of Hot Wires

Prior to using single- and X-wire probes to measure turbulence quantities, they must of course first be calibrated to determine how (1) U_{cal} is related to E_1 for a single-wire probe and (2) how U_{cal} and θ_{probe} are related to E_1 and E_2 for a X-wire probe. U_{cal} is the calibration velocity in the horizontal or free-stream direction, θ_{probe} is the pitch angle of the X-wire probe, and E_1 and E_2 are anemometer output voltages from anemometers 1 and 2 respectively.

Calibrations can drift throughout the course of an experiment due to factors such as changes in the air temperature, oxidation of the hot wire(s), and build up of debris on the wire(s). To allow for the possible drifting of a calibration during a test, calibrations can be carried out both before and after taking measurements in a turbulent flow. Turbulence quantities can be computed using both calibrations using some type of interpolation scheme.

Checks must be made to ensure that anemometer output voltages, E_1 and E_2, sampled by the Microstar Labs® data acquisition system (see Section 4.2) during calibration and measurement of turbulence terms, will not exceed ±10.0 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 expected during subsequent tests and noting the variations in E_1 and E_2. It may be necessary to adjust gains on the anemometers so that voltages remain within acceptable limits.

6.1 Calibration of a Single-Wire Probe

The calibration of a single-wire probe is relatively straightforward. The probe is positioned in the free-stream of a flow so that its x_P axis points directly into the oncoming flow and its y_P axis is horizontal, as shown in Figure 8. A Pitot-static probe is positioned in the flow close to the hot-wire probe, enabling calibration velocities, U_{cal}, to be measured. The filter dial on the OUTPUT AMPLIFIER panel is set to 1, corresponding to a frequency of 13.6 kHz. Anemometer output voltages, E_1, are measured for typically 8 calibration velocities, which cover the range of those expected in subsequent tests. Calibration data are acquired with the hot-wire probe stationary. For each calibration point, U_{cal} and E_1 are sampled 15000 times at a sampling frequency of 1000 Hz (typical values), enabling mean values of U_{cal} and E_1 to be calculated. The number of samples and sampling frequency to use will depend on the particular experiment carried out. Checks should be made for convergence of reduced data. Calibration relationships are determined by curve fitting plotted calibration data.

Calibration data are often plotted using axes E_1^2 *vs* U_{cal}^n and curve fitted using a relationship of the form (King's law)

$$E_1^2 = a_0 + a_1 U_{cal}^n \tag{5}$$

where the *a* coefficients are constant for a given fluid, hot wire, electronic circuit and hot-wire resistance ratio. The index, n, lies within the approximate range 0.45 to 0.5. A major shortcoming of this method is that the calibration depends on the value of n chosen.

Data can also be plotted using axes U_{cal} *vs* E_1 and curve fitted using a polynomial such as

$$U_{\mathrm{cal}} = b_0 + b_1 E_1 + b_2 E_1^2 + b_3 E_1^3 \tag{6}$$

where the *b* coefficients are constant.

This latter approach is generally used at DST Group when calibrating single-wire probes. Figure 11 shows data for a single-wire probe plotted and curve fitted using axes U_{cal} *vs* E_1 for a typical test calibration carried out in the LSWT.

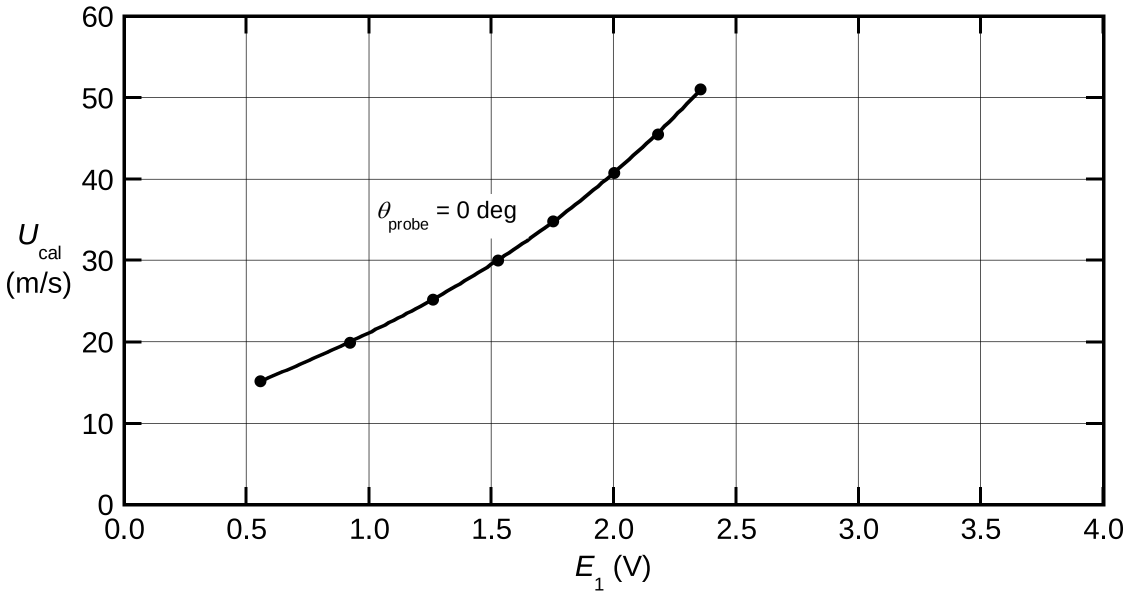

Figure 11 U_{cal} *vs* E_1 *for typical calibration data at DST Group for a single-wire probe.*

6.2 Calibration of a X-Wire Probe

Different researchers have used different techniques to calibrate X-wire probes and there is no universally-recognised technique to use. Both full-calibration methods and a simplified calibration method are described in the following.

6.2.1 Full Calibration of a X-Wire Probe

Full-calibration methods involve calibrating a X-wire probe for a range of calibration velocities, U_{cal}, for a range of probe pitch angles, θ_{probe}, at each of the velocities. The probe is positioned in the free-stream of a flow so that its y_{P} axis is horizontal, as shown in Figure 8. A Pitot-static probe is positioned in the flow close to the hot-wire probe, enabling values of U_{cal} to be measured, as for the single-wire probe. For each selected value of U_{cal}, E_1 and E_2 are measured for typically 9 fixed values of θ_{probe}, varying within the approximate range -35° < θ_{probe} < +35°. θ_{probe} is positive when the nose of probe is pitched up. U_{cal}, E_1 and E_2 are sampled 15000 times at a sampling frequency of 1000 Hz (typical values), enabling mean values of these variables to be calculated for the different values of θ_{probe}. The filter dial on the OUTPUT AMPLIFIER panel is set to 1, corresponding to a frequency of 13.6 kHz. The procedure is carried out for typically 8 values of U_{cal}, as for a single-wire probe.

Different researchers have adopted different approaches when carrying out a full calibration of a X-wire probe. The technique used by Oster & Wygnanski (1982), as applied to a typical test calibration carried out in the LSWT, is explained below. Calibration data are shown plotted in Figure 12. Each experimental point on this plot corresponds to a different combination of U_{cal} and θ_{probe}. The full lines on the plot correspond to constant values of θ_{probe} and the broken lines correspond to constant (nominal) values of U_{cal}. The data in Figure 12 can be replotted as two different three-dimensional plots, as shown in Figures 13 and 14. Data plotted in Figure 13 have axes E_1, E_2 and U_{cal}, and those plotted in Figure 14 have axes E_1, E_2 and θ_{probe}. By curve fitting the data using the method of least-squares, it is possible to establish equations for the two different three-dimensional surface plots. Full-cubic equations can be established, comprising

$$U_{cal} = a_0 + a_1E_1 + a_2E_2 + a_3E_1^2 + a_4E_2^2 + a_5E_1^3 + a_6E_2^3 + a_7E_1E_2 + a_8E_1^2E_2 + a_9E_1E_2^2 \quad (7)$$

and

$$\theta_{probe} = b_0 + b_1E_1 + b_2E_2 + b_3E_1^2 + b_4E_2^2 + b_5E_1^3 + b_6E_2^3 + b_7E_1E_2 + b_8E_1^2E_2 + b_9E_1E_2^2 \quad (8)$$

Alternatively, full quadratic equations can be established, comprising

$$U_{cal} = c_0 + c_1E_1 + c_2E_2 + c_3E_1^2 + c_4E_2^2 + c_5E_1E_2 \quad (9)$$

and

$$\theta_{probe} = d_0 + d_1E_1 + d_2E_2 + d_3E_1^2 + d_4E_2^2 + d_5E_1E_2 \quad (10)$$

where the a, b, c and d coefficients are constants. Using these equations, U_{cal} and θ_{probe} can be calculated for pairs of values of E_1 and E_2.

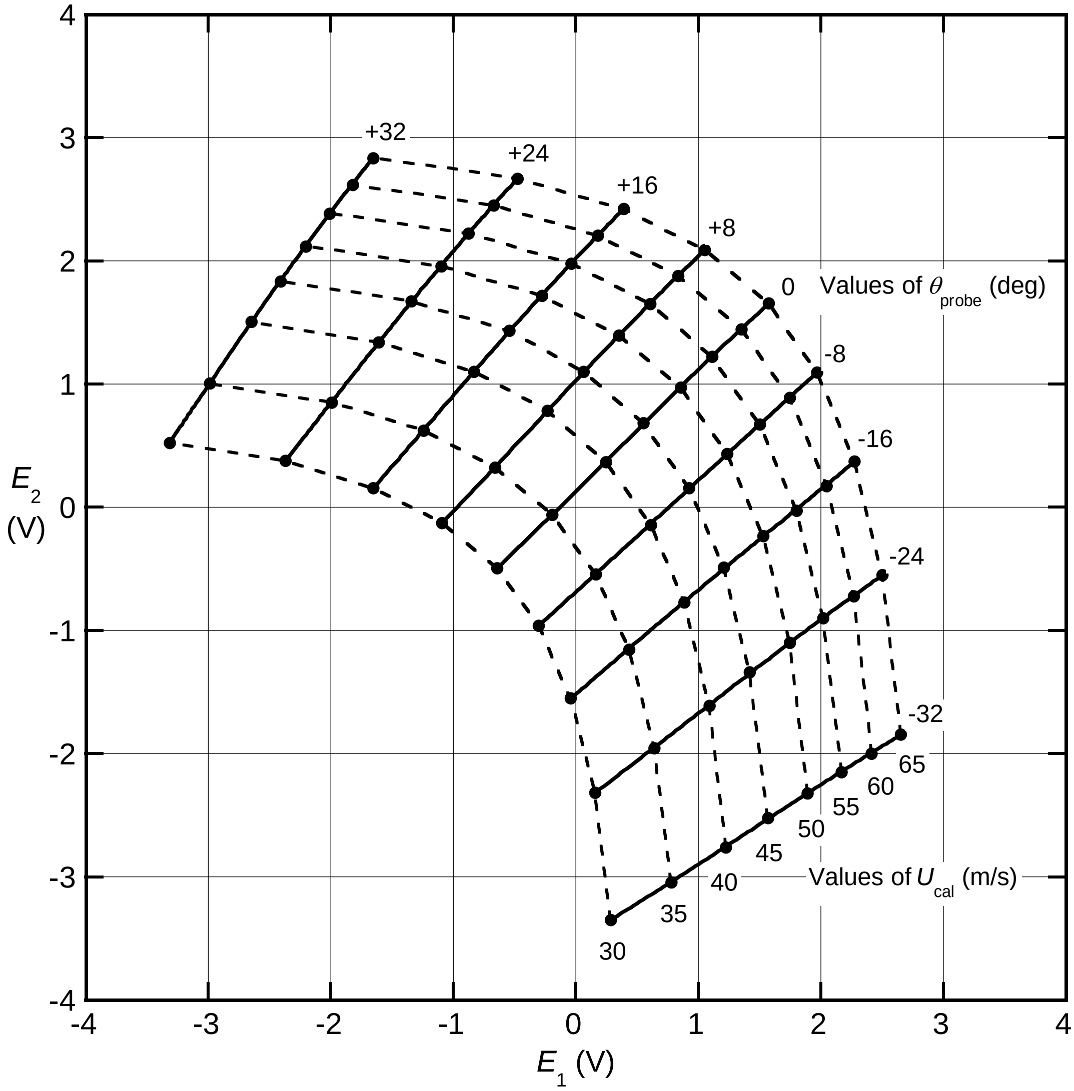

Figure 12 E_2 vs E_1 for typical calibration data at DST Group for a X-wire probe.

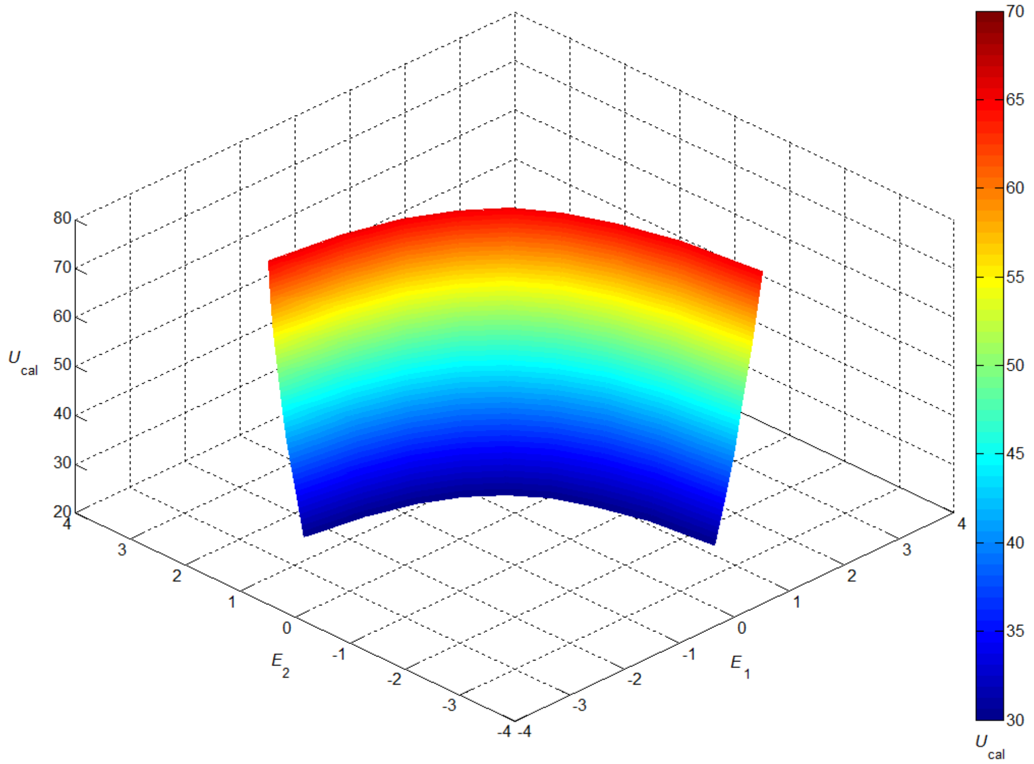

Figure 13 Three-dimensional surface plot having axes E_1, E_2 and U_{cal} for typical calibration data at DST Group for a X-wire probe.

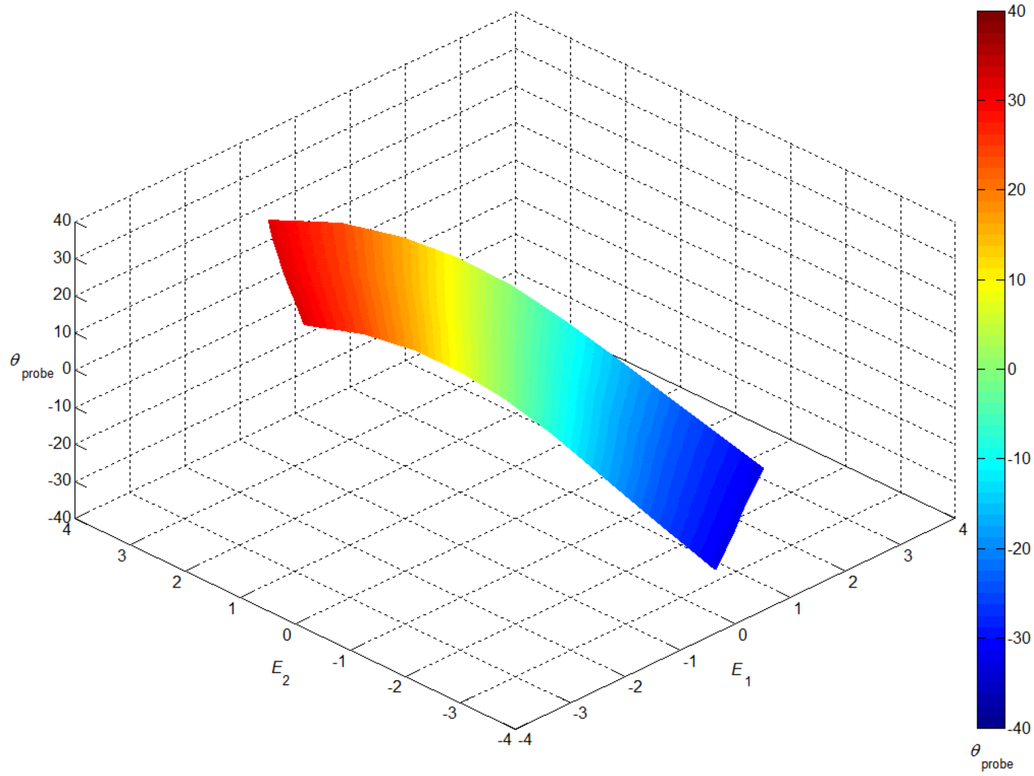

Figure 14 Three-dimensional surface plot having axes E_1, E_2 and θ_{probe} for typical calibration data at DST Group for a X-wire probe.

Lueptow, Breuer & Haritonidis (1988) also created a plot of E_2 *vs* E_1 when calibrating a X-wire probe, as shown in Figure 15. However, they used a different technique to process the raw data compared with that used by Oster & Wygnanski (1982), in that they created a calibration look-up table to determine U_{cal} and θ_{probe} for a selected pair of voltages E_1 and E_2. The technique of Lueptow, Breuer & Haritonidis, as applied to typical calibration data at DST Group, is explained below.

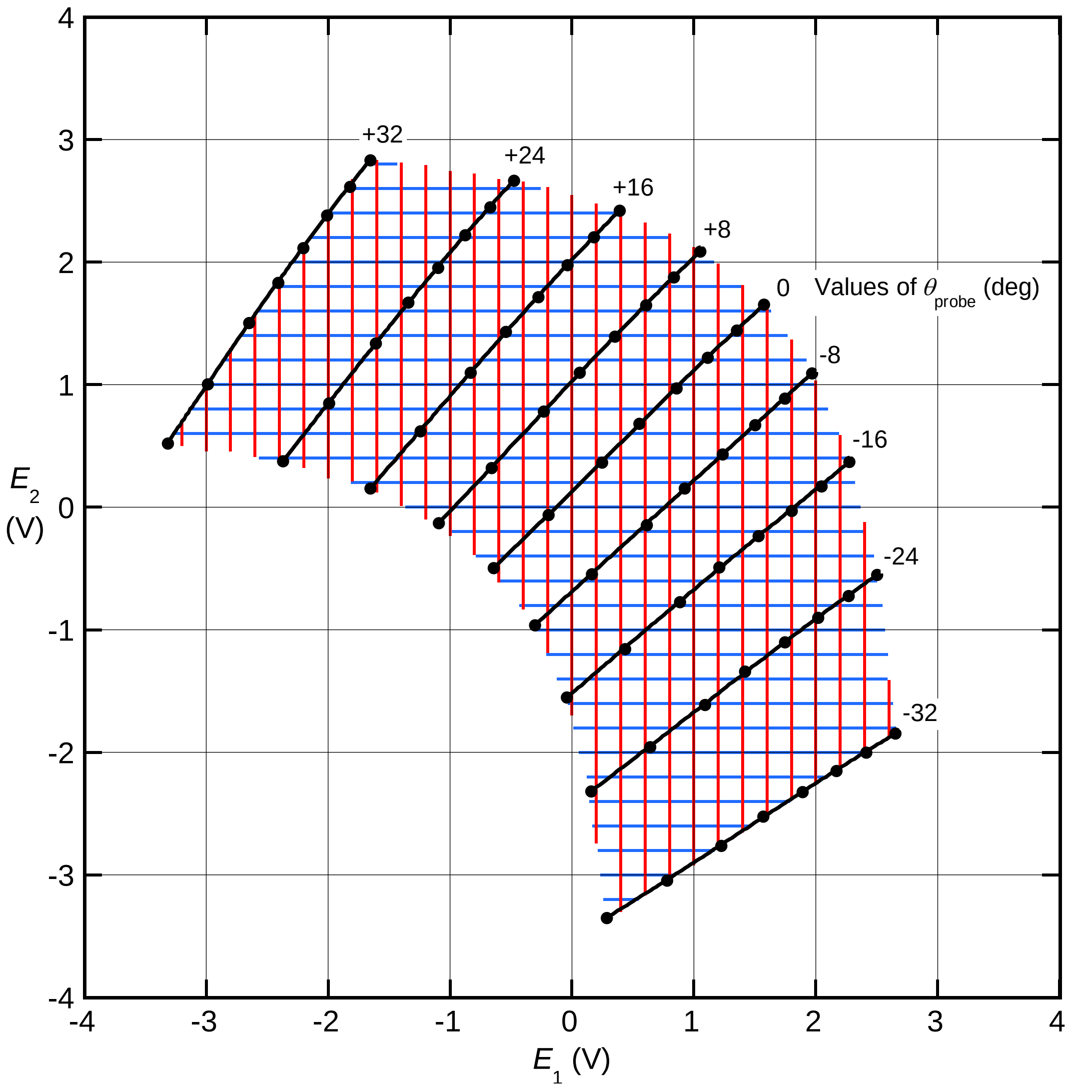

Figure 15 E_2 vs E_1 for typical calibration data at DST Group for a X-wire probe.

(1) Each of the 72 data points (8 values of $U_{cal} \times$ 9 values of θ_{probe}) shown in Figure 15 corresponds to known values of E_1, E_2, U_{cal} and θ_{probe}. Curves corresponding to constant values of θ_{probe} are shown in black in Figure 15. Each set of 8 data points corresponding to each fixed value of θ_{probe} can be curve fitted using the method of least squares to give 9 relationships of the form $E_2 = f(E_1)$ and 9 relationships of the form $U_{cal} = f(E_1)$. For any selected value of E_1, values of E_2, U_{cal} and θ_{probe} can therefore be calculated or are known at all locations (not just at the experimental points) along each of the curves.

(2) Lines corresponding to constant values of E_1 are shown in red in Figure 15. By curve fitting data along each of the lines of constant values of E_1 (i.e. curve fitting data corresponding to the different values of θ_{probe}), relationships of the form $U_{cal} = f(E_2)$ and $\theta_{probe} = f(E_2)$ can be established. For any selected value of E_2, values of U_{cal}, θ_{probe} and E_1 can therefore be calculated or are known at all locations along each of the red lines.

(3) Lines corresponding to constant values of E_2 are shown in blue in Figure 15. For any selected pair of values of E_1 and E_2, i. e. for any of the grid points (intersection of red and blue lines) on Figure 15, values of U_{cal} and θ_{probe} can therefore be calculated.

Thus it is possible to construct a look-up table so that values of U_{cal} and θ_{probe} can be found for any pair of values of E_1 and E_2 that may be chosen. Once the table has been established, it is not necessary to do any curve fitting. The accuracy of the look-up table depends on the fineness of the grid. If chosen values of E_1 and E_2 do not correspond to grid points, then U_{cal} and θ_{probe} can be determined using some interpolation scheme.

Browne, Antonia & Chua (1989) created plots of U_{cal} *vs* E_1 and U_{cal} *vs* E_2 when calibrating a X-wire probe. Figures 16 and 17 respectively show such plots for typical calibration data at DST Group. The full lines on the plots correspond to constant probe pitch angles, i.e. values of θ_{probe}, used in the calibration. Least-squares curve fits can be used to obtain mathematical equations of the form $U_{cal} = f(E_1)$ and $U_{cal} = f(E_2)$ for each of the individual values of θ_{probe} shown in the two figures. For selected values of E_1, it is possible to determine corresponding pairs of values of θ_{probe} and U_{cal} by using the mathematical equations for the curves for the different values of θ_{probe} shown in Figure 16. For example, for E_1 = 0.5 V (red line on Figure 16) it is possible to calculate 6 pairs of values of θ_{probe} and U_{cal} (since there are 6 curves within the calibration range on Figure 16 corresponding to E_1 = 0.5 V). Such values of U_{cal} and θ_{probe} can be plotted against each other, as shown by the red curve in Figure 18. The procedure can be repeated for values of E_2 measured in the calibration, using the mathematical equations for the curves shown in Figure 17. For example, for E_2 = 0.8 V (blue line on Figure 17) it is possible to calculate 6 pairs of values of θ_{probe} and U_{cal}, to produce the data shown by the blue curve in Figure 18. The data shown in red and blue can both be curve fitted to obtain two mathematical equations of the form $U_{cal} = f(\theta_{probe})$. By simultaneously solving these two equations (using say an iterative technique or the Newton-Raphson numerical method of solving non-linear equations), it is possible to determine a pair of values of θ_{probe} and U_{cal} corresponding to the pair of values of E_1 and E_2 measured in the calibration. The solution corresponds to the location where the red and blue curves shown in Figure 18 intersect.

Willmarth & Bogar (1977) were the first researchers to carry out a full calibration of a X-wire probe. Their X-wire probes were very small by conventional standards (wire length, spacing was typically 100 μm = 0.1 mm) and it was necessary for them to carry out full calibrations since the wires on their probes could not be attached to the prongs so that they were precisely aligned and oriented. They selected a number of discreet probe pitch angles within the range $\theta_{probe} = \pm 75°$ and for each pitch angle the tunnel velocity was continuously varied over the calibration range. Values of U_{cal}, E_1 and E_2 were measured as the velocity was being varied at each of the pitch angles. They constructed a look-up table containing 400 E_1, E_2 entries, corresponding to the combination of 20 discrete values of E_1 with 20 discrete values of E_2, enabling U_{cal} and θ_{probe} to be calculated for pairs of values of E_1 and E_2. An interpolation scheme was used to determine variables at locations between data entries in the table. Their calibration method is not used at DST Group due to the difficulty of continuously varying the velocity in the LSWT during a calibration.

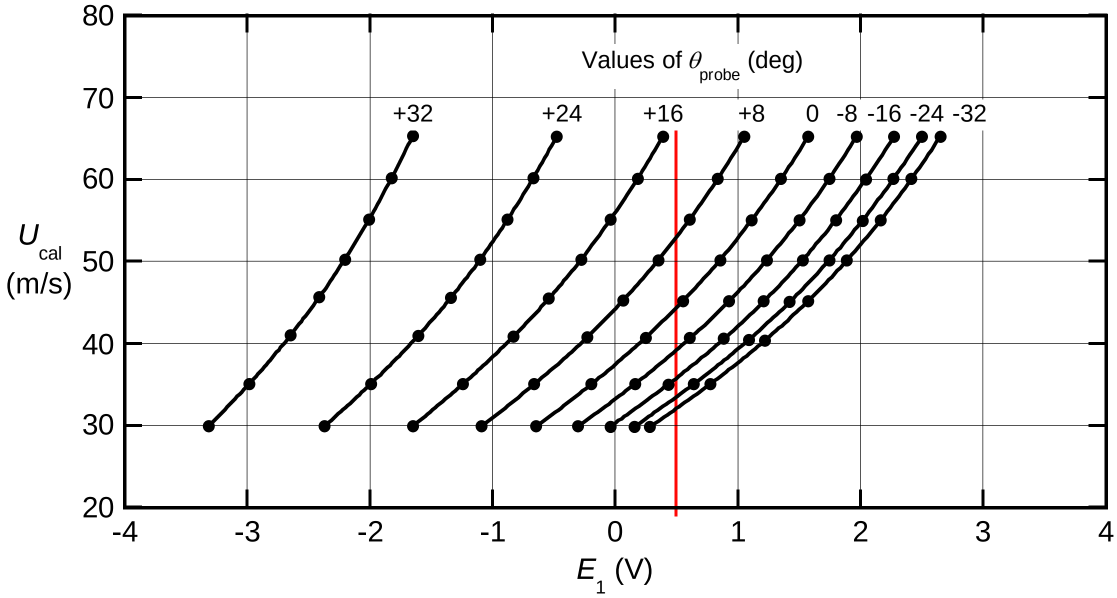

Figure 16 U_{cal} vs E_1 for typical calibration data DST Group for a X-wire probe.

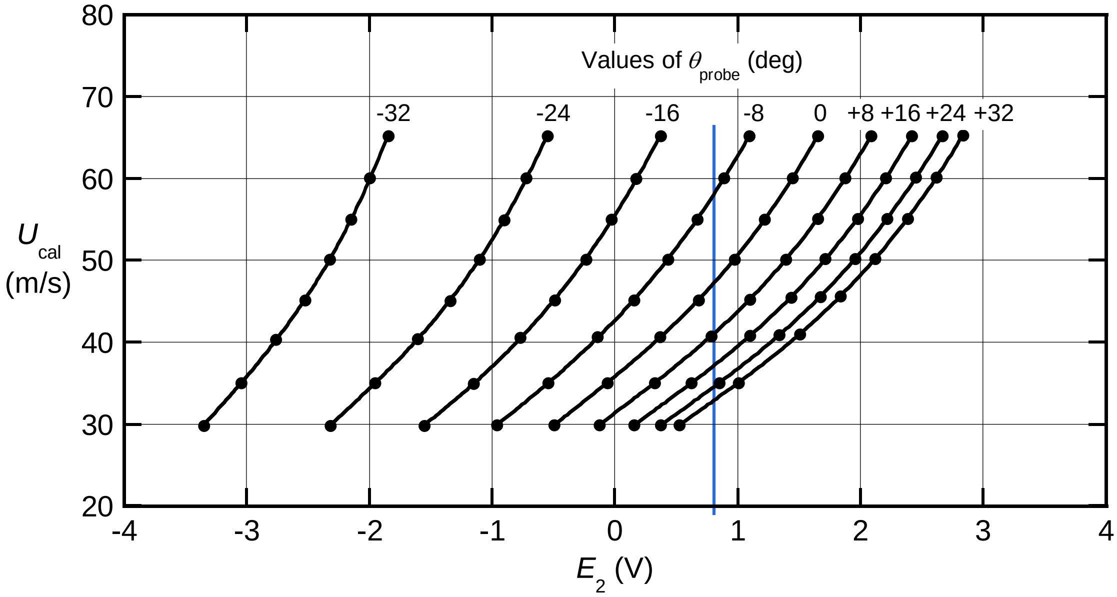

Figure 17 U_{cal} vs E_2 for typical calibration data at DST Group for a X-wire probe.

Full calibrations of X-wire probes have an advantage over simpler methods in that they do not require any assumptions regarding the geometry of the sensors on a probe or the physical laws associated with their cooling, so that full calibrations may result in increased accuracy of measurements. However, full calibrations can take significantly more time to carry out than simplified calibrations and an assessment has to be made on whether possible increased accuracy obtained using a full calibration is worth the extra time involved. Simplified calibrations may be adequate

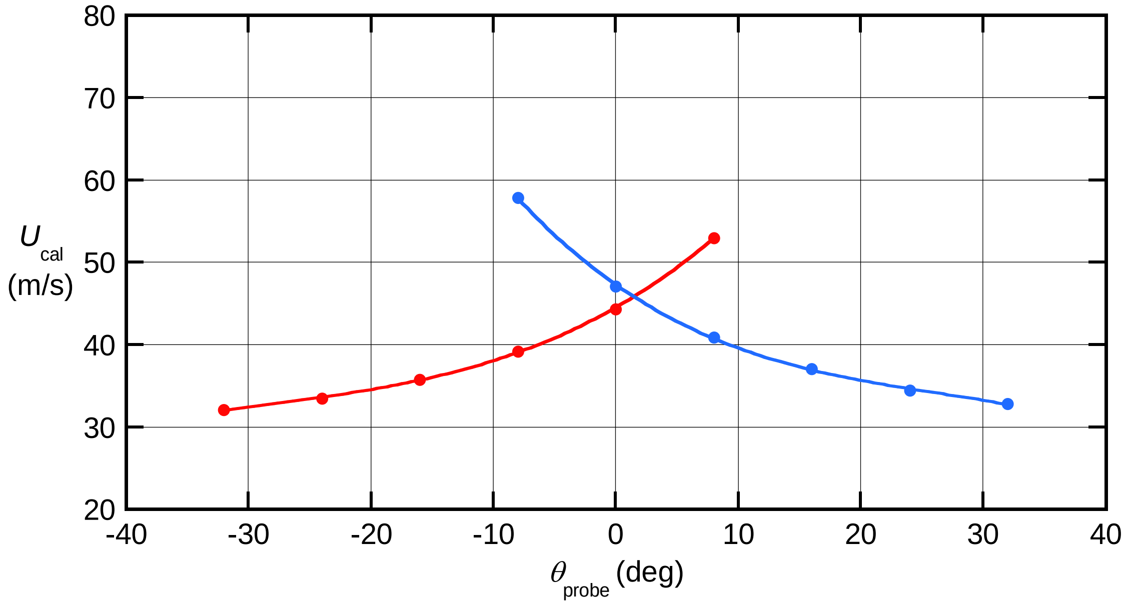

Figure 18 U_{cal} vs θ_{probe} corresponding to a pair of values of E_1 and E_2 for typical calibration data at DST Group.

6.2.2 Simplified Calibration of a X-Wire Probe

One such simplified method of calibrating a X-wire probe is based on the concepts of an effective velocity, U_{eff}, and a corresponding effective angle, θ_{eff}, for the flow over a hot wire. U_{eff} is defined as that velocity, which if it were "normal" to a wire, would produce the same output voltage as the actual velocity. θ_{eff} is approximately equal to the angle between a velocity vector and the "normal" to a hot wire, but a strict geometrical interpretation of an effective angle is not possible. Browne, Antonia & Chua (1989) describe a simplified calibration method, based on effective angles, the main features of which are given below for a typical calibration at DST Group. The simplified method is an adaptation of that given by Bradshaw (1971).

6.2.2.1 Acquisition of Calibration Data

The simplified calibration described by Browne, Antonia & Chua (1989) for a X-wire probe is a two-stage process. Calibration data applicable to the simplified calibration are a subset of data for the full calibration, shown in Figures 16 and 17 .

For the first part of the calibration, the probe is positioned in the free-stream so that its x_P axis points directly into the oncoming flow and its y_P axis is horizontal, as shown in Figure 8. A Pitot-static probe is positioned in the flow close to the hot-wire probe, enabling calibration velocities, U_{cal}, to be measured. Anemometer output voltages, E_1 and E_2, are measured for typically 8 values of U_{cal}, which cover the range of velocities likely to be encountered in subsequent tests. Calibration data are acquired with the hot-wire probe stationary. For each calibration point, U_{cal}, E_1 and E_2 and are sampled 15000 times at a sampling frequency of 1000 Hz (typical values), enabling mean values of U_{cal}, E_1 and E_2 to be calculated. The filter dial on the OUTPUT AMPLIFIER panel is set to 1, corresponding to a frequency of 13.6 kHz. Calibration data are shown plotted in Figures 19 and 20 using axes of U_{cal} *vs* E_1 and U_{cal} *vs* E_2 respectively for typical calibration data at DST Group. Calibration relationships are established by curve fitting the data in Figures 19 and 20 using polynomials of the form.

$$U_{cal} = a_0 + a_1 E_1 + a_2 E_1^2 + a_3 E_1^3 \tag{11}$$

and

$$U_{cal} = b_0 + b_1 E_2 + b_2 E_2^2 + b_3 E_2^3 \tag{12}$$

respectively, where the *a* and *b* coefficients are constants. The initial part of the calibration, described above, is similar to that used for a single-wire probe (see Section 6.1).

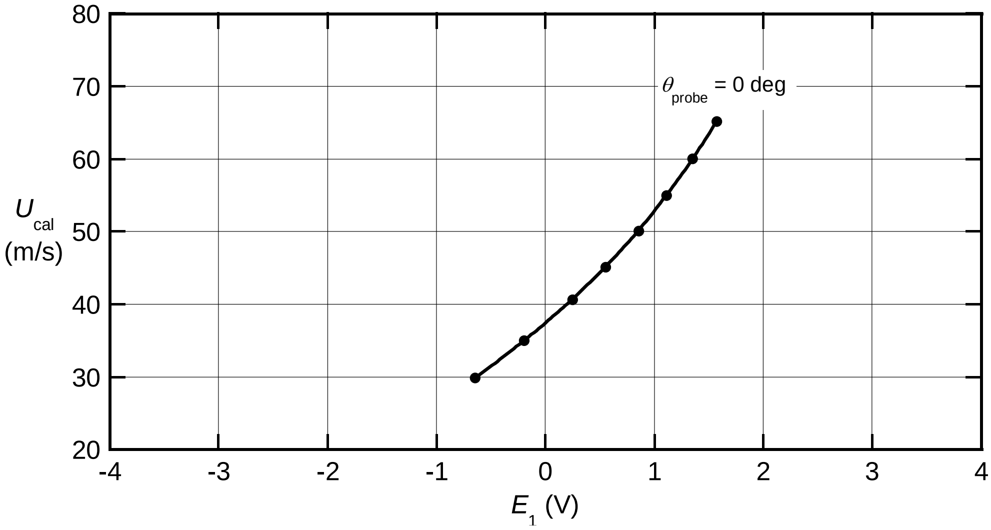

Figure 19 U_{cal} *vs* E_1 *for wire 1 on a X-wire probe for typical calibration data at DST Group.*

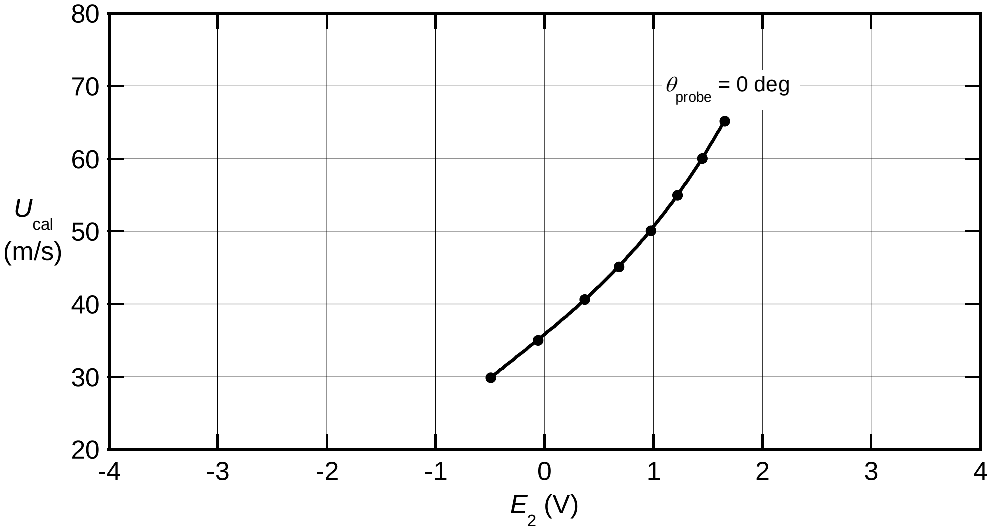

Figure 20 U_{cal} *vs* E_2 *for wire 2 on a X-wire probe for typical calibration data at DST Group.*

For the second part of the calibration, the probe is subjected to a single calibration velocity, close to the midpoint of velocities expected in subsequent measurements, and U_{cal}, E_1 and E_2 and are measured for typically 9 values of θ_{probe}, varying within the approximate range -35° < θ_{probe} < +35°. U_{cal}, E_1 and E_2 are each sampled 15000 times at a sampling frequency of 1000 Hz (typical values), enabling mean values of these variables to be calculated for the different values of θ_{probe}. The filter dial on the OUTPUT AMPLIFIER panel is set to 1, corresponding to a frequency of 13.6 kHz. Calibration data are acquired with the hot-wire probe stationary at each value of θ_{probe}. Calibration data are shown plotted in Figures 21 and 22 using axes of θ_{probe} *vs* E_1 and θ_{probe} *vs* E_2 respectively for the typical test calibration carried out in the LSWT.

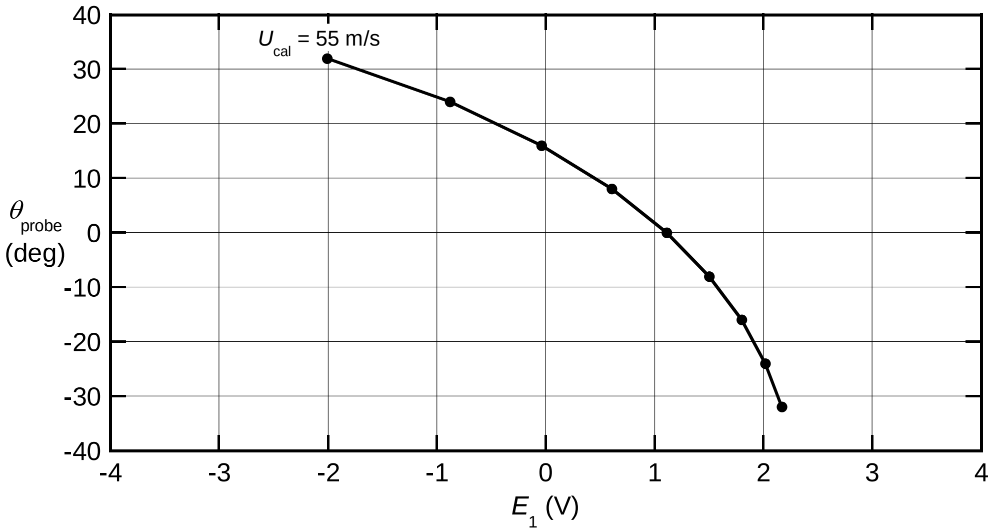

Figure 21 θ_{probe} *vs* E_1 *for wire 1 on a X-wire probe for typical calibration data at DST Group.*

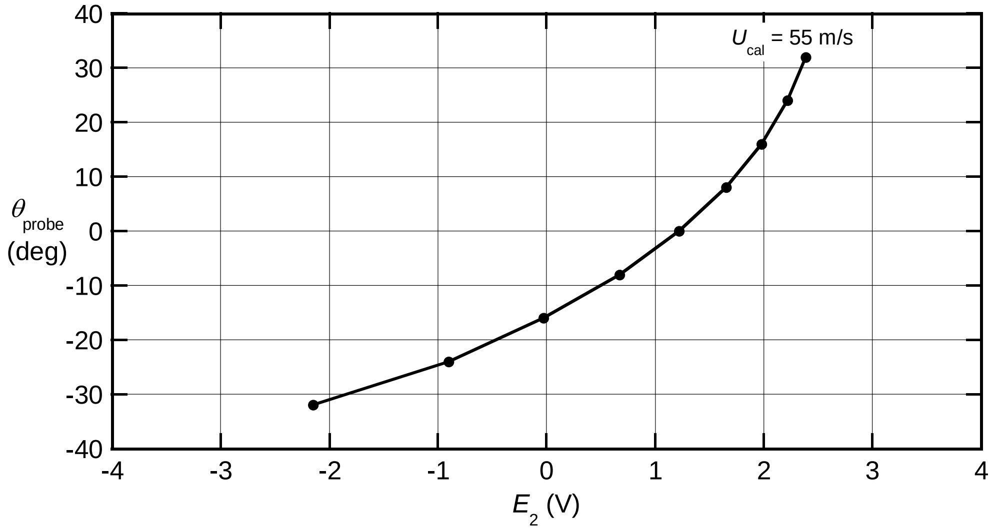

Figure 22 θ_{probe} *vs* E_2 *for wire 2 on a X-wire probe for typical calibration data at DST Group.*

6.2.2.2 Calculation of Effective Angles

The method used to calculate the effective angle, θ_{eff}, of an inclined wire will be explained with reference to Figure 23. When the wire is subjected to a flow velocity U_A, the output voltage of the wire is E_A, as shown in Figure 23a. If the wire is pitched through an angle θ_{probe}, the output voltage becomes E_B, as shown in Figure 23a. Assume that the effective angle of the wire in its new position has been increased by θ_{probe}. Let U_B be an equivalent velocity that produces the same output voltage for the wire when it is in its unyawed position, i.e. E_B, as shown in Figure 23b. U_B is obtained from one of the calibration plots shown in Figures 19 and 20, depending on which of the two wires is being considered. Since the output voltage E_B is the same for 2 cases, an assumption is made that the effective velocity over the wire using U_A with the wire in its yawed position is the same as the effective velocity over the wire using U_B with the wire in its unyawed position, i.e.

$$U_A f(\theta_{eff} + \theta_{probe}) = U_B f(\theta_{eff}) \tag{13}$$

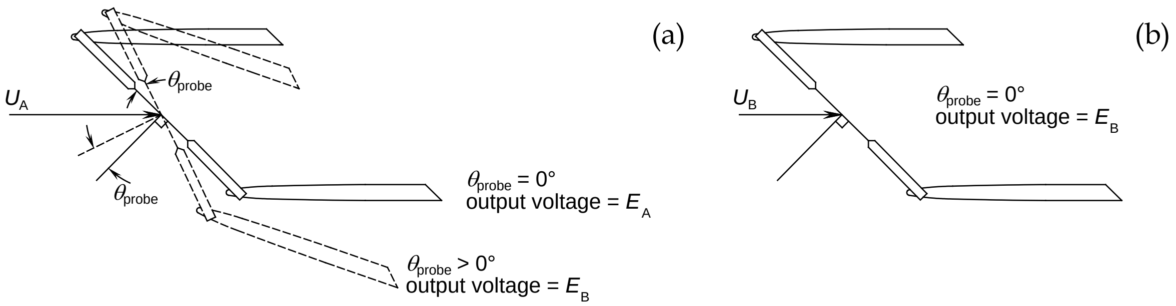

Figure 23 (a) Unyawed and yawed hot wire subjected to a single velocity, (b) unyawed wire subjected to an equivalent velocity to produce the same output voltage as the yawed wire.

It is necessary to select a form for $f(\theta)$ in equation 13. A simplified form, the so-called cosine cooling law, assumes that the cooling of the wire is only affected by the velocity component normal to the wire axis. Hinze (1959) proposed that the cooling is also influenced by the velocity component along the wire. He proposed that $f(\theta)$ is given by

$$f(\theta) = (\cos^2\theta + k^2 \sin^2\theta)^{0.5} \tag{14}$$

The k^2 term has a value between about 0.0 and 0.04 and accounts for the cooling effect of the velocity component along the wire. When $k^2 = 0$, the simplified cosine cooling law applies, i.e.

$$f(\theta) = \cos\theta \tag{15}$$

Substituting equation 14 into equation 13 yields the following equation.

$$\begin{aligned} &U_A[\cos^2(\theta_{eff} + \theta_{probe}) + k^2 \sin^2(\theta_{eff} + \theta_{probe})]^{0.5} \\ &= U_B[\cos^2(\theta_{eff}) + k^2 \sin^2(\theta_{eff})]^{0.5} \end{aligned} \tag{16}$$

For a selected value of k^2, equation 16 can be solved to give the effective angle of the wire, θ_{eff}, for the particular pitch angle, θ_{probe}, used.

For $k^2 = 0°$, the effective angles of wires 1 and 2 for different pitch angles for typical calibration data at DST Group are shown in Figures 24 and 25 respectively.

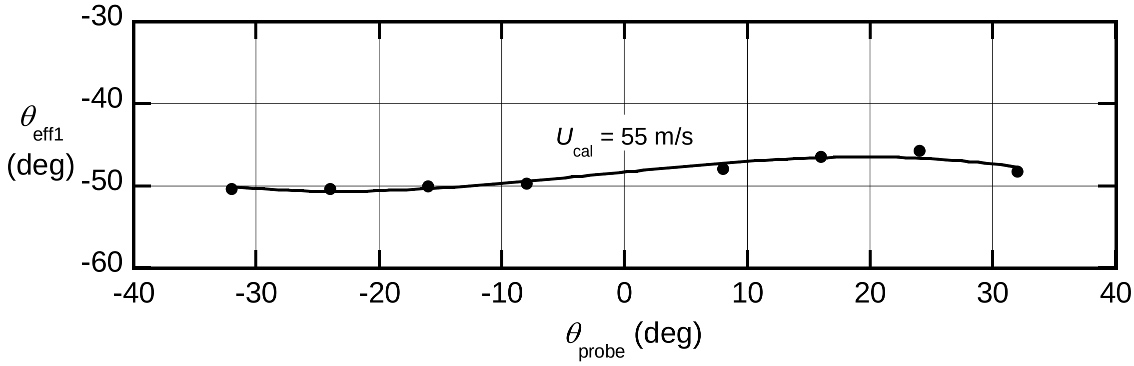

Figure 24 θ_{eff1} *vs* θ_{probe} *for wire 1 on a X-wire probe for typical calibration data at DST Group.*

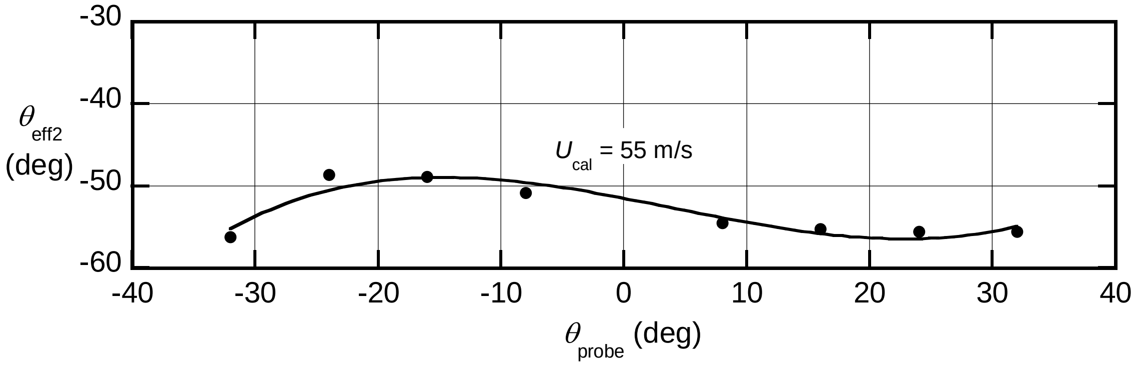

Figure 25 θ_{eff2} *vs* θ_{probe} *for wire 2 on a X-wire probe for typical calibration data at DST Group.*

Mean values of effective angles for both wires, i.e. $\overline{\theta_{eff1}}$ and $\overline{\theta_{eff2}}$, can be determined by averaging the respective individual values of θ_{eff} for the different values of θ_{probe}. $\overline{\theta_{eff1}}$ and $\overline{\theta_{eff2}}$ were found to be -48.61° and -53.20° respectively.

6.2.2.3 *Use of Effective Angles When Measuring Fluctuating Velocities*

The mean effective angles, determined in the previous section, can be used when measuring fluctuating velocities, as explained below. The two wires on a X-wire probe are shown in Figure 26, where the wires have been separated for clarity. The probe is in a turbulent flow field and both of the wires are subjected to an instantaneous velocity vector, U_{cal}, at an instantaneous angle θ_{probe} to the direction of the mean flow, which produces instantaneous output voltages E_1 and E_2 for wires 1 and 2 respectively. The mean effective angles for wires 1 and 2 are $\overline{\theta_{eff1}}$ and $\overline{\theta_{eff2}}$ respectively. U_1 and U_2 are longitudinal velocities corresponding to E_1 and E_2 respectively, as determined from a calibration. If the assumption is made that the effective velocity over wire 1 due to U_{cal} is the same as the effective velocity over wire 1 due to U_1, and similarly for wire 2, then using the definitions of effective velocity it is possible to write

$$U_{\text{cal}} f(\overline{\theta_{\text{eff1}}} - \theta_{\text{probe}}) = U_1 f(\overline{\theta_{\text{eff1}}}) \tag{17}$$

$$U_{\text{cal}} f(\overline{\theta_{\text{eff2}}} + \theta_{\text{probe}}) = U_2 f(\overline{\theta_{\text{eff2}}}) \tag{18}$$

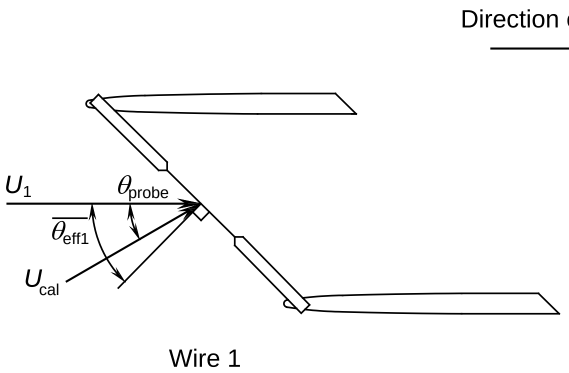

Figure 26 X-wire probe in a turbulent flow field, showing wires separated for clarity. Wires are subjected to an instantaneous velocity vector, U_{cal}, at an instantaneous angle θ_{probe}.

Equations 17 and 18 contain two unknowns, U_{cal} and θ_{probe}. If $f(\theta) = (\cos^2\theta + k^2 \sin^2\theta)^{0.5}$, then it is necessary to use special techniques to solve the transcendental simultaneous equations to determine U_{cal} and θ_{probe}. If $f(\theta) = \cos\theta$, then U_{cal} and θ_{probe} can be determined by solving a pair of linear simultaneous equations.

The simplified method used to calibrate X wires can be completed relatively quickly compared with full-calibration methods, but there may be a loss of accuracy. Conversely, full calibrations take significantly longer to complete, but they would be expected to be more accurate. However, the longer time taken for full calibrations means that they are more prone to drift than the simplified calibration. Factors causing a calibration to change during testing include changes in the temperature of the air in a tunnel, oxidisation of the wire(s), and build-up of debris on the wire(s). For both simplified an full calibrations, loss of accuracy due to drifting can be counteracted to some extent by carrying out calibrations both before and after turbulence quantities are measured, and correcting processed data for the effects of drifting using linear interpolation. However, such an approach accentuates the time difference required to carry out simplified and full calibrations.

6.3 Data Acquired for Different Types of Calibrations

Calibration data acquired when calibrating (1) a single-wire probe, (2) a X-wire probe using a full calibration, and (3) a X-wire probe using a simplified calibration, are summarised in Tables, 1, 2 and 3 respectively.

Table 1. Calibration data for a single-wire probe.

Single-Wire Probe		
U_{cal}	θ_{probe}	Calibration data acquired
Typically 8 values of U_{cal}	1 value of θ_{probe} θ_{probe} = 0 deg	8 sets of $\overline{U_{\text{cal}}}$, θ_{probe}, $\overline{E_1}$

Table 2. Calibration data for a X-wire probe, full calibration.

X-Wire Probe, Full Calibration		
U_{cal}	θ_{probe}	Calibration data acquired
Typically 8 values of U_{cal}	Typically 9 values of θ_{probe} $-35 \le \theta_{probe} \le +35$ deg	72 sets of $\overline{U_{cal}}$, θ_{probe}, $\overline{E_1}$, $\overline{E_2}$

Table 3. Calibration data for a X-wire probe, simplified calibration.

X-Wire Probe, Simplified Calibration		
U_{cal}	θ_{probe}	Calibration data acquired
Typically 8 values of U_{cal}	1 value of θ_{probe} $\theta_{probe} = 0$ deg	8 sets of $\overline{U_{cal}}$, θ_{probe}, $\overline{E_1}$, $\overline{E_2}$
1 value of U_{cal}	Typically 9 values of θ_{probe} $-35 \le \theta_{probe} \le +35$ deg	9 sets of $\overline{U_{cal}}$, θ_{probe}, $\overline{E_1}$, $\overline{E_2}$

6.4 Verification of Calibration

After a calibration has been completed, it is necessary to check its accuracy since calibration coefficients may have drifted during the calibration process. With a single- or X-wire probe mounted on the rotatable arm of the overhead traversing mechanism, with the probe in the free-stream and set at $\theta_{probe} = 0°$, several free-stream velocities can be measured with a hot wire, using the calibration coefficients being tested, and compared with free-stream velocities measured using a Pitot-static probe located near the hot-wire probe. The checks should be done for velocities close to the extremes of those used in the calibration as well as for a velocity close to the midpoint of these extremes.

For a X-wire probe, additional checks can be done by measuring longitudinal and transverse velocities relative to the probe, with the probe set at several pitch angles, θ_{probe}, and checking whether the measurements are consistent with the free-stream velocities measured using a Pitot-static probe and the pitch angles of the X-wire probe.

If the above comparisons show unacceptable discrepancies between velocities and flow angles, then the calibration would need to be repeated until acceptable agreement is obtained.

6.5 Evaluation of Instantaneous Horizontal and Vertical Velocities and Flow Angles

When calibrating a single-wire probe, its longitudinal x_P axis is aligned with the tunnel $-x_T$ direction, whereas when calibrating a X-wire probe, its x_P axis is set at different values of θ_{probe} in the x_T-z_T plane. The roll angle of the probes is set to 0° in both cases. Probe and tunnel coordinate systems are given in Figure 8. Calibrations establish mathematical expressions or look-up tables giving either (1) U_{cal} in terms of E_1 for a single-wire probe, or (2) U_{cal} and θ_{probe} in terms of E_1 and E_2 for a X-wire probe.

When single- and X-wire probes are then used to measure velocities and flow angles, the directions of their longitudinal x_P axes are generally fixed for a given set of measurements. For probes having a fixed orientation, values of U_{cal} computed from a calibration for a single-wire probe and values of U_{cal} and θ_{probe} computed from a calibration for a X-wire probe need clarifying. Consider the case when the x_P axes of probes are aligned with the tunnel $-x_T$ direction. For a single-wire probe, each value of U_{cal} computed from a calibration for each measured value of E_1 is in fact the instantaneous velocity in the x_T direction, i.e. $U = U_{cal}$. For a X-wire probe, each set of values of U_{cal} and θ_{probe} computed from a calibration for each measured set of values of E_1 and E_2, is in fact the instantaneous velocity and the instantaneous angle of the velocity respectively relative to the axes in the x_T-z_T plane. Instantaneous horizontal and vertical components of velocity in the x_T and z_T directions respectively, i.e. U and W respectively, can be calculated using

$$U = U_{\mathrm{cal}} \cos\theta_{\mathrm{probe}} \tag{19}$$

$$W = -U_{\mathrm{cal}} \sin\theta_{\mathrm{probe}} \tag{20}$$

respectively. Instantaneous flow angles are in fact instantaneous values of θ_{probe}.

6.6 Approximations Used When Measuring Velocities and Flow Angles

When single- and X-wire probes are placed in a flow to measure turbulence quantities, with their longitudinal x_P axes pointing in the tunnel $-x_T$ direction, instantaneous velocities as seen by the probes will not necessarily be in the x_T-z_T plane. It is important to note that values of U_{cal} computed from a calibration are assumed to be equivalent velocities in the x_T-z_T plane. It is expected that the projection of actual velocities onto the x_T-z_T plane will be close to associated values of U_{cal}, especially for flows of low turbulence intensity, but it is not possible to say how close (see Browne, Antonia & Chua, 1989). Flow angles computed from a calibration are also assumed to be equivalent flow angles in the x_T-z_T plane.

7. Measurement of Broadband-Turbulence Quantities at DST Group Using Hot Wires

Once a calibration has been verified, the hot-wire probe can be used to measure broadband-turbulence quantities. It is important that anemometer offset voltages and gains are not changed between a calibration and the measurement of turbulence quantities, since such measurements would then be meaningless. Filter cut-off frequencies can be changed, if required. It is not advisable to turn off the power to an anemometer after a calibration and turn it on again prior to measuring broadband-turbulence quantities.

7.1 Transfer of Hot-Wire Probe

Before a hot-wire probe can be used to measure turbulence quantities at DST Group, it may be necessary to transfer the probe from the overhead traversing mechanism, used for a calibration, to a traversing mechanism mounted on a model. 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, shocks could alter the calibration. To check that the calibration still holds after the hot-wire probe has been transferred, the probe can be moved into the free-stream and a few mean-flow velocities can be measured with the probe, as described previously.

7.2 Data Sampling

Before measuring broadband-turbulence quantities using a single- or X-wire probe at selected locations in a turbulent boundary layer or wake, it is first necessary to establish the number of samples of fluctuating hot-wire output voltages that need to be taken, the sampling frequency, and the setting of the filters. It has been found that 15000 voltages, or pairs of voltages, sampled at a frequency of 1000 Hz, with the filter dial on the OUTPUT AMPLIFIER panel set to 1, corresponding to a frequency of 13.6 kHz, are acceptable sampling parameters. This filter setting is used since velocity fluctuations above about 10 kHz in a turbulent boundary layer or wake 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 13.6 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. When measuring broadband-turbulence quantities, a fluctuating velocity 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 on the sampling frequency used. Tests can be done to select the optimum values of the number of samples to be taken for a given flow.

7.3 Processing of Measured Hot-Wire Output Voltages

Calibration equations are used to convert each of the 15000 sampled hot-wire output voltages, or pairs of voltages, into instantaneous velocities. For a single-wire probe, the 15000 calculated velocities, U, can be used to determine $\overline{U}$ and $\overline{u^2}$, as described in Section 2. Similarly, a X-wire probe set up to take measurements in the x_T-z_T plane can be used to measure $\overline{U}$, $\overline{W}$, $\overline{u^2}$, $\overline{w^2}$ and $\overline{uw}$. If a X-wire probe is rolled 90° about its x_P axis, so that measurements are taken in the x_T-y_T plane, then the probe can be used to measure $\overline{U}$, $\overline{V}$, $\overline{u^2}$, $\overline{v^2}$ and $\overline{uv}$.

8. Checklist for Calibrating Hot Wires and Measuring Broadband-Turbulence Quantities at DST Group

A checklist for calibrating hot wires and measuring broadband turbulence quantities at DST Group is given below for a single-wire probe connected to a single anemometer. It is assumed that the probe has an intact filament and is ready to use. The checklist is also applicable to a X-wire probe connected to 2 anemometers. It is instructive to read the checklist while referring to Figure 2, which gives details of the front panel of a hot-wire anemometer at DST Group.

1. Mount the hot-wire probe on the overhead traversing mechanism and position the probe in a tunnel in readiness to calibrate a hot wire.
2. Measure the resistance of the hot-wire filament and the leads combined and then measure the resistance of the leads separately. Set the thumb wheel switches on the RESISTANCE panel of the anemometer to correspond to the resistance of the filament and leads and the chosen hot-wire resistance ratio (typically 2) (see Section 3.4).
3. Set the Standby/Operate Switch to SBY on the FEEDBACK AMPLIFIER panel and switch on power to an anemometer using the POWER Switch on the OUTPUT AMPLIFIER panel, so that the POWER Indicator LED on the panel glows.
4. Connect the hot wire to the anemometer via the terminal labelled PROBE.
5. Set the cut-off frequency of the low-pass filter in the anemometer by adjusting the setting on the FILTER dial on the OUTPUT AMPLIFIER panel. Setting the FILTER dial to 1, corresponding to a frequency of 13.6 kHz, has been found to be satisfactory.
6. Set the Standby/Operate Switch to OP on the FEEDBACK AMPLIFIER panel.
7. Set the velocity at the approximate midpoint of velocities likely to be encountered during subsequent calibration and measurement of turbulence quantities. Adjust the OFFSET potentiometer on the OUTPUT AMPLIFIER panel until the anemometer output voltage at the terminal labelled AMP OUT is approximately zero, i.e. “buck” the anemometer (see Section 3.6).
8. Set the frequency response of the anemometer. To do this, perturb the anemometer electrically by superimposing on the offset voltage a square wave of frequency 885 Hz (approximately), corresponding to a setting of 3 on the FREQUENCY dial on the SQUARE WAVE panel of the anemometer. Using an oscilloscope, observe the anemometer output voltage at the terminal labelled AMP OUT and adjust the offset voltage and the cable compensation bridge inductance using the controls labelled OFFSET and INDUCTANCE respectively, on the FEEDBACK AMPLIFIER panel, until the frequency response is optimally damped, as shown in Figure 7. An OFFSET reading of about 5 was found to be satisfactory. Optimum frequency response has been found to occur when controls labelled GAIN and FILTER in the FEEDBACK AMPLIFIER panel are set to 3 and 3 respectively.
9. Subject the wire to a range of velocities expected during the subsequent calibration and the measurement of turbulence quantities and ensure that output voltages do not exceed limits imposed by the data-acquisition system. It may be necessary to adjust the setting on the GAIN dial on the OUTPUT AMPLIFIER panel and repeat the checking process until output voltages are within acceptable limits.
10. Calibrate the hot wire – see Section 6.1.
11. Verify the accuracy of the calibration by comparing a few velocities measured using the hot-wire probe with those measured using a Pitot-static probe positioned near

the hot-wire probe. If unacceptable discrepancies are found in the measurements, then repeat Step 10.

12. If applicable, transfer the hot-wire probe from the overhead traversing mechanism to a surface-mounted traversing mechanism on a model.
13. Verify that the calibration is still valid by carrying out checks as in Step 11. If the calibration has changed by an unacceptable amount, then repeat Step 10 and later steps.
14. Measure raw hot-wire voltages from the anemometer.
15. Verify that the calibration is still valid by carrying out checks as in Step 11. If the calibration has changed by an unacceptable amount, then repeat Step 10 and later steps.
16. Process the sampled raw hot-wire voltages to obtain the required turbulence terms.

9. Comparison of Different Calibration and Data Processing Methods for X Wires for a Test at DST Group

In Section 6.2, details are given of how different researchers have used different methods to calibrate X wires and to calculate mean velocities and turbulence quantities from measured fluctuating X-wire output voltages. Full calibration methods and data-processing methods for X wires developed by Oster & Wygnanski (1982), Lueptow, Breuer & Haritonidis (1988) and Browne, Antonia & Chua (1989) have been discussed. Also discussed has been a simplified calibration method and data-processing method for X-wires, based on a method developed by Bradshaw (1971). A question that must be addressed is which calibration method and data-processing method is the best to use at DST Group when acquiring mean flow and turbulence data. To help answer this question, the different approaches will be compared for a typical test at DST Group.

It will be recalled that a typical full calibration for a X-wire probe was carried out in the LSWT in which probe output voltages, E_1 and E_2, were measured for a range of calibration velocities, U_{cal}, and probe pitch angles, θ_{probe} – see Section 6.2. The full-calibration data are applicable to the calibration schemes of Oster & Wygnanski (1982), Lueptow, Breuer & Haritonidis (1988) and Browne, Antonia & Chua (1989). A subset of the data is applicable to the calibration scheme of Bradshaw (1971). After the full calibration had been completed, raw turbulence data were then acquired in the flow downstream of a pylon in the test section of the LSWT using the experimental setup shown in Figure 27. The raw data were then processed using the different data-processing methods proposed by the different researchers to determine mean velocities, turbulence intensities and Reynolds stresses. Calculated flow parameters corresponding to the different calibration and data processing methods, are given in Figure 28.

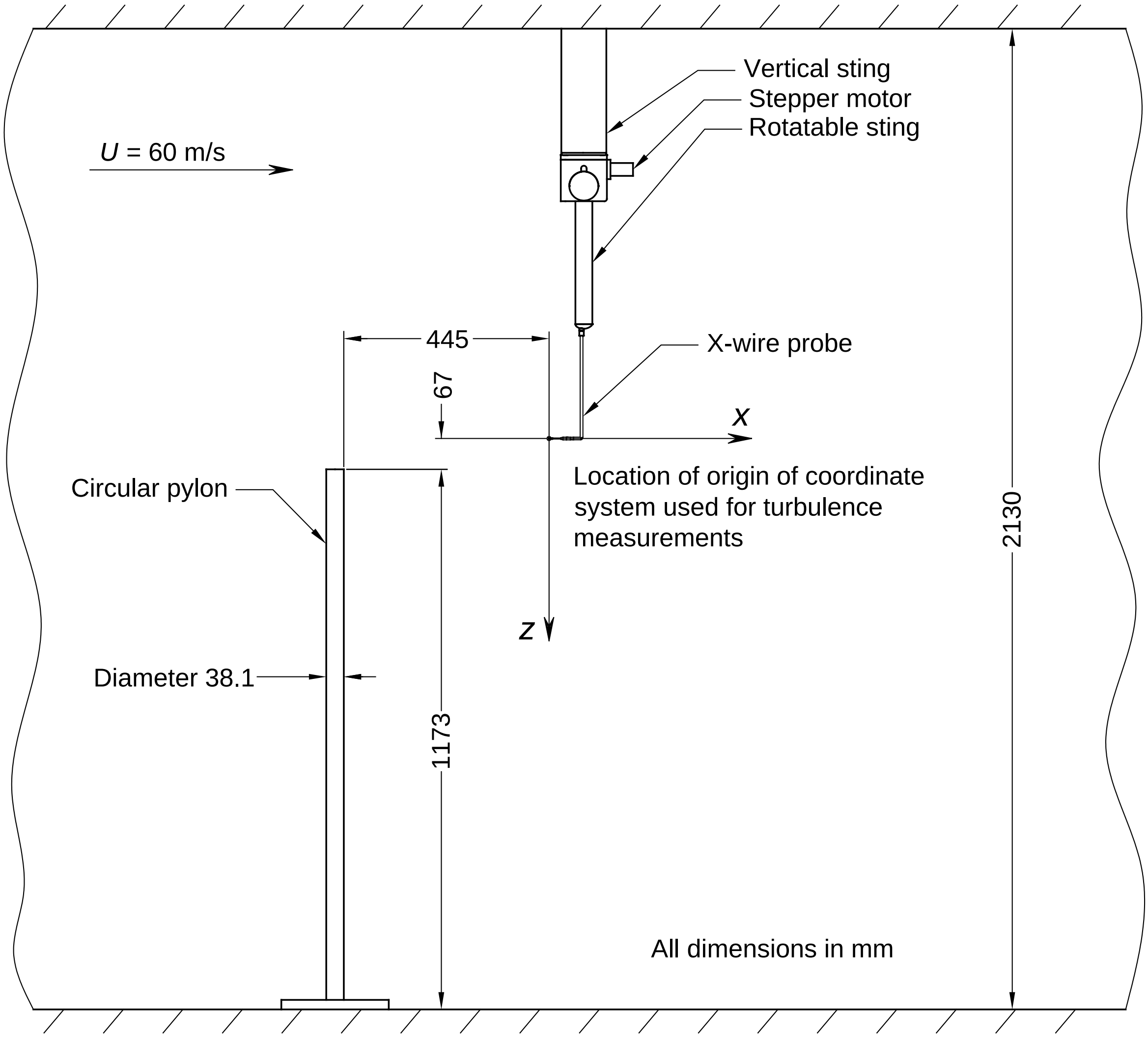

Figure 27 Experimental setup used to measure turbulence quantities in the flow downstream of a pylon in the LSWT.

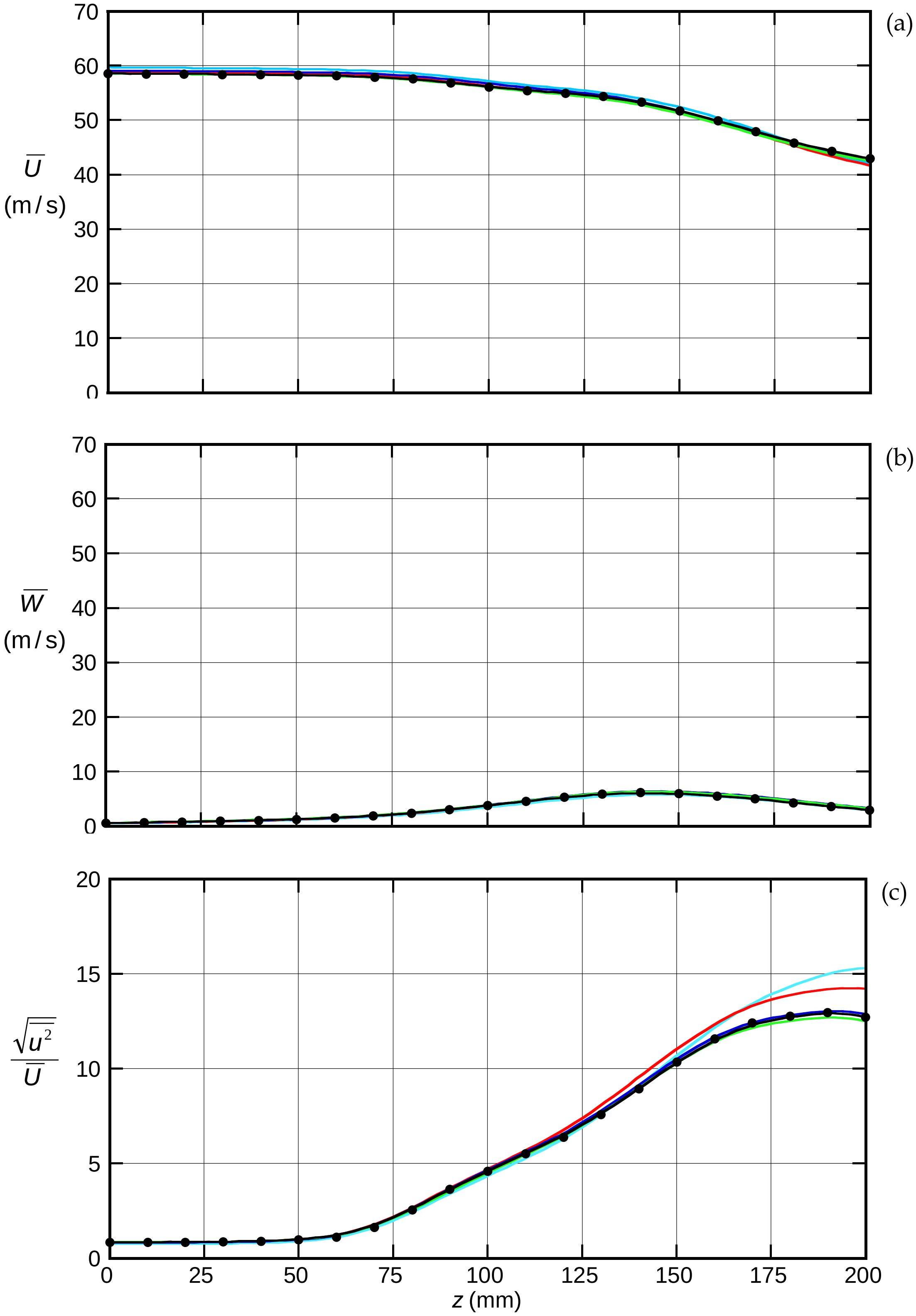

Figure 28 Flow parameters corresponding to different calibration and data-processing methods for a test at DST Group – see caption on next page.

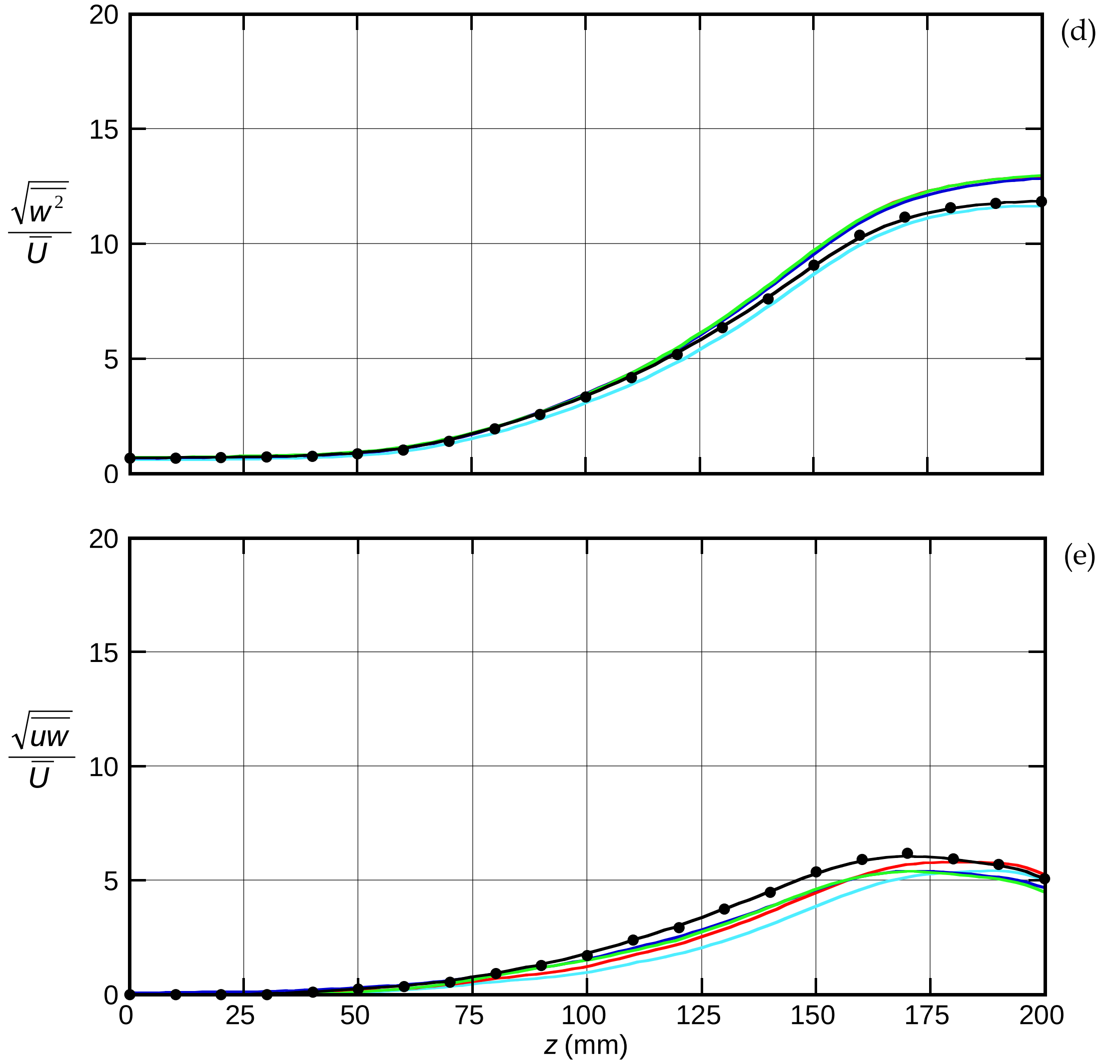

Figure 28 continued *Flow parameters corresponding to different calibration and data-processing methods for a test at DST Group.*

, Oster & Wygnanski (1982), full cubic equations;

, Oster & Wygnanski (1982), full quadratic equations;

, Lueptow, Breuer & Haritonidis (1988);

, Browne, Antonia & Chua (1989);

, Bradshaw (1971).

(a) $\overline{U}$ *; (b)* $\overline{W}$ *; (c)* $\sqrt{\overline{u^2}}/\overline{U}$ *; (d)* $\sqrt{\overline{w^2}}/\overline{U}$ *; (e)* $\sqrt{\overline{uw}}/\overline{U}$.

Prior to calculating mean velocities and turbulence terms in an experimental investigation, checks need to be done to see if the measured instantaneous anemometer output voltages, E_1 and E_2, obtained when the probe is located in a turbulent flow, are within the range of the average calibration voltages, E_1 and E_2. For the current study of the flow downstream of a pylon, instantaneous output voltages for the case of $z = 150$ mm (for example) are shown plotted in Figure 29, along with the average calibration voltages (initially given in Figure 12). In Figure 29, there are 15000 red symbols, denoting 15000 pairs of instantaneous output voltages, E_1 and E_2, and 72 black symbols, denoting 72 average calibration voltages. As can be seen, some of the instantaneous voltages (red symbols) are located beyond the envelope of the calibration voltages (black symbols). When calculating mean velocities and turbulence terms, such instantaneous voltages are processed by extrapolating the calibration beyond its measured limits. This may lead to errors in the calculated mean velocities and turbulence terms. The size of the errors depends on (1) the percentage of the instantaneous voltages that are out of the calibration range, and (2) the extent of the deviations from the calibration range. After performing checks, as outlined above, it may be necessary to discard processed mean velocities and turbulence terms and repeat the calibration, so that a wider range of free-stream velocities and/or probe pitch angles are used, and also repeat the sampling and processing of instantaneous voltages. At the outset of a test program, it is not straightforward to select a range of calibration free-stream velocities and probe pitch angles that will cover the subsequent range of measured instantaneous output voltages. A trial and error approach is generally necessary.

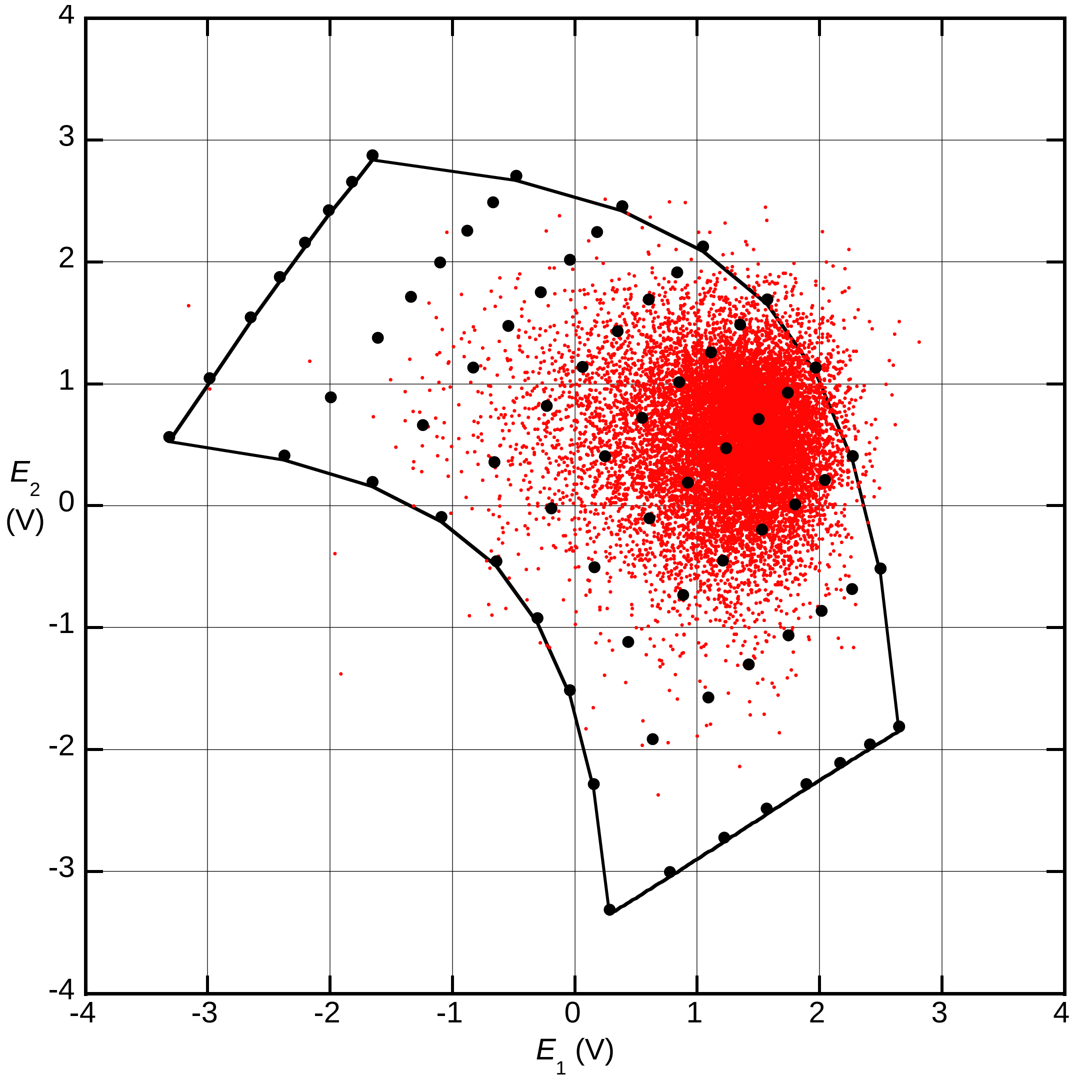

Figure 29 Instantaneous anemometer output voltages associated with the flow downstream of a pylon for the case of z = 150 mm, denoted by red symbols, together with average calibration voltages, denoted by black symbols.

For the current study of the flow downstream of a pylon, the times taken to carry out calibrations and to post-process raw hot-wire output voltages to determine turbulence quantities are given in Table 4 for different calibration and associated processing methods.

Table 4. Typical times associated with different calibration and data-processing methods for a test at DST Group.

Calibration and Data-Processing Method	Typical time for calibration (minutes)	Time to post-process raw data, expressed as a percentage of processing time for Bradshaw's (1971) method (%)
Oster & Wygnanski (1982), full cubic equations	45	27
Oster & Wygnanski (1982), full quadratic equations	45	21
Lueptow, Breuer & Haritonidis (1988)	45	135
Browne, Antonia & Chua (1989)	45	981
Bradshaw (1971) (simplified method)	20	100

Factors affecting the outcome regarding the best calibration and data-processing methods to use at DST Group include the accuracy of calculated turbulence terms, the time taken to carry out a calibration, and the time taken to calculate the turbulence terms. The time taken to compute turbulence terms may be an important consideration if data are to be processed as an experiment proceeds.

For the test case chosen, the foregoing shows that Bradshaw's (1971) simplified calibration and data-processing method is the preferred choice when acquiring mean-flow and turbulence data. Processed mean velocities and turbulence terms show acceptable agreement with data acquired using full calibration and data-processing methods. It is noteworthy that a simplified calibration can be completed in less than 50% of the time required for full calibrations. Time to process raw data is favourable using the method of Oster & Wygnanski (1982), and adverse using the method of Browne, Antonia & Chua (1989), but this will not be a concern if data are processed at the end of tests. Full-calibration and data-processing methods may be better suited to other types of turbulent flows studied at DST Group. The preferred calibration and data-processing methods to be used to study turbulent flows need to be assessed on a case-by-case basis.

10. Measurement of Spectra Using Hot Wires

Turbulence is characterised by chaotic motions of eddies over a wide range of length scales and spectra are commonly used to help indicate the distribution of the fluctuations in the flow over the different scales. Spectra are useful in helping to identify irregularities in a turbulent flow. If such a flow contains eddies of dominant frequencies, such as vortices shed by a fan, then the eddies will produce harmonics or spikes on spectra. If there is any significant noise on a fluctuating turbulent signal, caused by say electrical interference or probe or model vibration, then these will also produce spikes.

When measuring spectra in turbulent flows at DST Group, hot-wire output voltages are typically sampled 65536 times (i.e. 2^{16} times –see below) at a sampling frequency of 10 kHz, and the filter dial on the OUTPUT AMPLIFIER panel is set to 1, corresponding to a frequency of 13.6 kHz. This filter setting is used since velocity fluctuations above this frequency in such flows have negligible energy. When sampling at 10 kHz, the maximum frequency that can be resolved is 5 kHz, due to aliasing. To obtain spectra, it is first necessary to calibrate a wire and use the calibration to calculate velocities from measured hot-wire output voltages. Power spectral densities can then be computed from the velocities using a Fast-Fourier-Transform (FFT) algorithm, where the number of data points required is a power of 2. For a set of 65536 (=2^{16}) calculated velocities, and for a sampling frequency of 10 kHz, the frequencies at which power spectral densities are computed range from 0.1526 Hz to 5 kHz in increments of 0.1526 Hz, i.e. 10000/65536 Hz, corresponding to 32768 (=2^{15}) values of frequency.

11. Software Used to Control Experiments

Specialised software has been written to facilitate the measurement of turbulence quantities in the LSWT. The software is used to (1) calibrate both single- and X-wire probes, (2) acquire raw turbulence data, (3) calculate turbulence quantities from the raw data, and (4) control the movement of the traversing mechanism used when acquiring data. The software incorporates a graphical-user interface, which simplifies test programs. Tests are largely automated, with minimal input from an operator. Only a brief overview of the use of the software is given here.

When using the software to calibrate a hot wire, it is necessary to set calibration parameters, including (1) the number of hot-wire voltages and pressures to be sampled as well as the sampling frequency, (2) the number of velocities to be used in the calibration and the range of the velocities, (3) the number of pitch angles to be used in the calibration and the range of the pitch angles (only applicable to the calibration of a X-wire probe), and (4) the type of calibration to be carried out, i.e. calibration of a single-wire probe, full calibration of a X-wire probe, or simplified calibration of a X-wire probe. Once the above calibration parameters have been set, all probe movement (only applicable to a X-wire probe) and data sampling and processing during the calibration proceeds automatically, as instructed by the software. The tunnel free-stream velocities used in a calibration do, however, have to be set manually when users are notified by the software.

When using the software to acquire broadband-turbulence data and spectra, parameters that have to be set include (1) the number of hot-wire voltages to be sampled as well as the sampling frequency, and (2) the locations in the vertical direction at which data are to be acquired. Once the above parameters have been set, all probe movement and data sampling and processing proceeds automatically, as instructed by the software. The tunnel free-stream velocity has to be set manually, as for the calibration.

The software can also be used to post-process measured X-wire data, using different calibration methods and different methods to calculate mean velocities and turbulence quantities from measured fluctuating X-wire output voltages, as proposed by different researchers.

12. Concluding Remarks

The report describes how to use the constant-temperature hot-wire-anemometer system at DST Group to obtain mean velocities, turbulence intensities, Reynolds stresses and spectra in a turbulent flow field. Areas covered include a description of the anemometers and probes, soldering hot-wire filaments onto the prongs of a probe, etching the filaments, setting up of anemometers in readiness for testing, calibration of single- and X-wire probes, measurement of broadband turbulence quantities and spectra using hot wires, and use of associated software.

For a X-wire probe, an important question that was addressed was which calibration method and associated method of processing fluctuating hot-wire output voltages to obtain turbulence quantities, was the best to use at DST Group. To address the above question, a test was carried out in the LSWT whereby a X-wire was used to measure turbulence quantities in the flow downstream of a circular pylon. Full calibration methods and data-processing methods for X wires developed by Oster & Wygnanski (1982), Lueptow, Breuer & Haritonidis (1988) and Browne, Antonia & Chua (1989) have been compared. The simplified calibration method and data-processing method for X-wires developed by Bradshaw (1971) (effective-angle method) have also been used in the comparison. For the given test case, it was found that Bradshaw's (1971) simplified calibration method and data-processing method was the best to use to measure mean velocities and turbulence quantities. Although data obtained using Bradshaw's method may not have been as accurate as those obtained using full-calibration and data-processing methods, the small loss of accuracy was easily offset by the simplicity of Bradshaw's approach.

The report has been written so that experimentalists at DST Group with limited knowledge on the procedures involved in carrying out experiments in the LSWT with hot wires will be able to use the new system to obtain reliable turbulence data.

13. Acknowledgements

The author is grateful to Malcolm Jones and Simon Henbest who willingly shared their knowledge on the use of the hot-wire anemometers. Staff from QinetiQ Engineering Services built the anemometers and designed and manufactured the overhead traversing mechanism. Kane Partridge from QinetiQ wrote software used when measuring turbulence quantities. Chris Jones from QinetiQ produced many of the figures used in this report.

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19. ABSTRACT

This report gives details of how to use the constant-temperature hot-wire-anemometer system at DST Group to measure mean velocities, broadband turbulence terms and spectra of velocity fluctuations in the low-speed wind tunnel at DST Group. The use of both single-wire and crossed-wire (2 wire) probes is described. Areas covered include a description of the anemometers and probes, soldering hot-wire filaments onto the prongs of a probe, etching the filaments, setting up of instrumentation, setting resistance ratios of hot wires, setting the frequency response of anemometers, calibration of hot wires, acquisition of data, reduction of data to obtain turbulence quantities, and use of associated software. The report is not highly technical and can be used as an operator's manual, so that experimentalists at DST Group that have some knowledge of hot-wire anemometry will be able to use the system to obtain reliable turbulence data. References are given that will enable personnel to gain an in-depth understanding of different technical aspects of the use of hot-wire anemometers, if required.