APPLICATION OF ON-LINE COMPUTER TECHNIQUES
TO MEASUREMENT AND CONTROL IN A MULTIPLE-JET WIND TUNNEL

by

Eric Gordon Hartwell

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I would like to thank my supervisor, Dr. L. D. Reid, for the opportunity to do this investigation and for his many helpful suggestions. I would also like to thank Dr. J. H. de Leeuw for his supervision and assistance during Dr. Reid's absence. The expertise of W. O. Graf has proven invaluable in the design and debugging of the interface and control system (and, at times, the computer), and I am especially grateful for his assistance in writing the hardware interface subroutines.

A project of this nature could not be realized without the aid of many people. Rather, it could, but it would be foolish to do it that way when there are so many talented people around willing to give their help. The contribution of P. S. Spedaler is especially significant in terms of the number of hours I would have otherwise spent calibrating the hot-wire probes and setting up the analog system. It is impossible to thank by name every single person who helped, and many of them would prefer to remain anonymous, so I must refrain from mentioning my parents, my fellow students, and certain other sources of moral support.

Financial support for this project was received from the National Research Council of Canada.
Summary

The control and measurement system for the UTIAS boundary layer simulation wind tunnel has been automated. A digital computer is used to control the positioning of a hot-wire probe in the tunnel, to measure the mean velocity, and to adjust the velocity profile by setting the flow conditions at the upstream jet grid.

The use of the system has been demonstrated by measuring certain aspects of the tunnel characteristics, and by automating the power law velocity profile setup procedure.
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<tr>
<td>A</td>
<td>area</td>
</tr>
<tr>
<td>A</td>
<td>influence coefficient matrix</td>
</tr>
<tr>
<td>ADC</td>
<td>analog-to-digital converter</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary metal oxide semiconductor</td>
</tr>
<tr>
<td>DAC</td>
<td>digital-to-analog converter</td>
</tr>
<tr>
<td>DC</td>
<td>direct coupled</td>
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<tr>
<td>ICn</td>
<td>integrated circuit n</td>
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<tr>
<td>JFET</td>
<td>junction field-effect transistor</td>
</tr>
<tr>
<td>K</td>
<td>1024 words of computer memory</td>
</tr>
<tr>
<td>L</td>
<td>perimeter length</td>
</tr>
<tr>
<td>m</td>
<td>mass</td>
</tr>
<tr>
<td>n</td>
<td>power-law profile exponent</td>
</tr>
<tr>
<td>P</td>
<td>pressure</td>
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<tr>
<td>Qn</td>
<td>transistor n</td>
</tr>
<tr>
<td>Rn</td>
<td>resistor or potentiometer n</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
</tr>
<tr>
<td>SWn</td>
<td>switch n</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>T</td>
<td>time constant</td>
</tr>
<tr>
<td>TTL</td>
<td>transistor-transistor logic</td>
</tr>
<tr>
<td>U</td>
<td>mean velocity</td>
</tr>
<tr>
<td>UG</td>
<td>velocity at gradient height</td>
</tr>
<tr>
<td>V</td>
<td>mean velocity</td>
</tr>
<tr>
<td>Vss</td>
<td>steady state velocity</td>
</tr>
<tr>
<td>z</td>
<td>height</td>
</tr>
<tr>
<td>ZG</td>
<td>gradient height</td>
</tr>
<tr>
<td>λ</td>
<td>inverse of characteristic distance</td>
</tr>
<tr>
<td>ρ</td>
<td>air density</td>
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Tunnel co-ordinates are normally expressed as (row, column) ordered pairs corresponding to \((z,y)\) axes.
1. INTRODUCTION

The characteristics of low altitude atmospheric flows have a profound effect on a variety of disciplines. The planetary boundary layer, that region of the atmosphere extending from the earth's surface to heights of about 500 metres, is of fundamental importance to studies of low-flying aircraft, wind effects on buildings, and the dispersal of pollutants, to name but a few examples.

Due to the extremely complex nature of these time and space variant, turbulent flows, theoretical models are generally oversimplified if they can be obtained at all. Since full-scale experiments are expensive and may be difficult to repeat, laboratory simulations play an important role in boundary layer studies.

The planetary boundary layer can be simulated in a wind tunnel by a variety of methods. The most common is to use a long, rough surface to develop a 'natural' boundary layer of suitable thickness, requiring a correspondingly long tunnel. Various devices can be used to generate an artificially thick boundary layer in a much shorter tunnel, however.

The UTIAS boundary layer wind tunnel uses an array of adjustable ejectors, or air jets, across the upstream end of the tunnel test section to assist in developing the boundary layer flow. The jets create a turbulence field as a result of the shear between the flow out of the nozzles and the flow of the air passing between them. A wide variety of turbulent shear flows can be produced by controlling the flow velocity of individual jets, as well as by employing other devices such as the use of bluff barriers and surface roughness on the floor of the tunnel.

To simplify the simulation of flows with different velocity and turbulence profiles, the control and data acquisition process has been automated. A digital computer is used to control the positioning of a velocity probe at essentially any location across the test section, and an interface has been constructed to allow the computer to adjust the jet velocities. An extensive software system has been developed to facilitate both automatic and manually controlled use of the system, and a number of previously tedious operations such as tunnel calibration and profile setup have been automated.

In the present report, a summary of the equipment is given (Section 2), the interface and control software is described (Section 3), the tunnel calibration procedures and results are discussed (Section 4), and an automated profile setup system is described (Section 5). Conclusions and recommendations for future work are presented in Section 6.

2. WIND TUNNEL FACILITY

2.1 The UTIAS Boundary Layer Wind Tunnel

The original UTIAS subsonic wind tunnel was redesigned and modified into the multiple jet configuration in the early 1970's, as detailed in Ref. 1. An overall view of the tunnel facility is shown in Fig. 1, and a drawing of its aerodynamic outline in Fig. 2.

The modified facility is still a closed circuit tunnel, but exhaust ports are provided downstream of the test section to provide an escape for the air supplied
by the jets. An axial fan and 45 kW drive motor are located in the return section. The fan can be used to augment the jet flow, reducing the jet velocity required for a given test section velocity, or, conversely, the jets can be used to modify the fan flow, creating profiles not otherwise attainable. The fan speed can be set to one of eleven fixed levels (No. 1 to 11), or varied continuously below setting No. 1. In the fan only mode, the tunnel can be used for reduced turbulence flows of up to 21 metres/second at setting No. 6 and up to 30 m/sec at No. 11.

An unusually abrupt contraction cone is used after the fourth corner to provide the longest possible boundary layer growth and test sections within the constraints of the existing tunnel length. The most significant consequence of this is a higher local velocity in the outer flow, superimposing a 'dish-shaped' profile on the return and fan flow.

The jets are located at the end of the contraction cone. It was decided to use eight horizontal rows of jets to provide a good degree of control over the vertical velocity profile, and hence twelve columns are required for equal lateral and vertical spacing. The resulting array of 96 jets on a 14 cm grid provides reasonable control over the flow.

Because the profiles of interest vary mostly in the vertical direction, a lesser degree of control is needed laterally. To reduce the cost and complexity of the jet control system, it was decided to control each group of three jets in a single row by a single valve. The resulting array of 32 valves provides a simplified system with little sacrifice in actual utility. The co-ordinate system used for the jet and valve grids is shown in Fig. 3. Jet columns 0 to 2 are controlled by valve column 0, columns 3 to 5 by column 1, and so on.

The jets are supplied by a single 56 kW blower operating at constant speed, providing sufficient static pressure rise to drive the jets to a maximum nozzle velocity of 80 m/sec. The blower chamber is connected by ducting to the valves, which are mounted in four groups of eight on each side of the jet grid section, outside the tunnel (see Fig. 4). The actual exits have a square cross-section of about 3.2 by 3.2 cm, and each row is covered with an airfoil to reduce friction losses in the return flow (Figs. 5 to 8). The tunnel can be run in the jet only mode to a maximum test section velocity of about 17 m/sec.

The test section has a cross-section 1.12 metres high by 1.68 metres wide, and a usable length of about 3.6 metres. It is a continuation of the 'growth' section, which extends about 5.75 metres downstream from the jet grid (see Fig. 6). Various turbulence producing devices can be located in the growth section, and are used in conjunction with the jets to produce boundary layer flows up to 91 cm high.

2.2 Jet Control Valves

Each group of three jets in a row is controlled by a single butterfly valve in their common supply line. The valve consists of a rotating, flat 9 cm diameter plate mounted in a short length of 10 cm pipe, so that even when the valve is fully 'closed', the flow is not completely cut off. A single valve and its associated control equipment is shown in Fig. 7.

The plate is connected directly to a large gear mounted outside the pipe,
and driven through an 8:1 gear ratio by a Beckman Model 942 DC servo motor/potentiometer. The motor in turn has an internal 560:1 gearing, providing high position sensitivity and sufficient torque to drive the valve against the jet flow when the blower is operating. The valves turn at a maximum speed of about 1.6 degrees per second, and there is sufficient mechanical friction in the system that the settings do not drift appreciably when the motors are turned off.

Position feedback is provided by a three-turn potentiometer mounted on the motor shaft. Because of the 8:1 gear ratio, the valve would turn 135° for the full 1080° travel of the potentiometer, and hence the 90° useful valve range uses only two thirds of the potential control range.

Automatic limit stops are provided to prevent damage to the motor in case the valve is driven to the extremes of the potentiometer travel. Switches wired in series with the motor leads are opened by pegs mounted on the valve gear, so that if the normal range is exceeded the motor is disconnected and a warning light is activated.

Downstream of the valve, the flow is split into three jet supply lines (see Fig. 8). Trimming valves are provided to equalize the friction losses and to compensate for other variations, so that all three velocities in a group are the same for the same valve setting. These valves provide a limited degree of control and are not easily changed. They were originally adjusted by setting all of the valves to the same setting and using the trim valves to equalize the dynamic pressure measured at each jet exit.

2.3 Valve Servo Control System

The original valve control system consisted of 32 identical analog servo motor and feedback loops, one for each valve, and the schematic for one channel is shown in Fig. 9. In the manual mode, each valve setting was selected using a multi-turn potentiometer mounted on a control rack (see Fig. 10).

 Provision was also made for an automatic mode, in which the control panel would be used to select the desired velocity and a hot-wire probe in the test section would be used to provide feedback instead of the servo potentiometer. However, because of the cost and difficulty of maintaining and calibrating the 32 hot-wire probes this would have required, this option was never implemented.

In the current system, a computer is used to measure the velocity and adjust the valve settings, and an interface unit has been developed to provide the necessary control functions. A major constraint was that existing hardware be used wherever possible to reduce costs, to ensure that previous settings could be repeated, and to retain a firm backup in the form of the previous controller.

Initial investigations were directed at modifying the existing 32 channel system to allow computer control in place of the originally planned velocity feedback mode. Although conceptually quite simple, this would have required extensive rewiring of the hardware to distribute the signals and monitor the servo status, as well as the acquisition of a 32 channel digital to analog converter. Therefore, it was felt that there would be no significant advantage to such a modification over constructing a totally new controller specifically designed for computer interface.
The system ultimately adopted uses a single active servo loop, connected in turn to each valve to be adjusted. Only one servo amplifier and its supporting circuitry is needed instead of 32, with a corresponding decrease in complexity and increase in reliability, and the system is easily expanded if more valves are added in the future. The servo control interface is shown in Fig. 11, and a block diagram of its operation in Fig. 12. A detailed description of the circuitry and operation is given in Appendix A.

The servo motors are selectively enabled by solid-state switches, controlled by digital control signals from the computer. Transistors were used instead of relays because of their higher reliability, and their smaller size which allows all 32 switches to be mounted on a single small circuit board.

The valves are driven to a particular setting as in the previous system, rather than to null a measured velocity difference. Aside from the obvious advantage in being able to reset a previously known profile without having to run the tunnel, the amount of computer overhead required is greatly reduced since only a single value is required for each change, rather than a continuously varying velocity error.

A manual control mode is also provided so that the valves can be controlled when the computer is unavailable. The interface is provided with a control panel similar to that of the original system, with the addition of switches to select the desired valve and some extra status indicators. The same logic and circuitry is generally used for both modes, to simplify the construction and system testing and maintenance.

With computer control of the valve settings, it is possible to restrict the range of travel using appropriate software. However, in the case of equipment failure, or at any time in the manual mode, the valves can still be driven to their limits. Therefore, an automatic limit stop system was retained. If a limit switch is activated, all of the servos are disabled and a warning light is turned on. The recovery must be done in manual mode once the fault is corrected.

2.4 Instrumentation

An overall view of the instrumentation facility is shown in Fig. 13, and a schematic of the system in Fig. 14.

The system is controlled through a dedicated HP 2100A digital mini-computer, equipped with 24 K of core storage and a magnetic tape system for supplementary storage. The computer is a general purpose 16 bit machine with a typical instruction cycle time of 1.96 microseconds, and supports ASSEMBLER, FORTRAN, ALGOL and BASIC languages. Programs are entered through a keyboard terminal, and are stored and edited using punched paper tape, or, once fully debugged, on magnetic tape. The computer also controls a digital plotter.

Up to 16 channels of analog data can be digitized by an HP 5610A Analog to Digital Converter (ADC). The ADC is capable of making 100,000 samples per second with ten bit resolution.

An HP 6940A multiprogramming unit equipped with various interface cards permits other communication with the laboratory hardware. A four channel, twelve bit Digital to Analog Converter (DAC) allows analog voltages to be output over a ±10 Volt range. Twelve digital input and twelve digital output lines are also
available.

The computer controls the jet valves through the interface described in the previous section. The multiprogrammer is used to output a five bit code corresponding to the number of the valve to be controlled, and another bit enables the servo motor. If the valve setting is to be changed, the new setting is output via the DAC and the motor is enabled. The valve setting can be read at any time using the ADC, and a single digital return line indicates when the valve is set, i.e. the potentiometer voltage matches the DAC setting.

The tunnel is equipped with a single probe traversing rig, with its two transverse displacements under digital control through the use of stepping motors. The computer outputs the stepping pulses, which are conditioned and buffered by the stepping motor controller, and then used to drive the vertical and lateral motors. It is possible to position the probe to within one step, or 0.0126 mm in the lateral and 0.254 mm in the vertical direction, by counting the number of steps from a reference point.

At its highest speed, the traverse travels at about 18 cm/sec in the lateral, and 0.63 cm/sec in the vertical direction. The traverse can also be moved manually to any position along the length of the growth and test sections, and is normally parked at the extreme downstream end of the test section when not in use.

The traversing rig is shown in Fig. 15, and is described in detail in Ref. 2. The horizontal structure is covered with an airfoil to reduce its effect on the flow, and the complete rig causes blockage of about ten per cent of the test section area. The probe is mounted below and ahead of the airfoil so that it measures relatively undisturbed flow. The physical limitations of the structure limit the probe travel to the bottom six rows and middle ten columns of jets (see Fig. 3). Electrical and software stops prevent the traverse from being driven outside this region.

The probe is equipped with a cross-wire hot-wire transducer, processed by DISA 55D01 anemometers and DISA 55D10 linearizers. These provide measurement capability for flows from 1 to 90 m/sec with a frequency response of up to 100 kHz. The velocity output is then processed by a PACE TR48 analog computer, and input to the HP 2100A through its ADC. The analog computer is a solid state, 10 V machine with 40 amplifiers, 10 integrators and 2 multipliers. A typical patch used to calculate the mean flow velocity from the linearizer output is shown in Fig. 16.

A discussion of experimental errors is given in Appendix B. In general, the tolerance on valve settings is under one per cent, that for relative velocity readings one to two per cent, and absolute velocity two to three per cent.

2.5 Tunnel Configuration

For the purpose of this study the tunnel was configured for the production of simulated planetary boundary layer flows. Surface roughness was provided by 1.5 cm bristles on a vinyl mat starting 1.85 metres from the jet exit plane and
extending to the end of the test section, and a 13 cm high barrier was located 1.7 metres from the jet plane (see Fig. 6). The traverse was positioned near the front of the test section, approximately 7 metres from the jet exists.

3. MEASUREMENT AND CONTROL SOFTWARE

3.1 Software System Structure

The basic control of the wind tunnel system is through the digital computer, and an extensive software system has been developed to simplify the process.

The system is organized as a library of small subroutines and functional modules to provide the greatest possible flexibility, as well as to ease debugging and testing. The programs are written in FORTRAN IV, except for the basic hardware interface routines which are of necessity written in the machine-level ASSEMBLER language.

Because the programs are generally used to control the physical system hardware or to provide human input or output, high speed response is not essential. Since the available core memory is only 24 K, the programs are optimized for minimal storage rather than fast execution.

There are a number of basic hardware interface and utility routines which are common to most of the main control programs. Subroutines are called to perform such common operations as changing the setting of a valve, or all 32 valves, or measuring the velocity at a particular point or along a given row. Finally, an extensive library of routines has been developed to process and plot the data thus obtained.

The routines can be controlled in an interactive manner, as well as being called by special purpose programs. The manual control systems TUSYS, DATAS and PLOTS provide real-time control of the tunnel, data measurement, data processing, and plotting functions, respectively. These systems may be easily expanded by a command in each to call an arbitrary subroutine (TSPEC, DSPEC or PSPEC) which is not stored in the library and may be loaded at run-time.

A number of special purpose systems have also been developed. For example, CALS is used for automatic calibration of tunnel parameters, and PROFL for automated profile setup. These systems also operate in an interactive manner, but the amount of operator intervention required is minimized.

A block diagram of the general software structure is given in Fig. 17, and an index to the currently available routines in Appendix C.

3.2 Hardware Interface and Utility Routines

The interface routines perform the actual detailed control over communication between the computer and the tunnel equipment, and the utility routines simplify the use of the interface routines by the rest of the software system.

The input of analog voltages is controlled through the machine level routine SAMPS, which samples eight channels of the ADC and returns the digital results in data array. Normally, the FORTRAN routine RDADC is used to actually measure an
RDADC averages the value for one channel over 1/60 second to reduce the effect of any AC power line noise in the signal cable, and scales the binary number returned by SAMPS to return a decimal voltage value.

RDPOT is used to measure a valve potentiometer setting, and returns the per cent ratio of pot voltage to the pot reference voltage, again averaged over 1/60 second. USAMP measures the velocity output from the analog computer using RDADC, after a delay time to allow the filter to settle, and returns a decimal value in metres/second.

Similarly, MPTIN actually reads the digital input status, but IZERO is used to extract the value of the single bit corresponding to the valve set/not set indicator. MPDAS outputs a voltage on one channel of the DAC, and JET outputs a digital number representing the valve column and row number and motor enable bit setting to the servo interface.

Actual control of the valves is performed by the FORTRAN routine DRIVE. DRIVE first uses LTEST to compare the desired valve setting to a table of measured limits, and if the setting is outside the allowable range, prints an error message and halts the computer. If the setting is valid, the servo is selected using JET and the setting output using MPDAS. The status is checked every 1/10 second using IZERO, and the routine exits either when the valve is set, or after a maximum time has elapsed. The 'set'bit status, the column and row number, and the remaining drive time are displayed on the computer's front panel using the machine routine SREG.

The traverse is controlled through the stepping motor routine MOVE, which performs software and electrical checks for boundary stops as well as calculating and generating the number of steps required to move the probe to a new position. The FORTRAN routine PMOVE is normally used to operate the traverse using jet exit grid co-ordinates. If an error or limit condition is encountered, PMOVE prints an appropriate message and halts the computer.

A number of FORTRAN utility routines are provided to simplify programming. DELAY causes the computer to wait for a specified time delay in seconds. OK stops execution and prints a message asking the operator whether to proceed or abort the next operation. PUNCH punches velocity data with a fixed format, and awaits until the output operation is completed before returning control to the calling program to avoid conflicts in the computer's input/output system.

SETUP is used for general system initialization, asking for the analog input and output channel numbers, the time constants for measurement, and initializing the traverse control subsystem. VALIM stores the table of measured valve limits in a common memory area for use by the valve setting routines. SETAT scans all 32 valves and measures their settings; MPRIN formats and prints the settings.

### 3.3 Tunnel Control and Measurement

The interface routines are in turn called by a series of operations routines, to perform such common functions as measuring the velocity profile along a particular row in the test section. These routines are also stored in the subroutine library, and may be called as needed for specific applications.
Manual control of the valve system, the traverse, and the velocity measurement routines is provided by the TUSYS system. The program operates in an interactive manner, with the operator being prompted for commands and control parameters as required. A block diagram of the system is shown in Fig. 18.

Control is through the keyboard, in conjunction with paper tape in some cases. System commands can be used to list all the valid commands at any time, to initialize the hardware, or to exit from the program.

The valve control commands can be used to read the setting of any or all valves, and the results can be printed or punched for future reference. The setting of one valve can be changed with DRIVE, or all 32 sequentially with GRID.

The traverse control commands are used to move the probe to any given position with PMOVE, or any standard measurement point with PROBE.

The velocity measurement routines are designed to automate the most commonly used procedures. The velocity can be sampled at adjustable intervals along any row or column using GDROW or UCOL, for selectable grid points across the test section with UGRID, or along an arbitrary path with PSCAN. As the velocities are measured, the values are printed and punched, as well as being stored in a special buffer area of memory for use by other routines.

3.4 Data Processing and Plotting

Because of the limited computer memory, it is not practical to have all the routines potentially useful for measurement and analysis on-line at the same time. Therefore, it is necessary to set up intermediate storage on paper tape for some purposes.

The data processing system DATAS is used to perform various sorting, arithmetic and utility functions on velocity data stored on paper tape. For example, measurements along a particular column or row may be extracted from the data for a grid scan and printed or punched. A block diagram of the system is shown in Fig. 19.

The numerical data obtained through the measurement system are useful, but it is difficult to spot trends and other aspects of system behaviour without some sort of graphical output. The computer is equipped with a digital plotter and a basic library of plotting routines, and a comprehensive plotting system has been developed for specific use with the tunnel system.

Like the tunnel control system, the plotting system is organized as a collection of utility subroutines called by a set of operations routines; a block diagram is shown in Fig. 20.

The basic plotter control subroutine is PLOT, which draws a line from the current pen position to another point. This is joined in the HP library by other routines such as SYMB which draws a symbol or character string, and NUMB which draws a number.

A number of additional utility routines have been developed to simplify the
production of graphs and other plots. A single subroutine call is used to initialize the plotter and plot parameters (PINIT); to draw the division marks (TICKS), plot the co-ordinates (AXNUM), and label the axes (LABEL); to draw a dashed line (DASH); or to draw a rectangular border around the finished plot (BORDR).

Standard routines are available to plot the data obtained with the standard measurement routines. COLPT plots the readings along a single column, with suitably labelled axes, and ROWPT along a single row. VLVPT provides an orthogonal view of the settings of all 32 valves, and VELPT of the velocities measured across the tunnel. VELPT uses the utility routine RANGE to find the maximum and minimum velocity, column and row range in the data set, and sets its axes accordingly without the need for these parameters to be specified in advance.

The PLOTS system provides interactive control of the plotting routines. Data are read from paper tape using TAPIN, any of the standard formats may be plotted, or a number of utility functions may be called. The PLTUT utility package allows the pen to be moved to any point on the plotter, lines and borders to be drawn, and symbols or words to be drawn on the plot in real-time without the need for writing and compiling a special program.

4. WIND TUNNEL CALIBRATION

4.1 Measurement System Characteristics

The physical characteristics of the wind tunnel and measurement system impose certain restrictions on the methods and accuracy of velocity measurement.

For example, it was originally expected that the blockage due to the traversing rig would not significantly affect the flow. However, experiments have shown that the velocity as measured with the traverse is up to five per cent higher than that measured with the probe alone mounted on a fixed support. The correction factor is sensitive to height, velocity and velocity gradient, and is particularly large near the bottom of the tunnel where the airfoil is near the floor and the mean velocity is low.

Therefore, a set of empirically determined correction factors must be used to convert the measured velocities to those actually present when the traverse is removed for normal tunnel operation. A typical set of correction factors is shown in Fig. 21 for measurement points at each two along the centre line of the tunnel.

The velocities presented in this report are as measured and are not corrected for the traverse effect, since the correction factors only apply to a limited range of tunnel conditions.

Fig. 22 shows the tunnel temperature as a function of time after startup. The temperature rises to about 14° C above ambient, then levels off during operation since there is a steady exchange of air due to the jet contribution. It can be seen that a 15 to 30 minute warmup time is needed to eliminate most of the temperature drift and the corresponding change in the probe output.

Although the hot-wire probes have a high bandwidth and correspondingly fast response time, the wide range of turbulence frequencies in the tunnel means that
the velocity output must be heavily low-pass filtered to obtain the mean value. For the current setup, a filter time constant of 13 seconds is used, and the filter is allowed to settle for 26 seconds before each reading is taken.

The characteristic time for the tunnel itself to react to a change in flow conditions can be estimated by simple fluid mechanics. It can be shown that the overall tunnel time constant varies inversely as the velocity. For a typical profile with velocities from 14 to 27 m/sec, at least 15 to 30 seconds must be allowed for the flow to settle after any change in addition to the filter settling time. This delay must be taken into consideration when changing the fan speed, valve settings or the position of the traverse airfoil.

Fig. 23 shows the response of the filtered mean velocity output to a step change in fan speed, and Fig. 24 to a change in the upstream valve, both measured near the centre of the tunnel. It can be seen that the combined tunnel/filter system has settled to better than 0.5 per cent within 30 to 50 seconds.

Fig. 25 shows the result of monitoring the steady flow at a fixed point over a period of time. It can be seen that the filtered output is essentially flat for the higher rows, but that for the bottom two rows there is some extremely low frequency fluctuation that is not filtered out. Analysis of these readings suggests that this fluctuation has a period of approximately 70 seconds, which is significantly longer than even the 20 to 25 second tunnel time constant at this velocity.

The variation has an amplitude of about one per cent, which can be significant in precision work such as measuring small changes for valve calibration. Consequently, in such cases the filter output must be further smoothed by averaging the readings over one or more periods.

4.2 Natural Profile Development

The boundary layer wind tunnel is used to simulate natural turbulent shear flows with varying turbulence and mean velocity profiles. In earlier experiments with a scaled-down, prototype ejector driven tunnel, it has been shown that virtually any desired velocity profile can be obtained through a combination of jet settings and various other devices (Refs. 3 and 4).

Surface roughness on the floor of the tunnel helps to set up and maintain the natural boundary layer type of profile, as well as creating turbulence in the flow. Small 'tripping' barriers are generally used as well, since their wake turbulence was found to have a significant effect on the net turbulence over the entire tunnel height. Selection of these turbulence producing devices is an empirical process, since there is as yet no detailed model to accurately predict their effect.

In general, it was found that through adjustment of the jets, the same mean velocity profile could be obtained with different turbulence causing devices and intensities, while fine adjustment of the jets had only a limited effect on the final turbulence profile. Consequently, the barrier and roughness are selected mainly on the basis of turbulence considerations, and the jets and fan setting are used to determine the final velocity profile.

Since the roughness suppresses the contribution of the bottom rows of jets, and the barrier may block or severely modify their flow, the behaviour of the jet
system depends on the particular wind tunnel configuration being used.

4.3 Profile Growth Characteristics

At the present time, the wind tunnel is configured for the production of boundary layer flows as described in Section 2.5. Fig. 26 shows the inside of the tunnel, looking upstream past the traverse from the downstream end of the test section. It can be seen that the tripping barrier completely blocks the bottom row of jets.

The velocity profile obtained by running the tunnel with the fan alone is shown in Fig. 27 for points downstream of the jet exits laterally and at every half row vertically, and for selected columns and rows in Fig. 28. The development of a natural boundary layer type profile due to the barrier and roughness can clearly be seen, as can the 'dishing' due to the abrupt contraction cone described in Section 2.1.

The profile obtained by running the tunnel with the jets alone, and all valves set to the same angle, is shown in Figs. 29 and 30. The natural profile development can again be seen, but the dishing effect is much less prominent, since in this mode the return flow plays a relatively minor role. The lateral flow is relatively uniform, except for a marked rise in velocity downstream of the jets controlled by the first column of valves. Since these valves have the shortest ducting, they are supplied with flow that has undergone less friction loss than in the other valves, and this may cause a higher output velocity. It may be possible to reduce this variation by suitable throttling of the feed lines or through readjustment of the trim valves, but for the present work the system was left unchanged.

The profile obtained by running the tunnel with both the fan and uniform valve angle jet flows is shown in Figs. 31 and 32. The effects of both the dishing and the jet rise can be seen in the combined flow.

The contribution of the fan and jet flow mixing to the profile development is more clearly seen in the velocities measured along the test section centre lines. Fig. 33 shows the profile for the tunnel driven by the fan alone, the jets alone, and the combined flow. It can be seen that the mixing is highly non-linear. The fold-back of the profile towards the top of the tunnel is due to the growth of the ceiling boundary layer, which is more prominent at the higher velocities.

Fig. 34 shows the effect of setting the valves to a fixed angle and varying the fan setting. The overall magnitude of the change is under 10 per cent for one step in fan speed, but the shape of the profile is seen to change as well. Fig. 35 shows the effect of fixing the fan and varying the valve settings. Here the change is up to 25 per cent, and the curves obtained with the valves at 0° and 90° give a good indication of the maximum and minimum profile velocities that may be achieved by controlling the jet velocities.

4.4 Valve Characteristics

The servo system provides control of the valve angle, or more precisely, the potentiometer angle. Since the velocity is the variable of interest, some form of velocity/angle calibration is useful.
Figure 36 shows the velocity at a typical jet exit as a function of pot setting. The velocity was calculated by measuring the dynamic pressure at the jet exit plane. The curve has the characteristic 'S' shape of a 'butterfly' valve, and the non-zero velocity for the 'closed' position is due to the valve construction (see Section 2.2).

Because of the unit-to-unit variation in valve assembly, the pot setting for the same angle varies from valve to valve. However, the limit pegs are mounted rigidly to the valve plates, and provide an external reference point. Table 1 lists the measured limit settings as a per cent of pot travel. The gearing causes the valves to change 3/2 times as fast as the pots, so the range of travel in degrees can be calculated and is shown in Table 2. The values are generally close to the expected 90°, and hence the valve angle can be determined by assuming that the 45° point is exactly half-way between the stops. Table 3 shows the limits as angles calculated in this manner.

Since the jets are controlled by a single valve for each group of three horizontally, the velocities cannot be adjusted independently when setting up a profile. Consequently, a single measurement point is used for each set of three jets. Fig. 37 shows the measurement positions normally used. The column 2 and 9 positions are used for measuring at the sides in order to achieve better uniformity in the centre of the tunnel, since the wall boundary layers extend to the outer two columns of jets.

While the valves could be calibrated by measuring the flow at the jet exits, their contribution to the fully mixed flow in the test section is of primary importance. Therefore, the valves are calibrated by measuring the change in test section velocity as a function of valve angle.

Fig. 38 shows the results obtained for four valves, for three different flat settings for the remaining valves, and with the results normalized to the 45° value. It can be seen that the change in velocity is relatively independent of the local flow velocity, except at the extremes of valve travel.

In the interest of reducing the number of calibration measurements required, a number of simple models for the change in test section velocity as a function of change in valve angle were studied. A simple four segment linear curve requiring only three measurements was found to be accurate to within ten per cent over most of the range of valve travel. The best fit was found to use the velocities measured at settings of 20, 45 and 75 degrees, and assumes that the change in velocity is linear from 15 to 45 and 45 to 85 degrees, but zero outside these limits. The resulting curves for four valves are shown in Fig. 39, and can be compared to the measured values for the same valves in Fig. 38.

Because the barrier completely blocks the bottom row of jets, the transfer function for the corresponding valves is significantly modified. Fig. 40 shows the measured calibration curve for the two outside valves in the bottom row. It is seen that opening the valves actually causes a decrease in the test section flow velocity directly downstream, though the magnitude of the change is much smaller than that for the other valves. Other measurements have shown a similar effect on the flow measured at surrounding points.

It is thought that the air from the bottom row of jets is deflected upwards by the barrier, causing a loss of momentum in the flow from the higher jets as it passes
through this transverse flow. Removal of the barrier causes a return to a more
typical calibration curve, as is seen in Fig. 41.

4.5 Automated Calibration System

Since the profile development and valve response depend on the barrier and rough-
ness used, the calibration procedure must be carried out for each new tunnel configur-
ation. This process has been considerably simplified by the development of a number of
special purpose subroutines to perform the tedious calibration measurements without the
need for manual control.

The software system CALS is used to provide control of the calibration routines.
A block diagram of the system is shown in Fig. 42.

TRESP is used to measure the tunnel velocity as a function of time, and was used
to obtain the results of Figs. 23 to 25. VACAL is used to measure the detailed
calibration curve for one valve, as in Figs. 38 to 40. VFLAT is a utility routine
used to set all the valves to the same angle.

The development of the natural boundary layer profile, for a given fan setting and
tunnel configuration, is measured as a function of valve settings using PCAL. The
valves are all set to a uniform 15 degrees, the resulting profile is measured at the
valve grid points (Columns 2, 4, 7 and 9), and the procedure is repeated for settings
of 30, 45, 60 and 75 degrees. A typical set of profile measurements takes about
three hours, and the results for a fan setting of No. 6 are shown in Figs. 43 and 44.
The velocity/angle data (Fig. 43) can be used to estimate the initial settings for the
profile setup procedure, and the column curves (Fig. 44b) can be used to estimate the
range of possible profile velocities and shapes attainable for a given fan setting.

VCAL is used to obtain the three-point calibration curves (Fig. 39) for the test
section velocity change available from the 24 measurable valves. A typical calibration
set takes about four hours, and Fig. 45 shows the resulting calibration curves for a
fan setting of No. 6. Since the calibration curves represent a small change in local
flow due to the effect of the upstream valve, it is expected that this measurement is
relatively insensitive to the fan setting, and need only be done once for each new
tunnel configuration.

Because of the limited computer memory and the great complexity of these routines,
it is not possible to load the entire calibration system at any one time. The utility
system CALUT can be used to reprocess and plot the data without the need to load the
tunnel control and measurement routines, hence such features as paper tape merge and
the plotter utility package described in Section 3.4 can be included. CALUT can
also be used to recalculate the calibration coefficients from the measurement data
in case the original was lost or the routine was halted before completion.

5. AUTOMATED PROFILE SETUP

5.1 Analytic Models for Boundary Layer Profiles

The primary purpose of the wind tunnel facility is to simulate the flow in the
earth's planetary boundary layer. Both the shape and the height of the boundary layer
profile are found to vary with the characteristics of the terrain (Ref. 5), but in general the mean velocity profile is found to approximate a power law function of the form

\[
\frac{U}{U_G} = \left(\frac{z}{Z_G}\right)^n
\]

(5.1.1)

where \(U_G\) = mean velocity at the top of the boundary layer, or 'gradient' velocity
\(U\) = mean velocity at height \(z\)
\(Z_G\) = boundary layer, or gradient, height
\(n\) = power law exponent, typically ranging from 0.16 for a flat surface to 0.35 for urban areas.

Experiments with the prototype tunnel of Ref. 4 have shown that simply setting the jet velocities to a power law profile results in a rather poor approximation to a power law velocity profile, and in fact to one with a different exponent. The development of the final flow from the mixing of the return and jet flows is a complicated process, subject to a wide variety of external and internal influences, and is not easily predicted.

However, it was found that for a given tunnel configuration and desired velocity profile, the jet settings are generally unique and repeatable. Using an iterative process of measuring the test section velocities, adjusting the valve settings, and repeating as required, the same valve profile is attained to within a few per cent in four or five passes, even with widely different starting values.

Because the jet settings are unique, they are in theory completely specified and calculable, provided an adequate model for the flow development can be found. Since there is no precise analytic theory for real, turbulent boundary layer flows, especially in the finite jet-driven wind tunnel case, the only likely candidate is a numerical approximation.

To obtain a high degree of accuracy with a numerical model for a complicated system, assuming the model can be developed, it is necessary to obtain a correspondingly large amount of calibration data. In practice, this would probably be more difficult and time-consuming than iteration through straightforward measurement and correction. Consequently, it was decided to adopt a simplified linear model for the profile growth, and to allow the actual nonlinearities to be compensated for by the feedback inherent in the iterative procedure.

5.2 Jet Velocity Influence Coefficients

Since the barrier and floor roughness are selected on the basis of turbulence considerations, and the fan setting affects the velocity across the entire tunnel, the fine trimming of the profile shape must be done by adjusting the jet velocities.

Since the total range of velocity control due to the jets is under 25 per cent, (refer to Fig. 35), a linearized model can be used to predict the effect of small changes in the jet flow.
To a first approximation, velocity changes in the fully mixed test section flow can be modelled as a linear superpositioning of changes in the jet velocities. The effect of the jet grid can be considered as the superposition of the influence of 96 ejectors each of which, if acting alone, produces a mean velocity directly downstream in the test section of $U_{ij}$. With all the jets operating, the resultant mean velocity in the test section at points directly downstream of the jet exits is represented by the 96 element array $U$. 

The transfer function relating changes in these velocities would take the form of a 96 x 96 matrix of 'influence coefficients' $\{c_{ij}\}$, such that

$$
\Delta U_{96x1} = C_{96x96} \Delta U_{96x1}
$$

However, since the jets are controlled in groups of three horizontally, there is a resulting reduction in the number of actual control variables, and the measurement points can be reduced to 32, giving

$$
\Delta U_{32x1} = A_{32x32} \Delta U_{32x1}
$$

Thus, if the 1024 elements of $A = \{a_{ij}\}$ 32x32 can be determined, and the difference between the desired and actual profile velocities is known for each measurement point, then (5.2.2) can be solved to find the required $\Delta U_J$.

5.3 Influence Coefficient Measurement

The relative influence of a particular jet on the test section flow at a given point is defined as the ratio of the change in flow velocity measured at that point to the change in velocity in the test section directly downstream of the jet, for the same change in valve setting (see Fig. 46). Results for a jet near the centre of the tunnel are shown in Fig. 47 for a $30^\circ$ change in valve setting. As expected, the influence has a roughly Gaussian falloff with distance, modified since the jet is not a true point source and because of the change in the other two jets controlled by the same valve.

The numerical values of the relative influence, expressed as a percent, are also shown in Fig. 47 for the jet grid points. If only the values at the 32 measurement grid positions are considered, and terms less than five percent are neglected, the $\{a_{ij}\}$ matrix is seen to be quite sparse. Only terms on or near the diagonal, corresponding to a given valve and the column and two rows surrounding it, are non-zero, and hence the number of coefficients which must be measured is vastly reduced.

The influence coefficients for the 24 measurable valves can be automatically measured using the INFCO program (see Fig. 48). The valves are initially all set to 45 degrees, and the probe is positioned directly downstream of each valve grid point in turn. The surrounding valves are set to $75^\circ$ one at a time, and the relative influence coefficient is determined from the ratio of the measured velocity change to the velocity change in the test section downstream of the $75^\circ$ valve as previously measured during the valve calibration process.

The velocities for the bottom two rows are averaged over a number of readings to compensate for the low frequency fluctuation described in Section 4.1. The
entire calibration takes about four hours and requires no operator intervention.

The measured influence coefficients for a fan setting of No. 6 with the tunnel configuration of Section 2.5 are shown in Fig. 49. It can be seen that the coefficients generally lack symmetry from column to column and row to row. Due to the natural profile development, the effect of the valves above a given position is greater than those below, and the values for the bottom row are also typical due to the barrier effects of Section 4.4. Consequently, the measurement must be performed for each valve and for each new tunnel configuration, rather than using a single simple model.

5.4 Profile Setup Procedure

With computer control of the valves and measurement system, it becomes possible to fully automate the profile setup process. Due to the lack of a detailed flow development model which can be simply solved for the required valve settings, a more empirical approach is required.

It was originally thought that the valves could be set using an approach analogous to the previously envisaged 32 channel hot-wire probe/valve servo system. Instead of measuring the downstream velocity and adjusting the settings of all of the valves at the same time, a single probe would be used and each valve adjusted in turn.

However, this technique is unworkable in practice, since the intermediate velocities measured during the process depend on which valves have already been changed, and therefore a detailed flow development model is still required. Furthermore, the settling time of up to a minute for the tunnel/filter system imposes severe restrictions on the speed with which changes can be made.

The approach finally adopted was to set all of the valves to some calculated setting, measure all of the downstream velocities, calculate the new valve settings based on the calibration data and the difference from the desired profile velocities, and repeat the procedure until the error is within an acceptable tolerance range.

This procedure is performed with the PROFL profile setup system. A block diagram of the program structure is shown in Fig. 50.

Since the top two rows of jets are outside the range of traverse travel, the velocities downstream cannot be measured with the automatic system. Based on previous results with manually set profiles, it was decided to fix the valves in the top row almost fully open (80, 90, 90 and 80 degrees for columns 0, 1, 2, 3) to compensate for the ceiling boundary layer, and the next row to settings half way between these and those of the highest measurable row.

The valves in the bottom row exert a relatively small effect on the mean profile velocity since the jets are blocked by the barrier, and the automatic routine would tend to set them to the limits for even a small change in velocity. Because previous results indicate that the bottom row valve settings significantly affect the turbulence profile (Ref. 4), for
the present work it was decided to set these valves fully closed (0°) and treat them as a constant of the tunnel configuration.

The profile setup procedure begins by selecting the profile parameters. As discussed previously, it is not possible to set up any arbitrary profile for a given tunnel configuration and fan setting, so the PCAL profile calibration results must be used to find the range of profiles attainable. For a given exponent and gradient height, the gradient velocity is selected manually using the column curves (Fig. 44b) to choose a value that places the profile within the measured range of profile velocities. The most critical parameter is usually the velocity at the bottom row of jets, since the corresponding valve settings are fixed throughout the iteration process.

The profile calibration curves (Fig. 43) are also used to determine the initial valve settings by assuming that the setting required to produce a given test section velocity with all valves set to the same angle is close to the ultimate profile setting. Only the range of settings from 15° to 75° is used to allow some leeway in the subsequent iteration process, and experiments have shown that the resulting initial velocities are all within ten per cent of the final values, thereby reducing the number of iterations required.

The next step is to set the valves and measure the actual velocity at the standard measurement points. The required velocity correction is then calculated and converted to a change in jet velocity according to the particular flow development model being used.

The change in setting for the valves is calculated by using the four segment calibration curves (Fig. 39) for all but the bottom and top two rows as discussed previously. The subroutine VASET determines which segment the previous setting is in, based on the valve angle, then uses the model to calculate the change in angle needed to produce the desired velocity change. If the new setting is outside the limits of valve travel, a warning message is printed and the valve is set to just inside the appropriate limit.

5.5 Influence Coefficient Model Results

The automated profile setup system was tested using the influence coefficient model for an n = 0.23 profile with a fan setting of No. 6 and the tunnel configuration of Section 2.5. The gradient height was set at 91.44 cm (3 feet) to agree with previous work, and the gradient velocity at 26 m/sec based on the profile calibration results. The calibration measurements of Figs. 43, 45 and 49 were used.

The velocity contribution from each valve for a given overall change was calculated using the subroutine SOLVE to solve by Gaussian elimination the system of equations represented by the coefficient matrix and the required test section velocity changes (see equation 5.2.2 and Fig. 49).

It was found that the maximum and RMS deviation from the desired profile velocities at the 24 measurable grid points actually increased from pass to
pass. The valve settings diverged from the 'correct' values as the system attempted to set some valves high and others low to compensate.

The procedure was first executed with the settings of the bottom row valves under program control instead of being fixed. As expected, these valves made extreme changes from pass to pass and almost half ended up at their limits after four passes (see Fig. 51 for the sequence of valve settings). Examination of the influence coefficient matrix of Fig. 49 shows some coefficients for the bottom row valves to be as large as 300 percent, so the routine would attempt to minimize changes in the row 0 valves to reduce their effect on the other rows. The desired row 0 correction would then be made mostly by a change in row 1, which would be compensated for by row 2, and so on. This leads to the wide variation in settings when combined with the large angle change needed for a given velocity change in the bottom row.

The process was then repeated with the valves in the bottom row left fully closed, and their influence coefficients deleted from the matrix.

The valve settings were seen to be better behaved (see Fig. 52), but there was still considerable row-to-row variation. While the velocities for the top rows rapidly converged to the desired values (within one percent in three iterations), those near the bottom of the tunnel slowly diverged.

In previous manual profile setup, results with less than three percent variation from the desired velocities were achieved in three to five iterations, and the corresponding valve setting profiles were relatively smooth. Since the valve settings are unique for a given profile, it was decided that both the row-to-row variation and the velocity divergence are due to fundamental inadequacies of the highly linearized model used.

The rapid convergence in the top half of the tunnel occurs in a region where the velocity gradient is small and the shear between individual jet flows is minimal. The required changes in valve settings are small, and the resulting valve settings are all clear of the limits. Consequently, it was decided that the failure of the influence coefficient technique is due to the inability of the model to cope with significant shear in the flow or valves at their limits which cannot provide the calculated flow changes.

5.6 Simplified Model Results

The setup procedure was repeated with a further simplified model which does not attempt to accurately predict the interaction between individual jet contributions, but instead relies on the iterative process to compensate for the actual effects of the flow mixing in a manner analogous to the previously used manual setup procedure.

An empirical gain factor was used to calculate the change in velocity required from each valve as a function of the desired change at the point directly downstream only. A gain factor of 0.4 was selected on the basis of an average value for the contributions of each upstream (diagonal) valve to the total contributions of the surrounding valves (each row), using the influence coefficient matrix of Fig. 49.
The procedure was tested for the $n = 0.23$ profile and 91.44 cm gradient height, but with the gradient velocity increased slightly to 27 m/sec to provide a higher target velocity for the bottom row. The traverse velocity correction factors previously obtained with the manually established 0.23 profile (Fig. 21) were used to modify the target profile velocities; the velocities measured and plotted were left uncorrected due to uncertainty about the range of applicability of these correction factors.

After five passes using the 0.4 gain factor, the maximum velocity difference at the grid points was 2.2 percent in the bottom row, and 1.4 percent in the other five measurable rows. The RMS error for all 24 positions decreased on each pass, and when the procedure was halted after five passes, was under one percent.

A detailed velocity scan of the resulting profile can be compared to the profile measured at the grid points only in Fig. 53. It can be seen that while the profile has been set quite smoothly at the measurement points, there is considerable variation in the flow at intermediate positions. The dishing effect is particularly prominent along the centre columns, with a departure from the desired velocity of up to five percent. The profile is generally well behaved in the vertical direction, though there is some variation in the flow between jet rows (e.g. rows 3 and 4).

The profile can be compared to that obtained by the previously mentioned manual approach in Fig. 54. This profile was established by manually setting the valves using a less rigid algorithm which also took into account the velocities at intermediate points, and particularly along the centre axis of the tunnel. It can be seen that the velocities downstream of the centre valve columns have been boosted to offset the dishing effect, resulting in grid point velocities which are slightly high, but giving a smoother profile overall.

The slight differences in the valve settings are also visible in the figure. The overall valve profiles are both smooth and of the same general shape, with a levelling of the settings between rows 2 and 4. The centre boost can be seen as the combination of lower settings at the edges and higher settings at the centre of the manual profile. The anomalously high manual setting for the row 0, column 0 valve is an effect of the limited range of velocity control and the peculiar transfer function of the bottom row of valves, and not the technique itself.

These results suggested that the setting criterion of minimal velocity error at the grid points is not optimal in terms of overall profile uniformity, particularly along the tunnel centre. Therefore, the setup procedure was repeated with the velocity correction for the two centre columns of valves calculated by averaging the desired correction for the two centre columns of valves calculated by averaging the desired correction at the corresponding grid point and at the tunnel centre on the same row.

The resulting series of valve settings is shown in Fig. 55, and a detailed scan of the velocity profile after five passes is compared to the manually set profile in Fig. 56. It can be seen that the profiles are quite similar, with the dishing effect minimized by boosting the grid point velocities in
the centre columns slightly above the target values. The auto profile is slightly smoother than the manual one, but both display the same irregularities (e.g. row 0) which are presumably due to peculiarities of the tunnel.

The velocity differences from the ideal values after five passes are shown in Table 4. The maximum deviation was 5.9 percent in the bottom row and 2.9 percent in the other five rows, and the RMS value 4.1 percent for the bottom row, 1.5 percent for the other five, and 2.2 percent for all 30 measurement positions (grid points plus tunnel centre column).

The velocity differences in the bottom row are significantly higher than those in the other rows since the corresponding valves were set fully closed and were not adjusted during the setup procedure. Since the resulting velocities are all high as well, it is reasonable to expect that the overall velocity profile could be significantly improved by setting the profile for a slightly higher gradient velocity, so that the target velocities for the bottom row match those actually measured.

Figure 57 shows a statistical analysis of the performance of the model during iteration. It can be seen that the mean, variance and standard deviation of the difference from the ideal velocities all converge to a fixed value by the third pass and there is no significant improvement on subsequent passes. Therefore, the procedure can be stopped after three passes, or about 1.5 hours of tunnel time.

In summary, it appears that the use of influence coefficients is not necessary for the successful operation of the automatic profile setup procedure in order to achieve results that are as good as or better than those obtained manually.

6. CONCLUSIONS

6.1 General

The automation of the control and measurement process has significantly improved the use of the boundary layer wind tunnel.

Using the new system, it is practical to obtain highly detailed calibration results and other data with minimal effort. For example, the mean velocity profiles of Fig. 56 each represent 120 measurements made in one hour, a number that would be unworkable with a manually controlled system. Consequently, it is possible to perform detailed studies of the tunnel characteristics and determine the effects of changing the tunnel configuration on the resulting velocity and turbulence profiles.

An extensive library of tunnel control, data processing and plotting subroutines has been developed, and is available to assist in general use of the facility. Both the hardware and the software have been designed in a modular manner to allow ease of modification in the future.

The use of the system has been demonstrated by measuring certain aspects
of the tunnel characteristics, and by automating the mean velocity profile
setup process.

6.2 Wind Tunnel Characteristics

Experiments have shown that mean velocity profiles obtained with the
jet-drive tunnel have a characteristic 'roughness' of the order of a few
per cent. The unevenness is evidently due to small variations in jet output
and the differential shear between jet flows, and would therefore be
difficult to reduce with the existing tunnel.

The 'dishing' effect due to the tunnel construction causes a pronounced
velocity defect along the centre columns, and attempts should be made to
compensate for this effect by adjusting the jet trim valves. The rise in
velocity downstream of the jets controlled by the column 0 valves might
also be corrected in this manner. Further investigation is required to
determine if this trimming is sensitive to overall flow conditions, however.

It has been shown that the use of a 'tripping' barrier strongly
affects the flow from nearby jets. Further investigation is required to
determine the effect of varying the settings of the blocked jets on the
overall turbulence profile, and to discover the cause of the extremely
low frequency velocity fluctuation encountered near the tunnel floor.

The modification of the flow due to the presence of the traverse air-
foil is significant and must be compensated for by determining an empirical
relationship to predict its effect. Alternatively, the traverse could be
redesigned to move the probe further away from the region of disturbed flow.
Efforts should also be made to modify the traverse so that it can be used
to measure the velocities in the upper two rows of the tunnel.

6.3 Automated Profile Setup

The automated tunnel control system can be used to set up a power law
mean velocity profile with almost no human intervention required.

It was found that the best results were obtained with the simplest
model of flow development. The partial success of the influence coefficient
model, with rapid convergence to the desired velocities in the upper half
of the tunnel, suggests that this approach is worthy of further study. However,
satisfactory results were obtained with the straight gain factor model, though
further investigation would be required to optimize the procedure and gain
factor used.

Particular difficulty was encountered in establishing a smooth lateral
profile across the tunnel centre. A much greater degree of control
flexibility would be provided by adding a fifth column of controlled valves,
and redistributing the centre six columns of jets so that each valve
controls two jets instead of three. However, the current departures of
a few per cent from a flat lateral profile are acceptable for general use
of the tunnel.
The system has been used to set up an $n = 0.23$ profile, with the velocity difference from the desired values having a mean under 0.5 per cent, a variance of 2 per cent and a standard deviation under two per cent for the 30 measured positions (grid points plus tunnel centre column). This profile was established automatically in 1.5 hours (three passes), as opposed to several days for the same profile set to similar accuracy by the previous manual technique.

Consequently, it is now much more practical to perform a series of experiments with varying boundary layer profiles.
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### Table 1 - Valve limits as per cent of pot travel

<table>
<thead>
<tr>
<th>ROW</th>
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### Table 2 - Range of valve travel in degrees

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### Table 3 - Valve limits in degrees

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Table 4 - Per cent velocity correction, n = 0.23 profile, final model after 5 passes.

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* MAX DIFFERENCE IS - 5.87%
* RMS DIFFERENCE IS 2.20%
Figure 1. General view of wind tunnel facility.

Figure 2. Wind tunnel plan view. (Ref. 1)
Figure 3. Tunnel co-ordinate system. Grid reference is looking upstream.
Figure 4. Layout of the jet supply system (Ref. 1)

Figure 5. Layout of the jet grid section (Ref. 1)
Figure 6. Typical boundary layer tunnel configuration.
Figure 7. Detail of butterfly valve and servo motor assembly.

Figure 8. Layout of a jet row and the jet supply lines (from Reference 1).
Figure 9. Original valve controller schematic.

Figure 10. Control panel of original valve controller.
Figure 11. New valve servo interface and controller.

Figure 12. Servo system block diagram.
Figure 13. General view of instrumentation system.
Figure 14. Instrumentation and control system block diagram.
Figure 15. Remote controlled traversing rig.

Figure 16. Analog computer circuit for mean velocity. Potentiometers adjust input gain, filter cutoff frequency $f_{\text{max}}$ and output scale ($1V = 10$ m/sec).
Figure 17. Software system general structure.
Figure 18. TUSYS tunnel control system block diagram.
Figure 19. DATAS data processing system block diagram.
Figure 20. PLOTS plotting system block diagram.
Figure 21. Traverse velocity effect correction factors. (n = 0.23 profile, fan setting = 6. Data is from Reference 8.)

Figure 22. Tunnel temperature (Ref. 1).
Figure 23. Velocity response for a step change in fan speed at time = 10 seconds (tunnel centre).

Figure 24. Velocity response for a 25 second ramp change in upstream valve setting starting at time = 10 seconds (tunnel centre).
Figure 25. Low frequency fluctuation of filtered mean velocity output at various jet (row,col) positions.

Figure 26. Upstream view of tunnel interior. The traverse is near the front of the test section. The jet exits are visible at the far end of the growth section behind the tripping barrier. The vinyl roughness mat is on the floor.
Figure 27. Fan driven velocity profile.
(Fan setting = No. 6)

Figure 28. Details of fan-only profile.
Figure 29. Jet driven velocity profile.
(All valves at 60 degrees)

Figure 30. Details of jet-only profile.
Figure 31. Combined fan and jet driven mean velocity profile. (Fan = 6, all valves 60 degrees)

Figure 32. Details of fan plus jet profile.
Figure 33. Overall profile development. Upper plot is column 5.5 (tunnel centre) and lower plot is row 3.5 (centre row) - see figure 3. Profiles are shown for jets-only-driven tunnel (all valves at 45 and 90 degrees), fan only (setting No. 6), and combined jets and fan drive.
Figure 34. Effect of fan speed on profile development. Tunnel driven by fan only.

Figure 35. Effect of valve setting on profile development. All valves same angle, tunnel driven by jets only.
Figure 36. Effect of valve setting on jet output velocity.

Figure 37. Standard measurement grid positions.
Figure 38. Valve calibration curves.

Figure 39. Linear valve calibration model.
Figure 40. Calibration curves for bottom row valves. Upper curve for (row,col) valve (0,0) and lower curve (at 90 degrees) for valve (0,3).

Figure 41. Bottom row calibration curve with no barrier for valve (0,3).
Figure 42. CALS and CALUT calibration system block diagram.
Figure 43. Profile development calibration curves. (fan = No. 6) Vertical axis is velocity (m/sec); horizontal is valve angle.
Figure 44a. Profile development at measurement grid points. (Fan setting = No. 6)
Figure 44b. Profile development at measurement grid points (by columns). Fan setting = No. 6, valves set flat 15 to 75 degrees by 15 degrees.
Figure 45. Valve calibration curves. (Fan = No. 6)
Vertical axis is velocity (m/sec); horizontal is angle.
Figure 46. Measurement of relative influence coefficients.

Figure 47. Relative influence of a single valve.
Figure 48. INFCO influence coefficient measurement block diagram.
Figure 49. Measured relative influence coefficients, expressed as per cent change in test section velocity at the measurement point compared to previously calibrated change directly downstream. Coefficients that are left blank are zero. Co-ordinates are valve (row,column).
Figure 50. PROFL profile setup system block diagram.
Figure 51. Valve settings for automatic setup using full influence coefficient matrix.
Fan setting = No. 6, $U_G = 26$ m/sec, $n = 0.23$. 
Figure 52. Valve settings for automatic setup with partial influence coefficient matrix. Bottom row valves set fully closed. Fan setting = No. 6, $U_G = 26$ m/sec, $n = 0.23$. 
Figure 53. Profile velocities at grid points and detailed scan after 5 passes using first simplified model. (Fan = 6, \( U_G = 26 \) m/sec, \( n = 0.23 \)).
Figure 54. Comparison of automatically set up and manually set up 0.23 profile for simplified model.
Figure 55. Valve settings for automatic setup with final simplified model. (Fan setting = No. 6, \( U_G = 27 \text{ m/sec} \), \( n = 0.23 \)).
Figure 56. Comparison of auto and manual 0.23 profiles, final simplified model after five passes. (Fan setting = No. 6, $U_G = 27$ m/sec).
Figure 57. Statistical analysis of performance of the final model during iteration.
APPENDIX A

SERVO INTERFACE HARDWARE

A-1 System Structure

The new servo interface provides the control functions necessary for the computer to measure or change the setting of any valve. A major design constraint was that the system remain compatible with the previous controller. In particular, this meant that the servo cables were not rewired, and the necessary modifications had to be made at the interface connectors.

A single analog servo loop is used, connected in turn to each motor/potentiometer to be adjusted. The basic system structure is shown in block diagram form in Fig. A-1.1; to the basic servo circuitry is added some additional control logic, a means of measuring the voltage at any one pot or enabling a particular motor, and a means of selecting the control signals for each operating mode.

There are three basic control modes: automatic, manual, and limit. The valve number, pot setting voltage and run/hold command are provided by the computer in the auto mode, and by front panel switches in the manual mode. In the limit mode, the normal system operation is disabled until the setting of the out-of-range valve is corrected.

A-2 Digital Control Signals

A particular valve is identified by a five bit binary number: two bits for one of four columns, and three bits for one of eight rows. A two channel digital multiplexer formed by IC2 and IC3 selects the address source depending on the state of the front panel AUTO/MANUAL mode control switch SW1 (see Fig. A-2.1). For manual control the address is set as a decimal number with thumbwheel switches SW3 and SW4. The computer's digital output lines are connected to the interface with about 10 metres of cable, terminated by the impedance matching networks R2/R3 to R10/R11 and buffered by IC1.

The RUN/HOLD line from the computer is terminated with a pull-down resistor (R1) only to ensure that the line is in the HOLD state when the interface is powered but the computer is off. In the manual mode the panel switch SW2 is used instead.

The actual state of the RUN/HOLD line is indicated by a green light (L1) on the front panel. High brightness and relatively high current incandescent lamps are used for the panel indicators so that they can be seen easily from a distance, such as from the computer booth. Consequently, the logic lines must be buffered by transistor power drivers such as Q1.

A-3 Basic Servo Loop

The voltage at any valve potentiometer can be measured using the 32 channel analog multiplexer formed by IC3 to IC6 and the associated decoder IC8 (see Fig. A-3.1). CMOS analog switches operating at 15 volts are used to pass the 0 to 10 V pot voltages, and consequently the 5 V TTL address
signals must be level shifted by IC7 and pullup resistors R12-17 to provide the necessary 15 V control voltage swing.

The multiplexer output is permanently enabled so that the valve settings can be read even when the motors are disabled, and is buffered by amplifier IC9 to reduce loading errors due to the relatively low input impedance of the computer's ADC.

The actual pot voltage is compared to a voltage representing the desired setting and provided by either the computer's DAG or a manually programmed DAC, IC12 (see Fig. A-3.2). IC12 is controlled by decimal thumbwheel switches on the panel, and its current output is converted to a voltage (with a resolution of 0.1 V over a 10 V range) by amplifier IC13.

The difference between the actual and desired settings is amplified by the power amp A1 and is used to drive the servo motor so as to null the difference. A1 is a Beckman Instruments Model 966, specifically designed for servo motor use. It is mounted on a small circuit board, and provides a current limited output of ±100 mA and a voltage gain adjustable from 30 to 400 Volts/Volt.

The servo amp output is continuously monitored by the window comparator formed by IC14a and IC14b to determine when the drive voltage is within a certain range about zero (set by trim pots R20 and R21). This provides a digital indication of when the valve has been 'set' and is used to turn on a blue panel light (L2, driven by Q4) as well as being returned to the computer's digital input.

A-4 Motor Switching

The drive voltage is normally connected to a common 'drive' line for all 32 motors, through the solid state switch Q6 and its associated driving logic IC11 and IC10d (Fig. A-3.2). The motors are individually enabled or disabled by making or breaking their other connection to ground with the switching circuitry of Fig. A-4.1.

Since the drive voltages can be either positive or negative depending on the direction of travel, bidirectional switches must be used for the motor control. Mechanical switches are cumbersome and relatively unreliable, and standard 'bipolar' transistors pass current in only one direction, so the inherently bidirectional Junction Field-Effect Transistors (JFET's) are used for the switching function. The 2N4859 JFET's used (Q5, Q6 and Q7-Q39) are rated to pass the 100 mA maximum drive current without overheating, but each transistor is provided with a heat sink for additional protection.

The JFET's must be controlled by a voltage that equals or exceeds the maximum input range, isolated from the 'gate' lead by a diode (see Ref. 6). It was decided to use two diodes per transistor, such that both diode inputs need to be high before the switch is turned on. One of the diodes is connected to one of four column lines, and the other to one of eight row lines, and consequently, only 12 driver lines are needed to control the 32 switches. The column and row lines are decoded with the TTL decoders IC15 and IC16, and are enabled by the RUN/HOLD signal. The signals are level shifted to the necessary ±15 V range by amplifiers
IC17a-IC19d operating as comparators.

**A-5 Limit Logic and Recovery**

When a valve is driven to one of its limit stops, a peg opens one of the two switches in series with the 'drive' lead for each motor (see Fig. A-1.1). Since in the current system all of the DRIVE lines are connected in parallel, the opened switch would be bypassed by the common DRIVE/RESET line connection for the other valves if a common 'reset' line is also used. This would allow the motor to continue to run if not otherwise disabled, and hence some additional limit detection logic was added to avoid the need for separate RESET lines for each valve.

Comparators IC10a and IC10b continuously monitor the original limit light leads, which are now connected in common for all 32 valves (see Fig. A-1.1). When a limit switch is operated, it connects one of these lines to the amplifier output, pulling the voltage up from the -15 V established by resistors R18 and R19. This is detected by one of the comparators and is used to turn on the appropriate red or amber warning light (L3 or L4) with Q2 or Q3, as well as to disable the motors.

The DRIVE line is disconnected by Q6 by the limit signal, which overrides the RUN/HOLD signal at the comparator IC11. As long as the limit switch contact is made, the motors can only be operated by the recovery system.

The recovery procedure is normally performed in the manual mode, since the RUN/HOLD signal must be active to connect the motors to ground. The temporary contact push-button switches enable the recovery mode as long as they are pressed. The appropriate voltage to move the valve away from the limit is connected by the switch, and connected to the RESET line through Q5, driven by IC10c. The DRIVE line is always disconnected in recovery mode in case the switches are pressed when none of the valves are limiting.

Once the limit switch has been cleared and the button is released, control reverts to the previous mode.

Since the valves would never be run to the limits under computer control except due to a hardware or software failure, which would have to be corrected manually, it was decided that the warning lights are sufficient and no limit signal is sent to the computer.

**A-6 Power Supply and Construction**

The power supply is of a standard design, and provides regulated +5 and +15 Volts for the circuitry, a 10 V reference for the potentiometers, and unregulated +4 V for the limit recovery voltage and lamp power (see Fig. A-6.1).

The stability of the pot reference voltage as a function of time is shown in Fig. A-6.2. It can be seen that there is a slight, but detectable, drift over several hours of operation after a 30 minute warm-up period. Since the local DAC uses the pot reference as its reference voltage, the manual settings are insensitive to this drift. However, the computer has an internal
reference and would therefore see the pot reference drift as a drift in valve settings.

Since the total pot current is under 100 mA, a precision temperature compensated reference could be substituted at reasonable cost. However, since several spare ADC channels are available, it was instead decided to let the computer measure the actual value of the reference voltage and use this to scale the pot readings. This is performed automatically at each call to the interface subroutines RDPOT and DRIVE and if a precision reference is installed in the future the only other change necessary is to delete the pot reference channel assignment in SETUP.

The interface control and logic circuitry is contained on three 10 by 13 cm circuit boards, and these are mounted along with the power supply and cable connectors in a standard 48 cm rack case (see Fig. A-6.3). The control switches and status lights can be seen in the figure.

APPENDIX B

EXPERIMENTAL ERRORS

1. Computer DAC (Analog Output)

The DAC has 12 bit resolution and is specified as being accurate to \( \pm 1 \) bit, after a few minutes' warmup. Over the \( \pm 10 \) V output range this means an absolute accuracy of \( \pm 9.76 \) mV.

2. Computer ADC (Analog Input)

The HP 5610A ADC has 10 bit resolution, and after warmup is specified to have <20 mV gain and noise error and <10 mV quantization error over the \( \pm 10 \) V input range. The RMS error is therefore less than \( \pm 22 \) mV.

3. Valve Setting

3.1 Measurement: The measured potentiometer voltage is compared to the pot reference voltage, so the RMS error for the ratio is \( \pm 31 \) mV for the 10 V scale, or less than \( \pm 0.3\% \) of full scale.

3.2 Setting: The actual valve setting depends on the servo amplifier gain and the motor deadband characteristics, as well as the DAC accuracy. In practice, settings can be repeated to within 2% always and usually better than 1%.

4. Probe Positioning

The traverse position has been found to be repeatable to one step, or less than 0.01 cm. The absolute positioning with respect to the jet exit grid depends on tolerances of tunnel construction, and is accurate to about \( \pm 1 \) cm.

5. Velocity Measurement

5.1 Equipment Uncertainty: The analog computer is scaled for a 10 V output
for 30.48 m/sec (100 feet/sec), so the corresponding ADC error is 0.2% of full scale. Other errors in the analog system are of the order of 0.1% for the computer, and 0.5% absolute and 0.25% relative for the anemnometer and linearizer.

5.2 Hot Wire Probe: Temperature effects are minimized by the use of temperature compensated probes, as well as by the tunnel's nearly constant temperature after warm-up. However, due to aging and other effects on the hot wire itself, the velocity calibration is found to drift unpredictably. Typically, the drift is under 0.5% over 3.5 hours, but drifts larger than 1% have been encountered.

5.3 Mean Velocity: The overall absolute error of the hot-wire probe and processing system is of the order of 2 to 3 per cent (Ref. 1). However, for small velocity changes and readings made within a short time period, the relative accuracy is to within one per cent or better.

5.4 Low Frequency Fluctuation: The lower two rows of measurement positions are subject to an extremely low frequency velocity fluctuation ($T \approx 70$ sec) with an amplitude up to 1% of the local velocity. This fluctuation is passed by the 13 sec time constant mean velocity filter and must be further filtered by averaging the readings over a period of more for precision work in these rows.

5.5 Traverse Velocity Effect: The presence of the traverse airfoil can significantly affect the flow, particularly near the bottom of the tunnel where changes as large as 5% have been found with a power law profile (see Fig. 21 and Ref. 8). This flow modification has been found to be dependent both on local flow velocity and on the overall velocity gradient, and is not easily predicted.

A set of empirical correction factors must be determined for each new tunnel configuration and profile by measuring the velocities with and without the traverse at a number of locations across the tunnel. When setting a profile using the traverse, the velocities must first be set using estimated correction factors, then trimmed using the factors measured at the approximate profile settings.

APPENDIX C

SOFTWARE SYSTEM

The software system is organized as a library of small subroutines and functional modules. The programs are written in the FORTRAN IV language, except for the basic hardware interface routines which are written in HP ASSEMBLER.

D-1: Interface and Utility subroutines (FORTRAN)

SETUP - initializes system parameters and traverse
VALIM - sets up table of limits for valve travel
PMOVE - positions traverse using jet grid co-ordinates
DRIVE - changes the setting of one valve
LTEST - tests for valve settings outside limits and corrects
IZERO - tests to see if valve is set
USAMP - measures mean velocity at probe position
RDPOT - measures potentiometer setting
RDADC - inputs an analog voltage for one ADC channel
OK - halts execution until operator gives an 'OK'
DELAY - generates a time delay in seconds
PUNCH - punches velocity measurement data on paper tape
SETAT - reads current setting of all 32 valves
MPRIN - prints current settings of all 32 valves

Interface and Utility subroutines (assembler)
SAMPS - samples 8 channels of Analog to Digital Converter
MPTIN - inputs 12 digital bits from TTL input card
MPDAS - outputs analog voltage on Digital/Analog Converter
JET - outputs valve column and row number and run signal
MOVE - moves the probe on the traversing rig
SREG - displays a (binary) number on the computer panel

D-2: Tunnel Control and Measurement System (FORTRAN)

Calling program: TUNNL (Manual control)
              COMBO (Manual control and plotting)

TUSYS - main system routine
DGRID - sets up new settings for change of all valves
GRID - changes the settings of all 32 valves
PROBE - moves the probe to a valve grid measurement position
TUSCN - controls velocity scan routines
GDROW - measures mean velocities along one row
UGRID - measures velocity along a column/row grid
PSCAN - measures velocity along an arbitrary route
UCOL - measures velocity along a column
TSPEC, ROWAX: Special demonstration routine

D-3: Data processing system (FORTRAN)

Calling program: DPROC

DATAS - main system routine
PTAPE - controls paper tape I/O for DATAS
RSORT - reorders data along a column or row
REORD - reorders data according to arbitrary order
MATH - performs mathematical operations on the data
DPRIN - controls printer output of data

D-4: Plotting system and subroutines (FORTRAN)

Calling program: GRAPH

PLTST - main system routine
COLPT - plots velocity readings along one column
ROWPT - plots velocity readings along a row
VELPT - orthogonal plot of velocities across tunnel
VVLVPT - orthogonal plot of valve settings
TAPIN - inputs data from paper tape
RANGE - finds column, row and velocity range in data
BOUND - finds column, row and velocity extremes
PLTUT - controls assorted plotter utility routines
BORDR - draws a border
DASH - draws a dashed line
CURSR - moves plotter pen according to keyboard commands
WORDS - writes a string of characters on plotter
TICKS - draws division marks along a line
AXNUM - numbers co-ordinates along an axis
LABEL - labels an axis
PSPEC - special routine to sketch the jet grid

These subroutines call the HP FORTRAN 'PLOT' library.

D-5: Tunnel Calibration System (FORTRAN)
Calling program: CALS
CALSB - main system routine
PCAL - performs 'profile' calibration measurements
VCAL - performs valve calibration measurements
TRESP - measures time response of mean velocity
VACAL - measures calibration curve of a single valve
VFLAT - sets all 32 valves to the same angle
PINIT - initializes plotter
PPSCN - plots orthogonal view of PCAL results
PPCOL - plots PCAL results for four columns
PPCAL - plots PCAL results as velocity/setting curves
PVCAL - plots VCAL results as velocity/setting curves
INFCO - measures relative influence coefficients
PRINF - prints influence coefficients

D-6: Calibration Utility System (FORTRAN)
Calling program: CALUT
CALUS - main system routine
PUNUT - paper tape utilities for CALUT
PTIME - plots TRESP results as velocity/time curves
PVALC - plots vacal results as a velocity/setting curve

The CALUS system also calls the CALS plotting routines PINIT to PVCAL

D-7: Automated Profile Setup (FORTRAN)
Calling program: PROFL
PROFS - main system routine
PRSET - initializes profile parameters
FIRST - determines valve settings for initial pass
PRERR - calculates velocity error for each pass
PROPT - plots measurement results for one pass
VASET - calculates new valve settings for a velocity change
SOLVE - calculates relative U change using influence matrix
The control and measurement system for the UTIAS boundary layer simulation wind tunnel has been automated. A digital computer is used to control the positioning of a hot-wire probe in the tunnel, to measure the mean velocity, and to adjust the velocity profile by setting the flow conditions at the upstream jet grid.

The use of the system has been demonstrated by measuring certain aspects of the tunnel characteristics, and by automating the power law velocity profile setup procedure.