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# Introducing Instrumentation and Data Acquisition to Mechanical Engineers using LabVIEW™*

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*For several years, LabVIEW has been used within the Department of Mechanical Engineering at the University of Strathclyde as the basis for introducing the underlying concepts and practice of data acquisition, and more generally, instrumentation, to postgraduate engineering students and undergraduate project students. The objectives of introducing LabVIEW within the curriculum were to expose students to instrumentation and experimental analysis, and to create courseware that could be used flexibly for a range of students. It was also important that staff time for laboratory work be kept to manageable levels. A course module was developed which allows engineering students with very little or no previous knowledge of instrumentation or programming to become acquainted with the basics of programming, experimentation and data acquisition. The basic course structure has been used to teach both undergraduates and postgraduates as well as laboratory technical staff. The paper describes the objectives of the use of LabVIEW for teaching, the structure of the module developed, how it is used for various student groups, and the experience gained from four years of teaching.*

## INTRODUCTION

LABORATORY WORK within university engineering departments is expensive, both in terms of the finance required to run laboratories and their equipment, and in terms of staff and technician time. This situation has been exacerbated in the UK by the rapid recent increase in student numbers. As a result, there has been a gradual reduction in the exposure that students get in experimentation, and a move towards simulation. It is clear, however, that engineering students should have knowledge of the role that experimentation plays in modern engineering practice, and engineering departments should expose students to modern data acquisition techniques.

For several years, LabVIEW™ has been used within the Department of Mechanical Engineering at the University of Strathclyde as the basis for introducing the basic concepts and practice of data acquisition, and more generally, instrumentation, to postgraduate engineering students and undergraduate project students. The number of students using LabVIEW has gradually increased. Currently, all students have experimental rigs demonstrated to them at second-year level with a focus on the data acquisition systems: these range from simple chart recordings, through systems based on programs written in the C programming language, to recent systems built with LabVIEW. In addition, final-year project students with an experimental project, and postgraduate students, follow an introductory course based on LabVIEW. It is the intention that all mechanical engineering students should have a basic knowledge of modern data acquisition with hands-on experience. An additional benefit is that students are then also introduced to concepts of programming. Although mechanical engineering students were formerly given instruction in programming in a high level language, they are now only taught how to use analysis software such as spreadsheets and maths packages. The graphical programming environment of LabVIEW has proven to be a suitable teaching mechanism for students to understand basic concepts of loops, case structures, etc., in a short period and to generate working programs.

As the result of being a long-standing traditional department, the mechanical engineering laboratories contain a large variety of experimental rigs. These have a variety of data acquisition systems, ranging from manual readings from gauges, through simple chart recordings, to the use of specially written computer programs in Basic or C programming language. With regard to the computer programs, it was generally found difficult to maintain the programs when the program author had left, largely due to the obscure low level calls to the A/D cards that were embedded within the programs. In 1995, the Energy Systems Division of the department therefore decided to standardise on LabVIEW for data acquisition, and this is gradually permeating through the whole

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department. There were clear benefits to be derived from standardising on one software package, and LabVIEW was selected after a review of the available software packages.

The objectives of introducing LabVIEW within the curriculum were:

1. to expose students to modern instrumentation and experimental analysis;
2. to create courseware flexible enough to be used by a range of students (postgraduate, undergraduate, technical staff);
3. to develop courseware that takes advantage of the comprehensive nature of LabVIEW to provide applications across a wide range of engineering disciplines;
4. to ensure staff time required for laboratory work is kept to manageable levels.

A course module was developed which allows engineering students with very little or no previous knowledge of instrumentation or programming to become acquainted with the basics of programming, experimentation and data acquisition. The module was designed as a mixture of lectures, tutorials and practical work, but with the emphasis on self-learning.

The basic course structure has been implemented:

- for groups of Faculty PhD students working on industrial Postgraduate Training Partnership projects (working with the National Engineering Laboratory at East Kilbride, near Glasgow);
- as a module within a postgraduate Master's taught course;
- for final year undergraduate project students who undertake a major final year experiment-based project;
- as a Continued Professional Development module for laboratory technical staff to appreciate modern data acquisition software.

The following sections describe the structure and content of the module developed, and the experience gained from tutors and student feedback. In addition, a description is given of other uses of LabVIEW in the department, particularly with respect to final-year project student work.

The data acquisition systems that were made available for both courses and project work were trolley-based systems with PCs with a low-cost A/D board. The simplest system used a National Instruments LabPC+ card with a ribbon connector and terminal block for connecting sensors. Other systems use National Instruments MIO cards linked to SCXI signal conditioning chassis, with modules for thermocouples, strain gauges, and a feed-through panel for other voltage signals, D/A channels and timing/counter functions. These trolley-mounted systems have proved to be flexible general-purpose data acquisition platforms that can be easily moved from one rig to another. In some cases, e.g. for the wind tunnel, fixed data acquisition stations were developed. The complete data acquisition system based on the LabPC+ card (including Pentium PC, A/D card, connectors and trolley) is in the order of US$2240; the larger systems based on SCXI cost in the order of US$7360. Note that these figures do not include the cost of the LabVIEW software, as the University of Strathclyde Engineering Faculty has a College Licence.

## COURSE STRUCTURE AND CONTENT

The course has been developed to be flexible, so that it can be followed by students with different levels of experience and ability. The target students are predominantly mechanical engineering students, although students from other engineering disciplines have also followed the course. The focus is not on giving the students a detailed knowledge of instrumentation, but enabling them to understand the basic concepts, and to give them a starting point for developing the data acquisition systems and analysis procedures they may need in their own project work (or indeed, in future industrial or research jobs).

In essence the students should:

- understand the underlying capabilities and structure of a state-of-the-art PC-based data acquisition system;
- be able to select and run existing library programs for data gathering and analysis;
- be able to write or modify simple programs for acquiring, processing and storing data.

Table 1 sets out the course structure in its most commonly used form—as an intensive one week module.

The important features are as follows.

- Background lectures on the components of a data acquisition system.
- An initial demonstration of LabVIEW to introduce the basic layout and concepts of the programming environment.
- Self-learning of the programming environment through the use of tutorials.
- Two experiments for which the students write their own programs—the first a simple experimental test rig, the second a more complex rig.
- Demonstration of data acquisition software applications on a variety of experimental rigs.
- Additional lectures covering common sensors and fundamentals of instrumentation (e.g. sampling and aliasing). This can be changed or extended if the students are likely to use other sensors e.g. for the measurement of pressure, strain, or vibration.

The course structure was extended to M.Sc. students who received a course module on instrumentation. This contained more detail at each level, but used essentially the same structure.

Table 1. Example syllabus for instrumentation course based on LabVIEW.

**Measurement Systems—Syllabus**
*Monday 18 Jan to Friday 22 Jan 1999*

| | |
|---|---|
| **Staff Involvement** | P Strachan, A Oldroyd, M Stickland |
| **Course Structure** | 5 days @ 6hrs/day; lectures: 6 hours; practical laboratory work 24 hours. Students are expected to work outside formal contact times. |
| **Laboratory Description** | A large part of the course will be undertaken in the computer laboratory for the student using data acquisition software as a 'virtual' laboratory. There will be two experimental exercises |
| **Main Text Books** | E. O. Doebelin, *Measurement Systems: Application and Design*, McGraw-Hill, 4th Ed, 1990. *LabVIEW Student Edition* (on temporary loan during classes). |
| **Overview and Aims:** | The use of computer-based data acquisition and processing systems is now routine for experimental engineering applications. The aim of this course is to introduce the student to measurement systems by considering transducers, calibration and data acquisition requirements. The particular focus will be the use of state-of-the-art virtual instrumentation software, LabVIEW. By the end of the course the student should understand the procedure and necessary considerations for obtaining experimental data and be familiar with current software for data acquisition and processing |

| **Time** | **Topic** |
|---|---|
| Mon 9:00–11:00 | Introduction and course overview: (the measurement system, reasons for measuring, active and passive transducers, analogue and digital signals, examples of system implementations.) Demonstration of LabVIEW. |
| Mon 11:00–12:00 | Computer lab—LabVIEW tutorial |
| Mon 14:00–17:00 | Computer lab—LabVIEW tutorial |
| Tues 9:00–12:00 | Computer lab—LabVIEW tutorial |
| Tues 14:00–15:00 | Lecture: Sensor and instrument specifications, noise, errors and calibration |
| Tues 15:00–17:00 | Computer lab—LabVIEW tutorial |
| Wed 9:00–10:00 | Lecture: Transducers for temperature measurement (temperature, heat flux and radiation sensors. calibration and standards.) |
| Wed 10:30–12:00 | Experiment. Write LabVIEW program to acquire data from pressure, temperature and volume sensors, then to process and analyse the acquired data., |
| Wed 14:00–17:00 | Continue with experiment and program development and testing |
| Thurs 9:00–10:00 | Lecture: Transducers for flow measurement (orifice plates, hot wire anemometry, flow visualisation, particle image velocimetry.) |
| Thurs 10:30–12:00 | Demonstrations: wind tunnel experiment, combined heat and power rig etc |
| Thurs 14:00–17:00 | Computer lab: LabVIEW program development for hot wire anemometry experiment |
| Fri 9:00–12:00 | Computer lab: LabVIEW program development for hot wire anemometry experiment. Test program to acquire calibration data. |
| Fri 14:00–17:00 | Continued program development and testing program on laboratory rig. |

Fig. 1. PVT gas law rig with data acquisition workstation.

## EXPERIMENTAL RIGS

The selection criteria for the experimental rigs were as follows.

- They should provide a range of complexity from simple acquisition of pressure and temperature signals through to more complex systems requiring control.
- They should demonstrate common mechanical engineering experiments.
- It should be possible to write a simple program to acquire, process and display the data.
- It should be possible to set more complex analysis tasks for more advanced and able students.
- The experiments should be easy to set up.

The two rigs selected were an adiabatic gas law apparatus and a flow experiment using hot wire anemometry. In both cases, the rigs could be used at different levels: from letting students simply run an existing program and observe and comment on the data acquisition system through to students writing programs from scratch to undertake the data acquisition and analysis.

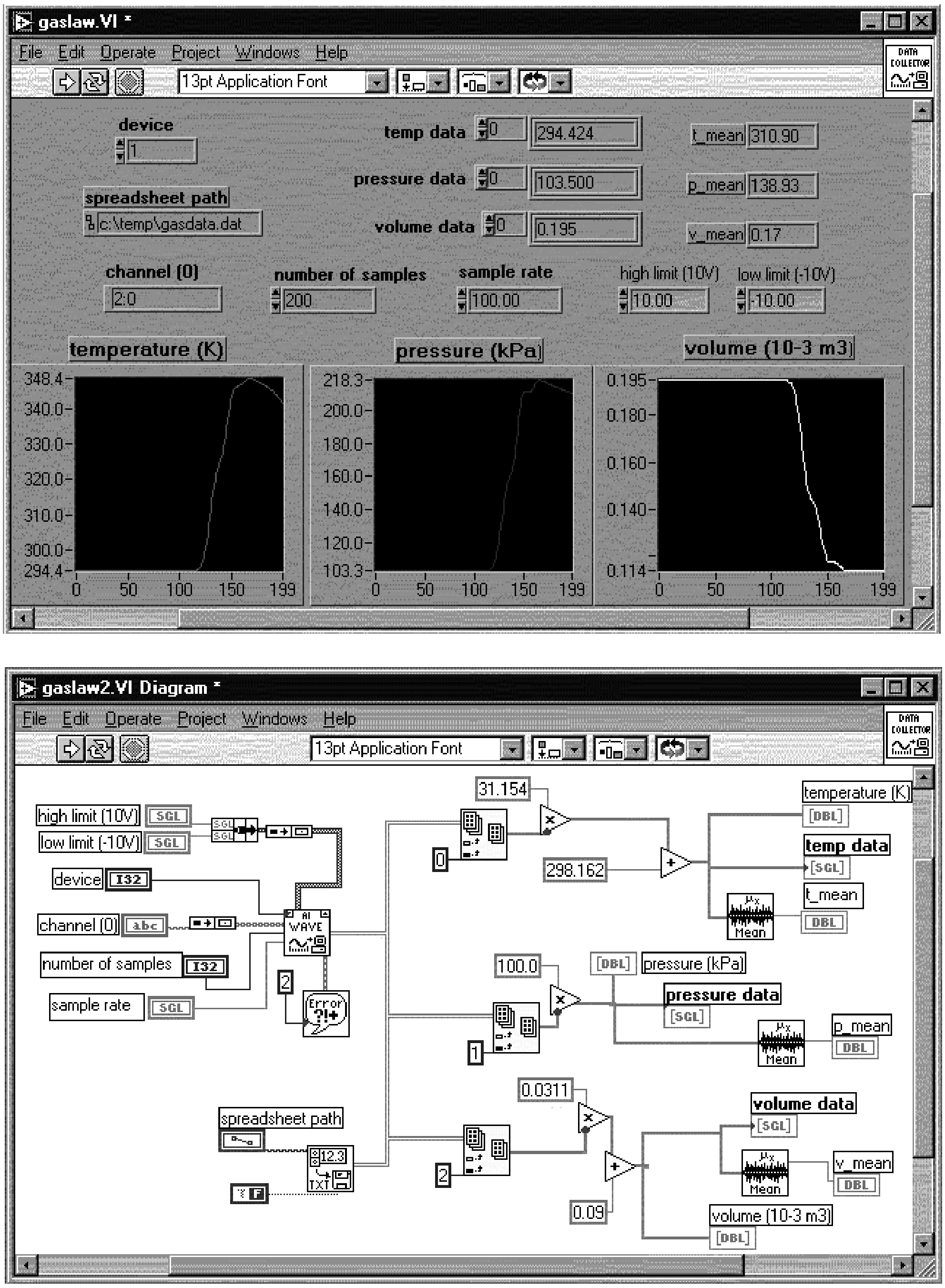


Fig. 2. (a) Front panel of PVT experiment VI; (b) Diagram of PVT experiment VI.

*Experiment 1:*
*Adiabatic gas law apparatus (PVT rig)*

The students are given an instrumented piston-cylinder device with a manually operated piston (Fig. 1) which, when displaced, will either compress or expand the gas contained within the cylinder adiabatically. The cylinder is instrumented with the following devices:

- Pressure transducer
- Temperature transducer
- Linear displacement transducer (for volume measurement)

The data acquisition system consists of a PC with an analogue to digital converter (A/D) card. The signals are all conditioned to the range from 0 to +5 V.

The students are given the calibration coefficients for the three measurement devices and are asked to write a data acquisition program that will record the variation in output voltage from the pressure, temperature and displacement transducers. When the data is recorded they are asked to convert the raw data to engineering data and then display the time-varying data from the three sensors. This is the minimum requirement. Students are asked to use additional time to progress the analysis to select the adiabatic compression part of the experimental data, and calculate the gas constant, then to calculate the work done during the compression.

The students are given a laboratory sheet describing the experiment and the sensors. They are given wiring instructions. They have already followed the student tutorial on graphical programming, so the only additional information they are given is on the analogue input VI (virtual instrumentation) to be used and its required inputs.

Tutorial assistance is given to the students as required to enable them to get a working program. Figure 2 shows a VI to undertake simple data acquisition, processing and display which all students are expected to produce as a minimum. It illustrates the ease with which a simple data acquisition system can be constructed.

At the end of the time allowed for this part of the course, students are shown a complete program for those who have not completed the extended analysis. The following VI (Fig. 3), written by one of the students, shows the extended analysis for selecting the adiabatic compression part of the experimental data, and calculating the gas constant.

This first experiment enables the student to test their ability in using a data acquisition system to acquire raw data and, given the calibration coefficient, to turn the raw data into engineering data. The analysis of the data is limited but does allow the student to present the acquired data graphically and to recognise that the experimental raw data can be post processed to form meaningful information.

Regarding specific learning outcomes, at the end of this experiment, the students have:

- worked with simple measurement of temperature, pressure and displacement;
- written a simple program to acquire, process, analyse and display data (and therefore developed a 'complete' data acquisition system);
- demonstrated the adiabatic gas law.

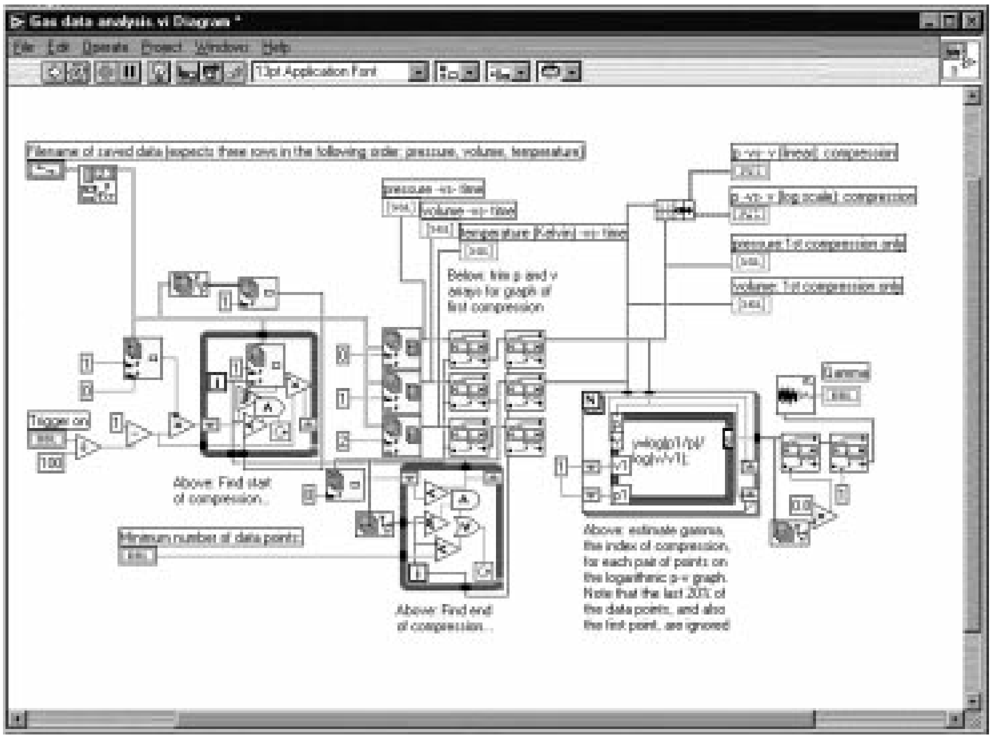


Fig. 3. Diagram of PVT extended analysis VI.

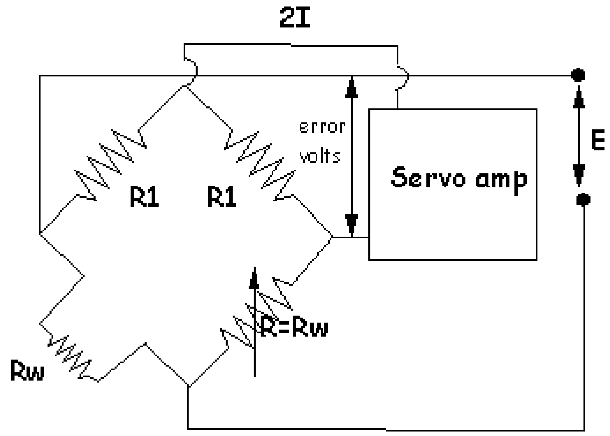


Fig. 4. Hot wire bridge circuit.


Fig. 5. Hot wire calibration curve.

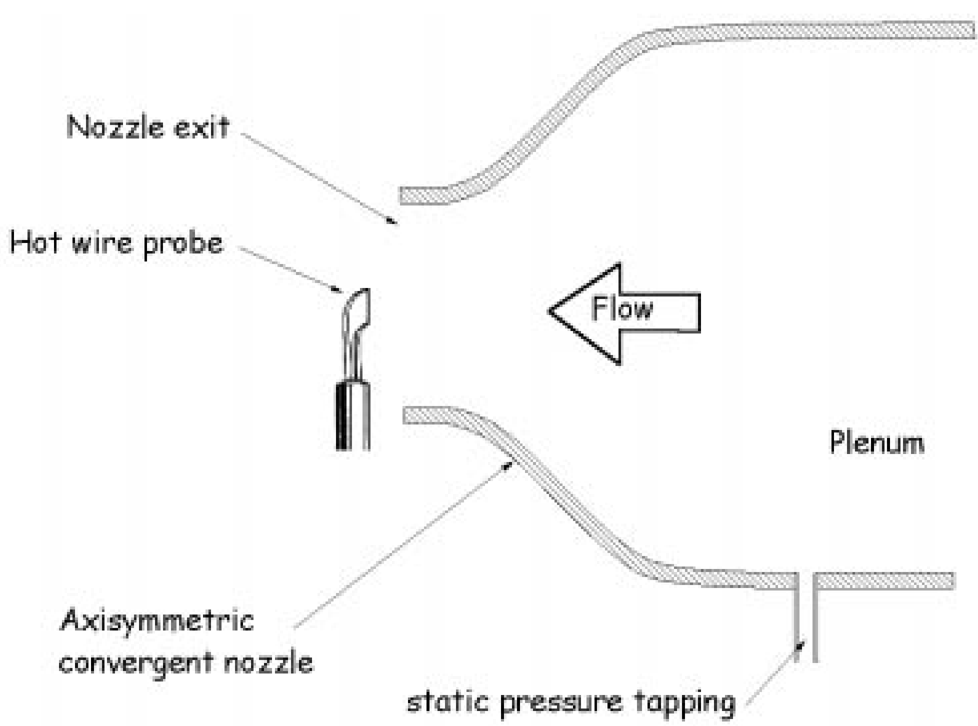


Fig. 6. Hot wire calibration rig.

*Experiment 2: hot-wire anemometry*

In this experiment, the students are required to acquire data from a constant temperature hot wire anemometer bridge circuit, to calibrate the transducers, to carry out an analysis of the transient signals, and, optionally, to control a stepper-motor-driven traversing system using the D/A function of the card mounted in the PC.

The output of the hot wire anemometer bridge is dependent upon the speed of the air blowing over the hot wire probe and is nonlinear. The bridge circuit may be seen in Fig. 4, with the hot wire probe represented as the resistance, $R_w$, and the output as the voltage, $E$. A typical calibration curve of voltage, $E$, against air speed, $V$, may be seen in Fig. 5.

The probe is calibrated by placing the probe in the jet issuing from a convergent nozzle fed by a plenum chamber attached to a high pressure air supply as shown in Figs 6 and 7. The total pressure in the flow can be measured by an inclined manometer attached to a static pressure tapping in the plenum. The pressure in the exit plane is atmospheric and hence the velocity in the exit plane can be calculated from Bernoulli's equation. The students record the variation in bridge output with air speed and create a calibration curve of air speed against bridge output. The students then fit either a polynomial or power law equation to the data set and produce a calibration equation which may be used within the data acquisition system to convert from raw to engineering data.

When the calibration is complete the students are required to undertake one or more of three experiments with the hot wire probe.

- **Jet traverse:** The students traverse the calibrated probe along the length of the jet to analyse how the jet decays over a distance. This allows the student to plot a simple graph of velocity against distance, such as shown in Fig. 8. The traverse is carried out manually.
- **Vortex shedding:** The student places the hot wire anemometer downstream of a circular cylinder and uses the hot wire probe to measure the transient flow field in the cylinder's wake. When the data has been acquired the student may plot the variation of velocity with time and recognise that the flow field is highly transient. The student is then required to undertake a spectral analysis of the velocity waveform in order to identify any dominant frequencies within the wake. This signal analysis yields the frequency of the Von Karman vortex street that is shed by the cylinder. The dominant frequency is then used to calculate the Strouhal number of the flow and it is compared with the published value for the cylinder.
- **Wake traverse:** The hot wire probe is traversed across the wake of a two-dimensional wing section in a small wind tunnel. The probe is traversed by a stepper-motor-driven traversing rig, which is controlled by the data acquisition system via the A/D card. As the velocity at each point across the wake is recorded, the total loss in momentum within the wake can be calculated and the drag force and hence the drag coefficient of the section determined and compared with published data. The student is also asked to undertake a spectral analysis of the wake in order to determine whether there are any dominant frequencies within the wake or whether it is just random turbulence. Figure 9 shows an example analysis VI written by one student to apply calibration coefficients, display velocity data, undertake a frequency analysis and calculate turbulence intensity.

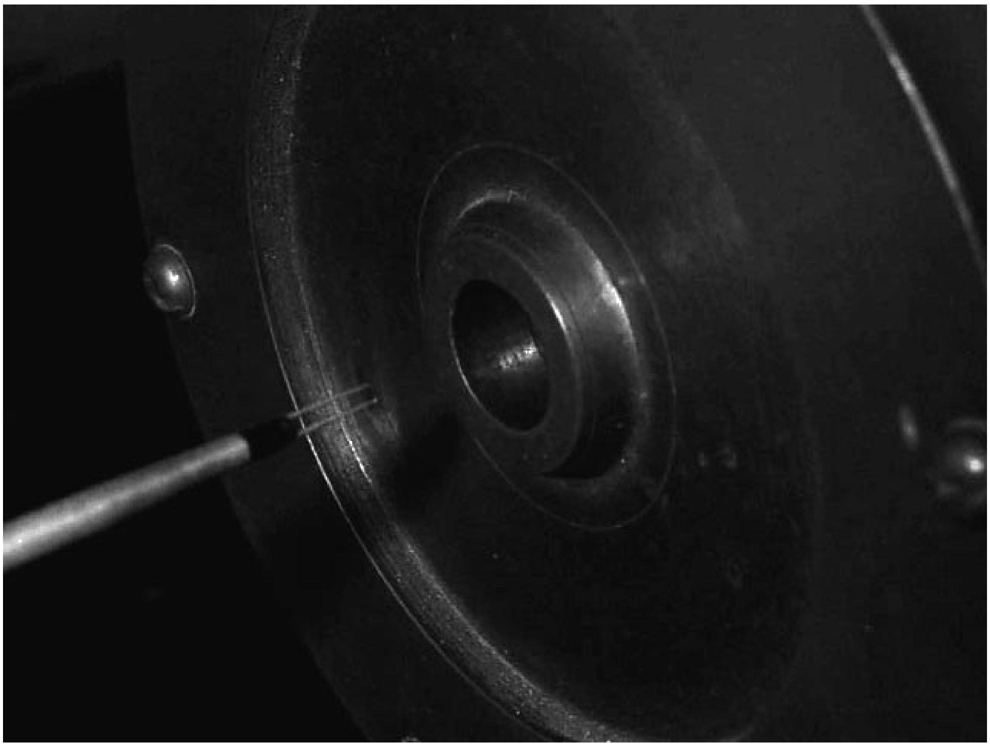

Fig. 7. Hot wire probe in calibration rig.

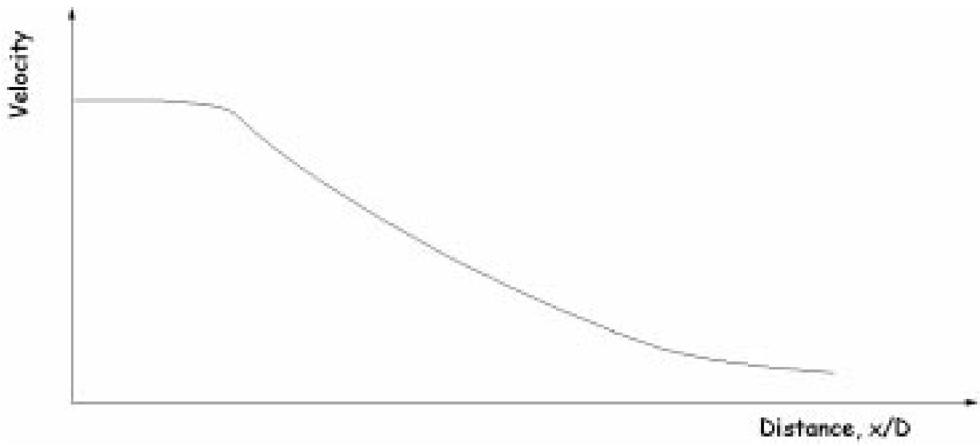


Fig. 8. Axial jet traverse.

Regarding specific learning outcomes, at the end of this experiment, the students have:

- undertaken calibration and realised its importance;
- written programs to acquire, process, analyse, save and display data (the level of analysis can be tailored from simple to complex);
- written programs with a control function (optional extension);
- observed turbulence and understood how it can be measured and analysed.
- written a laboratory report focusing on the experimental configuration data acquisition and analysis.

## DATA ACQUISITION DEMONSTRATION RIGS

An important element of the teaching is to show modern data acquisition systems applied to a variety of experimental configurations. Over the last few years, a number of rigs have been developed, or modified, to LabVIEW-based systems. The following summarises the rigs demonstrated to students.

*Wind tunnel*

For the wind tunnel demonstration, the 1.5 m diameter open working section closed return tunnel within the University of Strathclyde is

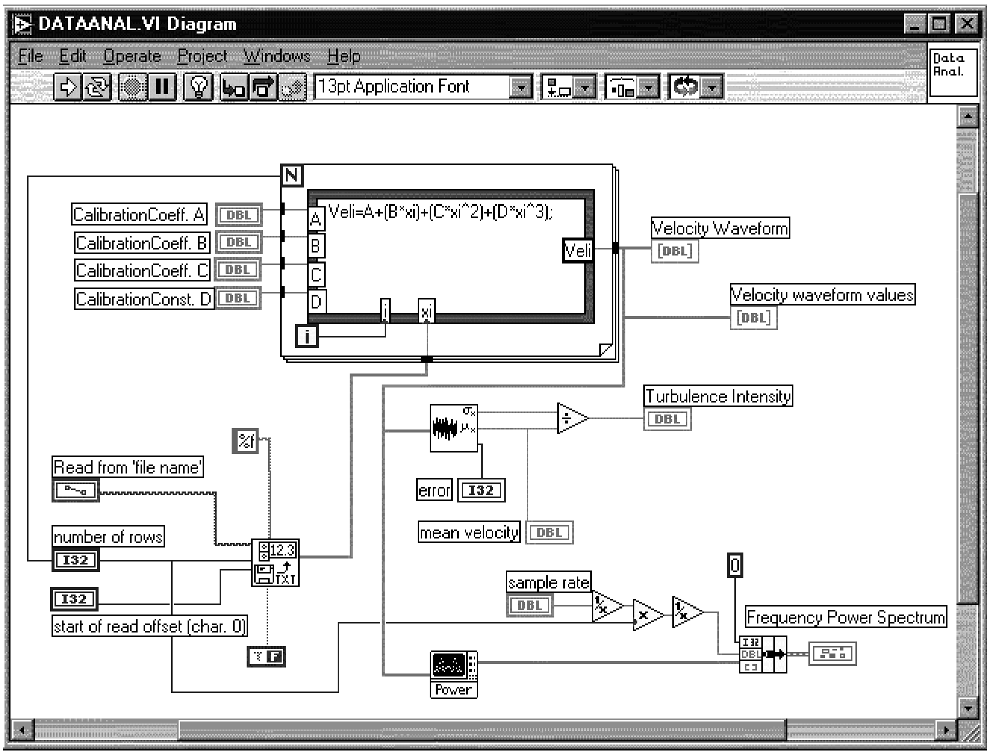


Fig. 9. Diagram of hot wire anemometry analysis.

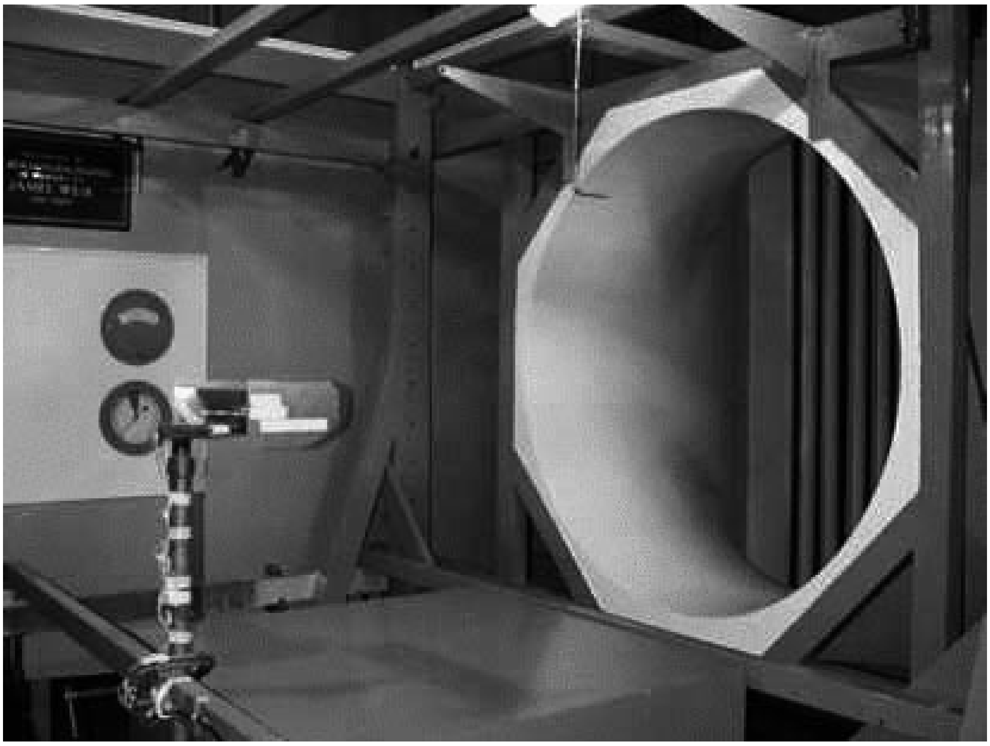

Fig. 10. University of Strathclyde wind tunnel showing a sting mounted model.

used. A NACA 2412 aerofoil section is pressure-tapped and fixed in the tunnel (Fig. 10).

The pressure taps from the working section are fixed to a 20-port Scanivalve which is in turn connected to an electromanometer pressure transducer that converts the pressure to a voltage in the range ±2 V. The voltage signal is then fed into a PC via a National Instruments AT-MIO16 card. Another electromanometer is used to monitor the wind tunnel free stream velocity and the aerofoil pressure taps are connected to a multi-tube inclined manometer as well as the Scanivalve. The system is then used to obtain pressure data and hence calculate the lift and drag coefficients for the object under test. The pressure data is displayed on a graph and then compared with the inclined manometer readings.

The demonstration shows the use of data acquisition in acquiring and analysing data, the control of other equipment via digital outputs and the speed of the system in acquiring data in comparison to the old traditional method as demonstrated by the multi-tube manometer.

The system is also used to measure aerodynamic forces on a test object using a two-component strain gauge balance connected to the PC via a SG-2413 add-on card. This is a developing project.

*Combined heat and power*

The small scale Combined Heat and Power (CHP) unit demonstrates how using both electrical power output and heat recovery improves the overall efficiency of the system. The two-cylinder Petter diesel engine (Fig. 11) is connected to a single-phase, self-exciting induction generator. The resulting electrical AC output is connected to resistance heaters.

There are two heat recovery circuits. The first is a circuit of the engine cooling water which feeds panel radiators. The second is a multi-pass exhaust gas-to-water heat exchanger surrounding the engine exhaust, with the heated water flowing through a radiator before returning to the heat exchanger.

A large number of sensors are demonstrated on the rig. For calculation of system efficiency, the following measurements are made:

- water and fuel flow rates, with turbine flow meters;
- inlet and outlet temperatures for the water and gas flowing through the exhaust heat exchanger and the inlet and outlet temperatures for the cooling water circuit, with type K thermocouples;
- real and reactive power, with measurement of true power, voltage and current sensors.

In addition, control of load switching using digital output lines and control of engine speed can be demonstrated. Engine speed is measured by a magnetic pickup adjacent to the toothed flywheel, and a control signal (based on LabVIEW's in-built PID controller VI) sent to a DC servomotor attached to the engine throttle. A standard LabVIEW VI was modified to send out a pulse-width modulated pulse train to the servomotor.

The front panel of the VI displays all the outputs from the sensors, as well as calculated system efficiencies. It is thus a good demonstration

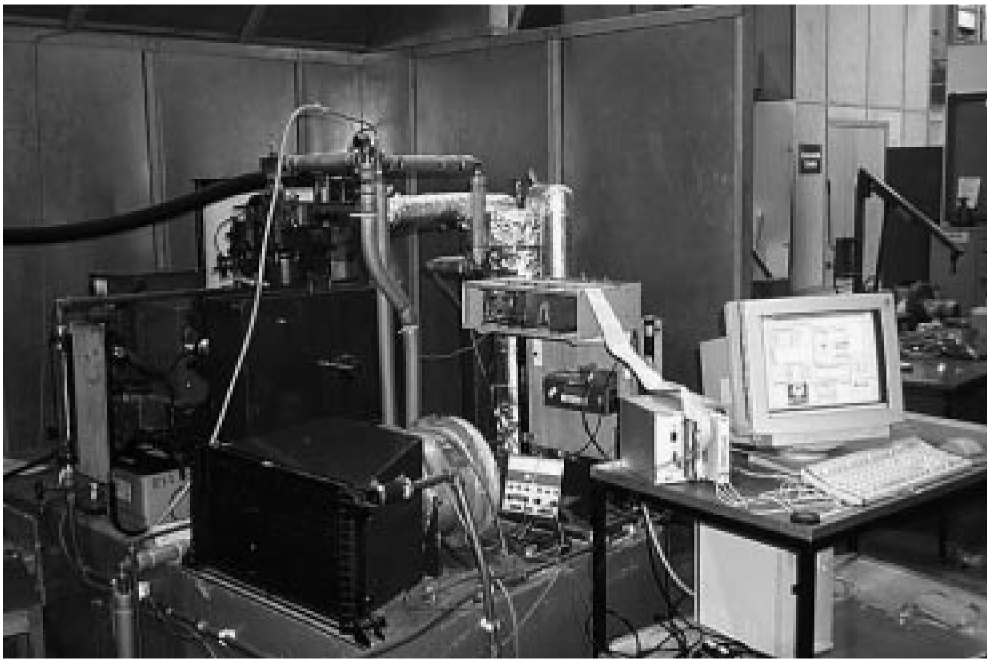

Fig. 11. CHP rig with LabVIEW workstation and SCXI chassis.

package for data acquisition learners as well as a useful energy demonstration for second-year undergraduates.

*Ricardo engine*

The Ricardo engine has been used as a second-year undergraduate data acquisition and engine cycle demonstration within Thermofluids for a number of years. The engine is a single cylinder, four-stroke capable of running on either diesel or petrol cycles by changing the cylinder head. The compression ratio of the engine can also be altered while the engine is in operation. Normal running speed is between 1000 and 3000 rpm.

Recently a project was initiated to update the data acquisition system using LabVIEW. An AT-MIO 16 XE-50 card is mated to a SCXI chassis. Measurements are taken from the air flow meter to determine air consumption. Pressure sensors are used to determine the pressure within the cylinder and the crank angle is measured via a photo-optic device. Synchronisation of the two sensors is provided by an additional sensor measuring the piston top-dead-centre. Temperature measurements are taken for the cooling water intake and outlet, along with exhaust gas temperature. Hence the compression ratio and efficiency of the engine can be monitored along with the pressure-volume diagram, demonstrating an actual four-stroke cycle to the students.

The system demonstrates the use of SCXI for reading multiple data inputs that originate from different sensors. Also, the use of external triggering is demonstrated as a means of initiating data acquisition as opposed to the more normal user-started process.

*Laser laboratory*

The control of external devices via a GPIB interface is demonstrated using an experimental set-up in Laser Physics, where a Hewlett Packard analyser is controlled, with acquired data passed back into the LabVIEW program.

## FINAL YEAR PROJECT WORK

In their final year, the undergraduate students in Mechanical Engineering undertake a four-credit project. Table 2 shows a list of the final year undergraduate current projects that utilise LabVIEW. The main stumbling block in these projects is the different levels of computer literacy of the students involved. As these projects are primarily treated as the students' own work, the onus is on the student to learn and use LabVIEW with minimal staff involvement.

To do this, a set structure has been devised and implemented which appears to work well with the students. The first step is to provide the students with access to the LabVIEW student edition [1]. This allows the students to get used to the graphical user interface LabVIEW employs and to learn basic programming skills. The students are given around two weeks to do this and are then asked to write a program as in Experiment 1 above. When this has been completed successfully, guidance specific to the student's project is given as necessary.

## DISCUSSION

The experience of running the course for postgraduate students was that all the students, even

Table 2. Current final year undergraduate projects using LabVIEW.

| Project | Description | Measurements |
|---|---|---|
| 3-D Strain gauge balance | Design, test and build a 3-component strain gauge balance. | Drag, lift, and pitching moment. |
| Combined heat and power | Modify a data acquisition system to obtain data to extend measurement system and analysis. | Thermal and electrical efficiency, and torque measurement. |
| Stirling engine | Instrument and assess performance characteristics of a pressurised Stirling engine | Pressure, temperature and rotational speed. |
| Building materials conductivity | Design and build a test rig to British Standards that will determine the thermal conductivity of building materials. | Temperatures. |
| Ducted wind turbines | Acquire data from a small scale ducted wind turbine and analyse its performance. | Wind speed and direction, rotational velocity and power output. |
| Small scale jet engine | Control and performance analysis of a small-scale 100 N jet engine. | Flow rates, pressure, feedback control and temperature. |
| Closed working section wind tunnel | Control wind tunnel speed and a scanning pressure instrument, and acquire pressure and velocity data. | Feedback control, tunnel air speed, pressures, and velocities. |
| Two-phase flow rig | Measure frequency, velocity and weight of slugs. | Strain gauges. |
| Climate station | Set up climate monitoring station on roof. | Solar radiation, wet and dry bulb temperatures, wind speed and direction, pressure. |
| Welding plate | Monitor temperature distribution as two plates are welded together. | Temperatures. |

though the majority had no previous experience of programming or data acquisition, were able at the end of one week to produce programs to undertake simple data acquisition. Several of these students have gone on to develop and/or use quite complex experimental rigs (with or without LabVIEW). Final year project students have also picked up the basic concepts easily, although they follow the course with a greater element of self-learning over a longer period.

All students (for the last three years) who followed the standard course outlined above were asked for feedback on whether they thought the structure of the course gave them a good introduction to the basics of instrumentation, and in particular what they thought of the computer laboratories and experimental work. The responses were generally very positive. Several students commented that it was rewarding being able to learn, in a short time, how to write a data acquisition program and to be able to analyse, display and save the data. Even those students not involved in experimentally based projects reported that they found the course worthwhile.

## CONCLUSIONS

The primary benefits that the authors have perceived from standardising on common data acquisition software (in this case, LabVIEW) are as follows.

- Having a common software base means that several academics can understand the data acquisition programs, so the department is not reliant on individuals.
- An excellent range of analysis functions is readily available.
- Trolley-based data acquisition stations can be used on a variety of experimental rigs.
- The use of simple acquisition VIs means the students (or academics) do not have to get involved in low level calls to the data acquisition cards.

From the student's perspective, the observed benefits are as follows.

- They gain confidence with data acquisition and instrumentation as a result of being able to write and run their own programs.
- They understand basic programming concepts such as loops and flow control.
- They have been introduced to the use and importance of calibration.
- They have applied simple signal analysis methods.

Teaching of data acquisition with LabVIEW is not without problems. The size of LabVIEW is often daunting at first, and although student edition user guides [1] are used to provide tutorial material for the programming concepts, it is sometimes difficult for students to locate relevant examples. Other data acquisition software may be easier to use, but it is believed that the comprehensive nature of LabVIEW makes it better as general-purpose software.

For the future, it is planned to extend the teaching of modern data acquisition to all mechanical engineering students, not as a major module, but as a common element at various stages in the curriculum. This will be done:

1. by gradually updating rigs used in laboratory

work through all stages so that students can run pre-set programs to acquire data;
2. by including the availability of data acquisition systems within design classes; and
3. by including introductory data acquisition lectures and laboratories in undergraduate courses.

The updating of equipment and experimental rigs, and the inclusion of modern data acquisition in the curriculum will be an evolutionary process. It is intended that the data acquisition provision will be gradually enhanced, with more flexibility built into the courseware described in this paper.

## REFERENCE

1. L. K. Wells, *LabVIEW Student Edition User's Guide*, Prentice-Hall, New Jersey (1994).

**Paul Strachan** is a lecturer within the Department of Mechanical Engineering at the University of Strathclyde. He is also Deputy Director of the Energy Systems Research Unit (ESRU). His primary research interest for the last 11 years has involved the development, validation and application of simulation tools for use in the performance evaluation of energy systems, focused in particular on the ESP-r thermal simulation software developed at the University of Strathclyde. He has been active over a number of years in running training courses involving the use of both simulation and data acquisition.

**Andrew Oldroyd,** after graduating from Strathclyde University in 1995, has spent the last 4 years working as a Teaching Assistant within the Department of Mechanical Engineering at the University of Strathclyde. His main research topics are Computational Fluid Dynamics and experimental aerodynamics, and he has been actively involved in updating the instrumentation and data acquisition capabilities of the Department's 3 low-speed wind tunnels. Current projects include the upgrading of one tunnel to a fully computer controlled facility using LabVIEW, and the design and construction of a sports prototype racecar.

**Matt Stickland** is a lecturer within the Department of Mechanical Engineering at the University of Strathclyde. He graduated with a BSc in Aeronautical Engineering from the University of Manchester and obtained a PhD in Mechanical Engineering from the University of Strathclyde. He has worked as a project engineer in the Wind Tunnel Department of British Aerospace and as a Senior Design Engineer at Yard Consulting Engineers. His current research interests are experimental fluid mechanics, the application of PIV to two phase flow and flows in turbomachinery, and the development of three dimensional imaging in the presentation of experimental and computational datasets.