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Data Acquisition and Control Equipment for Studying Unsteady Flow in an Axial Compressor

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SUMMARY Specifications are developed for a data acquisition and control system to study various effects of unsteady flow in an axial compressor. Progress in implementing this system is discussed.

1 INTRODUCTION

Unsteady flow research at the University of Tasmania has lately been centred on investigating the interaction of wakes shed from neighbouring blade rows in an axial compressor. The dispersion of wakes from an inlet guide vane (IGV) row by the blades of a following rotor row is shown in Fig. 1. The rotor blades chop the IGV wakes into segments which are rotated by the effects of blade circulation as they move through the rotor row. At exit from the rotor, the initially continuous IGV wakes have been transformed into a street of discontinuous segments. The individual IGV wake segments are terminated by the wakes of the rotor blades which caused their dispersion. As detailed by Lockhart and Walker (1974), the interaction of adjacent turbulent shear layers together with the relative flows within the wakes can significantly modify the rotor wake decay. This leads to regular circumferential variations in both the time-mean and unsteady flow fields.

A blade in a following stationary row will experience differing flow unsteadiness according to its circumferential position relative to the wake streets of Fig. 1. This is illustrated by Fig. 2, which shows ensembles of streamwise velocity fluctuation records observed by a fixed probe at two different circumferential positions. Experimental work reported by Walker and Oliver (1972) showed the radiation of noise from a single-stage axial compressor to be significantly influenced by the relative circumferential positions of the inlet and outlet guide vane rows. The observed behaviour was largely ascribed to variations in acoustic source intensity associated with wake interactions.

The abovementioned investigations were largely qualitative in nature. A new experimental program has commenced with the aim of making detailed quantitative observations of wake interactions and their influence on unsteady velocity and pressure fields and sound propagation. Variations in the time-mean flow and machine performance will also be investigated. Hopefully, some useful design recommendations for axial machines will eventually emerge. Some information on basic physical processes involved in the interaction of turbulent free shear layers may also be obtained.

The proposed measurement program requires the collection and processing of large quantities of experimental data, whilst maintaining precise control of flow through the compressor. This is to be achieved with a computer-based data-acquisition and control system. The present paper discusses the requirements for this system and progress in implementing it.

2 RESEARCH COMPRESSOR

The research compressor is a single-stage machine with three blade rows: IGV, rotor and stator. In the standard blading configuration there are 38 blades in each of the guide vane rows and 37 blades in the rotor, giving a space-chord ratio at mid-blade height of 0.99 and 1.02 respectively. The blades are all 228 mm long with a constant chord of 76 mm and are housed in a constant area annular duct with 1.14 m outside diameter. Instrument slots in the outer shell of the compressor allow for radial and axial traversing of measuring probes at a fixed circumferential position. The IGV and stator rows are each mounted on rotatable supporting rings to permit circumferential traversing of these blades relative to a stationary probe.

The compressor is driven by a 30 kW DC motor. Normal operating speeds vary from 150 to 750 rpm. A sliding

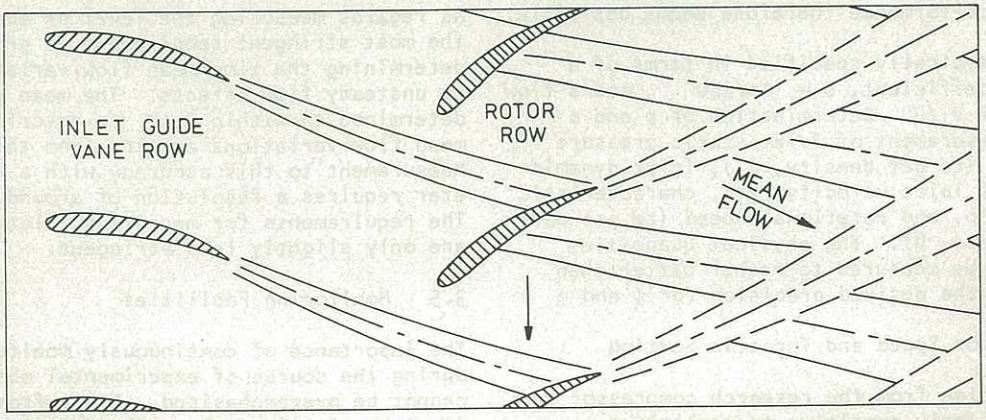

Figure 1 Dispersion of inlet guide vane wakes by rotor row

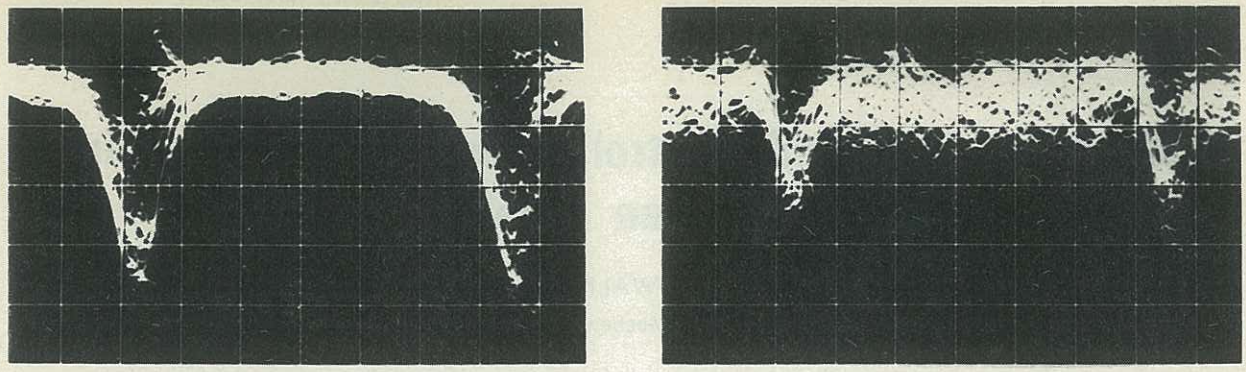

Figure 2 Velocity fluctuation records obtained at different circumferential positions downstream of rotor

cylindrical throttle at the outlet is used to control the throughflow.

3 DATA ACQUISITION AND CONTROL REQUIREMENTS

3.1 Introduction

Experimental observations of unsteady flow in turbomachinery inevitably involve a great amount of data acquisition and processing. Traversing in the axial, radial and circumferential directions is essential as both the time-mean and unsteady flow components vary three-dimensionally. At each point in space, sufficient records must be obtained to resolve the unsteady flow field into its periodic and random components, carry out spectral analysis, and so on. Precise control of operating conditions is needed to obtain accurate values of spatial derivatives from data obtained over an extended period. A further consideration is the reduced averaging time required for individual measurements which may be achieved by greater stability in operation.

This section discusses requirements for the experimental program outlined in Section 1, and develops specifications for the accuracy required in measuring and controlling various physical parameters.

3.2 Overall Performance

Walker and Oliver (1972) reported that significant changes in noise radiation from the research compressor could be obtained by altering the blading configuration so as to vary the unsteady flow field. These changes seemed to be accompanied by small variations in overall performance (less than $\frac{1}{4}$%), but this could not be definitely established with the existing instrumentation. Even such small changes in compressor performance are of considerable economic significance because of their greatly magnified effect on the overall efficiency of a gas turbine engine. An accuracy of 0.1% in measuring the compressor performance therefore seems desirable.

Performance is typically specified in terms of a pressure rise coefficient, $\psi = \Delta p/\frac{1}{2}\rho U^2$, and a flow coefficient, $\phi = V_i/U$. Determination of ψ and ϕ involves the measurement of inlet static pressure and temperature (to get density, ρ), inlet dynamic pressure (to get inlet velocity, V_i), characteristic pressure rise Δp, and rotational speed (to get peripheral blade speed, U). The physical quantities Δp & U must all be measured to rather better than 0.1% to achieve the desired precision for ψ and ϕ

3.3 Compressor Speed and Throttle Setting

Radiation of noise from the research compressor has been found peculiarly sensitive to variations in compressor speed. This phenomenon is not yet understood, but it means that the speed must both be measured and held constant to within 1 rpm to obtain reliable measurements of standing acoustic wave patterns. With a maximum operating speed of 750 rpm, this again suggests a precision of around 0.1%.

In previous work the compressor has been operated only at constant throttle opening and nominally constant speed. But with the computer-controlled system outlined in Section 4, more sophisticated operating techniques can be contemplated. It should, for example, be possible to maintain kinematic similarity of flow by independently varying the speed and throttle settings to achieve constant Reynolds number and flow coefficient.

3.4 Analogue Signal Measurements and Timing

Observations of fluctuating velocities and pressures in the compressor will involve digital sampling of the appropriate analogue signals. At the maximum compressor speed of 750 rpm, the rotor blade passing frequency is 462.5 Hz. To adequately define the rotor wake disturbances (see Fig. 2) will require around 50 samples per rotor blade passing period. This dictates a sampling rate of about 25 kHz for a single channel, or 50 kHz where two channels are being sampled for correlation purposes.

Each measuring sequence should commence at the same phase relative to the passage of a particular rotor blade (to eliminate apparent unsteadiness due to variations between the flow fields of different blades). This requires first a suitable triggering device which will discriminate to within 1% of the blade passing period. Then a real-time clock is needed to initiate measurements at regular intervals (for continuous measurement), or after a specified time delay (when obtaining ensemble averages to resolve the unsteady flow field into periodic and random components).

As regards measuring the level of analogue signals, the most stringent requirement is probably that of determining the time-mean flow variations produced by unsteady flow effects. The mean velocity must be determined to within 0.1% to describe the typical mean flow variations arising from this source. Measurement to this accuracy with a hot-wire anemometer requires a resolution of around 1 in 10,000. The requirements for measuring inlet flow conditions are only slightly less stringent.

3.5 Monitoring Facilities

The importance of continuously monitoring raw data during the course of experimental observations cannot be overemphasised. Apart from looking for spurious signals such as those produced by mechanical vibration of hot-wire probes or resonance of pressure

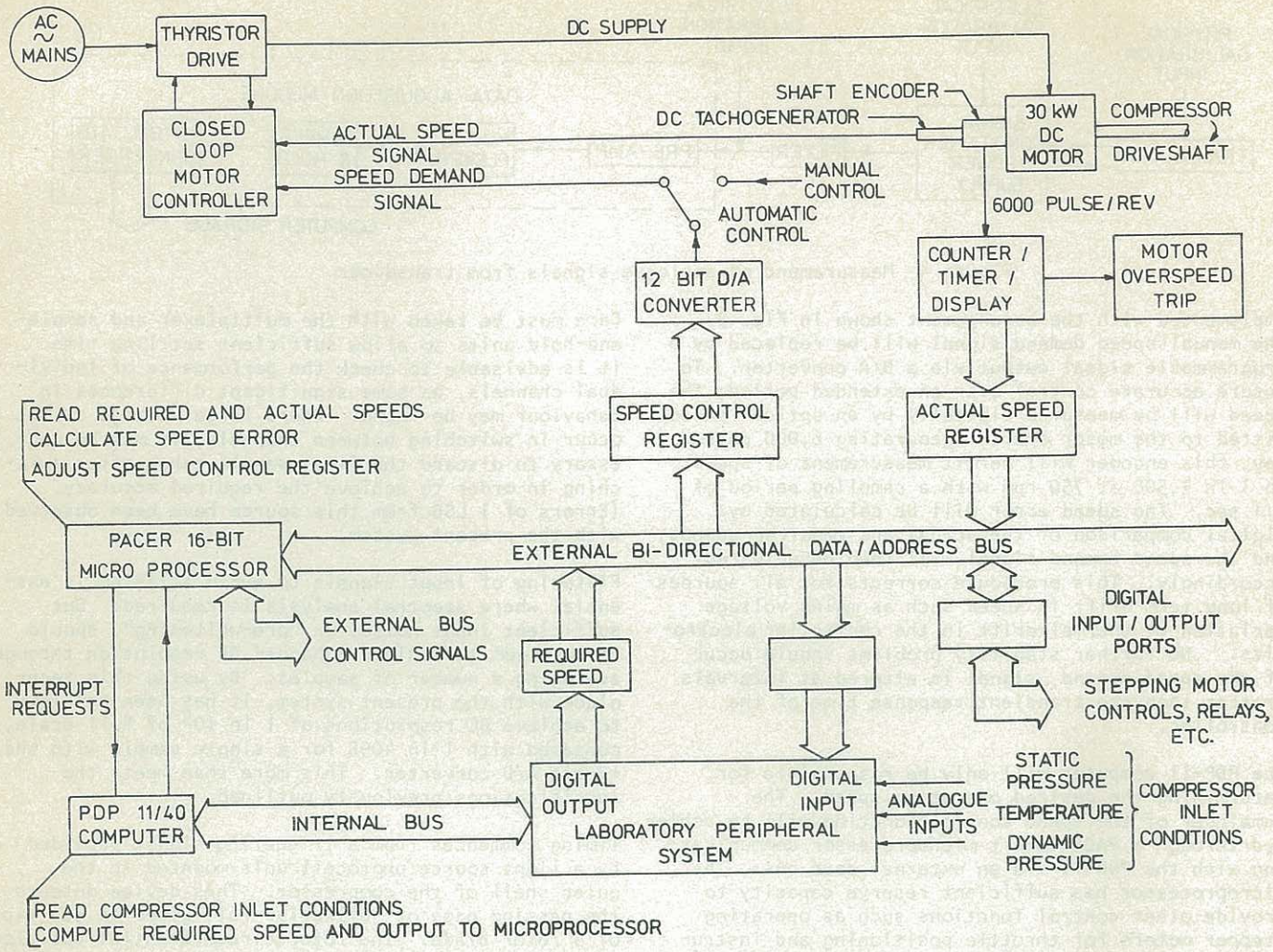

Figure 3 System for automatic long-term control of compressor speed

transducers, it is possible that significant flow phenomena may be overlooked by considering only the final processed data. In the compressor used in the present investigation, for example, there are large periodic flow fluctuations associated with instability in the IGV wakes which do not bear a fixed phase relationship to the rotor disturbances. The IGV wake fluctuations significantly perturb the flow through the rotor row, but all evidence of their periodicity disappears on taking ensemble averages of records commencing at a fixed phase relative to the rotor blade passage.

4 DATA ACQUISITION AND CONTROL IMPLEMENTATION

4.1 Computer Installation

Implementation of the research program outlined in Section 1 is based on the Digital Equipment Corporation DECLAB-11/40 Laboratory Data System. This unit is based on a PDP-11/40 digital computer with 16K of core memory and 2 x 1.2 Mword disk cartridge drives for bulk data storage. It has a data acquisition system comprising 16 analogue input channels with two 8-channel multiplexers and a dual sample-and-hold facility, a 12-bit A/D converter with 47 kHz sampling rate under direct memory access, and a programmable real-time clock with base frequencies up to 1 MHz. A 16-bit buffered output register and a 16-bit buffered input register provide digital input/output facilities.

The computer and associated equipment is installed as a free-standing unit in the laboratory. No air-conditioning is provided, as local temperatures only rarely exceed the allowable maximum of 35°C. However, the laboratory is continuously pressurised by two ventilating fans drawing filtered air from the outside atmosphere to prevent ingress of humid air from an adjoining hydraulics laboratory. The air filtration helps to maintain cleanliness in the laboratory, and this arrangement has proved very satisfactory.

4.2 Compressor Speed Control

To facilitate automatic control of the compressor speed and eliminate background noise from the existing Ward-Leonard drive, a thyristor-controlled adjustable speed drive reputed to give ± 0.1% speed regulation has been installed. The thyristor drive has a closed-loop controller which responds to a manually-set analogue speed demand signal. An actual speed feedback signal is provided by a DC tachogenerator, gear-driven at several times the motor speed to increase the frequency of voltage ripple due to commutation.

Some difficulties were experienced in commissioning this controller, as the combination of controller and load characteristics led to unstable operation. This problem was overcome by converting the controller's speed error amplifier from a true integrator to an averaging device. The averaging time constant was adjusted to give optimum response and stable operation at the minimum operating speed; stable operation at higher speeds was then assured due to the higher load torque under those conditions.

Computer control of the compressor speed is being

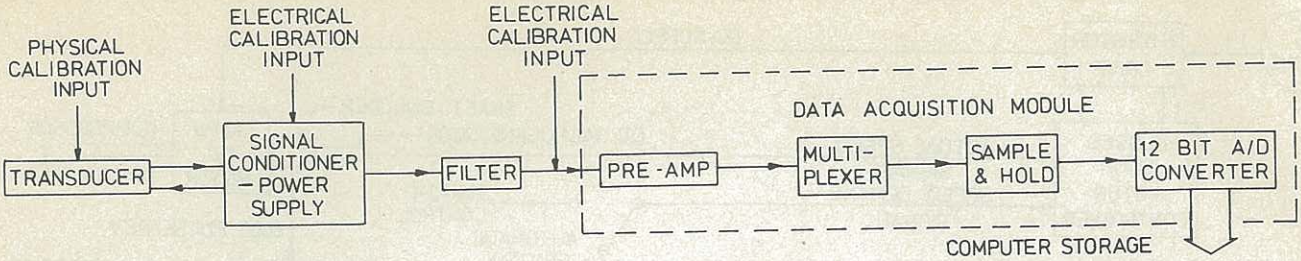

Figure 4 Measurement of analogue signals from transducer

implemented with the arrangement shown in Fig. 3. The manual speed demand signal will be replaced by a programmable signal output via a D/A converter. To ensure accurate control over an extended period, the speed will be measured digitally by an optical encoder fitted to the motor shaft; generating 6,000 pulse/rev, this encoder will permit measurement of speed to 1 in 7,500 at 750 rpm with a sampling period of 0.1 sec. The speed error will be calculated by digital comparison of the actual and required speeds, and the speed demand signal will then be adjusted accordingly. This procedure corrects for all sources of long term drift in speed such as mains voltage variation or thermal drift in the controller electronics. No further stability problems should occur if the speed demand signal is altered at intervals greater than the transient response time of the controller.

The PDP-11 computer will only be responsible for determining the desired operating speed. The remainder of the speed control function will be achieved through a PACE 16-bit microprocessor communicating with the PDP-11 via an external data bus. The microprocessor has sufficient reserve capacity to provide other control functions such as operating stepper motors for throttle positioning and instrument traversing; it can also monitor digital signals from measuring equipment and supervise data transfers between peripheral input/output ports and the computer.

The compressor inlet conditions required for determining the desired speed are monitored in the annulus upstream of the IGV row. Static and dynamic pressures from a pitot-static tube are measured by Datametrics differential-capacitance type pressure transducers accurate to better than 0.1% of reading. Temperature is obtained from a slow-response platinum resistance thermometer accurate to 0.1°C.

4.3 Analogue Signal Measurements and Timing

The equipment used in analogue signal measurement is indicated in Fig. 4. Signals are processed by several different pieces of equipment before digital conversion occurs. Each operation on the signal can contribute errors from non-linearity, DC offset, and scale factor variation. To achieve the desired accuracy of DC measurement, it is therefore essential to provide suitable calibration facilities, preferably self-calibration under program control. Ideally, there should be provision for standard physical reference inputs to the transducer (e.g. valving input ports together to check the zero of a differential pressure transducer so that the whole chain of measuring, conditioning and conversion equipment is calibrated. Where physical inputs to the transducer are impracticable, it may be possible to use standard electrical inputs to the transducer signal conditioning equipment (e.g. to electronically simulate zero and full-scale transducer inputs). At the very least, zero and full scale voltages can be applied to the preamplifier at input to the data acquisition system.

Care must be taken with the multiplexer and sample-and-hold units to allow sufficient settling time. It is advisable to check the performance of individual channels, as some significant differences in behaviour may be found. Where large voltage swings occur in switching between channels, it may be necessary to discard the first sample taken after switching in order to achieve the required accuracy. (Errors of 1 LSB from this source have been observed with the present system).

Filtering of input signals to avoid aliasing is essential where spectral analysis is required. But sufficient input noise, or "pre-whitening", should be retained to achieve enhanced DC resolution through averaging a number of samples. By using this technique with the present system, it has been possible to achieve DC resolutions of 1 in 10^5 of full scale, compared with 1 in 4095 for a single sample with the 12-bit A/D converter. This more than meets the specifications previously outlined.

Timing commences from a triggering signal provided by a light source/photocell unit mounted in the outer shell of the compressor. This device detects the passing edge of reflective foil glued to the tip of a rotor blade. The rotor circumferential position at the time of triggering is determined to within 0.2% of the rotor blade spacing.

5 CONCLUSIONS

An accuracy of around 0.1% is needed to measure the mean flow variations and overall performance changes produced by unsteady flow effects in axial turbomachinery. The proposed data acquisition and control system should fulfil this requirement.

6 ACKNOWLEDGEMENTS

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