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INSTRUMENTATION SYSTEMS FOR A CONTINUOUS FLOW TURBINE ROTOR

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ABSTRACT

The design and testing of instrumentation systems for the measurement of steady and unsteady turbine blade surface pressure and boundary layer condition for a turbine stage operating at design Mach and Reynolds numbers is presented. The boundary layer condition is monitored by an array of suction and pressure surface heated thin-film gauges. This paper describes the desigo of a forty channel constant temperature bridge to drive these gauges. The bridge fits into the centre of a sub-shaft driven by the turbine wheel. The amplified bridge output is transferred from the rotor via an array of light emitting diodes. The surface pressure is recorded by unpackaged pressure transducer chips laid into the surface of the blade. This paper also describes the circuitry necessary to drive these transducers. The position of these circuits and the transmission method are the same as those used for the thin film gauges. Both systems have a bandwidth sufficient for the resolution of vane-blade interactions.

NOMENCLATURE

a_1	Overheat ratio	
u	x-direction velocity	m/s
C	True chord	m
G	Gain	—
P	Pressure	Bar
M	Mach number	—
R	Resistance	R
Re	Reynolds number	—
T	Temperature	K
I	Electric Current	mA
V	Voltage	V
ρ	Density	Kg/m^3
μ	Dynamic viscosity	Kg/m.s

SUBSCRIPTS

c	Cable	sensor	Hot-Film Gauge
con	Constant	t	Total
gc	Gauge Cold	x	Adjust
gh	Gauge Hot	∞	Free stream condition
O	Total Condition		

INTRODUCTION

There are two choices available to the research engineer for making measurements within a turbine rotor blade passage: either use a stationary optical system that is phased locked to take measurements as the blade passage of interest passes, or mount the instrumentation on the rotor blade. The first option makes the tracking of unsteady phenomena difficult because the free stream flow is moving relative to the measurement system. The second option has many problems of electronic noise and stress associated with rotating instruments but it has the advantage that measurements are made relative to the rotor blade. It is the implementation of this second option that is discussed in this paper.

No significant aerodynamic measurements have ever been published from a turbine operating at engine conditions. Rotational speeds and, more importantly temperatures are too high for conventional measurement systems. There is also no need to make such measurements, dimensional scaling rules state that it is not the value of the dimensioned parameters that is significant, but instead, the value of the relevant non-dimensional groups. Davies and Wallace (1995) outline the correct scaling of a turbine rotor and Ainsworth et al. (1988, 1989) and Dunn (1984, 1986) present scaled rotor blade data and the associated instrumentation. In the experiment described here relative geometric, Reynolds and Mach number scaling is achieved. This leads to a relatively low temperature, low speed operation which greatly facilitates the design of instrumentation. The turbine to be instrumented is situated at Deutsche Forschungsanstalt fur Luft- und Raumfahrt (DLR), Goettingen. In 1992 the European Union agreed funding for a project to investigate turbine aerodynamics and heat transfer which included the installation of a new instrumented turbine rotor at DLR, and an extensive measurement program.

As part of the same program, a turbine was installed in the von Karman Institutes (VKI) light piston tunnel. The instrumentation system used there, described by Byrne and Davies (1996) has many similarities to the one presented here. The DLR

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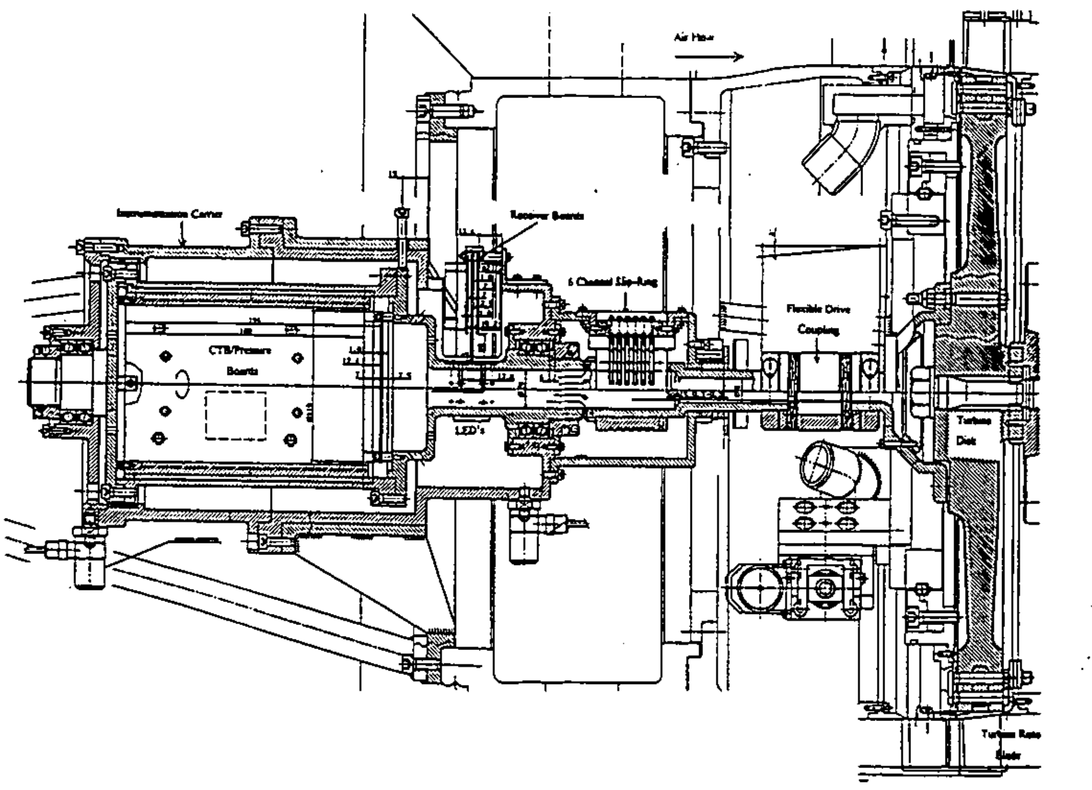

Fig. 1: Core of DLR turbine facility
[Picture courtesy of DLR]

rotor blade was to be instrumented with forty heated thin film gauges covering the mid-span section to monitor the condition of the boundary layer as it interacts with the Nozzle Guide Vane (NGV) shocks and wakes. The rotor was also to carry sixteen small imbedded Kulite pressure transducers for the measurement of the mid-span steady and unsteady rotor pressure. The prime interest in the thin-film data is to measure the position of transition on the rotor and how this moves with vane interaction. The pressure data will give the steady pressure distribution and the vane shock wave interaction with the rotor.

It has become accepted practice to mount instrumentation systems in the turbine rotor so that signals of order of magnitude of volts are transmitted. The electronic noise of transmission is then relatively small. In the systems described here the noise levels are reduced further by using an optical transmission system for data very similar to that pioneered by Kappler et al. (1987) and then Sieverding et al. (1992) and developed by Byrne and Davies (1996). This contrasts with the slip-ring technology used by most other groups, Dunn (1984) and Ainsworth (1988). Neal et al. (1992) proposes a system whereby during a simulation run, the data is sampled, converted from analogue to digital form and stored inside the shaft from where it is retrieved after the run. The advantages of optical diodes over slip-rings is that the noise level is low and there is no wear. Typical life times can be less than 1,000 hours for an instrumentation slip-ring and this is far less than expected from the optical system. No speed limitation on the design concept can be seen so it can be applied to high speed turbine applications. A high speed contact system, with contact resistance also needs to be cooled. The system works with a two channel shaft encoder that provides one pulse per revolution on the first channel and 1024 pulses on the second channel. The one-per-revolution channel is used as a clock that measures the time in terms of rotor revolutions. The other channel is needed to pace the data acquisition Analogue-to-digital (A/D) converter. Due to variations in the rotor speed, ensemble averaging of the acquired data would be very complicated if the computer clock was used to pace the A/D converter. The use of the encoder signal ensures that exactly 1024 values per revolution are acquired, independent of variations in speed.

One of the key design constraints was the lack of space for mounting instrumentation, as can be seen from figure 1 which shows the core of the DLR continuous flow axial turbine. There was neither enough room to mount a row of optical transmitters so that all gauge signals could be transmitted simultaneously, or to have one conditioning circuit for each transducer channel. It was therefore decided to switch between channels during the operation of the turbine, and to design the thin film system so that one bridge was shared between a number of channels. It was also necessary to have two separate instrumentation systems, one for pressure and the other for thin film measurement that could be changed over with relative ease. The DLR turbine air supply is provided by a continuous centrifugal compressor giving a flow inlet temperature of 305 K and the recirculated air is continuously cooled and dried. The turbine is braked by an electrical generator. In this turbine it was not possible to mount the instrumentation inside the turbine shaft. Instead, a separate sub-shaft and bearing system driven from the turbine disc, was designed at DLR to carry the instrumentation as shown in figure 1.

THIN-FILM INSTRUMENTATION

The gauges to be used were identical to those presented by Schroeder (1989) who demonstrated their use on a five stage low pressure turbine. When connected the gauges make up one arm of a wheatstone bridge. A feed back loop is used to keep the bridge very near balance and by this means, the gauge is held at a constant resistance and therefore constant temperature. The operating temperature of the gauge is set by the resistance in the adjacent bridge arm. With this operation the gauge may be used to measure aerodynamic sheer stress as first shown by Bellhouse and Schultz (1966) and later by Davies and Duffy (1995) and Duffy and Davies (1995). In this application this is not attempted. Instead, the gauges are used to qualitatively interpret the condition of a blade boundary layer. This paper describes the instrumentation between the transducer and the data acquisition system

Table 1: Turbine Design Operating Conditions : The turbine consists of 43 NGVs and the instrumented rotor contains 64 blades:

Speed [rpm]	T_0 [K]	P_0 [bar]	Re $\times 10^{-6}$ (Re=$\rho u_\infty C/\mu$)	M (NGV exit)	Mid-height rotor radius [mm]
7819	305	1.458	0.95	1.03	256

The gauges are supplied on a thin flexible substrate which is stuck onto the blade surface. In this application a rotor mid-height passage was instrumented with forty gauges. The design operating condition of the turbine is given in Table 1. The Constant Temperature Bridge (CTB) is the circuit that drives the hot-film gauges that are mounted on the rotor blade. Much of the literature refers to this type of circuit as a Constant Temperature Anemometer (CTA) because of its association with hot-wire anemometry. In this context, however, velocity is not being measured, therefore to refer to this circuit as a CTA is incorrect.

CTB - AN OVERVIEW

A basic CTB block diagram is shown in figure 2. The CTB contains a wheatstone bridge circuit with the sensor as one arm of the bridge with two fixed resistors and one adjustable resistor comprising the other arms.

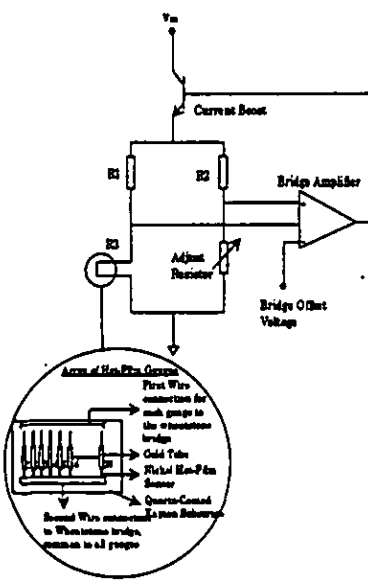

Fig. 2: Basic CTB block diagram.

To be able to meaningfully compare the voltage across each sensor in the array and interpret the comparison as a reflection of the condition of the boundary layer they must all be held at the same overheat ratio. The value selected for the adjustable resistor is used to set the sensor overheat ratio, a_1, defined as:

$$a_1 = \frac{R_{sensor} - R_0}{R_0} \qquad (1)$$

The setting of the overheat ratio is discussed later.

In CTB operation, a differential amplifier with a high common mode rejection senses the bridge imbalance and controls current to hold the sensor temperature constant. Before the system is used, the adjustable resistor is set to a value larger than would be required to balance the bridge. When power is applied, the feedback amplifier increases the sensor heating current causing the sensor temperature to rise and therefore increasing the resistance of the hot-film gauge until the bridge becomes balanced. A balance point occurs when the voltage across the sensor and the adjust resistor are equal, when the ohmic heating of the sensor is balanced by the heat transfer from the gauge to the surroundings. For hot-film gauges, the heat transfer rate is proportional to the third power of the local velocity gradient at the wall where the films are mounted. An increase in velocity cools the sensor and unbalances the bridge causing the feedback amplifier to increase the sensor heating current and to bring the bridge back into balance. As the amplifier responds rapidly and the thermal mass of the sensor is very small, the sensor temperature remains virtually constant as the velocity changes.

The traditional approach to CTB design is to use a high gain amplifier to keep the bridge error voltage as small as possible, thereby maintaining the probe resistance close to the resistance in the adjust arm of the wheatstone bridge. Unfortunately, high gain amplifiers have limited bandwidth. Perry and Morrison (1971) described how this can be overcome by maintaining a high d.c. gain and reducing the a.c. gain to maintain wide bandwidth and stable operation. With reference to figure 2, Lomas (1986) discusses the use of a third amplifier terminal as an offset control. When a suitable offset voltage is applied, the output terminals show a voltage difference when there is no voltage difference at the input terminals. This is needed to allow the circuit to begin to operate when the CTB is turned on as zero current is the stable operating point of the circuit: this technique is adopted in the design presented here.

The frequency response optimisation of CTB circuits normally consists of applying a small amplitude square wave in parallel with the sensor at the maximum flow condition, Freymuth (1981) and Lomas (1986). It is important to note that much of the analysis of square wave testing is for hot-wires or cylindrical hot-films, and the theory for non-cylindrical hot-films is not as developed. Potential problems with this are discussed by Bellhouse and Schultz (1966). The test is based on the assumption that heating and cooling of the sensor by varying the fluid velocity is identical to heating and cooling of the sensor by varying the heating current. When the square wave current is introduced, the sensor current will rise and then fall about its original value as the feedback amplifier varies the heating current to balance the bridge. A sudden decrease in fluid velocity has the same effect. The time constant for the system is calculated by measuring the time required for the output voltage to drop by 63% of the peak amplitude.

As the sensor forms part of the wheatstone bridge, the total hot-film resistance consists of the sensor resistance plus the resistance of the leads and connecting cable. Capacitance in the probe arm of the bridge has a negligible effect on performance, Perry and Morrison (1971), but cable inductance is significant. If the inductance of one arm of the bridge is larger than the other, a bridge balanced for slow variations in bridge current will become unbalanced as the frequency of the fluctuations increases. This cable inductance effect can be reduced either by using a shorter cable or, more reliably, compensated for by adding a fixed inductance to the bridge arm containing the variable resistance. The second approach was adopted here and the inductance value was set close to the optimum for maximum bandwidth.

CTB SPECIFICATION

Before the commencement of the CTB design, a specification was agreed between all project partners which took into consideration cost, space available for the instrumentation and data requirements. A brief summary is given below:

- The instrumentation will consist of two separate CTB circuit boards, each with signal conditioning and a single data transmission channel including an LED array because there is insufficient space available for 40 separate CTB units.
- Each CTB unit will have 20 hot-film gauges connected to the CTB bridge via power Mosfet switches, giving a total of 40 gauges.
- Synchronisation between the internal measurement system and the external data acquisition system will be controlled externally by a PC via slip-ring channels to the internal electronics.
- Power to the internal electronics will be provided via high quality power slip-rings
- The overheat ratio will be selected by installing a resistance of known value into the adjust arm of the bridge.
- The total bandwidth of the system from the gauge to the output of the transmission system will be 20 kHz which is adequate to resolve vane-blade interactions which occur at approximately 6kHz and may be high enough to resolve the turbulence in the boundary layer.
- A square wave test shall be performed by connecting an external signal generator to the bridge. This test will be performed outside the rotor shaft.

CTB DESIGN

The CTB design draws on much of the analysis presented by Perry and Morrison (1971), Freymuth (1967, 1977, 1981) and Lomas (1986). The block diagram of the complete circuit is given in figure 3.

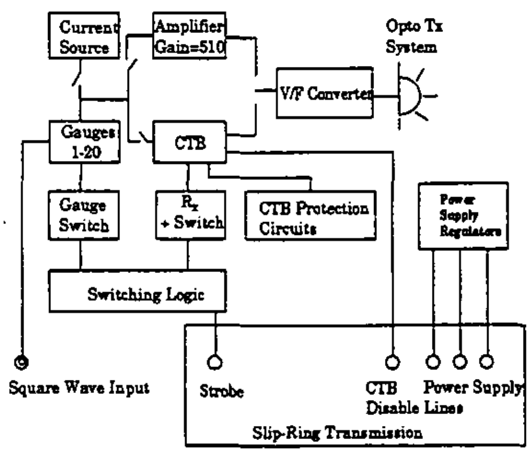

Fig. 3: CTB block diagram.

The CTB bridge contains four resistances, two of which are the hot-film gauge, and an adjust resistor. Because there is only one bridge circuit and 20 gauges with corresponding adjust resistances, these gauges and resistances are switched into the bridge. All the adjust resistors are located on a separate daughter board which plugs directly into the main CTB board. A fixed inductance is included in the resistor adjust arm of the bridge to compensate for the sensor cable inductance. A small variable capacitor is also added in that arm of the bridge to allow trimming of the adjust arm impedance over a small range. Optimisation of frequency response is achieved by adjustment of the bridge offset and amplifier gain. These resistances in the upper arms of the bridge, R1 and R2 in figure 2, are selected such that the bridge has a 20:1 ratio, with low adjust arm resistor values to keep bridge noise to a minimum.

The differential bridge output connects to a feedback voltage amplifier which is divided into three gain stages with an overall gain of 500-1000. The first stage is designed around a wide-bandwidth instrumentation amplifier, AD524 which is characterised by its high linearity, a high common mode rejection ratio of 120dB at a gain of 1000. Low offset voltage drift of less than 25μV/°C. This amplifier also has a 25Mhz gain bandwidth product. To make it suitable for high speed data acquisition systems, the AD524 has an output slew rate of 5V/μs. The second amplifier has an additional gain of between 1 and 5. At this stage, the offset voltage is added to the circuit because the voltage is at a higher level and less prone to noise and drift. Gain and offset control are achieved by adjusting two variable resistors built around this amplifier. An additional amplifier with a gain of 5 is used to level shift the voltage before driving the current boosting Darlington power transistor that compensates for voltage drops and allows a maximum bridge voltage of 11 V. The second and third stage amplifiers use a dual precision, high speed BiFET op-amp. This amplifier settles to ±0.01% in 1μs, has a common mode rejection of 88dB and a minimum slew rate of 16V/μs. These sections together form a transconductance amplifier of the CTB, converting a small bridge voltage difference into a high current drive sufficient to maintain the bridge at balance.

Switching between gauges is performed using Mosfets devices. As the maximum gauge current was expected to be 250 mA it was not possible to use multiplexing circuits because these are only suitable for much lower level currents. Relays could not be used in this application due to the high rotational forces and the lack of space. The Mosfets used have approximately the characteristics of an ideal switch. They have, however, a drain-source capacitance when turned off and this capacitance in series with a gauge resistance produces an RC circuit in parallel with the operating gauge. This reduces the sensor arm impedance with frequency and gives rise to bridge imbalance at relatively low frequencies. To solve this problem, Mosfets are also used to switch between the adjust resistors. The Mosfets in both arms of the bridge were selected to have approximately the same ratio of drain-source capacitance as the bridge ratio. This configuration also solves the problem of temperature drift of the sensor arm Mosfet as this is compensated by similar behaviour in the adjust arm Mosfet. Because of the 20:1 bridge ratio, the on-resistance of the Mosfet in the adjust arm is 4Ω, this is accounted for when balancing the bridge.

DETERMINATION OF ADJUST RESISTORS

As described the system can operate either as a CTB or as a resistance thermometer. The mode of operation is programmed by wire connections on the daughter board containing the adjust resistors. Two wire connections are soldered onto the daughter board for resistance measurement. When this measurement is completed, these connections are desoldered and two other connections are made for CTB mode. To determine the overheat ratio, the adiabatic wall temperature for each gauge must be measured. The gauges are run therefore first in a constant current mode as resistance thermometers, before they are run in a CTB mode. 1mA constant current sources for all gauges were therefore part of the instrumentation system. This, together with the temperature coefficient of resistance calibration data for each gauge allows the gauge hot resistance to be established for a given overheat. In resistance measurement mode, one of the two wire links connects the hot-film gauges and Mosfet switches into the current source and the other link connects the amplifier output to the transmission circuit. The current passes through the selected gauge and a small voltage is produced which is proportional to the total resistance of the Mosfet, gauge, connector and cable resistances in the sensor arm. This voltage is amplified by 510 to give a high level signal, V_{out} for transmission. The total resistance, R_t in the probe arm of the bridge is:

$$R_t = \frac{V_{out}}{I_{con} \times G} \tag{2}$$

The cable resistance, R_c, remains constant throughout, and is evaluated by subtracting the total resistance in the probe arm from the gauge resistance. To calculate the gauge cold resistance, R_{gc}, the turbine is operated and the total resistance is evaluated again using equation 2. Thus, the gauge cold resistance is:

$$R_{gc} = R_t - R_c \tag{3}$$

The sensor hot resistance, R_{gh} is obtained by multiplying the sensor cold resistance by the overheat ratio:

$$R_{gh} = R_{gc}\left(\frac{R_{sensor} - R_0}{R_0}\right) \tag{4}$$

The bridge adjust resistance for each gauge is then evaluated using:

$$R_x = A\left(R_{gh} + R_c\right) + 4 \tag{5}$$

Where A is the bridge ratio. The 0.1% precision metal film resistors with a temperature coefficient of 15 ppm used are mounted on a replaceable daughter board. After these resistances have been evaluated, the wire links are changed so that the board operates in CTB mode. One of these two links connects the CTB output voltage to the transmission system and the other connects the gauges as part of the wheatstone bridge.

CTB GAUGE SWITCHING

The timing diagram for the gauge switching is given in figure 4.

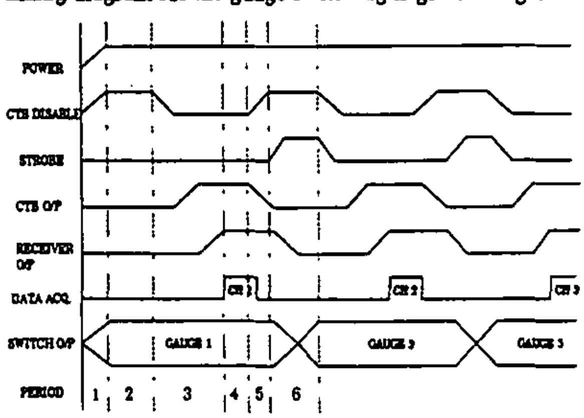

Fig. 4: CTB timing diagram showing the phase relationship between channel data acquisition and gauge switching.

The switching of all the Mosfets is controlled using a digital circuit containing Johnson counters. The CTB is turned off when switching between gauges to prevent gauge damage. Switching is initiated by an externally generated software control signal labelled CTB DISABLE. Setting this high turns on a transistor in a control circuit which in turn removes the base drive to the Darlington transistor, turning the CTB off. Another software generated control signal labelled STROBE is then applied to the counters to switch to the next gauge and corresponding adjust resistor. Each channel on the counter connects directly to each pair of corresponding Mosfets. Once switching has taken place, the CTB is turned back on by setting the CTB DISABLE line low. The digital logic circuit incorporates a power-on reset to ensure that channel one is always selected on power-up.

Figure 4 can be explained by describing the events that take place for each period. Period one is the start-up period with a minimum duration of 10 ms. In this period, the power is applied to the system and the power-on reset circuit ensures that channel one is selected. The CTB DISABLE line is held in a high (5 V Transistor-Transistor-Logic(TTL)) state to ensure that the CTB remains off. Period two is warm-up period which is of the order 30 minutes, allowing the circuits to settle and thus minimising drift during operation and data acquisition. In period three, the CTB DISABLE signal is changed from a high to a low state (0 V) to enable the CTB. After this, a settling period is required to allow the bridge to balance and the heat transfer from the gauge to the surroundings to come to a steady state. Data acquisition occurs during period four, and the duration of this period is determined by the data acquisition system. The CTB is disabled in period five by setting the CTB DISABLE signal high. This period requires a delay to allow for the rise time of the applied signal and the time for the CTB to switch off. After the CTB is disabled, channel two is selected by setting the STROBE line high in period six. A delay of 20 ms is required to allow for the logic switching time and the Mosfet turn-on time. Periods three to six are repeated until all twenty gauges on each board have been addressed.

SQUARE WAVE TEST

To perform the square wave test, a 1 kHz 5 V TTL square wave is applied via a sub-miniature BNC connector. Because there are 20 gauges common to one CTB, only one frequency stabilisation point can be set for all gauges. The optimum response of the bridge to a square wave test is shown in figure 5. Frequency stabilisation of the CTB is performed by a combination of bridge amplifier gain adjustment, which will improve the bandwidth at the expense of increased ringing, and offset voltage adjustment which will reduce the ringing. To reduce the level of overshoot in the waveform, the variable capacitor in the adjust arm of the bridge is adjusted.

OTHER CTB FEATURES

Each CTB unit has an in-built current limit of 0.5 A to protect the gauge from excessive current surges. This has to be set high in anticipation of high currents during turbine operation and therefore it gives little protectinn to the gauges in still air. There is also a protection circuit in the event that one or more power supply lines fail, which would cause the CTB bridge to be driven to saturation. The protection circuit consists of a diode bridge to which power supply and reference voltages are connected via resistors. The diode bridge connects to two transistors which remain off if all the correct power supply and reference voltages are present. If one or more on, removing power to the CTB power transistor. voltage supplies are absent, then one or both transistors will turn on removing power to the CTB power transistor.

A sine wave of varying frequency and fixed amplitude was applied to both CTB boards and the resultant gain and phase response curves from one of the boards is shown in figure 5.

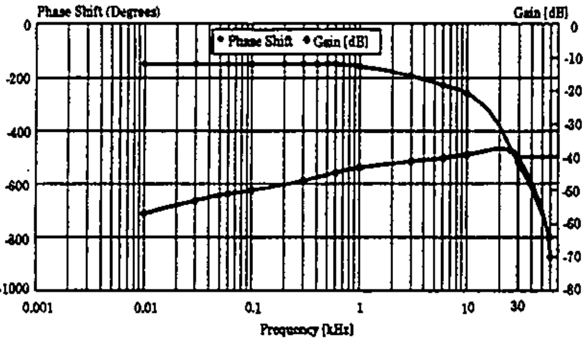

Fig. 5: CTB circuit gain and phase response curves showing a bandwidth of 30 kHz at the 3 dB point.

A CTB bandwidth of 30 kHz was measured from the gain response curve. The rise in the frequency response curve is because the CTB response is the first derivative of the applied response. A square wave test was performed on both boards and an example of the resultant response is shown in figure 6, also showing a bandwidth of approximately 30 kHz.

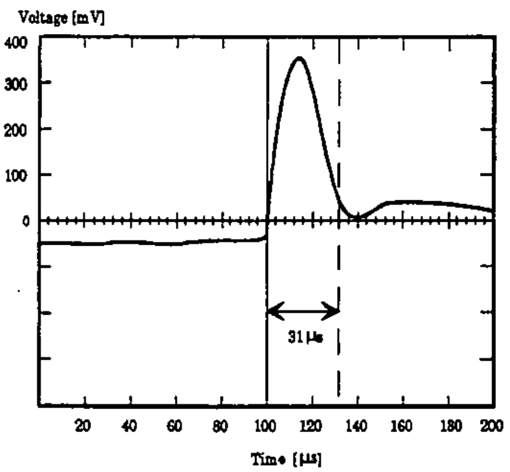

Fig. 6: CTB Square wave response curve showing approximately a 30 kHz bandwidth

PRESSURE INSTRUMENTATION

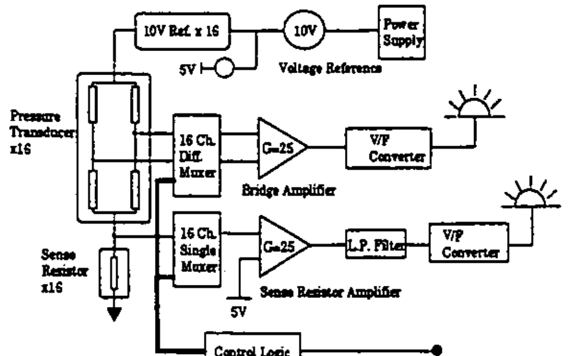

Fig. 7: DLR Pressure transducer circuit block diagram

A sixteen-channel pressure transducer instrumentation system was designed to measure the steady and unsteady mid-span pressure distribution. The primary reason for these measurements was to test the aerodynamic similarity between the VKI and DLR rotors. Figure 7 illustrates the pressure transducer block diagram. The transducers used are described by Ainsworth et al. (1991). The design of the electronic signal conditioning circuitry is almost identical to that used in VKI described by Byrne and Davies (1996) and therefore only a brief overview is given. The pressure transducers are sensitive to both pressure and temperature. The temperature effect can be calibrated for if the temperature of the transducer during operation is known. In this application it is monitored by measuring the bridge supply current as it passes through a sense resistor. Thus two signals per transducer are required, one proportional to temperature and the other proportional to pressure.

The electronic design consists of two precision instrumentation amplifiers; one to convert the pressure transducer bridge output with a specified voltage range of 0-200 mV from a differential to a single ended signal. The second is used to amplify the deviation voltage, of order 0-60 mV, caused by a change in transducer temperature, across the sense resistor. As only the mean voltage is required, the signal is filtered with a second order low-pass Butterworth filter with a cut-off frequency of 400 Hz.

The two major differences between the DLR and VKI systems are firstly that the DLR transducers are addressed sequentially because there are only two transmission channels, and secondly, that the amplification gain of 50 is twice that used in the VKI circuit.

PRESSURE TRANSDUCER SWITCHING

The 16 pressure transducer output voltages are connected between two eight-channel differential multiplexers. The sense resistor output are connected to a 16-channel single-ended multiplexer. The switching between all channels is controlled by an externally generated signal labelled STROBE and this connects to a 4-bit counter. The counter counts the STROBE pulses and generates a 4-bit binary address which selects the appropriate channel on the multiplexers. The counter returns to a zero state (0000), channel 1, after a count of 15 (1111). A power-on reset circuit ensures that the count is always set to zero when the circuit power is first applied.

TRANSMISSION SYSTEM

The two-channel opto-electronic transmission system used at DLR is common to both the CTB and the pressure transducer systems, and it is almost identical to that used at VKI and therefore only an overview is presented here. The use of optical diodes requires that the signals to be transmitted must be digitised. For each channel the system is divided into stationary and rotating components. Components in the rotating frame include a Voltage-to-frequency (V/F) converter transforming the analogue signal into a frequency between 500 kHz and 1 MHz and a buffer circuit to drive the infra-red Light Emitting Diodes (LEDs). The linearity error of the V/F is typically 20ppm and 50ppm maximum at 10kHz full scale. This corresponds to approximately 14-bit linearity in an analogue-to-digital converter circuit. Five LEDs are mounted around the circumference of a shaft as shown in figure 1. In the stationary frame, the signal is picked up by photodiode with a built in preamplifier and converted to the original analogue signal using a Phase-Locked-Loop (PLL). At the PLL output, a low-pass filter of 30 kHz is used to filter out the residual frequencies of the PLL. The V/F gain is set at 50 kHz/V for the range 500 kHz to 1 MHz representing a 0-10 V signal. No output filter was needed in the circuit as DLR used a variable filter immediately upstream of the data acquisition. For this transmission system, to prove that the appearance of the signal does not change during transmission, it was chosen to compare square wave responses at the gauge/bridge area and at the filtered PLL output. The shape of the signal remained unaltered except that it was shifted in phase in comparsion to the signal before transmission.

MECHANICAL LAYOUT
BACKPLANE BOARD

A circular backplane board perpendicular to the plane of the other boards and the axis of the machine with a diameter of 110 mm is used as the interface between the rotating instrumentation boards, the sensors on the rotor blade, the LEDs and the power supplies. The instrumentation boards plug into connections on this board, this enables the instrumentation boards to be removed and installed without repetitious rewiring. It is permanently in place, and the CTB and pressure boards are connected to it in turn. The backplane board contains four 96-way DIN41612 class C connectors, two for each of the CTB boards and two for the pressure boards. Either two CTB or pressure boards, depending on the measurements being taken, are placed side by side in the instrumentation carrying.

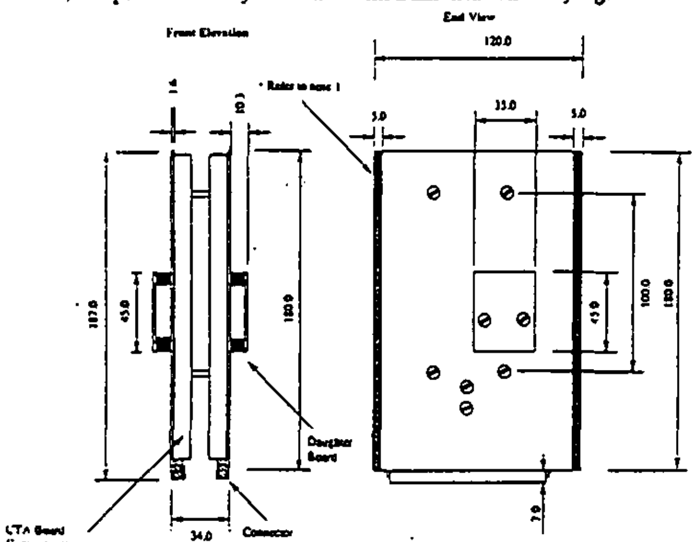

Fig. 8: CTB board dimensions

Figure 8 gives the dimensions of the CTB boards, they are similar in outline to those of the pressure boards. Before being slotted into the turbine shaft, the two CTB or pressure boards are screwed together at two points. Figure 9 shows an axial view of a pair of installed boards.

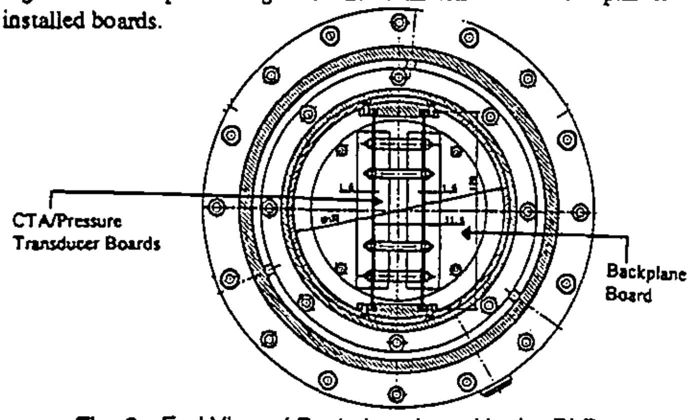

Fig. 9: End View of Backplane board in the DLR turbine shaft. (Drawing courtesy DLR)

The backplane board contains 200 through holes which are used for connection to: the sixteen pressure transducers, four wires per gauge; 42 hot-film wires; 3 power supply wires; 2 control signal wires; and 2 pairs of emitter diode drive wires. The backplane board also contains a circuit which is required to shift the 5 V TTL strobe signal from a remote PC to a 15 V Complementary Metal Oxide Semiconductor (CMOS) strobe signal required by the digital logic on the CTB board. Two receiver boards connected by a fibre optic link are used per channel, one board containing the photodiode, amplifier and Schmitt trigger and the other containing the PLL circuitry.

STRESS SCREENING

All boards were stress screened at a speed of 6000 rpm to test their mechanical integrity. The boards were electrically tested when stationary, then spun to their maximum speed and tested again. No mechanical problems were detected. To further test the CTB system, the boards were successfully used by Hamilton (1995) in an experiment to measure the aerodynamic wall shear stress on a cylinder rotating within a concentric stationary cylinder at speeds up to 7150 rpm.

CONCLUSIONS

- Electronic circuits for the measurement of steady and unsteady turbine blade surface pressure and boundary layer condition in a continuous turbine stage have been designed and tested.
- A two channel optical data transmission system has been developed.
- The complete system meets the specification required to resolve vane-blade interactions.
- The rotating systems have been successfully mechanically stressed tested to a speed of 6000 rpm.
- The CTB and transmission system electronics have been used sucessfullly at DLR to acquire data that will be used to determine the condition of the boundary layer.

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