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SIMPLE INSTRUMENTATION RAKE DESIGNS FOR GAS TURBINE ENGINE TESTING

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BREAK

ABSTRACT

The determination of gas turbine engine performance relies heavily on intrusive rakes of pitot tubes and thermocouples for gas path pressure and temperature measurement. For over forty years, Kiel-shrouds mounted on the rake body leading edge have been used as the industry standard to de-sensitise the instrument to variations in flow incidence and velocity. This results in a complex rake design which is expensive to manufacture, susceptible to mechanical damage, and difficult to repair.

This paper describes an exercise aimed at radically reducing rake manufacture and repair costs. A novel 'common cavity rake' (CCR) design is presented where the pressure and/or temperature sensors are housed in a single slot let into the rake leading edge. Aerodynamic calibration data is included to show that the performance of the CCR design under uniform flow conditions and in an imposed total pressure gradient is equivalent to that of a conventional Kiel-shrouded rake.

NOMENCLATURE

C_t	Total pressure coefficient	=	$(p_i-p_t)/(p_t-p_s)$
p	Pressure		
R_r	Temperature recovery ratio	=	(T_i/T_t)
T	Temperature		

Subscripts

i	indicated
s	static value
t	total value

1. INTRODUCTION

The determination of gas turbine engine performance requires an accurate knowledge of gas properties through the compressor, combustor and turbine components of the engine. Gas pressure and temperature are the most fundamental of these properties, and various measurement techniques have been developed for sensing pressure and temperature in a range of environments. Individual compressors or turbines are often rig tested to ascertain their isolated performance characteristics. In such cases, a shaft torquemeter (compressor) or dynamometer (turbine) might be used to measure the work input or extracted from the machine respectively. Given a measure of the inlet massflow, the temperature change through the machine can then be calculated. This technique is not appropriate for whole engine testing where the performance of an embedded compressor or turbine is required, and direct measurements are made using intrusive arrays of pressure and temperature sensors. Point measurements are then averaged appropriately to give mean parameter values for use in subsequent performance calculations. The overall measurement uncertainty depends on the degree of radial and circumferential pressure or temperature variation and the number and location of the sensors, in addition to the errors associated with the point measurements themselves.

A familiar and widely used form of sensor array is the pressure or temperature rake, so called because the sensors mount forward of a common spine in a manner akin to the well-known gardening implement. Figure 1a) is taken from Saravanamuttoo (1990), and shows a six headed rake for total pressure measurement. Square ended pitot tubes are used as the pressure sensors, each pitot tube being housed in a discrete cylinder or 'Kiel-shroud'. When the rake is operated at incidence relative to the gas stream, the Kiel-shrouds act to align the flow more closely with the axis of the pitot-tube before the flow stagnates on the pitot-tube front face. This

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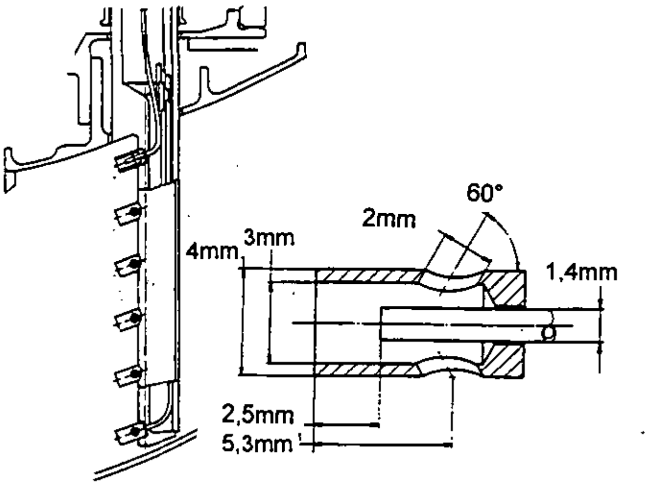

FIGURE 1a): 'Standard' Kiel-Shrouded Pressure Rake Design, taken from Saravanamuttoo (1990)

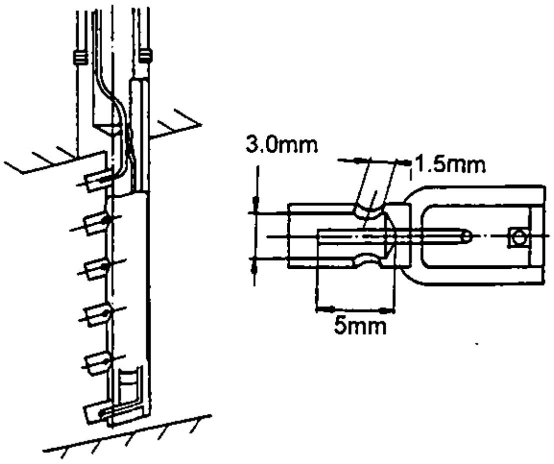

FIGURE 1b): 'Standard' Kiel-Shrouded Temperature Rake Design, taken from Saravanamuttoo (1990)

effectively increases the instrument's insensitivity to yaw angle from typically ±8° for an ordinary pitot-tube to ±20° or more for a Kiel-shrouded device, (Benedict, 1983). Air exhausts from the Kiel-shrouds through bleed holes positioned either side and towards the rear of each shroud. In a temperature rake, the pitot-tubes are replaced typically with thermocouples, (figure 1b). In this case, the Kiel-shroud design also influences the heat transfer in and around the thermocouple junction, and governs the temperature indicated by the sensor at a given flow condition. For both rake types, the relationship between indicated and actual pressure or temperature is normally established by aerodynamic calibration under representative flow conditions.

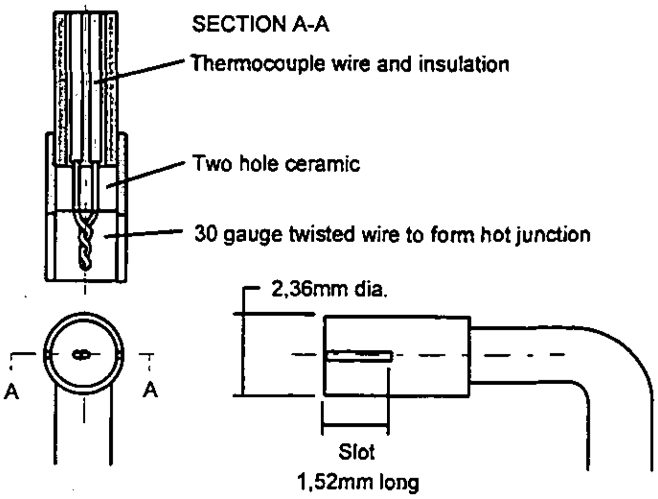

FIGURE 2: Early Kiel-Shrouded Temperature Sensor, taken from Stickney (1955)

Section 2 of this paper gives a review of developments in pressure and temperature rake design over the last forty years. An exercise aimed at substantially reducing rake manufacture and repair costs is reported in section 3, and a novel 'common cavity rake' (CCR) design is described in section 4. Aerodynamic test data for a prototype pressure CCR is presented in section 5, and compared with that from a conventional Kiel-shrouded instrument. Concluding remarks are made in section 6.

2. REVIEW OF PREVIOUS WORK

An early design of Kiel-shrouded thermocouple (figure 2) was described by Stickney (1955). This design adopted short thermocouple wires, and slots rather than holes for venting the shrouds. It was configured as a single point probe for aerodynamic characterisation, but is similar in other respects to the 'standard' Kiel-shrouded rake design shown in figure 1. This arrangement of slotted shroud gave a recovery ratio of 0.999 at 0.2 Mach number, where recovery ratio is defined as the ratio of indicated temperature (T_i) to true total temperature (T_t). Recovery ratio reduced almost linearly with increasing Mach number to a value of 0.994 at 0.9 Mach number. Stickney also showed that, under subsonic flow conditions, the instrument was insensitive to yaw angle over ±14° at 0° pitch, and similarly insensitive to pitch angle at 0° yaw.

In a review of aerodynamic measurement techniques for turbomachines, Fleeger and Seyb (1975) describe multi-point pressure and temperature rake designs which closely resemble those shown in figure 1. The most obvious differences relate to the number, positioning and diameter of the air exit holes. Although no criteria are given for sizing these holes in a pressure rake, Fleeger and Seyb show that the heat transfer mechanism around a Kiel-shrouded thermocouple depends on the air gas velocity through the shroud, and

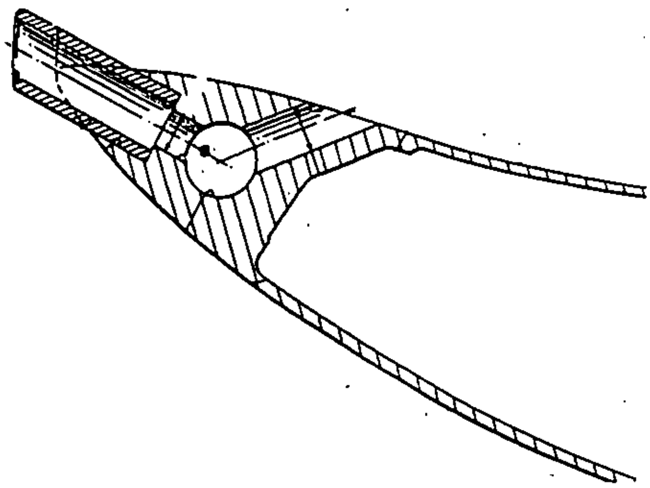

FIGURE 3: Scarfed Kiel-Shroud for NGV Leading Edge Temperature Sensor, taken from Kokoszka and Tommasini (1985)

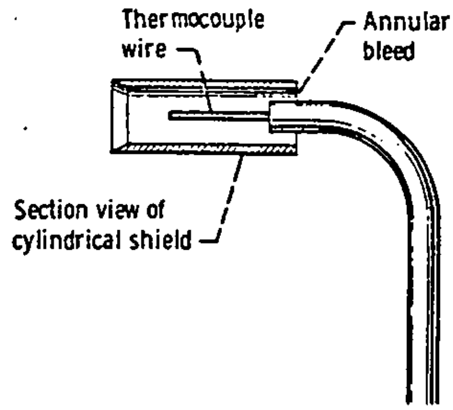

FIGURE 4: Temperature Probe with Annular Shrouded Thermocouple, taken from Glawe et al.(1978)

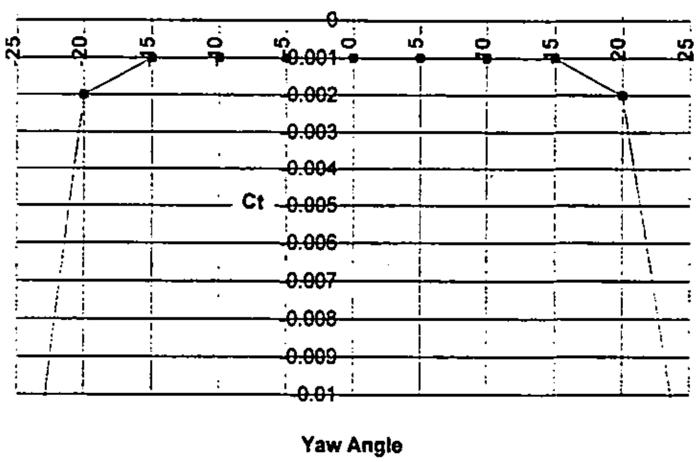

FIGURE 5: Aerodynamic Characteristic of 'Standard' Pressure Rake in Figure 1a)

hence on the aspiration ratio, (i.e. the ratio of inlet to exit hole diameters). Heat energy is transferred from the gas into the thermocouple wires by convection, but may then be conducted along the wires towards the rake body. At elevated temperatures, radiative heat transfer from the gas to the thermocouple or from the thermocouple to the surrounding metal work becomes increasingly significant. The temperature indicated by the probe represents a balance of these three heat transfer mechanisms. It is explained that reducing the diameter of the Kiel-shroud air exit holes for a given Kiel-shroud internal diameter would lower the gas velocity through the shroud and reduce the convective heat transfer coefficient, so shifting the balance towards conductive heat transfer. Smout and Cook (1991) report an experimental investigation of various temperature Kiel-shroud designs at representative flow conditions. It was found that probe recovery ratio was dependent on aspiration ratio, Mach number and Reynolds number in a manner consistent with the heat transfer balance described by Fleeger and Seyb. Moffat (1962) observed that conduction along the thermocouple wires to other parts of the rake body also depends on thermocouple temperature gradient, and therefore on the unsupported length of the thermocouple at a given flow condition. This effect was also observed in the experimental work of Smout and Cook.

Several other variants from the 'standard' Kiel-shroud design in figure 1 are given in the literature. The majority of these involve minor modifications to the Kiel-shroud or, in the case of temperature rakes, to the thermocouple length and type. Valentini et al. (1988) report using a computer code during temperature rake design optimisation to minimise measurement errors due to conduction and radiative heat transfer. Kokoszka and Tommasini (1985) describe a Kiel-shroud variant for use in the leading edge of turbine nozzle guide vanes, (figure 3). Air is drawn into the shroud and passes over the thermocouple before exhausting through a single hole in the vane pressure surface. The leading edge of the shroud is scarfed to achieve satisfactory operation of the sensor over the full range of engine operating conditions. Glawe et al. (1978) show a Kiel-shrouded thermocouple probe with annular bleed (figure 4). They argue that this design would give improved radiation shielding at high gas temperatures, since mixing of the shroud internal boundary layer with gas flowing down the centre of the shroud at the air exit holes of a conventional Kiel-shroud would be avoided. Overall however, the similarity of the 'standard' rake design (figure 1) to the Stickney design reported forty years ago (figure 2) is indicative of a low level of investment in pressure and temperature rake design improvement.

3. MOTIVATION FOR CHANGE

The established nature of pressure and temperature rake technology requires that good reason be furnished for any significant departure from the norm. Saravanamuttoo (1990) presents aerodynamic calibration data for the pressure rake in figure 1a); this is reproduced in figure 5, where total pressure coefficient is plotted against yaw angle. Total pressure coefficient (C_t) is defined as the difference between probe indicated total pressure (p_i) and actual total pressure (p_t), non-dimensionalised by the dynamic pressure head (p_t-p_s). For rake design assessment, yaw insensitivity is taken to be the yaw angle at which the error in indicated total pressure exceedes1% dynamic head (Ct less than -0.01). Against this criteria, it is seen from figure 5 that the 'standard' rake design is yaw angle insensitivity over ±24°. This result holds for the range of Mach numbers typically encountered in turbomachinery testing, so there is not generally a requirement to apply aerodynamic calibrations to pressure rake test results. Rather than an improvement in measurement capability therefore, the motivation for change arises from the cost of rake manufacture and repair.

Depending on their physical size, pressure and temperature rake bodies are either machined from solid or fabricated from sheet material. Carefully controlled machining of the Kiel-shrouds is necessary to ensure uniformity between shrouds, and to avoid burrs or blemishes which could adversely affect the instrument's characteristics. The pitot tubes and thermocouples must also be formed carefully and arranged centrally in their respective Kiel-shrouds to avoid unnecessary sensitivity to flow incidence. Being intentionally as small as possible commensurate with mechanical integrity, rakes are labour intensive to produce, and difficult to inspect. All these aspects of the manufacturing process are reflected in the rake procurement cost.

Rake maintenance and repair is also expensive, due to the intricacy of temperature rakes in-particular. Because they protrude forward of a relatively massive rake body, Kiel-shrouds are prone to mechanical damage at the sharp corners around the chamfered leading edge region. The Kiel-shroud itself furnishes a degree of mechanical protection to the pitot tube or thermocouple, but either sensor type may fail under vibration or high temperature conditions. It is often impractical to replace a single sensor, and one failure may result in refurbishing the entire rake. It was required to produce designs of pressure and temperature rake which were substantially cheaper to manufacture and repair than current designs, but which retained or improved upon current design aerodynamic performance. The exercise was undertaken as part of Rolls-Royce's Systems Engineering initiative known as 'Project 2000', where the overall target was to achieve at least 25% cost saving throughout the Experimental Engineering organisation.

4. RAKE DESIGN EXERCISE

Having recognised the scope for improving on current rake designs, three specific criteria were formulated against which design options could be assessed:

i) pressure and temperature rake procurement costs should be reduced by at least 25%,

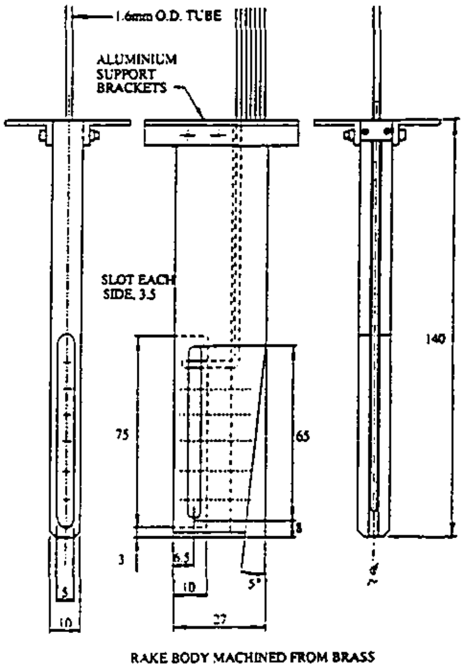

FIGURE 6: Common Cavity Kiel Rake

ii) pressure and temperature rake repair costs should be reduced by at least 25%, and

iii) the measurement capability of current rake designs should at least be retained, and preferably improved.

Because the data acquisition infrastructure was in-place and well established, any new rake design was also constrained to use existing types of sensor (i.e. pitot tubes for pressure and thermocouples for temperature).

It was clear that the first two criteria could only be met by simplifying and reducing the number of machining operations required to form the rake body, and by simplifying sensor installation and replacement. The greatest opportunity for simplifying the machining process appeared to come from deleting the protruding Kiel-shrouds, and incorporating the sensors in an alternative shroud which was an integral part of the rake body. This idea gave rise to the 'common cavity rake', a pressure version of which is shown in figure 6. For this prototype design, it was intended that the rake body be machined from solid material and slotted down the length of the leading edge to form the common cavity. Radial slots, rather than holes, were detailed in both sides of the rake to vent the cavity. The ratio of inlet to combined exit slot area was set to unity in-line with standard design practice for pressure Kiel-shrouds, (see figure 1). Six equi-spaced pitot tubes were provisioned, to be inserted into the cavity from a narrow slot cut in the rake trailing edge. Simple bracketry was detailed at the rake head to support the instrument for wind-tunnel evaluation. The design, which is patent protected (Cook and Smout, 1995), was intended to cut machining operations to an absolute minimum.

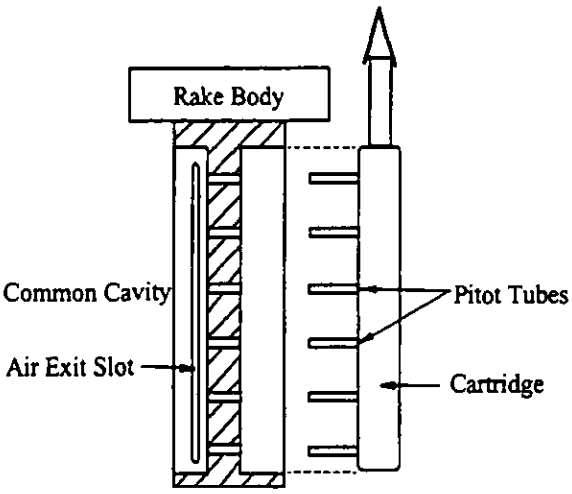

FIGURE 7: Schematic Representation of Pressure Rake Cartridge

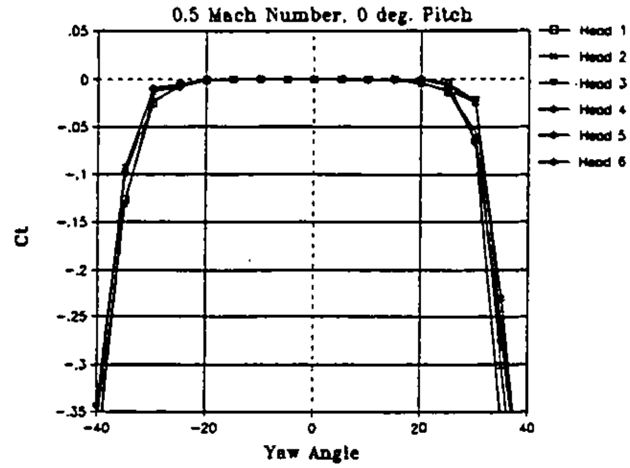

FIGURE 8: Ct vs. Yaw Angle for Prototype Common Cavity Pressure Rake

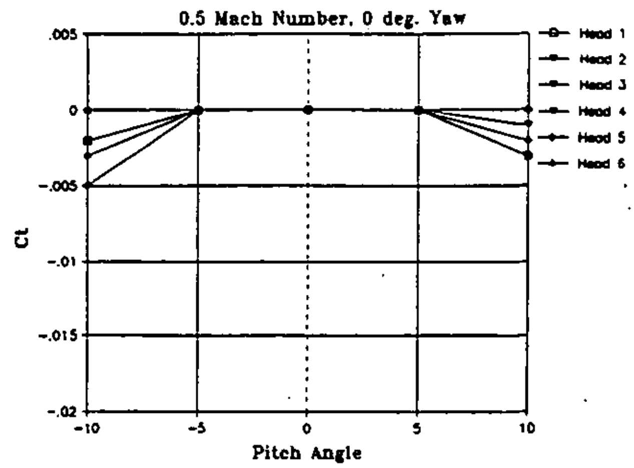

FIGURE 9: Ct vs. Pitch Angle for Prototype Common Cavity Pressure Rake

It was anticipated that the common cavity would assist the mounting and in-situ inspection of pitot tubes or thermocouples by providing more space around the installed sensors. It was also recognised that difficulties encountered in rake refurbishment arose from the practice of adhesively bonding the sensors into the rake body. An alternative approach, that of bonding the sensors to themselves to form a sensor cartridge which could then be mechanically located in the rake body was proposed. One possible embodiment of this idea is shown in figure 7. Refurbishment becomes a simple matter of replacing a damaged cartridge with a new one, with considerable time and cost savings. This approach also offers an opportunity to alter the number and type of sensors mounted in a common cavity rake simply by changing to an alternative cartridge.

5. DESIGN VALIDATION

A pressure rake was manufactured to the prototype design in figure 6, and aerodynamically tested to determine whether it met the third of the design criteria in section 4. Tests were performed in an open jet to determine sensitivity to yaw angle, pitch angle and Mach number, and in a closed section wind tunnel with an imposed radial pressure gradient.

5.1 Open Jet Testing

The prototype pressure rake was calibrated in the jet from an octagonal nozzle (100mm across flats) which exhausts to atmosphere. Air is supplied at approximately 70°C and at Mach numbers between 0.1 and 0.9. This facility is used routinely for calibrating aerodynamic instrumentation, and has been checked for uniformity of total pressure upto 150mm downstream of the nozzle front face.

Yaw angle and pitch angle were varied between ±30° and ±10° respectively, at flows of 0.3, 0.5, 0.7 and 0.9 Mach number. The rake indicated total pressure at all six tappings and the tunnel reference total and static pressures were recorded for each combination of variables. C_t values for each tapping were calculated and plotted as a function of either yaw angle or pitch angle at a given Mach number to present the results in the same form as figure 5.

The variation of C_t with yaw angle at 0° pitch and at 0.5 Mach number is shown in figure 8. Each tapping read the true total pressure to within 1% dynamic head for yaw angles upto ±20°, and this result was repeated at all tested Mach numbers. Against the yaw insensitivity criteria, the common cavity rake was therefore slightly more yaw sensitivie than the 'standard' rake in figure 1a). The variation in C_t with pitch angle at 0° yaw was less than 0.5% dynamic head for Mach numbers upto 0.5. Some sensitivity to pitch angle was observed at negative pitch and at 0.7 Mach number, particularly for the tappings furthest away from the rake head, (figure 9). This result is indicative of flow within the cavity from the rake head towards the free end. Saravanamuttoo (1990) does not publish any pitch calibration data for the 'standard' rake in figure 1, but the authors' own experience is that Kiel-shrouded rakes are normally insensitive to pitch angles of up to ±10° at least.

5.2 Tests in Imposed Total Pressure Gradient

Total pressure rakes used for engine testing are often exposed to strong radial pressure gradients which may give rise to radial flows along the rake body. Radial flow within the cavity of the common cavity rake had been suggested as a cause of pitch sensitivity at higher Mach numbers, (section 5.1), and evaluation of the prototype rake performance in a representative pressure gradient was required.

A suction wind tunnel of 200mm internal diameter and fitted with a bellmouth intake was chosen for this test. A radial total pressure gradient was generated by introducing a square mesh of circular wires at a plane 1.6 wind tunnel diameters upstream of the measurement plane. The common cavity rake could be inserted at the measurement plane such that all six tappings were immersed in the flow. This introduced a blockage based on frontal area of 2.2%, and it was recognised that the presence of the rake might influence the total pressure profile at the measurement plane. Rather than quantify the measurement section total pressure gradient by pitot tube traverse, a back-to-back test approach was adopted. A more conventional Kiel-shrouded rake with identical frontal area and pressure tapping positions to the CCR rake was built and used as a control against which the common cavity rake results were compared.

Figure 10 plots the Ct values derived from the six tappings of the control rake at 0.3 Mach number. Ct varies by 6.1% dynamic head from tapping no.1 near the tunnel wall to tapping no.3, 33mm from the wall. In figure 11, the difference between Ct values for the control rake and the common cavity rake is plotted as a function of tapping immersion, each rake having been tested in turn at 0.3 Mach number. The difference ranges from +0.8% dynamic head for tapping no.3 to -0.2% dynamic head for tapping no.5. This discrepancy is similar to the level of measurement uncertainty associated with the back-to-back test; although the greatest difference between the two rakes occurs at the point of lowest total pressure, there does not appear to be a consistent correlation between the differences observed and the total pressure gradient in which the rakes were tested. Tests at higher Mach numbers have yet to be completed.

6. DISCUSSION

Despite some evidence of pitch sensitivity at higher Mach numbers, it was concluded from the design validation exercise that the prototype common cavity rake performed in a very similar manner to a conventional Kiel-shrouded rake design. The yaw angle insensitivity of the common cavity rake could probably be improved to the ±24° level typical of 'standard' rake designs by chamfering the internal edge of the cavity in a manner similar to conventional Kiel-shrouds. A prototype common cavity temperature rake has now been constructed and is shortly to be evaluated. The arrangement of the thermocouples, and the sizing of the inlet and exit slots was based on the heat balance criteria given by Fleeger and Seyb (1975). If successful, then future pressure and temperature rake designs will adopt the common cavity and removable instrumentation cartridge ideas.

A brief survey of the costs invnlved in manufacturing and repairing current rake designs has been conducted to judge the potential savings offered by the new designs. Although the precise

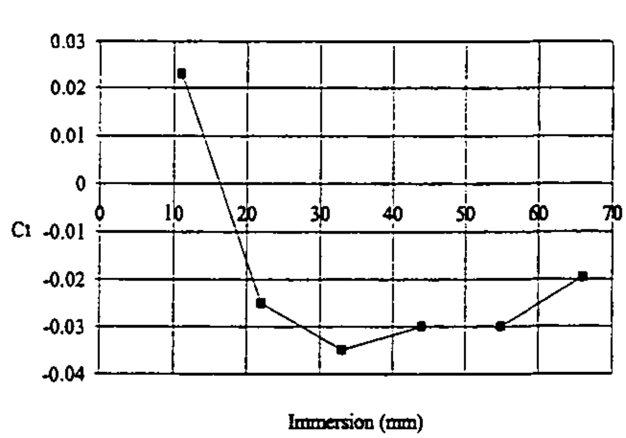

FIGURE 10: Total Pressure Profile in Closed Section Wind Tunnel

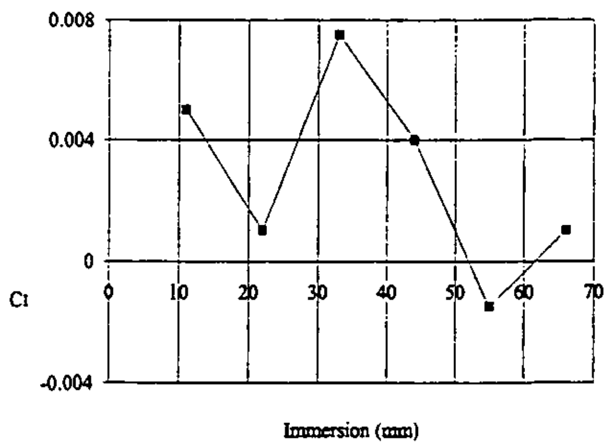

FIGURE 11: Difference in Ct Values Between Reference and CCR Rakes in Total Pressure Gradient at 0.3 Mn

figures will depend on the final rake design for a given application, it is estimated that upto 65% of current rake procurement costs will be saved as a result of adopting the common cavity approach. These savings come partly through simplified machining operations; all the required rake body machining operations may be completed on a single machine tool, avoiding the costly fabrication and electro-discharge machining techniques used currently. Sensor installation is also simplified, since the additional volume within the common cavity relative to a Kiel-shroud eases manual assembly, and offers scope for a mechanised approach to sensor installation. The visual and dimensional inspection of completed rakes is also eased.

Rake maintenance costs could be reduced by an estimated 75% through the use of instrumentation cartridges, with no deterioration in measurement capability. This saving comes chiefly through the reduction in time required by an instrument technician to replace the pitot tubes or thermocouples in a rake body. Given the more robust nature of the common cavity design, it is anticipated that the frequency of repair to a given rake will decrease, reducing further the cost of ownership in real terms. Overall, the first two design criteria in section 4 have been met comfortably. Measurement capability has been reduced slightly, but this is thought to be recoverable through design modification.

7. CONCLUSIONS

The common cavity approach to aerodynamic rake design, where pressure and temperature sensors are housed in a single slot in the rake body leading edge, offers savings of upto 65% on current rake procurement costs. Because protruding Kiel -shrouds have been eliminated, common cavity rakes should require far less maintenance; the use of replaceable cartridges to carry the instrumentation will further reduce repair costs. Aerodynamic validation has shown that the pressure variant of the common cavity rake design is as insensitive to Mach number, but slightly more sensitive to yaw angle and pitch angle than conventional Kiel-shrouded rake designs. A design modification to improve yaw angle insensitivity has been proposed, but has yet to be evaluated. Aerodynamic testing of a common cavity temperature rake is still required.

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REFERENCES

Benedict, R.P., 1983, "*Fundamentals of Temperature, Pressure and Flow Measurement*," John Wiley and Sons Inc., Third edition

Cook, S.C.P. and Smout, P.D., 1995, "Pressure and Temperature Measuring Apparatus and a Cartridge of Sensors for Use in the Same," US Patent No. US5433114A and UK Patent No. GB2272768B

Fleeger, D.W. and Seyb, N.J., 1975, "Aerodynamic Measurements in Turbomachines," AGARD-AG-207

Glawe, G.E. et al., 1978, "Recovery and Radiation Corrections and Time Constants of Several Sizes of Shielded and Unshielded Thermocouple Probes for Measuring Gas Temperature," NASA Technical Paper 1099

Kokoszka, J.M., and Tommasini, R.M., 1985, "Temperature Probe - European Patent Application," Application number 85630221.1, Publication number 0186609.

Moffat, R.J., 1962, "Gas Temperature Measurement," from "*Temperature, its Measurement and Control in Science and Industry*," Rheinhold Publishing Corporation, pp553 to 571.

Saravanamuttoo, H.I.H., 1990, "Recommended Practices for Measurement of Gas Path Pressures and Temperatures for Performance Assessment of Aircraft Turbine Engines and Components," AGARD-AR-245

Smout, P.D. and Cook, S.C.P., 1991, "The Dependence of Thermocouple Probe Calibration on Stagnation Density Changes," AIAA-91-2276

Stickney, T.M., 1955, "Recovery and Time-Response Characteristics of Six Thermocouple Probes in Subsonic and Supersonic Flow," NACA TN-3455.

Valentini, E. et al., 1988, "Progress on Measurement Techniques for Industrial Gas Turbine Technology," ASME 88-GT-113