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Modern Experimental Techniques in Turbine Engine Testing

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MODERN EXPERIMENTAL TECHNIQUES IN TURBINE ENGINE TESTING

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The paper describes application of two modern experimental techniques, thin-film thermocouples and pressure sensitive paint, to measurement in turbine engine components. A growing trend of using computational codes in turbomachinery design and development requires experimental techniques to refocus from overall performance testing to acquisition of detailed data on flow and heat transfer physics to validate these codes for design applications. The discussed experimental techniques satisfy this shift in focus. Both techniques are nonintrusive in practical terms. The thin-film thermocouple technique improves accuracy of surface temperature and heat transfer measurements. The pressure sensitive paint technique supplies areal surface pressure data rather than discrete point values only. The paper summarizes our experience with these techniques and suggests improvements to ease the application of these techniques for future turbomachinery research and code verifications.

Nomenclature

Ma_{IA}		inlet axial Mach number
P_{PT}	$[kPa]$	inlet plenum total pressure
Re_{C_0}		Reynolds number, coolant side
Re_{H_3}		Reynolds number, hot-gas side
T_{PT}	$[K]$	inlet plenum total temperature
m_c	$[kg.s^{-1}]$	corrected mass flow rate
n		dimensionless rotative speed
n_c	$[min^{-1}]$	corrected rotative speed
q	$[kW.m^{-2}]$	heat flow rate
q_B	$[kW.m^{-2}]$	bulk heat flow rate
v_{IA}	$[m.s^{-1}]$	inlet axial velocity
ΔT_{S_HC}	$[K]$	static temperature difference (hot-gas, coolant side)
π_{S_PR}		stage pressure ratio

Introduction

Experimentation in turbomachinery is undergoing a fundamental change. Modern experimental techniques for turbomachinery applications must refocus from overall performance testing to understanding of details of flow and heat transfer physics inside a machine. Until now, development of new turbine engines and their components has relied heavily on intense overall parameter testing to determine component performance characteristics. Design of future turbine engine components and predictions of their performance will to a great extent depend on sophisticated computational fluid dynamics (CFD) and heat transfer (HT) codes. Decreased demand for performance testing of individual components will reduce the price and shorten the engine development cycle. However, the CFD and HT codes must be thoroughly verified and their reliability and accuracy tested before they can successfully be used for production designs. Consequently, there is a growing demand for new types of data revealing flow physics details pertinent to CFD and HT code verifications.

For code validation, there is a need to acquire benchmark experimental data with sufficient accuracy and high temporal and a spatial resolutions. The benchmark data must be global, illustrating trends under a variety of operating conditions rather than only showing flow parameters at individual point locations at specific operating regimes. Current conventional experimental techniques with intrusive probes do not suffice for that purpose because they produce time- and area-averaged data that do not capture flow physics in sufficient details for code verifications. Further, the data accuracy is often affected by the fact that intrusive probes alter the flow parameters, at least in the immediate vicinity of the probe. Nonintrusive (or "zero disturbance") and fast response experimental techniques are needed for such measurements.

The paper describes experience with applications of two new distinct experimental techniques to measurements in flight-size jet engine components: thin-film thermocouples (TFT) and pressure sensitive paint (PSP). Both techniques are nonintrusive in practical terms. The TFT technique improves accuracy of surface temperature and heat transfer measurements. The PSP technique supplies areal surface pressure data rather than discrete point values only.

Thin-Film Thermocouples

At present, heat transfer data measured on thin walls of turbine components suffer rather high inaccuracy. Turbine blade temperature and heat transfer measurements are currently accomplished by embedding conventional thermocouples in the blade walls. The measurement uncertainty for this approach can be as high as *50 K* (Grant et al., 1985) because of heat path distortion, uncertainty of exact location of thermocouple junctions, and perturbation in the coolant flow pattern caused by "bulky" thermocouple wires very often routed through narrow cooling passages. These problems can be significantly diminished by applying thin-film thermocouples to blade surface temperature (Englund and Seasholtz, 1989) and heat transfer measurements (Lepicovsky et al., 1995). Very fine thin-film sensors (less than *15 μm* thick) offer an ideal solution because they do not alter wall thickness and guarantee virtually no perturbation of the heat flow path and the coolant flow pattern. Thin-film thermocouples are very fine temperature sensors manufactured directly on a particular surface by a sputtering process (Lepicovsky et al., 1995). Fig. 1 shows a test article instrumented with four thin-film thermocouples on its external surface.

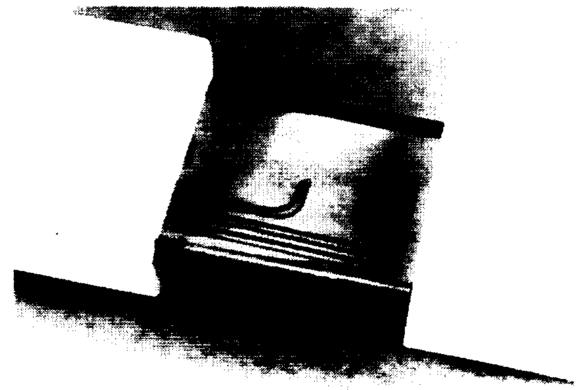

Fig. 1 Test article instrumented with four thin-film thermocouples.

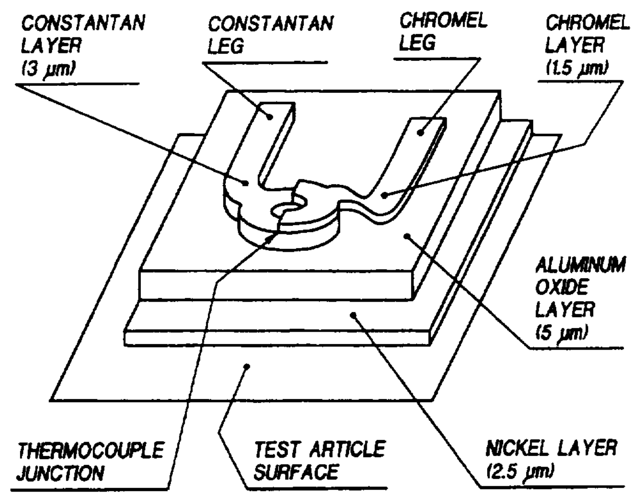

Fig. 2 Thin-film thermocouple (Type E).

Fig. 2 offers a magnified view of the anatomy of a typical thin-film thermocouple. As seen in this picture, the sensor consists of several layers deposited on the test article surface (Lepicovsky et al., 1995). A bond coat of nickel layer is sputtered first, followed by a layer of aluminum oxide to isolate the thermocouple electrically from the substrate. The thermocouple (type E) consists of layers of constantan and chromel, deposited using suitable masking during the process. Manufacturing of thin-film sensors is not extremely complicated; however, splicing the thin layers to strong lead wires to connect the sensors with data acquisition equipment is a major technological challenge. The thermocouples are spliced to the lead wires in two steps: the thin-film thermocouple legs are first connected to bare *25 μm* thermocouple-alloy wires, which are then connected to *0.25 mm* insulated thermocouple lead wires (Lepicovsky et al., 1995).

Before applying thin-film sensors to turbine blades, a simple model was tested in an arrangement simulating flow and heat transfer conditions, in terms of Re, Ma, and Nu numbers, typical for warm turbine tests. The conditions for cooled components of turbine engines were modeled using simple and controllable geometry. In essence the test article consisted of an internally cooled flat plate submerged in a stream of heated air. The principle is depicted in Fig. 3, and an overall view of the test rig is shown in Fig. 4. The photograph in Fig. 5 shows the test section with a removed side wall to expose the cooled flat plate in the middle of the channel.

During the verification tests, two kinds of measurements were performed: total (bulk) heat transfer and local heat flow rates. The total heat transfer was determined from the increase of the coolant total temperature in the test rig (measured by conventional thermocouples) and the coolant mass flow rate. The inlet and exit coolant total temperatures were measured in the upper and lower coolant plenums (cans), respectively (Fig. 4). The local heat flow rates were determined from the external and internal wall temperatures (measured by the thin-film thermocouples), known local wall thickness, and metal heat conductivity. One pair of thin-film thermocouples was located in the region of expected high local heat transfer and the other pair was in the region of low local heat transfer.

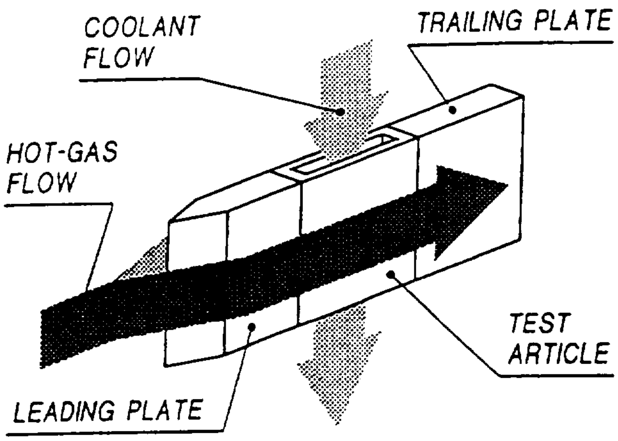

Fig. 3 Concept of heat transfer rig.

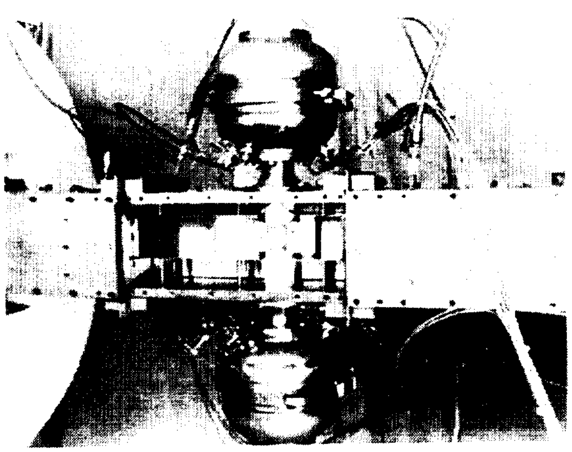

Fig. 4 Overall view of the heat transfer test rig.

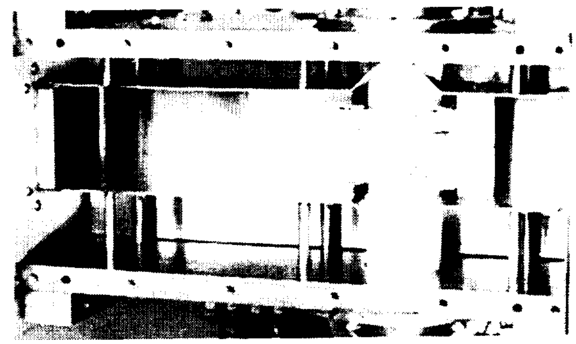

Fig. 5 Assembled test section.

The results of heat flow rate measurements are plotted in Figs. 6 and 7 as functions of coolant Reynolds number. Fig. 6 shows average (bulk) heat flow rate determined from the total heat transfer (measured on the coolant side) and the heat transfer area. No data from thin-film thermocouples were used here. The plot shows averaged heat transfer rates for three hot-gas-side flow conditions (see Tab. 1). Fig. 7 provides a comparison of the averaged heat flow rate with the local heat flow rates for a medium hot-gas-side Reynolds number of *647,000*. The average (bulk) heat flow rate was determined from data taken by the conventional thermocouples (single line in Fig. 7), and the local heat flow rates were obtained from thin-film thermocouple data. The local heat transfer rates are for the region of expected high local heat transfer rate (solid double line in Fig. 7) and the region of expected low local heat transfer rate (broken double line in Fig. 7). In general, experimental data acquired from thin-film thermocouples and their trends agree very well with data acquired on the coolant side using conventional thermocouples. Of course a rigorous comparison would require determination of the distribution of local heat flow rates over the heat transfer area, average it, and then compare it with the average heat transfer rate shown by the solid line in Fig. 7. The results demonstrate usability of thin-film thermocouples for heat transfer rate measurements in warm turbine tests.

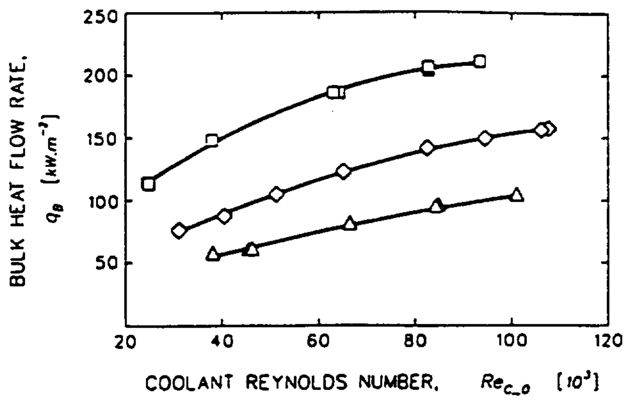

Fig. 6 Bulk heat flow rate (for symbols see Tab. 1).

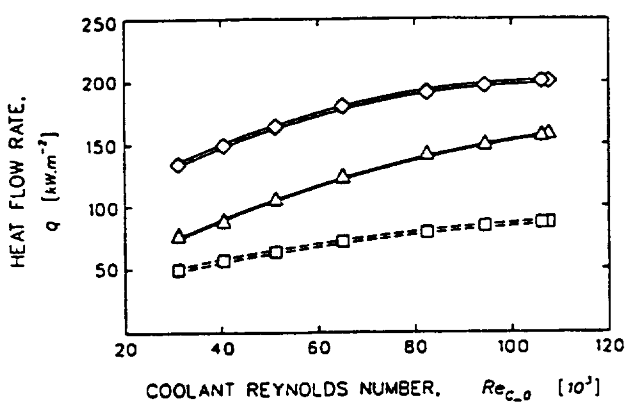

Fig. 7 Comparison of bulk and local heat flow rates (solid single line - bulk heat flow rate; solid double line - high local heat flow rate; broken double line - low local heat flow rate).

□	Test cond. III;	$Re_{H\_3} = 976*10^3$ $\Delta T_{S\_HC} = 131\ K$
◇	Test cond. II;	$Re_{H\_3} = 647*10^3$ $\Delta T_{S\_HC} = 128\ K$
△	Test cond. I;	$Re_{H\_3} = 554*10^3$ $\Delta T_{S\_HC} = 94\ K$

Tab. 1 Test conditions, assignment of symbols for Fig. 6.

The experiment with thin-film thermocouples succeeded. The sensors proved to be reliable: no sensor was lost during 30 hours of testing even though the sensors had no protection against external damage. The sensor can be protected against erosion by depositing a thin layer of aluminum oxide over the entire instrumented surface. The sensors are 'nonintrusive' in practical terms. Manufacturing of the sensors on external surfaces is not prohibitively complicated. For heat transfer measurements, however, the sensors must be also located on the test article internal (coolant) surface. Securing the necessary access to internal surfaces can be extremely complicated for flight-size gas turbine blades.

Pressure Sensitive Paint

Pressure sensitive paint (PSP) technology is a new, rapidly developing measurement technique with potential for broad use. This technique is already well established in external aerodynamics and wind tunnel measurements. However, confined flows, turbomachinery, and elevated temperature applications, pose yet unresolved problems. Several PSP techniques are available; the technique used in this investigation, labeled MDA, was developed at McDonnel Douglas Aerospace (Crites, 1993).

PSP techniques are based on oxygen quenched photoluminescence (Fig. 8). Photoluminescence is the property of some compounds to emit light when

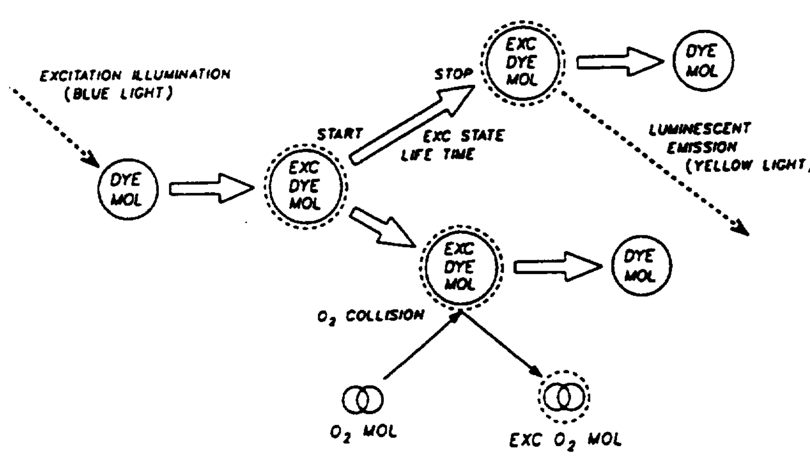

Fig. 8 Oxygen quenched photoluminescence.

excited by a suitable light source. For certain compounds the intensity of the emitted light depends on the oxygen partial pressure; it decreases with an increasing oxygen pressure; therefore, the intensity of emitted light can be directly related to the ambient pressure of a surrounding gas containing oxygen. The process of oxygen quenched photoluminescence is schematically depicted in Fig. 8 (Crites, 1993). A molecule of the active compound absorbs a photon supplied by the excitation blue light and is raised to an excited energy level. The molecule remains in the excited state for a short period up to several seconds (Kavandi et al., 1990) and then emits a photon of yellow light as it relaxes back to the ground energy state. However, if while still excited the molecule collides with a molecule of oxygen, the compound molecule suffers a collisional deactivation, and no photon is emitted. In this way, the intensity of emitted light from a given area is controlled by the number of oxygen molecules colliding with excited compound molecules in the same area.

Pressure sensitive paint consists of molecules of the photoluminescence compound suspended in a binder. The binder must have three important characteristics: (1) transparent to both excitation and luminescence light, (2) permeable to oxygen, and (3) adhere well to the tested surface.

The MDA paint requires an excitation illumination in the visible blue region of the spectrum. Halogen lamps with an interference filter at a center wavelength of *450 ± 25 nm* were used (Bencic, 1995). The yellow light emitted from the paint has a wavelength of *600 nm*. A CCD (charge-coupled device) imager (camera) was used to detect and record the emitted light containing the pressure information. This camera has *14 bit* resolution (approximately *16,000* intensity graduations) and *512* by *512* pixels. The camera must be optically filtered (*600 ± 40 nm*) to allow only the luminesced yellow light to be incident on the imager. The camera communicates to a PC via a camera controller board that handles all camera control functions and CCD data transfer (Bencic, 1995).

The detected brightness of the painted surface depends on several factors: illumination intensity, air pressure, surface temperature, viewing angle, and paint thickness. To detect only the pressure changes, two images must be acquire: a reference image at constant pressure and a data image at the run conditions. During postprocessing, the data image is spatially aligned with the reference image and a field of intensity ratios between these two images is generated. Then, the resulting local intensity ratios can be related to local pressure values if a generic calibration of the given PSP batch is known. It is preferable and more accurate, however, to perform in-situ calibration using several pressure ports and relate directly measured port pressures to the camera readings (intensity ratios) at the same locations (Crites, 1993 and Bencic, 1995).

The test setup for application of PSP technique to turbomachinery testing is shown in Fig. 9. The CCD camera and two halogen lamps are in the foreground (camera in middle). The camera is facing an access window over a stator of a single stage fan. Three stator vanes are visible in the access window. The suction side of the middle vane (the upper surface) was painted for testing. The air in the fan flows from right to left; therefore, the vane's leading edge is on the right side and the trailing edge on the left.

A camera image of the tested suction surface is shown in Fig. 10. The recorded light intensity field was already converted to pressure units following the procedures discussed by Crites (1993) and Bencic (1995). In this figure, the suction-side vane-surface pressure field is recorded in a skewed view that does not allow for direct comparison with design data because of the obscured relation between the skewed and design vane geometries.

In compressor designs, it is customary to plot blade or vane surface pressure fields in meridional plane projections (perpendicular at each surface element). In a test setup, however, very often it is impossible to arrange for such projection; due to optical accessibility restrictions, the CCD camera can be only placed in a location that records the three-dimensional vane surface as a skewed

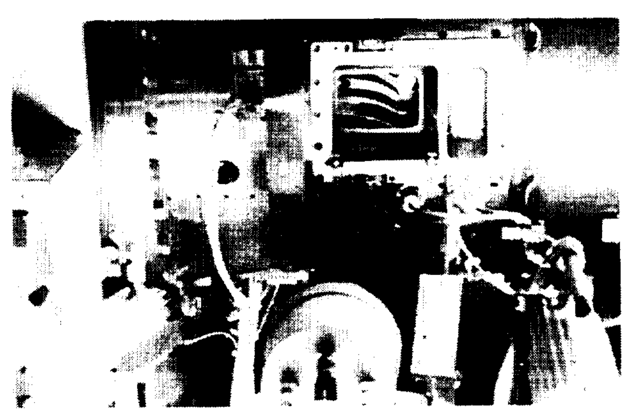

Fig. 9 PSP setup for turbomachinery application.

two-dimensional image. Consequently, a data reduction algorithm must be devised to convert skewed-viewed data into the meridional projection view.

Fig. 11 outlines the process of image conversion. The procedure starts in the camera plane (upper left corner). Here, the camera pixel grid (*512* by *512*) is indicated with the captured contour of the vane suction side. It must be stressed here that the contour image position is "free to drift" with respect to the camera grid. A particular contour position depends on the vane position, camera position, and the camera objective. For a given image, the vane contour position can be retrieved in pixel coordinates of the camera grid.

The picture in the image plane (lower left corner of Fig. 11) shows the vane cell grid that is now anchored to the vane contour. This grid was calculated using the contour coordinates in pixels from the camera plane. In this particular case, the cell grid height/chord size is *80* by *360*. The cell corner coordinates are calculated in both the camera pixel coordinate system and the vane grid coordinate system. The dual nature of the cell coordinates allows reassignment of pixel pressures to cell pressures. The reassigning mechanism works as follows. For a selected cell in the image plane, the corresponding pixel coordinates are determined and then the cell is projected from the image plane into the camera pixel grid plane. Then, an area *5* by *5* pixels around the projected cell in the camera plane is checked and pressure values for all pixels that fall in the cell area are summed; finally, a single average pressure value is calculated and assigned to the currently selected grid cell in the image plane. This procedure is repeated for all cells in the image plane.

Next, the vane cell grid in the meridional plane is calculated using a procedure similar to that for the image plane; however, this time the vane contour design geometry is used. To display the resulting pressure field with comparable spatial resolution in the height and chord directions, the meridional plane height/chord grid size *80* by *120* was selected. In order to generate the meridional pressure field, the image plane data in the chord direction were averaged in groups of three cells (reduction from *360* to *120* cells) and the resulting cell pressure values were plotted in the meridional plane in the reversed order -- to invert the flow direction and vane orientation. The solid

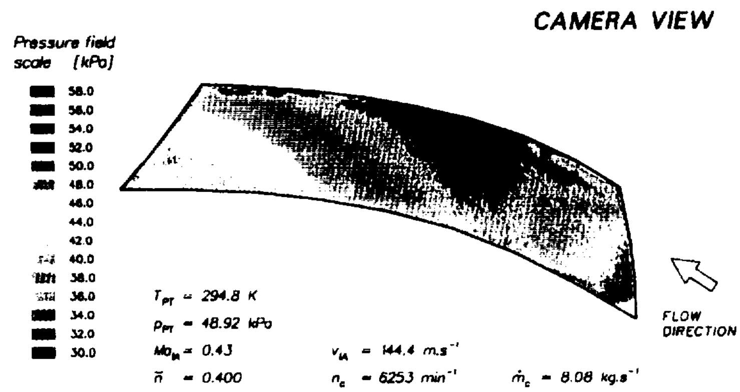

Fig. 10 Camera image of tested surface.

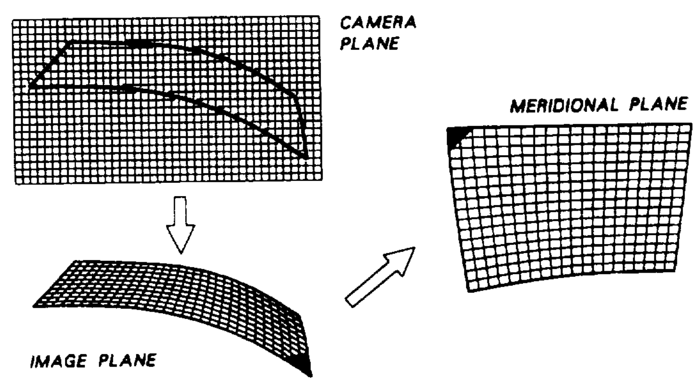

Fig. 11 Process of image conversion.

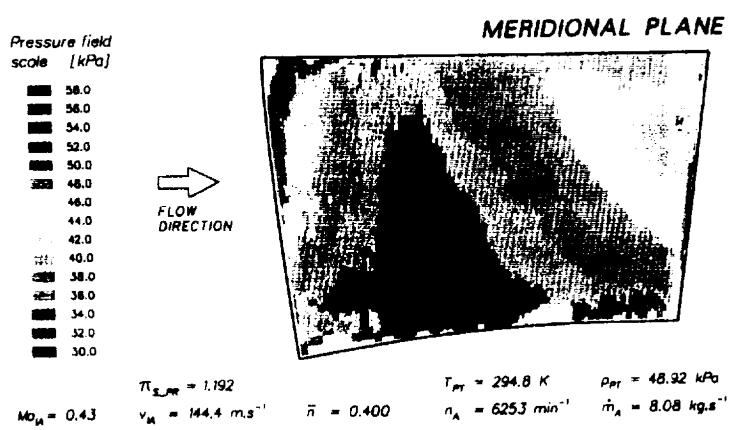

Fig. 12 Meridional plane suction-side vane-surface pressure field.

triangles in the image and meridional plane contours in Figure 11 indicate the tip/leading-edge corner of the tested vane.

The resulting suction-side vane surface pressure field is shown in Fig. 12 together with the pressure scale and the fan operating parameters. The pressure field map is in a form suitable for direct comparison with the surface pressure CFD predictions. The performance of a CFD code for off-design regimes can be verified by acquiring surface pressure fields for variety of operating conditions.

During the PSP experiments several problems were encountered. The two most serious were (1) paint contamination by oil and (2) paint adherence to the tested surface. Both problems always interrupted tests and required repainting the tested surface. Even a small oil leak in a tested fan is fatal for PSP. Oil dramatically decreases the paint binder permeability to oxygen and thus eliminates the paint sensitivity to ambient pressure. The other problem, paint erosion and peeling, is illustrated in Figs. 13 and 14 showing completely and partially striped vanes. The paint erosion was caused by dust particles in the flow. The problem of paint peeling was relieved by a modification of the fan operating procedure during testing. For example, the test started with a reduced total pressure at the fan inlet and the inlet plenum full pressure was set only after reaching the particular speed conditions.

The test results show that the PSP technique can play an important role in turbomachinery CFD code verification and in improving our understanding of flow physics in these machines.

Technical Challenges

The experience acquired with the TFT and PSP experimental techniques suggests the need for additional work in the following areas to improve the applications of these techniques for turbomachinery research. In particular, thin-film thermocouple improvements should (1) increase the sensor temperature operating range; currently the restricting factor is the temperature limit of the cement used in the thermocouple splicings; (2) improve thermocouple resistance to flow erosion, by applying additional protective layers; and (3) design multi-point sensor systems with a single common leg to decrease the number of thin-layer to thick-wire splicings. Pressure sensitive paint improvements should (1) improve paint adherence to substrates, (2) increase paint surface hardness to decrease the flow erosion, and (3) decrease or eliminate signal dependence on temperature that affects pressure measurement accuracy for cases of different surface temperatures between reference and run conditions.

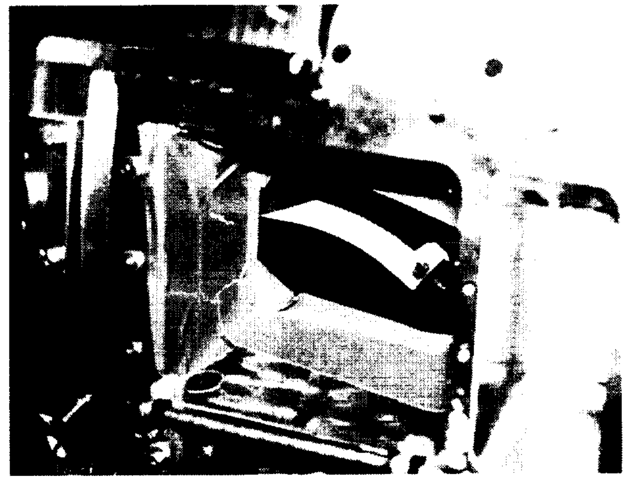

Fig. 13 Fully stripped vane suction side.

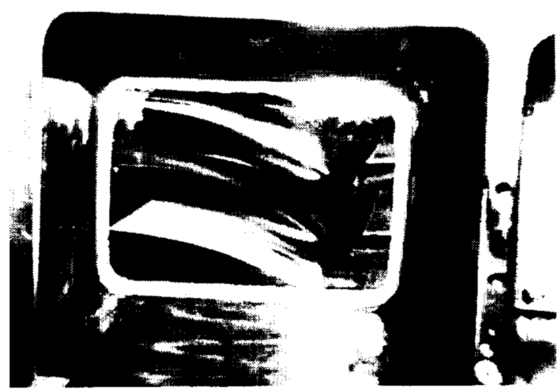

Fig. 14 Partially stripped vane suction side.

Conclusion

Experience gained in testing turbine engine components shows that applying advanced nonintrusive experimental techniques is possible; however, only a careful and meticulous approach and in-house developed know-how will guarantee success. The high operational cost of these sophisticated techniques will be balanced by high potential payoffs in understanding of flow physics and validating production CFD codes, thus leading to efficient designs of new generation of turbine engines.

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13. ABSTRACT ***(Maximum 200 words)***

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