POROUS PRESSURE-SENSITIVE PAINT FOR MEASUREMENT OF UNSTEADY PRESSURES IN TURBOMACHINERY

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Abstract
This work details the development and application of porous pressure-sensitive paint (PSP) for measuring unsteady surface pressures in turbomachinery. The advantages of porous PSP over conventional methods include global pressure measurement, fast response time, and instrumentation of thin turbomachinery components that are otherwise difficult or impossible to instrument. In this paper, the development, calibration, and application of porous PSP to turbomachinery are discussed. Porous PSP formulations were developed to ensure fast response times and good adhesion characteristics to rotating parts. Experimental methods such as phase-locking and image registration were developed to acquire quality data. Dynamic response calibrations of PSP with a fluidic oscillator were performed, indicating that porous PSP formulations have a response time of up to 40 kHz. For a turbomachinery application, the inlet wall and impeller blades of a turbocharger compressor were painted with fast-responding polymer/ceramic PSP. The turbocharger was operated at 100,000 rpm, corresponding to a blade-passage frequency (BPF) of 10 kHz. Even at this high speed and BPF, porous PSP was able to resolve the unsteady wall pressure distributions about the blade. In addition, a flow blockage was created to induce an inlet flow distortion on the compressor. Porous PSP was able to resolve the 1.67 kHz unsteady blade loading. Potential applications of porous PSP to unsteady turbomachinery testing include evaluations of rotor/stator interaction, flutter, inlet flow distortion, rotating stall, and surge.

Introduction
Turbomachinery flow fields are inherently unsteady. The surface pressures on the stage walls and rotating components can fluctuate at frequencies up to 100 kHz. In recent years, there has been a growing interest in measuring these unsteady pressure fluctuations. In particular, unsteady aerodynamic phenomena in the compressor such as rotating stall, rotor/stator interaction, and flutter need to be measured and evaluated. Ainsworth et al.¹ and Sieverding et al.² have done significant work in developing embedded semi-conductor sensors to measure these unsteady pressure fluctuations. Semi-conductor sensors, however, are only capable of providing discrete point measurements.

Pressure-sensitive paint has become an attractive alternative to traditional methods of surface pressure measurement. In many cases, PSP is a superior measurement technique over traditional methods because it can provide global pressure distributions at a much lower cost. Another advantage is the capability of PSP to perform pressure measurements on turbomachinery components that would otherwise be difficult with conventional instrumentation. For example, PSP may be applied to the thin leading edge of a compressor blade, where it would be extremely difficult to place pressure taps or transducers. PSP measures surface pressure distributions through the processes of luminescence and oxygen quenching. Typically, PSP is illuminated with light of short wavelength, which excites luminescent molecules in the paint to a higher energy level. These molecules, referred to as the luminophore, convert this energy to light, which is emitted at a longer wavelength. In the presence of oxygen in a test gas, the luminescent intensity of the luminophore is reduced by oxygen molecules from the gas through the process of oxygen quenching. Therefore, the intensity of light emitted from the paint is directly proportional to the oxygen concentration. Since the amount of oxygen in air is proportional to pressure, one can obtain static pressure levels from the change in the luminescent intensity of PSP. Further details of the PSP technique may be found in comprehensive reviews published by Bell et al.³ and Sieverding et al.²

Conventional PSP has been successfully implemented to measure steady flows in turbomachinery in the past. Liu et al.⁴ measured static temperature and pressure on a compressor blade in an axial compressor facility using a laser scanning system. Torgerson et al.⁵ performed PSP tests on a fan blade in an Allied Signal F109 gas turbine engine. Lepicovsky and Bencic have done much work at NASA Glenn Research Center, including measurements on a high-speed fan.⁶ Jordan et al.⁷ have used PSP to investigate high-cycle fatigue on a fan blade. Trinks⁸ has investigated the three-dimensional flow around the
suction side of a compressor blade row in a non-rotating facility, and has studied the effect of 15-Hz unsteady flow oscillations on a single compressor blade. It is important to note that all of the previous work, with the exception of Trinks and Jordan et al., has dealt strictly with steady pressures in the stationary or rotating frame of reference. The work of Trinks and Jordan et al. included unsteady pressure measurement, but the frequencies were very low – on the order of a few hundred Hertz.

The PSP formulation traditionally used for conventional testing includes a polymer binder. Conventional polymer-based PSPs are limited in response time to several seconds, however. The slow response time characteristic of conventional PSP makes it a limited tool in the measurement of unsteady flowfields. Therefore, a fast responding paint is needed for application to unsteady flows in turbomachinery. A new type of PSP, porous pressure-sensitive paint, has been developed for measurement of unsteady flowfields.

Porous PSP uses a porous matrix as a PSP binder, which improves the oxygen diffusion process. Figure 1 schematically describes the difference between conventional polymer-based PSP and porous PSP. For conventional PSP, oxygen molecules in a test gas need to permeate into the binder layer for oxygen quenching. The process of oxygen permeation in a polymer binder layer produces slow response times for conventional PSP. On the other hand, the luminophore in porous PSP is opened to the test gas so that the oxygen molecules are free to interact with the luminophore. The open binder creates a PSP that responds much more quickly to changes in oxygen concentration, and thus pressure.

The capabilities of porous PSP have been demonstrated through shock tube experiments and high-frequency fluidic oscillator jet flows. This paper summarizes the proven capabilities of porous PSP to measure unsteady flowfields. In this work, porous PSP has been applied to the unsteady flowfield of a turbocharger compressor inlet. Porous PSP was used to measure the pressure fluctuations on the inlet wall as each blade passed a given point. Even with a blade passage frequency of 10 kHz, the porous PSP was able to resolve the pressure distribution about each compressor blade. The PSP was also applied to the thin compressor blade (0.027"), and global pressure measurements are made for both steady and unsteady flows.

**Porous PSP**

There are three main types of Porous PSPs currently in use, depending on the type of binder used. Anodized aluminum PSP (AA-PSP) uses anodized aluminum as a porous PSP binder. Thin-layer chromatography PSP (TLC-PSP) uses a commercial porous silica thin-layer chromatography (TLC) plate as the binder. Polymer/ceramic PSP (PC-PSP) uses a porous binder containing hard ceramic particles in polymer. For each of these porous surfaces, the luminophore is applied directly by dipping or spraying.

For the current work with PSP applied to a turbocharger, polymer/ceramic PSP (PC-PSP) was used. The PC-PSP for these experiments was prepared in a manner similar to Scroggin’s procedure, using bathophen ruthenium as the luminophore. The other types of porous PSPs proved to be impractical for these tests. The TLC binder was fragile and would not hold up to the aerodynamic forces inside the turbocharger. The anodized surface was not practical because the turbocharger housing is too large to be anodized with the Purdue anodization equipment.

**Dynamic Response Calibrations**

Before attempting to use Porous PSP for unsteady flowfield measurements, it is important to characterize the response time of the paint. This characterization defines the operational limitations of the paint. Other methods of dynamic response calibration include using a shock tube, solenoid valve, loudspeaker, siren pressure generator, periodic shock generator, or pulsating jet. These dynamic calibration techniques vary in a sawtooth fashion. These dynamic calibration techniques have various advantages and disadvantages, which are discussed in detail elsewhere. Most of these dynamic calibration methods are unable to fully characterize the high-frequency response of PSP. Therefore, a new calibration technique was needed, and the high-frequency miniature fluidic oscillator was chosen as a dynamic calibration tool.

**Fluidic Oscillator Description**

The miniature fluidic oscillator, shown in Figure 2, is a device that produces an oscillating jet when supplied with a pressurized fluid. The oscillating motion of the jet is created by the introduction of transverse control jets on either side of the primary jet that cause the jet to alternate attachment to either side wall. The fluidic oscillator is unique in that it can produce a high-frequency oscillating flowfield with no moving parts. The flow pattern of the fluidic oscillator is shown in the schlieren images in Figure 3. A miniature-electret microphone was used for triggering the light source for the camera. HFC-134a refrigerant gas was used as a supply fluid for these images, since it can be easily viewed with schlieren instrumentation. Notice that the jet varies in a sawtooth fashion. These images serve as a useful reference when compared to the images acquired with pressure-sensitive paint.
A hot film probe was used to determine the frequency content of the oscillating jet. The signal from the hot film probe was acquired digitally, and a plot of the power spectrum was generated from the raw signal, as shown in Figure 4. Note that the hot film probe used for these measurements has a maximum specified frequency response of 10 kHz. As the oscillator operates at 5 kHz, the flowfield has its primary frequency peak in the power spectrum at 5 kHz. In addition to the primary frequency, there is higher order frequency content in the flow, ranging up to 30 kHz.

The fluidic oscillator can be used to provide a qualitative evaluation of frequency response, as well as quantitative results. The oscillator was operated with either nitrogen or compressed air as a supply gas. The oscillating nitrogen jet provided high-contrast qualitative PSP data, using both point measurement and full-field instrumentation. When the oscillator was operated with compressed air impinging on the PSP, qualitative comparisons with a Kulite pressure transducer were made.

**Fluidic Oscillator Experimental Setup**

The equipment setup for the oscillating jet calibration experiments is shown Figure 5. A porous PSP sample was placed under the fluidic oscillator and the jet from the oscillator was oriented either parallel to the PSP sample, or impinging on the PSP. A diode laser (λ=405nm) was used as an excitation source for a single point. The laser spot was focused to a small spot relative to the width of the oscillator jet. The emitted light from the excited point on the paint sample was collected optically, band pass filtered, and measured with a photomultiplier tube (PMT). The PMT signal was high-pass filtered and then sampled digitally at 250 kHz with LabVIEW. For full-field flow visualization images with porous PSP, a similar setup was used, but with a 12-bit or 16-bit CCD camera, and a pulsed array of LEDs for excitation.

**Fluidic Oscillator Results**

The flow pattern of the fluidic oscillator at one phase position, obtained by PC-PSP with the nitrogen jet parallel to the paint surface, is shown in Figure 6. The PSP images were ratioed with a wind off image to eliminate the effects of paint and illumination non-uniformities. Lower values on the image scale indicate brighter paint luminescence caused by the oscillating nitrogen flow. The presence of nitrogen gas displaces the oxygen molecules from the paint layer so that the luminescent intensity signal of the paint in the flow increases. A distinct sawtooth pattern can be seen in the flow – very similar to the flow shown in the schlieren images Figure 3. It is clear from this comparison that the PC-PSP sample does an excellent job of measuring the oscillating jet position with little blurring of the image.

The luminescent signal from the PSP was also measured at a small point as the jet passes by within the oscillation cycle. The measurement volume was located in the center of the jet region, directly below the oscillator exit. This location sees the complete jet pass by twice within each cycle. Thus, the jet passage frequency was 10 kHz when the fluidic oscillator was operating at 5 kHz. The laser spot was focused to a small spot relative to the width of the jet.

Plots of the power spectra for the point measurement signals from TLC-PSP, AA-PSP, and PC-PSP are shown in Figure 7. The primary frequency of these signals is at 10 kHz, with higher order harmonics up to 40 kHz. These power spectra may be compared with the actual power spectrum of Figure 4, which is recorded from the hot film probe. Since the power level of the power spectrum plots have been normalized, the relative magnitude of peaks for individual frequencies may be compared between the porous binders and the hot film spectrum. A binder with frequency peaks of lower relative magnitude than the other binders indicates that it has a lower frequency response. Clearly, all three paint samples are able to resolve 10 kHz fluctuations. The PC-PSP is capable of measuring pressure fluctuations at least up to 40 kHz.

A second set of experiments was performed with compressed air exiting the fluidic oscillator and impinging on the paint surface. These measurements were compared with the signal from a Kulite pressure transducer to quantitatively evaluate the frequency response of the paint. Full-field data with PC-PSP at two points in the oscillation cycle is shown in Figure 8. In these images, the oscillator is positioned near the bottom, pointing upwards with the jet impinging on the painted surface, and oscillating at a rate of 2.7 kHz. The two images, approximately 155° out of phase from each other, demonstrate the capability of PC-PSP to respond to an unsteady flowfield using compressed air. Point measurement data with the same experimental setup was also recorded to evaluate the PSP response in comparison to a Kulite pressure transducer. Power spectra were calculated from pressure data from both the Kulite and the PSP point measurements. The power spectrum for one point in the flowfield is shown in Figure 9. Notice that the flowfield has high-frequency content of at least 15 kHz. The response of the PSP sample matches the Kulite response very well, with no attenuation of the signal at higher frequencies. The noise floor of the PSP results is somewhat higher, however, making it difficult to determine the response at frequencies higher than 15 kHz.
Turbomachinery Application: 
The Turbocharger Compressor

With the demonstrated fast response characteristics of porous pressure-sensitive paint, it is now feasible to apply this instrumentation tool to a practical flowfield. Within turbomachinery components, there are significant unsteady flowfields for which porous PSP may be used. This application will use porous PSP for measurements of unsteady pressures in the inlet of a turbocharger compressor. This flowfield is representative of many practical turbomachinery applications.

Experimental Setup

Turbocharger Description

The turbocharger used in these experiments was a Garrett T25 ball-bearing model, provided by Honeywell. This turbocharger, shown in Figure 10, is a small type typically used in automotive applications. The turbo compressor wheel has six primary blades with six splitter blades. The impeller tip radius on the primary blades is 1.03”, and the blade tip thickness is 0.027”. The turbocharger was mounted off-engine in a bench-top setting, as shown in the diagram of Figure 11. Compressed air from the building shop air supply was used to drive the turbine. The air supply provided sufficient airflow to drive the turbocharger to speeds in excess of 100,000 rpm at almost all operating conditions. Lubrication was provided by a Greylor PQM-1-120 gear pump, which circulated Mobil 1 0W-30 synthetic oil through the turbo at about 30 psi.

Control of Operating Point

The operating condition of the turbocharger was set by controlling the flow rate of the air driving the turbine, and by creating a pressure drop at the compressor inlet. The turbine supply was controlled through an air regulator. The compressor inlet pressure drop was controlled through the placement of a series of fine-mesh screens over the inlet. An acrylic tube measuring 12” long, 2-1/4” OD, and 1-7/8” ID was fit in the compressor inlet, with the screen mounted at the end of the tube. The screen size was chosen to produce the desired pressure drop, with finer mesh screens giving a larger pressure drop.

To simulate non-uniform inlet flow conditions, an acrylic divider plate separated the tube in half (longitudinally), dividing the tube into two separate regions. The inlet flow on each half of the tube was then conditioned independently to create non-uniform inlet flow. For the unsteady PSP testing on the turbocharger blades, one half of the inlet was completely blocked off, while the other half used a coarse mesh screen to condition the flow, as shown in Figure 12. This created a once-per-revolution unsteady inlet flow condition that represents situations such as rotating stall, inlet distortions, or surge. When the turbocharger was operated at 100,000 rpm, the frequency of blade passage through the inlet distortion was 1.67 kHz. The orientation of the inlet blockage was varied while the CCD camera position remained constant, so that the pressure distribution over the blade at various phase angles could be measured. The phase angle (\(\theta\)) of the impeller blade is defined as the rotation angle of the compressor from an arbitrary point, shown in Figure 12.

Instrumentation

The turbocharger setup was instrumented with a pitot probe at the compressor exit, a pitot probe mounted inside the inlet tube, and a static pressure tap on the inlet tube. A thermocouple was mounted on the inlet portion of the compressor housing. The rotational speed of the turbocharger was measured with a Monarch Instruments ROS-5W optical sensor, which provided a TTL pulse to an ACT-3 panel meter. A small piece of 3M 580-Series reflective sheeting was placed on a turbine blade to provide a trigger point for the optical sensor.

PSP Setup

The pressure-sensitive paint instrumentation is described as follows. Porous polymer/ceramic PSP (PC-PSP) was applied to either the blades or the compressor inlet wall. Bathophen Ruthenium served as the luminophore. A pulsed array of 72 blue LEDs (ISSI model LM2) was used for PSP excitation. A Photometrics 12-bit CCD camera with 512 by 768 pixel resolution captured the PSP images. A 580-nm long-pass filter was placed in front of a Nikon 55-mm f/2.8 micro lens mounted on the camera. The acrylic viewing tube was milled down to a small wall thickness in the camera field of view, to minimize image distortion.

PSP Data Collection and Reduction

Synchronization of Excitation Light

The camera shutter must remain open long enough for the available light to nearly fill the pixel-depth of the CCD array. This is required to get the most intensity depth out of the 4096 counts possible, and to obtain more accurate pressure data. For the equipment used in these tests, camera exposures on the order of one or two seconds were required. However, the compressor rotated at speeds up to 100,000 rpm during the time the camera shutter was open. Therefore, the excitation light was strobed to “freeze” the motion of the compressor. The once-per-revolution TTL pulse from the optical sensor synchronized the pulsed excitation light with the rotation of the turbocharger. The TTL signal was fed...
through an oscilloscope with a delay function so that the azimuth of the rotor could be set throughout a range of 360° by varying the delay. The delayed TTL signal from the oscilloscope was then passed to a pulse generator that set the excitation pulse width and strobed the excitation light array.

Selection of Pulse Width

The pulse width of the excitation light had to be set such that the blurring of the compressor blades was reduced to an acceptable level. If the pulse width was too long, there would have been significant blade rotation while the light exposed the paint. If the pulse width was too short, the camera exposure time would have lengthened to a point where noise interfered with the PSP signal. A reasonable limit of 5% maximum blade motion, with respect to the blade chord length was chosen as a compromise value. When the turbocharger rotated at 100,000 rpm, the blade tip speed was 899 ft/sec. At this speed the blade moves 5% of its chord length in 2.5 μs. Therefore, the pulse width for all wind-on PSP images was set at 2.5 μs. It should be noted that the blue LED excitation array used in these experiments has a specified rise time of 0.7 μs and a decay time of 0.2 μs. Thus, the light pulse at full intensity was on the order of 1.8 μs long.

Wind-Off Image

In the intensity method of pressure-sensitive paint, the pressure is derived from a ratio of wind-on and wind-off images. The two images must be perfectly aligned; otherwise significant noise will be introduced into the pressure data. Misalignments of as little as one or two pixels can severely corrupt pressure data, as shown by Guille. Bell et al. stipulate that registration error should be less than half a pixel. In turbocharger testing with PSP, there are two ways in which portions of the image could become misaligned. First, camera motion or movement of the turbocharger can shift the whole field of view of the camera. This can be prevented by securely mounting the turbocharger. Even then, there may be small movement, which must be corrected by image-registration methods.

The more difficult alignment problem with the turbocharger is the difficulty in matching the azimuth position of the impeller between the wind-on and wind-off images. It would be virtually impossible to manually position the rotor at rest in the exact same location as the wind-on position captured by the strobe light. Therefore, a rolling wind-off image was used to approach proper image alignment. The wind-off image was taken at a rotational speed of 1000 rpm. At this low speed, there is very little flow through the compressor, and the pressure field induced by this low-speed flow is negligible. Since the wind-off rotational speed was a factor of 100 slower than the wind-on speed, the pulse width of the excitation light was increased by the same factor. Therefore, the camera exposure time remained constant, while the excitation pulse width was set to 250 μs, maintaining the same total level of illumination. Even with the rolling wind-off, there was still a slight misalignment of the rotor position between wind-on and wind-off. This was due to phase delay in the triggering system. It is difficult to remove this delay from the system, so an iterative process was used to match the rotor position in the wind-on and wind-off images. The rotor position in the wind-on image was recorded to the nearest pixel. The wind-off reference image was then taken after the wind-on image, and the trigger delay adjusted until the rotor moved to the same position as the wind-on case. This iterative process typically can achieve rotor alignment within two pixels.

In addition to matching the rotor position and illumination light for the reference image, the housing temperature must also be the same. In these tests, the wind-on image was taken first, and then the reference image was matched to the wind-on. As the turbocharger was brought up to speed, the housing temperature quickly increased in temperature. Therefore, several minutes had to pass for the housing to cool down before the reference image could be made at the same temperature. It is important that the two images be taken at the same temperature, because the calibration curve of PSP shifts with temperature (sensitivity decreases as temperature rises).

Data Reduction

PSP relies on a ratio of images to obtain pressure data. Therefore, the wind-on and reference images were divided with image processing software in the data reduction process. An a priori calibration was used to convert the intensity ratio into a pressure ratio. The calibration data was fit to the well-known Stern-Volmer relation,

\[
\frac{I_{\text{ref}}}{I} = A(T) + B(T) \frac{P}{P_{\text{ref}}}
\]

where \(I\) is intensity, \(P\) is pressure, \(A\) indicates reference conditions (wind-off), and \(A(T)\) and \(B(T)\) are calibration coefficients. The calibration was used to determine the coefficients, and if a reference pressure is known, the static pressure can be obtained throughout the intensity-ratioed image. In these experiments, the static pressure on the compressor inlet was measured with a pressure transducer. A temperature distribution based on the recovery temperature was assumed over the blade surface, and used to correct for the temperature sensitivity of PSP. In addition to the
temperature correction, the images for the unsteady PSP tests require image registration. Even though image registration markers were not used, this was accomplished by selecting distinctive features on the edge of the blade. A piecewise linear mapping was used to rotate the wind-on image to match the reference image. After the pressure ratio was calculated from the registered intensity ratio, the data was spatially filtered to minimize noise in the image.

Results

Compressor Performance Map

A compressor performance map is a vital tool for selection of testing conditions for the turbocharger. It is of interest in PSP testing to choose an operating point with a high pressure ratio. At high pressure ratios, it is expected that the PSP will have a significant response due to the large pressure rise in the compressor.

The performance map for the turbocharger used in these experiments is shown in Figure 13. At high mass-flow rates the turbocharger is limited by the available air supply to a rotational speed of about 100,000 rpm. This speed is used as an upper limit due to operational reliability of the turbocharger and the frequency response of the PSP. Also, it should be noted that the curves do not reach the surge limit at the right of the performance map.

The mass flow is controlled by the addition of wire-mesh screens to the inlet of the compressor. These screens create a pressure drop and restrict the flow. The total pressure ratio is measured directly by the pitot probes. Mass flow is calculated assuming a uniform velocity profile in the inlet tube.

The operating point for the PSP experiments is fixed at a mass flow rate of 245 cfm and a total pressure ratio of 1.75. At this condition, the compressor is spinning at 100,000 rpm, which corresponds to a blade passage frequency of 10 kHz (if only the primary blades are counted). The corresponding tip speed is 899 ft/sec, and the axial velocity is 173 ft/sec. The relative velocity is 915.5 ft/sec, which corresponds to a blade tip relative Mach number of 0.81.

Unsteady Wall Pressure Measurements

Full unsteady wall pressure data is shown in Figure 14. This camera viewing angle is shown by the inset image. In this case, the inlet wall of the compressor shroud is painted, while the impeller blades are painted flat black to minimize reflections and self-illumination. As in the previous case, the compressor is rotating in a clockwise fashion.

One striking feature of this data set is that the PSP resolves the wall pressure distribution about the blade. As expected, the pressure is high on the pressure side of the blade, and low on the suction side. As the blade passes a given point on the shroud, the pressure drops quickly from the pressure side to the suction side. This image demonstrates the ability of PC-PSP to delineate between the regions of high and low pressure on either side of the blade. This wall pressure distribution matches up well with data obtained by Eckardt et al. with unsteady pressure transducers. In addition, the average pressure increases axially into the turbo housing, agreeing well with the results of Joslyn et al.

Blade Pressure Measurements

Global pressure data for a large portion of a compressor blade is shown in Figure 15. This pressure field is steady in the rotating frame. The viewing angle of the camera is demonstrated by the inset picture showing the blade painted with PSP. In this view, the compressor is rotating clockwise. The leading-edge blade tip is in the lower-center portion of the image, and the leading edge at the hub is left-center. The trailing edge of the impeller blade is in the upper right corner. For these tests, the compressor inlet wall is painted black to minimize reflections of luminescence from the blade.

Several interesting features are noticeable upon examination of the pressure distribution. As expected, the pressure rises steadily along the chord of the blade. The pressure ratio increases to a maximum value near the trailing edge of the blade. Note that the entire blade is not visible – only about 90% of the blade is shown. The complex geometry of the impeller blades limits optical access to a portion of the blade. A chordwise plot of the pressure gradient at 50% span is shown in Figure 16. This plot clearly shows a steady rise in pressure ratio along the blade.

Blade pressure measurements were made at various phase angles as the impeller blade rotated through non-uniform inlet conditions. The flow was completely blocked on one half of the inlet tube, while the flow in the other half was conditioned with the same inlet screen used in the steady tests. It is expected that the pressure distribution on the impeller blades would fluctuate between two extremes as the blade rotates through the step change in inlet flow twice per cycle. The phase angle of $\phi=0^\circ$ is defined as the point where the blade is positioned behind the flow blockage, about to enter the half of the inlet tube where inlet flow is passing through. The phase angle of $\phi=180^\circ$ is defined as the point opposite $0^\circ$ phase, where the impeller blade is in the region of the tube with no flow distortion and about to pass into the region of flow blockage. The effect of the inlet flow conditioning is to change the effective velocity and angle of attack that the impeller blade experiences. When there is complete flow...
blockage, the velocity triangle distorts such that the effective angle of attack is increased, even to the point where the flow may be separated from the blade. In addition, the static pressure is decreased in the half of the tube where the flow is blocked.

The unsteady pressure distributions over the blade at $\phi=0^\circ$ and $\phi=180^\circ$ are shown in Figure 17. A plot of the chordwise pressure distribution at approximately 50% span is shown in Figure 18. Notice that the pressure distribution on the leading edge of the blade is similar for both cases. In the distorted flow regime, however, the pressure rise along the blade is much less than the undistorted case. At 40% chord the pressure gradient between the two flow conditions begins to diverge. The undistorted pressure distribution increases at a higher rate closer to the trailing edge of the blade. The pressure distribution for the undistorted case ($\phi=180^\circ$) is very similar to the steady flow conditions in Figure 15. This data demonstrates the usefulness of porous pressure-sensitive paint for characterizing the unsteady blade loading in the turbocharger environment. Even at the blade passage frequency of 1.67 kHz, the PSP is able to resolve the pressure fluctuations.

Discussion of Error Sources

There are several potentially significant sources of error in these experiments. Fortunately, there are solutions available to reduce or eliminate these errors. First, the quality of the paint job is important. A good paint layer must be extremely uniform and must not chip off under aerodynamic and centrifugal loading. It was found that several thin coats of the paint hold up much better to centrifugal forces that a single thick coat of paint. Also, a thinner paint layer is less likely to chip off, although the luminescent intensity is decreased.

Second, reflections between the blades and the wall can induce false readings in pressure. This was alleviated by painting reflective surfaces flat black when they were not being tested. The disadvantage of this procedure is that wall pressure and blade pressure cannot be simultaneously measured.

Third, and probably most significant, are errors in image alignment between the wind-on and reference conditions. Image registration is an essential addition to the data reduction process to ensure proper alignment between the two images. Proper alignment will mitigate the effects of non-uniform paint application or irregular light illumination. The complex motion of the impeller blade, however, makes effective image registration difficult. In particular, the edges of the image suffer the most error from image misalignment, making it difficult to obtain quality data for the leading edge.

Finally, surface temperature gradients can introduce error in PSP data. Unfortunately, pressure-sensitive paint also has some sensitivity to temperature. For these experiments, a temperature distribution was assumed to correct the pressure data. Another alternative for eliminating the temperature effect is to use temperature-sensitive paint to measure the temperature distribution. When PSP is calibrated for both pressure and temperature, the pressure can be backed out if the temperature is known.

Conclusions

Fast responding porous PSP has been used in the measurement of unsteady flow fields in turbomachinery. For the first time, full unsteady pressure distributions on a global scale may be measured with porous PSP. Dynamic response calibrations with a fluidic oscillator have demonstrated the capability of porous PSP to respond to pressure fluctuations as fast as 40 kHz. Porous PSP is now being considered as a viable instrumentation tool for measurement of unsteady phenomena in turbomachinery, including rotor/stator interactions, flutter, rotating stall, and surge.

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References


Figure 1: Comparison of porous PSP and polymer (conventional) PSP

Figure 2: Photograph of fluidic oscillator

Figure 3: Schlieren images of jet oscillation from fluidic oscillator

Figure 4: Normalized power spectrum of the oscillating jet, measured by hot film probe

Figure 5: Oscillating jet dynamic calibration setup

Figure 6: Polymer/Ceramic PSP results from fluidic oscillator (5 kHz oscillation frequency)
Figure 7: Frequency response results from fluidic oscillator dynamic calibration with nitrogen gas

Figure 8: PC-PSP full-field results with compressed air, (a) 40 μs (φ=40°), (b) 200 μs (φ=195°)

Figure 9: Frequency response results from fluidic oscillator dynamic calibration with compressed air

Figure 10: Garrett T25 Turbocharger with PSP applied to compressor housing wall

Figure 11: Turbocharger experimental setup

Figure 12: Creation of non-uniform inlet conditions
Figure 13: Compressor performance map

Figure 14: Unsteady wall pressure about compressor blades (normalized with respect to inlet total pressure)

Figure 15: Steady blade pressure data, normalized with respect to inlet reference pressure ($P/P_{ref}$)

Figure 16: Compressor blade distribution at 50% span

Figure 17: Compressor blade unsteady pressure distribution ($P/P_{ref}$),
(a) $\phi=0^\circ$, inlet distortion, (b) $\phi=180^\circ$, no inlet distortion

Figure 18: Chordwise pressure distribution at 50% span, unsteady blade loading