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Visualization of Pulsed Vortex Generator Jets with Porous Pressure Sensitive Paint

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This work highlights the use of porous pressure-sensitive paint (PSP) as a visualization tool for unsteady flows in turbomachinery. Surface pressure measurements on turbomachinery components with semiconductor sensors or pressure taps are limited by sparse spatial resolution and complex installation. As a result, resolving high-frequency pressure fluctuations in unsteady flows has proven to be difficult. Recent advancements in the development of porous pressure-sensitive paint (PSP) have enabled unsteady surface pressure measurements at frequencies of at least 20 kHz with very fine spatial resolution. Conventional PSP formulas use a polymer binder which results in a response time of several seconds; however, response characteristics have recently been improved by the formulation of a porous matrix binder. Dynamic response calibrations are presented, and the application of PSP to a low pressure turbine blade is discussed. In particular, PSP is used to visualize the unsteady behavior of a spanwise row of vortex generator jets (VGJs) on an L1A low-pressure turbine blade placed in a cascade wind tunnel. The blade was painted with polymer/ceramic PSP (PC-PSP), and the VGJs were pulsed at 10.6 Hz with nitrogen. Intensity-based, time-resolved PSP measurements reveal the development and structure of the VGJs.

Introduction

Unsteady pressures are inherent to the operation of turbomachinery. Unsteady blade loadings determine the fatigue life of turbine blades. Inlet distortions have significant impact on engine operability and efficiency. Rotor/stator interactions contribute significantly to problems such as high-cycle fatigue and engine tonal noise. Consequently, knowledge of the unsteady surface pressure distributions for a given operating condition is imperative to blade design. Conventional techniques for measuring blade surface pressures can be quite cumbersome, particularly when dealing with rotating components. Furthermore, pressure data obtained by conventional methods is limited to point measurements which may not capture significant pressure features such as shocks with sufficient spatial resolution. Porous pressure-sensitive paint is a measurement tool that is particularly suited for the unsteady flow fields in turbomachinery. Fast-responding porous PSP provides the advantages of fast frequency response, measurement of global pressure distributions, and high spatial resolution. Furthermore, PSP is an optical measurement technique, eliminating the need for complex slip rings or radio transmitters for data acquisition on rotating components. The PSP technique is based on the photoluminescence of oxygen-sensitive molecules, or luminophore. Designed specifically for unsteady aerodynamics, the paint has a fast time response to pressure fluctuations that is derived from the porosity of the paint binder. A porous matrix promotes high rates of oxygen diffusion within the binder, which ultimately dictates the luminescent intensity of the paint that is measured and

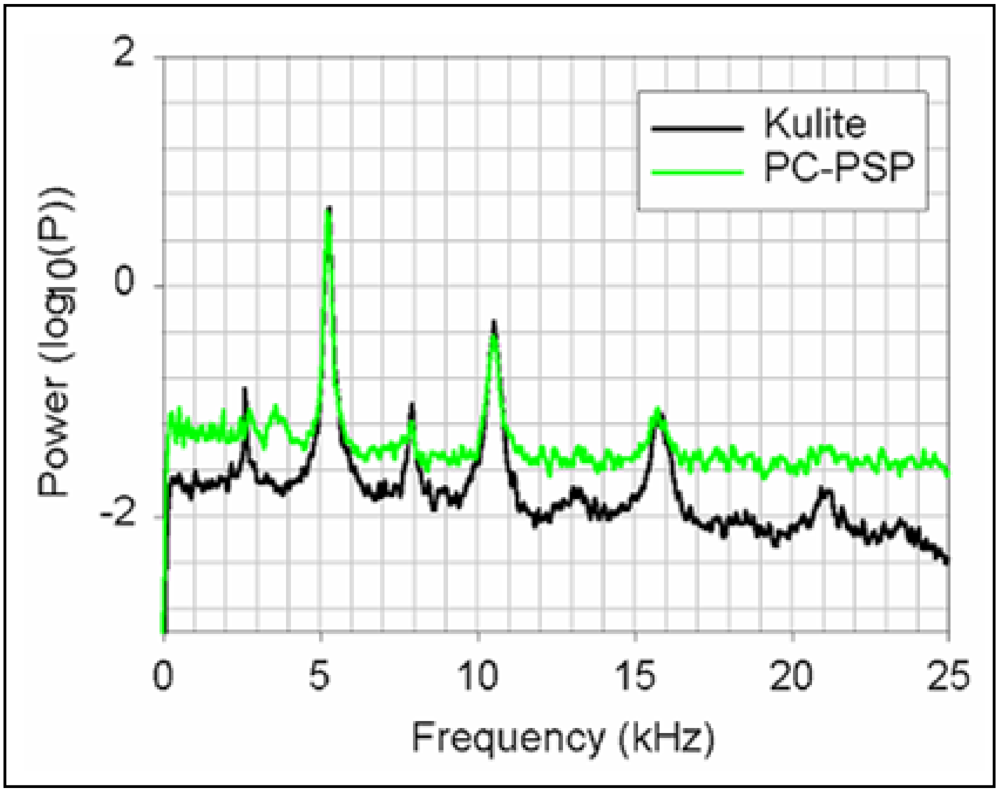

Fig 1 Frequency response characteristics for PC-PSP and a Kulite™ pressure transducer at a point in the fluidic oscillator flow field. (From Gregory [4]).

converted to pressure by one of several methods [1]. The luminophore molecules emit light with an intensity that is inversely proportional to the local pressure.

In the intensity-based method of PSP, the pressure is derived from a ratio of wind-on and wind-off images. The wind-off image captures the reference conditions of the test, while the wind-on image is taken with air flowing over the painted surface of interest. The two images must be perfectly aligned; otherwise significant noise will be introduced into the pressure data. A process of image registration can be used to align the wind-off and wind-on images to within acceptable error; Bell *et al.* [2] stipulate that registration error should be less than half a pixel. The intensity-based method of PSP is used for all cases in this paper.

There are three primary types of porous matrix formulations used as binders for unsteady PSP: anodized aluminum (AA-PSP), polymer/ceramic (PC-PSP), and thin-layer chromatography plate (TLC-PSP). These paint formulations, which are described in detail by Gregory *et al.* [3], were developed to have highly porous binder materials that enhance the diffusion of gas within the binder and reduce the response times. In this paper, the porous PSP formulation used for all experiments was based on a polymer/ceramic binder. PC-PSP is capable of resolving pressure oscillations of at least 20 kHz, as demonstrated by Gregory [4-6] using a fluidic oscillator as a dynamic calibration tool. The results from this dynamic calibration are discussed, as well as a comparison between the time response of PC-PSP and a Kulite™ pressure transducer.

PSP has been used extensively in a number of aerodynamic applications too large to list here. Moreover, the use of porous PSP for unsteady flow applications, such as the study of transient phenomena in shock tubes and Hartmann oscillators, has been well documented [3]. However, many problems in turbomachinery remain unexplored. Much of the previous work with PSP on turbomachinery has been done with steady-state measurement in a rotating frame of reference, such as axial compressors and rotors [7-10]. The work presented in this paper extends PSP to unsteady turbomachinery flows. In order to demonstrate the PSP technique as a viable experimental tool for unsteady turbomachinery applications, the results of a visualization study of pulsed vortex generator jets (VGJs) on a L1A low-speed turbine blade section are presented and discussed.

Dynamic Response Of PC-PSP

The frequency response characteristics of porous PSP must be thoroughly evaluated in order to establish the limits of the paint performance. Unsteady pressure fluctuations in turbomachinery applications can include very high frequencies, making conventional paint formulations unsuitable due to their slow response times. The frequency response of porous PSP was determined by implementing a well-known oscillating pressure field and evaluating the response [4]. A fluidic oscillator was used to produce high-frequency pressure fluctuations due to an oscillating jet. The fluidic oscillator was arranged such that the oscillating jet impinged on the PSP sample under evaluation. A laser spot was used to illuminate a small region of the PSP sample, while a photomultiplier tube was used to collect the luminescence in real-time. The response from a Kulite™ pressure transducer was compared directly with the PSP results in order to evaluate the response characteristics of the paint. Full details of the fluidic oscillator flowfield and the experimental configuration are provided by Gregory *et al.* [3-5].

The response characteristics of the PSP and Kulite™

Fig 2 L1A blade section with approximate location of separation line in steady flow.

signals are shown in Figure 1. This data for 5.2-kHz oscillations from the fluidic oscillator clearly shows that the PSP frequency response is at least 15 kHz with no roll-off in the paint response. The frequency peak resolved by the Kulite™ at 20 kHz is not detected by the PSP due to the higher noise floor present in the PSP measurements. The sub-harmonic frequency peaks detected by the Kulite™ transducer at 2.5 kHz and 8 kHz, but not detected by the PSP signal, are due to the fact that the Kulite™ transducer face was larger than the PSP interrogation area, rather than being due to a deficiency in the paint response. Thus, the power spectra provided in Figure 1 indicate that the paint response exceeds 15 kHz, while the upper limit of the paint response is high enough such that it cannot be determined with the fluidic oscillator experimental setup.

Low-Pressure Turbine Blade

With the demonstrated fast response characteristics of porous pressure-sensitive paint, it is feasible to apply this instrumentation tool to a practical flow field. Within turbomachinery components, there are significant unsteady flows for which porous PSP may be used but which the technique has yet to be applied. One of the few applications, for example, utilizes porous PSP for measurements of unsteady pressures on the impeller blades of a turbocharger compressor [4]. This flow field is representative of many practical turbomachinery applications. The following discussion investigates the use of porous PSP as a flow visualization tool for unsteady flow control with pulsed vortex generator jets (VGJs) on a turbine cascade blade.

VGJs are an active form of flow control for delaying separation on low-pressure turbine blades. Compared to air injection through rectangular slots, VGJs have been shown to be more effective in pressure recovery at low speeds [11]. Moreover, the effectiveness in controlling separation is enhanced when VGJs are pulsed. In fact, Bons *et al.* found reductions in the wake loss profile of over 50% with pulsed blowing [12]. A vortex is produced which entrains higher-momentum fluid into the boundary layer, thereby delaying separation. These results were suggested by the computational work of Postl *et al.* [13] and validated by Bloxham *et al.* [14].

The aim of the present work is to visualize the surface imprint of pulsed VGJs with PSP. An image sequence is presented which tracks the local development of the VGJs on the surface of an L1A low-pressure turbine blade. The L1A blade section is characterized by an aft-loaded pressure profile with a separation bubble beginning near 57% Cx (without upstream wakes present) and continuing to the blade trailing edge, with the VGJs rows located at 59% Cx and 72% Cx [15]. The blade profile and VGJ row locations are illustrated in Figure 2.

Experimental Methodology

The L1A blade was coated with PC-PSP by airbrushing the polymer/ceramic base onto the model, followed by an application of the luminophore solution by the same technique. Bathophen ruthenium complex (GFS Chemicals) served as the luminophore. The blade was placed in the low-speed linear cascade facility at The Ohio State University Aeronautical and Astronautical Research Laboratory. A description of this facility is given in Bons *et al.* [16]. The cascade tunnel offers a wake generator consisting of carbon-fiber tubes mounted on a motor-driven chain assembly in order to imitate the effects of a rotor. The upstream rods were removed from the chain assembly so that the jet-only

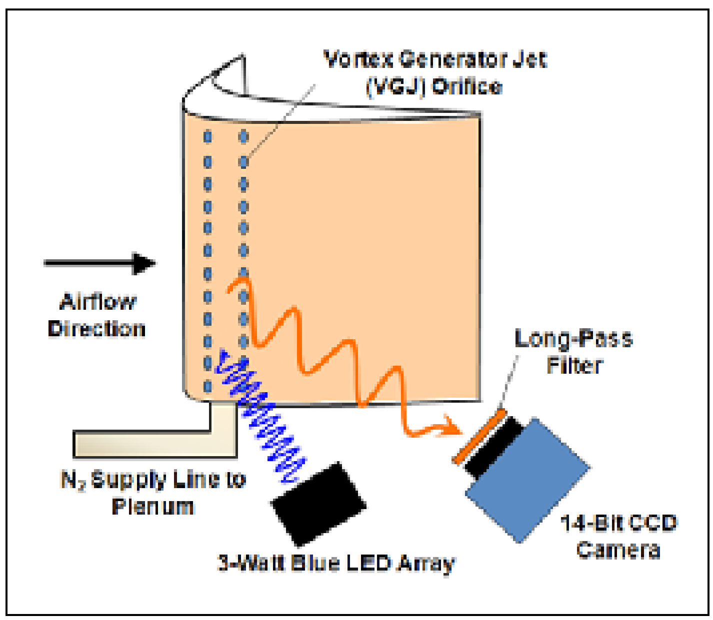

Fig 3 Experimental setup showing L1A turbine blade painted with PC-PSP (acrylic duct walls and second L1A blade not shown).

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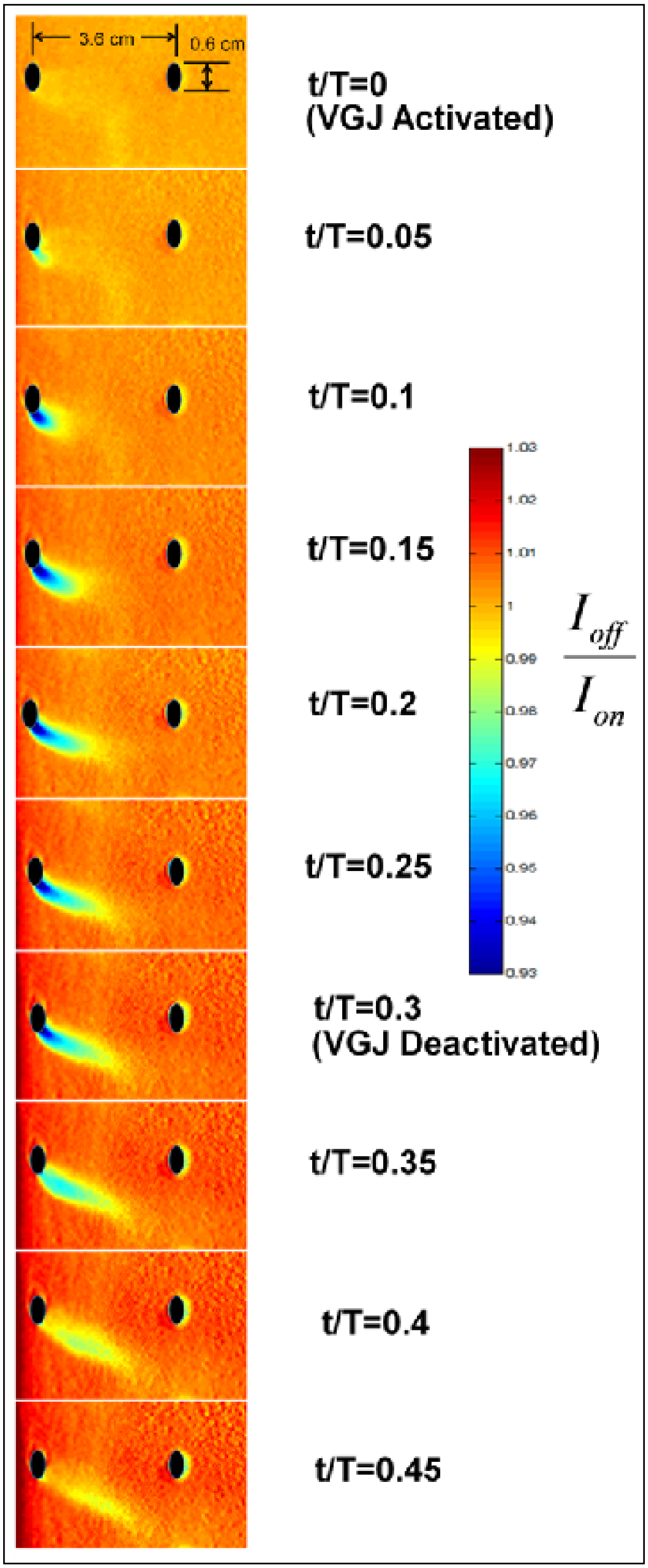

Fig 4 Time-resolved image sequence of single VGJ for t/T=0 to 35% of pulsing period.

case could be examined with PSP.

The tunnel flow is initiated by a centrifugal blower. After conditioning the air in such a way to achieve a velocity uniformity of ±2%, the stream passes through an acrylic duct which houses two blade sections. Although a single blade was painted with PSP, the second L1A blade was also mounted in the turbine cascade in order to replicate the conditions inside a low-pressure turbine stage with periodic blade geometry. The flow velocity at the cascade inlet was measured to be 2.25 m/s (Rec=20,000) with a pitot-static probe.

The eighth VGJ hole located on the upstream row at 80*d* from the base of the blade was chosen for acquiring data because of its proximity to midspan. Having identified a region of interest, a 14-bit CCD camera (Cooke Corp., pco.1600 model) was positioned on a tripod at an angle to the square optical access window of the tunnel, as shown in Figure 3. The CCD camera had a resolution of 1200 x 1600 pixels and a memory cache of 4 MB for on-board frame averaging (frame rate of 30 frames/second).

The optical window material was a clear acrylic which could be removed from the side of the test section. The geometry of the tunnel as well as the hindrance of the non-painted L1A blade next to the test blade prevented the camera from being positioned directly in front of the blade surface. Therefore, the camera tripod was set up at an angle to the region of interest without any consequences for data collection. In order to collect only the light emitted by the luminophore (λ=630 nm), a 580nm long-pass filter was placed in front of a Nikon 55mm f/2.8 micro lens on the camera. A pulsed array of 72 LEDs (λ=405 nm) from Innovative Scientific Solutions, Inc. with a power rating of 3 watts was used to excite the luminophore molecules. The shorter excitation wavelength results in an emission of light with longer wavelength, a property of luminescence known as the Stokes shift.

For this visualization study, nitrogen gas served as the jet fluid to provide a greater contrast to the free stream air; this was done out of consideration for the PSP sensor molecules. Although the sensor molecules are designed to measure the partial pressure of oxygen, they are still effective for this mixed flow. In this case, the emitted light intensity of the luminophore is directly proportional to the local concentration of nitrogen on the blade surface.

Images were acquired by phase-locking the excitation light to the pulsing frequency of the VGJs. As a baseline for future experiments, the pulsing frequency of the jets in this study was set to 10.6 Hz (T=94 ms), a figure that lends itself to easy set up of equipment. Pulsing was accomplished with a General Valve Inc. Iota One unit, which was set to pulse the jets on an internal cycle of 10.6 Hz on a 30% duty cycle. The 11 mm-diameter plenum of the painted L1A blade was connected to an inline Parker-Hannifin high-speed solenoid valve and supplied by a compressed nitrogen cylinder. The solenoid valve also regulated the plenum pressure at 50 psi, corresponding to the proper plenum pressure for a blowing ratio of approximately 2 under the tunnel testing conditions.

The Iota One output TTL signal was split and sent to the external trigger input of the camera and LED array. The LED pulse width was set to 0.025T=2.35 ms. A Berkeley Nucleonics Model 575 time delay generator was used to step through the period with a time delay of 0.05T, or Δt=4.7 ms. The time delay was incremented by the same step for each successive image capture. The exposure time of the camera was set to a value of 1 second with the software program OMS Acquire. Using the camera's on-board image averaging function, 15 images were captured for each phase in the period and averaged.

An intensity-based method was employed to obtain the ratio of Ioff/Ion by dividing each pixel in the wind-off image by the intensity associated with its corresponding position in the wind-on image. In the context of the VGJ study, wind-off corresponds to "jet-off"—that is, the wind tunnel was operating, but the jets were not activated. Wind-on is synonymous with the jets being pulsed.

Results

The image sequence shown in Figure 4 displays the state of the VGJ structure at ten phases in the period, with the corresponding percentage of the period noted. The intensity levels Ioff/Ion are inversely proportional to the concentration of nitrogen on the surface of the blade.

At t/T=0, the pulse of nitrogen gas has not yet made its way into the plenum. A wisp of intensity variation appears in the image due to the remnants of a VGJ from previous phases that were averaged with the camera to produce this single image. The VGJ structure begins to take shape at t/T=0.1 after first emerging from its orifice. As expected, high gas concentrations characterize the inner core of the jet (shown in dark blue), with concentration decreasing as the radius of the jet footprint increases. The image shows that the flow turns the jet by 47° (measured from the image) from the skew angle of 90°, vertically downward, as designed for the L1A blade. By t/T=0.25, the VGJ is well developed. The surface footprint of the VGJ was calculated to grow at a rate of 76.6 cm/sec over the first 25% of the period. After 30% of the period, the stream of nitrogen was deactivated by the pulse driver according to the established 30% duty cycle. The high-concentration core that is present in the previous images consequently vanishes as the jet is turned off. The footprint of the jet structure, however, maintains its integrity at t/T=0.40, a full 33% of the entire time that the jet was activated. The surface footprint begins to slowly diffuse as the period progresses.

The PSP was also able to diagnose spanwise nonuniform blowing on the upstream VGJ row. Compared to the surface footprint of the VGJ issuing from the eighth hole of the upstream row, the hole located 30*d* above it (hole eleven) did not exhibit the same surface characteristics, as shown in Figure 5. Instead, the jet issuing from hole eleven appears to have a lower blowing ratio than the jet issuing from hole eight. One plausible explanation for this is due to the location of hole eleven at a greater height from the plenum inlet. The nitrogen gas injected into the plenum most likely has a nonuniform pressure that varies with distance from the chamber inlet. Due to the configuration of the cascade facility, the nitrogen supply line injects gas vertically upward into the plenum, which could result in lower gas pressures at higher elevations. A similar effect was observed in the study by Bourgois *et al.* [17] in which microjets were implemented on an airfoil. A nonuniform exit velocity profile for two slots in the spanwise direction was observed in their work. Although the plenum shapes in the airfoils used by Bourgois *et al.* were trapezoidal and the L1A plenum was a tube of 11 mm diameter, the same effect of pressure nonuniformity in the plenum was observed.

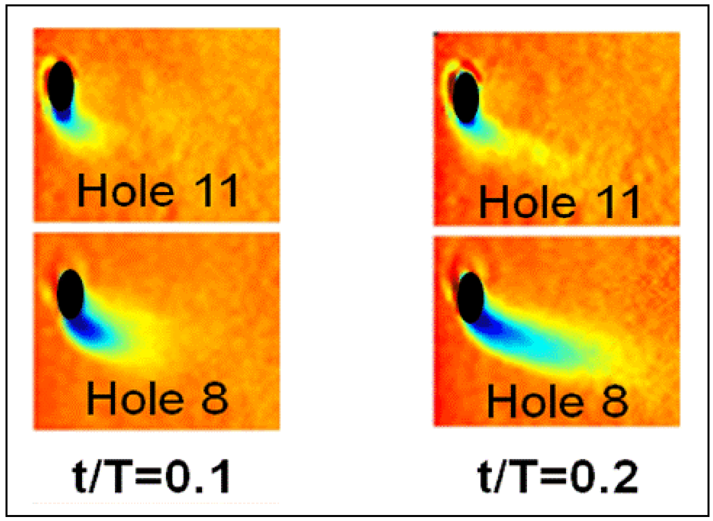

Fig 5 Nonuniformity between two holes on upstream VGJ row.

Conclusions

In this work, fast-response porous PSP was demonstrated for an unsteady turbomachinery application. A dynamic response calibration which compared the pressure data from polymer/ceramic PSP and a Kulite™ pressure transducer in the oscillating flow field set up by a miniature fluidic oscillator was presented. The calibration revealed that PC-PSP was able to successfully resolve flows with frequency content of at least 15 kHz. Results of a visualization study on pulsed vortex generator jets for turbine blade flow control were presented, in which the jet pulsing frequency was 10.6 Hz. The PC-PSP successfully resolved the pulsed jets. A time-resolved image sequence showed the turning angle of the jets due to the low-speed flow as well as the spanwise and chordwise extent of coverage. Furthermore, the PSP technique proved to be effective at diagnosing a nonuniform blowing profile on the blade.

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