

Transition measurements of upper and lower rotor blade surfaces in forward flight with thermography

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Thermography allows for imaging the location of laminar-to-turbulent boundary layer transition on surfaces in air flows. The determination of BL transition of rotor blades was done in 2017 on the lower surface of a rotor blade in forward flight in the NASA Langley 14-by 22-Foot Subsonic Tunnel Subsonic Wind Tunnel. This article reports on the follow-on experiment in the same facility and the same blades where thermography was performed on both upper and lower surface synchronously, with the upper surface mapped throughout the full azimuthal range. Blade-tracking rotating mirrors were used for each thermal camera and were synchronized for simultaneous image acquisition. Furthermore, the Differential Infrared Thermography (DIT) technique depicts the unsteady nature of the BL transition in forward flight. Results are presented and discussed. These data are the first ever recorded of both surfaces of a rotor in forward flight.

I. Introduction

The state of the boundary layer on any airfoil is critical in the understanding of that airfoil's performance and among the most difficult to model. It is particularly difficult to predict transition on a rotor blade as it encounters ever changing inflow conditions in forward flight. Along with the changing inflow, cyclic pitch is imparted to maintain lift throughout the rotation. Furthermore, modern blade design employs radial changes in chord thickness, twist, and airfoil cross section. Reynolds Number and Mach number vary radially as well. Traditional measurements of the boundary layer include arrays of pressure taps, imbedded microphones (such as Kulites) and hot-film anemometry. Visualizations have been made with tufts, sublimation, and oil-film sheer interferometry. Each method has advantages, yet all are intrusive or difficult to implement or both, and none are able to measure a rapidly moving boundary layer transition point.

Thermographic imagery of boundary layer states was first attempted on fixed wing wind tunnel installations in the 1980's [1]. The technology of the time yielded low resolution imagery, yet was successful at detecting the minute

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temperature differences on the surface caused by the different heat flux of the laminar and turbulent boundary layers when a temperature difference between the surface and flow was present. Thermography became the first truly passive technique to witness the boundary layer transition.

Thermography was first applied to visualize boundary layer transition on a subscale helicopter rotor in forward flight in a wind tunnel in 2017 [2, 3] where the transition of the lower surface was mapped over most of the rotor azimuthal range. This milestone was reached due to the development of the modern Focal Plane Array CMOS thermal camera and a blade-tracking optical system. The imaging method employed the use of a rotating mirror to freeze the motion on the sensor. This method, described in [4], requires the mirror rotation axis to be pointed at the center of rotation of the rotor disk and its rotation frequency to be $\frac{1}{2}$ the rotation frequency of the rotor itself. By capturing the virtual image, the rotating mirror can affix the image of the blade in the same spot on the sensor for the duration of the exposure, thus permitting longer integration times. The maximum integration time required to freeze the blade motion without the use of blade tracking is 10 μsec . These data were collected with 200 μsec integration times, which corresponds to 1.3 degrees of blade movement. This longer integration time yielded imagery much higher signal to noise ratio than that acquired at 10 μsec . Additionally, a number of images can be acquired of the blade as it passes since the image area is only slightly larger than the blade image.

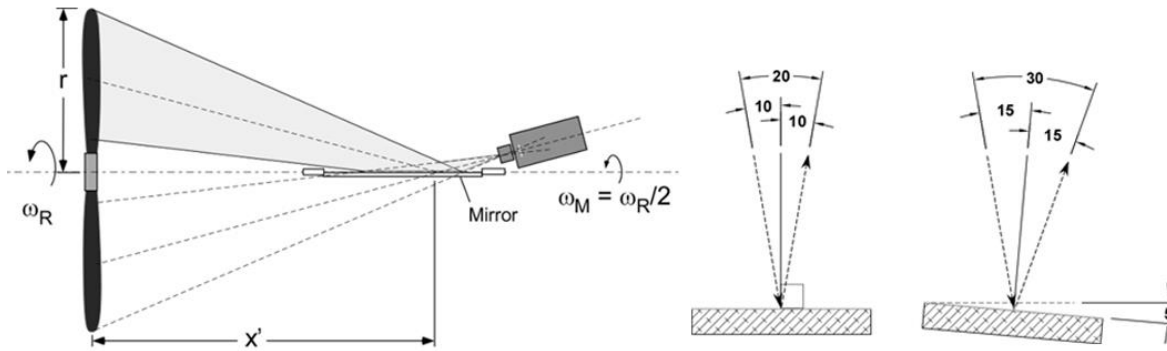


Fig. 1. Illustration of the image de-rotation principle.

A mirror system that synchronized to the rotor encoder output developed by DLR Göttingen was installed in the center of the turntable to acquire imagery of the lower surface. The rotor disk was also centered over the center of the turntable with an extended sting of a heaving and pitching strut mounted in a downstream location. The viewing aperture over the mirror and camera was wide enough to permit the acquisition of 90 degrees of usable images of rotor rotation per blade passage.

A follow-on entry was performed in April of 2018 where both the lower surface camera using the DLR mirror and the upper surface was imaged by a new mirror system. Both entries were performed in the NASA Langley 14- by 22-Foot Subsonic Tunnel (14x22) Subsonic Wind Tunnel. The second tunnel entry used a rotating mirror system designed and built at NASA Ames Research Center specifically for the tight space above the test section of the 14 x 22. It was integrated with a small turntable designed in the U.S. Army CCDC AvMC at NASA Langley that oriented the camera field of view toward any azimuthal position. In addition to the thermographic effort, photogrammetry was performed on the blades to measure twist and bending under aerodynamic loads on the advancing and retreating sides.

Both surfaces were imaged so that Differential Infrared Thermographic (DIT) processing [4] could be applied to produce a map of the unsteady boundary layer transition locations. This method has proven to be a powerful tool for unsteady boundary layer measurements in both laboratory and flight experiments [5, 6].

II. Experimental Setup

A. Model and Wind tunnel

The rotor system and fuselage setup was identical to the first entry [2]. The rotor system used the PSP rotor blades with a 66.75 in. radius (1.7 m). Each blade was coated with flat black paint to increase emissivity, and targets of silver paint to act as fiducial marks for registering images from different azimuthal positions. There are trip dots added to the lower surface at the tip to provide a visual signal as to what tonal change represents turbulent flow. Additionally the blades were manufactured with surface heaters that used high-resistance coatings. This was to permit establishing a significant difference in temperature between the surface and the flow. The heaters were operated remotely, where

voltage control establishes the heater power level. This feature was not used for this entry since there was a natural temperature difference between the blade surface and the flow.

The General Rotor Model System (GRMS) was fitted with the Robin- Mod 7 fuselage. The GRMS has six internal strain gauges for torque and moment measurements. Figure 1 shows the GRMS with the blades mounted on a sting centered over the yaw turntable. The lower surface spinning mirror and camera system are mounted in the center of the turntable so that the camera can be pointed at any azimuthal position of the rotor disk. Figure 2 shows the blade planform with dimensions, and the blade treatment of black paint with silver painted targets. The blades had 14-degree linear twist.

The experiment was performed in the NASA Langley 14x22, a closed-circuit, atmospheric tunnel with top operating speed of 348 ft/sec (106 m/s) yielding a Reynolds Number of 2.2 Million per foot. The tunnel speed was set to establish the Advance Ratio based on the rotor RPM. All data were acquired at 1090 RPM. The hub was instrumented with an optical encoder that output a quadrature of signals, each signal a square wave of 1024 counts/rev, and a one-per-rev pulse whose location was carefully aligned with the 0 deg, blade 1 over the tail.

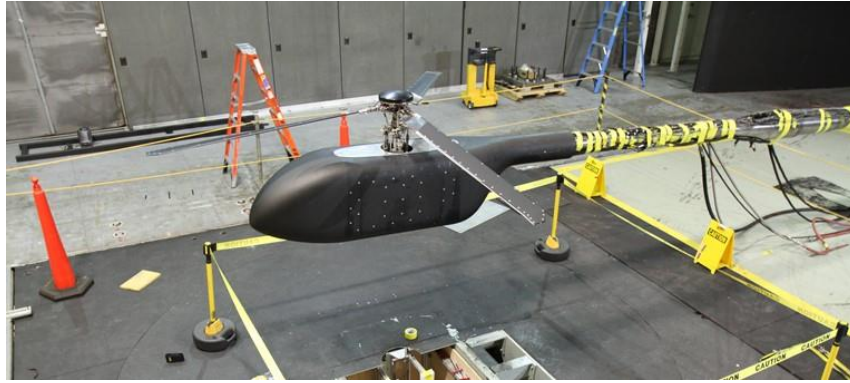


Fig. 1. General Rotor Model System with three-bladed hub

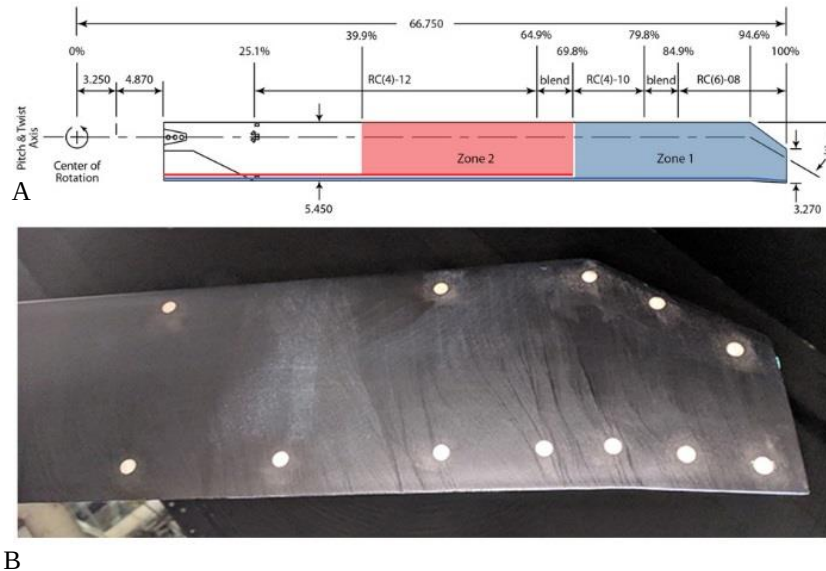


Fig. 2. A) RC-Series blade planform and B) blade treatment of black paint and silver-painted targets.

B. Optical Setup

Two FLIR X8500 Strained Lattice Supercrystal cameras, whose spectral sensitivity band is 7.5 – 11 microns, were integrated with the spinning mirror structures. This long-wave band offers the most photonic energy in the thermal band at the temperatures we tested since the Plank Blackbody Curve peaks in this band at room temperature. Also many epoxy composites are transparent in the medium-wave IR range, meaning that the long wave camera is required to make infrared measurements on the surface. The sensor resolution was 1280 x 1024 and the maximum

frame rate at full resolution was 180 fps. In addition to the state-of-the-art sensor, the cameras operate as do modern high-speed digital cameras. There is 8 Gbytes of RAM which provides a circular buffer. There is an on-board solid-state drive for quick buffer dumps, and it offers a variety of synchronization inputs and outputs. All of these features make it optimal for production wind tunnel testing.

We chose to reduce the vertical resolution and orient the camera view to match the aspect ratio of the rotor blade and to increase the frame rate. The frame rate was set so that the interframe time corresponded to the 15 degree sweep of the blade, which was 436 frames/sec. The lower surface imaging aperture was open to capture 90 degrees of blade passage (Fig. 3). This camera was configured to capture 6 images per pass. The upper surface camera viewed the model through a 6-inch diameter Germanium window which corresponded to 15 degrees of blade passage. For each blade passage a burst of two images were acquired to allow for the DIT technique to be applied. 250 blade passages per condition were acquired. This camera system was mounted on an independently controlled turntable which was belt-driven with a stepper motor. This permitted the control of the azimuthal pointing angle. (Fig. 5).



Fig. 3. Lower surface camera and mirror system with open viewport

C. The second generation mirror system

The space was tight where the camera had to be positioned geometrically to be centered over the center of the turntable and rotor hub. While the lower camera and mirror system had plenty of room, a complete redesign of the apparatus was required for the upper surface system. The illustrations in Figure 4 are depicting A) the folded path of the image view and B) a simulated view predicted by the modeling program Vinci [8,9]. This provided an opportunity to address other issues encountered with the DLR version. The second generation version started with a new method of synchronization with the rotor through a LabView program and Compact RIO controller. Figure 5 shows the installation of the resulting design in the tight space under a major support beam.

The mirror was connected via a 1:1 belt drive with a Kollmorgen AKM-11C servo motor. Stepper motors are traditionally used in positioning applications (this is fundamentally a positioning problem as gearing two motion axes generally operates on position and not velocity) however steppers are generally not suited for large velocities with demanding accuracy requirements: at high speeds, torque capability drops off with increasing velocity and most steppers do not incorporate an external feedback device for closed-loop control. Servo motors address both of these issues.

The servo was commanded by a matched Kollmorgen AKD-P00306-NBEC-000 drive. The drive received commands from a National Instruments cRIO-9030 controller acting as an industrial programmable logic controller

(PLC). As such, all programming related to gearing, synchronization, and phase adjustments was accomplished in LabView.

The cRIO PLC has the added capability of high-speed DIO. This allowed the single-ended TTL A, B, and index pulses from the rotor hub encoder to be passed directly to the PLC FPGA. The LabView program interpreted the pulses and created a virtual “master axis” used to gear the slave mirror axis. Once the slave axis was “geared-in” it would follow the position of the master encoder, and, by extension, the rotor itself. In this way, the mirror would be phase-locked to any desired blade. The entire program was executed directly on the PLC FPGA and its real-time operating system (RTOS). This allowed the program to preserve determinism to the greatest extent possible and reduce jitter: two requirements key to properly tracking the blade at the expected speeds.

This did not, however, ensure proper initial alignment of the mirror to the blade test article. Gearing considers relative changes in position, not absolute: if the mirror was out of alignment with the desired blade, once geared in, it would follow the motion of the blade but maintain a constant misalignment angle. Therefore, the control program gave the operator the ability to superimpose an “offset move” on top of the geared motion. For example, if the mirror were rotating at 9 Hz, the operator could command a 5 degree offset move and the mirror would continue moving at 9 HZ but jump forward (or backward, depending on the sign of the command) 5 degrees. This allowed the operator to “hunt” for the desired blade and view despite any initial misalignments. Once the operator had performed the necessary series of offset moves and had the test article positioned properly in the field of view, the mirror would continue to track that position so long as there was no interruption to any communication pathways.

Two adjustments were always required whenever positioning the turntable to a new azimuthal position: the mirror phase adjustment re-aligned the window in the image and a user-programmed camera trigger delay re-centered the blade in the window..

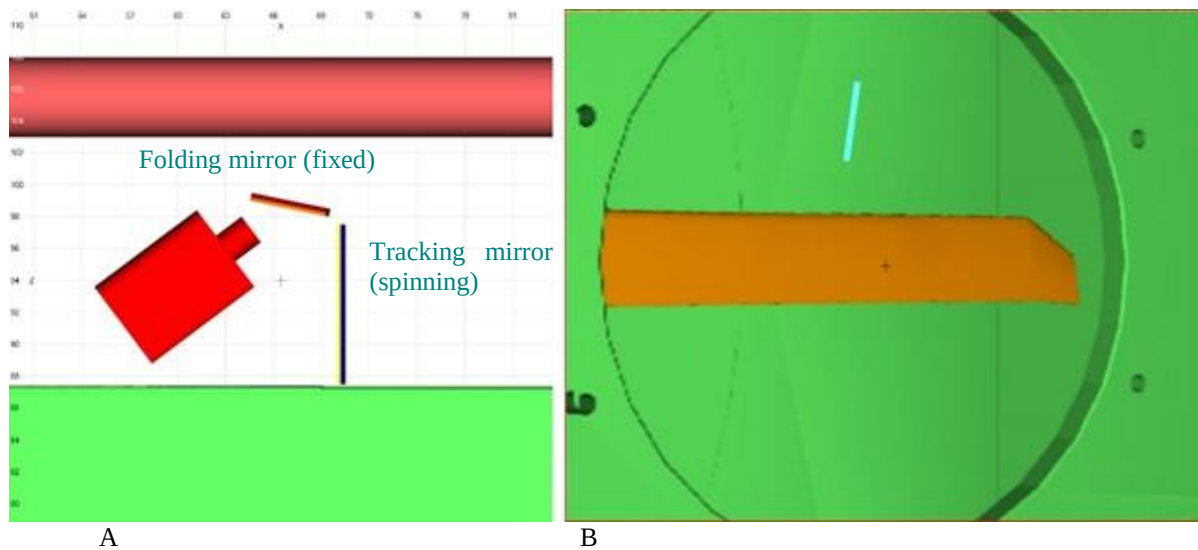


Fig. 4. A) Illustration of the folded path required by the restricted space of the centerline window of the 14x22 and B) predicted field of view

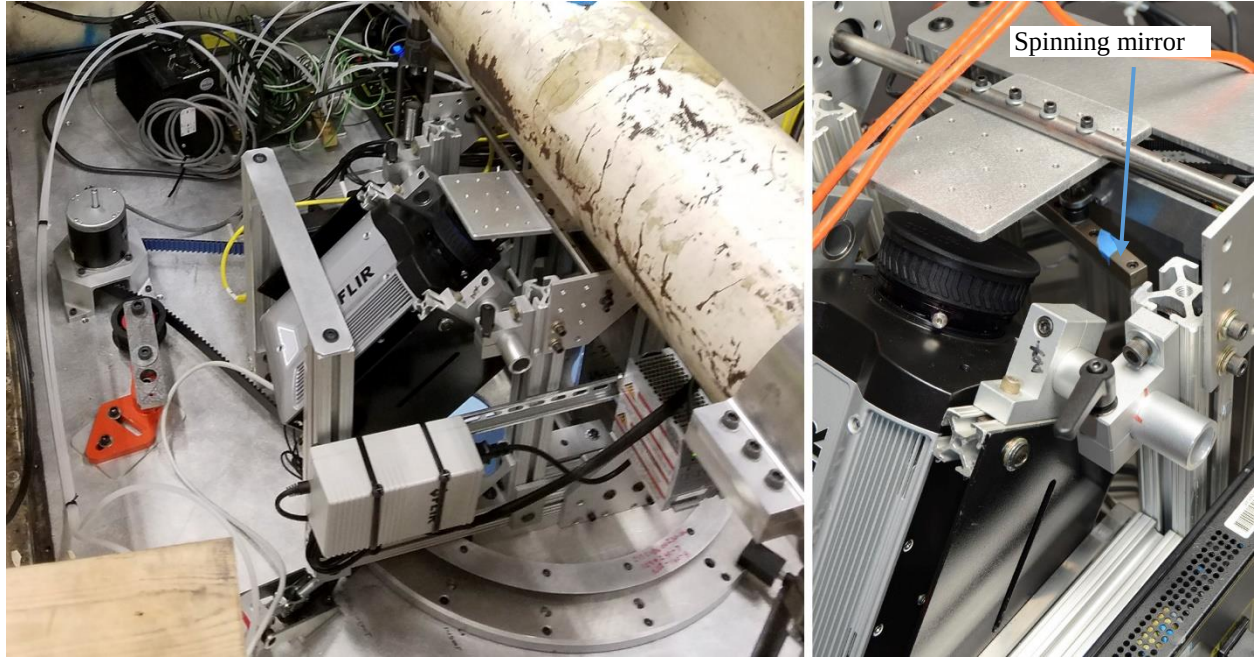


Fig. 5. Installation of camera with folded mirror path mounted to turntable for controlling system pointing

III. Results

A. Lower surface (pressure side)

The lower surface data from the second entry were acquired synchronously with the upper surface with the intent of capturing the two surfaces at the data conditions. The photogrammetry of blade, also synchronous to the thermal data, required that retroreflective targets (1/4-inch disks of Scotchlite 7610) were placed on the lower surface. Figure 6 shows a sample raw image of a targeted blade lower surface. The raw image shows an average of the heat transfer activity on the rotor blade over a cycle, and so is not directly related to the boundary layer transition position at the moment when the image was taken. Since the air was warmer than the surface of the blade, the darker region indicates an average of more laminar flow over a cycle, and the lighter regions indicate an average of more turbulent flow. The turbulence wedges are generated by the retroreflective targets and trip dots, and vary in extent and width over a pitching cycle. The objective of proving that the two cameras could be operated synchronously was proven, so it was decided that since there are an increased number of turbulence wedges in this entry, we would rely on the data for the first entry for analysis.

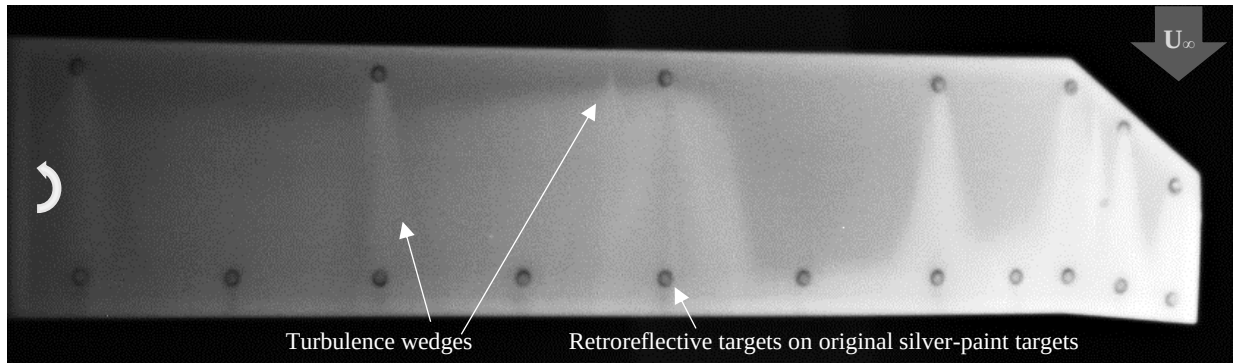
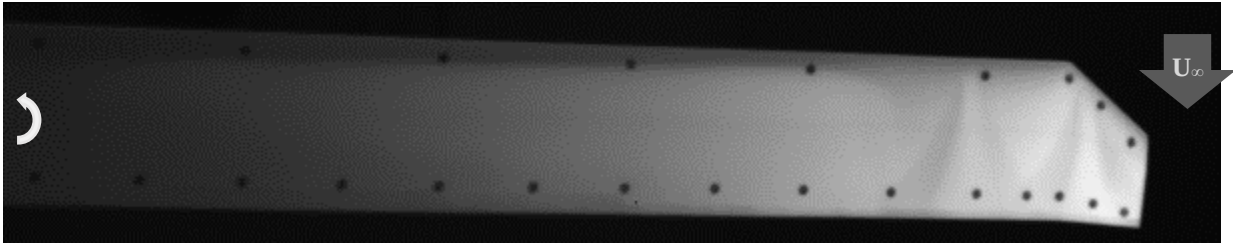
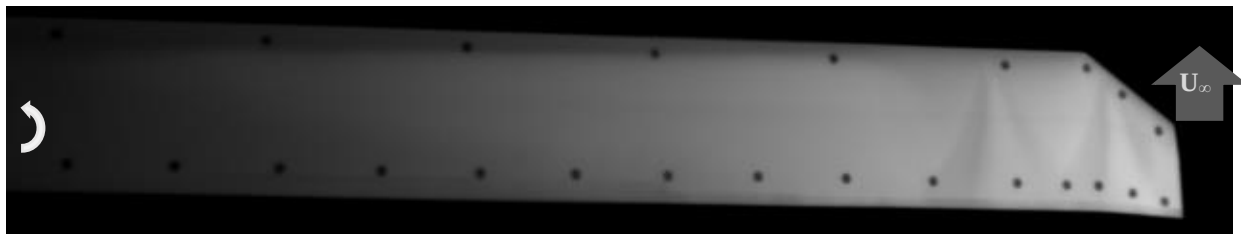


Figure 6. Contrast enhanced raw thermal image of the lower surface.

Figure 7 shows two images from the first entry, from opposite sides of the rotor disk, where the silver-paint targets show as dark dots, due to the low emissivity of the paint. The turbulence wedges are generated by trip dots. It is impossible to detect the change of the state of the boundary layer visually, since there is a “burn-in” pattern established from continuous running. This makes the DIT technique necessary for understanding the unsteady nature of the boundary layer on the blade surface in forward flight.



A



B

Fig. 7. Contrast enhanced thermal image of the retreating lower surface blade from first tunnel entry, A) $\psi = 90$ deg, and B) $\psi = 270$ deg, at $\mu = 0.38$, $CT/\sigma = 0.080$

Figure 8 is a composite map of the lower surface DIT images done by the DLR Göttingen team, where each image is made by subtracting the preceding frame ~ 15 degrees earlier in a single pass. Note the full heating cycle, as well as the change in the boundary layer. Areas of zero intensity change (green) represent areas of the blade which do not have a dynamic event occurring over the time step between images. Areas of high intensity change are represented by dark blue (decrease in intensity) and red (increase in intensity). Note at Location 1, the turbulence wedges have been swept outward radially, as the freestream flow drives the surface flow in that direction, while the boundary layer remains laminar. At location 2, the laminarity is due to the reduced lift condition at this point in the pitch cycle; the blade is pitching down and the airfoils are at lower lift coefficients. This causes transition to run forward over majority of the blade, except at the tip which is still fully laminar. Notice the wedges are still visible at the trip dot locations as transition was fixed to the leading edge. At location 3 near $\psi = 135$ deg, the wedges are no longer visible and transition at the tip has moved forward of the trip location over the entire tip.

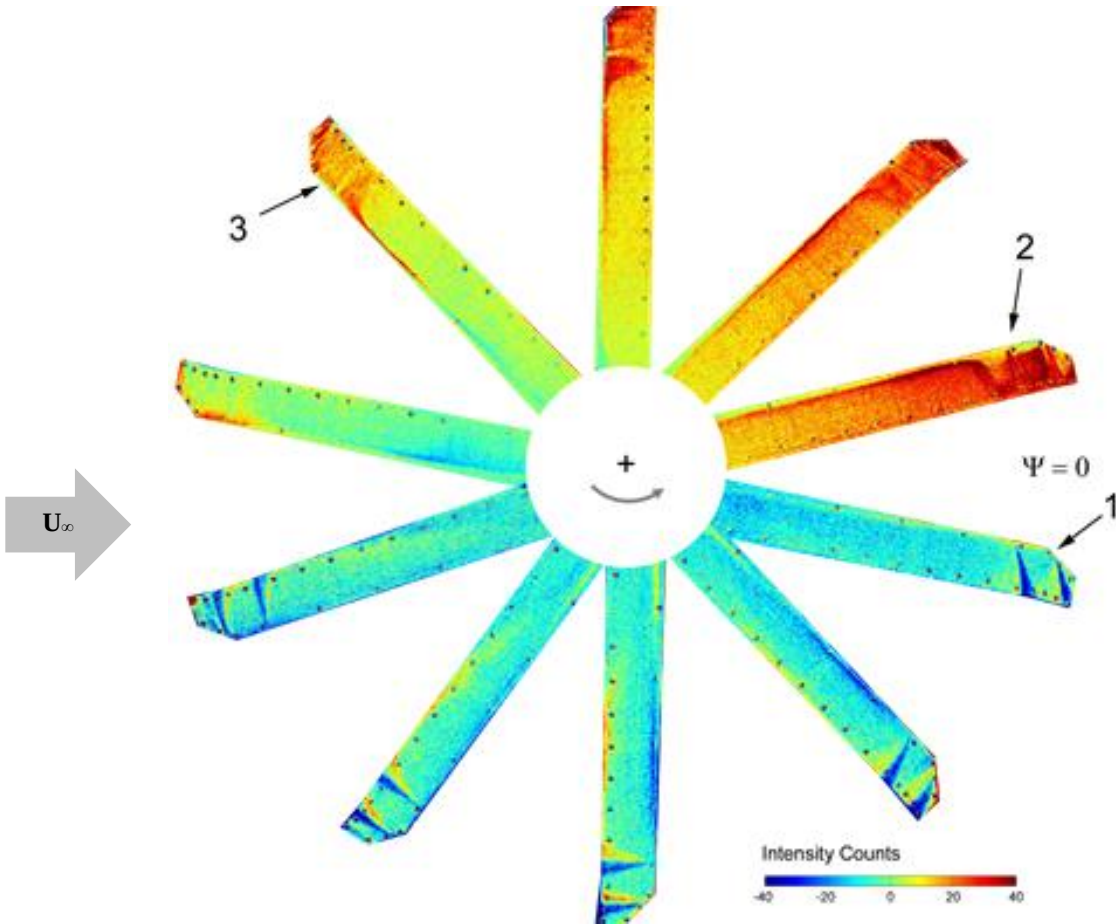


Fig. 8. Change in lower surface boundary layer using DIT from 15 deg. separation. : $\mu = 0.38$, $CT/\sigma=0.080$

B. Upper Surface (suction side)

Data were acquired over the full rotor disk by rotating the turntable 7.5 degree intervals, realigning the window in the image and adjusting the phase of the blade to capture two images with 15 degrees of blade travel. This was performed at 6 tunnel conditions. We will discuss the results from a subset of the data. The lower surface was blocked by the tail strut and the nose of the fuselage. Figure 9 shows a contrast enhanced image of the upper surface at the 90-deg (advancing) position. Note the turbulence wedges near the tip caused by trip dots. These were added to help interpret the imagery. The brighter areas indicate the heat transfer from the flow into the blade, occurring

during this portion of the blade revolution. Note that in these images the changes that are present in the boundary layer are not apparent, thus the requirement for the DIT treatment.

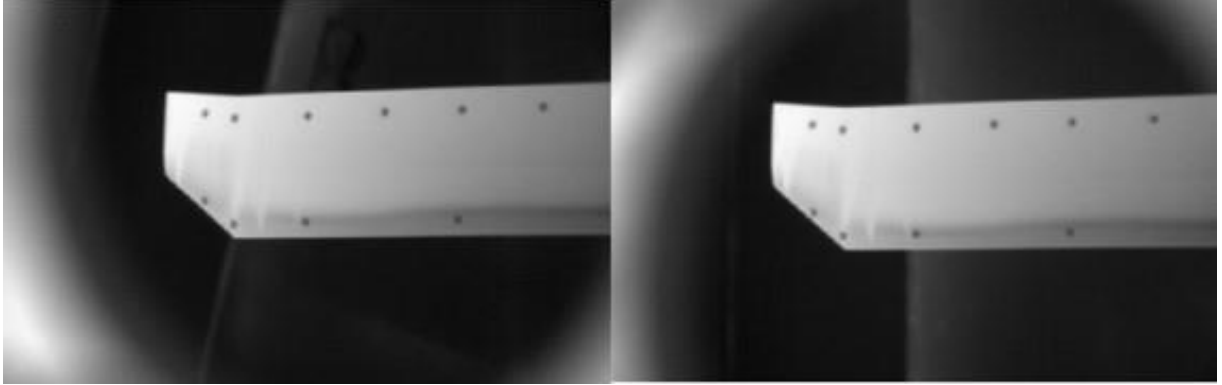
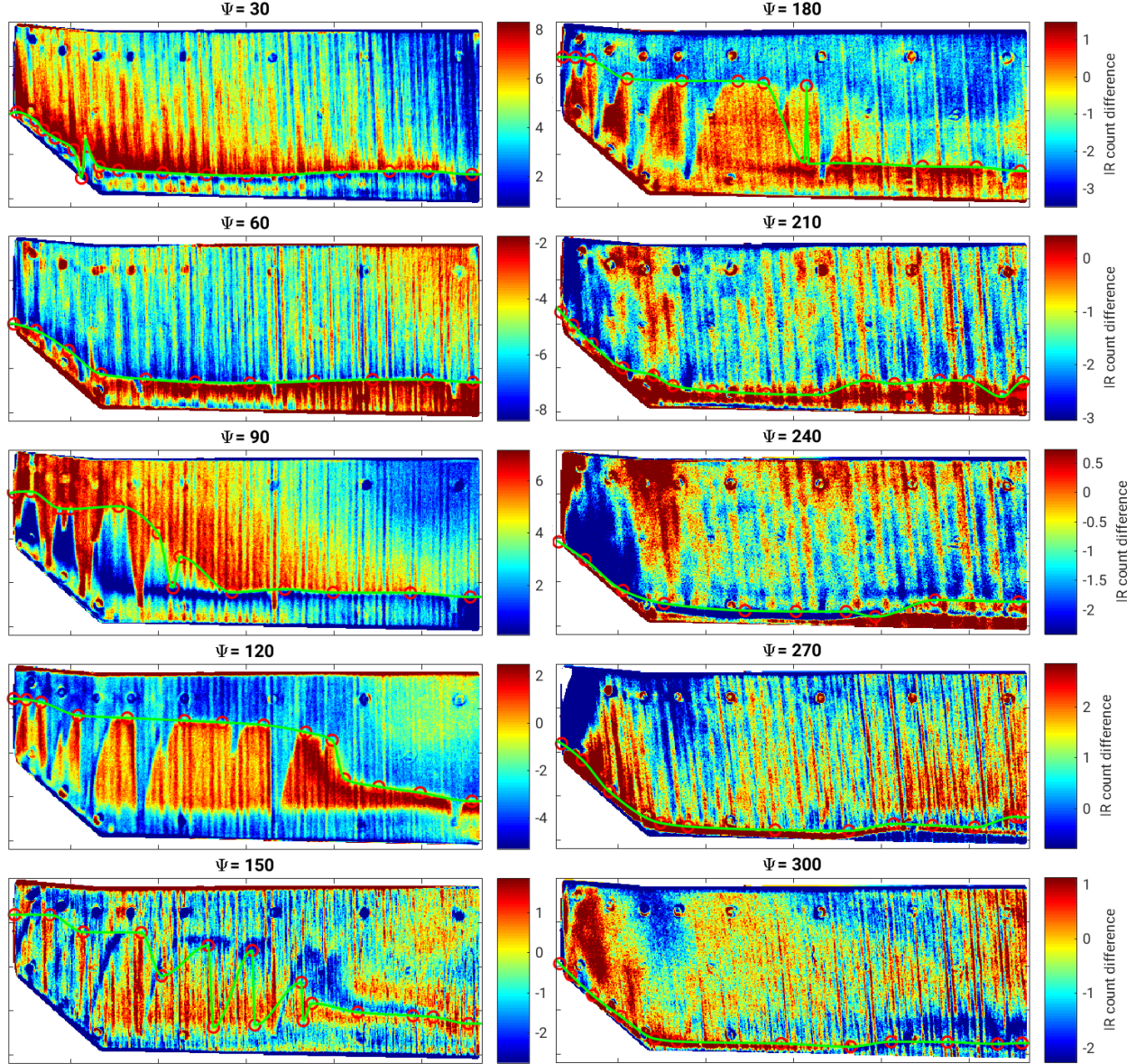


Fig. 9. Typical contrast enhanced raw image pair of the upper surface. Note the shifting of the window position in the image and the tunnel floor feature rotating 15 degrees while the blade remains fixed in the field of view.

C. DIT Processing

The 249 image pairs acquired during a single run at $\pm 7.5^\circ$ around each nominal azimuth position were sorted and imported into the DLR software *ToPas* (as in [10]). The images contained around 550 pixels on the rotor blade in the radial direction, and around 200 pixels in the chord-wise direction. All images had the levels adjusted, subtracting 5000 counts and multiplying by 100, since TOPAS works in integers, and this is consistent with preserving data for the NETD=40mK. All images were aligned with an arbitrarily chosen reference image (at 82.5° azimuth) using a second order polynomial transformation. Following this, the 249 image pairs at each azimuth were averaged to produce a single image pair, and the resulting two images were subtracted to produce a single DIT Image for each azimuth. Since the nominal azimuthal positions were stepped at 7.5° , there are actually two sets of data at each azimuthal position, however only those acquired during a single run were used to produce the DIT images. Figure 10 is a series of DIT results at discrete azimuthal positions.

A manual picking method was used to identify positions on the airfoil where the flow was not disturbed by turbulent wedges, since the assumption is that the primary purpose of this data is compared with CFD which uses a hydraulically smooth surface. For these points, slices were extracted in the flow direction and averaged over 9 pixels in width. The resulting line was smoothed with a moving window of 10 pixels, and then evaluated using the method in [6]: the data was evaluated from the trailing edge, and the point of the maximum gradient in the first step was defined as the transition point. This is analogous to the normal evaluation of IR images for boundary layer transition, with the exception that now a difference image is evaluated, and the data is evaluated from the trailing edge. Between 8 and 23 transition points were extracted, depending on the geometric complexity of the transition line. The transition points were then joined to a line using a piecewise cubic Hermite interpolating



polynomial (PCHIP).

Fig. 10. Differential imaging results at discrete azimuthal locations for the $C_t/\sigma = 0.38$ condition

For the initial data set shown, the coordinates were provisionally transformed into the rotor coordinate system, with final transformation using the deformed markers using the photogrammetry data still to be done. On the blade tip, where the leading edge moves rearward and the chord is reduced, the same transition point was noted as though the chord had not changed, so that a transition position of $x/c=0.5$ actually indicates transition at the blade leading edge. The resulting set of structured data (Transition x/c , Azimuthal position, r/R) was converted to a rotor map using Delaunay triangulation. With the exception of the region around $\Psi=150^\circ$, where the low signal makes it difficult to differentiate between two transition positions, the transition moves smoothly with azimuthal angle. The maximal laminarity is centered around $\Psi=130^\circ$ and the minimal laminarity is centered around $\Psi=300^\circ$, leading to a phase shift of $\Psi=30^\circ$ - 40° compared to a perfectly stiff rotor with no aerodynamic hysteresis. Around $\Psi=300^\circ$, the effect of the swept-back tip can be seen, with the fully turbulent flow moving back compared to the blade elastic chord due to the geometry. Around $\Psi=130^\circ$, there is substantial laminar flow near the blade tip, with 70-80% of the chord laminar. Further inboard, around 25% of the chord is laminar, and the transition between these two regions is by a similar S-shaped transition line to that seen in [2]. As seen in the difference images at different azimuth angles,

there is a significant difference in the signal-to-noise ratio of the images, with 3 counts of peak-peak signal at $\Psi=150^\circ$, and on most of the retreating blade side, and up to 8 counts on the advancing blade side where the surface temperature is rapidly changing and the dynamic pressure is high.

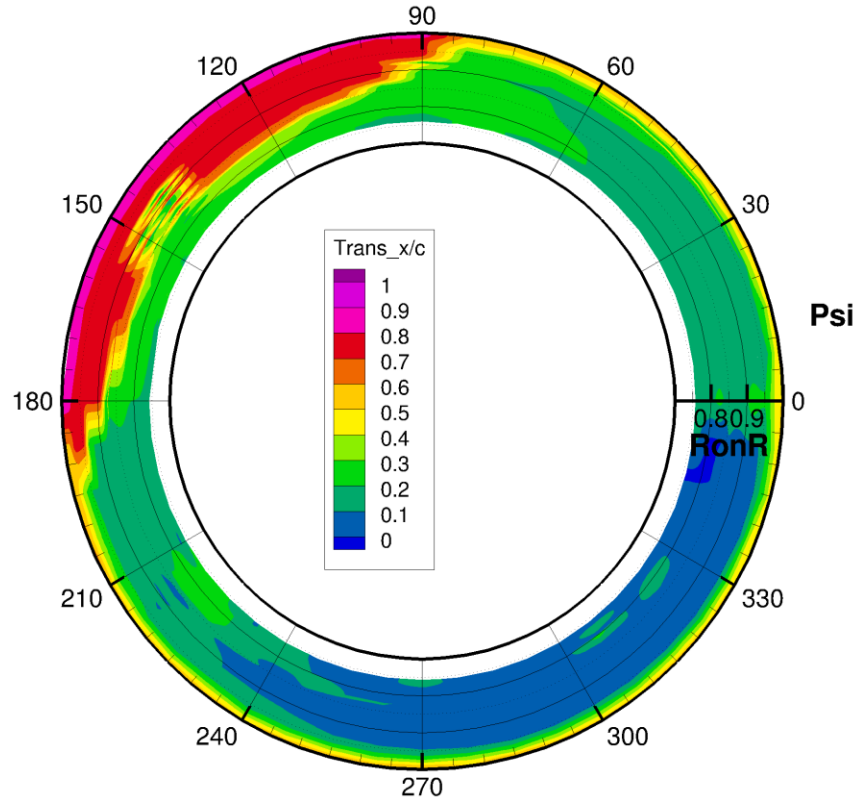


Fig. 11. Full azimuthal map of transition of the upper surface outer 15% radial location

IV Conclusion and future work

Thermography has been shown to be a powerful and productive measurement technique for the detection of boundary layer transition in a wind tunnel test of a rotor blade in forward flight. The technique produced a map of transition locations on the upper surface of a rotor blade over the rotor disk and of the advancing and retreating portions on the lower surface. By intelligently finding the location of transition from these data through image processing, the transition map of the full rotor disk has been demonstrated. Improvements in the image de-rotation system has been made, with more robust image tracking and phase-angle adjustments.

This technique has been used in a flight test campaign and will be used for a benchmark hover out-of-ground effect in an upcoming joint Army/NASA sponsored campaign in the NFAC 80- x- 120 test section. For that effort two new spinning mirror systems designed to work synchronously have been built. While the cameras will view only one azimuthal location, the design of this system required considerable improvements to the two independent systems described in this article. Included is a more robust phase-angle adjustment, the control of the second mirror system by the main controller of the first, and, though not used for the hover testing, an additional capability to automatically adjust the phase angle when integrated with a turntable. This last capability will permit the programming of an automated data acquisition of the full rotor disk at a single operation condition.

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