

Boundary layer transition measured by DIT on the PSP rotor in forward flight

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A well-defined reference set of data for CFD and comprehensive code validation for a scaled helicopter main rotor with boundary layer transition in forward flight is presented (Fig. 1). The boundary layer transition was measured using differential infrared thermography (DIT) on the top (suction) side of the three-bladed NASA/Army “PSP rotor”, in the NASA Langley 14- by 22-Foot Subsonic Tunnel at an advance ratio of 0.3 (115kt).

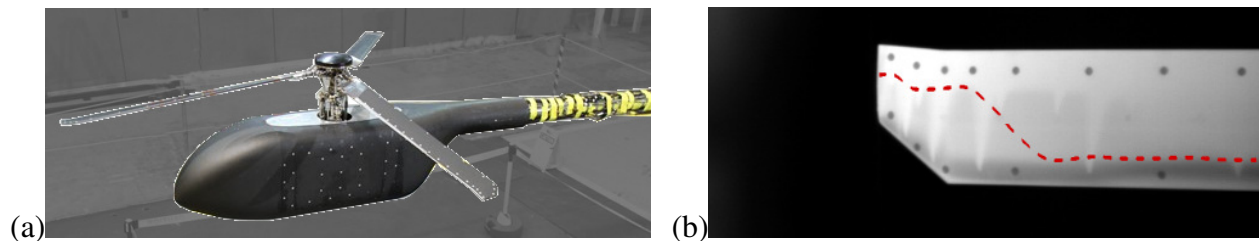


Figure 1. (a) General Rotor Model System (GRMS) with three-bladed hub, adapted from (Ref. 4). (b) Example image taken using the FLIR X8500 SLS camera. The boundary layer transition line (red) is not related to the average surface temperature visible through the greyscale.

Data from a four-bladed version of this rotor using standard IR measurements in hover has provided good reference data (Ref. 6) for the AIAA hover prediction workshop for transition (Ref. 5). Additionally, initial measurements were made on the pressure side of this rotor in 2018 (Ref. 7). Figure 1b shows an example IR image for a rotor in forward flight. The dewarping markers are visible, as is a surface intensity pattern which looks like a static infrared image. The actual boundary layer transition position, which can be extracted using the DIT analysis method, is drawn on that image as a red dashed line, and is not otherwise visible in the intensity distribution.

A FLIR X8500 Strained Layer Superlattice (SLS) camera, sensitive in the range 7.5–11 μ m, was used together with a deblurring rotating mirror as described in Ref. 9. The camera took two images in each rotation with $\Delta\Psi=15^\circ$ separation and the resulting image pairs were subtracted to produce a single DIT

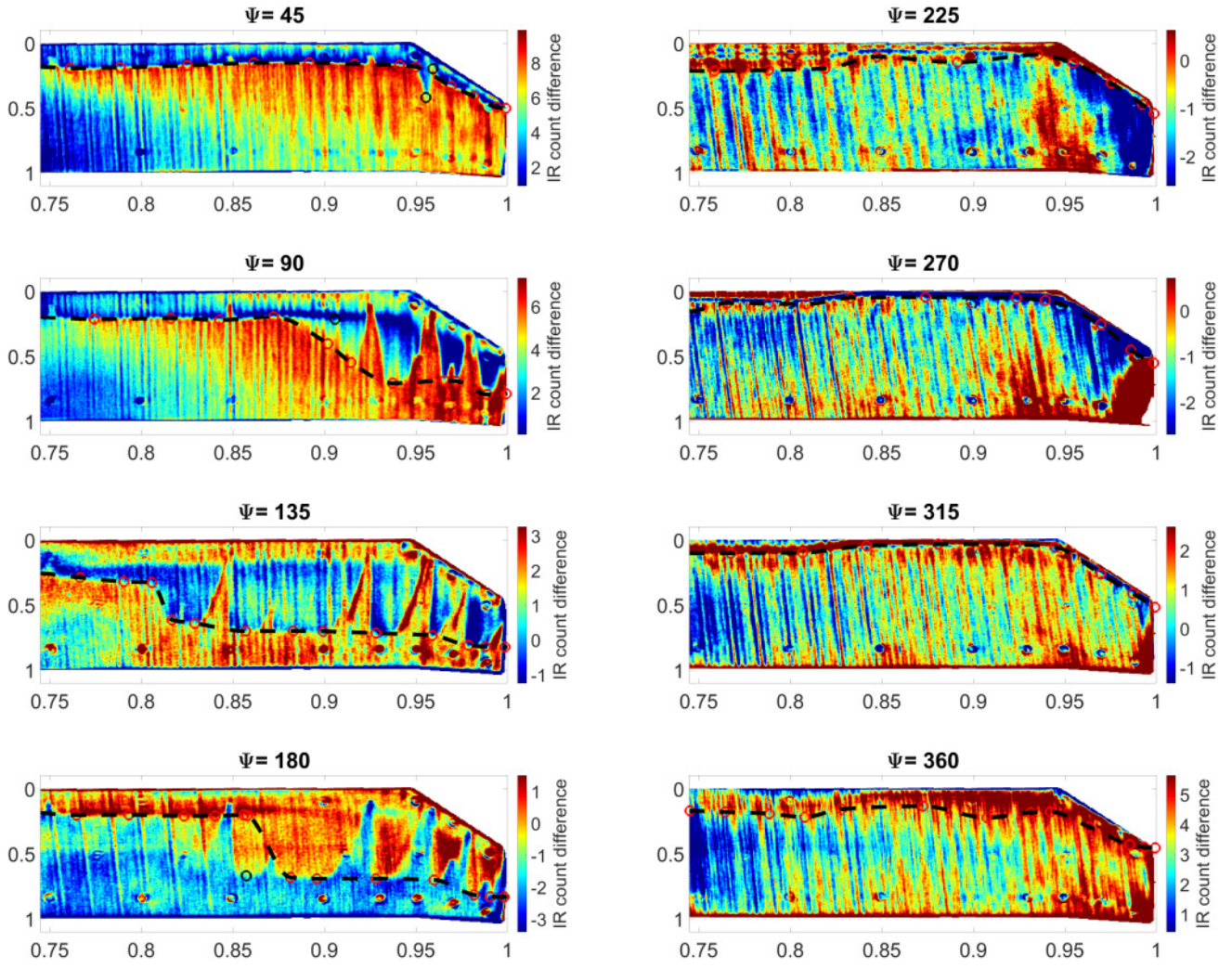


Figure 2. Derotated surface contours of DIT signal with $\Delta\Psi=15^\circ$. The points of detected boundary layer transition are marked with red and black circles and the reconstructed line in black.

image for each azimuth. The measurement position was stepped at $\Delta\Psi=7.5^\circ$, for 48 azimuthal measurement positions. 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 were aligned and dewarped into the r/R and x/c coordinate system.

DIT has not been well validated for forward flight, and up to the present time there has been no purely experimental validation of DIT in forward flight against other measurement techniques. This paper will give the first good validation comparisons, using the numerical method of Ref. 3, showing that the analysis of DIT images from the blade trailing edge results in a good estimate of the boundary layer transition.

Figure 2 shows a selection of DIT results at 45° azimuthal steps. The turbulent wedges were ignored to produce data for comparison with CFD which uses a hydraulically smooth surface. Slices were extracted in the flow direction and evaluated using the method in Ref. 3: the data was evaluated from the trailing edge, and the transition point was defined as the chordwise point of the maximum gradient of the DIT signal in the first step when looking from the trailing edge. Between 8 and 23 transition points were extracted, and these points are shown as red and black circles in Fig. 2. Some transition points were removed (black circles), since the zigzag in the transition line due to the vortical flow at the tip kink position on the rotor was obscured for many azimuthal positions by turbulent wedges (See particularly $\Psi=45^\circ$). Despite not being included in the extracted transition line, this zigzag is a real feature which is visible in the

experiment, and should be expected in a computed surface transition distribution. Additionally, some detected points were removed as erroneous. The remaining red transition points were then joined to a line using a piecewise cubic Hermite interpolating polynomial (PCHIP).

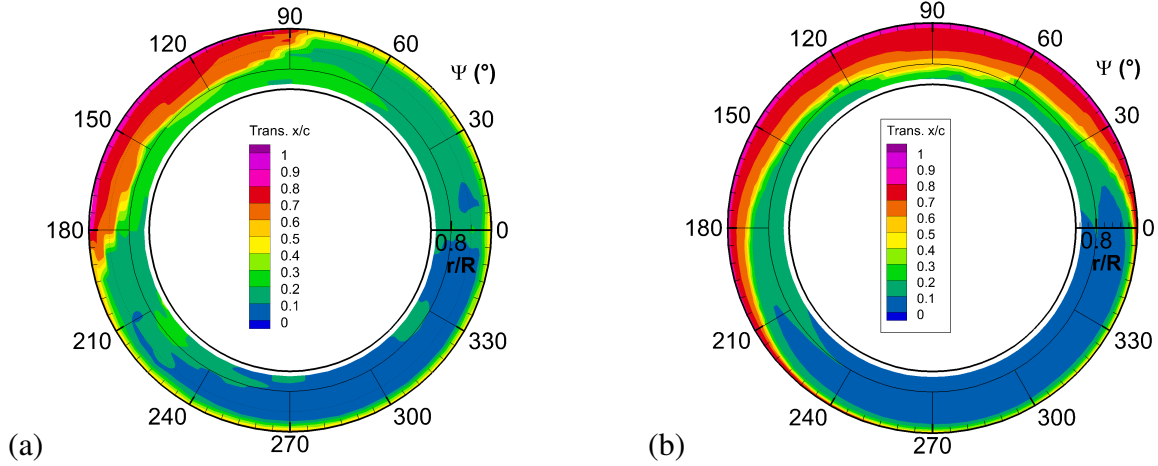


Figure 3. Rotor maps of transition position. (a) Map of experimental transition positions on the rotor suction side, with the same data as the black lines from Fig. 2 (b) Rotor suction side transition positions computed with RCAS/MSES using $N=9$.

Parallel to the experimental evaluation, the flow was computed using the rotor comprehensive code RCAS (Ref. 11), trimmed to match the experimental thrust. The azimuthal and radial distribution of Mach number, Reynolds number and aerodynamic angle of attack resulting from the RCAS computations was provided to the 2D Euler-boundary-layer code MSES (Ref. 1), and transition positions were computed as an output. A comparison between the experimentally measured and the computed transition positions is shown in Fig. 3. There is a phase difference between the two data sets (for example comparing Figs 3a and b), due to the many simplifications inherent in this approach, however a qualitative similarity is achieved between the experiment and computation, giving confidence in the results.

The pressure and skin friction distributions now available from MSES were used as inputs to compute the surface temperature using the 1-D finite element method developed in Ref. 2 and extended to the forward flight case in Ref. 3.

Figure 4 shows data extracted from a cut at constant $r/R=0.80$ on the rotor. The red line is a single-pixel row from the images in Fig. 2 without smoothing, and the green line is the same data subjected to a 10×10 px moving average smoothing. Considering the data for $\Psi=45^\circ$ (top left), starting at the trailing edge and moving upstream, the value of the difference counts rises from about $T_2 - T_1=3$ counts at the trailing edge to $T_2 - T_1=8$ counts at $x/c=0.2$. An interruption is provided by the marker dot at this radial position, visible as a valley at $0.8 < x/c < 0.9$. For some other azimuthal positions the dot is visible as a hill, depending on the surface temperature and the temperature of the background reflected in the conductive silver paint of the marker. The boundary layer transition is associated with the first step seen when evaluating the image from the trailing edge. The transition position from the experiment is marked with the magenta line.

In black is the temperature difference from the RCAS/MSES computation coupled with the 1-D surface heat flow solver from Ref. 3. In this case the boundary layer transition point is the beginning of transition given as an output by MSES, rather than the intermittency=50% position targeted by experiments. Although the three possible transition points (beginning (end of laminar flow), 50% intermittency and end (start of turbulent flow)) are physically adjacent for some test cases, for others they span a range of 10-20% chord (Ref. 10), and thus care must be taken in choosing which of these to compare to the

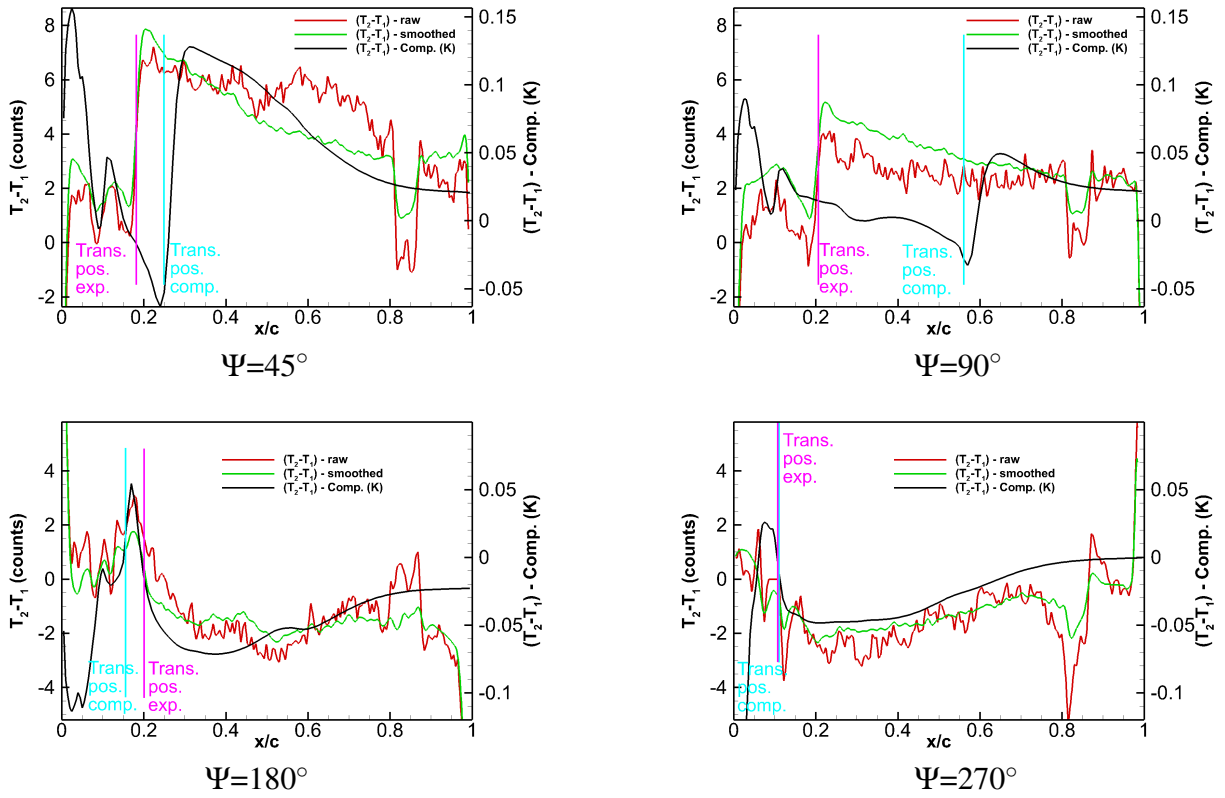


Figure 4. Data extracted from a cut at constant $r/R=0.80$ on the rotor.

experimental data for consistency. The DIT results attempt to measure the 50% intermittency point of transition (Ref. 12). For $\Psi=45^\circ$ (top left), the shape of the rise in difference from the trailing edge, the step shape and the relationship of the step to the transition position are all consistent with the experiment, although the boundary layer transition was computed to be slightly more downstream than measured in the experiment.

The signal-to-noise ratio varies widely over the azimuthal position, with the best at 7-8 counts peak-peak for $\Psi=45^\circ$, and the worst at 2-3 counts peak-peak for $\Psi=135^\circ$. The qualitative agreement in the shape of the black and red/green curves in Fig. 4 is good except at $\Psi=90^\circ$ where the shape is similar, but the transition at this position is much further downstream in the computation than in the experiment. Even where a flat temperature difference distribution near the trailing edge is seen, indicative that the temperature difference between the surface and outside flow is in the process of changing sign, the maximum error in the transition position due to the maximum gradient analysis method is $\Delta x/c < 0.1$, consistent with the computational results in Ref. 3. The comparisons in Fig. 4 give a good validation of the DIT method, and an assurance that it is being used correctly in this flow situation.

CONCLUSIONS

The paper contains a dataset for boundary layer transition on a scaled helicopter main rotor in forward flight. The helicopter rotor was trimmed and thrust and advance ratio were set. The main results of the paper are:

1. The evaluation method of DIT, using images separated by $\Psi=15^\circ$ and analyzed from the trailing edge was shown to be valid in comparison with computed surface temperature differences.
2. The boundary layer transition on the suction side had a maximum laminarity at $\Psi=135^\circ$ and a minimum laminarity at $\Psi=300^\circ$, roughly coincident with the maximum and minimum cyclic pitch.

3. Comparison with computations using RCAS and MSES showed that the computations capture the basic features of the boundary layer transition movement, but that considering unsteady aerodynamics and 3D flow is likely to lead to significant improvements.
4. Experimental and numerical results of the test case shown in this paper (run#142), as shown in the figures, are available online (http://www.as.dlr.de/files/supplementary/PSP_rotor_forward_flight_2020_Gardner_et_al/) or from the authors.

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