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DYNAMIC VISUALIZATION OF BOUNDARY-LAYER TRANSITION IN A PITCH-SWEEP TEST USING A CARBON NANOTUBE TSP

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Fluid: low-speed flows
Visualization method(s): Temperature Sensitive Paint (TSP)
Other keywords: carbon nanotube, luminescence, dynamic wind tunnel test

ABSTRACT: *A combination of carbon nanotube and Temperature Sensitive Paint (cntTSP) has a potential to visualize dynamic movement of the boundary-layer transition on a model surface. The cntTSP sensor can visualize the surface boundary-layer conditions as temperature distribution based on different heat transfer coefficients in the laminar and turbulent flow. One wide area of interest for the use of cntTSP is the continuous model angle-sweep tests, which are desired in order to improve the data productivity of the wind tunnel tests. In this paper, the applicability of cntTSP to a continuous moving model (pitch-sweep test) is investigated in a low-speed wind tunnel. The laminar to turbulent boundary-layer transition appearing on a simplified airplane model wing is visualized and compared between the pitch-fix and pitch-sweep tests. With the model pitch angel varying transition patterns were successfully visualized by the cntTSP. Influences of the test parameters, e.g. sweep speed and direction, were examined and optimal parameters for the application of cntTSP in angle-sweep test are proposed in this paper.*

1 Introduction

The visualization of the temperature distribution on a whole wind tunnel model is possible using Temperature Sensitive Paint (TSP). This paint has to be excited by light at an appropriate wavelength, e.g. in the UV range, and its temperature-dependent emission is detected by a camera system (CCD or CMOS). TSP measurement method is based on the dependence of the intensity or decay time of its luminescence on the temperature, caused by thermal quenching [1]. One major area of interest for such technique is the examination of the laminar-to-turbulent boundary layer transition behavior on wind tunnel models. However, the naturally established wall temperature difference in adiabatic wall temperature caused by the recovery process is typically too small to be detected with TSP, especially in low-speed tests. Therefore, the TSP technique requires an increase of the adiabatic wall temperature difference for transition detection measurements. Several methods have been used and reported [2,3]. The working principle of all of these methods is the imposition of a heat transfer between the flow and the surface of the wind tunnel model. In the previous work carbon nanotubes (CNT) [4] were presented as a source for electrical heating in order to generate temperature differences between laminar and turbulent boundary layers which are sufficient for the TSP technique [5.6]. CNT has several desirable properties: for example a very high electric conductivity, and its ease of applicability as a coating with a thickness of few micrometers, which enables a successful combination with TSP for transition detection measurements in the wind tunnel environment (cntTSP).

One big advantage of cntTSP is that the boundary-layer transition can be detected without changing the flow parameters. In addition, based on its capability of constant model surface heating, the cntTSP has

a potential to be used for the dynamic visualization of boundary-layer transition, leading to the application of cntTSP in continuous model angle-sweep tests. The use of cntTSP in the angle-sweep tests is strongly desirable by the industrial partners in order to improve the data productivity of wind tunnel tests.
In this paper, cntTSP applied on a continuous moving model (pitch-sweep test) is investigated in a low-speed wind tunnel with various test parameters, e.g. sweep speed, and sweep direction.

2 Methods

2.1 Temperature Sensitive Paint

The working principle of TSP is based on the thermal quenching process of dye molecules, also called luminophores, inside a binder material. A dye molecule can be excited by absorption of light of an appropriate wavelength which is specific for the dye molecule. The excited dye molecules can return to the electronic ground state by emission of light, which is Stokes-shifted to a longer wavelength relative to the excitation wavelength. The thermal quenching process leads to a radiationless transition of the dye molecule to the electronic ground state; the degree of quenching depends on the temperature. This means in practice that the emission intensity of the TSP dye decreases with increasing temperatures, since the degree of thermal quenching increases with temperature. The relationship between the emission intensity of the TSP and the temperature is given by the Arrhenius relation [1].
The dye molecule used in this work were complexes of Europium (excitation = UV light, emission = red light). This Europium-based TSP is suitable for the application at ambient conditions because of its high luminescent intensity and high temperature sensitivity. As a binder material for TSP, commercially available three component polyurethane-based binder (PU) was used. To enhance the TSP signal, an additional PU-based screen layer was applied below the TSP active layer.

2.2 Carbon Nanotube for Electric Heating

Boundary layer transition detection by means of TSP involves visualizing the temperature difference between the laminar and turbulent flow regimes. The “natural” temperature difference between the laminar and turbulent domains near the model surface is rather small (< 0.1 K for low-speed flows), caused by different recovery factors for the two boundary layer states. Therefore, the temperature difference must be artificially enhanced by creating a temperature difference between flow and surface. Due to the different heat transfer coefficients for convective heat transfer in the laminar and turbulent boundary-layers, heat transfer between flow and model surface is higher within the turbulent region than within the laminar one.
In this work, a thin heating layer consisting of carbon nanotubes (CNT) was employed for generating the temperature difference between flow and surface. CNT are allotropes of carbon with a cylindrical nanostructure. In 1991 Iijima published work on helical microtubules of graphitic carbon and brought CNT into scientific community [4]. The cylindrical carbon structures have properties such as very high electrical conductivity (>1,000 times greater than copper) which can be used for example as electrical resistance heater even in very thin layers. Due to the low electrical resistance of the CNT layer, an effective heating with this layer can be achieved with a relatively low voltage. CNT mixed with a polyurethane solution (same component as TSP layer) is sprayable and can be applied to complex 3D surfaces using an airbrush [5]. This combination of CNT heating and TSP is called cntTSP. Figure 1 shows a comparison of heating distribution between a commercially available heating foil and cntTSP. The cntTSP can be used to generate a very homogeneous temperature increase over the model surface

whereas the conventional heating foil shows the strong internal wiring patterns. The temperature variation on the cntTSP heating is below ±0.1 ℃ over the model surface.

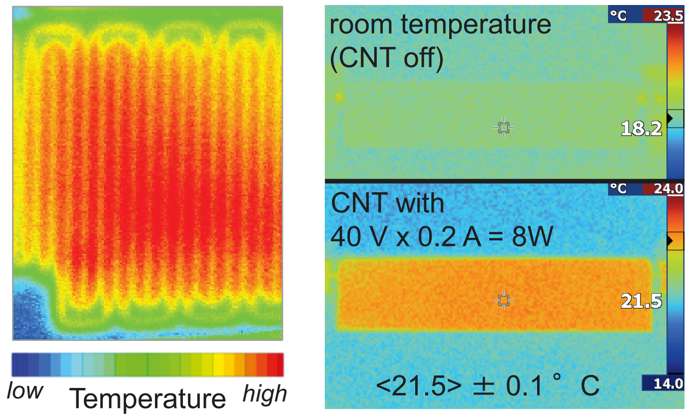


Fig. 1. Surface temperature distribution between a normal heating foil (left) and cntTSP (right)

2.3 Detection Method of Boundary-Layer Transition

The measurement principle of transition detection using CNT and TSP relies on the ability of cntTSP to generate a constant and continuous heating of the model surface. At the same time, the TSP layer is cooled by the thermal convection. This cooling effect depends on the boundary-layer condition with higher cooling rate in the turbulent region compared to the laminar region. As a result, the boundary-layer conditions appear as surface temperature difference, which can be visualized by TSP.

In order to determine the boundary-layer transition position from the temperature map, a maximum slope method [7] is employed in this work. Figure 2 shows a typical temperature profile along the chord influenced by the boundary-layer transition (red line). The gradient of temperature change $\partial T/\partial x$ is also plotted in the figure (black line). The temperature becomes highest at the position before the transition point. Then the temperature decreases with the development of turbulent flow due to the increase of the heat transfer. Finally, the temperature becomes nearly constant when the flow becomes completely turbulent. The transition position in this study is defined as the maximum temperature slop point inside the temperature drop area.

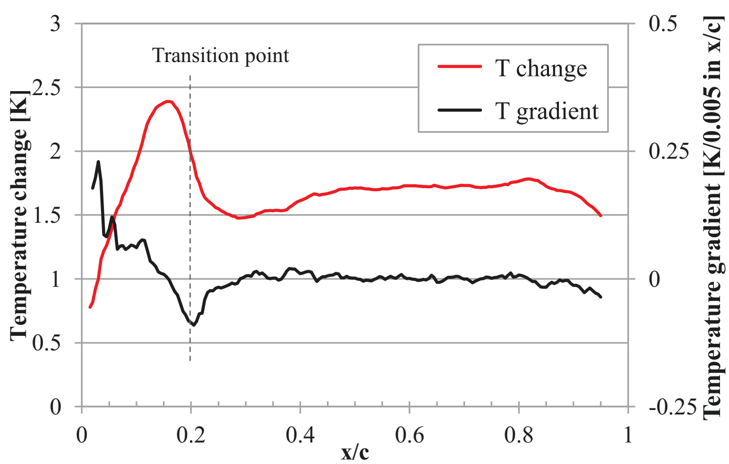


Fig. 2. Detection of the boundary-layer transition from the temperature profile with the temperature gradient ∂T/∂x

3 Experimental Setup

3.1 Wind Tunnel and Model

The test was conducted in the low-turbulence heat-transfer wind tunnel facility of Tohoku University. In this test, an open-type test section with an octagonal cross section was used. The width of the test section is 810 mm and the length of the test section is 1420 mm.

The model was a simplified airplane configuration featuring wings with NACA0012 airfoil profile. A sketch of the model is shown in Fig. 3. It has a chord length of c = 75 mm and a half wing span of b = 185 mm. The wing was 3D printed with Acrylate Styrene Acrylonitrile (ASA). The cntTSP sensor was applied on the suction side of the airfoil. In the first step, copper tapes were attached near the wing tip and fuselage as the electric connections inside a pocket to minimize surface imperfections. The pocket was included in the 3D Print of the model. Next, CNT layer was directly sprayed onto the model and copper tape surfaces. Subsequently, the screen layer and TSP active layer were applied on the CNT layer. The thickness of each layer was approximately 10 micrometer (CNT), 5 micrometer (screen), and 40 micrometer (active). For the sweep tests the model was supported by a sting, which was mounted on a remote rotating stage as shown in Fig. 4. The distance between the center of rotation and the wing's leading edge was 270 mm.

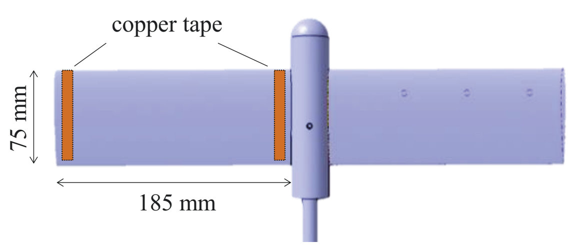


Fig. 3. A sketch of the model in top view, flow from top to bottom

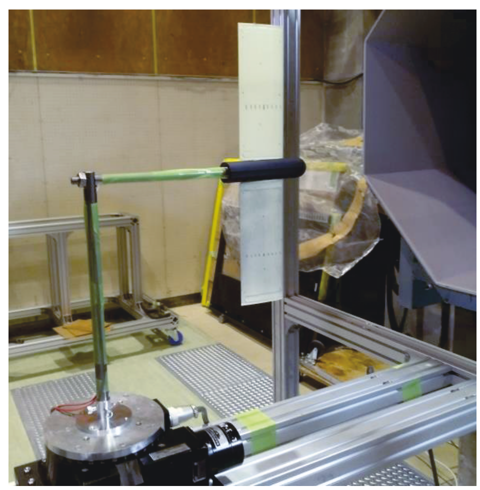


Fig. 4. Setup of the model in the wind tunnel, flow from right to left

3.2 Equipment

Two UV-LEDs (IL-106, HARDsoft) were used as TSP excitation light sources. The emission peak of each UV-LED was at 405 nm and operated in a constant current mode. The TSP luminescence was acquired using a 12-bit high-speed camera (SA-X2, Photron) with a 620±12 nm optical band-pass filter. The distance between the camera and the model was approximately 600 mm.

The synchronization of the camera shutter timing and the model pitch motion was controlled by I/O device and LabVIEW software from National Instruments.

3.3 Experimental Conditions

The simplified aircraft model was investigated with the flow speed fixed at 25 m/s. Only the port wing was used for TSP visualizations. Further test parameters of the cntTSP sensor test were:

- pitch angle range α = 0 to + 10 degrees
- pitch-sweep speed Δα = 0.25, 0.5, 1.0 degrees/s
- sweep direction = up or down
- CNT input electric power = 0.4, 1.8, 4.1, 7.3 W

The camera frame rate was adjusted to the pitch-sweep speed of the model: f = 60 fps (pitch-fix and Δα = 0.25 degrees/s), f = 125 fps (Δα = 0.5 degrees/s) and f = 250 fps (Δα = 1.0 degrees/s). The camera shutter width was always 1/1666 s.

3.4 Data Acquisition and Processing

In the pitch-fix test, 200 run images were acquired and ensemble-averaged at each condition. The image acquisition was started 25 s after the CNT heating start. The reference images were taken under same flow and pitch-angle conditions but without the CNT heating.

In the pitch-sweep test, the model pitch-sweep motion was started 15 s after the CNT heating start. The TSP run images were continuously acquired during the model motion. The reference images were also taken under same flow condition with the pitch-sweep motion but without CNT heating. In the post-data processing, each 30 images, which are corresponding to 0.125 degrees pitch movement, were ensemble-averaged to enhance the signal-to-noise ratio (SNR) of TSP images.

The temperature distribution was calculated from the ratio of the reference and run image. Since the repeatability of the model position between the run and reference condition is very good, any image alignment was not required in this test.

4 Results and Discussions

4.1 Pitch-fix Test

Figure 5 shows one visualization result of the boundary-layer transition of the pitch-fixed test. The model pitch angle is +5 degrees and the flow speed is 25 m/s. The flow is coming from the left and the wing tip is situated on the bottom of the image. In the images the darker areas towards the trailing edge of the wing indicate a higher heat transfer, which is caused by turbulent flow. The transition position near the root and the tip of the wing are influenced by the interactions with the model fuselage and the wing tip vortex. Figure 6 shows the temperature profiles along the chord at y/b = 0.3. The temperature profile obtained from four different electric input powers are plotted here. Other test conditions are the same as for the image shown in Fig. 5. Even though the magnitude of the developed temperature is changed by the input power, the shape of the profiles itself are similar and the detected transition positions are x/c = 0.54 in all results (vertical dashed line in the figure). The surface heating does not change the transition position for this input power range. In the following part, the input power of 4.1 W is used.

Figure 7 shows that the transition pattern changes with the model pitch-angle. The development of the turbulent region with increasing pitch-angle is well visualized in these results. Not only is the motion of the global transition position but also interesting small structures are visible, e.g. wedges caused by imperfections of the leading edge (α = +8 degrees), streaky lines in the turbulent region (α = +3 degrees). The cntTSP works well for the visualization of the complex boundary-layer transition patterns in low-speed flow.

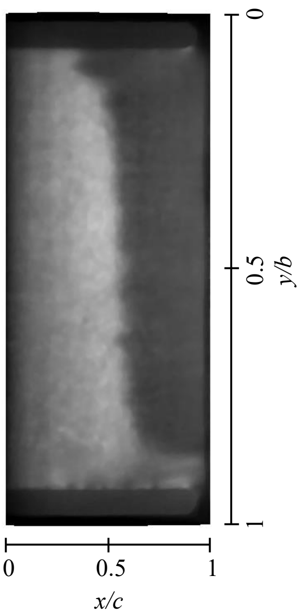


Fig. 5. One visualization result of the boundary-layer transition of the pitch-fixed test (+5 degrees)

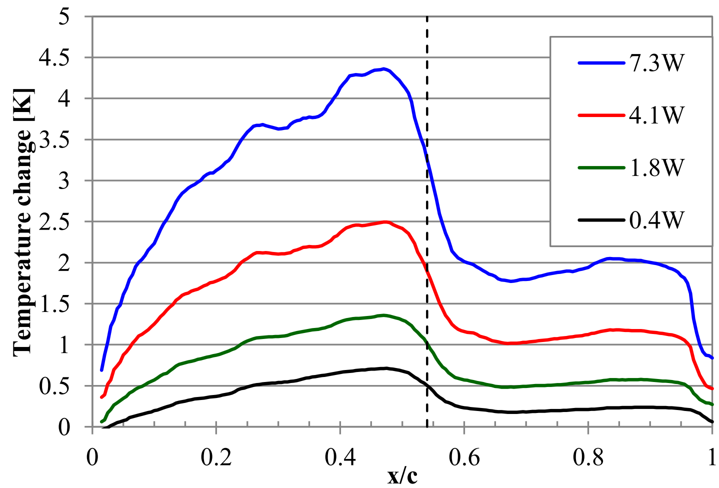


Fig. 6. Temperature profiles for different electric powers

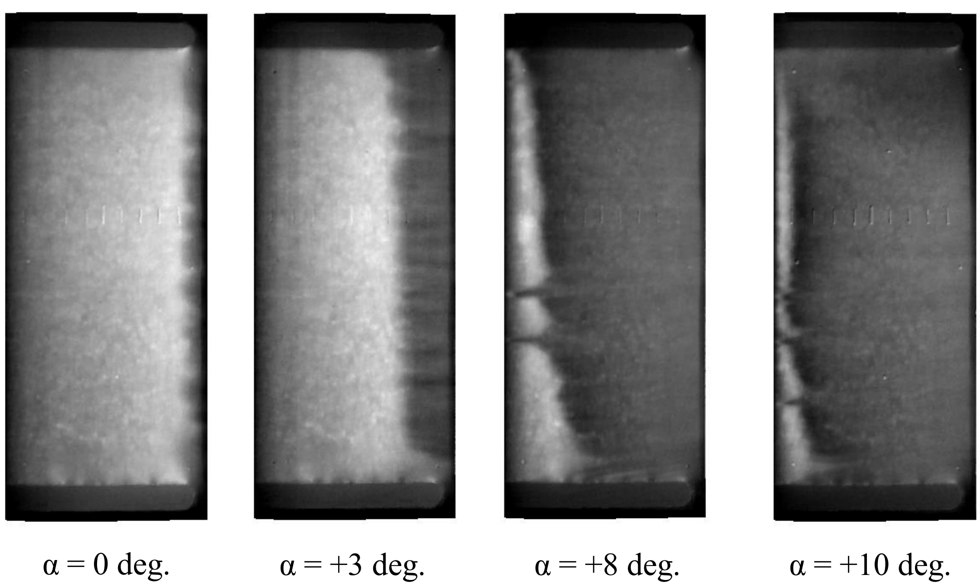


Fig. 7. Transition pattern change with the model pitch-angle

4.2 Pitch-sweep Test

Two different pitch-sweep tests, i.e. the pitch-up and the pitch-down, are compared in Fig. 8. The pitch-angle of these results is +5 degrees, which corresponds to Fig. 5 in the pitch-fix test. The pitch-sweep speed is 0.25 degrees/s with other test conditions same as in the pitch-fixed test. The transition pattern appearing in these results is comparable to the pattern in the pitch-fix test. However the temperature contrast and also SNR are smaller compared to the pitch-fix test, especially in the pitch-down test. The decreased SNR is the result of the smaller number of ensemble-averaged images (200 images in the pitch-fix test, 30 images in the pitch-sweep test). The acquisition of more images by increasing the camera frame rate could easily solve this problem. On the other hand, the smaller temperature contrast between laminar and turbulent flow can be considered as a systematic problem in the pitch-sweep test. Figure 9 shows the temperature profiles along the chord from the pitch-fix and two pitch-sweep tests (span position y/b = 0.3). In addition, the detected transition positions are plotted as the circler symbols in this figure. The temperature profiles near the transition location are different for these three conditions. These differences could be explained by the response of the surface temperature to the differently changing heat transfer. In the pitch-up test, the turbulent region is expanding toward the leading edge with increasing pitch-angle indicating the surface heat transfer changes from low (laminar) to high (turbulent). In contrast, the laminar region is expanding toward the trailing edge in the pitch-down test and the surface heat transfer changes from high to low. The change of the surface temperature is quicker when the heat transfer is higher. As a result, the region where the boundary-layer condition changes from laminar to turbulent is cooled quickly in the pitch-up test and the region where the boundary-layer condition changes from turbulent to laminar is relatively slowly warm up in the pitch-down test. For practical applications, the pitch-up test is more favorable rather than the pitch-down test.

Figure 10(a) shows a comparison of the transition location detected by the maximum slope method (span position y/b = 0.3). The transition positions below α = +2 degrees are hardly detectable in this test because the transition position is too close to the trailing edge. In this figure, there appears constant shift (or delay) of the transition position in the pitch-sweep test from the pitch-fix test. This delay can be corrected by a constant angle shift as shown in Fig. 10(b). In both, the pitch-up and the pitch-down tests, the transition positons match well after the angle shift of 0.25 degrees. A comparison of the detected transition location with different pitch-sweep speeds is show in Fig. 11. Only the results from the pitch-up test are plotted in this figure. It looks like that the delay of the detected transition location between pitch-fix and pitch-sweep does not change even when the sweep speed is increased by a factor of four. Same results are obtained in the pitch-down tests. Any systematic delay of the model pitch motion is not identified in this test. Currently the reason of this delay in the pitch-sweep test is unclear. Further parametric investigation is needed.

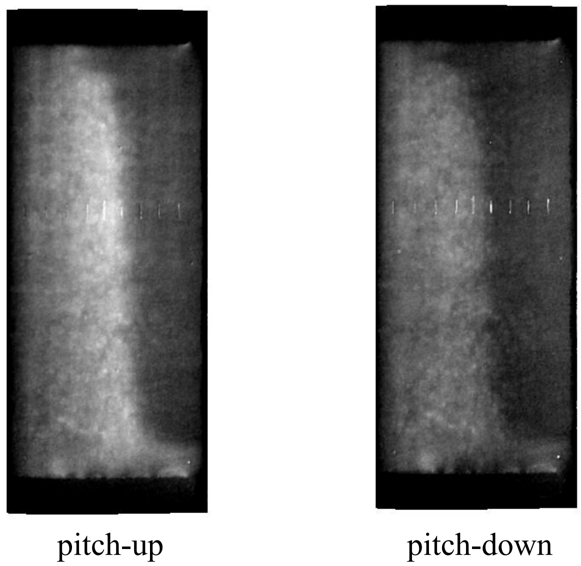


Fig. 8. Transition patterns in the pitch-sweep test. (left) pitch-up, (right) pitch-down. α = +5 degrees.

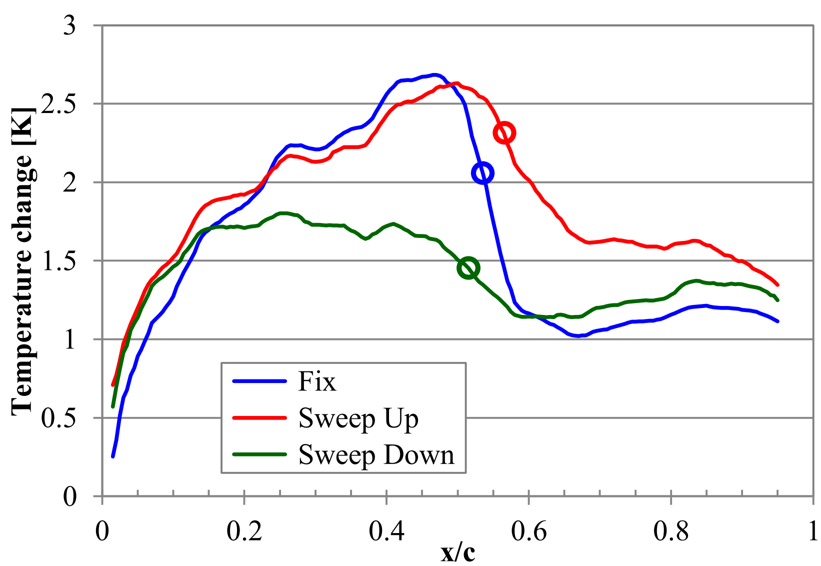
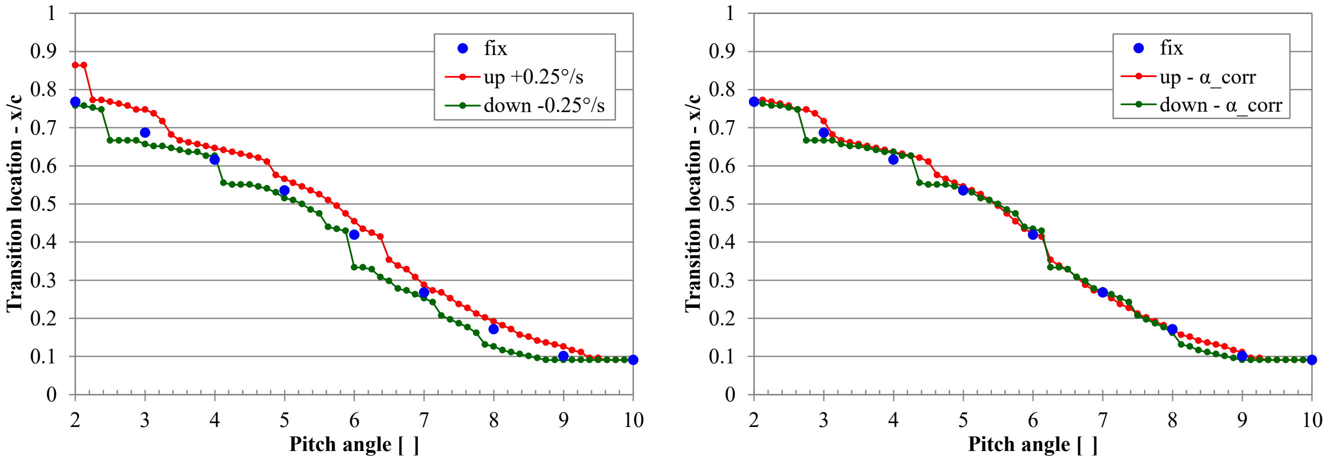


Fig. 9. Comparison of temperature profile and the transition position obtained from the pitch-fix and pitch-sweep tests



(a) without angle shift correction **(b) with angle shift correction**

Fig. 10. Comparison of transition points in the pitch-fix and pitch-sweep tests

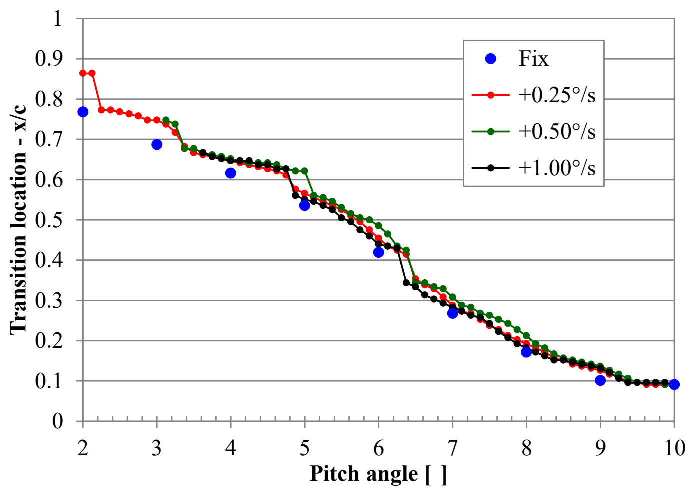


Fig. 11. Comparison of the transition points for the different pitch-sweep speeds

5 Conclusions

The applicability of cntTSP to the continuous moving model (pitch-sweep test) was investigated in the low-speed wind tunnel. The laminar to turbulent boundary-layer transition appeared on the simplified airplane model was visualized in the pitch-fix and pitch-sweep test. The transition patterns varied with the model pitch angle were successfully visualized by cntTSP.

The temperature distributions generated by the boundary-layer transition shows small dependency on the pitch-sweep direction, which is a result of the different surface temperature response. The pitch-up motion can generate better temperature contrast between the laminar and turbulent regions compared to the pitch-down motion.

The detected transition positions in the pitch-sweep tests show small delays from the pitch-fix result. This delay can be corrected by the constant angle shift. However the reason of this delay in the pitch-sweep test is still unclear in this work.

Following investigations are suggested in the future test.

- Influence of the TSP active layer thickness to the response of cntTSP sensor.
- Surface temperature change after stopping the model motion in the pitch-sweep test.
- Comparison with other surface measurements, e.g. oil flow visualization or hot film, for further understanding of the surface flow topology.

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