

Investigation of Image-based Lifetime PSP Measurements with Sinusoidal Excitation Light

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The applicability of frequency-domain fluorescence lifetime imaging (FLIM) with a newly developed CMOS camera sensor (pco.flim) to Pressure-Sensitive Paint (PSP) measurements in wind tunnel tests was investigated. Two lifetime parameters, the phase angle and demodulation index, can be used as a function of pressure in FLIM technique. First, the characteristics of FLIM-PSP technique were examined in calibration tests. The two lifetime parameters, a phase shift and a modulation index, show different sensitivity to pressure and temperature. This indicates a potential of simultaneous pressure and temperature measurement of the FLIM-PSP technique. Next, the FLIM-PSP technique is demonstrated in a transonic wind tunnel using a delta-wing model. The obtained PSP results successfully visualize the complex pressure distribution on the model surface and the quantitative agreement with conventional pressure tap data is good.

I. Introduction

Pressure Sensitive Paint (PSP) measurement technique is based on the dependence of the intensity or decay time of its luminescence on pressure, brought about by oxygen quenching [1]. PSP is usually excited by light at an appropriate wavelength (e.g. UV-Light) and its pressure dependent luminescence intensity or lifetime is detected by a camera system (CCD or CMOS). In the method based on the luminescent lifetime, two basic types of measurement exist: The first type is the time-domain lifetime method, which is mostly used in various PSP applications. For this method a pulsed light is used to excite the paint and the pressure dependent time constant is determined from decay curve of luminescence intensity. The second type is the frequency-domain fluorescence lifetime imaging (FLIM) where modulated light is used to excite the paint and the PSP luminescence is simultaneously detected to calculate pressure dependent phase shift or amplitude. Only few applications were reported using this method [2].

Recently, a new CMOS image sensor has been developed by CSEM and PCO for frequency-domain FLIM system and equipped in the pco.flim camera for fluorescence lifetime imaging in microscopy [3]. In our previous work, the frequency-domain lifetime PSP technique (FLIM-PSP) with the pco.flim camera was investigated in calibration tests and a low-speed wind tunnel test [4]. The pressure distribution caused by the vortex on a delta wing was successfully visualized. However, the results were limited to qualitative analysis mainly due to instability of the modulation light source.

In this study, the FLIM-PSP technique is further investigated with pco.flim camera and more stable high power modulation light source. First, characteristics of the FLIM-PSP technique are investigated in calibration tests. Then, a transonic wind tunnel test is performed with the same system. The pressure distribution produced by the vortex on

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the delta-wing model is visualized and results of the FLIM-PSP technique are compared with those of the conventional lifetime PSP technique.

II. FLIM-PSP Technique

A. Principle

Figure 1 shows a typical response of PSP luminescence to a modulated (sinusoidal) excitation light with a frequency f_{mod} . The luminescence phase and amplitude is dependent on the luminescence lifetime of PSP which is determined by the partial oxygen pressure i.e. local air pressure. Two parameters can be used as a function of pressure (and also temperature). The first parameter is the phase angle Φ or phase shift between excitation and emission from PSP, which is estimated as a time delay. Second parameter is the demodulation index of emission m_{em} , which is the ratio of the amplitude a_{em} to the average intensity b_{em} .

In the image-based technique, these quantities can be calculated from gated images obtained during the modulation period. Here four gated image method is introduced [3]. The gated images are acquired delayed corresponding to phase of 0, 90, 180, and 270° of the modulation signal with the width of each image being half of the modulation period. Each gated image is denoted as I_1 , I_2 , I_3 and I_4 , respectively. Figure 2 shows the timing of the second gated image I_2 as an example. From these four gated images, the tangent of phase angle Φ and the demodulation index m_{em} can be calculated by Eq. 1 and Eq. 2.

$$\tan\Phi = \frac{I_4 - I_2}{I_1 - I_3} \quad (1)$$

$$m_{em} = \frac{a_{em}}{b_{em}} = 2 \cdot \frac{\sqrt{(I_1 - I_3)^2 + (I_4 - I_2)^2}}{I_1 + I_2 + I_3 + I_4} \quad (2)$$

Usually, the PSP emission intensity for a single-shot gated image is very small. Therefore, a multi-exposure camera is required for the accumulation of PSP signal with thousands periods of modulation.

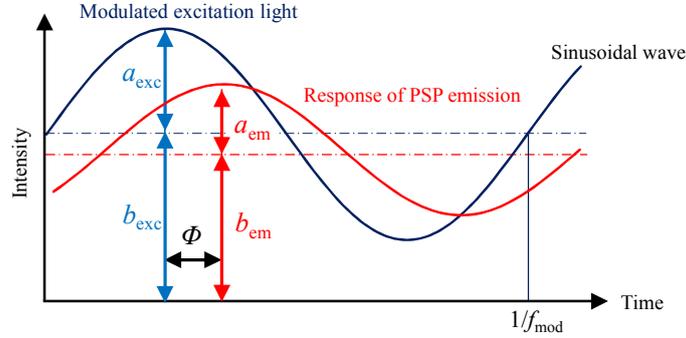


Figure 1. Typical response of PSP luminescence to a modulated (sinusoidal) excitation light.

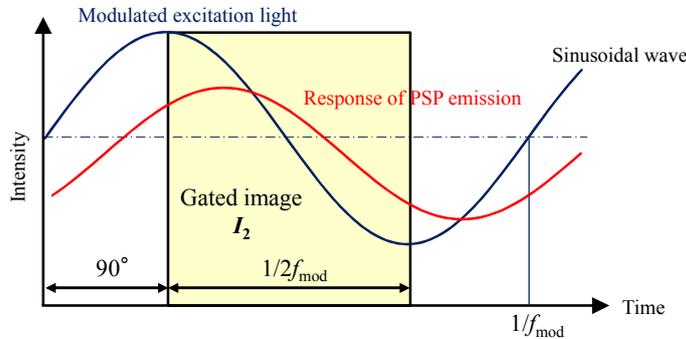


Figure 2. Timing of the second gated image I_2 .

B. pco.flim camera

The FLIM technique is applied to acquire pressure distribution from PSP using a pco.flim camera (PCO AG), which has an in-pixel dual tap control CMOS image sensor, 1008×1008 pixels resolution and 14 bit A/D converter [3]. The pco.flim camera is able to accumulate multi-exposure images using the following mechanism: The CMOS image sensor is composed of a single photodiode and two charge collection sites, called tap A and tap B as shown in Fig. 3. The sensor can selectively guide photo-generated charge carriers to each tap triggered by an external signal (tap control signal). When tap A is active, the charge carriers are guided and accumulated into tap A charge bucket. Then the control signal is switched, the carriers drift into the tap B bucket. By switching the control signal again, the accumulation of the carriers in tap A is restarted. In order to use this CMOS sensor for FLIM–PSP technique, following needs to be considered:

- (1) Use of same frequency for the excitation light modulation and the tap control signal. The pco.flim camera is able to output the frequency master signal for the excitation light.
- (2) The duty cycle of the tap control signal is set to 50 %. This means that the tap A and B have same integration time with half the period of the modulation.
- (3) When the delay from the excitation light modulation to the tap control signal is zero, the tap A collects the charge carriers during first half of the light modulation and the tap B collects during second half of the light modulation. They are corresponding to the gated images of I_1 and I_3 as introduced in the section II.A.
- (4) When the delay of a quarter of the period is given from the light modulation to the tap control signal, the images obtained by tap A and B correspond to I_2 and I_4 respectively.

As a result, a set of PSP images (I_1, I_3) or (I_2, I_4) can be obtained from the same image acquisition. Since the characteristics of tap A and B are not the same, additional image sets with a delay of half period (I_3 in tap A, I_1 in tap B) and a delay of three quarter period (I_4 in tap A, I_2 in tap B) are acquired for a tap correction. Finally, each gated image is obtained by a sum of tap images, e.g. $I_1 = I_{1,tapA} + I_{1,tapB}$.

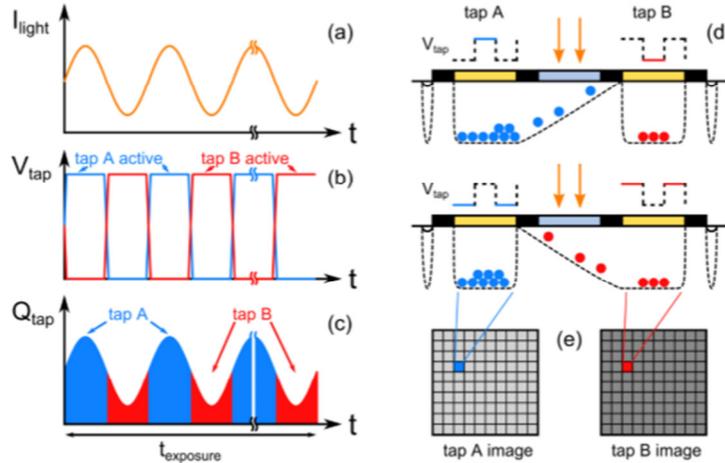


Figure 3. The sinusoidally modulated waveform of light incident on one pixel of the image sensor over time is shown in (a). The charge carriers (electrons) are generated by absorption of light in the photodiode and directed into one of two charge buckets, called tap A and B (d). The taps are alternately selected by applying a voltage waveform shown in (b). The rectangular modulation of the tap A control voltage (blue curve) is inverted for the opposite tap B (red curve) [3].

C. Modulation light source

It is important for the FLIM-PSP technique to use a reliable and stable sinusoidal excitation light [4]. In this work, the excitation light intensity with sinusoidal modulation is generated by a HARDsoft UV-LED [5], which was modified for our purpose. Figure 4 shows an oscillogram of input signals to the LED and an emitted light from LED. This LED can be operated with a sinusoidal input signal of 1 V_{pp} generated by the pco.flim camera and a gate input (TTL signal from pco.flim) for switching the generated light on and off. Detailed features of the modulation light source are introduced in the Ref[5].



Figure 4. Oscilloscope of TTL gate input signal (yellow), sine modulation input signal (magenta) and measured light flux (cyan). LED current 10 A max and offset 0.53 V [5].

III. Calibration Test

A. PSP

The paint used in this work is composed of platinum-meso-tetra(pentafluorophenyl)porphine (PtTFPP) [6] as a sensor dye and poly(4-tert-butyl styrene) as a polymer binder. This paint has approximately a lifetime of 10 μ s at ambient conditions and 50 μ s at vacuum condition [7,8]. Before applying this PSP coating on a calibration test piece, two additional paint layers, a white polyurethane screen layer and an intermediate layer, are applied. The intermediate layer is composed of white pigments and the polymer used in the PSP coating. This layer works as a barrier coating to prevent an interaction between the PSP coating and the white screen coating.

B. Setup and Conditions

A bandpass filter around 385 \pm 70 nm was attached in front of LED and a bandpass filter around 650 \pm 50 nm was attached to the camera to separate the PSP emission light. A modulation frequency of the sinusoidal excitation light was set to 20 kHz consequently the image gate width was 25 μ s. The LED current was set to 10 A max with 5 A offset. A total exposure time of each gated image was set to 110 ms. 32 images were acquired and averaged for each gate to enhance the signal-to-noise ratio of the PSP data.

The calibration test was performed at a pressure range between $P = 5$ kPa and 100 kPa and the temperature range between $T = 293$ K and 313 K (5 K step).

C. Results

Figure 5 shows the pressure and temperature dependency of tangent Φ and m_{em} . For a simpler post image processing tangent Φ is used instead of Φ . It is shown that both parameters have sensitivity to pressure and temperature.

In order to correct for inhomogeneous lifetime distribution over the model surface each parameter is normalized by the reference condition [7,9]. Figure 6 shows the normalized plot of each parameter by the reference condition at $P_{ref} = 60$ kPa and $T_{ref} = 303$ K. Figure 7 shows pressure sensitivities of both parameters at $T = 303$ K. The phase angle shows higher sensitivity compared to the demodulation index, especially at higher pressure range. The pressure sensitivity of the phase angle is comparable to the conventional two-gated lifetime technique [8]. For the pressure calculation in the wind tunnel test, a 4th-order polynomial equation was used to fit the calibration data.

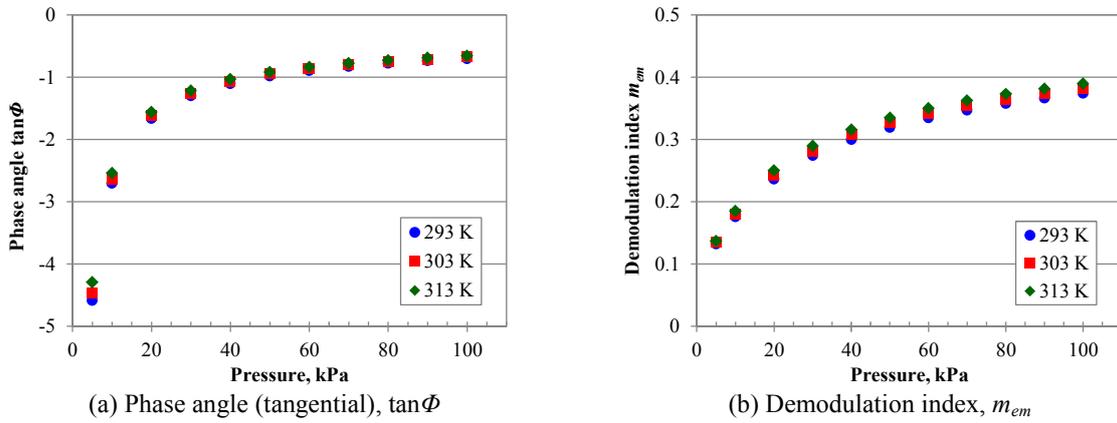


Figure 5. Pressure and temperature dependency of each parameter.

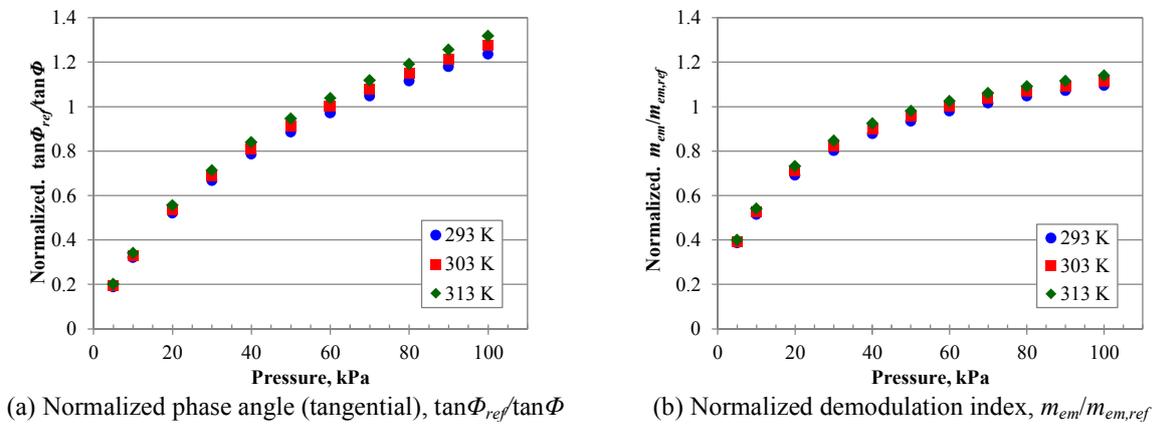


Figure 6. Pressure and temperature dependency of each normalized parameter.

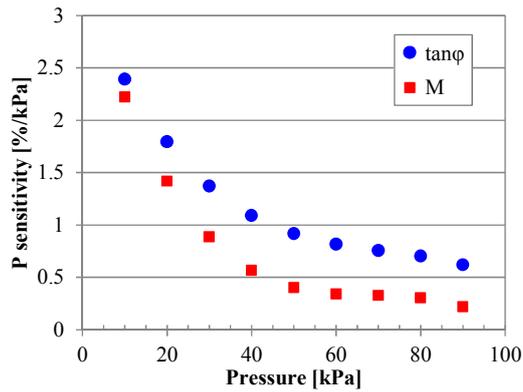


Figure 7. Pressure sensitivities at $T = 303$ K.

IV. Wind Tunnel Test

A. Setup

Evaluation tests of the FLIM-PSP technique were conducted in the Transonic Wind Tunnel in Göttingen (TWG). The test section size is 1 m x 1 m and the operation range of the wind tunnel is from $M = 0.3$ to 2.2.

As a test model a delta-wing model was used [10]. The same PSP coating as well as camera and LED operation parameters were used in the calibration and wind tunnel tests. The coating was applied on the suction side of the model wing and body part.

The pco.flim camera and the UV-LED were mounted on top of the test section. The distance between the model and equipment was approximately 600 mm. The forward part of the model was not included in the PSP images because of a limited view angle of the setup.

The reference image of PSP was acquired at wind-off condition. The tangent of phase angle and the demodulation index were calculated from Eqs. 1 and 2 after image ensemble averaging and dark image subtraction. Finally, the pressure was calculated from the ratio of the reference and wind-on conditions using the calibration test results.

B. Results

One data point measured by the FLIM-PSP technique is introduced in Fig. 8. These pressure distributions were calculated for the flow Mach number of 0.85 and high model angle-of-attack. Pressure patterns caused by leading-edge vortices are successfully visualized by both phase angle Φ and demodulation index m_{em} .

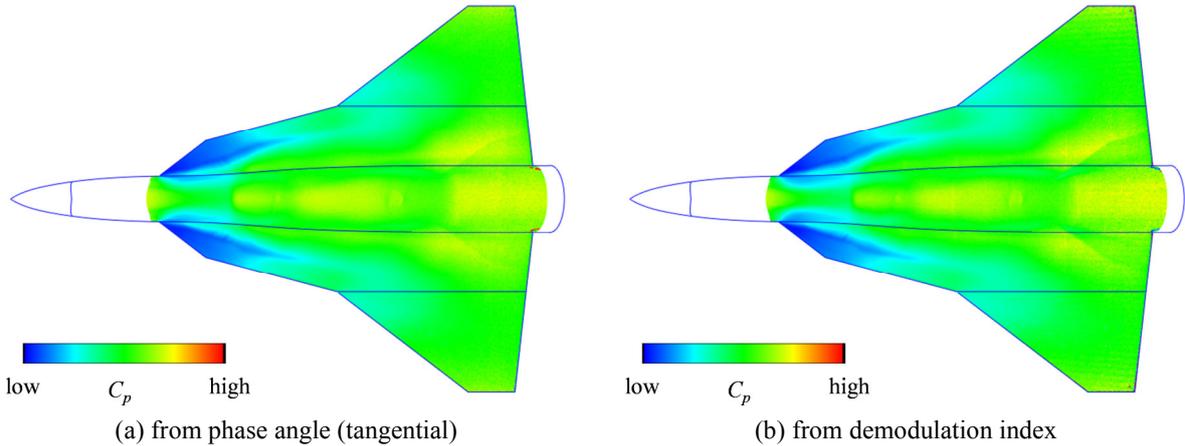


Figure 8. Pressure distributions obtained by the FLIM-PSP technique.

C. Measurement Accuracy and Errors

In this test, four pressure taps, two near the leading edge and two near the wing tip, are available on the area coated with PSP (Fig. 9). The comparison of the pressure tap data and PSP data is summarized in Table 1. Both PSP results from the phase angle and modulation index match well with the pressure tap data. In this test, PSP data at the tap locations P1 and P2 shows consistently higher pressure values compared to the pressure taps. This could be a result of paint aging which over time leads to changing local pressure sensitivities and lifetime patterns appearing at wind-off conditions, as shown in Fig. 10 where the footprints of the leading-edge vortices appear as different lifetime values in the wind-off image. The aging is a result of prolonged preliminary tests on the same coating and in order to correct for these effects the correction of the calibration data is required.

Figure 11 shows effects of the image averaging to the signal-to-noise ratio (SNR) of PSP data. The SNRs are calculated from an area of 50x50 pixels at a mid-part of the wing. The PSP image without spatial filtering is used. The SNR of the demodulation index is nearly two times higher than that of the phase angle. However, as shown in Fig. 7, the pressure sensitivity of the demodulation index is only half than that of the phase angle. Therefore, the final PSP data converted to pressures shows comparable SNR level between the phase angle and the demodulation index. It is noted that the SNR of the conventional lifetime technique used in DLR (two-gate method with CCD camera and

pulsed LED) with 8 image averaging [8] is approximately three times higher compared to the current FLIM-PSP technique with 32 image averaging.

In Fig. 11, fitted curves with a square root function are also plotted. The increase of SNR with the number of averaging fits very well to the square root function in the phase angle but not in the demodulation index. This indicates that the dominant noise component in the phase angle is the shot-noise and the demodulation index has an additional noise component. Figure 12 shows enlarged PSP images near the wing tip. The colormaps are adjusted to the same pressure range in both images. The shot-noise in these results is further reduced by a spatial filtering. It is visible that the PSP result in demodulation index image contains stripe patterns which are caused by a camera-fixed noise. This camera-fixed noise seems to be a constant component in each camera pixel. Therefore, the subtraction of two different gated images (e.g. $I_1 - I_3$) can remove this noise. Based on Eqs. 1 and 2, the phase angle is free from this type of noise, however, for the demodulation index the noise remains in the denominator part. A proper camera flat-field correction would be required for removing the camera-fixed noise from the demodulation index results.

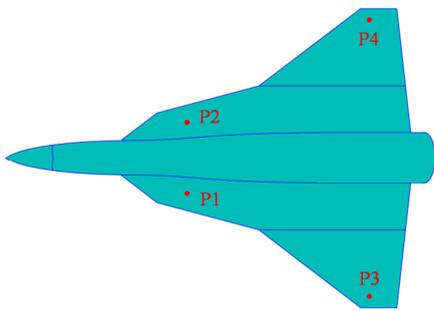


Figure 9. Pressure tap locations.

Table 1 Comparison of the pressure tap data and PSP data

| Tap name | Pressure difference in C_p ($C_{p,psp} - C_{p,tap}$) | |
|----------|--|--------------------|
| | Phase angle | Demodulation index |
| P1 | +0.067 | +0.047 |
| P2 | +0.069 | +0.044 |
| P3 | -0.001 | +0.010 |
| P4 | -0.018 | -0.077 |
| RMS | 0.049 | 0.050 |

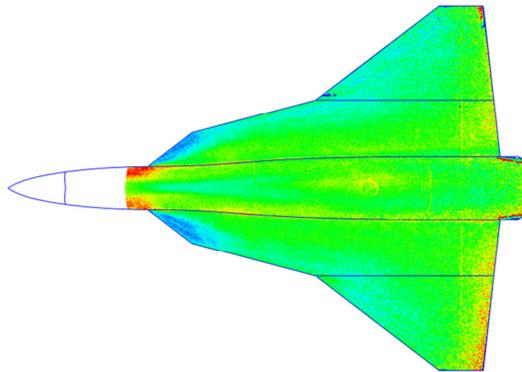


Figure 10. Inhomogeneous lifetime distribution under wind-off condition (phase angle).

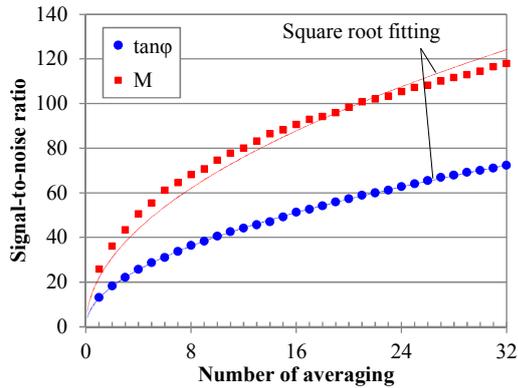
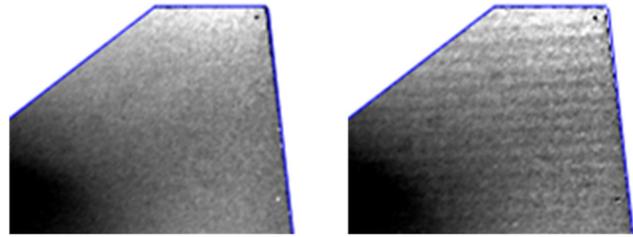


Figure 11. Number of image averaging vs SNR.



(a) Phase angle

(b) Demodulation index

Figure 12. Enlarged PSP images near the wing tip.

V. Future Works

Further investigation for the optimization of measurement parameters is required; e.g. the modulation light frequency, the ratio of the amplitude and the averaged power of the excitation light. The camera calibration is also important to obtain higher quality PSP images by pco.flim camera.

One great interest of the FLIM-PSP technique is a simultaneous pressure and temperature measurement based on the different sensitivity to pressure and temperature in the phase angle and the demodulation index. DLR is starting the investigations of this topic in laboratory tests.

VI. Conclusions

The applicability of a frequency-domain fluorescence lifetime imaging (FLIM) with a new CMOS camera sensor (pco.flim) to Pressure-Sensitive Paint (PSP) measurement in wind tunnel tests was investigated in calibration tests and in transonic wind tunnel test. In the calibration tests, two lifetime parameters obtained in the FLIM-PSP technique, the phase angle and demodulation index, showed different sensitivity to pressure and temperature. This indicates a potential of simultaneous pressure and temperature measurement. In the wind tunnel test, the FLIM-PSP technique was demonstrated using a delta-wing model. The obtained PSP results successfully visualized the complex pressure distribution on the model surface and the quantitative agreement with conventional pressure tap data was good.

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