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INVESTIGATION OF FREQUENCY-DOMAIN LIFETIME PSP TECHNIQUE USING A FLUORESCENCE LIFETIME IMAGING (FLIM) CAMERA

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- Fluid: subsonic flow
- Visualization method(s): Pressure Sensitive Paint (PSP)
- Other keywords: lifetime-based method, delta wing

ABSTRACT: Frequency-domain fluorescence lifetime imaging (FLIM) is applied for acquiring pressure sensitive paint (PSP) images by using a pco.flim camera, which has an in-pixel dual tap control CMOS image sensor. In this FLIM technique, an excitation light is modulated sinusoidally, and modulation depth and phase angle, which depend on lifetime or pressure, are estimated from four gated images. In the calibration test, the influences of modulated excitation light, exposure time and modulation frequency are shown. The pressure sensitivity of phase angle has similar sensitivity to that in the standard lifetime method (gated intensity ratio). As the first step of application, a low speed wind tunnel test was performed. The pressure distribution caused by the vortex on a delta wing is visualized successfully by this technique.

1 Introduction

Pressure sensitive paint (PSP) measurement technique is based on the dependence of the intensity or decay time of its luminescence on the pressure, brought about by oxygen quenching [1]. PSP is usually exited 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 this study, the frequency-domain lifetime PSP technique (FLIM-PSP) with the pco.flim camera is investigated. First, characteristics of the FLIM-PSP technique are investigated in calibration tests. Then, a low speed wind tunnel test is performed with the same system. The pressure distribution caused by the vortex on a generic delta wing model is visualized and results of the FLIM-PSP technique are shown.
2. FLIM-PSP Technique

2.1 Principle

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

In the image-based technique, these phase angle and demodulation index can be calculated from gated images obtained during the modulation period, as introduced by Franke and Holst [3]. A width of all gated images is a half of the modulation period and timings of the gated images are shifted to 0, 90, 180, and 270° from the modulation signal. 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 phase angle $\Phi_{\text{em}}$ and demodulation index $m_{\text{em}}$ can be calculated using Eq. (1) and Eq. (2).

$$\tan \Phi_{\text{em}} = \frac{I_4 - I_2}{I_1 - I_3}$$

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

Note that $a_{\text{em}}$ and $b_{\text{em}}$ are calculated using following equations.

$$a_{\text{em}} = \frac{\sqrt{(I_1 - I_3)^2 + (I_4 - I_2)^2}}{2}$$

$$b_{\text{em}} = \frac{I_1 + I_2 + I_3 + I_4}{4}$$

Normally, the PSP signal for a single-shot gated image is very small. Therefore, a multi-exposure camera is required for accumulation of PSP signal with thousands periods of the modulation.
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Fig. 2 Timing of the second gated image $I_2$

Fig. 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) [4]

2.2 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 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 [4]. The sensor can selectively guide photo-generated charge carriers to each tap triggered by an external signal (tap control signal). When the tap A is active, the charge carriers are guided and accumulated in 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 a half period of the modulation.
3. When the delay between two signals 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 2.1.
4. When the delay of quarter 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 the tap A, $I_1$ in the tap B) and a delay of three quarter period ($I_4$ in the tap A, $I_2$ in the tap B) are acquired for a tap correction. Finally, each gated image is obtained by a sum of tap images, e.g. $I_1 = I_{1,\text{tapA}} + I_{1,\text{tapB}}$.

### 2.3 Modulated Excitation Light

Careful selection and setup of modulated excitation light is very important for the FLIM-PSP technique. Several parameters like a distortion of the sinusoidal waveform and light stability could influence the PSP results. Two different LEDs, UV flat LED (Luminus) and an Omicron LED (LedHUB® LED Light Engine, Omicron-Laserage Laserprodukte GmbH), are employed and compared as the sinusoidal modulation light source in this work. Main features of these LEDs are summarized in Table 1. The used PSP can be excited with both wavelengths without changing the resulting pressure sensitivity [5].

<table>
<thead>
<tr>
<th>Table 1 Main features of the modulation light source</th>
<th>UV flat LED</th>
<th>Omicron LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>405 nm</td>
<td>528 nm</td>
</tr>
<tr>
<td>Control unit</td>
<td>External unit (Development kit from Luminus)</td>
<td>Option unit for the pco.flim camera developed by Omicron</td>
</tr>
<tr>
<td>Optical attachment</td>
<td>None</td>
<td>Light guide</td>
</tr>
</tbody>
</table>

The modulation of both LEDs is controlled by a sinusoidal AC output signal ($\pm0.5$ V, 50 Ω impedance) from the pco.flim camera. The Omicron LED with an option unit can directly use this AC signal for the output light control. In contrast, the UV flat LED requires additional signal converter from AC to DC signal (0-5V in DC) between the pco.flim camera and the control unit of LED.
2.4 PSP coating for FLIM Technique

The PSP 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 µs at ambient conditions [7]. This lifetime is suitable for the excitation frequency over 10 kHz [4]. Before applying this PSP coating on a model surface, two additional paint layers, a white 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.

3 Calibration Test

The calibration test was conducted for understanding of the influences of the test parameters to the FLIM-PSP technique. An aluminum plate (30 mm × 30 mm) coated by PtTFPP-based PSP was placed inside the calibration chamber. The UV flat LED or the Omicron LED were used as the excitation light source. A bandpass filter around 650 ± 40 nm was attached to the pco.flim camera to separate the PSP emission light. The test was performed at a pressure range between 95 kPa and 105 kPa and the temperature range between 283 K and 303 K, simulating the following low speed wind tunnel tests. The calibration tests were performed at multiple modulation frequencies from 10 kHz to 50 kHz.

The amplitude $a_{em}$ and the averaged intensity $b_{em}$ of emission intensity decrease as the pressure increases. However, their ratio ($a_{em}/b_{em}$) or the demodulation index $m_{em}$ increases linearly with increasing pressure, in this pressure range. This means that the change of the averaged intensity is stronger than the amplitude change. The absolute of phase angle decreases as the pressure increases which is consistent with shortening of the lifetime with increasing pressure.

In this study, tangent of the phase angle $\phi_{em}$ (Eq. 1) is calculated from the images and together with the demodulation index (Eq. 2). Then normalization at known (reference) condition is performed to correct for inhomogeneous lifetime distribution [7]. In the calibration test, both parameters are normalized by a condition at $P_{ref} = 100$ kPa and $T_{ref} = 293$ K.

3.1 Comparison of LED on Stability and Distortion

Figure 4 shows the results of calibration tests with the UV flat LED and the Omicron LED, when the modulation frequency is 20 kHz and the temperature is 293 K. The normalized demodulation index and the phase angle increase linearly with increasing pressure in both LED. The results from both LEDs seem to be very similar. However the Omicron LED features considerably better reproducibility than the UV flat LED. This is also shown in the error of slope estimated by regression analysis and presented in Table 2. The error of slope of the Omicron LED is dramatically reduced. This is because that the light from UV flat LED shows a larger distortion, longer delay, larger jitter and an unstable averaged power compared to the Omicron LED. Those properties greatly affect the reproducibility of the calibration data.
Fig. 4 The results of calibration tests with the UV flat LED and the Omicron LED at $f_{\text{mod}} = 20 \text{ kHz} (P_{\text{ref}} = 100 \text{ kPa})$

<table>
<thead>
<tr>
<th>$m_{\text{em}}$</th>
<th>UV flat LED</th>
<th>± 16 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\text{tan}\phi_{\text{em}})^{-1}$</td>
<td>± 15 %</td>
<td>± 4.4 %</td>
</tr>
</tbody>
</table>

3.2 Influence of modulation frequency
Figure 5 shows the influence of modulation frequency $f_{\text{mod}}$ on the calibration results with the Omicron LED. In the demodulation index, the slope increases with increasing $f_{\text{mod}}$. On the other side, in the phase angle the influence of $f_{\text{mod}}$ is smaller than that in the demodulation index, however, the slope decreases slightly with increasing $f_{\text{mod}}$. Those relations are shown by the pressure sensitivity at 100 kPa in Fig.6. The pressure sensitivity of $m_{\text{em}}$ has its maximum at 50 kHz and is reduced drastically with decreasing $f_{\text{mod}}$. In the phase angle, the pressure sensitivity has its maximum at 10 kHz and decreases gradually with increasing $f_{\text{mod}}$. Note that the pressure sensitivity of phase angle at $f_{\text{mod}} < 25 \text{ kHz}$ is comparable to the standard time-domain lifetime method (gated intensity ratio), which is 0.55 %/kPa at 100 kPa [7].

3.3 Influence of exposure time
It was found during the calibration tests that the dark current noise is linearly increased by the exposure time and reaches 20 % of full count when the exposure time is 1000 ms. The increase of the dark current noise causes a reduction of a camera dynamic range. In addition, amount of hot pixels is also increased with the exposure time increase. The camera operation below 1000 ms exposure time is favorable by these reasons.
4 Low speed Wind Tunnel Test

First demonstrated wind tunnel test of FLIM-PSP technique was conducted in the low speed 1m wind tunnel at DLR Göttingen (1MG). The PSP coating was applied on a delta wing model with a sweep angle of 75°, span width of 150 mm and chord length of 260.2 mm [8]. The model was mounted by a sting with the angle-of-attack of 25°. The flow speed was set to 50 m/s. Due to the model size, the UV flat LED, which has wider illumination area, was used instead of the Omicron LED despite its worse performance. The pco.flim camera and the UV flat LED were mounted on top of the test section. The distance between the model and equipment was approximately 800 mm. The FLIM operations for the image sequence were chosen based on the calibration test as shown in Table 3.
Table 3 The FLIM operating conditions for the wind tunnel test

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation frequency (Sine)</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Exposure time</td>
<td>300 ms</td>
</tr>
<tr>
<td>Phase number</td>
<td>4</td>
</tr>
<tr>
<td>Number of image</td>
<td>256 (64 for each gated image)</td>
</tr>
</tbody>
</table>

The reference image of PSP was acquired at wind-off condition. The tangent of phase angle and the demodulation index were calculated from Eq. (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. The color contour maps of pressure distribution estimated from the demodulation index and the phase angle are shown in Fig.7. The flow direction is from left to right. The pressure distribution influenced by the footprint of a vortex is successfully captured using the FLIM-PSP technique.

![Image](image1.png)

(a) The demodulation index  
(b) The phase angle  

Fig. 7 The pressure distributions on the delta (359 μm/pix)

5 Future Works

It is important for the FLIM-PSP technique to use a reliable and stable excitation light. So a new LED in cooperation with company HARDsoft is under development. The new LED is driven by the sinusoidal signal of 1 V_{p-p} provided by the pco.flim camera. Its amplitude and offset can be adjusted using the software. The frequency range of the sinusoidal modulation is 5-50 kHz. In order to better understand the influence of measurement parameters such as light source and camera further calibration tests are needed. Additional transonic wind tunnel tests using the new LED are scheduled.

6 Conclusion

Frequency-domain lifetime PSP technique is investigated with a pco.flim camera and is successfully applied in calibration and wind tunnel tests to obtain spatial pressure distribution. In the calibration test, the influence of parameters on the phase angle and the demodulation index are shown. The pressure sensitivity of phase angle has similar sensitivity to that in the standard time-domain lifetime method.
As a first application, a low speed wind tunnel test was performed. In this test, the pressure distribution caused by the vortex on a delta wing is visualized.

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