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A Sine-Modulated High-Intensity UV-LED Light Source for Pressure-Sensitive Paint Applications using Fluorescence Lifetime Imaging Technique

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Abstract

The 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. PSP is usually exited by light of an appropriate wavelength (e.g. UV-light) and its pressure dependent luminescence decay time or lifetime is detected by a camera system (CCD or CMOS). Two basic types of lifetime measurement exist: the first type is a time-domain lifetime method. For this method a pulsed light is used to excite the paint and the pressure dependent time constant is determined from the decay curve of luminescence intensity. The second type is a frequency-domain fluorescence lifetime imaging (FLIM) where sinusoidal modulated light is used to excite the paint and the PSP luminescence is simultaneously detected to calculate its pressure dependent phase shift and amplitude ratio. Based on UV-LEDs a light source has been designed which provides high intensity stable and low distorted sine-modulated light of constant amplitude which is essential for the accuracy of the presented method. The new light source is used to investigate the influence of frequency on pressure sensitivity of a PSP sample to optimize the system for application in transonic wind tunnel tests.

Keywords: Sine-Modulated UV-LED Light Source, Pressure-Sensitive Paint, Fluorescence Lifetime Imaging

1. INTRODUCTION

Holmes[1] used the FLIM method to acquire the pressure distribution from PSP applied to a fighter wing model using a solid-state phase-sensitive camera. A new CMOS image sensor has been developed by CSEM and PCO for the frequency-domain FLIM system and equipped in the pco.flim camera for fluorescence lifetime imaging microscopy[2]. The pco.flim camera, which has an in-pixel dual tap control CMOS image sensor, 1008 × 1008 pixels resolution and 14 bit A/D converter, provides a sinusoidal voltage output and captures images with precise timing, i.e. for well-defined phases with respect to the sinusoidal output. Each image contains many single exposures with this exact timing and allows thus accumulation over an overall exposure time covering many periods of the modulated signal.

The determination of the pressure dependent phase shift and amplitude ratio would require a perfect sinusoidal light modulation. Nevertheless, for pressure measurement a perfect sine is not required if calibration is performed with exactly the same excitation light modulation shape. But this shape must be well reproducible with negligible phase shift and must not change with any parameter. The best way to ensure these requirements is to use a light source which provides a fast linear response to the camera output signal. The shape must be maintained even for different amplitudes and different frequencies in order to obtain reproducible results for different setups but also to ensure that during parameter variations, only the parameter of interest is changed. Otherwise it remains unclear whether the changed parameter affects the result or the change in signal shape. Another requirement is that the amplitude should be very constant with respect to temperature and time, because in wind tunnel environments the ambient temperature may change and for different flow conditions the overall exposure time must be adapted.

In this study, a high-intensity LED system was developed by DLR and HARDsoft providing a linear response to an arbitrary input signal over a wide frequency range which is used in combination with the pco.flim camera to generate a real sine wave output of UV light for investigation of large scale surfaces, relevant for wind tunnel models. To verify the possible application for wind tunnel tests and to investigate the influence of parameters on pressure sensitivity, a setup for calibration of PSP samples was used.

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2. PSP CALIBRATION WITH FREQUENCY-DOMAIN FLUORESCENCE LIFETIME IMAGING

The excitation light intensity provided by the high-intensity LED system is modulated by a sinusoidal signal from the pco.flim camera. The luminescence phase and amplitude depends on the luminescence lifetime of PSP which is changing with the partial oxygen pressure i.e. local air pressure. Four integration windows (images), each with a width of a half period of a sinusoidal wave, are acquired. To acquire one image, multiple exposures at discrete phases of the excitation waveform are collected within the overall exposure time. The intensities of the four integration windows (images) are indicated by I_1, I_2, I_3, and I_4 at $\Phi = 0$, 90, 180, and 270° of the sinusoidal wave, respectively. Actually, in dual tap mode[2] the camera acquires two images with 180° phase shift simultaneously, as depicted in the acquisition scheme in Fig. 1. The phase is defined here with respect to the start of the first exposure. Each single exposure-time is half of the modulation period. Thus I_1 and I_3 as well as I_2 and I_4 are acquired simultaneously.

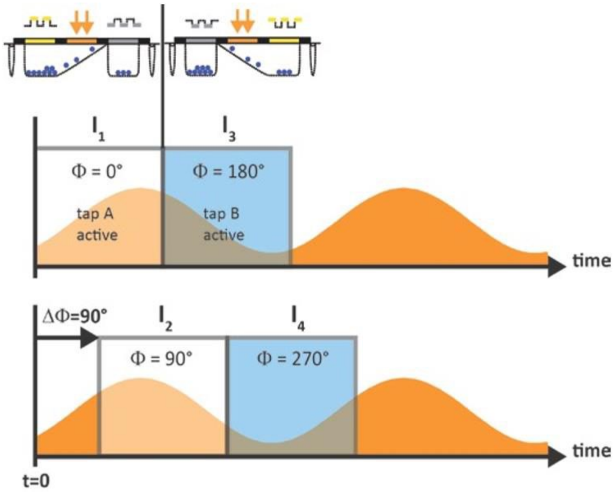


Fig. 1. Acquisition scheme of the pco.flim camera in dual tap mode

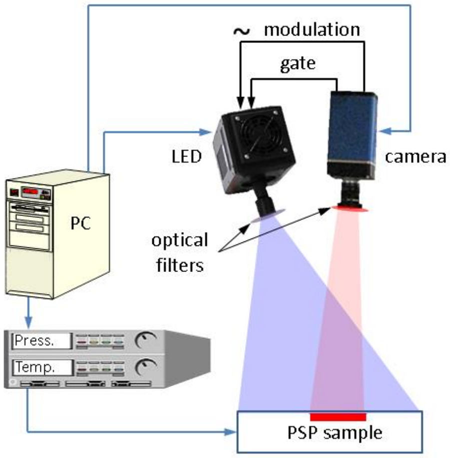


Fig. 2. Setup for PSP calibration

Important for PSP application is, that the result does not depend on absolute intensities, since homogeneous illumination is hardly possible on complex geometries. This requirement is fulfilled by using ratios of intensities, as done in the calculation of the phase angle Φ, i.e. the phase shift between excitation and emission from PSP, and the demodulation index m_{em}, i.e. the ratio of the amplitude a_{em} to the average intensity b_{em}. These quantities can be calculated from the four measured intensities as follows:

$$tan\ \Phi = \frac{I_4 - I_2}{I_1 - I_3} \tag{1}$$

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

To determine these quantities for a typical PSP surface, a setup as depicted in Fig. 2 was used. A test sample plate coated with PSP based on PtTFPP (Platinum meso-tetra (pentafluorophenyl) porphine) was inserted in a calibration chamber, which allows independent variation of pressure and temperature. It is equipped with a high-quality quartz glass window for optical access. The newly developed LED illuminator was equipped with a bandpass filter around 385 nm and the camera with a bandpass filter around 650 nm to separate the luminescence light. The distance of 0.6 m between LED illuminator and sample was chosen to be similar to what can be achieved in a 1 m test section of a wind tunnel. The LED current was modulated (synchronized to the output of the camera) with an amplitude of 5 A and an offset of 5 A leading to a minimum of 0 A and a maximum of 10 A. Therefore, the linear operating range of the illuminator was used. The camera also provides a gate signal to ensure light off conditions during image readout and to allow background subtraction. The total exposure time of the camera was varied from 100 ms to 300 ms to provide sufficient signal level but also to avoid saturation.

The measurements were performed at a pressure range between 10 kPa and 100 kPa within a temperature range between 283 K and 303 K. The modulation frequency was varied between 10 and 30 kHz.

For each pressure and temperature a set of 128 images (32 averages of the 4 phases) was recorded and from the averaged images the mean intensity, the demodulation index, and the phase shift were calculated for each pixel, leading to the images shown in Fig. 3. For the parameter variation from these images the average of a region of 40 x 40 pixels was calculated providing the values shown in the calibration results of Section 4.2.

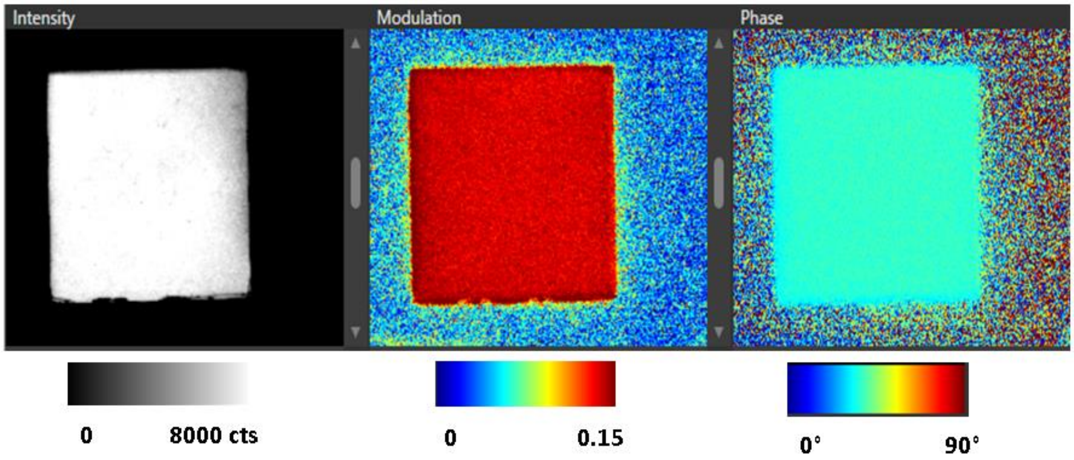


Fig. 3. Images of intensity, demodulation index and phase shift calculated from the four images at phase 0, 90, 180 and 270°. Conditions were P = 100 kPa and T = 20 °C. Modulation frequency was 20 kHz.

3. THE LINEARLY MODULATED LED LIGHT SOURCE

The light source device, called illuminator, was developed on the basis of an earlier single LED device[3,4] that generates both, CW or pulsed light of high power and can be precisely synchronized with different high-speed cameras. The CW-intensity is up to 2,100 lm and reaches 14,000 lm (at λ = 528 nm) in overdriven (250 A) pulsed operation. The light pulse width can be set in the range from 50 ns up to 300 μs or switched to CW mode. The new LED illuminator is equipped with exchangeable projection lenses providing homogenous light spots of 18, 36 and 72 cm diameter at a distance of 1 m. Moreover the light can be coupled with the experimental set-up using light guides and accompanying optics, e.g. light sheet lenses. Available light colors are red (λ = 623 nm), green (λ = 528 nm), blue (λ = 462 nm), UV (λ = 390 nm) and white.

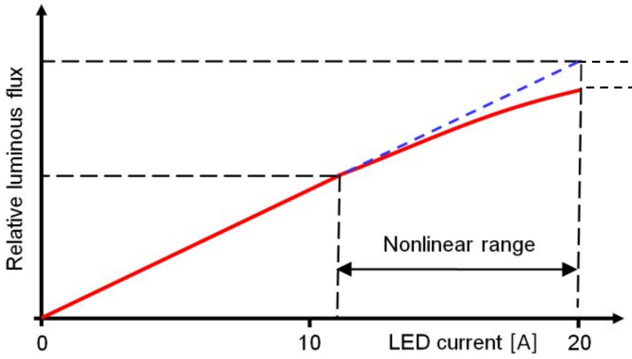


Fig. 4. LED relative luminous flux vs. drive current

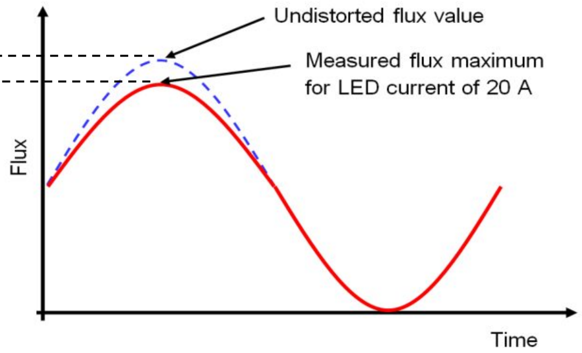


Fig. 5. Sine modulated flux distortion caused by nonlinearity of the LED flux

The apparatus presented here was designed around the single, high-power LED emitting UV light of 390 nm. The LED has a mosaic array device with surface emitting area of 12 mm^2, and 4:3 aspect ratio which has been specified for CW operation with a supply current of 18 A. However, it has been proven that this LED works with a sufficient linearity in the range up to about 10 A only, providing a maximum radiometric flux of about 11.5 W. Thus, to reduce the unwanted distortion of the sine-modulated light wave the peak value of the supply current shall not exceed this level. This restriction is visualized in Fig. 4 and Fig. 5.

The illuminator has been designed as a compact apparatus which is shown in Fig. 6. Its block circuit is displayed in Fig. 7. The unit provides a *linear modulation input* usually connected with a sine signal of 1 Vpp from the cooperating camera (in our case the pco.flim) and a *gate input* using a TTL signal for switching the generated light on and off. The LED driving current can be observed and/or measured on the *current monitor out*.

The mode of operation (CW or sine modulation) as well as all parameters e.g. amplification of the modulation signal and offset for the modulation input voltage in the range 0 to 0.9 V can be set on a computer, connected via an USB interface. The parameters can be stored within the device. The control software verifies the parameter combination and limits their certain values in order to prevent possible overload of the LED and/or of the driver electronic components. The light flux of the LED depends on its junction temperature. To keep it stable two temperature controlled fans are used to ensure the efficient cooling of the massive LED heat sink and of the electronic power components. The LED is driven by a digitally controlled, linearly modulated high-power current source.

The investigated object can be illuminated by means of interchangeable C-mount projection lenses designed for the UV light. Alternatively the light can be decoupled by means of light guides as mentioned above.

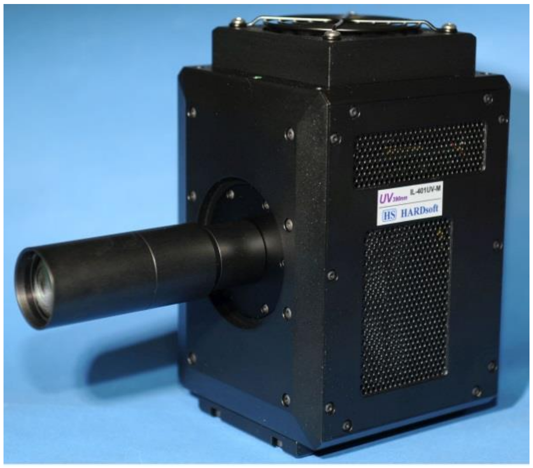


Fig. 6. Design of the apparatus

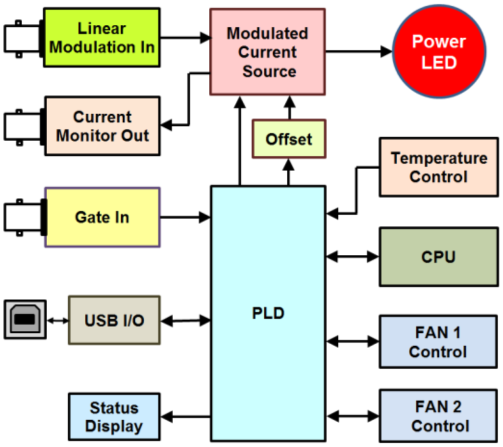


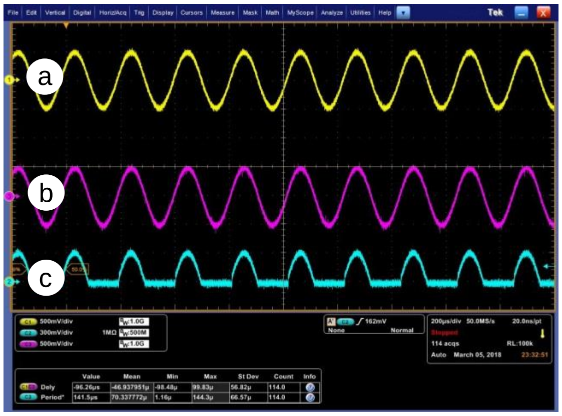
Fig. 7. Block circuit of linearly modulated LED illuminator

4. RESULTS

4.1 Laboratory tests of the illuminator

Some results of preliminary tests of the apparatus are shown in Figures 8 and 9. The sinusoidal modulating signal was applied to the *linear modulation input* and varied from 0 to 1 Vpp (Fig. 8a). The DC offset was initially set by software to 0 V. The LED driving current was observed on the *Current monitor output* (Fig. 8b). The resulting light flux was measured by means of a linear photodiode instrument. It is displayed in Fig. 8c. As expected, no light is emitted at the negative input voltage.

The gated operation is presented in Fig. 9. A low frequency TTL signal was connected to the *Gate input* (Fig: 9d) and a sinusoidal modulating signal to the *Linear modulation input* (Fig. 9e). The resulting modulated and gated light is shown in Fig. 9f. The minimum offset voltage for an undistorted light modulation was 0.53 V. The sine modulation of the light flux was tested up to 100 kHz. However, in the described PSP application a frequency range of 5-50 kHz was applied.



C1 500mV/div BW:1.0G
C2 300mV/div 1MΩ BW:500M
C3 500mV/div BW:1.0G

A' C2 162mV
None Normal

200µs/div 50.0MS/s 20.0ns/pt
Stopped
114 acqs RL:100k
Auto March 05, 2018 23:32:51

	Value	Mean	Min	Max	St Dev	Count	Info
C1 C3 Dely	-96.26µs	-46.937951µ	-98.48µ	99.83µ	56.82µ	114.0	
C3 Period*	141.5µs	70.337772µ	1.16µ	144.3µ	66.57µ	114.0	

Fig. 8. Oscillogram of (a) sine modulation signal
(b) current monitor out and (c) measured light flux.
LED current 10 A max and offset 0 V

C1 2.0V/div BW:1.0G
C2 300mV/div 1MΩ BW:500M
C3 500mV/div BW:1.0G

A' C1 920mV
None Normal

2.0ms/div 5.0MS/s 200ns/pt
Stopped
70 acqs RL:100k
Auto March 05, 2018 23:25:32

	Value	Mean	Min	Max	St Dev	Count	Info
C1 C3 Dely	-1.849ms	-1.8408858m	-1.849m	-1.838m	2.083µ	70.0	
C2 Period*	499.0µs	438.22329µ	265.7µ	504.0µ	101.6µ	70.0	

Fig. 9. Oscillogram of (d) TTL gate input signal,
(e) sine modulation signal and (f) measured light flux.
LED current 10 A max and offset 0.53 V

4.2 PSP Calibration

The values shown in the following figures are calculated from the recorded images as described in section 2.1. For easier comparison in the figures the resulting phase angle is shown as inverse tangent. Results of the calibration test at 293 K with a reference pressure of 80 kPa are shown for different modulation frequencies in Fig. 10. As expected, with increasing pressure the lifetime gets shorter and the demodulation index m_{em} increases accordingly whereas the phase decreases with rising pressure. Changing the modulation frequency from 10 to 30 kHz shows a significant increase of pressure sensitivity for both, demodulation index and phase.

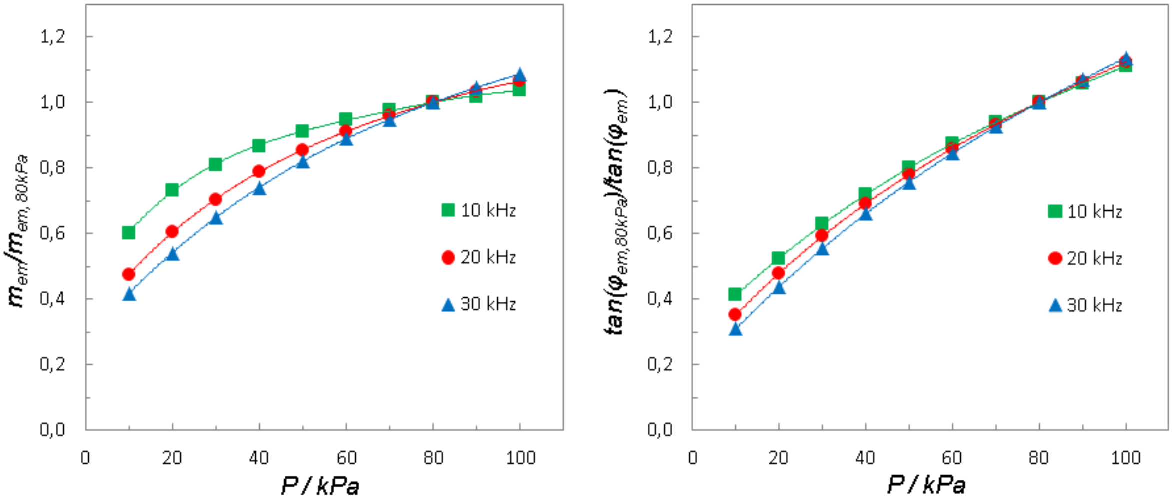


Fig. 10. Calibration curves for various frequencies of the demodulation index (left side) and for the inverse tangent of the phase angle (right side); both normalized to its values at a pressure of 80 kPa.

The demodulation index shows significant lower pressure sensitivity and less linear behavior than the phase but very similar temperature sensitivity as can be seen in Fig. 11. In future, this behavior may be used for compensation of PSPs temperature sensitivity in wind tunnel tests. Further parameter studies are required for optimization of the system with respect to pressure sensitivity and signal-to-noise ratio.

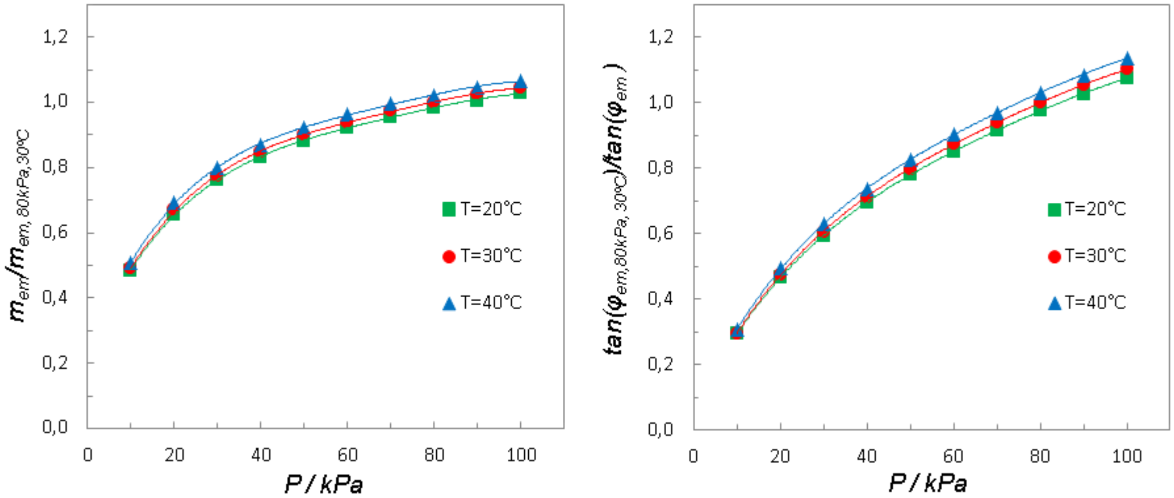


Fig. 11. Calibration curves for various temperatures of the demodulation index (left side) and for the inverse tangent of the phase angle (right side), both normalized to its values at a pressure of 80 kPa and a temperature of 30 °C. Modulation frequency was 20 kHz.

5. CONCLUSION

Frequency-domain lifetime PSP technique is investigated using a pco.flim camera in combination with the newly developed linearly modulated UV-LED illuminator system. In the calibration tests, the influences of modulation frequency on the phase angle and the demodulation index are determined. It is found that both quantities are pressure and to some extend also temperature dependent. The described PSP technique featuring the pco.flim camera along with the UV-LED-illuminator is available to measure pressure distributions on a length scale required for wind tunnel applications. The light output power of the illuminator system could almost be doubled if either the demands on linearity are reduced or after an analogue or digital linearizer is added to the system.

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