

# Pressure Measurement on Rotating Propeller Blades by Means of the Pressure-Sensitive Paint Lifetime Method

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**Abstract** The pressure distribution on the surface of a high-speed rotating propeller was measured using the Pressure-Sensitive Paint (PSP) lifetime method. This chapter describes the developed PSP formulation, the experimental setup as well as the image acquisition, processing procedure, and the data evaluation. The PSP lifetime method delivers a continuous pressure distribution, which allows even small pressure differences and aerodynamic phenomena such as vortices and flow separation to be detected. These phenomena occur often on rotating blades [1]. Based on the results from a feasibility study, a wind tunnel experiment was conducted in the low-speed wind-tunnel BLSWT of AIRBUS in Bremen at propeller rotation speeds up to 14,400 rpm.

## 1 Introduction

Surface pressure distributions can be determined by means of Pressure-Sensitive Paint (PSP). A specific measurement technique using PSP is the lifetime method which is based on the dependence of the lifetime of luminescence on the concentration of oxygen, and is proportional to the pressure. The PSP lifetime method has already

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been used in various wind tunnel tests [2–4]. The pressure distribution on a rotating propeller blade is of interest for the development of such systems. PSP is a contact-free and image-based measurement technique with which pressure gradients on a surface can be visualized. The PSP lifetime method is able to detect the expected pressure differences despite the short exposure times needed to capture the rapid decay of the fluorescence. This chapter describes in the first part a feasibility study on a high-speed rotating propeller using the PSP lifetime method. The following part describes the paint and binder as well as their relevant properties for PSP. The third section deals with the experimental setup for the feasibility study. Finally, the experiments in the low-speed wind tunnel BLSWT of AIRBUS Bremen at propeller rotation speeds up to 14,400 rpm are presented.

## 2 PSP Lifetime Method for Propeller Testing

The working principle of Pressure-Sensitive Paint (PSP) is based on the oxygen quenching mechanism of molecules which are embedded in the paint. These so-called luminophores are excited by incident light of a certain wavelength to an excited electronic state after which they relax back to the ground state (after some internal re-arrangement) via emission of a photon (luminescence). Since the fluorescence can be quenched by oxygen, the higher the concentration of oxygen in the surrounding air, the lower is the intensity of emission of the dye. Furthermore, the lifetime of the luminescence decreases with an increase of oxygen concentration (viz. pressure). The Stern-Volmer-equation shows this relation:

$$\frac{1}{\tau} = A(T) + B(T) p$$

where  $\tau$  is the lifetime of the luminescence,  $p$  is the ambient pressure and  $A$  and  $B$  are specific coefficients of the paint as a function of the ambient temperature  $T$  [5].

Several PSP formulations, containing sensor dye and binder, have been evaluated in calibration tests. The ideal PSP for the propeller measurements has to fulfill the following characteristics at ambient conditions: high luminescent intensity, high pressure sensitivity, low temperature sensitivity, and magnitude of lifetime  $\leq 10 \mu\text{s}$ .

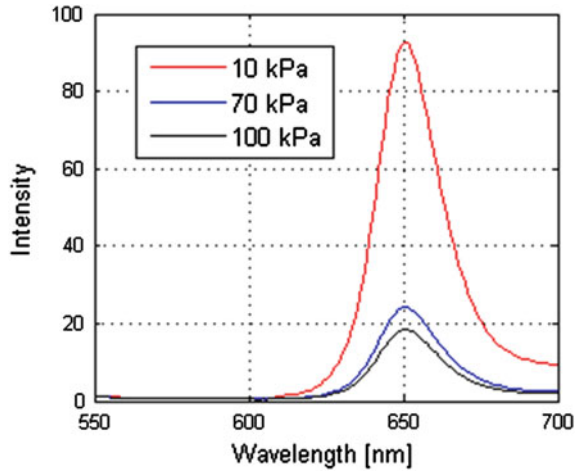
It was found that PtTFPP-based PSP is suitable for the propeller testing. The more relevant properties of this paint are listed in Table 1 and illustrated in the emission spectra in Fig. 1. This PSP has a sufficiently high pressure sensitivity ( $-0.8 \%/kPa$ ), a medium temperature sensitivity ( $-0.81 \%/K$ ), with a fluorescence lifetime in the required range ( $7.9 \mu\text{s}$  at 295.75 K and 100 kPa). The binder poly(4-tert-butylstyrene) has sufficient oxygen permeability to deliver good pressure sensitivity.

With lifetime systems, pressure is determined from the decay time of luminescence, which is based on time-resolved measurements of luminescence after the paint has been excited by a light pulse. Typically, decay times are determined from the ratio of intensities measured during at least two gates at different times after excitation [2].

**Table 1** PSP formulations and characteristics

PSP formulation	
Sensor dye	PtTFPP
Binder	Poly(4-tert-butylstyrene)
PSP characteristics (297.75 K, 100 kPa)	
Excitation wavelength	405 nm
Emission peak	650 nm
Pressure sensitivity	-0.8 %/kPa
Temperature sensitivity	-0.81 %/K
Lifetime	7.9 $\mu$ s

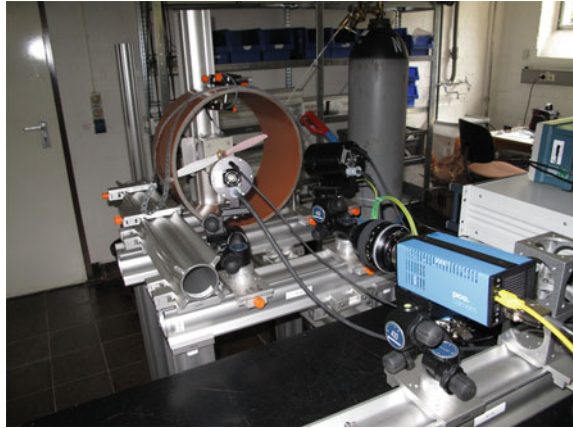
**Fig. 1** Pressure sensitivity of PSP



An important advantage of this approach is that, under ideal conditions, this ratio is independent of illumination intensity and luminophore concentration, and thus it is not necessary to normalize the data by measurements acquired at a reference condition.

The principal difficulty is simultaneously measuring the intensity time histories at all points on the model at the timescales of luminescence lifetimes ( $<10\mu$ s). In this work, the so called two gated intensity method [2] is used as a method to measure luminescent lifetimes. In this method, the luminescent images are obtained by integrating the luminescent decay curve at two different gates from which the lifetime can be calculated by the intensity ratio for the images taken at these two gates. It means that the lifetime method can measure pressure using only run images. Many researchers have reported the influence of temperature and the non-uniformity of PSP thickness on the pressure results obtained by PSP [6]. Therefore, the “double-ratio” method of run- and reference images has been proposed to calculate absolute pressure values with the lifetime method.

**Fig. 2** A picture of the PSP testing



### 3 Pre-test for the Wind Tunnel Experiments

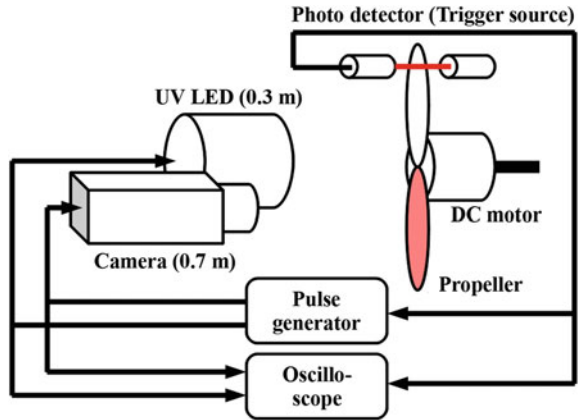
#### 3.1 Propeller

The commercial wooden propeller EVO-RC 30–10 cm was used in this experiment. It has a diameter of 0.33 m, a mean chord length of 0.03 m and a pitch of 0.1 m. The propeller was driven by a current-controlled direct-current motor. The maximum speed is 10,800 rpm. For this speed the maximum operating time is limited to 1 min because of motor heating [7]. One blade of the propeller was coated with PSP.

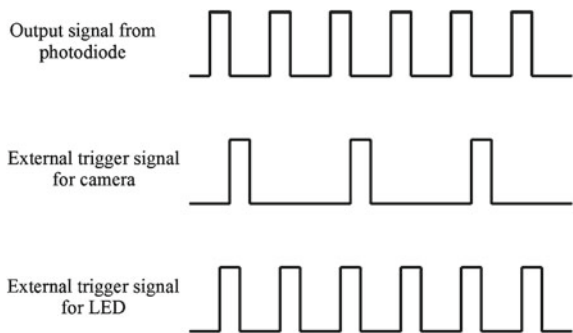
#### 3.2 Excitation Light and Camera System

A picture and schematic view of the PSP apparatus are shown in Figs. 2 and 3, respectively. The excitation light for PSP was provided by two high-power LED ULD 119 from Rapp Opto Electronic, with emission between 395 and 405 nm. The luminescent emission of PSP was captured by a 14-bit CCD camera (PCO 4000). A  $650 \pm 40$  nm optical band-pass filter was mounted in front of the camera lens to remove excitation and emission light. To increase the Signal-to-Noise Ratio (SNR) of the obtained images, the camera was operated in ‘modulation mode’. In this operational mode, the camera shutters were opened always at the same positions of the rotating propeller (same phase angle) and the small measured intensities of a single exposure were accumulated on the CCD chip. The camera exposure timing and excitation LED were controlled by an external trigger unit, as shown in Fig. 4. A photo detector generated a TTL signal when a propeller blade passed by it. This signal was the input signal for the pulse generator Model 725 by BNC, which generated two new TTL signals for the camera and the light sources. One TTL signal for the camera was generated for every second detector signal, because just one blade was coated with PSP.

**Fig. 3** A schematic view of the PSP testing



**Fig. 4** Timing of camera shutter and LED control

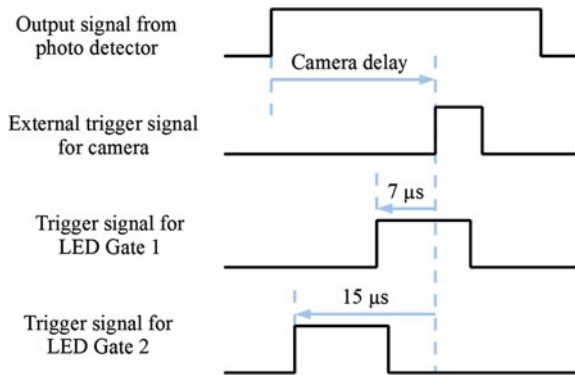


### 3.3 Acquisition and Processing Procedure of PSP Lifetime Images

To measure the lifetime of the PSP luminescence, images at two different times after the excitation pulse have to be acquired. As shown in Fig. 5, this was achieved by two different delay times for the excitation light trigger, while the delay of the external camera signal was kept fixed. The delay time of the camera signal depends on the rotational speed of the propeller, the delay times of the LED signals were 7 and 15  $\mu\text{s}$  shorter. The illumination time was 10  $\mu\text{s}$ . A single exposure time of the camera was 5  $\mu\text{s}$ , 750 single exposures were accumulated on chip to obtain the one image. The same sequence was used to acquire two reference images by using a pulse generator to trigger the individual experiment, since the propeller was not rotating and no signal from the photo detector was available. Furthermore, dark images for the run and reference cases, but without excitation light, were obtained.

With a distance between the camera lens and the propeller was 0.7 m. The resolution of the acquired images became 42 pixel per  $\text{mm}^2$ . The maximum rotational speed of the propeller during the measurements was 9,600rpm so that with these

**Fig. 5** Sequences for image acq. at gate 1 and 2



conditions the spatial resolution was better than 0.8 mm at all positions and at all frequencies.

A median filter was applied to the reference and run images, again to increase the SNR. The run images from gates 1 and 2 were divided to obtain an image of the change of luminescent intensity in time. The same was done with the reference images from gates 1 and 2. The gate images from run and reference were divided again to obtain the result image. The last division removed effects on the lifetime measurement due to paint non-homogeneity. Finally, four result images of distinct measurements at the same conditions were again averaged to further increase the SNR again.

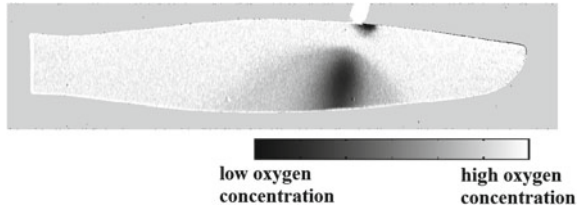
### 3.4 Results and Discussions

Figure 6 shows the result where a nitrogen jet impinged on the stationary propeller blade. The area where the nitrogen interacts with the PSP coated propeller has a low concentration of oxygen. As expected, this area in the image ratio has a low value and hence a dark color. The smaller dark area at the trailing edge of the blade is the shadow of the nitrogen canula, the white rectangular object above. This experiment verifies the developed method, because it shows the relation between the measured result image values and the partial pressure of oxygen.

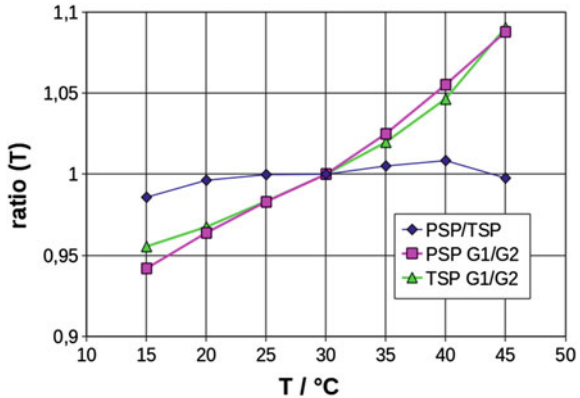
Measurements with a rotating propeller were carried out with the rotational speeds 6,000, 7,800, and 9,600 rpm [8]. For such high speeds of the propeller large thermal heating of the propeller blades occurs. The luminescence lifetime also decreases with a higher temperature because of thermal quenching, so that, to calculate the exact pressures, the temperatures on the blade at reference and run conditions must be known.

For an application of the PSP, as described in Sect. 2, on a propeller in a wind tunnel the temperature sensitivity of the paint would be still too high. Due the stronger

**Fig. 6** Propeller blade with nitrogen jet

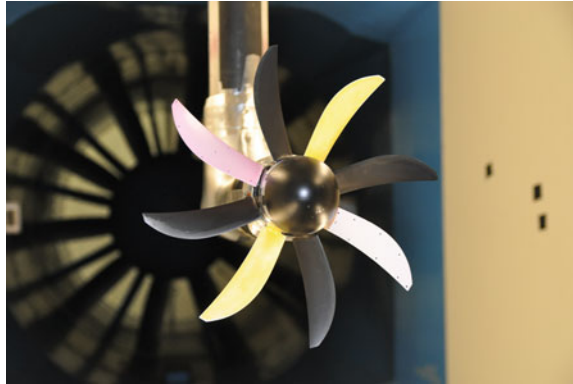


**Fig. 7** Gate ratios for PSP, TSP and ratio of ratios for temperature corrected signal



heating of the tip of the blades for high rotation frequencies a temperature difference of several degrees had been observed in previous IR measurements [7], which would make precise PSP measurements with this paint impossible. To compensate for the temperature sensitivity of the PSP it is possible to use another blade with the same luminophores but incorporated into an oxygen-impermeable polyurethane-based polymer. This temperature-sensitive paint (TSP) has very much the same spectral properties as the PSP coating and its luminescence can thus be acquired with the same setup as the luminescence of the PSP. Even though the lifetime itself as well as the temperature sensitivity of the TSP will differ significantly from that of the PSP, one can find settings (delays and exposure times) for the lifetime setup with the TSP where the temperature sensitivity of the gate ratios is almost the same as that for PSP at ambient pressures. This is shown in Fig. 7, where the normalized gate ratios for PSP (delay1 = -4 μs, delay2 = 6 μs) and TSP (delay1 = 6 μs, delay2 = 18 μs) are plotted as a function of temperature. For the ratio of TSP and PSP gate ratios (double ratio) the temperature sensitivity can be reduced by a factor of 10 with, however, the drawback that the acquisition of additional two images at delays of 6 and 18 μs between end of LED pulse and start of camera exposure is required. These settings have been applied to the wind-tunnel test described in the next Sect. 4, where the double ratio method has also been used for the data analysis.

**Fig. 8** Picture of the PSP/TSP coated propeller model in the test section of BLSWT



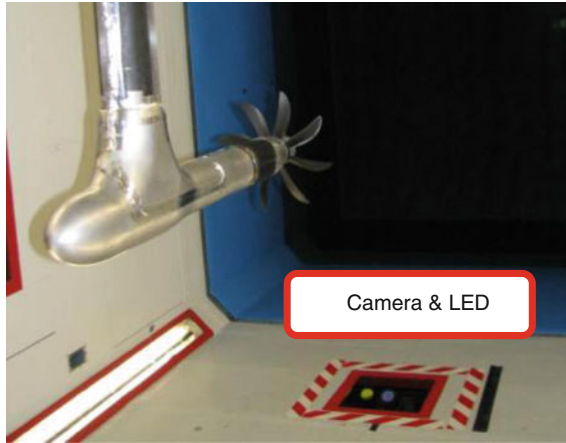
## 4 Wind Tunnel Experiments

Based on the results of the pre-test, a wind-tunnel experiment was conducted in the low-speed wind tunnel BLSWT of AIRBUS in Bremen. The experimental setup and wind tunnel setup are introduced here. The BLSWT is an Eiffel type wind tunnel having a test section with a cross sectional area of  $2 \times 2 \text{ m}^2$ . The wind speed is adjustable up to 70 m/s. The model consists of eight blades of diameter 0.3092 m, and it rotates clockwise when looking from the rear of the propeller. The pitch angle of the propeller blades can be chosen and manually adjusted. The number of revolutions per minute is adjustable between 3,000 and approximately 15,000 rpm. The propeller is driven by a pneumatic motor. PSP measurements were carried out in the low speed wind tunnel, with the propeller installed in the middle of the test section, as shown in Fig. 8. One CCD camera was installed upstream of the propeller and below the wind tunnel test-section wall. Another CCD camera was installed downstream of the propeller and in the sidewall of the wind tunnel test-section wall. The cameras were positioned behind glass windows where the high-power LED systems for excitation of the PSP were also located, see Fig. 9.

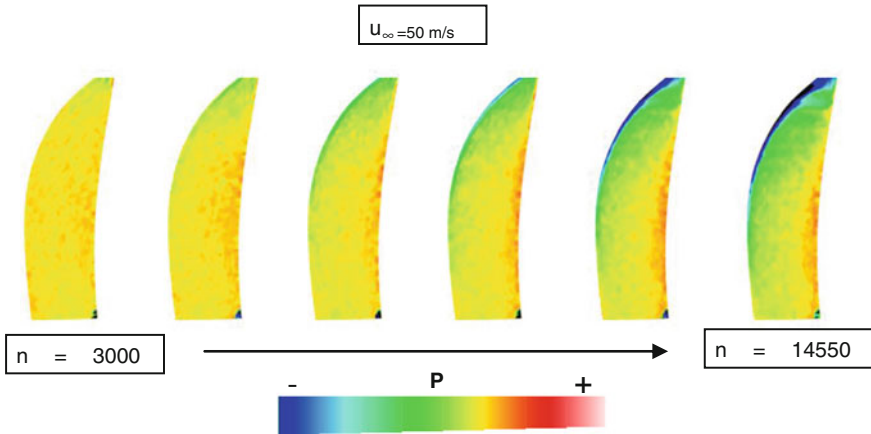
## 5 Results of the Wind Tunnel Test

With the above mentioned double-ratio lifetime approach for PSP and TSP quantitative pressure distributions could be measured on the fast rotating propeller. As an example for typical final results the pressure distribution on the suction side of the blade for  $U_\infty = 50 \text{ m/s}$  and different rotational speeds of the propeller from  $n = 3,000$  up to  $n = 14,550 \text{ rpm}$  are presented in Fig. 10. In this figure one can see the growth of the low pressure area along the leading edge of the propeller blade with increasing rotational speed. For very high rotational speeds a vortex has developed along the leading edge and the corresponding low pressure regions are clearly





**Fig. 9** Picture of the propeller model in the test section of BLSWT. One camera and one LED were mounted upstream the propeller



**Fig. 10** PSP results of the suction side of the propeller blade

visible in the PSP result. On the trailing edge of the blade the pressure increases with increasing rotational speed and the high pressure area along the trailing edge grows with increasing rotational speed. This behaviour is in good agreement with the expected flow separation near the trailing edge on the blade [9]. From the analysis of calibration characteristics of the paint one can conclude that with the installed PSP system pressures within an accuracy of better than  $\pm 10 \text{ mbar}$  could be measured. Since pressures were measured on both the suction and pressure sides of the blade, force and moments can thereby also be calculated by integrating the pressure data.

## 6 Conclusion

Pressure measurements using the PSP lifetime method were applied to a high-speed rotating propeller. PtTFPP-based PSP was used, which shows high pressure sensitivity. Furthermore, the lifetime of the PSP is sufficiently short ( $\sim 8 \mu\text{s}$ ) so that feasible exposure times of the cameras can be used. In a test under controlled conditions, the ability of the experimental setup to measure pressure differences was shown using a nitrogen jet. The images from a rotating propeller blade are sharp even at very high rotational speeds. For the large temperature differences which exist on the blade, the temperature sensitivity of the PSP used here is still too high, so that a combined PSP and TSP lifetime measurement system was suggested and implemented in the wind tunnel test. With this approach quantitative pressure values could be measured on the suction and pressure side of a propeller.

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