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# Fast rotating blade temperature imaging using a submicrosecond thermographic phosphor

Georgios Kasapis<sup>1</sup>, Francois Nicolas<sup>1</sup>, Jerome Delva<sup>1</sup>, Linda Dalipi<sup>2</sup> and Benoît Fond<sup>1,\*</sup>

<sup>1</sup>Department of Aerodynamics, Aeroelasticity and Acoustics, ONERA, Meudon & Lille, France

<sup>2</sup>Institute of fluid Dynamics and Thermodynamics, Otto von Guericke University Magdeburg, Germany

\*benoit.fond@onera.fr

**Abstract:** Blur-free temperature imaging of a fast rotating propeller blade is performed using an interframe camera in dual frame mode and a thermographic phosphor (CaS:Eu<sup>2+</sup>) paint with a temperature-sensitive lifetime in the sub-microsecond range. © 2024 The Author(s)

## 1. Introduction

Two-dimensional temperature or pressure data over aerodynamic model surfaces are a valuable source of information for research and development in the aerospace industry, as they reveal the local interaction between the flow and the model surface. The flow over rotating blades is of particular interest as it is challenging to model and there is a lack of experimental data to validate such simulations, as traditional sensors cannot be easily implemented. Temperature measurements can be obtained optically by infrared thermography or temperature-sensitive luminescent paints. Yet, to measure on surfaces moving over 100 m/s requires that the camera moves with the blade, or that the signal collection time is limited to a few microseconds at maximum.

Nanosecond pulsed lasers can be used for rapid excitation of luminescent paints. However, signal detection is limited by the paint's luminescence decay time. In addition, for a robust determination of temperature, self-referenced methods are necessary. That is, the temperature must be derived from a temperature-sensitive ratio of two images taken either simultaneously, or within a short time, as to correct for illumination variations or model deformations. An example of such method is the dual frame lifetime imaging, which exploits the temperature dependence of the luminescence decay time in 2D using the double frame feature of non-intensified interline transfer cameras used in Particle Image Velocimetry (PIV). The luminescent probe must, therefore, have a lifetime which is highly temperature-sensitive and short enough to avoid motion blur. However, it should not be too short, to be able to resolve it accurately with the PIV cameras. In this paper, we implement a new paint made of a thermographic phosphor which has a sub-microsecond decay time, and can be excited by a green laser. Measurements are demonstrated on a rotor blade at 9000 rpm.

## 2. Method

For this study, we have identified europium-doped calcium sulphide, CaS:Eu<sup>2+</sup>, as a promising thermographic phosphor for measurements on fast moving objects. This phosphor is a low-cost commercial lamp phosphor, which has also the advantage of a broad excitation band from 450 to 560 nm allowing direct excitation with a green PIV laser. Its emission spectrum is a broad band centered at 660 nm. Prior to its use, we characterised its decay time under LED excitation, which decreases from 570 ns to 418 ns between 20 °C and 40 °C. The phosphor was mixed with a polymer binder in toluene and spray painted onto the blade of a 0.14 m radius propeller (APC 11x6-4). Note that CaS dissolves in water, but not in toluene.

The setup is presented Fig. 1. The rotor was operating at a rotation speed of 9000 rotations per minute (rpm), corresponding to a blade tip velocity of 132 m/s. The paint was illuminated by nanosecond pulses from a frequency doubled Nd:YAG laser at 532 nm. Its luminescence was imaged by a interline transfer CCD operating in double exposure "PIV" mode, using a 105 mm f/2 lens. An optical sensor generated a once-per-revolution signal by detecting a piece of reflective tape attached to the propeller's shaft, which was used to synchronise the propeller's rotation cycle at about 150 Hz, and the laser and camera triggering cycle at about 10 Hz via a timing unit. To obtain temperature information, the single-shot dual-frame lifetime method was used as described in Fig. 1. The time between the laser pulse and the start of the second frame was set at 1 microsecond. As a result of the decay time decreasing with the temperature, the ratio between the first gate and the second gate is an increasing monotonic function of temperature.

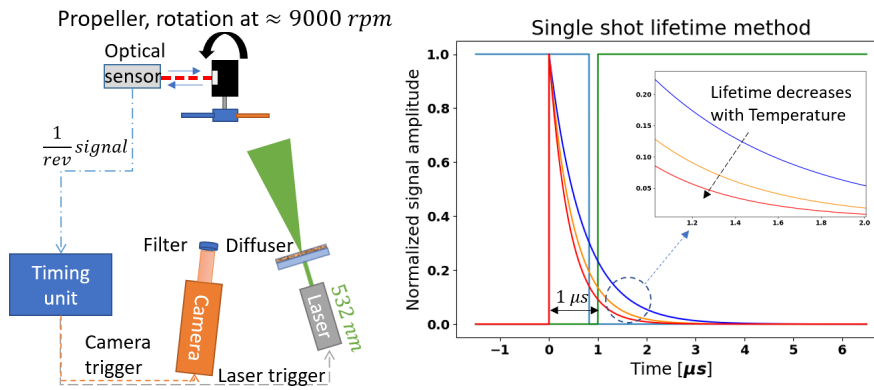


Fig. 1. Experimental setup (left) and timing scheme (right)

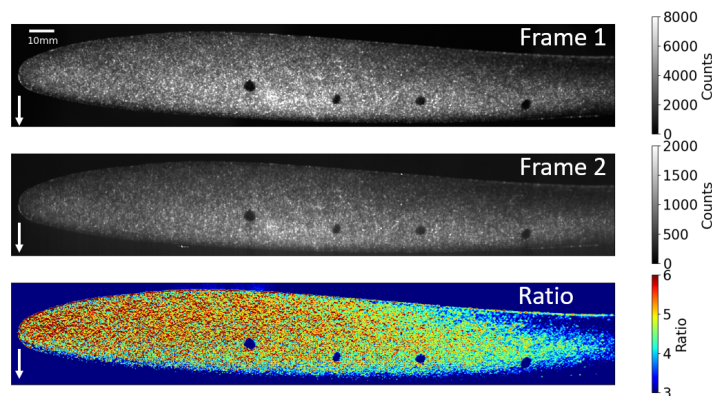


Fig. 2. Single shot images of blade rotating at 9000 rpm showing frame 1 (top), frame 2 (middle) and frame 1 to frame 2 ratio (bottom)

### 3. Results

A single pair of images, and their ratio, are shown in Fig. 2. No appreciable motion blur can be seen in either of these two frames, even at the blade tip where the displacement of the blade is approximately 0.4 pixels per microsecond. The ratio is shown to increase with radial position, as the temperature is linked to the local Mach number which increases linearly with radial position. The ratio map was obtained from a direct division of the image without pre- or post-processing steps applied. It can be converted to temperature after calibration of a painted sample in a pressure and temperature controlled cell. The paint preparation process will also be improved to reduce the grainy aspect of the paint due to particle agglomeration, and processing steps will be applied to correct for the effect of paint thickness and illumination non-uniformity on the luminescence decay time.

### 4. Conclusions

A new phosphor paint with a temperature sensitive decay time in the  $10^{-7}$  s range was developed for 2D thermometry on fast rotating objects by 2D rapid lifetime imaging. Blur free measurements were demonstrated on a rotor blade at a rotation speed of 9000 rpm corresponding to a tip speed of 132 m/s or 0.4 pixel per microsecond. Further improvements in paint uniformity, and inhomogeneity corrections are planned.

### 5. Acknowledgments

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