

Development of Time-resolved Multi-physical Field Measurement Techniques for High-speed Flows

Feng Gu¹, Naizhen Zhou², Jiajun Chen¹, Yan Duan², Yingzheng Liu¹, Di Peng¹

1: Key Lab of Education Ministry for Power Machinery and Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China

2: Science and Technology on Space Physics Laboratory, Beijing, China

* Correspondent author: idgnep8651@sjtu.edu.cn

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ABSTRACT

Fluid-structure interaction in high-speed flows involves coupled pressure, temperature, and deformation fields, requiring time-resolved full-field measurements. Although pressure-sensitive paint (PSP), temperature-sensitive paint (TSP), and digital image correlation (DIC) have been widely used, simultaneous measurement of all three fields under high-speed flow conditions remains challenging. This study developed and evaluated two multi-physical field measurement methods. The first was an intensity-based method derived from dual-luminophore PSP, in which the deformation- and temperature-induced intensity variations were compensated by taking the ratio of two emission channels. And stereo DIC was performed using the black speckles sprayed on the coating surface. The second was a lifetime-based method using a multi-physical sensing coating (MPC). The PSP regions and TSP speckles were spatially separated for pressure and temperature measurements, while they jointly served as features for deformation measurement using stereo DIC. The intensity-based method captured instantaneous pressure and deformation fields on a rotating blade, but its performance was limited by insufficient coating strength, intensity inconsistency for DIC, and angle-dependent filter transmission. In contrast, the lifetime-based MPC showed improved coating strength and intensity consistency for DIC. It successfully captured synchronous pressure, temperature, and deformation fields of a flexible wing model at Mach 5, revealing complex FSI phenomenon.

1. Introduction

Fluid-structure interaction (FSI) widely exists on aircraft, where aerodynamic loads can induce structural vibration, deformation, and even instability (McNamara & Friedmann, 2011). In high-speed flows, this coupling becomes more pronounced because of stronger pressure fluctuations and larger aerodynamic loads. Aerodynamic heating also increases the surface temperature, which further affects the structural response (McNamara & Friedmann, 2011; Shi & He, 2026). Understanding these interactions requires time-resolved measurements of surface pressure, temperature, and deformation. However, conventional point sensors, such as pressure taps, thermocouples, and strain gauges, provide only discrete data with limited spatial coverage. They

may also disturb the flow or alter the structural response.

Recent advances in optical measurement techniques provide new opportunities for non-intrusive, multi-field measurements. Pressure-sensitive paint (PSP), temperature-sensitive paint (TSP), and digital image correlation (DIC) have been widely used to measure surface pressure, temperature, and deformation, respectively (Liu et al., 2021; Peng & Liu, 2019; Sutton et al., 2009). Several strategies have been developed to integrate these techniques for simultaneous measurements. For example, dual-luminophore PSPs are able to measure pressure and temperature fields (Peng et al., 2013; Tiwari et al., 2022). PSP has also been integrated with stereo DIC to measure pressure and deformation fields on rotating blades, oscillating wings, and thin panels (Dong et al., 2022; Imai et al., 2022; Spottswood et al., 2019). It should be noted that the temperature effect cannot be ignored in high-speed FSI studies, because it can introduce large errors in PSP measurement if not corrected properly (Gu et al., 2022; Liu et al., 2021). Despite these efforts, a reliable method for simultaneous measurements of pressure, temperature, and deformation fields under high-speed flow conditions is still lacking.

To address this need, this study develops two time-resolved multi-physical field measurement methods for high-speed flows. The first is an intensity-based method derived from a dual-luminophore PSP. The pressure- and temperature-sensitive luminophores are arranged in a multilayer coating and their emission bands are spectrally separated. The formulation of dual-luminophore PSP is designed so that the two emission bands have nearly identical temperature sensitivity. By taking the intensity ratio between these emission bands, errors caused by temperature variation and model motion/deformation are removed altogether (Gu, Wei, et al., 2024; Kurihara et al., 2021). Random black speckles are added to the coating for stereo DIC. This intensity-based method provides a solution for simultaneous pressure and deformation measurements in high-speed flows.

The second is a lifetime-based method that relies on a multi-physical sensing coating (MPC). The coating is fabricated by a two-step mask-spraying process, where the PSP region is used for pressure measurement and dense random TSP speckles are embedded in the PSP region for temperature sensing, as well as DIC feature matching. For the single-shot lifetime imaging, the first frame captures the luminescence of PSP and TSP during a 20 μ s excitation pulse, and the second frame records the decay signals within 40 μ s. The intensity ratio of the two images yields both pressure and temperature data, which are not affected by the model motion/deformation. The pressure and temperature fields are reconstructed from the raw data in the corresponding regions, and the deformation field is calculated by stereo DIC using the TSP speckles. In this way,

simultaneous measurements of pressure, temperature, and deformation fields are realized.

2. Experimental Methods

2.1 Intensity-based Method with Dual-Luminophore PSP

The dual-luminophore PSP was fabricated by a three-step spraying process, as shown on the left in Figure 1. The bottom TSP layer was prepared from EuTTA and PMMA dissolved in dichloromethane, sprayed uniformly onto a clean substrate, and cured in air. The temperature sensitivity of the TSP layer can be adjusted by changing the mass ratio of EuTTA to PMMA (Egami et al., 2014). Therefore, the mass ratio was tuned to match the temperature sensitivity of the TSP layer with that of the PSP layer (Gu et al., 2024). After the TSP layer was cured, a thin water-based transparent resin layer was applied as a physical barrier to prevent chemical interaction between pressure- and temperature-sensitive luminescent molecules, which is a major cause of photodegradation in mixed coatings (Egami & Asai, 2002). Finally, a thin fast-response mesoporous-particle PSP (MP-PSP) layer was sprayed on top. The MP-PSP was formulated with PtTFPP as the luminescent probe, polystyrene as the binder, and 2 μm hollow silica microspheres to enhance the dynamic response (Peng et al., 2018). Because the MP-PSP layer was semi-transparent, the emission from the underlying TSP layer could pass through the top layers.

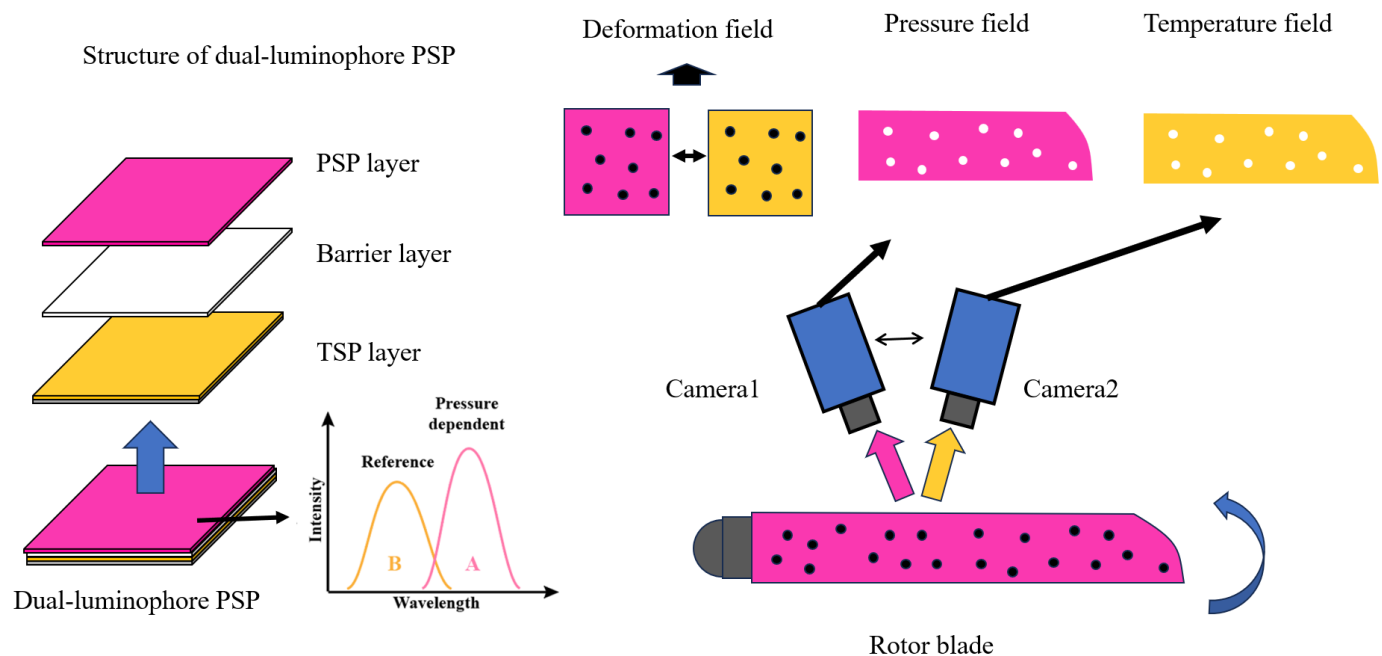


Figure. 1 Schematic of the dual-luminophore PSP coating preparation and the blade measurement setup.

The dual-luminophore PSP was applied to a rotor blade for pressure-deformation joint measurement, as shown on the right in Figure 1. Black speckles were sprayed on the blade surface

to provide features for stereo DIC. The rotor blade was a type HD 380A blade from ALIGN Corp., Ltd., with a radius of 0.425 m. The blade was operated at 1200 rpm with an angle of attack of -6° , corresponding to a tip speed of approximately 53.4 m/s and a tip Mach number of approximately 0.16 under ambient conditions. A high-power 400 nm LED provided uniform continuous excitation. Two synchronized high-speed cameras captured the rotating blade at 2kHz with a 20 μ s exposure time: one equipped with a 625-675 nm band-pass filter for the MP-PSP emission, and the other with a 600-630 nm filter for the EuTTA emission. The two cameras were arranged as a stereo configuration for deformation measurement. The left and right views corresponded to the PSP and TSP signals, respectively. A reference image of the stationary blade was acquired before the test.

The PSP signal (I_{PSP}) was affected by both pressure and temperature, whereas the TSP signal (I_{TSP}) was only dependent on temperature. Since the PSP and TSP layers had similar temperature sensitivities, the intensity ratio (I_{PSP}/I_{TSP}) was unaffected by temperature variation. Therefore, the ratio between the wind-off and wind-on intensity ratios could be related to pressure as follows:

$$\frac{(I_{PSP}/I_{TSP})_{wind-off}}{(I_{PSP}/I_{TSP})_{wind-on}} = A\left(\frac{P}{P_{ref}}\right)^2 + B\frac{P}{P_{ref}} + C \quad (1)$$

where A , B , and C were calibration coefficients obtained from the pressure calibration data, and P_{ref} was the reference pressure. This ratio of ratios was used to eliminate the influence of coating non-uniformity. A 15 minutes continuous illumination test showed that both the luminescent intensity and the pressure calibration curve remained nearly constant, as shown in Figure 2, confirming the good photostability of the multi-layer coating.

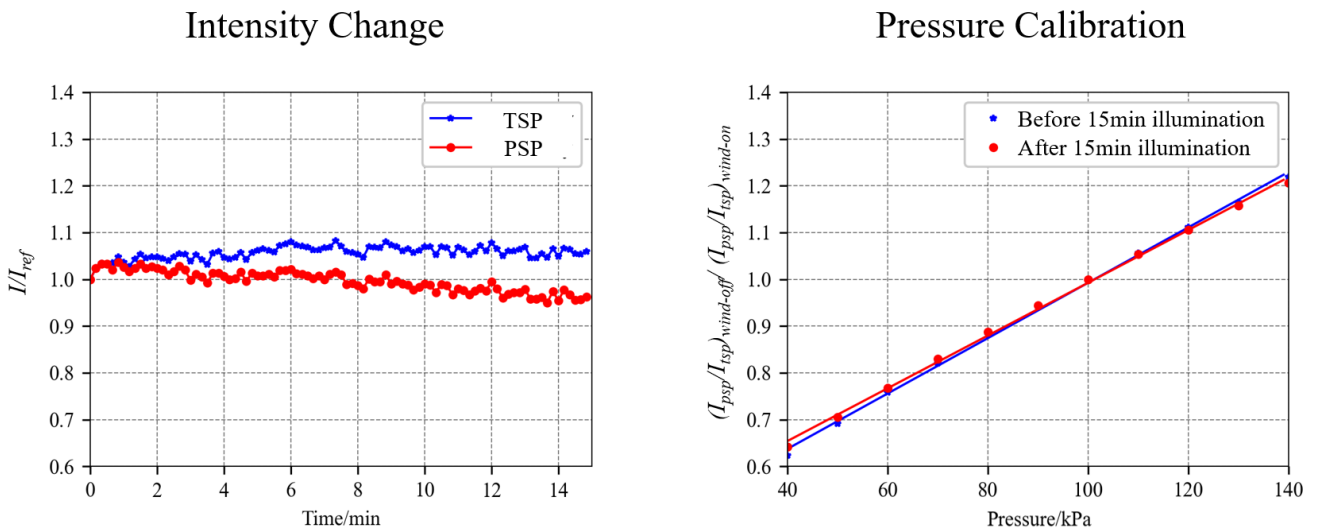


Figure. 2 Variations of luminescent intensity and pressure calibration of the dual-luminophore PSP during a 15-min illumination test.

2.2 Lifetime-based Method with MPC

The MPC was fabricated by a two-step masked spraying process that spatially separates pressure- and temperature-sensitive regions while providing features for DIC deformation measurement, as shown on the left in Figure 3. In the first step, temperature-sensitive speckles were produced. The TSP was prepared by mixing a Ru(dpp)_3 methanol solution with a commercial transparent varnish and curing agent. A 1 mm thick stainless-steel mask with randomly distributed circular through-holes was used to spray the solution, forming discrete circular speckles approximately 4 mm in diameter. The TSP layer was cured in a fume hood for 12 h. In the second step, the MP-PSP layer was deposited using a matching mask with circular blocking regions slightly larger than the TSP speckles. The MP-PSP solution was sprayed onto the exposed regions and cured for 1 h. The final coating contained continuous MP-PSP regions for pressure measurement and discrete TSP speckles for temperature sensing and DIC feature matching.

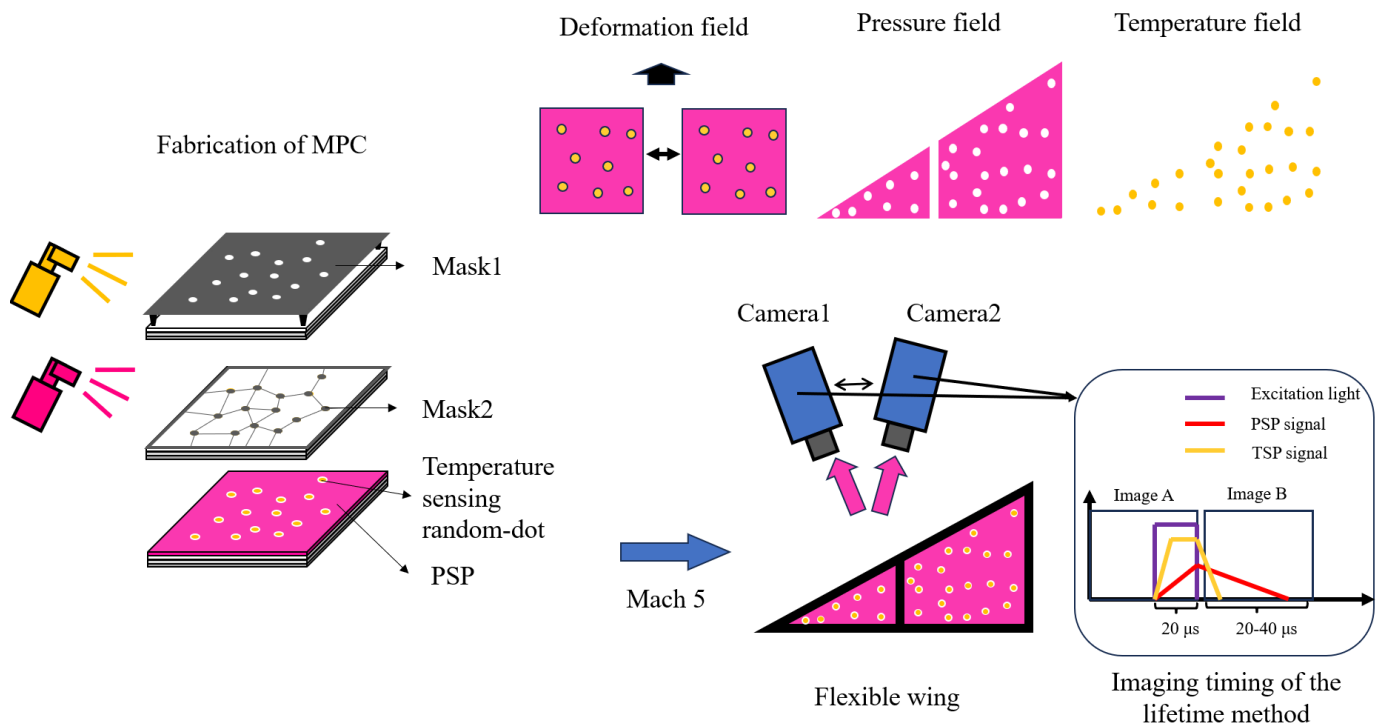


Figure. 3 Schematic of the lifetime-based MPC preparation and the measurement system for the flexible wing test.

The lifetime-based multi-physical field measurement technique was tested in a Mach 5 wind tunnel with a nozzle exit diameter of 2000 mm, as shown on the right in Figure 3. A large flexible wing model supported by two rods was used as the test model. Strong fluid-structural interaction is expected on the flexible wing under hypersonic flow. The wind tunnel tests were conducted

under Mach 5 with a total temperature of 408 K, a total pressure of 0.88 MPa and a dynamic pressure of 29,405 Pa. The angle of attack was increased from 0° to 10° in steps of 2.5° , with each angle held for 2 s, and the entire test lasted for 20 s.

The MPC was applied to the entire windward surface, and excited by a 50 W 400 nm LED operated at 1 kHz with a 20 μ s pulse duration. Two high-speed cameras, each equipped with a colored-glass 570 nm high-pass filter, were arranged with a viewing angle of approximately 40° for stereoscopic 3D deformation measurement. Before the test, a 500×500 mm chessboard target was used to calibrate the internal and external parameters of both cameras. A high-precision timing controller synchronized the excitation pulses and camera exposures. The single-shot lifetime imaging method was adopted: the image A (I_A) captured the emission during 20 μ s excitation pulse, while the image B (I_B) recorded the luminescent decay of both TSP and PSP after the excitation was turned off. The total duration of the luminescent signals was less than 60 μ s, during which structural deformation was negligible.

The ratio of two image (I_B/I_A) was first calculated. To eliminate the influence of coating non-uniformity caused by spraying, the ratio obtained under the wind-on condition was further divided by that obtained under the wind-off condition as $R = \frac{(I_B/I_A)_{wind-off}}{(I_B/I_A)_{wind-on}}$ (ratio-of-ratios). In the TSP speckle regions, the R was mainly dependent on temperature. This temperature-dependent relationship could be expressed as:

$$R_{TSP} = A_{TSP}T^2 + B_{TSP}T + C_{TSP} \quad (2)$$

where A_{TSP} , B_{TSP} , and C_{TSP} were the temperature calibration coefficients of TSP. Based on this relationship, the temperature values were calculated at the TSP speckle locations and then reconstructed into a continuous full-field temperature distribution.

For the PSP regions, the R was affected by both pressure and temperature, which could be expressed as:

$$R_{PSP} = A_{PSP}(T) \left(\frac{P}{P_{ref}} \right)^2 + B_{PSP}(T) \frac{P}{P_{ref}} + C_{PSP}(T) \quad (3)$$

where A_{PSP} , B_{PSP} , and C_{PSP} were temperature-dependent pressure calibration coefficients. The reconstructed temperature field was subsequently used to correct the PSP results and obtain the

pressure field.

3. Results and Discussion

3.1 Results of the Intensity-based Method

In this section, the coating strength of the intensity-based dual-luminophore PSP is first examined. The data processing procedure is then described. The DIC and pressure measurement results are then presented for the rotating blade experiment. The effects of inconsistent intensity between channels and angle-dependent filter transmission on the measurement results are further analyzed, and the limitations of this method are discussed.

3.1.1 Coating Strength Test

Coating strength is essential for luminescent coatings in high-speed flows because strong airflow can abrade or peel off the coating and degrade the luminescent signal. A 260 m/s air jet impinged on the coating at a 30° incident angle for 15 minutes to simulate high-speed shearing effect. Images were acquired before and after the test under identical conditions, and the corresponding luminescent intensities were calculated. After jet impingement, about 15% of PSP intensity was lost near the impingement region. This signal loss mainly resulted from damage of the thin MP-PSP top layer. The top layer enables TSP emission transmission but weakens the coating strength under high-speed flow. The coating was further tested in a high-speed wind tunnel. However, severe coating damage occurred after only one run in high-shear regions, causing an approximately 50% signal loss. These results showed that the strength of the multi-layer dual-luminophore coating was insufficient for high-speed wind tunnel tests. This method may be suitable for low-speed applications, and was later applied on a rotating blade for testing.

3.1.2 Data Processing

For the intensity-based method, the following procedure was developed to obtain the pressure and deformation fields from the two-channel image sequences:

1) Blade localization and image rectification: The blade region in each raw image was first identified by contour detection. Based on the detected blade contour, a minimum bounding

rectangle was calculated to determine the blade position and orientation in the image. The blade image was then rotated and cropped according to this rectangle, so that all blade images acquired at different phases were aligned to a nearly horizontal orientation. This rectification facilitated the subsequent DIC calculation. Meanwhile, the position, rotation angle, and transformation matrix of the bounding rectangle were recorded for later coordinate recovery and three-dimensional reconstruction.

2) Stereo DIC calculation: DIC was then performed on the rectified blade images acquired by the two cameras, yielding the pixel correspondence between the PSP and TSP images. To improve matching robustness, the DeepFlow optical flow algorithm was used because it is more tolerant of brightness changes than conventional DIC methods (Nguyen et al., 2018). Based on the pixel correspondence, the TSP image was registered onto the PSP image, allowing the subsequent intensity ratio calculation.

3) Pressure calculation: The intensity ratio I_{PSP}/I_{TSP} was calculated for both the wind-off and wind-on conditions. Another DIC calculation was then performed between the wind-off and wind-on rectified blade images to align the ratio images. After that, $\frac{(I_{PSP}/I_{TSP})_{wind-off}}{(I_{PSP}/I_{TSP})_{wind-on}}$ was calculated for each image pairs. The pressure field was then obtained using Eq. (1).

4) Three-dimensional point cloud reconstruction: Finally, the rectified-image coordinates were transformed back to the original camera-image coordinates using the previously recorded rectangle position and transformation matrix. Combined with the stereo camera calibration parameters obtained before the experiment, the corresponding pixels in the original left and right images were triangulated to reconstruct the three-dimensional point cloud of the blade surface. In this way, the deformation field and the pressure field were obtained.

3.1.3 Results of Pressure and Deformation Measurement

Figure 4 shows the raw PSP and TSP images together with the calculated displacement field. Although the displacement near the central leading-edge region was reasonable and followed the expected deformation trend, clear mismatch appeared near the blade edge and trailing-edge regions. In these regions, the displacement field became discontinuous and contained large errors, making deformation calculation and image registration difficult. This mismatch was mainly caused by the large intensity difference between the PSP and TSP images.

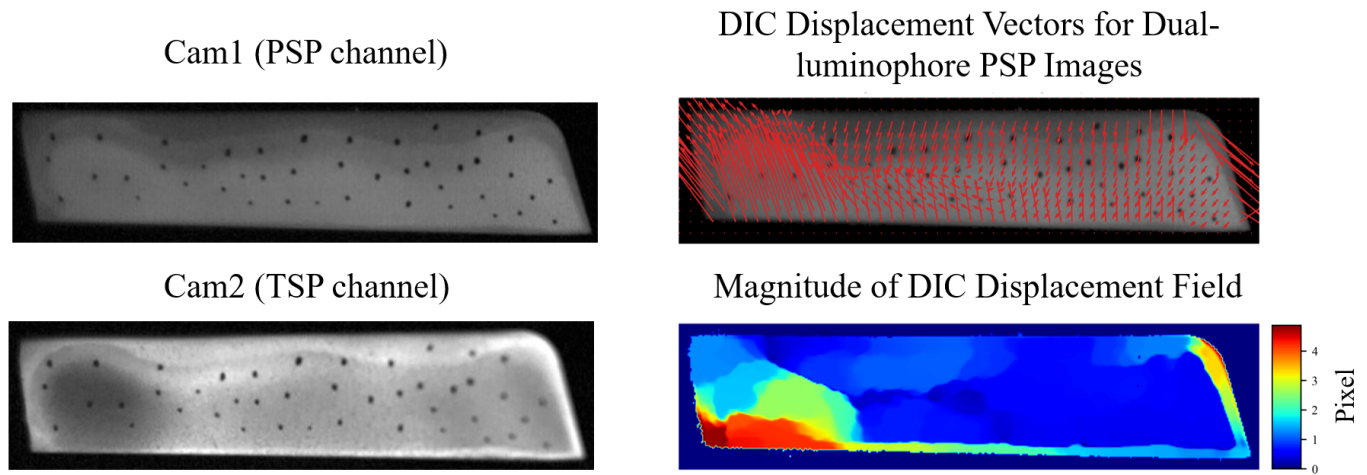


Figure. 4 Original PSP channel and TSP channel images and DIC-calculated displacement field of the dual-luminophore PSP on a rotor blade.

The DIC accuracy depends on the consistency of image features recorded by the left and right cameras. Though black speckles were sprayed on the dual-luminophore coating to provide deformation features, the three-layer coating structure introduced non-uniform emission signals, which compromised the accuracy of DIC matching. As shown in Figure 4, the different intensity levels in PSP and TSP images were mainly caused by non-uniform thickness of the isolation and PSP layers, especially in curved and edge regions. Near the blade edges, the PSP layer became thinner, so the PSP signal weakened while the TSP signal from the bottom layer became stronger. These inconsistent patterns led to large errors in the calculated displacement field and image registration. Alternatively, the PSP and TSP images were aligned using a conventional image registration method based on the rigid-body assumption and could not provide deformation information.

Examples of the pressure results obtained by the intensity-based method are shown in Figure 5. It should be noted that the wind-off images were captured at phase 0° . The wind-on and wind-off images had the same viewing angle at phase 0° , and the pressure field appears reasonable. A low pressure region can be seen near the leading edge at the blade tip, and the pressure increases gradually from the leading edge to the trailing edge. In contrast, the pressure field obtained at phase 30° shows a high-pressure region near the blade root, while low-pressure regions in the mid-span and tip extended across the entire chord. This result deviates significantly from the expected pressure distribution on a rotating blade. The error was mainly caused by the angle-dependent filter transmission and a large viewing angle difference between the wind-on and wind-off images. Blade rotation changes the incident angle between the camera and blade surface, shifting the band-

pass filter transmission bands, which in turn alters the PSP and TSP channel intensities and thereby introduces false pressure variations.

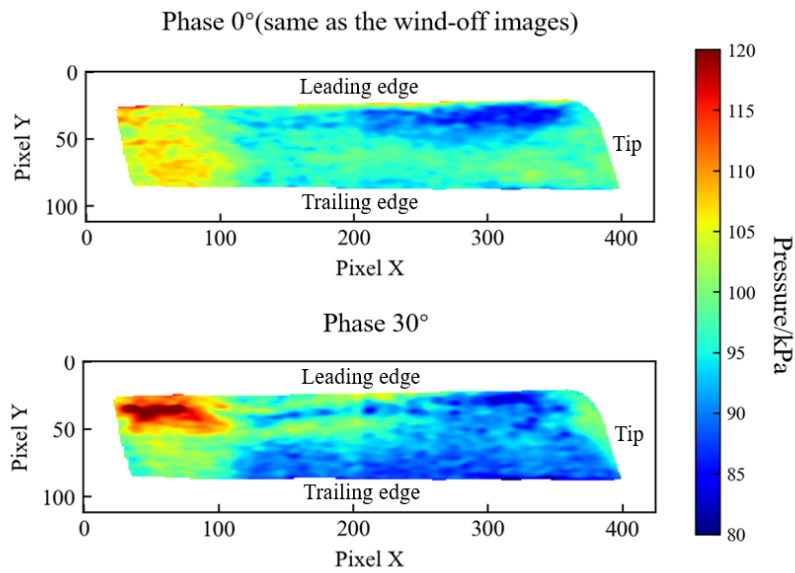


Figure. 5 Variation of Pressure at different phase angles.

To further explain this mechanism, the spectral characteristics of the filters at different incident angles was analyzed. Interference-based band-pass filters exhibit a blue-shift in their transmission band under off-normal incidence, causing spectral leakage between the two channels (Löfdahl et al., 2011). As shown in Figure 6, when the incident angle increased from 0° to 15°, the TSP-channel filter lost nearly 30% of the TSP emission. At the same time, the transmission band of PSP-channel filter shifted toward shorter wavelengths and captured part of the TSP signal. This spectral crosstalk distorted the response from both channels and significantly changed the intensity ratio, introducing a systematic error in pressure measurement. Therefore, the intensity-based method should be applied with the wind-on and wind-off images captured at the same location.

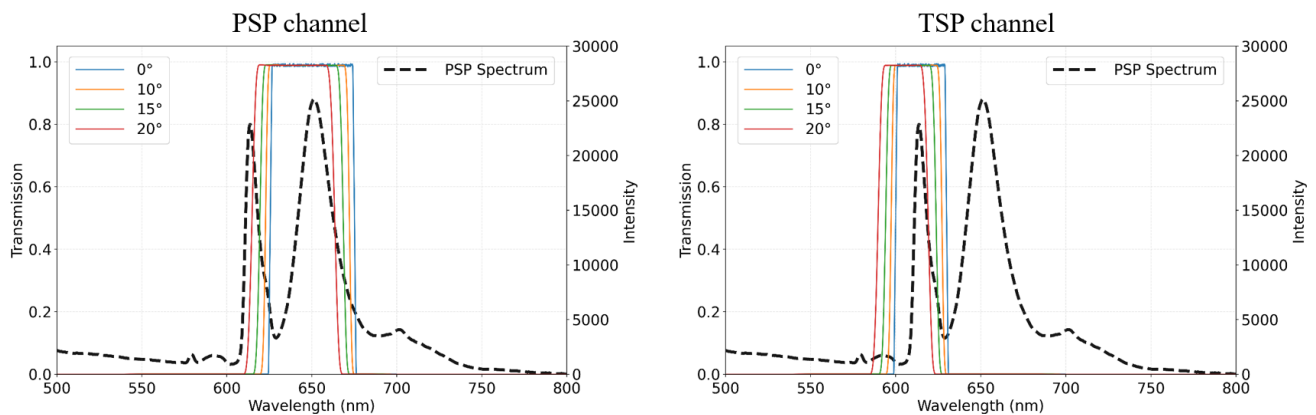


Figure. 6 Emission spectra of the dual-luminophore PSP and angle-dependent transmission shifts of filters.

The above results reveal three major issues of the intensity-based method in high-speed flow measurements. First, the thin MP-PSP top layer can be easily damaged under strong shearing effect, causing significant signal loss. Second, the layered coating structure produces non-uniform PSP and TSP images, causing inconsistent image features and DIC matching errors. Third, the angle-dependent blue-shift of the band-pass filters leads to systematic errors when the wind-on and wind-off images are captured at different locations. These issues must be resolved before the intensity-based method can be applied for high-speed FSI experiments.

3.2 Results of the Lifetime-based Method

The lifetime-based method using the MPC was developed to overcome the limitations of the previous intensity-based method. The coating strength of MPC was significantly improved by using a spatially separated coating structure instead of a multi-layer structure. In the jet impingement test, the MPC showed almost no intensity change, and after four consecutive Mach 5 wind tunnel runs, no obvious damage was observed on the coating. This coating structure also allowed simultaneous measurement of pressure, temperature, and deformation via the single-shot lifetime imaging strategy. In this section, the data processing procedure is first described. Then, the synchronous pressure, temperature, and deformation results of a flexible wing model in a Mach 5 flow are analyzed.

3.2.1 Data Processing

For the lifetime-based method, the following procedure was developed to obtain deformation, temperature, and pressure fields from the two-camera lifetime image sequences:

1. DIC calculation and three-dimensional point cloud reconstruction: DIC was performed using the MPC images from the two camera views. Since both cameras recorded the same PSP and TSP luminescence through the same filter, the image features were consistent in the two views, providing a reliable basis for stereo DIC. As shown in Figure 7, the MPC images produced a smooth displacement field without obvious mismatch. Combined with the stereo camera calibration parameters, the DIC-calculated pixel correspondence was used to reconstruct the three-dimensional point clouds under wind-off and wind-on conditions. The displacement field was then obtained from the difference between the point clouds at wind-on and wind-off conditions.

2. Lifetime image ratio calculation: The lifetime ratio image (I_B/I_A) was calculated from the two-

gate images from the left camera under both wind-off and wind-on conditions. The wind-off and wind-on ratios were then aligned according to the DIC-calculated pixel correspondence, so that the ratio-of-ratios R could be calculated at corresponding surface locations.

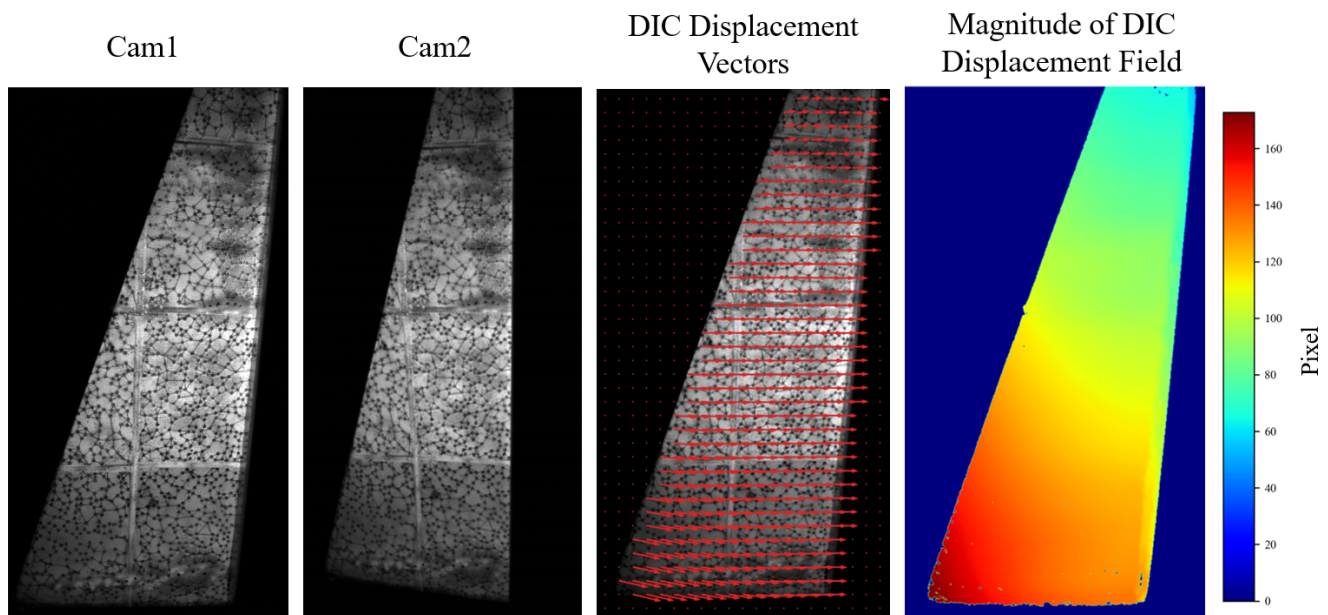


Figure. 7 Original images from the two cameras and DIC-calculated displacement field of the lifetime-based MPC on the flexible wing model.

3. PSP/TSP region segmentation: The PSP and TSP regions were segmented using the lifetime difference between the two luminophores. The TSP signal decayed faster than the PSP signal, so the TSP speckles and PSP regions showed different contrast between Image A and Image B. By calculating the image ratio, the continuous PSP region and discrete TSP speckles could be separated with clear boundaries, as shown in Figure 8. The corresponding binary masks were then used to extract the ratio-of-ratios of PSP and TSP, respectively.

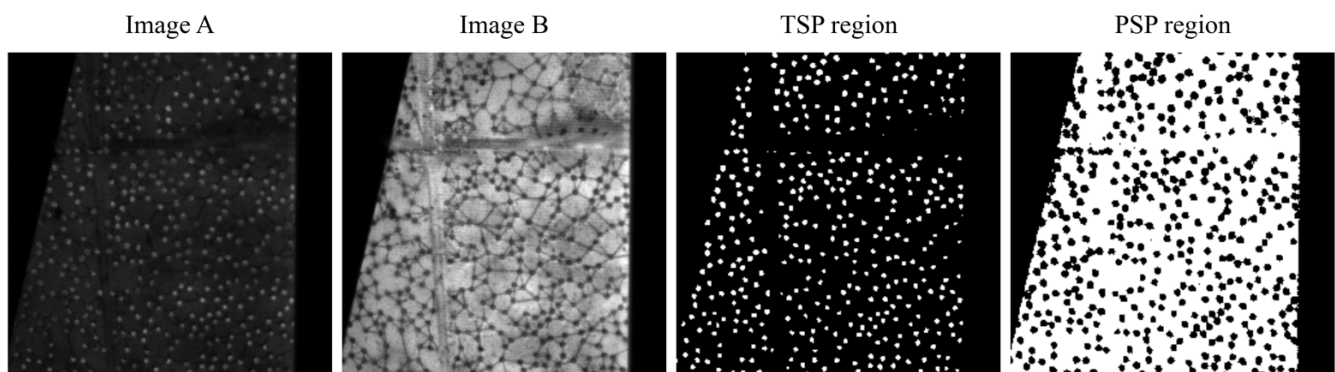


Figure. 8 Two-gate luminescence images and PSP/TSP region segmentation based on the image ratio.

4. AE-based reconstruction of PSP and TSP data: Because of the spatially separated coating structure, the PSP and TSP data were both incomplete in space. To recover complete fields, a dual-input autoencoder (AE) inpainting model was used (Gu, et al., 2024), as shown in Figure 9. The model took the sparse PSP and TSP data as synchronous inputs and reconstructed full ratio-of-ratio fields by learning the spatial correlation between the two signals. A mask-based loss was used during training so that the reconstruction error was calculated only in the valid measured regions.

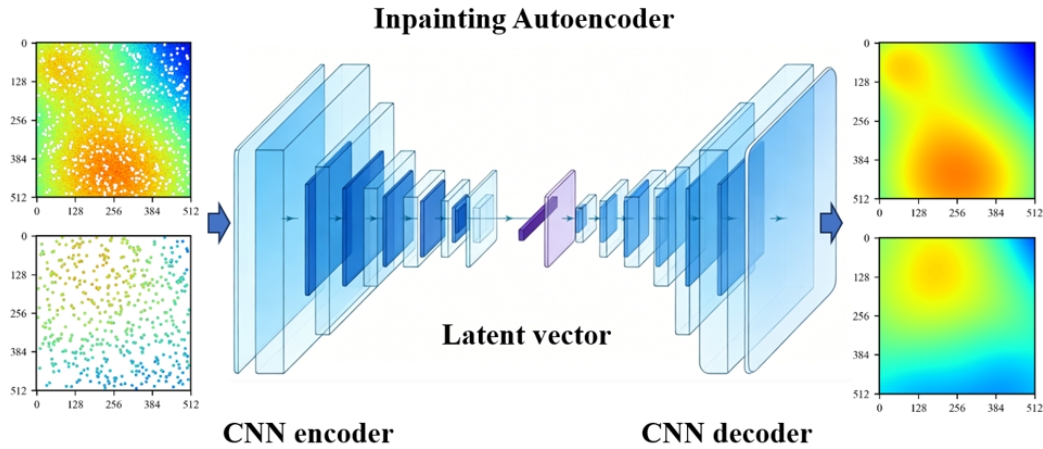


Figure. 9 Schematic of the dual-input deep autoencoder inpainting model.

5. Pressure and temperature fields calculation: After AE reconstruction, the complete TSP ratio-of-ratio field was first converted into the temperature field using the Eq. (2). The reconstructed temperature field was then used to correct the PSP results. The pressure field was calculated from the reconstructed PSP ratio-of-ratio field and reconstructed temperature field using Eq. (3). Finally, the pressure, temperature and deformation fields were obtained.

3.2.2 Multi-Field Measurement Results on a Flexible Wing Model

The lifetime-based method was applied to a flexible wing model in a Mach 5 wind tunnel test. This method obtained synchronous pressure, temperature, and deformation fields at a sampling frequency of 1 kHz. Figure 10 shows the time-resolved results at 0° angle of attack. Under this condition, clear out-of-plane oscillation was observed near the wing trailing edge. At 1.4 s, the trailing-edge region bulged upward, and the pressure and temperature in this area increased due to this deformation. Similar phenomenon is observed near the front rod but with less deformation and pressure/temperature rise. At 1.45 s, the wing was in a transitional state between upward bulging and downward deflection, with the front part remaining upward and the rear part

beginning to move downward. Correspondingly, the pressure and temperature near the trailing edge clearly decreased. At 1.5 s, the wing shows a downward-deflected shape at the trailing edge, and the pressure and temperature in the region increased again due to the flow impingement on the back of the concave surface. These results demonstrate the capability of the lifetime-based method to capture synchronized, time-resolved multi-physical field evolution in high-speed flows.

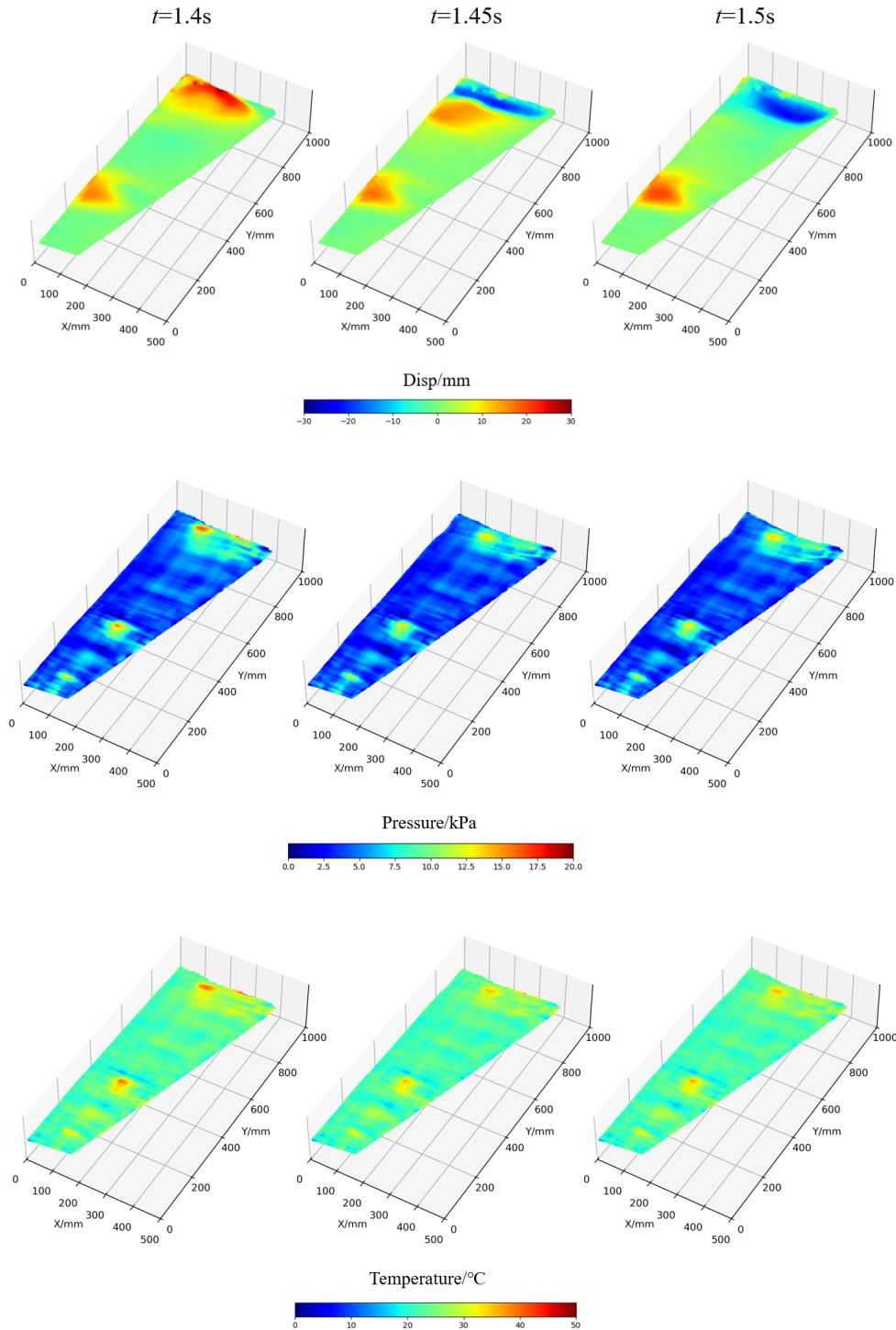


Figure. 10 Time-varying deformation, pressure, and temperature fields at 0° angle of attack.

Figure 11 presents the time-averaged pressure, temperature, and deformation fields as the angle of attack increased from 2.5° to 10° . At 2.5° , high-pressure and high-temperature regions appeared near the front support-rod region and the trailing-edge region, while the deformation occurred mainly near the trailing edge. When the angle of attack increased, the pressure and temperature rise near the front support-rod region and the trailing-edge region became stronger, and the deformation amplitude in these regions increased accordingly. These results show the correlated evolution of pressure, temperature, and deformation fields. As the angle of attack increased, stronger aerodynamic loading induced larger structural deformation, and the high-pressure and high-temperature regions expanded along with the deformed area.

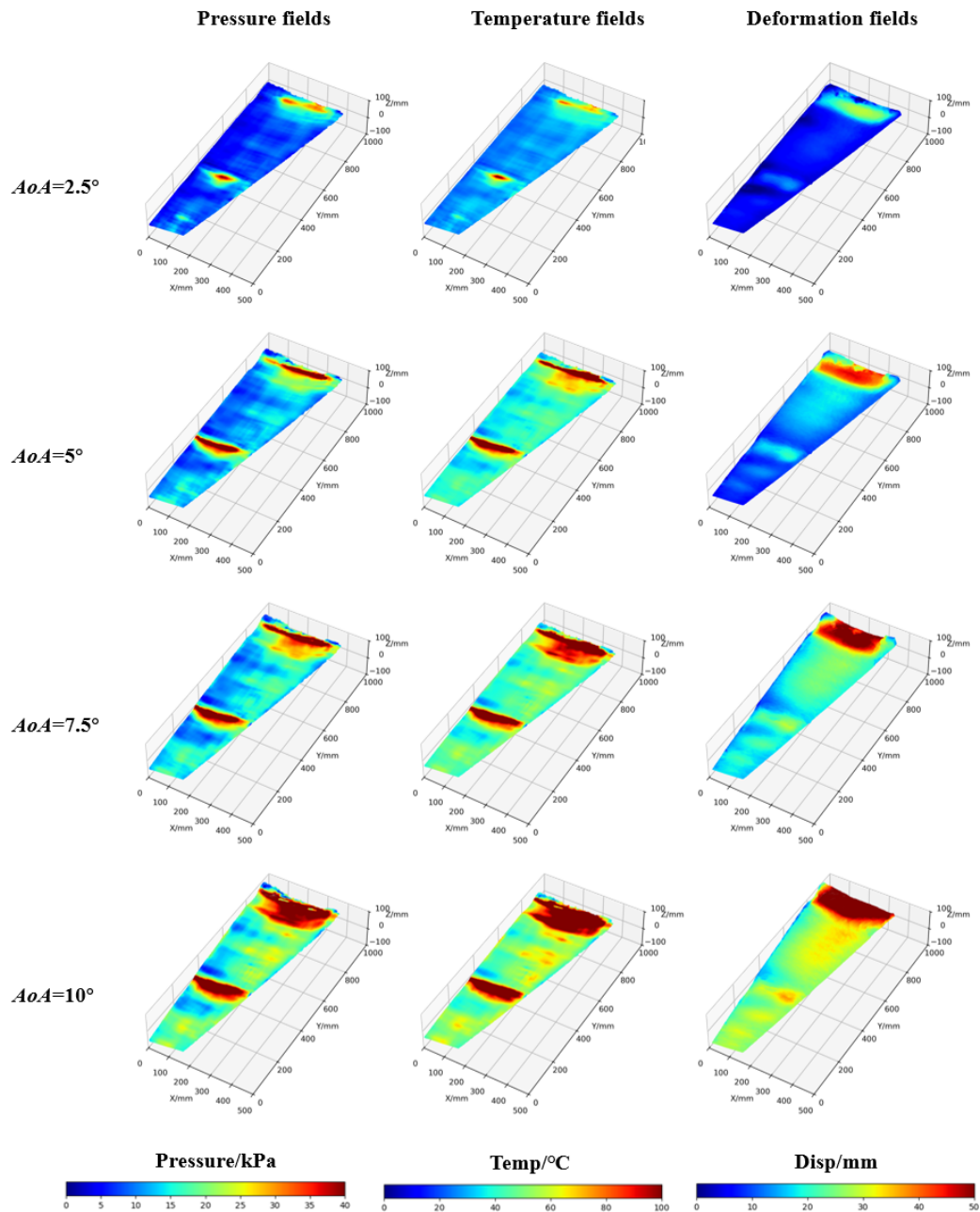


Figure. 11 Average of deformation, pressure, and temperature fields at angles of attack from 2.5° to 10° .

Overall, these results demonstrate that the lifetime-based method is suitable for time-resolved multi-physical field measurements of FSI in high-speed flows.

4. Conclusions

This study developed and evaluated two time-resolved multi-physical field measurement methods for high-speed flows: an intensity-based method using dual-luminophore PSP and a lifetime-based method using MPC. The intensity-based method achieved pressure-deformation joint measurement with temperature compensation on a rotating blade, but showed some limitations. The multilayer coating suffered from insufficient strength under strong shear, and the inconsistent PSP and TSP intensity caused DIC mismatch and registration errors. In addition, the angle-dependent transmission shift of the band-pass filters introduced pressure errors when the wind-off and wind-on images were acquired at different viewing angles. The lifetime-based method overcame these limitations by using spatially separated PSP/TSP regions and single-shot lifetime imaging. The coating showed improved strength, and the image features were consistent for stereo DIC. The full-field pressure and temperature distributions were reconstructed from the separated PSP and TSP data using a dual-input AE. This method was demonstrated on a flexible wing model in a Mach 5 wind tunnel test. Synchronous pressure, temperature, and deformation fields were obtained at 1 kHz sampling frequency. The results captured clear out-of-plane oscillation of the wing at 0° angle of attack. Then, as the angle of attack increased from 2.5° to 10° , the aerodynamic loading became stronger, the structural deformation increased, and the high-pressure and high-temperature regions also expanded. These results demonstrate the capability of the lifetime-based MPC method to capture complex FSI phenomenon in high-speed flows.

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References

Dong, Z., Li, Y., Jiao, L., Zhang, W., Liu, Y., & Peng, D. (2022). Pressure-sensitive paint integrated with digital image correlation for instantaneous measurement on rotating blades. *Aerospace Science and Technology*, 126, 107667. <https://doi.org/10.1016/j.ast.2022.107667>

- Egami, Y., & Asai, K. (2002). Effects of antioxidants on photodegradation of porous pressure-sensitive paint. In 22nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference. <https://doi.org/10.2514/6.2002-2905>
- Egami, Y., Matsuda, Y., Yamaguchi, H., & Niimi, T. (2014). Property changes of temperature-sensitive paint immobilized in acrylic polymer matrices. *Sensors and Actuators B: Chemical*, 195, 677–681. <https://doi.org/10.1016/j.snb.2014.01.091>
- Gu, F., Discetti, S., Liu, Y., Cao, Z., & Peng, D. (2024). Denoising image-based experimental data without clean targets based on deep autoencoders. *Experimental Thermal and Fluid Science*, 156, 111195. <https://doi.org/10.1016/j.expthermflusci.2024.111195>
- Gu, F., Wei, C., Jiao, L., Liu, Y., & Peng, D. (2024). Dual-luminophore fast-responding pressure-sensitive paint for the simultaneous elimination of motion- and temperature-induced errors. *Measurement Science and Technology*, 35(9), 095205. <https://doi.org/10.1088/1361-6501/ad53f0>
- Gu, F., Wei, C., Liu, Y., Peng, D., & Liang, L. (2022). Temperature sensitivity elimination in sprayable fast-responding pressure-sensitive paint. *Sensors and Actuators A: Physical*, 345, 113797. <https://doi.org/10.1016/j.sna.2022.113797>
- Imai, M., Nakakita, K., & Kameda, M. (2022). Random-dot pressure-sensitive paint for time-resolved measurement of deformation and surface pressure of transonic wing flutter. *Experiments in Fluids*, 63(11), 174. <https://doi.org/10.1007/s00348-022-03527-1>
- Kurihara, D., Hayashi, T., & Sakaue, H. (2021). Temperature dependency reduction in pressure-sensitive paint measurement by motion-capturing method. In AIAA Scitech 2021 Forum.
- Liu, T., Sullivan, J. P., Asai, K., Klein, C., & Egami, Y. (2021). Pressure and temperature sensitive paints. Springer Cham. <https://doi.org/10.1007/978-3-030-68056-5>
- Löfdahl, M. G., Henriques, V. M. J., & Kiselman, D. (2011). A tilted interference filter in a converging beam. *Astronomy & Astrophysics*, 533, A82. <https://doi.org/10.1051/0004-6361/201117305>
- McNamara, J. J., & Friedmann, P. P. (2011). Aeroelastic and aerothermoelastic analysis in hypersonic flow: Past, present, and future. *AIAA Journal*, 49(6), 1089–1122. <https://doi.org/10.2514/1.J050882>
- Nguyen, T., Chen, S. W., Shivakumar, S. S., Taylor, C. J., & Kumar, V. (2018). Unsupervised deep homography: A fast and robust homography estimation model. *IEEE Robotics and Automation Letters*, 3(3), 2346–2353. <https://doi.org/10.1109/LRA.2018.2809549>
- Peng, D., Gu, F., Li, Y., & Liu, Y. (2018). A novel sprayable fast-responding pressure-sensitive paint based on mesoporous silicone dioxide particles. *Sensors and Actuators A: Physical*, 279, 390–398. <https://doi.org/10.1016/j.sna.2018.06.048>

- Peng, D., Jensen, C. D., Juliano, T. J., Gregory, J. W., Crafton, J., Palluconi, S., & Liu, T. (2013). Temperature-compensated fast pressure-sensitive paint. *AIAA Journal*, 51(10), 2420–2431. <https://doi.org/10.2514/1.J052318>
- Peng, D., & Liu, Y. (2019). Fast pressure-sensitive paint for understanding complex flows: From regular to harsh environments. *Experiments in Fluids*, 61(1), 8. <https://doi.org/10.1007/s00348-019-2839-6>
- Shi, A., & He, Y. (2026). A survey of panel aeroelasticity in shock-dominated flow: Perspectives from fluid-structure interactions and shock wave-boundary layer interactions. *Chinese Journal of Aeronautics*, 39(1), 103674. <https://doi.org/10.1016/j.cja.2025.103674>
- Spottswood, S. M., Beberniss, T. J., Eason, T. G., Perez, R. A., Donbar, J. M., Ehrhardt, D. A., & Riley, Z. B. (2019). Exploring the response of a thin, flexible panel to shock-turbulent boundary-layer interactions. *Journal of Sound and Vibration*, 443, 74 – 89. <https://doi.org/10.1016/j.jsv.2018.11.035>
- Sutton, M. A., Orteu, J. J., & Schreier, H. W. (2009). *Image correlation for shape, motion and deformation measurements: Basic concepts, theory and applications*. Springer. <https://doi.org/10.1007/978-0-387-78747-3>
- Tiwari, N., Uchida, K., Inoba, R., Saito, Y., Asai, K., & Nonomura, T. (2022). Simultaneous measurement of pressure and temperature on the same surface by sensitive paints using the sensor selection method. *Experiments in Fluids*, 63(11), 175. <https://doi.org/10.1007/s00348-022-03501-x>