# DEVELOPMENT OF UNSTEADY PRESSURE-SENSITIVE PAINT FOR LOW REYNOLDS NUMBER WIND TUNNEL TESTS IN LOW-PRESSURE ENVIRONMENTS

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## Abstract

In this study, we conducted the development of unsteady pressure-sensitive paint (PSP) suitable for airfoil testing in low-pressure environments using an automatic painting system. Additionally, we performed wind tunnel tests on a flat plate wing under low-pressure conditions using the developed PSP, enabling the visualization of flow fields on the wing surface. The developed PSP successfully visualized the transition of aerodynamic phenomena on the wing surface with varying angles of attack at 30 kPa, demonstrating its effectiveness for pressure measurements in low-pressure environments.

**Keywords:** Pressure-Sensitive Paint, Shock Wave, Flow Visualization, Unsteady Flow Measurement

## 1. Introduction

In recent years, Martian aircraft have garnered attention as a novel method for Mars exploration. Various plans have been proposed, such as the “Airplane for Mars Exploration” (AME) (1) by NASA Ames Research Center in the 1990s and the “Aerial Regional-scale Environmental Survey” (ARES) (2) by NASA Langley Research Center in the 2000s. Among these, on April 19, 2021, the Martian helicopter Ingenuity, equipped with contra-rotating coaxial rotors, achieved the first powered flight on an extraterrestrial planet, proving the feasibility of utilizing aerodynamic effects for Martian exploration. Like aircraft on Earth, Martian aircraft use lift to fly through the Martian atmosphere. This allows them to traverse the Martian surface without being affected by the terrain, unlike traditional rover exploration methods, and cover wide areas. Moreover, Martian aircraft can observe the Martian surface from altitudes closer than satellite probes, enabling the acquisition of high-resolution observation data. The realization of Martian aircraft holds the potential for various unprecedented missions and is expected to see continued active development.

However, realizing Martian aircraft poses numerous technical challenges, one of which is how to generate sufficient lift to keep the aircraft aloft. The Martian atmosphere is extremely thin, with surface pressure approximately 1/100 th of that on Earth. Consequently, the lift generated by Martian aircraft is significantly lower than that on Earth. For the same reason, the Martian flight environment results in relatively low Reynolds numbers compared to Earth. Therefore, developing wings that can generate high lift under low Reynolds number conditions is essential for the realization of Martian aircraft. Research on airfoils suitable for Martian aircraft has been conducted in the past (3-5), and continued research is necessary for further development.

Pressure-sensitive paint (PSP) measurement techniques are effective for conducting aerodynamic studies on airfoils (6). PSP is a type of functional molecular sensor that uses pressure-sensitive dyes exhibiting oxygen quenching properties to measure surface pressure. During measurement, PSP is applied to the target surface and excited with excitation light. The luminescence of the excited PSP changes depending on the surrounding pressure, and by detecting this luminescence intensity with optical detectors such as cameras, surface pressure measurements are possible. This method allows for the acquisition of the entire pressure field on the PSP-coated surface in a single measurement, providing a spatially comprehensive pressure field compared to traditional point measurements with mechanical pressure sensors. Additionally, using unsteady PSP with excellent time responsiveness enables time-series measurements, allowing for both spatial and temporal acquisition of pressure fields on airfoil surfaces.

When conducting aerodynamic tests on wings for Martian aircraft, low Reynolds number conditions are essential. A wind tunnel test method using a shock tube is available to achieve aerodynamic tests under low Reynolds number conditions (7). This method realizes wind tunnel tests by applying the airflow behind shock waves generated in a shock tube to the model, capable of producing various airflow conditions corresponding to the Mach number of the shock waves. However, since aerodynamic tests in shock tubes are generally conducted under low-pressure conditions, developing PSP with sufficient performance for low-pressure environments is necessary when conducting PSP measurements in such environments. For example, a notable low-pressure PSP is the pressure-sensitive paint developed by Anyoji et al. for low-density wind tunnel tests (8). By combining the pressure-sensitive dye PdTFPP, which exhibits significant luminescence intensity changes in response to pressure changes in low-pressure environments, with a binder with excellent oxygen permeability, they enabled the application of PSP in steady-state wing tests in low-density wind tunnels. This study aims to advance these research efforts by developing unsteady PSP for conducting unsteady wing tests under low Reynolds number conditions using shock tube wind tunnel tests and establishing a PSP measurement system.

Based on the above, this study reports on the development of unsteady PSP that can be used in low-pressure environments to capture unsteady aerodynamic phenomena on wing surfaces, aiming to elucidate the unsteady aerodynamic characteristics of wings under low Reynolds number conditions for realizing high-performance Martian aircraft. Additionally, as a validation test, we conducted wind tunnel tests using a shock tube under low-pressure conditions on a flat plate wing and report the results of the validation tests of the developed PSP.

## 2. Principle

### 2.1 Pressure-Sensitive Paint, PSP

PSP is a type of functional molecular sensor that utilizes pressure-sensitive dyes exhibiting oxygen quenching properties. The luminescence of the excited PSP changes in intensity depending on the surrounding pressure of the coated surface, allowing the detection of pressure on the PSP-coated surface by measuring the emitted light. Typical PSP consists of dyes and binders, and various characteristics of PSP can be created by appropriately combining these components. Additionally, since PSP uses optical measurement techniques, it has the advantage of enabling non-contact and surface pressure measurements.

## 3. Experimental Equipment

### 3.1 Automatic Painting System

Fig. 1 shows the automatic painting system used in this study. This system is capable of moving any spray gun along a pre-programmed trajectory. During coating, it allows for the arbitrary setting of important coating parameters such as coating distance and the number of coating passes, as well as various spray gun-related parameters, including spray gun aperture and air pressure. Consequently, it enables the creation of samples under identical coating conditions with high reproducibility and allows for the investigation of the effects of specific coating parameters on PSP with high accuracy and reproducibility. Additionally, by using this system, various issues associated with manual coating, such as coating skill and habits of the painter, which can lead to variations in the properties of the PSP, can be mitigated.

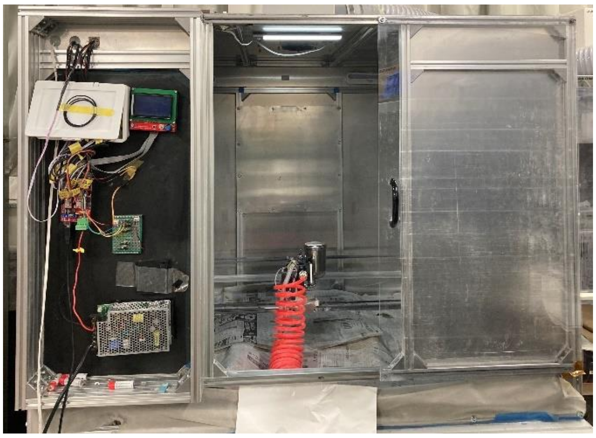

Fig.1 Automatic Painting System.

## 3.2 Automatic Calibration System

Fig. 2 shows a schematic diagram of the automatic calibration system used in this study. This system consists of a pressure chamber capable of controlling pressure and temperature, an excitation optical system, and a luminescence detection optical system. During testing, the sample is placed inside the chamber, and the pressure and temperature around the sample can be set to arbitrary values, allowing for the acquisition of fluorescence/phosphorescence and emission spectra from the excited sample under those environmental conditions.

Various imaging cameras and spectrofluorometers can be used for the luminescence detection system, and various LEDs and xenon light sources can be used as excitation light sources. The temperature of the sample inside the chamber is controlled by a Peltier controller (TDU-5000AR, Cellsystem Co., Ltd), and the pressure is controlled by a pressure controller (CPC4000, WIKA). Additionally, a mechanical shutter is installed in front of the excitation light source, allowing for the arbitrary adjustment of the shutter's opening and closing timing and duration during calibration tests. This enables the sample to be illuminated only during testing without turning off the excitation light source itself.

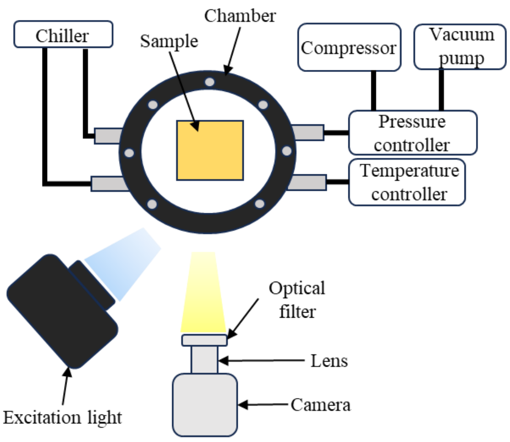


Fig.2 Schematic Illustration of Calibration System.

## 3.3 Shock Tube

Fig. 3 illustrates the conceptual diagram of the 60 [mm] × 150 [mm] cross-sectional diaphragm-less shock tube at Tokai University, used in this study. This shock tube utilizes a rubber membrane in the diaphragm section. By pressurizing the auxiliary high-pressure chamber, the rubber membrane protrudes downstream, physically separating the low-pressure chamber from the high-pressure chamber. After adjusting the pressures in the low-pressure and high-pressure chambers to the desired levels, the auxiliary high-pressure chamber is rapidly depressurized, causing the rubber diaphragm to swiftly move upstream, instantaneously merging the high-pressure chamber with the low-pressure chamber and creating a shock wave in the low-pressure section.

This system allows for the characterization of the time response characteristics of PSP. During time response testing, when the shock wave impacts the test sample, causing a step change in pressure, the change in luminescence intensity from the test sample is measured and converted to pressure. This is then compared with the pressure measurements obtained from a pressure sensor to evaluate the time response characteristics of the test sample. Additionally, this device can also function as a wind tunnel. By installing a test model in the test section and passing a shock wave through it, low-density wind tunnel tests using the flow behind the shock wave can be conducted.

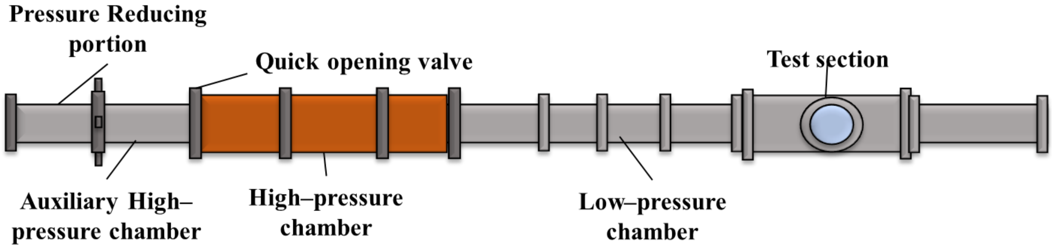


Fig.3 Schematic Diagram of 60 mm x 150 mm Cross-sectional Diaphragm-less Shock-tube at Tokai University.

## 4. Experimental methods and Experimental Conditions

### 4.1 Sample Test

#### 4.1.1 PC-PSP Sample Fabrication

In this study, the developed PC-PSP used Poly(IBM) (Poly(iso-butyl methacrylate)) (CAS No. 9011-15-8, Fujifilm Wako Pure Chemical Corporation) as the polymer and titanium oxide particles with a particle diameter of 500 nm (CAS No. 1317-80-2, Fujifilm Wako Pure Chemical Corporation) as the ceramic particles. After measuring these components, they were mixed with the non-aqueous dispersant (SN Spurse 2190, San Nopco) in the solvent toluene (CAS No. 108-88-3, Fujifilm Wako Pure Chemical Corporation) to create the binder solution. The content ratio of polymer, titanium oxide, and solvent was 4.950 g : 9.410 g : 30 ml.

For the dye solution applied to the coated binder, the pressure-sensitive dye PtTFPP (PT(II) Meso-tetra(pentafluorophenyl)porphine) (CAS No. 109781-47-7, Frontier Scientific) dissolved in toluene was used. The formulation ratio of the dye solution was 0.4 mg of PtTFPP to 10 ml of toluene.

To prepare the PC-PSP samples, A1050 aluminum plates cut into 20 mm squares were used as the substrate. These plates were cleaned with propanol to remove oil and other contaminants. Next, the binder solution was applied to the aluminum plates using the automatic painting system described in section 3.1. The samples were then dried in a desiccator for one day. After drying, the dye solution was applied as a top coat using the same automatic painting system to complete the PC-PSP.

#### 4.1.2 Evaluation Test of Sample Luminescence Intensity According to the Number of Coats

In this study, to create a painted PC-PSP, the optimal number of dye coatings was evaluated by applying the dye solution to samples with the binder already applied, using various numbers of coatings, and investigating the effect of the number of dye coatings on the luminescence intensity of the PC-PSP. During the tests, the number of dye coatings was varied from 3 to 102, in increments of 3, and the changes in luminescence intensity of these samples were examined. The luminescence intensity was measured under atmospheric pressure conditions.

For the evaluation of luminescence intensity, the sample specimens were placed in the chamber of the automatic calibration system described in section 3.2, and the excitation light and imaging camera were positioned so that their relative positions did not change for all evaluation samples. A UV-LED (IL-106, HARDsorf Microprocessor Systems) was used as the excitation light source for the samples. A 12-bit CCD camera (ORCA-ER C4742-80-12AG, Hamamatsu Photonics K. K.) was used as the imaging device, with a fixed focal length lens (Nikkor 50 mm f1.2, Nikon Imaging Japan) with a focal length of 50 mm attached to the front of the CCD camera. To capture only the luminescence from the PSP samples, a bandpass filter (Filter BP 650 × 50 nm OD4, Edmund Optics) that transmits only the pre-investigated luminescence spectrum of the PC-PSP was incorporated into the detection optical system.

### 4.1.3 Static Calibration Tests

In this study, to investigate the pressure dependence (pressure sensitivity) of the luminescence from the created PSP samples, the pressure in the chamber was varied in 15 increments from 10 [kPa] to 150 [kPa] in 10 [kPa] steps while keeping the temperature fixed at 20 [deg.C]. The luminescence intensity was measured under each condition. Additionally, to obtain the luminescence intensity changes (temperature sensitivity) due to temperature variations, the sample temperature was varied in 5 steps from 10 [deg.C] to 30 [deg.C] at an interval of 5 [deg.C] under a constant pressure of 100 [kPa]. The excitation light source and camera used during the static calibration tests were the same as those described in section 4.1.2.

To evaluate the effect of the number of dye coatings on the characteristics of the created PSP, calibration tests were conducted on samples made with the automatic painting system. The dye solution was applied 21, 30, 42, 54, 60, 72, 81, 90, and 102 times, approximately every 10 coatings, for the tests.

### 4.1.4 Dynamic Response Tests

Fig. 4 shows a schematic diagram of the setup for the frequency response test. In this study, a diaphragm-less shock tube described in section 3.3 was used to provide the step pressure input for the frequency response test. The test sample was mounted on the end wall of the shock tube. During the response test, the sample was excited by illuminating it with excitation light through a visualization window from outside the test section. The time history of the luminescence intensity, which changes sharply with the step increase in pressure due to the shock wave impact on the sample, was detected using a photodetector. The detected luminescence was converted to pressure values and compared with the actual pressure change to calculate the 90 % rise time. The frequency response characteristics were then determined from the inverse of the 90 % rise time.

The excitation light source was the same UV-LED (IL-106, HARDsorf Microprocessor Systems) used in the calibration tests. The luminescence detector was a photomultiplier tube (PMT) (H10721-20, Hamamatsu Photonics K. K.) equipped with a bandpass filter (Filter BP 650 × 50 nm OD4, Edmund Optics). The luminescence intensity history was recorded using a digital oscilloscope (DL716 , Yokogawa Test & Measurement Corporation) with a sampling rate of 5 [MS/s].

For the shock wave used in the response test, a shock wave with a Mach number of approximately 1.5 was generated under the conditions of an initial test section pressure of 30 [kPa] and a high-pressure chamber pressure of 240 [kPa].

The time response tests were conducted for all samples that underwent static calibration tests in section 4.1.3.

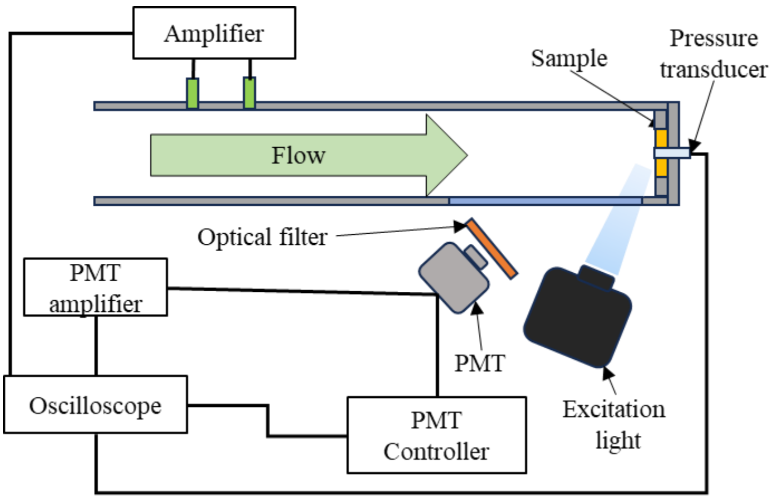


Fig.4 Schematic Illustration of Frequency Response Test Setup.

## 4.2 Wing Test

### 4.2.1 Wing Models

In this study, a flat plate wing with a chord length of 40 mm, a span length of 60 mm, and a thickness of 2 mm was used. The wing model was fabricated using a 3D printer (Form 3+, Formlabs), and the material used was Engineering Resin Tough 2000. The wing model was secured to the rotating flange installed in the test section of the shock tube using protrusions molded on both sides.

### 4.2.2 Optical Setup

For the excitation of PSP, a UV-LED (IL-106, HARDsorf Microprocessor Systems) was used. The imaging device used was a 12 bit CMOS camera (FASTCAM Nova S16、Photron), with close-up rings (PK-11, Nikon Imaging Japan) and an optical lens (Nikkor 35 mm f1.2, Nikon Imaging Japan) attached via an FC mount. To capture only the emission from the PSP, the detection optical system was equipped with a band-pass filter (Filter BP 650 × 50 nm OD4, Edmund Optics) that only transmits the emission spectrum of the PC-PSP identified in preliminary investigations. The frame rate for the imaging during the wing tests was set at 30,000 fps, with an exposure time of 33 [μs].

### 4.2.3 Test Condition

In this study, the angle of attack of the flat plate wing model relative to the test airflow was varied under six conditions: 0º, 3º, 5º, 7º, 9º, and 12º. The test conditions were set with a test section pressure of 30 kPa and a high-pressure chamber pressure of 155 [kPa]. The shock wave generated under these conditions had a Mach number of approximately $Ms$ = 1.33. The airflow velocity behind the shock wave was about $Ms$ = 0.77, and the estimated Reynolds number based on the wing chord was approximately $Re$ = 305,000.

# 5. Results and discussion

## 5.1 Sample Test

### 5.1.1 Relationship Between the Luminescence Intensity of Painted PC-PSP and the Number of Dye Coatings

First, to optimize the luminescence intensity of PC-PSP, the relationship between the number of dye solution coatings and the luminescence intensity of the PSP samples for each coating count is shown in Fig. 5. The vertical axis represents the detected count number [count] using the optical system evaluated in this study, and the horizontal axis represents the number of dye solution coatings.

As seen in the graph, the luminescence intensity of the samples increases with the number of coatings. Significant changes in luminescence intensity were observed for coating counts above 102, but there was also considerable variability in the brightness values, indicating instability in the luminescence behavior. The luminescence intensity did not increase monotonously but fluctuated, suggesting that when applying PSP to a model within this coating range, the brightness values on the model might vary significantly. Therefore, based on Fig. 5, the relatively smooth region with less variability in the luminescence intensity for coating counts within 102 was considered the optimal dye coating count for creating PC-PSP, and calibration tests were conducted within this range.

Generally, in PSP measurements, higher luminescence intensity is preferable for pressure measurements, enabling more accurate measurements. However, when applying PSP, slight deviations from the ideal coating conditions may occur due to model shapes and coating conditions. Considering these facts and possibilities, it is reasonable to define the optimal coating count as one where the luminescence intensity of the PSP does not significantly change with variations in the number of dye solution coatings and does not enter the quenching condition due to excessive dye. Therefore, including the results of the characteristic evaluation tests in 6.1.2 and subsequent sections, the determination of the optimal coating count will be made.

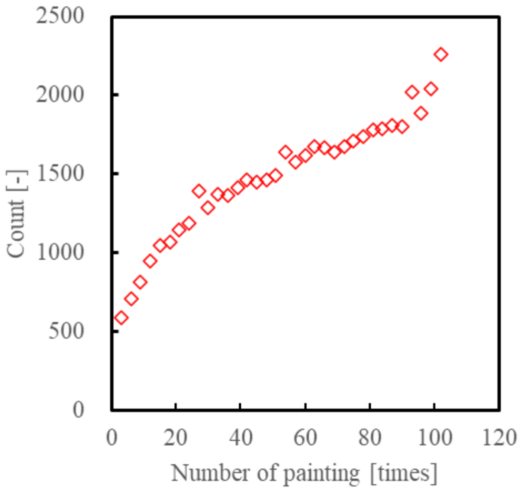


Fig.5 The effect of the number of coatings of the pressure-sensitive dye solution on the luminescence intensity of the PSP samples.

### 5.1.2 Impact of Coating Count on the Pressure Sensitivity of Painted PC-PSP

Fig. 6 shows the impact of the number of dye solution coatings on the pressure sensitivity of painted PC-PSP at 20°C and 100 kPa. The vertical axis represents the pressure sensitivity [%/kPa], and the horizontal axis represents the number of dye solution coatings.
From the figure, it is evident that with the minimum coating count of 12, the pressure sensitivity reached its lowest value of 0.73 [%/kPa]. As the number of coatings increased, the pressure sensitivity also increased, but beyond 90 coatings, there was little further increase, with a maximum value around 0.75 [%/kPa]. For coating counts of approximately 80 and above, the pressure sensitivity, despite some variability, remained relatively constant.

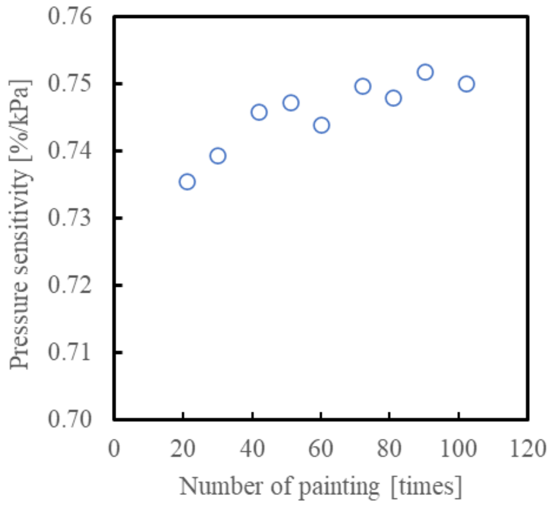


Fig.6 The effect of the number of coatings of the pressure-sensitive dye solution on the pressure sensitivity of the PSP samples.

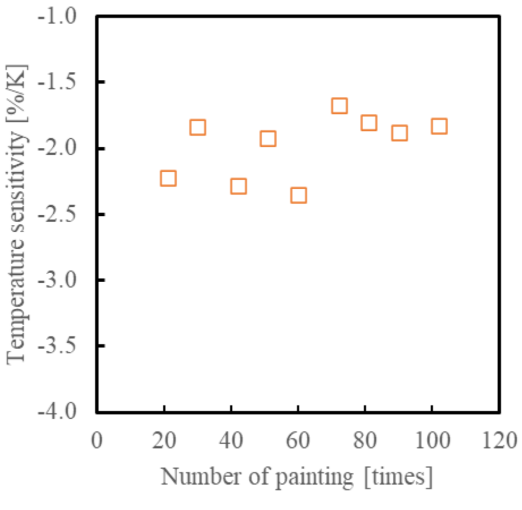


Fig.7 The effect of the number of coatings of the pressure-sensitive dye solution on the temperature sensitivity of the PSP samples.

### 5.1.3 Impact of Coating Count on the Frequency Response Characteristics of Painted PC-PSP

Fig. 8 illustrates the effect of the number of dye solution coatings on the time response characteristics of painted PC-PSP under a pressure of 3.5 kPa. The vertical axis represents the frequency response [kHz], calculated from the 90 % rise time, while the horizontal axis shows the number of dye solution coatings.
The figure reveals that the frequency response characteristics vary with the number of dye solution coatings. The response does not increase or decrease monotonically but appears to oscillate with changes in the number of dye coatings. This oscillatory behavior in response characteristics with

respect to dye coating count was observed consistently across repeated tests, indicating a periodic fluctuation in time response characteristics influenced by the number of coatings. This fluctuation is likely due to the partial dissolution of titanium oxide and Poly(IBM) by the dye solution during the coating process, leading to changes in the binder's coating structure. However, the precise details require further investigation.

The maximum frequency response for the painted PC-PSP samples developed in this study was approximately 12 kHz with 102 coatings, while the lowest frequency response was 8.5 kHz. Therefore, for the PSP samples coated using the automatic painting system in this study, the frequency response in a 3.5 kPa environment generally ranged from approximately 8.5 kHz to 12 kHz for coating counts below 100.

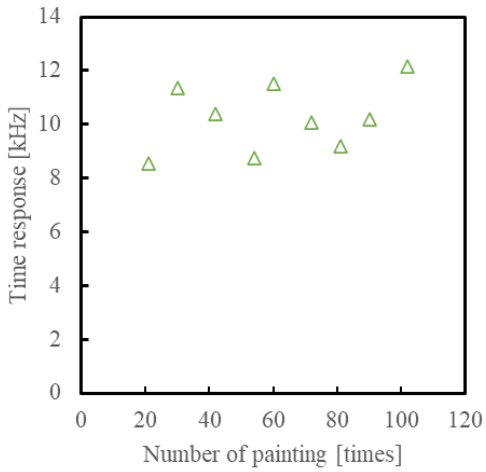


Fig.8 The effect of the number of coatings of the pressure-sensitive dye solution on the frequency response of the PSP samples.

### 5.1.4 Conclusion

Regarding the optimal coating conditions for PC-PSP prepared using an automatic painting system, the ideal conditions are those where the change in luminescence intensity with the number of coatings is gradual, and both pressure sensitivity and frequency response are high. From the results obtained, it is reasonable to consider that the optimal coating conditions correspond to a relatively high number of dye solution coatings.

However, as observed in Fig. 8, the time response characteristics exhibit periodic fluctuations with increasing dye solution coatings, and these results are reproducible. Therefore, to determine the optimal dye coating number, including time response characteristics, it is necessary to evaluate the impact of dye solution coating counts on the binder film structure and subsequently clarify their influence on time response characteristics. Currently, this aspect remains unresolved.

In this study, we decided to set the optimal dye solution coating count at 30 as a provisional optimal condition, based on the condition exhibiting the best time response characteristics before the oscillatory behavior of time response characteristics sets in.

Regarding the development of PSP, we will further investigate the aforementioned uncertainties. Moving forward, we plan to parametrically vary factors such as dye solution concentration and titanium oxide coating conditions to achieve PSP with superior temperature sensitivity, pressure sensitivity, and frequency response characteristics. As part of this process, updates to the optimal coating count will also be made.

## 5.2 Visualization of Angle of Attack Dependence on Pressure Distribution Over a Flat Plate Wing Surface

Figure 9 shows the angle of attack dependence on the pressure distribution over a flat plate wing. The figure displays the pressure field on the upper surface of the flat plate wing, trimmed around the central area and arranged for each angle of attack. In the figure, the leading edge (LE) is at the bottom, the trailing edge (TE) is at the top, and the color bar represents the pressure coefficient, Cp. The angles of attack increase from left to right. Figure 10 shows the Cp profiles along the chord length from the leading edge to the trailing edge on the upper surface of each wing derived from

Figure 9. The vertical axis represents the pressure coefficient, and the horizontal axis represents the normalized distance from the leading edge along the chord length.
From these figures, it is evident that for all conditions except for 12°, the leading edge of the wing shows a suction peak, followed by a sharp pressure recovery. The magnitude of the negative pressure increases with the angle of attack, continuing up to 9°. Additionally, based on the definition of the transition point and reattachment point from the pressure distribution proposed by Gerakopulos et al. [10], it is observed that both points move towards the trailing edge with an increasing angle of attack. However, beyond an angle of attack of 5°, their positions remain nearly stationary. At an angle of attack of 12°, an increase in negative pressure is observed near the leading edge, followed by a rapid pressure recovery, indicating a flow field not seen at other angles of attack.
These results clarify that using the developed PC-PSP, aerodynamic phenomena on the wing surface under low-pressure conditions can be clearly visualized.

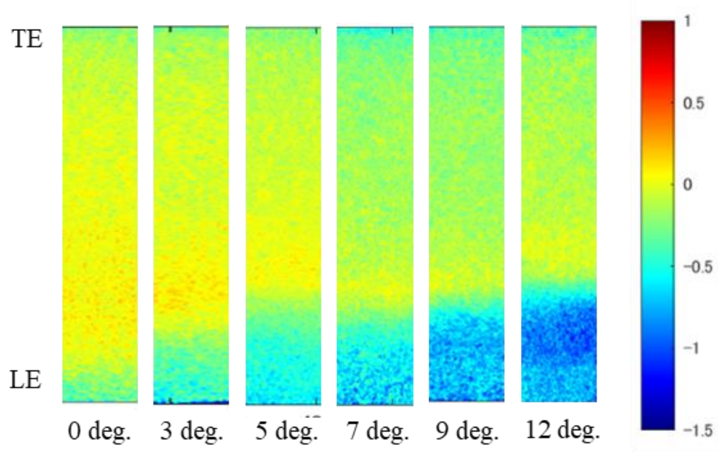


Fig. 9 The transition of the pressure distribution on a flat plate at an angle of attack change in $\boldsymbol{Ms}$ = 0.77 airflow using PSP ($\boldsymbol{Re}$ = 305,000)

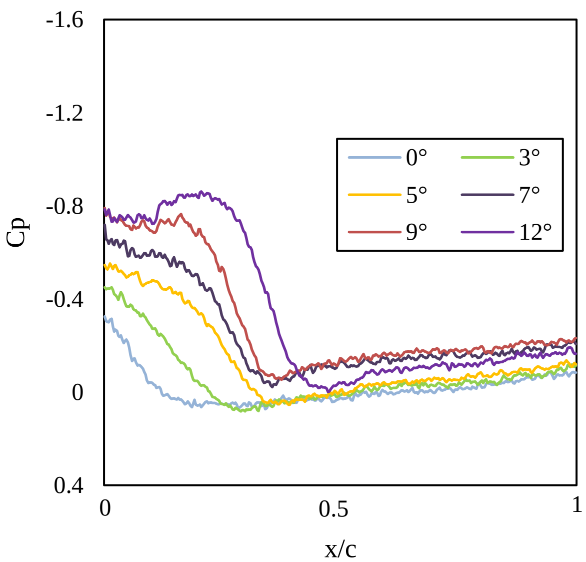


Fig. 10 The transition of the Cp profile on a flat plate in $\boldsymbol{Ms}$ = 0.77 airflow during angle of attack changes ($\boldsymbol{Re}$ = 305,000)

## 6. Conclusion

In this study, we aimed to develop a PSP for low Reynolds number wind tunnel tests using a shock tube under low-pressure conditions. The development of PC-PSP was conducted using an automatic painting system. The produced PSP exhibited time responses on the order of kHz in a 3.6 kPa environment and demonstrated sufficient pressure sensitivity. Using this PSP, we successfully visualized aerodynamic phenomena on the wing surface in a 30 kPa environment.

Moving forward, we will continue researching the characteristics of the developed PSP to achieve even higher performance and plan to conduct aerodynamic tests on various airfoil shapes under low Reynolds number conditions.

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