	よりた　だいすけ
氏　　　　　名	依　田　大　輔
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指導教員	東北大学教授　浅井　圭介
論文審査委員	主査　東北大学教授　浅井　圭介　東北大学教授　升谷　五郎 東北大学教授　大林　茂　東北大学准教授　永井　大樹

論文内容要旨

Quantitative measurements of surface pressure in wind tunnel testing play an important role for understanding the aerodynamic performances of vehicles such as airplanes and automobiles. Traditionally, surface pressure is measured by utilizing a system that consists of pressure taps and pressure transducers. Such systems are widely used in wind tunnels and their measurement accuracies are well validated, but they have several drawbacks such as low spatial resolution and inability of being used in thin edges and sharp corners of a model that are often the areas of most interest in fluid dynamics. Therefore, development of a new measurement system that can remove these drawbacks has been desired over the years.

Pressure-sensitive paint (PSP) is a surface pressure measurement technique, which eliminates the constraints of the conventional system. This technique is an optical measurement method utilizing the luminescence of luminophore which changes according to photochemical reaction with oxygen molecules. The great advantage of PSP measurement is that a quantitative pressure distribution over a model surface can be obtained with high spatial resolution. Therefore, PSP has been used for aerospace engineering applications to measure the pressure distribution over a model in high-speed wind tunnel testing since 1980s. The pressure accuracy of PSP measurement in high-speed flow (high-subsonic, transonic and supersonic flows) has been well validated by many studies at institutes, universities and industries all over the world. However, studies on PSP application to low-speed flow are very limited. This is because PSP is an absolute pressure measurement technique and considered not to work effectively in low-speed flow where pressure change around the model is relatively small.

The application of PSP measurement to unsteady low-speed flow has been desired in many industrial areas, although it is quite difficult now. The measurement accuracy of the current PSP is comparable to the pressure vitiation in unsteady low-speed flow, so that it is required to improve the measurement accuracy and to minimize various measurement errors due to optical noise, model displacement, photodegradation of luminophore, temperature variation of model substrate and so on. In this dissertation, to realize the PSP measurement with the pressure accuracy required for low-speed wind tunnel testing, studies were carried out theoretically and experimentally to evaluate the following subjects; (1) To clarify the effect of the dominant error sources in PSP measurement, (2) To establish a new image acquisition and data processing method for unsteady PSP measurement to reduce the errors due to the dominant factors. (3) To expanse application capability of PSP technique to practical unsteady flow fields in low-speed flow

First, pressure errors in low-speed PSP application were estimated based on the current steady PSP technique. By applying the uncertainty analysis, the effects of dominant error sources were evaluated and improved PSP techniques are proposed. This proposed technique claims that the Stern-Volmer coefficients A and B should be determined to meet the relation of "$A + B = 1$" when a-priori method applies to low-speed PSP measurement. Using this technique, the pressure error caused by the uncertainty of the Stern-Volmer coefficients could be reduced drastically. In addition, the model temperature change between the wind-on and wind-off should be minimized even the effective temperature correction is applied. In a practical procedure, the decline of the number of image acquisition is effective to reduce the pressure error even the SNR is slightly decreased. The proposed PSP techniques were applied to a 1/10 scaled Ahmed model in the wind-tunnel testing. As a result, the effectiveness of the proposed PSP techniques was demonstrated and the pressure error of $\Delta C_{p,rms} = 0.05$ is achieved, as shown in Figs. 1 and 2

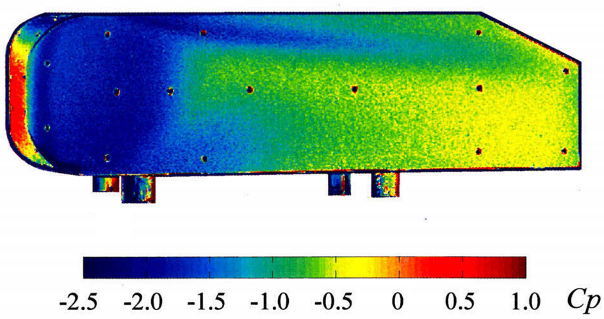


Fig. 1 Pressure map on the leeward side of the model

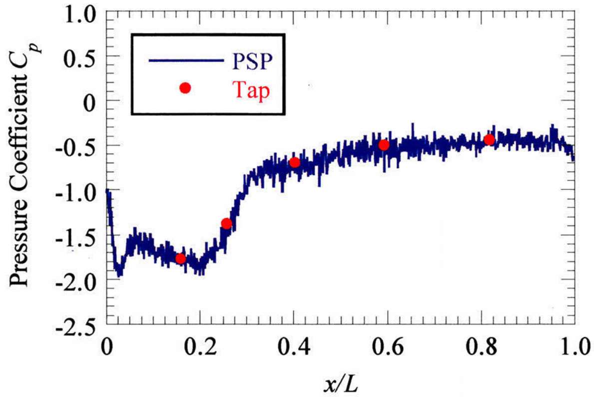


Fig. 2 Pressure profile along the center line of the model

Next, the quantitative unsteady PSP technique for low-speed phenomena was developed. First, the applicability of the optimal steady PSP technique to unsteady phenomena was discussed through the uncertainty analysis. The effect of characteristics of PSP and SNR of PSP image by various cameras were mainly focused here. On the basis of the above uncertainty analysis, the optimal unsteady PSP techniques were proposed. For enhancement of the SNR of PSP images, image phase-averaging techniques for CCD or CMOS camera were introduced. The High-speed Camera method (HCM) calculates high-SNR phase-averaged pressure images from a time-series high-speed CMOS camera images. In contrast, the Phase-lock method (PLM) can be obtained high-SNR images by summing up small PSP luminescence on a CCD sensor. The effects of model temperature change, photodegradation and model displacement can be canceled or reduced by using a time-averaged wind-on image as a reference. However, the obtained pressure is only dynamic components in pressure variation. The absolute pressure can be reconstructed can be resolved by the combination analysis of steady and unsteady PSP data. These proposed unsteady PSP techniques were applied to the unsteady pressure fields around an oscillating fence actuator. The accuracies of these results were much higher than that of the previous studies. HCM can obtain highly-accurate pressure data with simply experimental setup and data processing. In contrast, PLM can obtain high phase-resolution PSP images even at higher frequencies of the fence. In addition, the effect of the reference image selection was verified in this experiment. Finally, the high-accurate absolute pressure distribution could be obtained from the combined analysis of steady and unsteady PSP data as shown in Fig. 3. The accuracy of this technique reached $\Delta C_p = 0.01$ in maximum (Fig. 4).

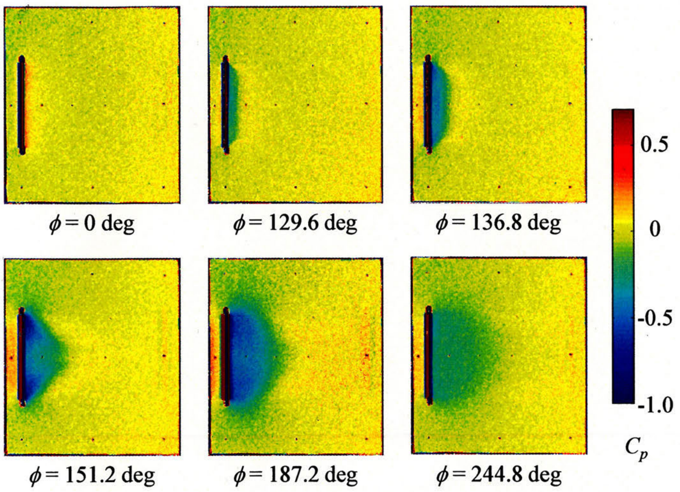


Fig. 3 Unsteady pressure maps behind the fence

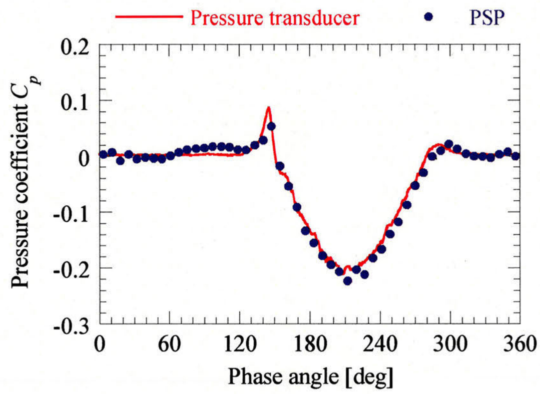
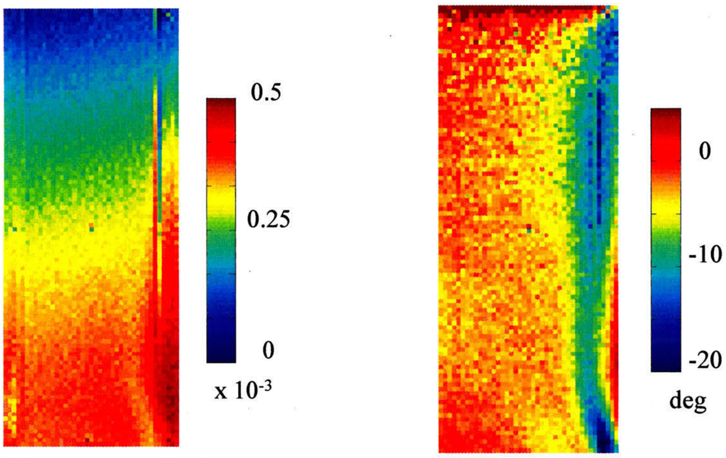


Fig. 4 Comparison of PSP data and the pressure tap data

The application of unsteady PSP techniques can be expended to practical unsteady flow fields such as vortex shedding, flow separation and reattachment. However, it is difficult to employ the current PLM and HCM directly to practical unsteady flow field. The available reference signals, which contain extracting phase information of phenomena, have broad frequency characteristics and random fluctuation in amplitude and zero-cross point. These naturally-disturbed components prevent an accurate phase-averaging of PSP images. In this study, two expanded unsteady PSP techniques have been developed; one is the modified phase-lock method (modified-PLM) and the other the conditional High-speed Camera method (conditional-HCM). In addition, the frequency-domain technique based on pixel-by-pixel FFT method, proposed by Nakakita, has also been implemented. The capabilities of these techniques were evaluated in a low-speed wind tunnel using a 3-D square cylinder model. As results, unsteady pressure fields around the cylinder caused by Karman vortex shedding were successfully measured by above three method. The modified-PLM and conditional-HCM can obtain the phase-averaged pressure images at arbitrary phase of periodic phenomena. In addition, the amplitude and the phase shift maps can be calculated from the phase-averaged images as shown in Fig. 5. The modified-PLM has the advantage of high phase-resolution while the conditional-HCM has the advantage of high-SNR of PSP image and simply system requirement. The FFT method can obtain the quantitative amplitudes of arbitrary frequency components, although it is difficult to extract a phase-shift map. This method also has the advantage that the reference signal is not necessary for evaluating pressure fields.



(a) pressure amplitude (b) phase shift

Fig. 5 2D distributions of pressure amplitude and phase shift obtained by conditional-HCM

Finally, advanced Temperature-Sensitive Paint (TSP) techniques for transition detection on a high-speed rotating propeller were developed based on the knowledge gained from the development of unsteady PSP techniques. First, TSP measurement techniques were optimized to visualize the boundary-layer condition on a rotating propeller. A new enhancement method of thermal signature, image acquisition and data processing were proposed to obtain high accuracy and to minimize the measurement errors. Next, an optimum TSP was selected for this propeller test through the paint evaluation tests. The selected TSP has high temperature sensitivity and a short fluorescence life-time. In the feasibility test, the experimental set-up and the image acquisition and processing procedures were evaluated and optimized for transition measurement. As a result, sharp propeller images can be obtained with high spatial-resolution at a rotational speed up to 9600 rpm. Obtained TSP images clearly show the temperature distribution due to the laminar-to-turbulent boundary-layer transition, even when the maximum temperature change is less than 2 K. On the basis of the feasibility test results, a wind tunnel experiment was successfully conducted in an industrial low-speed wind-tunnel at propeller rotation up to 14400 rpm. From the results, the development of laminar and turbulent regions on the propeller blade depending on propeller speed was successfully detected.

論文審査結果の要旨

風洞試験における新しい表面圧力計測手法として感圧塗料（PSP）が注目されている。本研究は，低速流れ，特に非定常圧力場に適用可能なPSP技術の開発について論じたものである。従来は定性的な圧力計測に限られていた非定常PSP計測に対し，理論誤差解析と風洞実験の両面から定量性を画期的に高める新手法を提案し，時間変動する流体現象へと適用することでその有効性を論じている。本論文はこれらの研究成果をまとめたものであり，全編７章からなる。

第１章は緒論であり，本研究の背景，目的及び構成を述べている。

第２章では，本論で使用される分子センサー技術の理論と基本情報をまとめている。

第３章では，低速の定常流れにおけるPSP計測技術の精度とその改善法が論じられている。低速の定常流れにおけるPSP計測の誤差要因を網羅し，各要因の影響を理論誤差解析により評価することにより，誤差を最小化する解決手法を提案し，風洞試験において流速50m/sという条件下で$\Delta C_p=0.05$という，きわめて定量性の高い圧力計測を安定的に行うことに成功している。これは、低速における実用実験に供することのできる定常PSP技術を確立した重要な成果である。

第４章では，低速の非定常流れに適用可能なPSP計測技術の開発が論じられている。計測カメラの特性を考慮した新しい画像取得法の適用と，PSP計測における基準画像の選択の工夫により，非定常PSP計測における主要な誤差要因の影響を大幅に低減・排除できることを示している。また，第３章の定常PSP技術との組み合わせによる新しい絶対圧計測手法を提案している。これらの手法を振動フェンスアクチュエータが誘起する変動圧力場の計測に適用し，定性的な圧力計測に限られていたこれまでの手法に対し，新手法を用いることでRMS値で最高$\Delta C_p=0.01$という高精度の定量圧力計測を実現できることを示している。これは低速流における非定常PSP技術を飛躍的に向上させる極めて重要な成果である。

第５章では，非定常PSP技術の適用可能性を，カルマン渦放出などに代表される自然ゆらぎを含むより一般的な非定常圧力場へと拡張する手法について述べられている。非定常圧力場に含まれるゆらぎ成分の特性を考慮した新しいPSP計測技術として，改良Phase-lock法と条件付画像平均法という２つの手法を提案している。３次元角柱模型を用いた風洞試験によりこれらの手法の系統的な比較評価を行い，それぞれの特徴の違いを明らかにしている。これらの成果は，非定常PSP技術の適用可能性を広めた実験流体力学上の重要な成果である。

第６章では，感温塗料（TSP）を用いた回転翼面上における境界層遷移パターンの可視化技術について述べている。非定常PSP技術について確立した技術をTSPによる温度場計測に適用し，TSPの特性，計測装置，計測シーケンスと画像解析手法を最適化することで，最大で14,400rpmで回転する回転翼面上における境界層遷移パターンを可視化することに成功している。これは，計測技術の飛躍だけではなく，プロペラなどの回転機械の効率化にTSP技術が有効であることを示した実用上重要な成果である。

第７章は結論である。

以上要するに本論文は，低速かつ非定常な流れ場に適用可能な定量PSP技術を確立するため，理論誤差解析と風洞実験を通して新しいPSP計測技術を提案し，種々の流体現象へと適用することでその有効性を示したものであり，航空宇宙工学および実験空気力学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。