Application of Fast Pressure-Sensitive Paint to an Oscillating Wind Turbine Airfoil

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BACKGROUND

In the unsteady flow environment experienced by wind turbine blades, large excursions in local angle of attack and significant three-dimensional flows arise that complicate the prediction of stall onset and unsteady loading. Accurate predictions of the dynamic loads are critical to the pursuit of lightweight, reliable structures to lower the cost of wind energy (Ref. 1). To this end, diagnostic measurement tools capable of fine spatial resolution and high frequency response are important for better understanding unsteady aerodynamic effects on blade pressure distribution.

The sparseness of conventional pressure transducers has historically provided motivation for the development of pressure-sensitive paint (PSP), an optical surface pressure measurement technique with inherently fine spatial resolution. Within the last decade, the bandwidth of certain paint formulations has been significantly increased to resolve unsteady flows; a flat frequency response on the order of several kHz is now readily achievable (Ref. 2). PSP consists of luminescent molecules adhered to the test surface by a thin binder layer, typically on the order of 10 microns. The luminophore responds to the local partial pressure of oxygen, which is directly proportional to absolute air pressure. An illumination source such as a light-emitting diode or expanded laser beam excites the luminophore, and the emitted light intensity captured by a scientific-grade camera is converted to absolute pressure via calibration. Each point on the painted surface thus responds as a molecular-sized transducer, with spatial resolution limited by the camera pixel size.

Recent advancements in unsteady PSP data acquisition and processing techniques have been developed for rotating blades to account for errors caused by model movement and deformation in nonuniform illumination fields. The single-shot lifetime technique (Ref. 3) and motion capturing technique (Ref. 4) are two methods which have arisen. Due to its straightforward procedure and commonality of required hardware, the single-shot technique has been used across a range of small test facilities (Ref. 5, 6) and large-scale wind tunnels (Ref. 7).

PSP measurements have been historically limited to the compressible flow regime to achieve sufficient signal-to-noise ratio in the data images (Ref. 8, 9). Recent wind tunnel testing with unsteady PSP has been geared toward helicopter applications (Ref. 10, 11), although temperature error due to compressibility effects has been noted. Under isothermal conditions or with an accurate temperature correction available, laser-based excitation and highly reflective paints can enable instantaneous PSP measurements at Mach numbers near $M \approx 0.15$, corresponding to dynamic pressures of approximately 1.5 kPa (Ref. 6, 12). Unsteady aerodynamic effects can result in even larger pressure differences, considering that peak suction levels on oscillating airfoils can reach factors of the free stream dynamic pressure (Ref. 13). With the present availability of suitable paints, the above considerations present an opportunity for PSP to be deployed as a measurement tool for resolving the global pressure distribution on wind turbine blades.

DESCRIPTION OF WORK

The work to be discussed has the objective of demonstrating PSP as a viable tool for measuring global surface pressure on wind turbine blades. To our knowledge, this work represents the first application of PSP to a low-speed airfoil undergoing pitch oscillation used to mimic unsteady changes in incidence angle. While much of the dynamic stall literature has focused on relatively thin airfoils for helicopter applications, the current effort will use the single-shot PSP technique to investigate the unsteady stalling behavior of a thick airfoil section (Delft DU97-W-300) representative of wind turbine blades. In the talk, aspects of the data collection method will be presented along with sample results demonstrating the capabilities of the measurement technique. Results to be presented will consist of global pressure maps obtained during dynamic stall development, including a controlled case with vortex generator tabs applied.

SUMMARY OF RESULTS

PSP experiments were performed in the University of Wyoming subsonic wind tunnel, an open-circuit facility. Flow conditions were Mach number M=0.13, chord Reynolds number Re=224,000, and reduced frequency k=0.106 based on semichord. The pitch schedule was given by $\alpha=15.7^\circ+11.2^\circ\sin(93.5t)$, with the measured lift hysteresis loop shown in Figure 1.

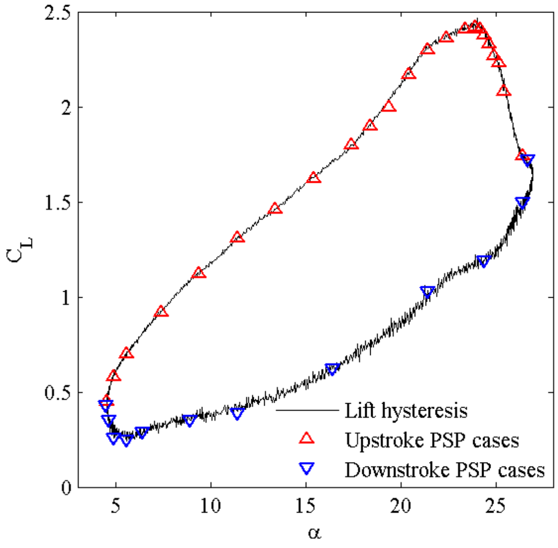
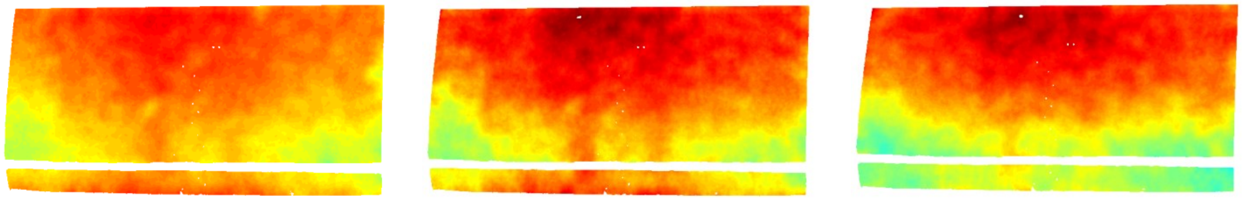


Figure 1: Phase positions for unsteady PSP data collection (*k*=0.106, *M*=0.13, *Re*=224,000).

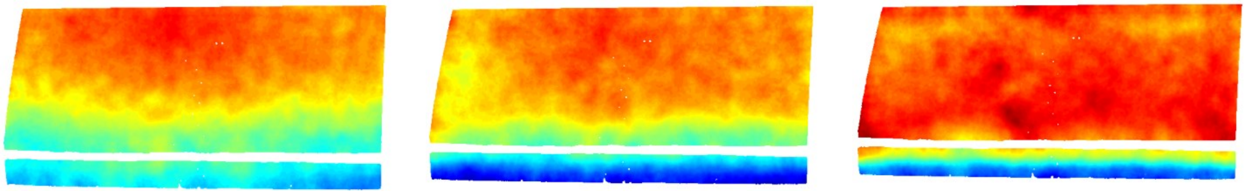
The static lift curve of the DU-97-W-300 airfoil was measured with and without PSP applied to the wing. The middle third of the airfoil span was painted with porous polymer/ceramic PSP basecoat doped with platinum tetra(pentafluorophenyl) porphyrin (PtTFPP) luminophore. Typical pressure sensitivity for this paint formulation is up to 0.6% per kPa at atmospheric pressure, and bandwidth up to 6 kHz – more than sufficient to capture the fundamental airfoil oscillation frequency of 15 Hz. An *in-situ* pressure calibration of the paint signal was performed with a set of 12 pressure taps situated near midspan on the upper airfoil surface. Phase-locking of the PSP system to a shaft encoder allowed the instantaneous surface pressure to be captured over a sweep of phase angles, as denoted on the lift coefficient (C_L) hysteresis loop in Figure 1. PSP data were acquired approximately once every fourth oscillation cycle, which was a limitation of the camera frame rate (Cooke Corp. PCO.1600).

In Figure 2, phase-averaged surface pressure maps measured by PSP (average of 64 cycles) are shown for selected phases of the oscillation in terms of pressure coefficient (C_p). The data were spatially filtered using a 13×13 pixel (4.2% chord) median filter to attenuate shot noise effects. At $\alpha=6.2^\circ$ rising (Figure 2a), the flow is reattaching and three-dimensionality in the spanwise direction is apparent. Trailing-edge stall progresses as the angle of attack increases (Figure 2b-e). Leading-edge suction ($C_p \sim -5$) begins to collapse at the lift stall angle, which occurs near $\alpha=24^\circ$ (Figure 2f). PSP indicates a complex breakdown of the flow in Figure 2f, with an isolated zone of increased suction developing on the aft part of the airfoil. Just beyond lift stall, the primary separation vortex grows stronger in Figure 2g-h, an observation also noted from the planar velocity field measurements of Ref. 13. The pressure signature of the vortex appears to show a mild degree of three-dimensionality. In the post-stall flow, the leading-edge suction zone entirely collapses and the aft region shows a flat pressure profile representing a fully stalled condition (Figure 2j-l). Surface maps such as these can provide powerful complementary insight to the flow field measurements of Ref. 13 which were previously conducted with the same test article.

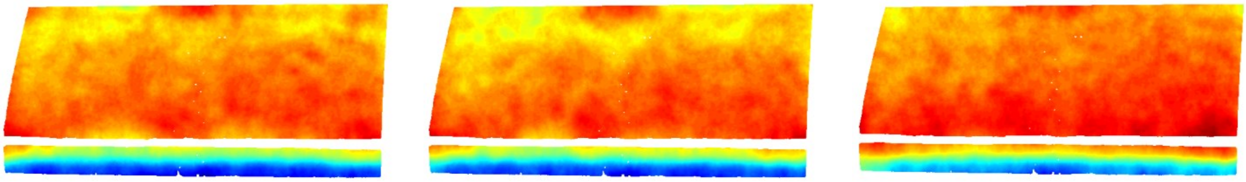
A controlled case featuring several vortex generator (VG) tabs applied to half of the painted region was acquired to demonstrate detection of 3-D patterns on the oscillating airfoil using PSP. The particular way in which VGs interact with the flow is extremely challenging to glean from a sparse set of pressure transducers. Therefore, this was a desirable case to demonstrate wherein PSP measurements could be used for direct validation of computational models desired by industry. A sample result of the measured flow pattern is shown in Figure 3, with the location of VGs labeled. The VG design was not optimized for the boundary layer flow in the test; this appears to be evident in the region of stagnant flow behind the tabs and the higher C_p levels ahead of them at the leading edge compared to the other side of midspan ($y/b = 0$).



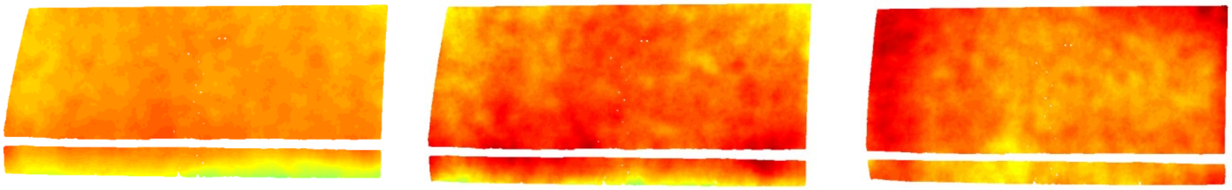
(a) α=6.2° ↑ (b) α=8.0° ↑ (c) α=12.1° ↑



(d) α=16.1° ↑ (e) α=22.0° ↑ (f) α=24.0° ↑



(g) α=24.4° ↑ (h) α=24.7° ↑ (i) α=26.0° ↑



(j) α=24.5° ↓ (k) α=16.4° ↓ (l) α=6.6° ↓

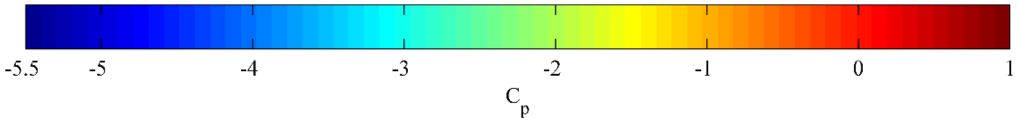


Figure 2: Phase-averaged PSP images of oscillating DU97-W-300 airfoil at selected phase positions. Flow is from bottom to top in each image; arrows indicate upstroke/downstroke directions.

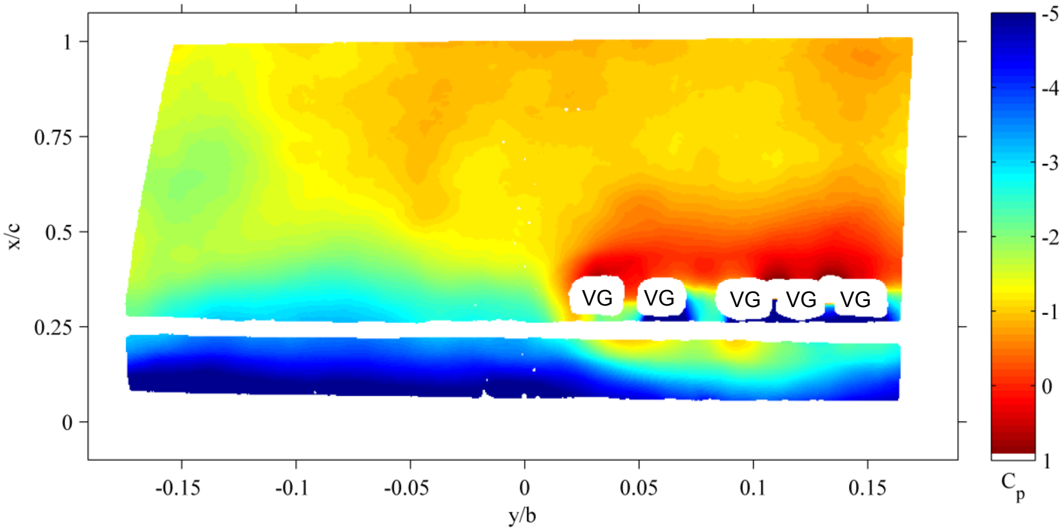


Figure 3: PSP image of flow pattern on oscillating airfoil with vortex generators installed (α=22.1°, upstroke).

CONCLUSIONS

The PSP tests were viewed as successfully demonstrating application of the technique to a low-speed flow with unsteady surface motion, a test condition historically outside the capabilities of conventional PSP systems. Pressure fields were obtained with strong signal-to-noise ratio by minimizing the effect of temperature error through test procedure, and the single-shot lifetime method cancelled the effects of surface movement and nonuniform illumination which otherwise introduce significant error to the measurement. Moreover, the fast frequency response of the paint appeared to capture unsteady pressure topologies tracking with oscillation phase.

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REFERENCES

1. Cohen, J., Schweizer, T., Laxson, A., Butterfield, S., Schreck, S., Fingersh, L., Veers, P., and Ashwill, T., "Technology Improvement Opportunities for Low Wind Speed Turbines and Implications for Cost of Energy Reduction: July 9, 2005 - July 8, 2006," National Renewable Energy Laboratory, NREL TP-500-41036, 2008.
2. Gregory, J.W., Sakaue, H., Liu, T., and Sullivan, J.P., "Fast Pressure-Sensitive Paint for Flow and Acoustic Diagnostics," *Annual Review of Fluid Mechanics,* Vol. 56, 2014, pp. 303-330. doi: 10.1146/annurev-fluid-010313-141304.
3. Juliano, T.J., Kumar, P., Peng, D., Gregory, J.W., Crafton, J., and Fonov, S., "Single-Shot, Lifetime-Based Pressure-Sensitive Paint for Rotating Blades," *Measurement Science and Technology,* Vol. 22, (8), 2011, pp. 085403. doi: 10.1088/0957-0233/22/8/085403.
4. Sakaue, H., Miyamoto, K., and Miyazaki, T., "A Motion-Capturing Pressure-Sensitive Paint Method," *Journal of Applied Physics,* Vol. 113, (8), 2013, pp. 084901. doi: 10.1063/1.4792761.
5. Juliano, T.J., Disotell, K.J., Gregory, J.W., Crafton, J.W., and Fonov, S.D., "Motion-Deblurred, Fast-Response Pressure-Sensitive Paint on a Rotor in Forward Flight," *Measurement Science and Technology,* Vol. 23, (4), 2012, pp. 045303. doi: 10.1088/0957-0233/23/4/045303.

6. Disotell, K.J., Peng, D., Juliano, T.J., Gregory, J.W., Crafton, J.W., and Komerath, N.M., "Single-Shot Temperature- and Pressure-Sensitive Paint Measurements on an Unsteady Helicopter Blade," *Experiments in Fluids,* Vol. 55, (2), 2014, pp. 1671. doi: 10.1007/s00348-014-1671-2.
7. Wong, O.D., Watkins, A.N., Goodman, K.Z., Crafton, J.W., Forlines, A., Goss, L., Gregory, J.W., and Juliano, T.J., "Blade Tip Pressure Measurements using Pressure Sensitive Paint," AHS 2012-000233, American Helicopter Society 68th Annual Forum and Technology Display, Fort Worth, TX, May 1-3, 2012.
8. Mendoza, D.R., "Limiting Mach Number for Quantitative Pressure-Sensitive Paint Measurements," *AIAA Journal,* Vol. 35, (7), 1997, pp. 1240-1241. doi: 10.2514/2.228.
9. Bell, J.H., "Applications of Pressure-Sensitive Paint to Testing at very Low Flow Speeds," AIAA 2004-0878, AIAA 42nd Aerospace Sciences Meeting and Exhibit, Reno, NV, January 5-8, 2004.
10. Gardner, A.D., Klein, C., Sachs, W.E., Henne, U., Mai, H., and Richter, K., "Investigation of Three-Dimensional Dynamic Stall on an Airfoil using Fast-Response Pressure-Sensitive Paint," *Experiments in Fluids,* Vol. 55, (9), 2014, pp. 1807. doi: 10.1007/s00348-014-1807-4.
11. Juliano, T.J., Peng, D., Jensen, C.D., Gregory, J.W., Liu, T., Montefort, J., Palluconi, S., Crafton, J., and Fonov, S., "PSP Measurements on an Oscillating NACA 0012 Airfoil in Compressible Flow," AIAA 2011-3728, 41st AIAA Fluid Dynamics Conference and Exhibit, Honolulu, HI, 2011.
12. Disotell, K.J., and Gregory, J.W., "Measurement of Transient Acoustic Fields using a Single-Shot Pressure-Sensitive Paint System," *Review of Scientific Instruments,* Vol. 82, (7), 2011, pp. 075112. doi: 10.1063/1.3609866.
13. Naughton, J.W., Strike, J., Hind, M., Magstadt, A., and Babbitt, A., "Measurements of Dynamic Stall on the DU Wind Turbine Airfoil Series," American Helicopter Society 69th Annual Forum, Phoenix, AZ, May 21-23, 2013.
14. Timmer, W.A., and van Rooij, R.P.J.O.M., "Summary of the Delft University Wind Turbine Dedicated Airfoils," *Journal of Solar Energy Engineering,* Vol. 125, (4), 2003, pp. 488-496. doi: 10.2514/2.228.