ND*nano* Summer Undergraduate Research
2018 Project Summary

1. Student name & home university: William Gothard, North Carolina State University

2. ND faculty name & department: Dr. Hirotaka Sakaue, Aerospace and Mechanical Engineering

3. Summer project title: Functional Chemical Sensor and Coating for Fluid Dynamic Applications

4. Briefly describe new skills you acquired during your summer research: Performing hands-on research in a graduate lab has been an incredible learning experience. Aside from honing my data acquisition and analysis skills using programs such as LabVIEW and MATLAB, I learned a great deal about the physical aspects of testing luminescent and pressure sensitive materials. I frequently used highly sensitive pressure measurement and control devices, high powered lasers, optical sensors, and optical filters to perform experiments. Prior to this summer, I had limited or no prior experience using this type of scientific instrumentation. Beyond these skills I learned how to work in an environment which requires careful planning and good time management, meticulous experimental practices, constant communication, and even cultural sensitivity. The technical skills I learned will certainly be an asset as I move forward, but some of the soft skills involved in working with a scientific team, like collaboration and communication, will likely be of equal or greater value as I continue to grow professionally.

5. Briefly share a practical application/end use of your research: The end use of this research is the possibility for accurate quantitative pressure measurements over bodies and surfaces subjected to high speed, unsteady pressure fluctuations. A perfect example of such measurements exists in the research being conducted at North Carolina State University, in which unsteady pressure measurements in cavities are being collected in supersonic flow. The use of pressure sensitive coatings will allow for a better method of understanding pressure distributions and aerodynamic forces on bodies that would otherwise be difficult and cumbersome to characterize due to the limitations of more conventional pressure measurement techniques.

6. 50- to 75-word abstract of your project: The possibility of using pressure sensitive paint (PSP) as a stand-alone measurement device in unsteady flow fields is being realized with the development of faster and more sensitive PSP. Unsteady phenomena occur quickly, often on the order of 10 kHz. To effectively apply PSP to such unsteady flow conditions, the response characteristics of the PSP must be understood by exposing PSP to a known controlled pressure field of acoustic waves and examining the response variation from traditional pressure measurement devices.

7. References for papers, posters, or presentations of your research:

H. Sakaue, T. Kakisako, H. Ishikawa “Characterization and Optimization of Polymer-Ceramic Pressure-Sensitive Paint by Controlling Polymer Content” *Sensors* **2011**,11, 6967-6977

Tamao Sugimoto, Yosuke Sugioka, Daiju Numata, Hiroki Nagai, and Keisuke Asai. "Characterization of Frequency Response of Pressure-Sensitive Paints", AIAA Journal, Vol. 55, No. 4 (2017), pp. 1460-1464.

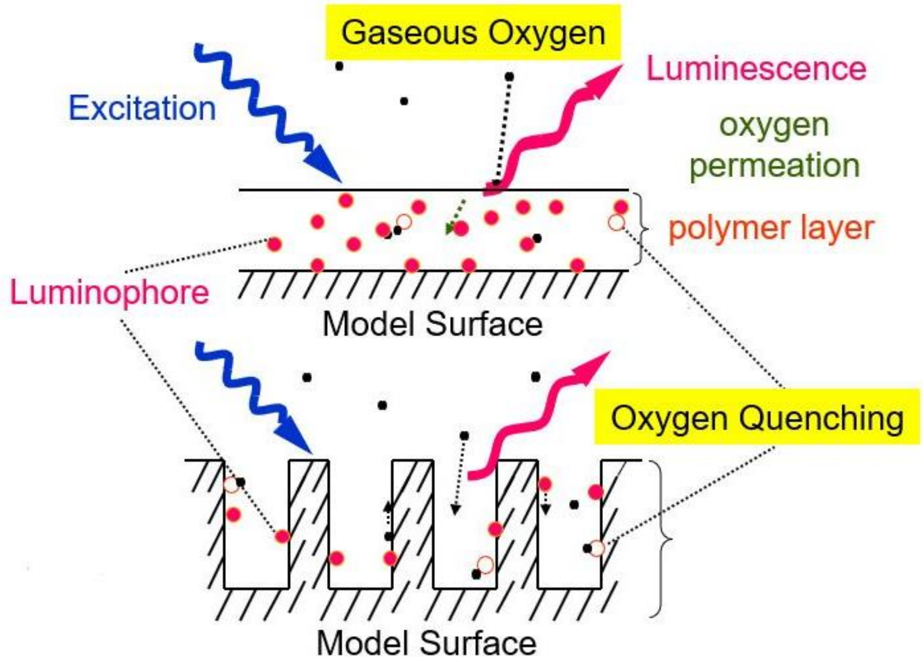
Jahanmiri, Mohsen. (2011). Pressure Sensitive Paints: The Basics & Applications. Chalmers University Library. Research report 2011:07. 35.

Frequency response characterization of luminescence based chemical sensor

The development of pressure sensitive paint (PSP), a luminescence-based sensor and alternative device for obtaining unsteady pressures over fluid dynamic surfaces, fostered a new era in our ability to understand fluid flow fields. The sensor emits luminescence, which can be acquired as an image by high speed camera. It has been shown that PSP is highly effective for understanding flow properties in low-speed, aerodynamic applications (Jahanmiri). The current trajectory of aerodynamic research shows an increasing interest in the understanding of unsteady flow phenomena. Unsteady flow phenomena occur very quickly. To apply PSP to these types of flow, the chemical sensor must be able to react to pressure fluctuations on the order of 10 kHz or greater. Previous research has led to fast-PSP formulations and application methods which have proven to be more effective in characterizing unsteady flow (Sugimoto et al.).

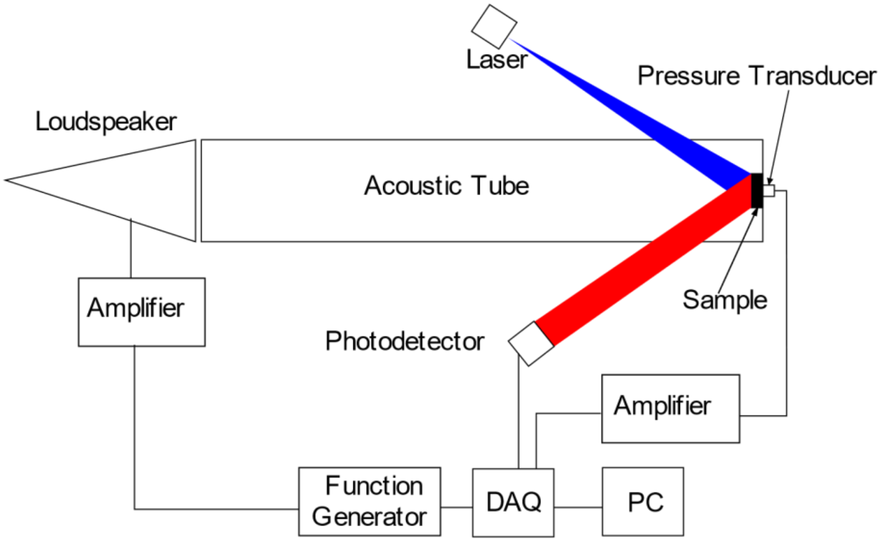
PSP functions by exploiting the sensitivity of certain luminescent materials to the presence of oxygen. The luminophores being implemented in PSP, such as a Ruthenium complex, absorb energy in the blue light spectrum, resulting in an increase in the energy state of the luminophore. To return to a reduced energy state, the luminophore releases energy in the form of red light. However, in the presence of oxygen some of the energy which would otherwise be released as red light is instead transferred into the oxygen molecules in the form of vibrational energy. This process of transferring energy to the oxygen molecules is known as quenching and ultimately results in reduced luminescent output as oxygen concentration (or air pressure) increases. To increase diffusivity of oxygen into PSP, different surface structures can be implemented, resulting in an improved ability to observe changes in luminescent intensity in unsteady flow environments. Specifically, porous PSP applications have proven more effective than polymer applications at accomplishing unsteady measurement. Such applications are known as “fast-PSP.” The following schematic depicts a slow diffusivity, polymer-based PSP (top) and a fast-PSP structure (bottom).

Figure 1: Slow- vs. fast-PSP surface structures



With the ability to produce different response characteristics by changing the luminophore type, luminophore concentration, model surface structure, and binder type comes the need to characterize how the specific type of PSP reacts to pressure fluctuation on the order of 10 kHz. An ideal form of instrumentation for performing such a characterization of frequency response is a resonance tube because it provides a method for producing a well-controlled fluid dynamic phenomenon in the form of sinusoidal pressure waves. The chemical sensor is monitored for changes in luminescence by a photodetector, which is then matched to a reference measurement collected by an electronic pressure transducer. The sensor can then be characterized using a bode plot to compare phase and amplitude changes between luminescence data and reference data. An example of the experimental setup implemented in this study is shown in the figure below.

Figure 2: Experimental setup of resonance tube characterization of PSP



To effectively characterize the PSP sample using this setup, the sample is first exposed to a series of low frequency pressure waves generated by the loudspeaker at around 162 Hz. This is perceived by the ear as a very low auditory tone. The frequency is then gradually increased up to 10 kHz or greater to analyze the rapid changes in luminescence of the PSP. Ideally, PSP will demonstrate very little change in signal intensity, even with pressure fluctuations on the order of 10 kHz and will also exhibit little or no delay in responding to closely spaced pressure waves as indicated by examining the phase delay between reference data and PSP data. An example of the results obtained for two samples are shown below. These samples were being investigated for the impact of changing the ceramic particle types found in the binder. Both samples are traditional, single color, polymer-ceramic PSP application techniques. Depicted here are the gain characteristics alone, as phase delay information is still being investigated. However, from the following plots we can observe that the aluminum oxide formulation provides significantly more favorable gain characteristics in the 100 to 2000 Hz frequency range. For both samples, however, the signal is essentially reduced to zero very rapidly beyond 2000 Hz as indicated by gain of -10 dB and lower.

Figure 3: Frequency response of PC-PSP with aluminum oxide (Al_2O_3) ceramic particles

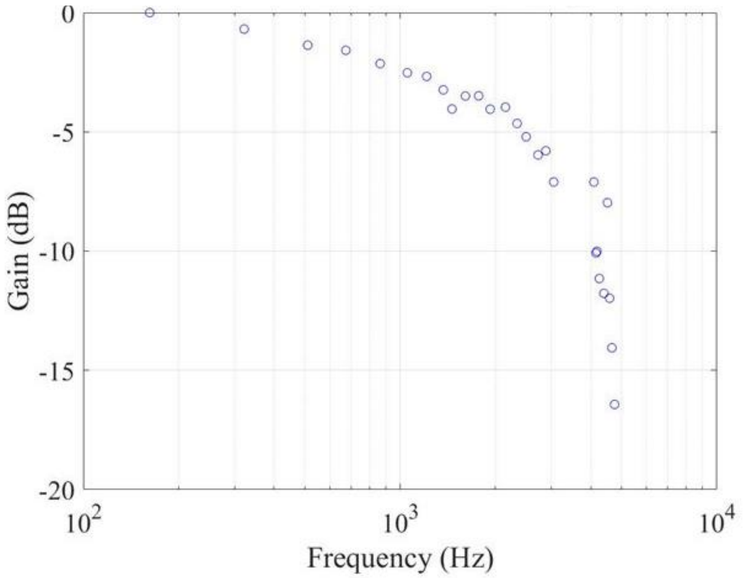
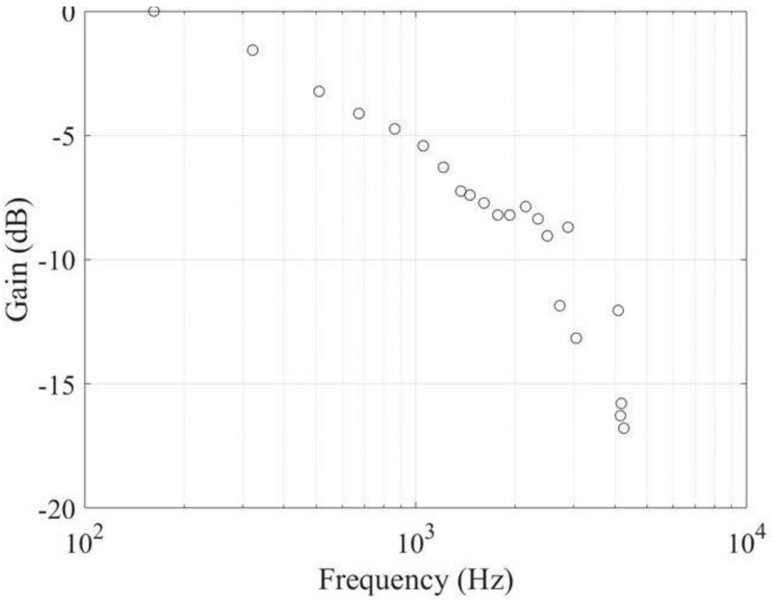


Figure 4: Frequency response of PC-PSP with titanium silicon oxide ($TiSiO_4$) ceramic particles



This summer, we were able to perform frequency response characterization tests on over 30 PSP samples and successfully showed that gain characteristics can be approximated by a first order system in many cases. That is, there exists a linear relationship between the gain exhibited by the PSP and the frequency of pressure fluctuations to which it is exposed. We were also able to observe how various types and concentrations of luminophores, as well as the surface properties in both traditional and binary PSP applications can alter the frequency response characteristics. Characterization of the phase delay exhibited by PSP is still under investigation but also appears to follow a first order trend. With the new information collected, further developments can be made toward making PSP a stand-alone pressure measurement device which can be used to provide continuous pressure mapping of surfaces in unsteady flow conditions.