**Synopsis of Technical Report
By Brian Cranton for OPTI 521
November 1, 2010**

Technical Report chosen:
“Optomechanical Characterization of Proton-Exchange Membrane Fuel Cells”
Available online at <http://alum.wpi.edu/~jalani/OEH.pdf>

**Overview**

At a high level of abstraction, this paper describes a multidisciplinary effort where chemists use optics and mechanics to measure a material property that is important in the application they are researching. The paper’s format is pragmatic, concise, and systematic; broken into four sections covering (1) the background of higher level application, (2) why reducing uncertainty in the knowledge a specific material property is important to this application, (3) how they measured this material property, and (4) brief conclusions and speculations as to their next logical steps forward.

The application is that of fuel cells, the material of interest is DuPont™ Nafion®, and the material property of interest is the Young’s Modulus. In the context of the paper’s title, Nafion® is the fuel cell proton-exchange membrane being characterized optomechanically by these researchers. The DuPont™ website[[1]](#footnote-1) gives a brief overview of Nafion® as:

“For the past 40 years, DuPont™ Nafion® membranes and dispersions have been the product of choice for the fuel cell industry, providing unparalleled power output and durability. Today, Nafion® polymer has evolved into a leading-edge fuel cell material for a wide variety of applications.”

In their fuel cell application, a key performance driver is the uptake of water molecules by Nafion®. The researchers explain this performance in terms of *sorption[[2]](#footnote-2)*, which is represented in a relationship (equation 13 in the paper) that is essentially their merit function. The Young’s Modulus of Nafion® plays an important role in this performance relationship, and reducing the uncertainty in the Young’s Modulus value increases their ability to accurately predict water sorption under different environmental conditions; in particular at different temperatures and relative humidity values.

Because Nafion® is a thin, weak membrane, measuring its properties by conventional mechanical means is not practical. The researches instead employed an alternative measurement technique which involves forming the Nafion® into small cantilever beams which are excited into vibration and observed with an optoelectronic holography setup to measure the first resonant frequency of those cantilever beams. Once the first resonant frequency is known, using that value in conjunction with knowledge of the beam thickness, beam length, and material density, the Young’s Modulus can be calculated.

**Target Audience for this Paper**

This paper would be of specific interest to people involved in applications which are sensitive to material properties that vary with environmental conditions and involve materials that are thin, weak, or otherwise have characteristics that make them difficult to measure using conventional means. It could be speculated that researchers working on establishing the material properties of substances such as paper, skin, or rubber would find this paper useful. The paper does not cover much optical subject matter, however it does describe a successful implementation of optoelectronic holography to solve an unusual material property measurement problem.

The format of the paper is concise and focused; the paper does not veer off-topic except for a couple sentences in the introduction that contain a bit of literary flourish. No novel new discoveries or breakthroughs are presented in this paper, instead one small but important step in a much larger research effort is documented.

This paper is of particular note in the context of OPTI 521 in that the information presented is multidisciplinary; covering chemical, mechanical, and optical concepts. OPTI 521 being a multidisciplinary optics and mechanics course. The paper describes an approach that parallels some aspects of optical design in that the researchers use something akin to a merit function (equation 13 in the paper), they perform an RSS uncertainty analysis on that function (equations 16 and 17 in the paper), construct a cantilever beam that is observed with an optical technique (optoelectronic holography in section 3 of the paper), to calculate a resonant frequency of a cantilever beam which is used to back out the material property of interest (equation 19 in the report). In particular, the RSS and cantilever beam frequency calculations are quite similar to those covered in OPTI 521.

**Comparison to other papers**

When compared to many of the papers upon which previous synopsis[[3]](#footnote-3) have been written, this paper is concise with fewer words, tables, charts, and graphics than most. In terms of subject matter, this paper is similar to those which describe how optics and mechanics are used to solve the problem of another discipline; except perhaps that this paper spends more time and written text on the application and less on the optical and mechanical characteristics of the solution. For example, “Optical Alignment of a Pupil Imaging Spectrometer”[[4]](#footnote-4) is mostly devoted to optics and mechanics and spends very little describing the spectrometer application. Similarly, “Optical Performance for the James Webb Space Telescope”[[5]](#footnote-5) is mostly devoted to the optical and mechanical requirements of the telescope and does not spent much time describing the where those requirements came from. This comparison is not meant to imply that the researchers who wrote this paper were remiss, simply that they approached writing this paper from a strongly chemical viewpoint rather than the optical or mechanical viewpoints common to many previously reviewed papers.

**Section 1 Synopsis: Introduction**

This paper starts with an overview of polymer electrolyte fuel cells (PEFC). These fuel cells are a low pollution means of converting between electrical and chemical energy. As such, they act as environmentally friendly batteries. In the quest to make better PEFC, the researchers are conducting studies to understand and improve the performance of the various elements comprising the PEFC. The specific PEFC element addressed in this paper is the proton conducting membrane, for which hydrated Nafion® is commonly used.

Researchers have developed a water sorption model for hydrated Nafion®, of which one key element is Nafion®’s Young’s Modulus. Unfortunately, the Young’s Modulus of Nafion varies substantially with environmental conditions and this variability impacts the performance of PEFC fuel cells. In particular, Nafion®’s Young’s Modulus is strongly affected by both relative humidity and temperature.

**Section 2 Synopsis: Water Sorption Model**

The first three subsections, 2.1 through 2.3, describe in detail the chemical process that is of interest for this fuel cell application, specifically the uptake of water molecules by the membrane. Young’s Modulus first appears in section 2.2 at equation 6, and is apparent in the comprehensive relationship given by equation 13 derived at the end of section 2.3.

A root sum square method is applied to this comprehensive relationship to determine the impact of specific uncertainties in each of the relevant parameters to the overall uncertainty. The methodology is similar to that employed in an optomechanical tolerance budget, except instead of terms such as wedge, tilt, and decenter this analysis involves Young’s Modulus, temperature, and some chemical properties.

Figure 3 plots the contribution to total uncertainty from several key factors as water sorption increases and at two different temperatures. Uncertainty in Nafion® Young’s Modulus clearly becomes the driving factor in total uncertainty as water sorption increases. From these figures, it is clear that minimizing uncertainty in knowledge of Nafion® Young’s Modulus is important, so employing a technique which can accurately measure this property across a range of environmental conditions is important. In this instance, the researchers opted to employ optoelectronic holography.

**Section 3 Synopsis: Optoelectronic Holography**

Optoelectronic holography is an established noninvasive, nondestructive means of measuring shape and deformation of objects subject to a variety of boundary or loading conditions. Although not explicitly stated, the researchers in this instance appear to be using a form of time-averaging holography[[6]](#footnote-6). Resonant frequencies in a time-averaging holography setup are typically measured by slowly increasing a vibrational excitation frequency and observing the magnitude of the resulting vibrations. The first frequency at which the resulting vibrations are at a maximum is the first resonant frequency.

The experimental setup for measuring Young’s Modulus, shown in figure 4 of the paper, shows an environmental chamber into which the Nafion® sample is presumably contained. The Nafion® sample is in the form of a cantilever beam and is excited into vibration. The optoelectronic holography setup is in front of the chamber and appears to observe the Nafion®beam through a large. In this manner the measurement equipment, the optoelectronic holography setup is not subjected to the effects of the environmental chamber.

Nafion® is normally provided in sheets less than 1mm thick and is a somewhat flexible membrane at the macroscopic level[[7]](#footnote-7). The Nafion® material tested during this research was 50µm thick.

The first resonant frequency of a simple spring-mass mechanical structure is given by



The mechanics of a cantilever beam in vibration are more complex than this, as the mass of the beam is distributed along its length. The researchers in this instance refer to prior work which provides the solution for the cantilever beam first vibration mode calculation. The resulting relationship, shown below, bears resemblance to the simple spring-mass equation, listed above, making it appear feasible. Specifically, where spring constant *k* is in the simple spring-mass model above, Young’s Modulus *E* is in the cantilever beam model below. Spring constant is expected to change linearly with Young’s Modulus so this makes sense. Similarly, where mass *m* is in the simple spring-mass model above, density is in the cantilever beam model below. Mass is expected to change linearly with density so this makes sense.



In section 3.3, the researchers note that the vendor Dupont™ only provided them with one Young’s Modulus value of relevance; 250MPa at 50% humidity and at room temperature. The researchers were able to duplicate this measurement, obtaining a value of 248MPa under similar conditions. Figure 5 in the paper is the culmination of the researchers’ effort, showing the tremendous variability of Young’s Modulus with both temperature and humidity.

**Section 4 Synopsis: Conclusions and Future Work**

In this portion of the paper, the researchers simply note that they have proven out their concept for measuring the Young’s Modulus of Nafion® and that future work will involve extending their measurements to higher temperatures and to the measurement of other properties such as hysteresis effects.

1. http://www2.dupont.com/FuelCells/en\_US/products/nafion.html [↑](#footnote-ref-1)
2. From [www.wikipedia.com](http://www.wikipedia.com): *Sorption* is a chemical term referring to the action of absorption or adsorption. Absorption is the incorporation of a substance in one phase state into another (e.g. air dissolved in water). Adsorption is the physical adherence of ions and molecules onto the surface of another phase (e.g. a water purification filter). [↑](#footnote-ref-2)
3. http://www.optics.arizona.edu/optomech/Technical%20Synopsis\_in\_optomechanics.htm [↑](#footnote-ref-3)
4. http://www.optics.arizona.edu/optomech/student%20reports/synopsis/paper/for%20Fasse.pdf [↑](#footnote-ref-4)
5. http://www.optics.arizona.edu/optomech/student%20reports/synopsis/paper/for%20Jed.pdf [↑](#footnote-ref-5)
6. http://www.optics.arizona.edu/jcwyant/Optics505%282000%29/ChapterNotes/Chapter17/Holography.pdf [↑](#footnote-ref-6)
7. http://www2.dupont.com/FuelCells/en\_US/products/literature.html [↑](#footnote-ref-7)