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| <b>ABSTRACT</b><br>Research results in support of creating a multifunctional UAV spar with capabilities of harvesting energy, storing energy, sensing, actuating and computing are presented. A multi layer multifunctional spar is fabricated and modeled. Experiments are performed to validate the model and simulations are reported that illustrate the use of harvested energy to perform active feedback control for gust alleviation is small UAVs. In addition a compensation algorithm was developed to account for the voltage dependence of the coupling coefficient in the feed back control law resulting from the PZT nonlinearity. A minimum energy control law was developed, implemented and compared against standard control laws. Formulas are derived to show how long a UAV must fly before enough energy is harvested to be able to suppress a gust.                                                                              |                             |                                |                                         |                                                          |                                                              |
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**Objectives:** There was no change in objectives.

### **Executive Summary**

The goal of the proposed research was to investigate the concept of using harvested energy to directly control the vibration response of flexible aerospace systems. Small, lightweight flexible Micro Air Vehicles (MAVs) operate near flutter providing both harvesting opportunities and vibration suppression requirements. The possibility that the aforementioned ambient energy might be harnessed and recycled to provide energy to mitigate the vibrations through various control laws was investigated and is reported here. Furthermore, our goal was to integrate harvesting, storage, control and computation all into one multifunctional structure, and to illustrate its benefits.

*Results:* The main results discovered during the proposal period are as follows. As ambient energy is relatively low level and our hope was to run vibration suppressions systems off of harvested ambient energy, we first searched for feedback control laws that used a minimum amount of energy. We had expected that such control laws would already exist but were mistaken. So our first significant result was to discover ways to minimize control effort for vibration suppression. We examined the basic control laws and tuned them all to achieve the same performance. We then calculated the required amount of energy in each case and compared them. This is listed in Table 1 where we also instituted a saturation function over the top of each controller to limit the amount of energy called for in the early part of the control law. These bang-bang or saturation controllers clearly used the least amount of energy to produce the same performance.

|                                           | <b>Open-Loop</b> | <b>PPF</b>   | <b>Bang-bang-PPF</b> | <b>PID</b>   | <b>Bang-bang-PID</b> | <b>Non-linear</b> | <b>Bang-bang-nonlinear</b> | <b>LQR</b>   | <b>Bang-bang-LQR</b> |
|-------------------------------------------|------------------|--------------|----------------------|--------------|----------------------|-------------------|----------------------------|--------------|----------------------|
| <b>Initial disp., velocity (mm, mm/s)</b> | <b>(5,0)</b>     | <b>(5,0)</b> | <b>(5,0)</b>         | <b>(5,0)</b> | <b>(5,0)</b>         | <b>(5,0)</b>      | <b>(5,0)</b>               | <b>(5,0)</b> | <b>(5,0)</b>         |
| <b>Settling time <math>T_s</math> (s)</b> | <b>10.8</b>      | <b>0.85</b>  | <b>0.85</b>          | <b>0.85</b>  | <b>0.85</b>          | <b>0.85</b>       | <b>0.85</b>                | <b>0.85</b>  | <b>0.85</b>          |
| <b>Maximum voltage (V)</b>                | <b>N/A</b>       | <b>450</b>   | <b>130</b>           | <b>450</b>   | <b>130</b>           | <b>450</b>        | <b>130</b>                 | <b>450</b>   | <b>130</b>           |
| <b>Maximum current (mA)</b>               | <b>N/A</b>       | <b>0.5</b>   | <b>0.7</b>           | <b>0.5</b>   | <b>0.7</b>           | <b>0.5</b>        | <b>0.7</b>                 | <b>0.5</b>   | <b>0.7</b>           |
| <b>Average power (mW)</b>                 | <b>N/A</b>       | <b>10.6</b>  | <b>5.73</b>          | <b>15.5</b>  | <b>6.47</b>          | <b>16.7</b>       | <b>5.46</b>                | <b>15.52</b> | <b>6.20</b>          |

Table 1 A comparison of energy used in control laws all tuned to give the same performance

The table shows clearly that as much as 2/3 of the required energy can be saved by using a saturation control. This reduction makes running a control law off of harvested energy possible.

In implementing these control laws we also discovered that the high voltages commanded by our control laws result in the piezoelectric coupling coefficient being non constant. Thus we also had to implement

an adaptive control law (exponential actually) to account for the change in coupling coefficient as the control voltage demand increased.

The next major result was to integrate harvesting and storage into the same package with a control actuator and a control law (i.e. the circuitry) all embedded in a multifunctional composite structure as illustrated in Figure 1.

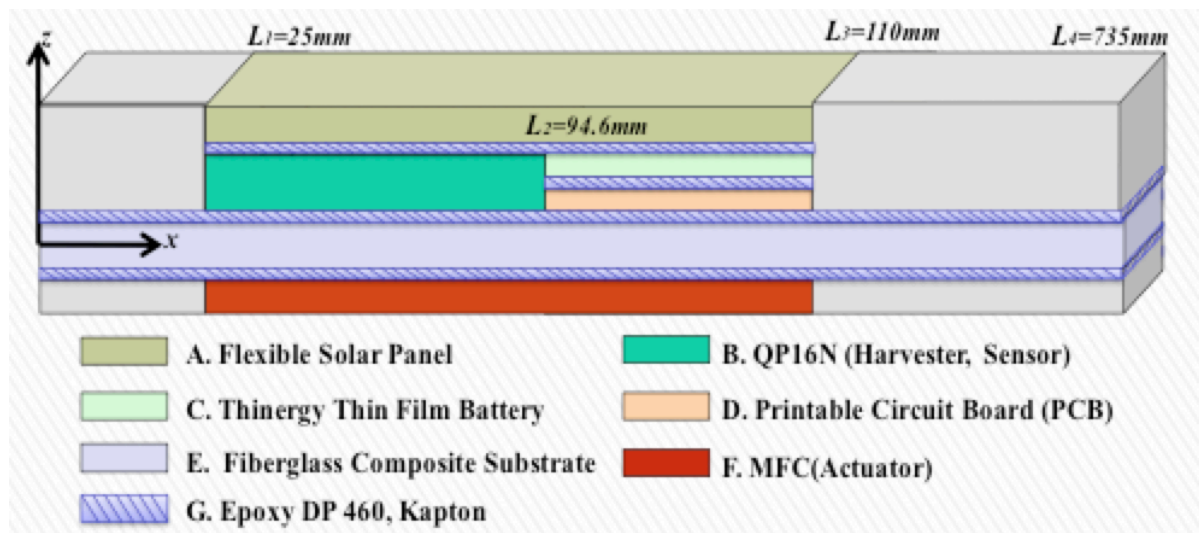


Figure 1 Schematic of a multifunctional structure containing harvesting, control, energy storage and computing.

The goal here was to integrate all of these components in order to provide a multifunctional system capable of the following functions:

1. Energy harvesting
2. Sensing
3. Energy Storage
4. Vibration Suppression Using Active Control
5. Embedded Computing (providing energy management and control laws)
6. Structural Integrity

This was all fabricated, modeled and tested. However before proceeding the harvesting, sensing and control authority of several different types of piezoelectric material were considered, in order to choose the best components for each task. It turns out that macro fiber composites form the best control actuation devices and monolithic piezoceramic forms the best sensing and harvesting device. All these results were validated with extensive experiments and documented in the papers referenced below.

*Application* Following these initial results the concept of a multifunctional composite beam was applied to a problem prevalent in unmanned air vehicles (UAVs). UAVs tend to be light and travel near their flutter speed, which means that they are susceptible to instabilities caused by gusts. The basic idea to solve this is as follows. While the UAV is in normal flight, its wing vibrates. The multifunctional wing spar, modeled after Figure 1, would transfer the wing vibration into electrical energy and store it in the embedded battery. When the UAV hits a gust, the sensor function of the multifunctional spar would then see the increases strain and turn on the active control system embedded in the PCB part of the spar. The resulting feedback control law would then quiet the gust response and keep the vibration suppressed during the period of the gust. A laboratory demonstration of this is pictured in Figure 2. The PCB circuit with control system and power management is clearly visible. The QP10N is used for both harvesting and sensing while the embedded macro fiber composite (MFC 8528P1) is used to provide the control actuation.

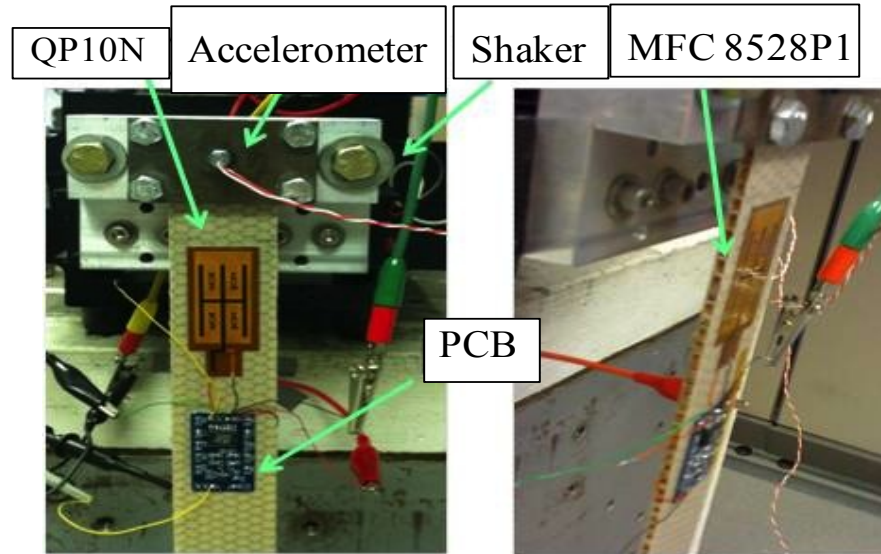


Figure 2 Photographs of the experimental validation of the multifunctional structure suggested in Figure 2, cable of performing harvesting and control based on harvested energy.

The laboratory results show great agreement with the theoretical models and numerical simulations. Figure 3 illustrates comparisons between simulations based on the modeling and experimental responses for displacement voltage and current for the multifunctional wing spar shown in Figure 2. Two different controllers are used. A positive position feedback controller (basically a second order filter) and the reduced energy controller to illustrate the settling time is about the same while the energy consumed is much less.

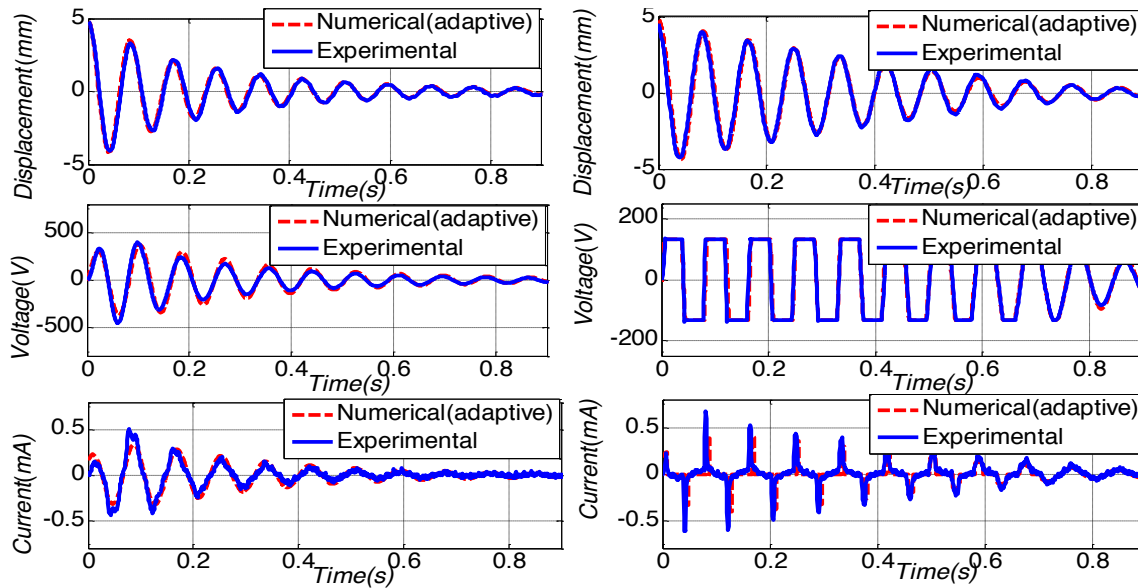


Figure 3 The plots on the left are comparisons between simulations and experiment for a standard positive position feedback controller and the plots in the right hand column are for the clipped or reduced energy controller.

With excellent validation of the model in hand, we next used simulations to predict how the system would behave as a gust suppression system for a small UAV. This is summarized in Figure 4, which illustrates the response of the system to gusts. The gust and clear sky condition (the condition of vibration induced during normal flight) are simulated using the Dryden PSD signal for both clear sky and gust. The plots indicate both conditions, clear sky in red and gust in blue.

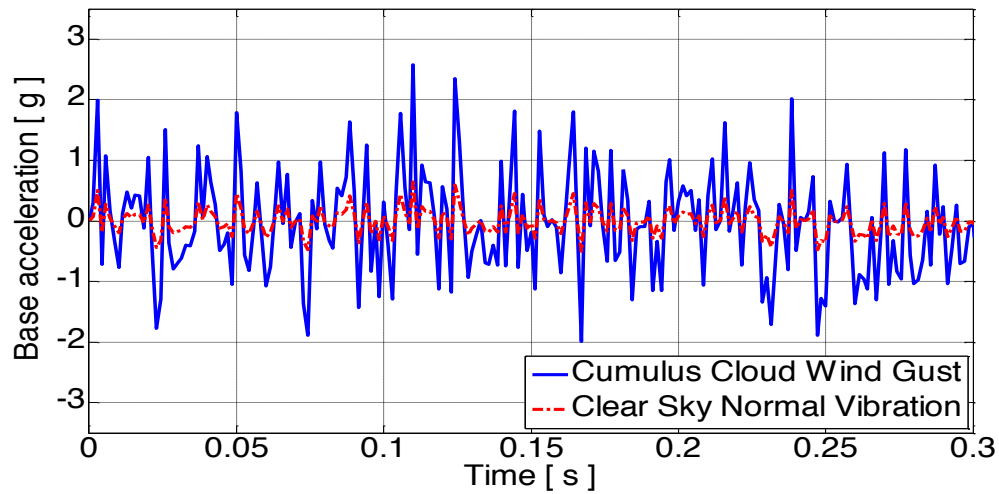


Figure 4 Vibration response due to flow simulated using Dryden PSD.

The simulations listed in Figure 4 are fed into the model of the multifunctional wing spar. The results are illustrated in Figure 5. Here the response of a the wing to a gust is giving showing a large tip deflection (blue line). The red line illustrates the response of the wing tip with the controller turned on and the gust as input. Substantial vibration reduction results.

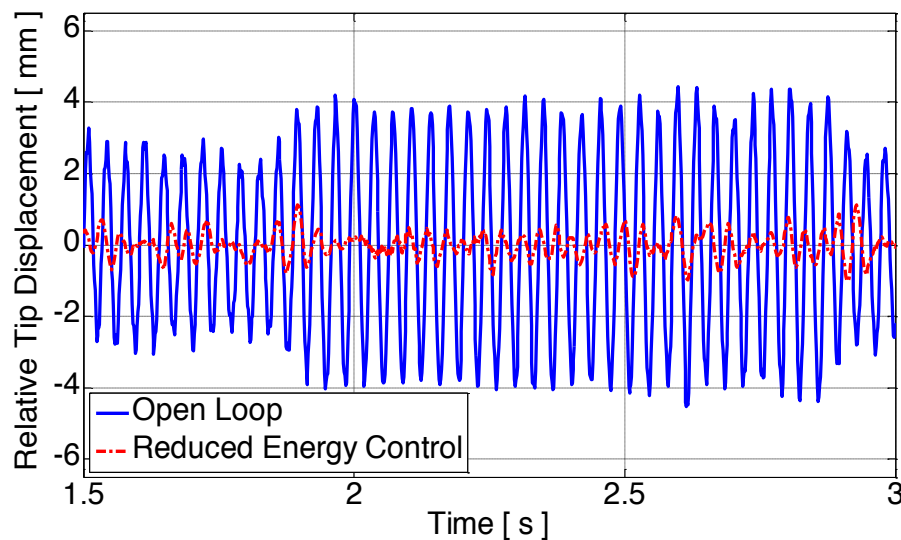


Figure 5 The results of the reduction in vibration (red) from a gust induced vibration (blue) using the multifunctional wing spar concept.

Other results that spun off of the proposed research include, a MEMs based energy harvesting device, the use of nonlinearity to improve the amount of energy captured by improving the mechanical efficiency and a look at harvesting impacts. These results as well as those mentioned above are all delineated in the papers and dissertations listed below.

### Conclusion and Outlook

This report gives an overview of the work performed under this funding and does not provide details. The complete details of the simultaneous harvesting and control effort can be found in the PhD dissertation of Ya Wang listed below which is free to download and publicly available. The other dissertations listed are also freely available and contain details that Wang's dissertation built off of. The main idea is that there are applications where harvested energy can be of use, even when the energy requirements exceed those that are required, if there is not a constant need for that energy. This is surely the case illustrated here with the gust alleviation example. However many other examples exist in the

area of structural health monitoring. The main contribution here is to show that closed loop control can be accomplished with harvested energy.

Future work could focus on combining modes of energy and to investigate applications to satellite vibration suppression systems.

### **Outreach:**

#### **Honors:**

Honorary Professorship, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu, China, awarded October 2009

The 2009 Structural Health Monitoring Lifetime Achievement Award, awarded September 2009

The 2009 Dean's Award for Excellence in Research, Virginia Tech, awarded April 2009

#### **Books**

Inman, D. J., *Engineering Vibration*, Prentice Hall, Upper Saddle River, NJ, 1994, 1996 (7th printing in 1999); Second edition, August 2000 (9<sup>th</sup> printing in 2006); Korean edition, January 2003; Third edition, 2007, 4<sup>th</sup> Edition, 2013.

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Bilgen, Onur, Aerodynamic and Electromechanical Design, Modeling and Implementation of Piezocomposite Airfoils, August 2010 (co-advised with Kevin Kochersberger in ME Dept.); currently an Assistant Professor at Old Dominion University, Norfolk, VA

#### **Book Chapters and Edited Books**

Babista, F. G., Filho, J. V. and Inman, D.J., "Structural Health Monitoring Based on Piezoelectric Transducers: Analysis and Design Based on the Electromechanical Impedance" Part V (Chapter 28) *Smart Sensors for Industrial Applications*, Ed K. Iniewski, May 2013, CRC Press.

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#### **Keynote/Plenary/Invited Addresses:**

Inman, D. J., "Genomics of Multifunctional Structures and Materials for Flight", Structures, Structural Dynamics and Materials (SDM) Conference Lecture (Keynote), 54<sup>th</sup> AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Boston, MA USA

- Inman, D. J., "Structural Health Monitoring, Control and Inverse Problems", Keynote Address, 2012 Inverse Problems Symposium, Michigan State University, June 10-12, 2012.
- Inman, D. J., "Smart Materials for Aerospace Structures: Harvesting and Morphing," 52<sup>nd</sup> Israel Annual Conference on Aerospace Sciences, 29 February- 1 March, 2012, Tel Aviv and Haifa, Israel.
- Inman, D. J., "Harvesting Energy from Vibrations: Making the Most of Nonlinearity," Belfer Symposium, The Technion, Haifa, Israel, February 27, 2012.
- Inman, D. J., "What Happened to 30 Years of IMAC Papers" Opening keynote address, IMAC, Society of Experimental Mechanics, Jacksonville, Florida, January 30, 2012.
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- Wang, Y. and Inman, D. J., "Experimental Validation of Simultaneous Gust Alleviation and Energy Harvesting for Multifunctional Composite Wing Spars", ASME Conference on Smart Materials, Adaptive Structures and Intelligent Materials, Stone Mountain, Georgia, September 19-21, 2012, paper number SMASIS2012-8176.
- Wang, Y. and Inman, D. J., "Experimental Validation of a Multifunctional Wing Spar Design with Sensing, Harvesting and Gust Alleviation Capabilities", *Proceedings AIAA 53<sup>rd</sup> Structures, Structural Dynamics and Materials Conference*, 23-26 April, Honolulu, Hawaii, Paper number AIAA-2012-1560.
- Wang, Y. and Inman, D. J., 2012, "Experimental Validation of Simultaneous Gust Alleviation and Energy Harvesting for Multifunctional Composite Wing Spars", *Proceedings SPIE's Smart Structures and NDE Conference*, San Diego, CA March 11-15, 2012, on CD, paper number 8341-102.
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