REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
15-08-2013

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*
15-08-2009 to 15-08-2013

4. TITLE AND SUBTITLE
Simultaneous Vibration Suppression and Energy Harvesting

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-09-1-0625

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Virginia Tech CIMSS M/C 0261 Blacksburg, VA 24061

8. PERFORMING ORGANIZATION REPORT

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

B.L. "LES" LEE, AFOSR 875 N.
Street, 703 696 8483 8483

10. SPONSOR/MONITOR'S ACRONYM(S)
AFMC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A for public Release

13. SUPPLEMENTARY NOTES

. ABSTRACT
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.

15. SUBJECT TERMS
Composites, Energy Harvesting, Self-sensing, Simultaneous Control, Gust Suppression

16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Daniel J. Inman
Unclassified	Unclassified	Unclassified	UL	11	**19b. TELEPHONE NUMBER** *(include area code)* 734 936-0102

Contract/Grant Title: "Simultaneous Vibration Suppression and Energy Harvesting"

Contract /Grant #: FA9550-09-1-0625

Reporting Period: 15 August 2009, to 14 August 2013

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 where 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 than 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. Theses bang-bang or saturation controllers clearly used the least amount of energy to produce the same performance.

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

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.

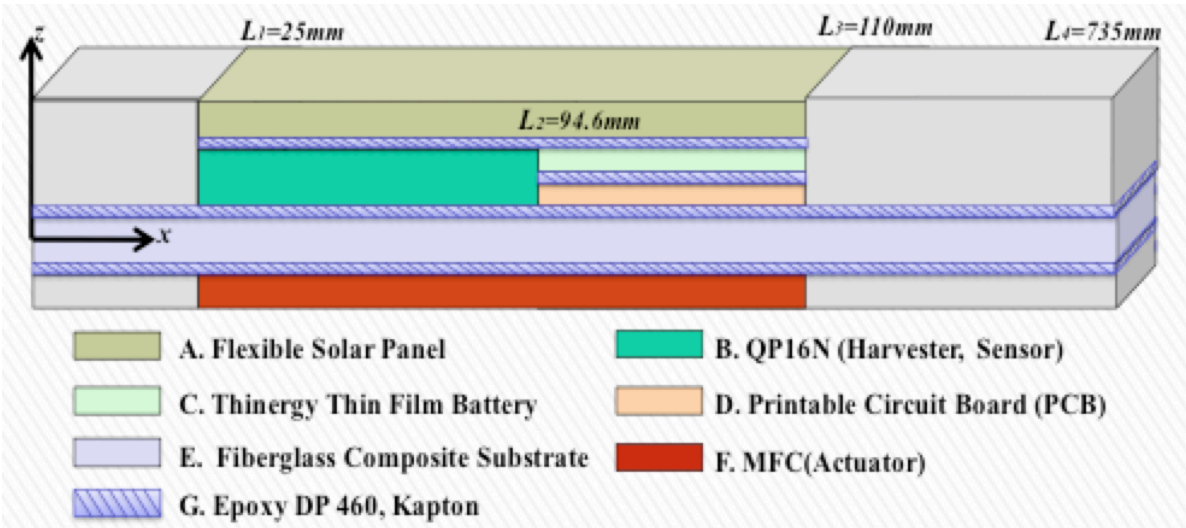

Figure 1 Schematic of a multifunctional structure containing harvesting, control, energy storage and computing.

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.

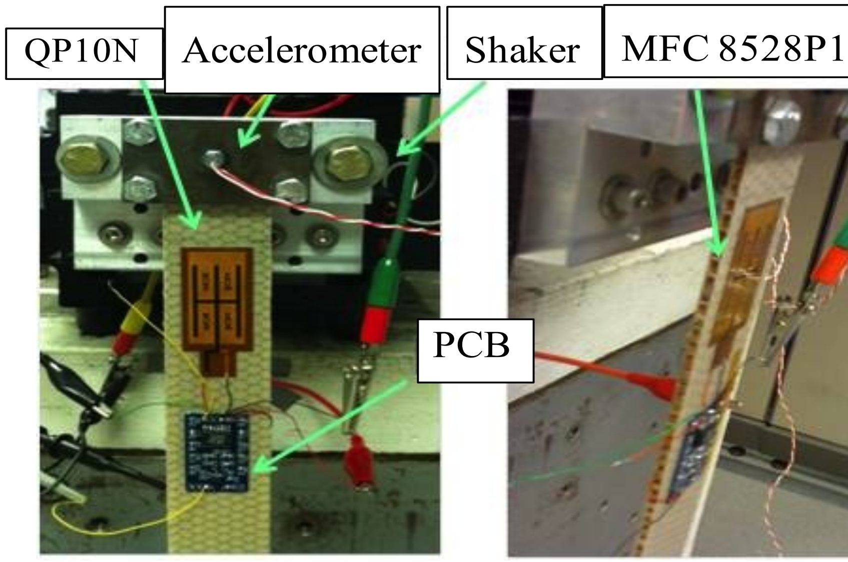

Figure 2 Photographs of the experimental validation of the multifunctional structure suggested in Figure 2, cable of perfoming harvesting and control based on harvested energy.

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.

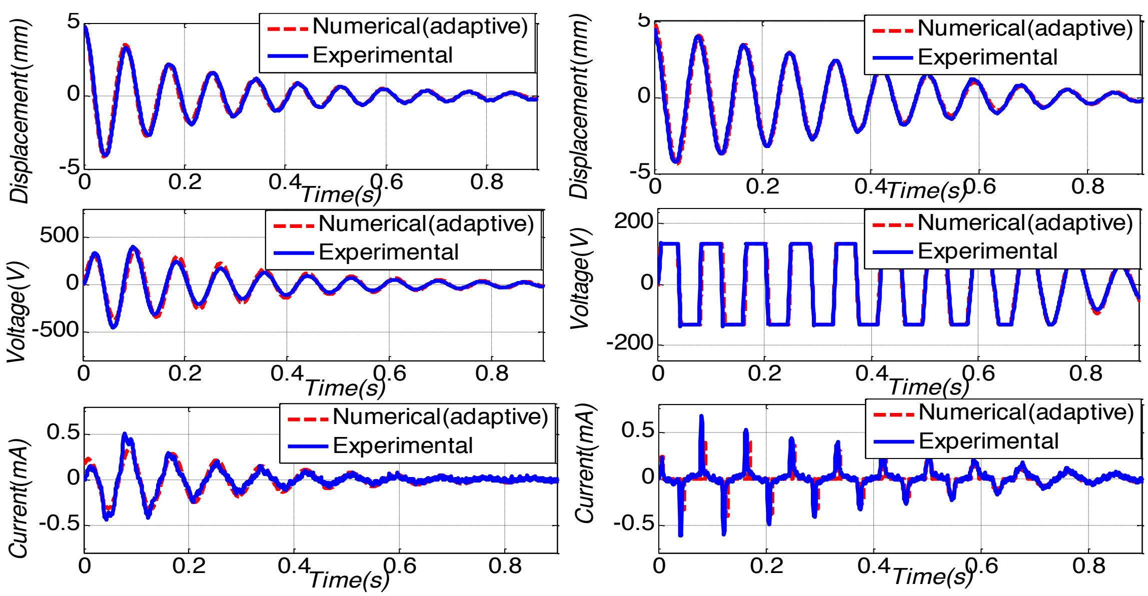

Figure 3 The plots on the left are comparisons between simulations and experiment for a standard positive position feedback controller and the plots in the right hand column are for the clipped or reduced energy controller.

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.

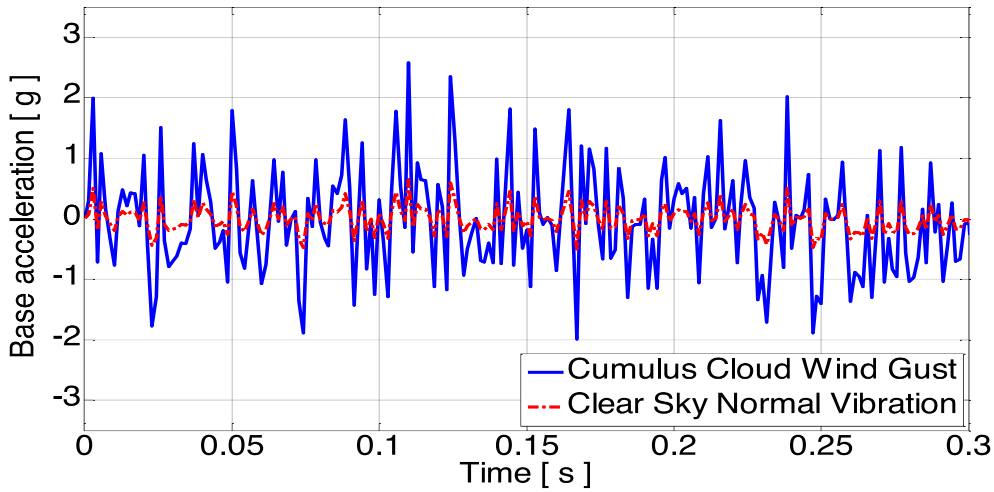

Figure 4 Vibration response due to flow simulated using Dryden PSD.

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.

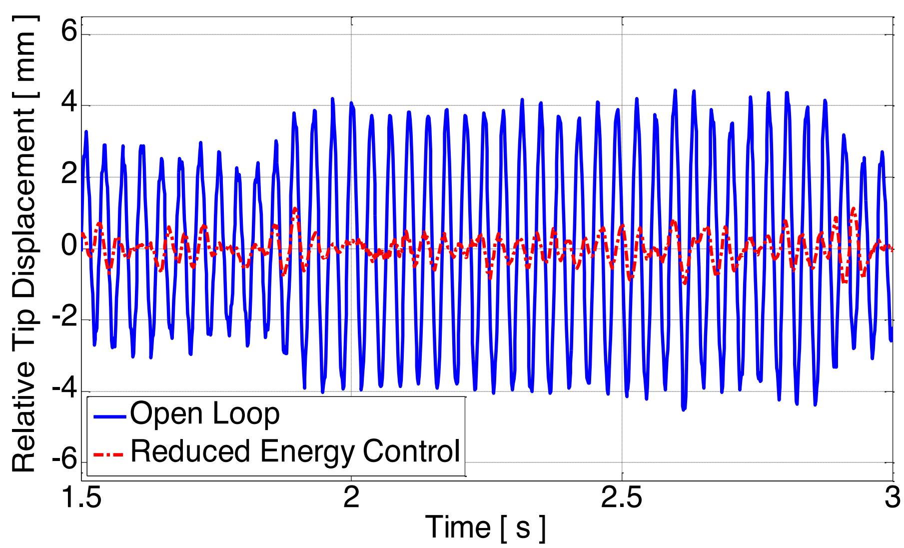

Figure 5 The results of the reduction in vibration (red) from a gust induced vibration (blue) using the multifunctional wing spar concept.

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

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Book Chapters and Edited Books

Babtista, 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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Priya, S. and Inman, D. J., Editors, 2008, *Energy Harvesting Technologies*, Springer Science+Business Media, Inc., Norwell, MA.

Keynote/Plenary/Invited Addresses:

Inman, D. J., *"Genomics of Multifunctional Structures and Materials for Flight",* Structures, Structural Dynamics and Materials (SDM) Conference Lecture (Keynote), 54th 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," 52nd 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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Inman, D. J., 2011, "Self-Charging Sensor Platforms," ASME Symposium on Multifunctional Materials and Structures (ASME McMAT 2011), Chicago, IL, 31 May to 2 June 2011 (*Keynote*).

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Inman, D. J., 2011, "Nonlinear Considerations in Energy Harvesting," EPSRC Energy Harvesting 2011, London, UK, 7 February 2011 *(Keynote)*.

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Inman, D. J., 2010, "An Overview of Smart Technologies," Institute of Mechanical Engineers Smart Technologies - Clever Thinking for Structures and Materials Conference, University of Bristol, Bristol, UK, 16 September *(Keynote)*.

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PhD’s Graduated and Supported:

1. Wang, Ya, Simultaneous Harvesting and Control, PhD, Virginia Tech, February, 2012, currently a Postdoctoral Research Associate, Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI.
2. Anton, Steve, Multifunctional Piezoelectric Energy Harvesting Concepts, PhD, Virginia Tech, April 2011; currently an assistant professor at the Tennessee Tech.
3. Erturk, Alper, Electromechanical Modeling of Piezoelectric Energy Harvesters, PhD Virginia Tech, December 2009; currently an Assistant Professor, Georgia Tech, Atlanta, GA.
4. Karami, M. Amin, Micro-Scale and Nonlinear Vibrational Energy Harvesting, June 2011, currently and Assistant Professor, State University of New York, Buffalo.
5. Anton, Steve, Multifunctional Piezoelectric Energy Harvesting Concepts, April 2011; currently an assistant professor at the Tennessee Tech.