



AFRL-RX-WP-TP-2012-0396

POLYMERIC SENSORS FOR HEALTH MONITORING OF COMPOSITE STRUCTURES (PREPRINT)

**Abhishek K. Singh, Huaxiang Yang, Rui Shen, Gusphyl Justin, and Ramil Marcelo L.
Mercado
Crosslink/Lumimove, Inc.**

**Andrew T. Zimmerman
Civionics, LLC**

**AUGUST 2012
Interim**

Approved for public release; distribution unlimited.

See additional restrictions described on inside pages

STINFO COPY

**AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE**

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE (DD-MM-YY) August 2012		2. REPORT TYPE Technical Paper		3. DATES COVERED (From - To) 1 July 2012 – 1 August 2012		
4. TITLE AND SUBTITLE POLYMERIC SENSORS FOR HEALTH MONITORING OF COMPOSITE STRUCTURES (PREPRINT)				5a. CONTRACT NUMBER FA8650-09-C-5227		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER 62102F		
6. AUTHOR(S) Abhishek K. Singh, Huaxiang Yang, Rui Shen, Gusphyl Justin, and Ramil Marcelo L. Mercado (Crosslink/Lumimove Inc.) Andrew T. Zimmerman (Civionics, LLC)				5d. PROJECT NUMBER 4349		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER X083		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Lumimove Inc./Crosslink 950 Bolger Ct. Fenton, MO 63026				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-RX-WP-TP-2012-0396		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Materials and Manufacturing Directorate Wright-Patterson Air Force Base, OH 45433-7750 Air Force Materiel Command United States Air Force				10. SPONSORING/MONITORING AGENCY ACRONYM(S) AFRL/RXCA		
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-RX-WP-TP-2012-0396		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. Preprint to be submitted to Advances in Structural Health Management and Com....						
13. SUPPLEMENTARY NOTES This work was funded in whole or in part by Department of the Air Force contract FA8650-09-C-5227. The U.S. Government has for itself and others acting on its behalf an unlimited, paid-up, nonexclusive, irrevocable worldwide license to use, modify, reproduce, release, perform, display, or disclose the work by or on behalf of the U.S. Government. PA Case Number and clearance date: 88ABW-2012-3448, 14 June 2012. This document contains color.						
14. ABSTRACT Composites are rapidly replacing metals in structural applications due to their ability to outperform metals at significant weight savings. This has resulted in the need for monitoring techniques to prevent catastrophic failures. Crosslink is developing a real-time, light-weight strain/damage sensor system that can be either embedded in or superficially bonded at strategic locations to monitor structural integrity. These sensors utilize inherently conducting polymer (ICP) films. ICP-based sensors do not deteriorate with fatigue and have been shown to possess higher strain sensing capabilities. These are capable of sensing physical stretching and acoustic waves, as well as fluctuations in humidity and temperature. Crosslink is developing modules for wireless transmission of the data to identify the location and extent of damage, along with the prediction capability of the structure's remaining service life.						
15. SUBJECT TERMS strain sensor, acoustic emission sensor, conducting polymer, structural health monitoring, wireless communication						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT: SAR	NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON (Monitor) Siamack Mazdiyasni 19b. TELEPHONE NUMBER (Include Area Code) N/A	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified				

POLYMERIC SENSORS FOR HEALTH MONITORING OF COMPOSITE STRUCTURES

Abhishek K. Singh ¹, Huaxiang Yang ¹, Rui Shen ¹, Gusphyl Justin ¹, Andrew T. Zimmerman ²,
and *Ramil Marcelo L. Mercado ¹

¹ Crosslink

950 Bolger Court, Fenton, MO 63026, USA

*Corresponding author: e-mail: rmercado@crosslinkusa.com

² Civionics, LLC

1600 Huron Pkwy, Ann Arbor, MI 48109, USA

e-mail: andy@civionics.com

ABSTRACT

Composites are rapidly replacing metals in structural applications due to their ability to outperform metals at significant weight savings. This has resulted in the need for monitoring techniques to prevent catastrophic failures. Crosslink is developing a real-time, light-weight strain/damage sensor system that can be either embedded in or superficially bonded at strategic locations to monitor structural integrity. These sensors utilize inherently conducting polymer (ICP) films. ICP-based sensors do not deteriorate with fatigue and have been shown to possess higher strain sensing capabilities. These are capable of sensing physical stretching and acoustic waves, as well as fluctuations in humidity and temperature. Crosslink is developing modules for wireless transmission of the data to identify the location and extent of damage, along with the prediction capability of the structure's remaining service life.

Keywords: Strain sensor, Acoustic emission sensor, Conducting polymer, Structural health monitoring, Wireless communication

1. INTRODUCTION

Structural health monitoring (SHM) is a process of implementing a damage sensing strategy that is expected to prevent catastrophic failure by predicting the onset of failure. However, composites may contain invisible microcracks and delaminations, which propagate under load. To date, limited information is available on the mechanisms of ageing and property degradation in the composites. The sensor system must be able to sense repetitive changes and sudden deformations. Several approaches have been proposed to detect strain in “real time” in composite structures such as optical fibers [1], electrical resistance strain gauges [2], acoustic emission [3], and piezoelectric transducers [4]. For any SHM system to be

acceptable, it must be able to withstand the rigors of composite manufacturing, if imbedded in the structure, and have non-intrusive connection systems for communication and interrogation. The focus of the current work is to develop a surface mounted sensor system sensitive to strain and acoustic waves. Crosslink has developed a processable polyaniline (PANI) formulation (PAC 1003) whose conductivity can be engineered to fit sensor needs. Films can be applied using methods such as inkjet printing and screen printing. PAC 1003 -based strain and acoustic emission sensors are shown in Fig. 1.

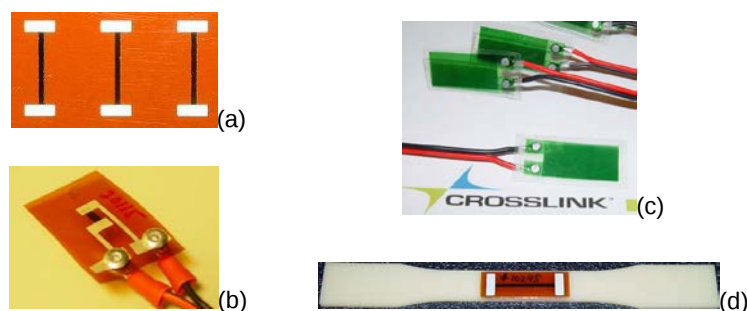


Fig. 1: Crosslink's ICP based sensors: (a) primary strain sensors, (b) modified strain sensors with modified connectivity, (c) acoustic emission sensors, and (d) a strain sensor on a test substrate.

2. SENSOR CHARACTERISTICS

2.1. Strain sensor

Strain sensors were fabricated by screen-printing PAC 1003 on a Kapton[®] substrate. Silver ink AG 530, obtained from Conducting Compounds, Inc. (Hudson, NH) was used at each end for electrical measurements. In static testing, the strain sensors showed sensitivity up to 150% strain. However, the Kapton[®] substrate failed. No deterioration in sensitivity was seen after exposing the sensors at 0.5% strain for 10^6 cycles.

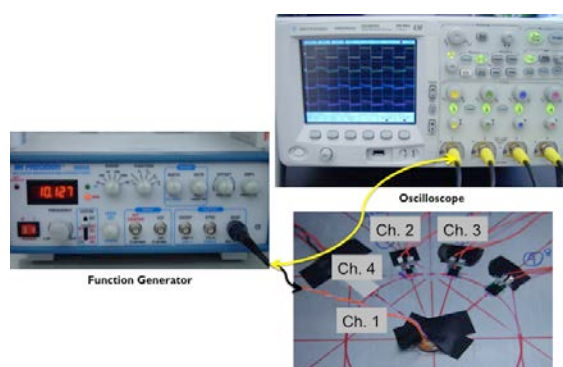


Fig. 2: Complete setup for the AE sensor characterization test. The input wave was directly fed to ch.1 of the oscilloscope and may not represent the actual vibrations generated by the piezo-transducer.

2.2. Acoustic emission (AE) sensor

ICP-based AE sensors were fabricated by printing PAC 1003 on polyvinylidene difluoride (PVDF) sheets obtained from Measurement Specialties, Inc. (Hampton, VA). A wave

generator (BK Precision 4003A) was used to generate voltage signals with selectable preset waveforms with controllable frequencies between 4 Hz and 4 MHz. A piezoelectric transducer introduced acoustic waves onto the substrate. The test setup is shown in Fig. 2. Crosslink's sensors responded to signals ranging from 10 Hz to 4 MHz while Mistras' R15 α piezoceramic sensor showed much higher signal strength between 100– 300 kHz, but showed minimal to no sensitivity at higher frequencies. The representative responses are shown in Fig. 3.

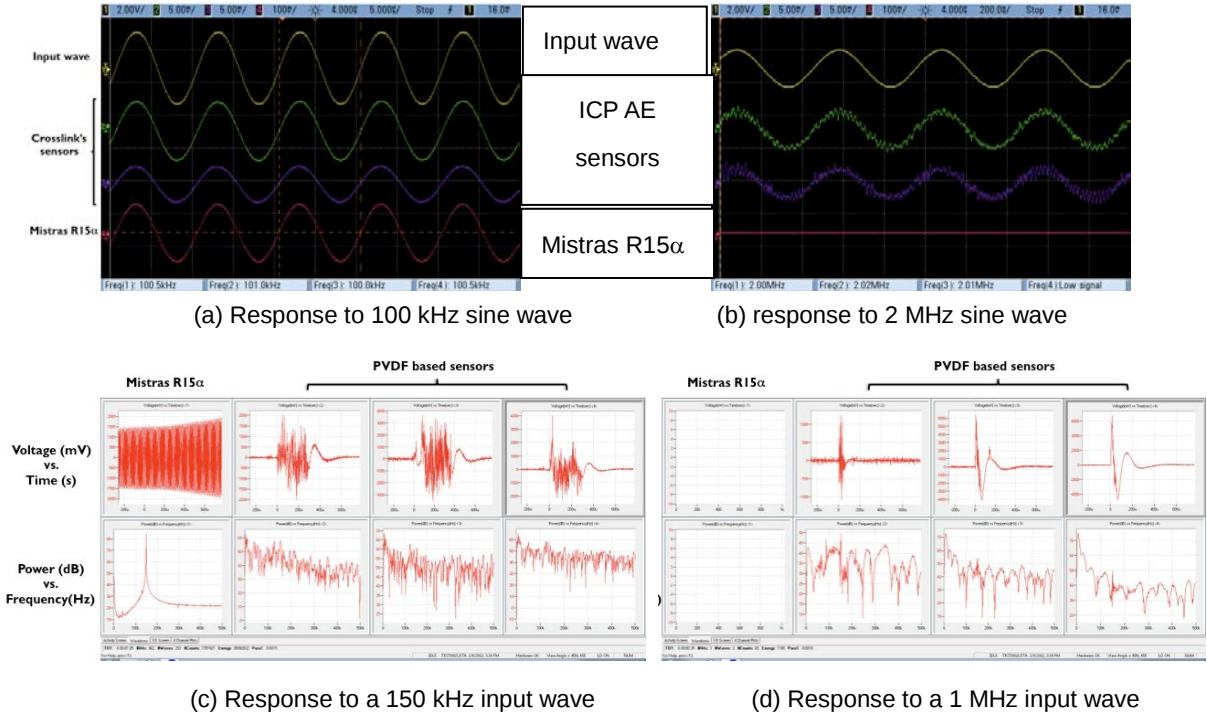


Fig. 3: Comparison of AE sensing characteristics of Crosslink's sensors and Mistras' R15 α sensor. Sensors were laid on an aluminum plate as shown in Fig. 2 (in place of ch. 4).

Figures 3(c) and 3(d) shows the AE sensor data. Mistras' sensor has a resonance frequency of 150 kHz and shows continuous wave capture and a high number of hits (not shown). However, the PVDF-ICP based AE sensors pick them as hits as well and show similar responses. The second row in 3c) and 3d represent the power spectrum and confirms the capability of Mistras' sensor at 150 kHz. PVDF-based sensors show several peaks, proving its wide range of applicability. When tested at 1 MHz, only the PVDF-based sensors pick up the signal and represent a unique advantage over piezo-ceramic sensors.

3. WIRELESS MODULE INTEGRATION

Civionics, LLC, (Ann Arbor, MI, USA) developed a wireless data acquisition system (Fig. 4) and an associated graphical user interface (GUI) system. This system abides by the IEEE 802.15.4 protocol and operates in the 2.4GHz band. It is capable of reporting the resistance

of up to four strain sensors with accuracy under $\pm 0.05\%$ and supports sampling rates of up to 200Hz. A wireless acquisition system for AE data handling is currently under development.

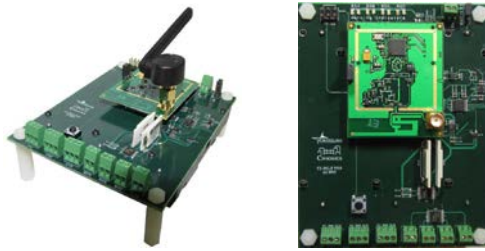


Fig. 4: Wireless sensor node for data acquisition from Crosslink's strain transducers.

4. SUMMARY & CONCLUSIONS

Crosslink has developed ICP-based strain and acoustic emission sensors. The strain sensors can be used to sense material strains up to 150% and do not demonstrate fatigue even after 1 million load cycles at 0.5% strain. ICP-based AE sensors respond to acoustic signals in a wide frequency range (100 kHz – 4 MHz). This enables ICP-based AE sensors to distinguish low frequency impact damage versus a high frequency fiber fracture in a single sensor.

5. ACKNOWLEDGEMENTS

This research is supported by the US Air Force (Contract No.: FA8650-09-C-5227). The authors are especially thankful to Siamack Mazdiyasni (WPAFB) and Dr. Charles Browning (University of Dayton) for providing helpful insights.

REFERENCES

- [1] Kuang, K.S.C., and Cantwell, W.J., "Detection of impact damage in thermoplastic-based glass fiber composites using embedded optical fiber sensors", *Journal of Thermoplastic Composite Materials*, (16), pp. 213-229, 2003.
- [2] Zhang, W., Sakalkar, V., and Koratkar, N., "In situ health monitoring and repair in composites using carbon nanotube additives", *Appl. Phys. Lett.*, (91), 133102, 2007.
- [3] Haque, A., and Raju, P.K., "Monitoring fatigue damage in carbon fiber composites using an acoustic impact technique", *Mater Eval* **56** (6), pp. 765–770, 1998.
- [4] Diamanti, K., Soutis, C., and Hodgkinson, J.M., "Piezoelectric transducer arrangement for the inspection of large composite structures", *Composites. Part A*, (38), pp. 1121-1130, 2007.