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Remote Impedance-based Loose Bolt Inspection Using a Radio-Frequency Active Sensing Node

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Abstract This paper introduces an active sensing node using radio-frequency (RF) telemetry. This device has brought the traditional impedance-based structural health monitoring (SHM) technique to a new paradigm. The RF active sensing node consists of a miniaturized impedance measuring device (AD5933), a microcontroller (ATmega128L), and a radio frequency (RF) transmitter (XBee). A macro-fiber composite (MFC) patch interrogates a host structure by using a self-sensing technique of the miniaturized impedance measuring device. All the process including structural interrogation, data acquisition, signal processing, and damage diagnostic is being performed at the sensor location by the microcontroller. The RF transmitter is used to communicate the current status of the host structure. The feasibility of the proposed SHM strategy is verified through an experimental study inspecting loose bolts in a bolt-jointed aluminum structure.

Keywords: Loose Bolt Inspection, Impedance, Piezoelectric Materials, Radio Frequency, Active Sensing Node

1. Introduction

Civil infrastructures such as buildings, bridges, dams, water supply lines, tunnels, and off-shore platforms are suffering the damage caused by fatigues, large earthquakes, strong winds, and environmental effects or traffic impact. Early detection of the structural damage or deterioration prior to local failure can prevent catastrophic failure of the structures. Sensors to monitor the structures have special requirements. They must be 1) inexpensive as many are required, 2) rugged as they are exposed to the strong elements of nature, 3) preferably wireless with some data processing capabilities, and 4) minimal power requirement or which can work with the harvested power. The large and complex civil infrastructures necessitate low cost but high effect smart sensors and appropriate technologies for data acquisition/reduction for rational health monitoring applications. The sensor systems should also be able to automatically detect, locate and assess damage anywhere within the structures, and to communicate the status to responsible authorities. In this context, this study introduces a self-contained RF active sensing node for impedance-based health monitoring of the civil infrastructures. The final goal of this research is to develop an intelligent multi-functional sensor which will utilize energy harvested from the ambient environment, analyze the sensing data on a single chip, and wirelessly provide the status of the structure to an end user.

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2. Impedance-Based Structural Health Monitoring Technique

Recent advances in the structural health monitoring (SHM) and nondestructive evaluation (NDE) field have led to the development of novel techniques such as smart sensors /sensor networks, on-line health monitoring and radio frequency (RF) telemetry. As one of the typical examples, anautomated electro-mechanical impedance-based SHM technique using piezoelectric materials has been investigated with keen interest as a powerful and innovative NDE method for local damage detection of a variety of structures, including civil, mechanical, and aerospace systems (Giurgiutiu and Rogers, 1997; Park, G. et al., 1999; Park, G. et al., 2000; Tseng et al., 2000; Zagrai and Giurgiutiu, 2001; Park, G. et al., 2003; Park, S. et al., 2004; Park, G. et al., 2005; Park, S. et al., 2005; Park, S. et al., 2006a). The electro-mechanical impedance-based SHM technique utilizes piezoelectric patch sensors such as PZT and MFC sensors as self-sensing actuators. The piezoelectric patches attached to a host structure excite the structure with high-frequency excitations, and simultaneously obtain the structural dynamic response as a shape of electrical impedance functions. By monitoring the changes of real parts of the electrical impedance functions of the piezoelectric patches, assessments can be made about the integrity of the host structure (Park, G. et al., 2003). However, the electro-mechanical impedance-based SHM technique has some limitations because the measured impedance data may have considerable deviations caused by environmental or operational condition changes, particularly a temperature change (Park, G. et al., 1999). Thus, the technique sometimes gives false-positive indication even for healthy structures. In order to overcome this limitation, an outlier analysis based on Mahalanobis squared distance (MSD) measure taking root mean square deviation (RMSD) values of impedance signatures as a damage-sensitive feature vector was proposed by Park, S. et al. (2006b). Through the proposed outlier analysis, an optimal threshold value that minimizes the false-positive indication rate could be determined.

Since the development of the piezo-ceramic materials such as PZT, they have been used extensively in the fields of sensing and actuation including the electro-mechanical impedance-based SHM techniques. However, these materials have several properties that limit their use in field applications. Due to the ceramic nature of the monolithic piezoelectric material, they are very brittle, making them vulnerable to accidental breakage during handling and bonding procedures. In addition, they have very poor ability to conform to curved surfaces and are very dense and stiff causing mass loading and localized stiffness to be a factor when working with very flexible or lightweight structures. These limitations have motivated researchers to develop alternative methods of manufacturing the next generation of piezoelectric material. To resolve the inadequacy of monolithic piezo-ceramic material for real applications, utilizing a composite material consisting of an active piezo-ceramic fiber embedded in a polymeric matrix was investigated. Typically, when in fiber form crystalline materials have much higher strengths, where the decrease in volume fraction of flaws leads to and increase in specific strength (Williams et al., 2002). In addition to this added strength of the base material, the flexibility of the polymer matrix allows the piezo-ceramic fibers to have greatly increased conformability to curved surfaces and provides a protective shell around the piezoelectric material. This polymer shell allows the piezo-fiber to withstand impacts and harsh environments far better than those monolithic piezoelectric materials. The result of configuring the piezo-fiber inside a polymer matrix is an actuator that can be incorporated into or bonded to a variety of structures. Based on above background, macro-fiber composite (MFC) actuators were constructed at NASA Langley Research Center

(Wilkie et al., 2000). The MFC consists of three primary components; active piezo-ceramic fibers aligned in a unidirectional manner, inter-digitated electrodes (IDE), and an adhesive polymer matrix, as shown in Fig. 1 (www.smart-material.com). The IDE is oriented orthogonal to the fiber direction allowing the larger d_{33} coefficient to couple the electric field to mechanical strain. This greatly improves the level of excitation applied to the structure. When embedded in a surface of the host structure, the MFC provides distributed solid-state deflection so as to efficiently excite the host structures. It is noted that the MFCs have directional sensing capability not seen in PZTs that could prove useful in damage location. In addition, the MFC electrodes are protected by Kapton, and would be robust sensors/actuators in corrosive environments. The MFC patches with above properties have been used as a self-sensing actuator for theelectro-mechanical impedance method in some previous studies (Simmers et al., 2005; Park, S. et al., 2006b).

Conventionally, the impedance-based SHM method requires the use of impedance analyzers such as HP4194A or HP4294A. Such analyzers are bulky and expensive (around 41,000 USD), and are not attractive for online SHM system. With a current trend of SHM techniques heading toward un obtrusive self-contained sensors, development of a wireless active sensing node incorporating all the function sincluding on-board actuating / sensing, power generation, on-board dataprocessing / damage diagnostic, and RF module is being strongly investigated. In particular, the approach integrating

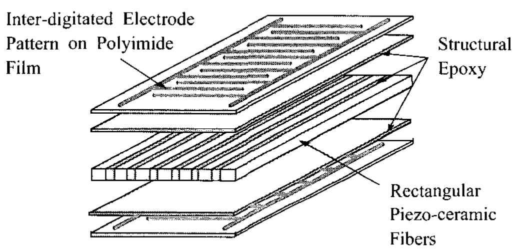


Fig. 1 A macro-fiber composite (MFC) patch (www.smart-material.com)

MEMS and RF telemetry-based active sensing systems on the electro-mechanical impedance-based damage detection technique was started with Inman and Grisso (2006).

3. Aproposed Radio-Frequency (RF) Active Sensing Node

One hardware component will need to measure the impedance of the structure of interest. Analog Devices has recently introduced single chip impedance measurement devices such as AD5933 and AD5934 (www.analog.com). The AD5933 and AD5934 impedance chips are nearly identical except for their sampling speeds. The AD5933 has a 1 MHz sampling rate, while the AD5934 uses a 250 kHz sampling speed. In order to demonstrate the functionality of the new chips, Analog Devices developed evaluation boards for both of the chips. The AD5933 evaluation board and its block diagram can be seen in Fig. 2 (www.analog.com). Using a USB connection and provided software, a user can make impedance measurements in the range of 10 100 kHz. The AD5933 primarily records the magnitude of the impedance. However, phase is also recorded, and the real and imaginary impedance components can be saved. In order to evaluate the possibility of incorporating the AD5933 chip, we compared the AD5933 impedance chip with the conventional impedance analyzer, HP4914A. The results of recording measurements in the 60 70 kHz frequency range are shown in Fig. 3. The same peaks are shown at the same frequencies between the HP4194A impedance analyzer and the AD5933 impedance chip, although the amplitudes are not same each other. The conventional electromechanical impedance-based SHM technique which uses HP4194A has never been attractive for real-world applications because they are bulky and expensive (around $40,000). Therefore, this study employs the AD5933 which is low-cost ($150) and portable. Our final device incorporating this device would be an intelligent multi- functional sensor which utilizes energy harvested from the ambient environment of the host structure, analyzes the sensing data on a single chip, and wirelessly provides the status of the structure to an end user. The big picture of the intelligent multi-functional sensor was conceptually designed by Inman and Grisso (2006), as illustrated in Fig. 4.

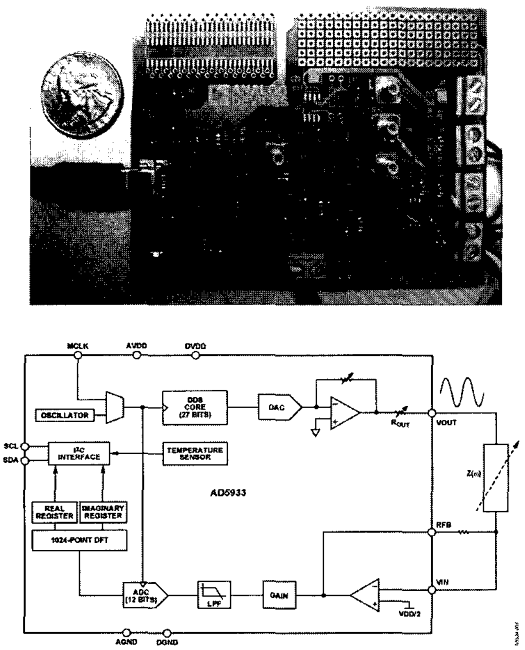


Fig. 2 A miniaturized impedance measuring chip (AD5933) and block diagram (www.analog.com)

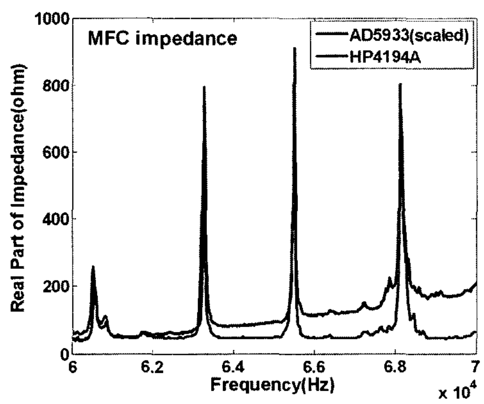


Fig. 3 Comparison of impedance measurement from AD5933 and HP4194A

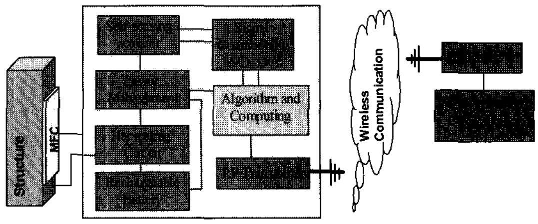


Fig. 4 An intelligent multi-functional sensor design (Inman and Grisso, 2006)

Mascarenas et al. (2006) designed a RF active sensing node which consists of a miniaturized impedance measuring device (AD5933), a microcontroller (ATmega128L), and a radio frequency (RF) transmitter (XBee), as illustrated in Fig. 5 (around \$ 300). ATmega128L is an 8-bit microcontroller (Atmel AVR) and costs \$ 5.00. It operates at low power levels, and has different peripheral features and memory capabilities. Inaddition, open-source C compilers are available. The RF transmitter utilized in this study is a 2.4 Ghz XBee radio (Maxstream). It costs only \$ 19.00 and operates from 3.3 V power supply. In addition, a variety of antenna configurations are available. Current RF module covers a range corresponding to distances of 30 m (indoor) and 100 m (outdoor).

In the on-board sensor system, all the process including structural interrogation, data acquisition, signal processing, soft computing and damage diagnosis is being carried out in near real-time at the sensor location. And only damage diagnostic result implying 'damage' or 'no damage' will be transmitted to the end-user through the RF telemetry. Finally, the LED light shows 'green' or 'red' color according to 'intact' or 'damage' state, respectively. The overall concept for online wireless SHM system using the active sensing node is displayed in Fig. 6. In reality, the individual components used to actually make up the sensor node should be able to fit on a single printed circuit board (PCB) roughly the size of a credit card. To validate the feasibility of the proposed RF technique, an experimental study inspecting loose bolts in a bolt-jointed structure is carried out.

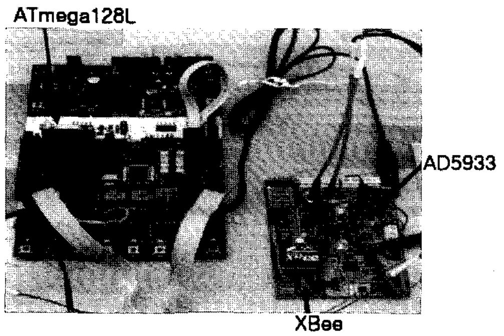


Fig. 5 A proposed RF active sensing node (Mascarenas et al., 2006)

4. Example Study

4.1 Remote Inspection Loose Bolts in a Bolt-Jointed Aluminum Beam

An example study inspecting remotely loose bolts in a bolt-jointed aluminum structure was performed. As shown in Fig. 7, the MFC patch of 4.00 x 2.54 x 0.03 cm^3 associated with the AD5933 was surface mounted to the specimen that consists of two aluminum beams of dimension 61.50 x 5.00 x 0.40 cm^3 jointed together with four pairs of bolts and nuts of diameter 8 mm. The MFC patch was placed at 16 cm apart from the middle of the joint section of the specimen. During the experiment, the boundary condition for the specimen was held as 'free-free'condition. Damage scenario for healthy and damage states repeated by several times was artificially inflicted in sequence, as described in Table 1. Electro-mechanical impedances according to the damage scenario were measured at a frequency range of 60-70 kHz from the AD5933, as shown in Fig. 8(a). Then, the RMSD metrics were calculated according to each damage case, as displayed in Fig. 8(b). An optimal threshold value for damage detection to enhance the damage detectible capability of the current system so that minimize a false-positive damage indication rate was obtained as 0.32 from an outlier analysis (Park, S. et al., 2006b). It is also noted that the damage diagnostic result implying 'damage' or 'no damage' was transmitted to the base station through the RF telemetry, and the LED light of the base station showed 'green color' on intact states and 'red color' on damage states. Conclusively, it can be said that the proposed active sensing node possesses a very

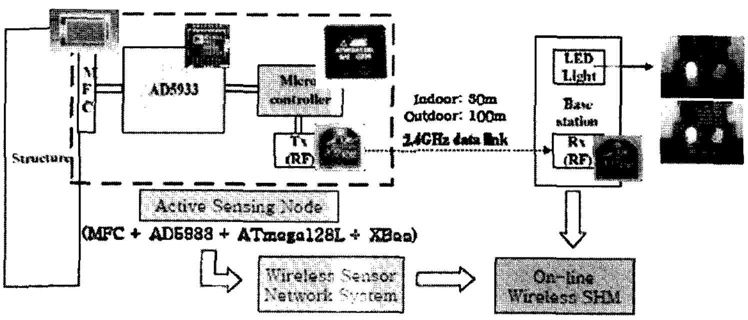


Fig. 6 Online wireless SHM system using a RF active sensing node

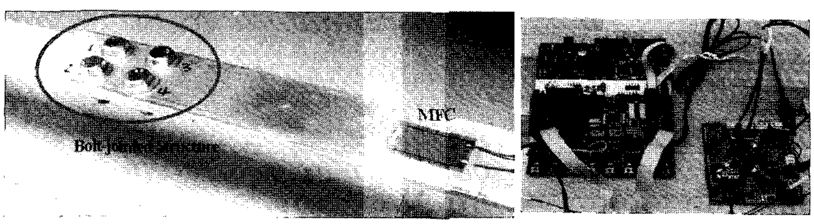


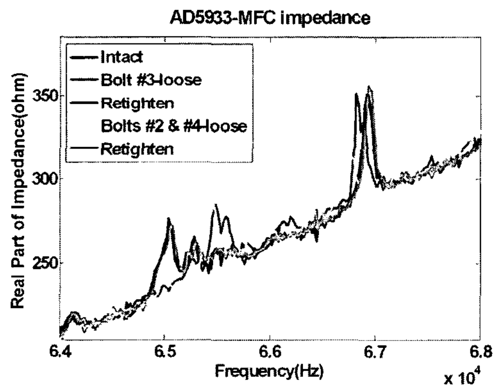
Fig. 7 Loose bolt inspection using a RF active sensing node

good damage detectible capability by providing consistent results according to bolt-loosening (damaged) and retightening (healthy) states in the bolt-jointed structure.

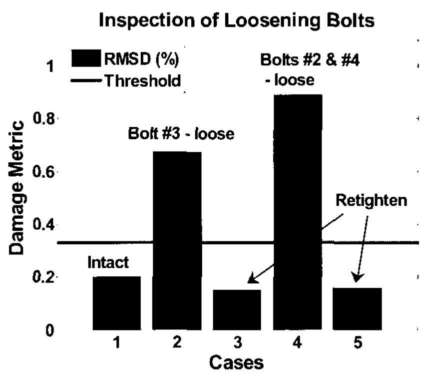
However, the above results show that the current method is difficult to detect the location of the damage, so it may be necessary to combine the method with other NDE techniques like Lamb waves or acoustic emission methods to locate the damage more exactly.

Table 1 Damage description

Cases	Scenario	Damage Descriptions
Case 1	Baseline	-
Case 2	Intact Case	Tighten
Case 3	Damage Case	Bolt #3: loose
Case 4	Healthy Case	Retighten
Case 5	Damage Case	Bolt s #2 and #4: loose
Case 6	Healthy Case	Retighten



(a) Electro-mechanical impedance signature



(b) RMSD metric results

Fig. 8 Loose bolt inspection results

5. Conclusions

This study presents experimental results using a RF active sensing node incorporating a miniaturized impedance measuring device (AD5933), an on-board microcontroller (ATmega128L) and a RF telemetry (XBee) devised for online wireless SHM system to detect damage in civil infrastructures. The scope of this study is to experimentally verify how well the electro-mechanical impedance method using the proposed RF active sensing device can detect and quantify damage which may occur in structural members. A feasibility test applying the current system to inspect remotely loose bolts in a laboratory sized bolt-jointed aluminum structure has been performed. Electro-mechanical impedance was measured according to the damage scenario designated for the test, and the changes of the impedance signature before and after damage were observed. As a result, it was confirmed that the current system can inspect remotely the loose bolts in a bolt-jointed structure. The results reported here provide motivation to apply the current RF active sensing system to in-service civil infrastructures by implying the automated on-line health monitoring technique.

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References

Giurgiutiu, V., and Rogers, C. A. (1997) Electro-mechanical (E/M) Impedance Method for Structural Health Monitoring and Nondestructive Evaluation, *International Workshop on Structural*

Health Monitoring, Stanford University, CA, September 18-20, pp. 433-444

Inman, D. J. and Grisso, B. L. (2006) Towards Autonomous Sensing, *Proceedings of SPIE's 13th International Symposium on Smart Structures and Materials*, San Diego, CA, February 26 - March 2, pp. 248-254

Mascarenas, D. L., Todd, M. D., Park, G., and Farrar, C. R. (2006) A Miniaturized Electromechanical Impedance-Based Node for the Wireless Interrogation of Structural Health, *Proceeding of SPIE's 13th Annual International Symposium on Smart Structures and Materials*, 6177

Park, G., Cudney, H., and Inman, D. J. (2000) Impedance-Based Health Monitoring of Civil Structural Components, ASCE Journal of Infrastructure Systems, Vol. 6, No. 4, pp. 153-160

Park, G., Inman, D. J. (2005) Impedance-Based Structural Health Monitoring, *Damage Prognosis for Aerospace, Civil and Mechanical Systems*, John Wiley & Sons Ltd, Part II (13), pp. 275-292

Park, G., Kabeya, K., Cudney, H., and Inman, D. J. (1999) Impedance-Based Health Monitoring for Temperature Varying Application, JSME International Journal, Vol. 42, pp. 249-258

Park, G., Sohn, H., Farrar, C. R. and Inman, D. J. (2003) Overview of Piezoelectric Impedance-Based Health Monitoring and Path Forward, The Shock and Vibration Digest, Vol. 35, No. 6, pp. 451-463

Park, S., Ahmad, S., Yun, C.-B., and Roh, Y. (2006a) Multiple Crack Detection of Concrete Structures Using Impedance-Based Structural Health Monitoring Techniques, Experimental Mechanics, Vol. 46, pp. 609-618

Park, S., Inman, D. J., and Yun, C.-B. (2006b) An Outlier Analysis of MFC-Based Impedance Sensing Data for Wireless Structural Health Monitoring of Railroads, Engineering Structures, accepted for publication

Park, S, Roh, Y., Yi, J. H., Yun, C. B, Kwak, H. K., and Lee, S. H. (2004) Impedance-Based Damage Detection for Civil Infrastructures, *Smart Structures and Materials, Proc. of SPIE*, 5391, pp. 705-716

Park, S., Yun, C.-B., Roh, Y., and Lee, J.-J. (2005) Health Monitoring of Steel Structures Using Impedance of Thickness Modes at PZT Patches, Smart Structures and Systems, Vol. 1, No. 4, pp. 339-353

Simmers Jr., G. E. (2005) Impedance-Based Structural Health Monitoring to Detect Corrosion, Mater's Thesis, Center for Intelligent Material Systems and Structures, Virginia Polytechnic Institute and State University

Tseng, K. K., Soh, C. K., Gupta, A., and Bhalla, S. (2000) Health Monitoring of Civil Infrastructures Using Smart Piezoceramic Transducers, 2^{nd} *Int. Conf. on Comp. Meth. For Smart Str. And Mat.*, pp. 153-162

Wilkie, W. K., Bryant, R. G., High, J. W., Fox, R. L., Hellbaum, R. F., Jalink, A., Little, B. D., and Mirick, P. H. (2000) Low-Cost Piezocomposite Actuator for Structural Control Applications, *Proc. of 7th SPIE Int'l Symposium on Smart Structures and Materials,* Newport Beach, CA, March 5-9

Williams, B. R., Park, G., Inman, D. J. and Wilkie, W. K. (2002) An Overview of Composite Actuators with Piezoceramic Fibers, *Proceeding of IMAC XX,* Los Angeles, CA, February 4-7

www.analog.com

www.smart-material.com

Zagrai, A. N. and Giurgiutiu, V. (2001) Electro-Mechanical Impedance Method for Crack Detection in Thin Wall Structures, *3rd Int. Workshop of Structural Health Monitoring*, Stanford Univ., CA, September 12-14