A Structural Health Monitoring System for Self-repairing

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ABSTRACT

Shape memory alloy (SMA) washers expand axially when heated, and the expansion for the one-way type SMA is permanent even if the heat is removed. We investigated a method to repair bolted joint loosening defects using SMA washers. We incorporated such a feature into our impedance-based structural health monitoring (SHM) system. An SMA washer wrapped with a heater is installed between a bolt and the nut. Upon detection of a loosening defect, the heater is turned on to expand the SMA washer, which in turn repairs the defect. Our experimental results show that (i) our enhanced SHM system can detect bolted-joint loosening defects, and (ii) it can repair such defects effectively. Our system suggests that self-repairing of some structural defects is feasible without human interventions.

Keywords: structural health monitoring, impedance method, PZT, self-repairing, shape memory alloy

1. INTRODUCTION

Self-repairing or self-healing is the highest level of structural health monitoring. A self-repairing system reacts to damage and produces some action to restore it to its undamaged condition after damage has been detected, located and quantified and possibly after parameters such as remaining life (damage prognosis) has been determined. It is crucial for some applications such as in-flight airplanes, spacecrafts deployed in space, and infrastructures in remote areas. Efforts has been made to realize self-repairing concept throughout various projects such as self-healing concrete, polymer composites, and self-healing space suit bladders [1].

Bolted joints are one of the most common mechanical components in all types of engineering structures. It was estimated that approximately 70% of all mechanical failures occur due to fastener failure [2]. The concept of self-sensing and self-repairing bolted joints was initially investigated by Muntges et al [3]. The concept was developed further by combining the impedance-based SHM technique with actuators to restore the tension of a loose bolt [2]. Shape memory alloy (SMA) washers expand axially when heated. The expansion of one-way type SMA washers is permanent even if the heat is removed. An SMA washer and a heater can act as an actuator for self-repairing bolted joints. Various methods and models for washer actuation have been proposed [4][5].

Previously, we developed a self-contained impedance-based SHM system using a digital signal processing (DSP) evaluation board [6]. Our SHM system adopts rectangular pulse trains, instead of sweeping sinusoidal signals, to excite the structure and senses the phase, not the magnitude, of the response signal. Therefore, our system is much simpler in hardware and dissipates far less power compared with other existing systems. We modified our SHM system to incorporate a self-repairing capability by adding necessary circuits (such as a heater power controller) and modifying necessary software. In addition, we added GUI (Graphic User's Interface) to our system, which eased the development process.

The paper is organized as follows. Section 2 describes our impedance-based SHM system and detection and repair of bolted joints. Section 3 describes the overall system architecture and the GUI for our system. Section 4 presents experimental results for self-repairing of a bolted joint, and Section 5 draws conclusions from our work.

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2. PRELIMINARY

We describe our impedance-based SHM method, which is used to detect loose bolted joint defects. We also describe the efficacy of self-repairing concept exploiting integration of our SHM method and SMA washers.

2.1. Impedance-based Structural Health Monitoring

The impedance method has many advantages over other damage detection methods. The small wavelengths at high frequencies allow the impedance method to detect minor changes in structural integrity. The impedance method can monitor the interior of complex structures, is very sensitive to changes in structural integrity, and often detects incipient damage at a far earlier stage than alternative systems [7]. Many examples, including bolted joints, gas pipelines, and composite structures, were investigated to illustrate effectiveness of the impedance technique to a wide variety of applications [8].

System Operation and Architecture:

We have developed an impedance-based digital SHM system [9][10]. Major differences for our digital impedance-based SHM system from traditional systems lie in the excitation signal and sensing the response. Our system excites a PZT with a train of rectangular pulses instead of a sinusoidal signal and measures the phase of the response signal instead of the magnitude. Figure 1 (a) shows a pulse train, whose pulse repetition period or the fundamental frequency changes to sweep the target frequency range. Use of a pulse train simplifies the excitation signal generation and eliminates a digital-to-analog converter (DAC). A pulse train introduces harmonic terms as shown in Figure 1 (b) and (c). Harmonic terms would not cause a problem in practical sense, as they would cause the same effect for healthy and damaged structures.

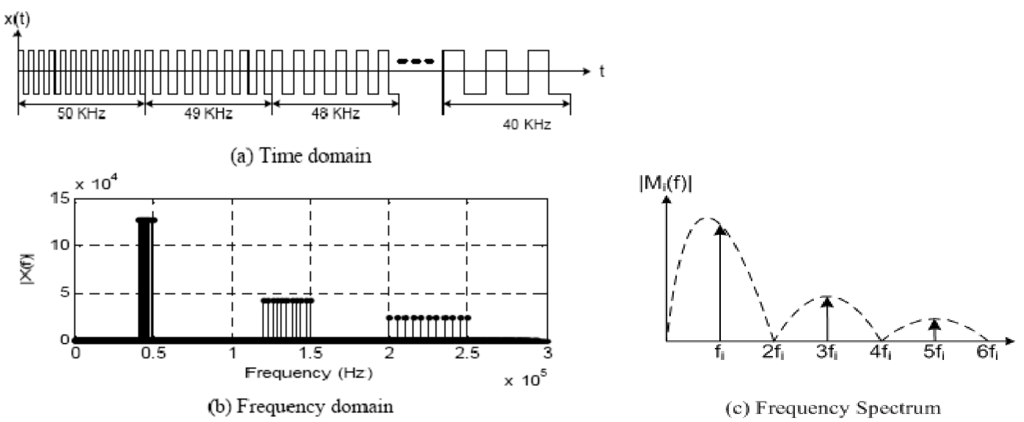


Figure1: Excitation Signal for Our Digital SHM system

Our digital SHM system measures the phase difference, specifically the time difference between the voltage and the current exerted to the structure. The measurement of the phase difference eliminates an analog-to-digital converter (ADC) and an FFT (Fast Fourier Transform) operation, which simplifies the complexity of the system in hardware and in computation.

The excitation and sensing part of our SHM system is shown in Figure 2. A digital signal processing (DSP) generates a train of rectangular pulses, which are applied to a PZT patch. The opamp output voltage $V_o(t)$, which represents the current through the PZT patch, is converted into a binary signal by the comparator. The binary signal and the input voltage $V_i(t)$ are compared using an exclusive-OR (XOR) gate to measure the phase difference of the two signals, i.e., the voltage and the current of the PZT patch.

More specifically, a train of pulses with each fundamental frequency f is applied for 10 ms. The XOR gate continuously compares the input voltage $V_i(t)$ and the binary signal of the output voltage $V_o(t)$. The output (either 1 or 0) of the XOR gate is sampled at the rate of 100 kHz, and its value is accumulated. It can be seen easily that the resultant accumulated value is $N\phi(f)$, where N is a constant depending on the sampling rate and duration of the train of pulses. The constant N is 160 for our SHM system. In order to avoid use of fractional numbers, the phase $\phi(f)$ is represented as an integer value $N\phi(f)$ for our system hereafter.

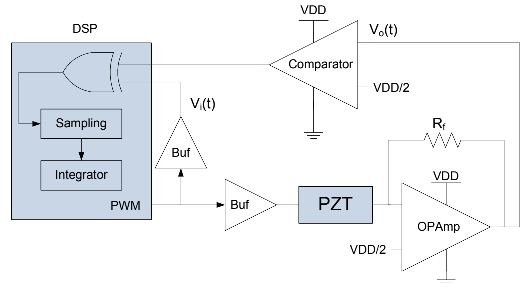


Figure 2: Excitation and Sensing Part of Our SHM System

Phase Profile and Damage Metric:

The excitation frequency f is swept from the target frequency range from f_l to f_h with increment of 0.12 kHz. The phase profile of a structure represents a set of phase values $\phi\ (f_i)$'s, where f_i is discrete values between the frequency range f_l to f_h with increment of 0.12 kHz. As noted above, we use an integer value to represent a phase $\phi\ (f_i)$ instead of the actual phase value.

The damage metric (DM) for our system is defined as an *absolute sum of difference (ASD)* between the baseline profile and the phase profile of the structure under test (SUT) and is calculated as below.

$$\mathrm{DM} = \sum_{f=f_1}^{f_2} \left| \phi_{base}(f) - \phi_{SUT}(f) \right|$$

The DM is compared against a threshold value, which may be set based on field experience. If DM is lower than the threshold value, the SUT is considered healthy. Otherwise, it is considered as damaged.

Prototyping of Our Digital SHM System:

Figure 3 shows a prototype developed with a DSP (digital signal processing) evaluation board (TMS320F2812 from Texas Instruments) and a breadboard for the interface circuit such as opamps. Since our system does not require an ADC and a DAC, our system is compact and power efficient.

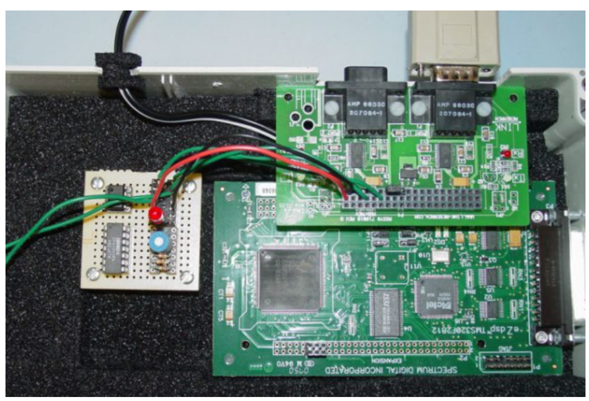


Figure 3: Prototype of Our Digital SHM System

2.2. Detection and Repair of Loose Bolted Joints

According to experimental results reported in [7], an impedance method can detect loose bolted joint defects. Figure 4 shows the real portion of measured electrical impedances of a bolted joint at 40 Nm of torque and at 10 Nm of torque. The sharp peaks in the real part of electrical impedance are one of the structural resonance frequencies, and a loose bolted joint causes a change in the impedance profile. When the applied torque is decreased, the peaks generally shift leftwards, which suggests a reduction of joint stiffness. In addition, the peak amplitudes are also reduced, which indicates increases in structural damping.

Peairs et el. proposed and demonstrated impedance-based repair assessment and self-healing called *SmartJoint* [1]. This concept combines the impedance-based health-monitoring technique with actuators to restore tension in a loose bolt. As shown in Figure 5, the damage control portion in the SmartJoint utilizes an SMA washer as an actuator which is installed between a bolt and the nut. SMA converts heat to mechanical energy through a phase transition and applies stress along the axis of the bolt shaft. The stress compresses the bolted members and creates a force, which effectively generates a preload and restores the lost torque. SMA produces relatively large strain (up to 10%) upon actuation, so that it is a good candidate to actively control the bolt preload. Among the several types of SMA technologies, one-way shape memory actuator is preferred for the SmartJoint because in most cases it remains in its high temperature configuration after cooling.

There are two possible heating methods for an SMA washer, resistive heating and use of an external heater [1][2]. The resistive heating treats an SMA ring as a solid wire and exploits the internal resistance of the SMA ring for heating. For example, [1] reports an SMA washer with the outer diameter of 26.7 mm and the length of 9.69 mm has resistance of 0.0018 Ω. It required 162 W to heat the ring for their experiment and a measure for electrical and thermal isolation. An external heater can address the problems. An external heater can heat an SMA ring with relatively small power, 12.5 W for our experiment. Use of an external heater eliminates the need for large wires and unconventional power sources. However, an external heater poses new issues such as maintaining contact with a shrinking ring and an increased possibility of uneven heating. These issues can be addressed with an insulation silicon tape, which aids to maintain contact with an SMA, preventing uneven heating. Considering the advantages, we adopted an external heater for our experiments.

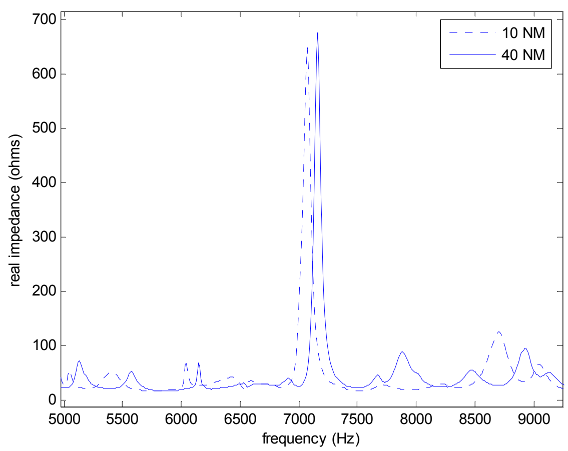


Figure 4: Impedance Profile of a SmartJoint

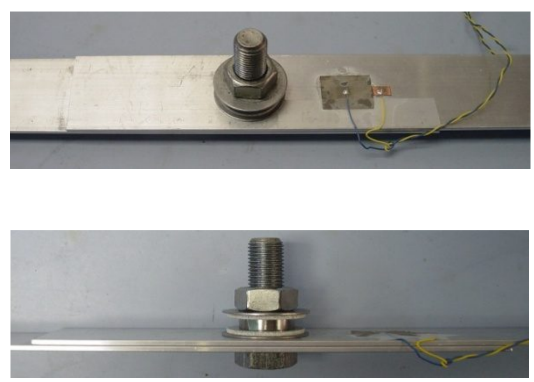


Figure 5. A SmartJoint

3. SELF-REPARING SHM SYSTEM

3.1. System Architecture

Figure 6 shows an overall SHM system architecture for self-repairing of loose bolted-joint defects. It comprises three functional blocks: an impedance-based SHM system, a heater power controller with a battery, and a structure equipped with a SmartJoint. Our impedance-based SHM system is based on a TMS320F2812 Evaluation Module (EVM) from Texas Instruments. The DSP (Digital Signal Processing) processor TMS320F2812 for the evaluation board is 32-bit fixed-point and supports up to 150 million instructions per second (MIPS) [11]. Use of a fixed-point (instead of floating point) and a relatively slow processor saves power consumption for our SHM system in addition to elimination of a DAC and an ADC as explained earlier.

The heater power controller controls delivery of power to the external heater attached to an SMA and consists of a buffer, a relay, and a battery. The buffer implemented with two opamps turns on or off the relay, and the relay requires a minimum of 9 V and 18 mA to maintain the turn-on state. When the relay is turned on, the Li-ion battery supplies about 12.5 W (or 10 V and 1.25 A) to drive the heater.

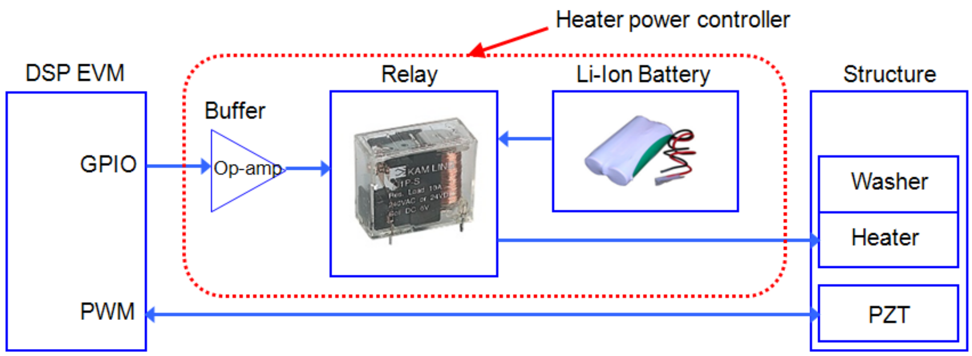


Figure 6: Overall System Architecture

3.2. Graphic User Interface

In order to ease the control of our impedance-based SHM system and to access the impedance profile of the structure under test, we have developed a graphic user interface (GUI) for a PC, which can communicate with our SHM system via a serial communication port. The speed of the serial port is 2400 bits per second, and it takes 0.46 second to transfer an impedance profile from the SHM system to the PC or in the other direction.

The GUI window and test flow for our system are shown in Figure 7. After an initial set up, the baseline impedance profile may be generated from the current structure (assuming the current structure is healthy) or a pre-generated profile can be uploaded from the PC. Users set the sweeping frequency range (with the upper limit of 2.5 MHz) and select a scheme to obtain the threshold value for the damage metric. A threshold value can be obtained by several means such as from the variance or the mean value of the current structure under test or a reference (or healthy) structure. It is also possible that the threshold value can be set to a certain value manually. When the "Run" button is clicked, the system uploads the settings to the SHM system, performs the SHM operation, and displays summarized results on the PC and stores the impedance profile in a directory. "Offline Test" is useful for field testing, in which the SHM system can run autonomously without a PC (once the settings are uploaded from a PC to the SHM system).

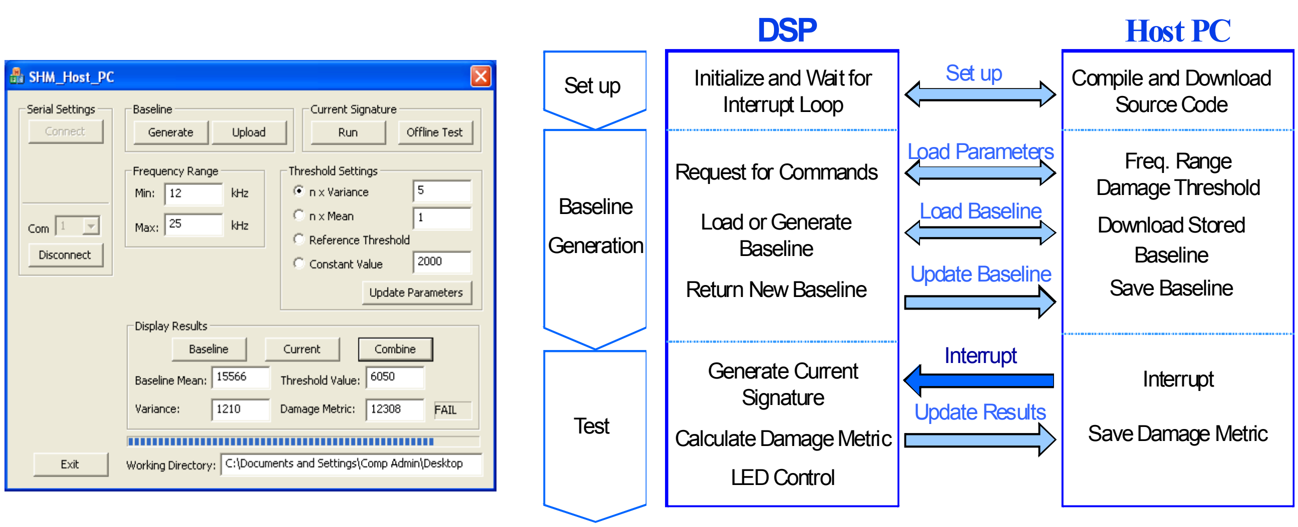


Figure 7: The GUI and the Test Flow for Our SHM System

4. EXPERIMENTAL RESULTS

We experimented with our SHM system to repair loose bolted joints and present experimental results in this section.

4.1. Test Specimen and a SmartJoint

The SHM system set up for our experiments is shown in Figure 8. The test specimen is two identical aluminum beams bolted together with a SmartJoint. Each beam is 298 mm long, 50 mm wide, and 3 mm thick. The overlap of the two beams is 194 mm long and are connected by a 16.5 mm bolt. A PZT sensor with size of 27 × 22 mm is attached to an aluminum bar and is apart 5 cm from the bolt. A close up picture of the SmartJoint is shown in Figure 9. The outer layer of the metal bolt is an SMA washer with the inner diameter of 24.4 mm, the outer diameter of 26.7 mm, and 9.7 mm long. A ceramic washer with diameter 34 mm is attached at each end of the SMA washer to reduce the thermal loss, and steel plate washers follow the two ceramic washers. Finally, an external heater is wrapped around the SMA washer. The flexible heater has size of 1 mm × 7.6 mm × 79 mm and is from Minco Products (model HR5208R6.4L12A).

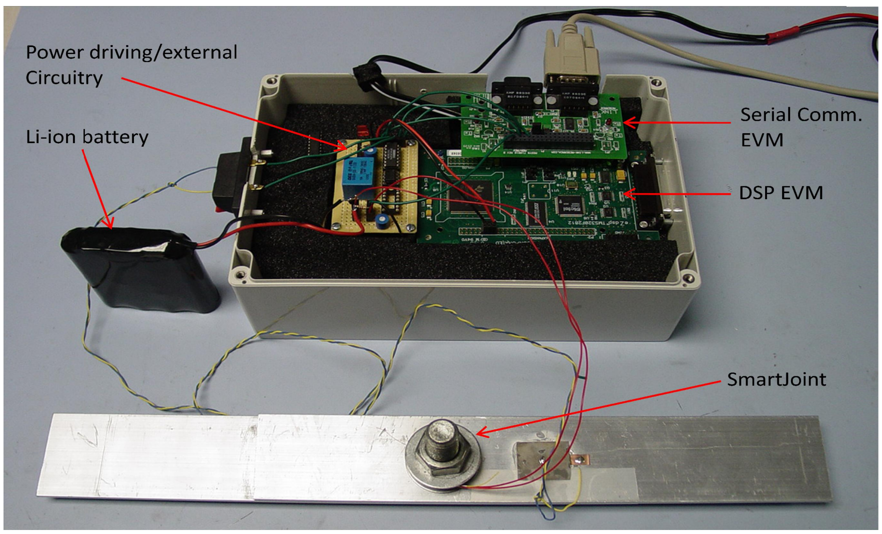


Figure 8: System Setup

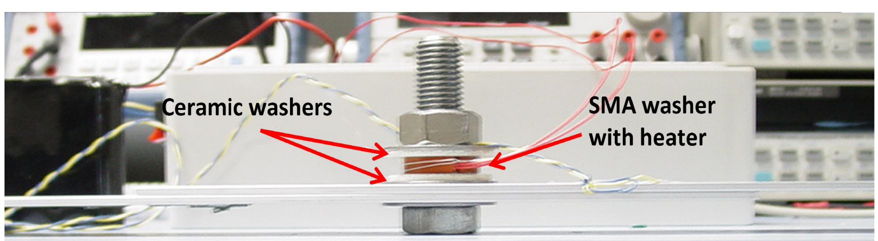
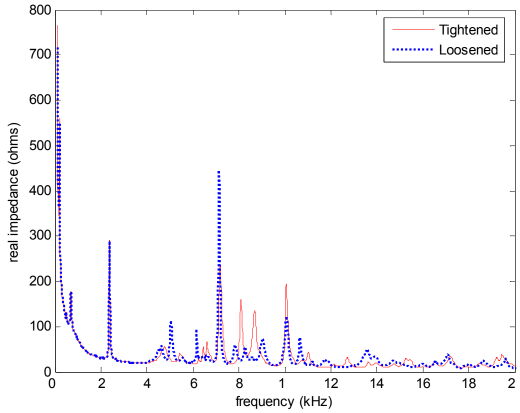


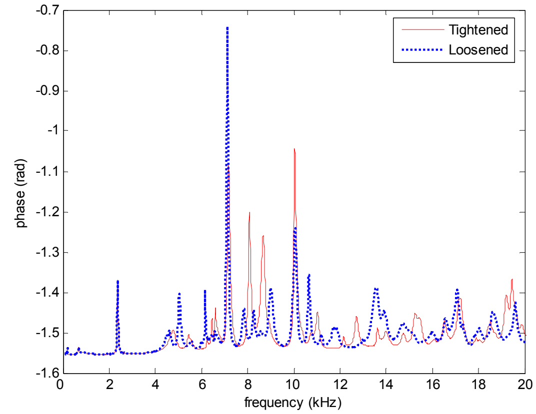
Figure 9: SmartJoint with an External heater

4.2. Experimental Results and Observations

The first step for our experiments is to identify a sweeping frequency range. We measured the impedances of the SmartJoint with an impedance analyzer (HP 4194A) for two different cases: the bolt tightened with 25 Nm of torque and the bolt loosened with 10 Nm of torque. The experimental results shown in Figure 10 indicate that the impedance difference between the two cases is most significant in the frequency range from 6 kHz to 10 kHz, which is set as the sweeping frequency range for our subsequent experiments.



(a) Real Part of the Impedance

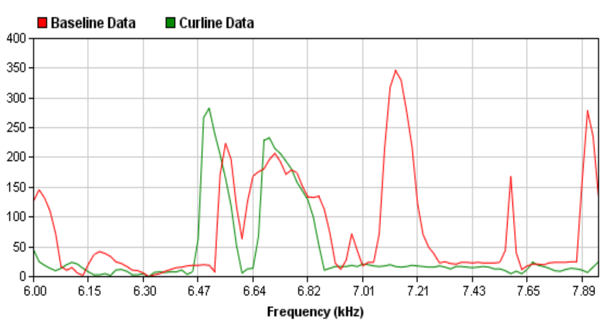


(b) Phase of the Impedance

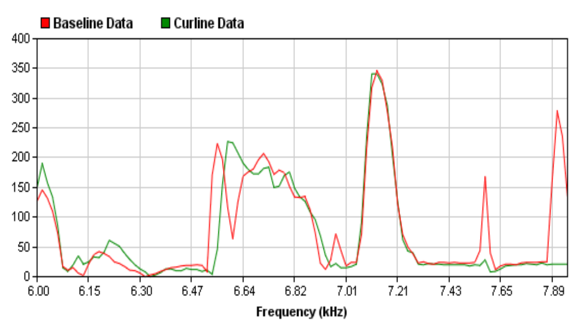
Figure 10: Impedance of the SmartJoint

The procedure for our experiments is as follows. A baseline impedance profile in the frequency range of 6 kHz to 8 kHz was obtained from the structure with the bolt tightened with 25 Nm of torque. Then, we loosened the bolt with 10 Nm of torque. Our SHM system detected the loosened bolt defect and turned on the heater of the SmartJoint. The SMA washer was heated to above the critical temperature of 165 °C in several minutes, while our system repeatedly performed the SHM operations during the heating up. Upon reaching the damage metric below the threshold value through gradual tightening the bolt, the system turned off the heater and the loosened bolt was tightened. The threshold value was set simply to multiple times the variation of the impedance profiles obtained by eight experiments. However, a more sophisticated method based on field testing could find a better threshold value.

Figure 11 (a) shows the impedance profiles of the baseline (tightened bolt) and of the loosened bolt. Some peaks of the baseline profile shift to lower frequencies as the bolt is loosened and some peaks disappear. When the loosened bolt is tightened up again by heating the SMA washer, the profile of the bolt is almost restored to its baseline profile as shown in Figure 11 (b). This implies that the SmartJoint has effectively repaired the loosened bolt defect.



(a) Profiles of the Baseline and the Loosened Bolt



(b) Profiles after Repairing of the Loosened Bolt

Figure 11: Profiles of the Baseline and the Loosened Bolt Before and After the Repair

5. CONCLUSION

We investigated a method to repair bolted joint loosening defects using SMA washers. We incorporated such a feature into our impedance-based SHM system. An SMA washer wrapped with a heater is installed between a bolt and the nut. Upon detection of a loosening defect, the heater is turned on to expand the SMA washer, which in turn repairs the defect. Our experimental results show that (i) our enhanced SHM system can detect bolted-joint loosening defects, and (ii) it can repair such defects effectively. Our system suggests that self-repairing of some structural defects is feasible without human interventions.

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