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Self-Repairing Joints Employing Shape Memory Alloy Actuators

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ABSTRACT

This paper illustrated the concept of self-sensing and self-repairing bolted joints employing piezoelectric and shape memory alloy elements. The piezoelectric materials are used to assess the conditions of joints using electrical impedance analysis. When damage occurs, the shape memory washers can be used to regain lost torque in an automated way. Specifically, the actuator is a cylindrical Nitinol washer that expands axially when heated, according to the shape memory effect. Upon actuation, the stress generated by its axial strain compresses the joint members and creates a force that has the effect of generating a preload and restoring lost torque. Through experimentation, we have documented a successful demonstration of the proposed concept. Due to complexity of constitutive modeling, qualitative analysis by the impedance method is used to illustrate the success. Additional considerations encountered in this investigation are made to guide further research required for the successful commercial application of this promising technique.

INTRODUCTION

Bolted connections are prevalent in civil structures, and in military and commercial equipment. The importance of these joints in maintaining structural integrity is imperative. It has been estimated that approximately 70% of all mechanical failures occur due to fastener failure (Simmons, 1986)[1]. These connections invariably promote damage growth and are often difficult to inspect due to the nature of the geometry and/or loading in structures. Various types of bolt failure that occur include self-loosening, tensile overload, shear overload, hydrogen embrittlement, and fatigue failure.

This paper is a report of an investigation into the active control of preload in the joint using a shape memory alloy (SMA) actuator. This research draws upon prior work from many sources with the goal of developing a self-sensing and self-healing structure. Rogers et al. (1991)[2] investigated the feasibility of using SMA recovery force to reduce the damage in a system. A complex sensing and control system was used to activate embedded SMA wires to close the crack propagation in graphite/epoxy host materials. Haimi et al. (1997)[3] used SMA actuators for pre-tensioning threaded joints, where light tooling due to space restrictions is needed. An active damage control relying on timed release of chemicals for composite structures was reported in the work of Dry (1994)[4]. Gaul (1997)[5] proposed a ‘semi-active’ joint, which varies the normal force in the friction interface of the joints by using piezoelectric stack disks.

The objective of this study is to significantly reduce resources that are dedicated to inspection routines of joint connections and allow systems to function longer between maintenance. We investigate the feasibility of creating smart structural bolted connections, which consist of structural members joined together by bolt and nut combinations equipped with piezoceramic and SMA elements. The piezoelectric elements, namely lead zirconate titanate (PZT), are used to remotely monitor changes in structural mechanical impedance due to the presence of connection damage. The resulting signal from the sensors can be integrated into control systems in a green/red light form to provide on-line structural integrity monitoring. When damage occurs, the temporary self-healing can be achieved using a shape memory actuator around the axis of the bolt shaft. Upon actuation, the stress generated by its axial strain compresses the bolted members and creates a force that has the effect of generating a preload and restoring lost torque. Coupled with established impedance-based structural health monitoring techniques, this research envisions future smart structures in which self-monitoring and self-healing are possible.

This paper summarizes theory behind this technique, proof-of-concept demonstration, and future issues for successful implementation of this technology.

IMPEDANCE-BASED STRUCTURAL HEALTH MONITORING

Piezoceramic transducers acting in the ‘direct’ manner produce an electrical charge when stressed mechanically. Conversely, a mechanical strain is produced when an electrical field is applied. The process to be used with the impedance-based monitoring method utilizes both the direct and converse versions of the piezoelectric effect simultaneously. Therefore, only one PZT patch can be used for both actuation and sensing of structural response.

By analyzing the interaction of the PZT with the host structure, it has been shown that the electrical impedance of PZT is directly related to the mechanical point impedance of the external structure, as shown in the following equation[6],

$$Y(\omega) = \frac{I}{V} = i\omega\, a\left(\bar{\varepsilon}_{33}{}^{T} - \frac{Z\ (\omega)}{Z\ (\omega) + Z_a(\omega)} d_{3x}^{2} \hat{Y}_{xx}{}^{E} \right) \tag{1}$$

where V is the input voltage to the PZT actuator, and I is the output current from the PZT, a, d_{3x}, $Y_{xx}{}^{E}$, $\bar{\varepsilon}_{33}{}^{T}$ are the geometry constant, piezoelectric coupling constant, Young's modulus, and complex dielectric constant of the PZT at zero stress, respectively.

Equation (1) sets groundwork for using PZTs for impedance-based structural health monitoring applications. Assuming that the intrinsic properties of the PZT do not change over the monitoring period of the host structure, Equation (1) clearly shows that the electrical impedance of the PZT is directly related to the mechanical impedance of the host structure. This relationship between electrical and mechanical impedance allows the monitoring of the host structure's mechanical properties using the measured electrical impedance. Consequently, any changes in the electrical impedance signature can be considered as changes in the structural integrity. The impedance method usually interrogates structures at high frequency ranges (> 30 kHz), which enables measurements that are very sensitive to minor defects in a structure.

Another advantage provided by the impedance method is that the technique provides global as well as local information regarding structures. It has been shown that the dynamic frequency response functions can be deduced from measured electrical impedance[7]. The significance of this approach is that it provides a convenient alternative to the shaker-impedance head approach commonly used in the field of experimental modal analysis, and it greatly reduces the extra equipment for the procedures required in vibration testing and structural health monitoring.

In order to allow quantitative analysis with the use of the impedance method, two different approaches have been proposed, one is based on a wave propagation modeling (Park et al., 2001)[8] and the other incorporates the use of neural networks (Lopes, Jr. et al., 2001)[9]. These works provided an example of the applications of the integrated health monitoring system. With the impedance-based health monitoring technique, the PZT sensors/actuators would be installed in the critical section to monitor the condition of a structure. After acquiring the signals from each sensor, it would be possible in real-time to qualitatively detect and locate structural damage, where more detailed inspection would be carried out to estimate the severity of damage using the wave propagation or neural networks.

Experimental implementation of the impedance method has been successfully demonstrated on several complex structures. A more complete description of the technique and recent trends in experimental investigations are summarized in the references[10,11].

Bolted connections are by nature very good applications for the impedance method. Damage to the bolt results in changes in the joint stiffness and damping. Small defects such as loosening joints, however, cannot be detected in modal-based approaches since such defects may not significantly affect the global system response. Furthermore, vibration-based diagnostics require a fairly large excitation energy that may be damaging a structure itself. The changes are easily detected by the impedance method and have distinct electronic signatures because of the high frequency ranges employed by this method.

SHAPE MEMORY ALLOY WASHER

Shape memory alloy actuators provide a variety of solutions to engineering problems that require actuators to deliver high force, high stroke, and high force-to-volume (or weight) ratios. Much attention has been devoted to the study of these actuators, as spring design is already an extensively developed field. The shape memory effect, in brief, is the ability of one of several metal alloys to change between two crystal structures, one at a high temperature (Austenite) and the other at a lower temperature (Martensite). The crystal change occurs as a result of twinning and de-twinning crystal planes. The macroscopic result is that the alloy can deform without the movement of crystalline dislocations. Rather, material deformation occurs due to the movement of twin planes. Therefore, material strains can be readily recovered, and the material appears to remember its original state when the shape memory transformation occurs.

The SMA actuator appears to be a good candidate to actively control the bolt preload because it produces relatively large strain (up to 10%) upon actuation. There are several possible types of SMA actuators that may be used as a bolt actuator element. In particular, SMA (Nithol) washers, as shown in figure 1, are an attractive option for a high-force, low-stroke actuator. These washers are readily available (for instance, Intrinsic Devices, Co.), for the primary purpose of coupling and fastening pipes. The washers are able to expand axially as a side effect of their intended radial contraction. The use of SMA spring as an actuator was also considered. However, it has been estimated that the commercially available SMA springs are not able to generate enough force to control the bolt preload.

The behavior of the SMA washer, and in fact the behavior of SMA in compression, has not been completely characterized. It certainly does not behave as a ring simply undergoing thermal axial elongation. The gripping force can be set between 50 lb and 30,000 lb by choice of the ring dimensions, but an exact amount of axial force that is produced by the SMA washer was not presently understood.

SELF-SENSING AND SELF-REPAIRING BOLTED JOINTS

The most common failure in bolted joints is its loosening modes. As the torque loosens, the joint cannot unite the structural members. Quantitatively, the bolt torque-preload is given in equation (2) for most bolts as a good approximation accounting for the friction occurring between surfaces.

$$T=0.2(F_\mathrm{i})(d_\mathrm{o}) \tag{2}$$

where T is torque, F_i is preload and d_o is the nominal diameter of the bolt shaft. The concept of self-healing bolts can be realized by developing a device, which is able to vary the normal forces of the joint. In addition, a sensing system needs to be implemented in order to monitor the condition of the joints and provide a decision signal to activate the device.

The impedance-based health monitoring was implemented as a sensing system and supplement measurements of torque in the monitoring of the joint preload, in which phase changes in the impedance of a piezoceramic sensor/actuator correspond to joint stiffness. This method is very effective in monitoring critical sections where high structural integrity should be maintained, as described in the previous section. As a concept of the joint actuator, the SMA washers (Intrinsic Devices, Co.) were selected and installed between bolt and nut. The washer can be electrically activated using direct resistance heating, which causes an increase in the bolt preload due to the constraining effect of the bolted joints.

PROOF-OF-CONCEPT EXPERIMENTS

An experiment was performed to demonstrate the concept. A test specimen consisting of two aluminum beams was constructed with a bolted joint. A list of dimensions of the test specimen is given in table 1. The bolted joint structure and monitoring system was hung vertically by a string. One PZT patch bonded to one of the members was used to measure the electrical impedance. An SMA washer (Intrinsic Devices AHE 0957) was inserted between the bolt and the nut, as illustrated in Figure 2.

Initially, the bolt was tightened to 40 N-m, and the torque was reduced to 14 N-m to introduce a loosening mode of a bolt failure. This damage, however, can be considered in its incipient stage, which still maintains the integrity of the joint.

The SMA actuator was then electrically activated to create a force to restore the lost torque. However, the relatively large mass and the short length of SMA washers make direct resistance heating particularly difficult. The heating of the SMA depends upon the amount of current and the geometry of the washer, in addition to the insulation of the system. Intrinsic Devices, Inc. informed that approximately 300 amps should be supplied for a period of several seconds to activate the washer. A car battery (500 C.C.A) has been chosen as a power source in this study. In addition, the direct contact to the members of the joints creates the short circuits and heat sinks. Therefore, several layers of Kapton tape have been used between the actuator and surrounding members for heat and electrical insulation on the washers. It has been observed, however, that the tape absorbed the expansion of the actuated washers to some degree.

The electrical impedance was measured at each step of torque, and qualitative analysis by the measured impedance was performed to track the changes in mechanical characteristics of the joint. To identify the joint property of the structure, the real portion of measured electrical impedance was used. The sharp peaks in the real part of electrical impedance correspond to the structural resonant frequencies. Figure 3 shows one of the structural major resonance frequencies. The decrease in the torque causes a regular downward shifting (up to 2%) of the resonance peak, which suggests a stiffness reduction. In the other resonance peaks shown in Figure 4, similar drops in resonance behavior occur as the stiffness of the bolt decreases. In addition, the peak amplitudes are reduced, which indicates increases in structural damping.

After the actuation of the SMA washer, one can clearly observe that the actuator causes an upward shifting of the resonance peaks, which in turn suggests a restoration of the degraded bolt preload. At frequency ranges around the major resonance, the locations of peaks that actuated are even slightly higher than those in baseline measurements. It is worthwhile to point out that the PZT excites all modes of the structure (bending, torsional and axial), so the change in preload may affect each mode somewhat differently, as shown in the figure. Especially, changes in damping are very difficult characterized. Therefore, only the changes in resonant frequencies have been analyzed in this study as an indicator of joint stiffness. The general trend of resonant frequency shows that shifting to the left upon loosening, then shifting back to the right when SMA washer activated, indicating successful restoring of lost preload.

The damping capacity of a bolted joint is an important parameter, however, some difficulties have been experienced with their analysis because the forces occurring at the matting section are nonlinear and therefore mathematically difficult to describe. Depending on the preload, the joint damping can be classified as macro-slip or micro-slip, which describe energy dissipation arising from the relative motion of the matting surfaces[12,13]. Because there is no general model available for predicting joint damping, only the stiffness changes have been investigated. Due to complexity of constitutive modeling, no analytical modeling effort has been attempted at this stage. In addition, the loss and recovery of the preload could be more accurately analyzed by some alternative methods like using load cells and strain gauges. However, only the dynamic analysis, especially resonant frequency changes, has been performed due to the equipment restrictions and no detailed analytical model available to describe the SMA actuation and damping of the structure.

Another set of experiments was performed with the same structure and the SMA washer. As can be seen in the figure 5 and 6, the results are similar to the first experiment. Upon SMA actuation, the resonant frequencies moved back towards original position, but not completely, indicating that actuation was partially successful in restoring the lost preload in the joint. The final torque measured was 25 ft-lb. It has been speculated that the several layers of the Kapton tape used for the insulation of the SMA resulted in loss of strain energy for the preload actuation.

The list of final dimensions of the SMA washer before and after the actuation is given in table 2. As shown in the table, the final length of the washer after actuation is somewhat constant. With this constant increase in the free length, it might be possible to define a threshold level of preload that the SMA actuator activates only when the threshold level is reached. Note that this method will be used in conjunction with the impedance-based health monitoring technique described in the previous section. The impedance method would detect and inspect whether the damage threshold value has been reached or not, and provides a signal to activate the SMA actuator in order to restore the loss of preload, that would otherwise lead to catastrophic failure of a structure.

The initial experimental results illustrate several key points. First, the results clearly demonstrate that the realization of a self-repairing joint using smart materials is possible. Apparently, the actuated SMA washer recovered the original stiffness of the joint. For real world structures, temporary adjustments of the bolt tension can be achieved actively and remotely for continued operation for damaged joints. The results also suggest that the modeling of the SMA washer and joint members is required in order to understand the phenomena in depth and to design such a structure. Additional considerations encountered in this initial investigation are detailed in the discussion section in order to guide further thorough research for the successful implementation of this technique.

DISCUSSION

The experimental results clearly indicate that the SMA actuator generates the force to recover the lost torque and allows the structure to continue in operation until a convenient time for a more permanent repair is possible. The proposed method is consistent with the ‘semi-active’ joint[5] using the PZT stack actuator to control the preload in the joint. However, the use of PZT actuator requires constant supply of relatively high voltage to maintain the elongation of the PZT actuators. In this method using the SMA actuator, only one-time activation is needed to reach the required torque level.

As the primary function of the SMA washer is the coupling of pipes, the behavior of the washer as a bolt actuator has not been completely characterized. The SMA washer is not simply behaving as though it were under a tensile load when it is actuated. The axial extension of the washer is a side effect of a much more complicated radial compression. Therefore, research is needed to develop an analytical model of the joint members, which incorporates the effects of SMA actuators. The model will be used to provide a basic understanding of the dynamic behavior of the bolted joint-SMA washer combination and how the parameters of the SMA actuator contribute to its dynamics. The model will provide an algorithm for selecting the size of the actuator for different configurations by examining the torque-preload relation.

The refinement of the impedance method is also under investigation. In order for the impedance-based bolted joint inspection to have its greatest utility, the technique must be able to quantitatively identify the state of the bolted joints. In particular, the method must be able to distinguish the pattern changes in impedance signature between the loss of preload and a crack in the bolt or some other changes. Without such information, it is possible that the application of the SMA actuator may even cause further failure due to additional stress, for example, in a cracked bolt. The recent studies on the impedance method address these issues, however. For instance, the Lopes et al.

(2000)[9] study shows that the impedance method is able to quantitatively identify joint failure coupled with neural network approaches. In addition, the statistical algorithms have been incorporated into the impedance method so that one can assess the conditions of bolted joints in a more conclusive manner[14,15].

In this investigation, direct resistance electrical heating was chosen as the method for activation of the SMA washers. An alternative to resistance heating worth mentioning is the use of an external heater tape, which would require only conventional power supplies[16]. The use of strain gauges and load cells to supplement measurements of torque in the monitoring of the bolted joint is currently under investigation and will be published in the near future.

CONCLUSIONS

A concept of self-sensing and self-repairing bolted joints is presented. The joint is equipped with a shape memory alloy actuator around the axis of the bolt shaft. Upon actuation, the stress generated by its axial strain compresses the joint members and has the effect of generating a preload that restores lost torque. In addition to torque wrenches, the system in question was monitored in all stages of testing using piezoelectric impedance analysis. The experimental results clearly indicate successful restoring of lost preload upon activation of the shape memory alloy actuators. Thus, the proposed method has set forth the results, which would allow the construction of a self-monitoring and self-healing system that could be added to an existing structures, and provide both condition monitoring and self repair. Extensive efforts are currently devoted to studying several implementation issues in order to handle real-life field applications

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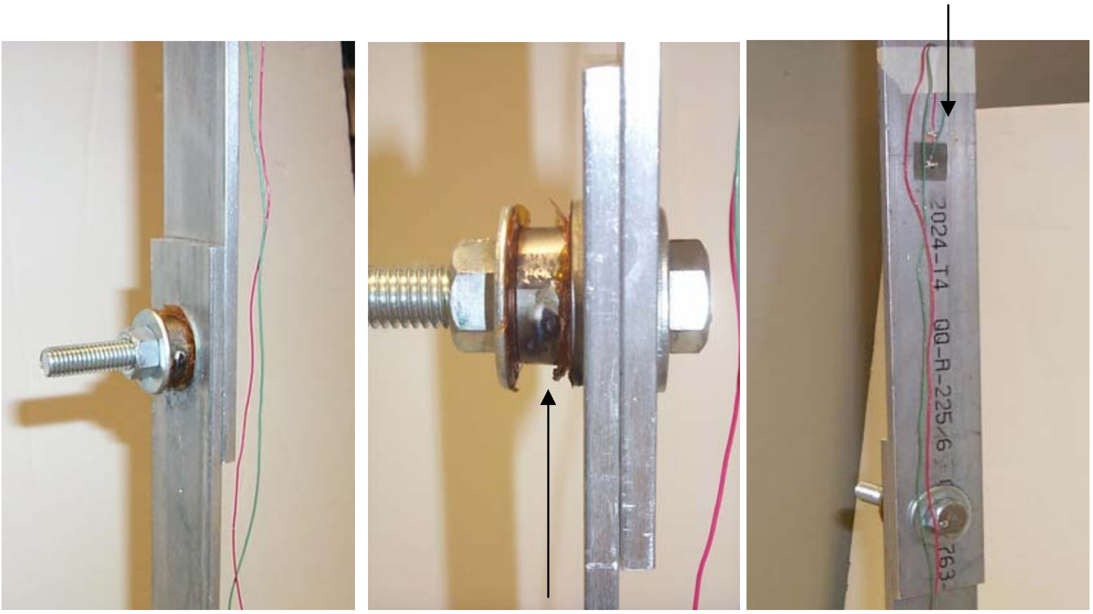
Figure 1

PZT used for impedance measurement



SMA washer

Figure 2

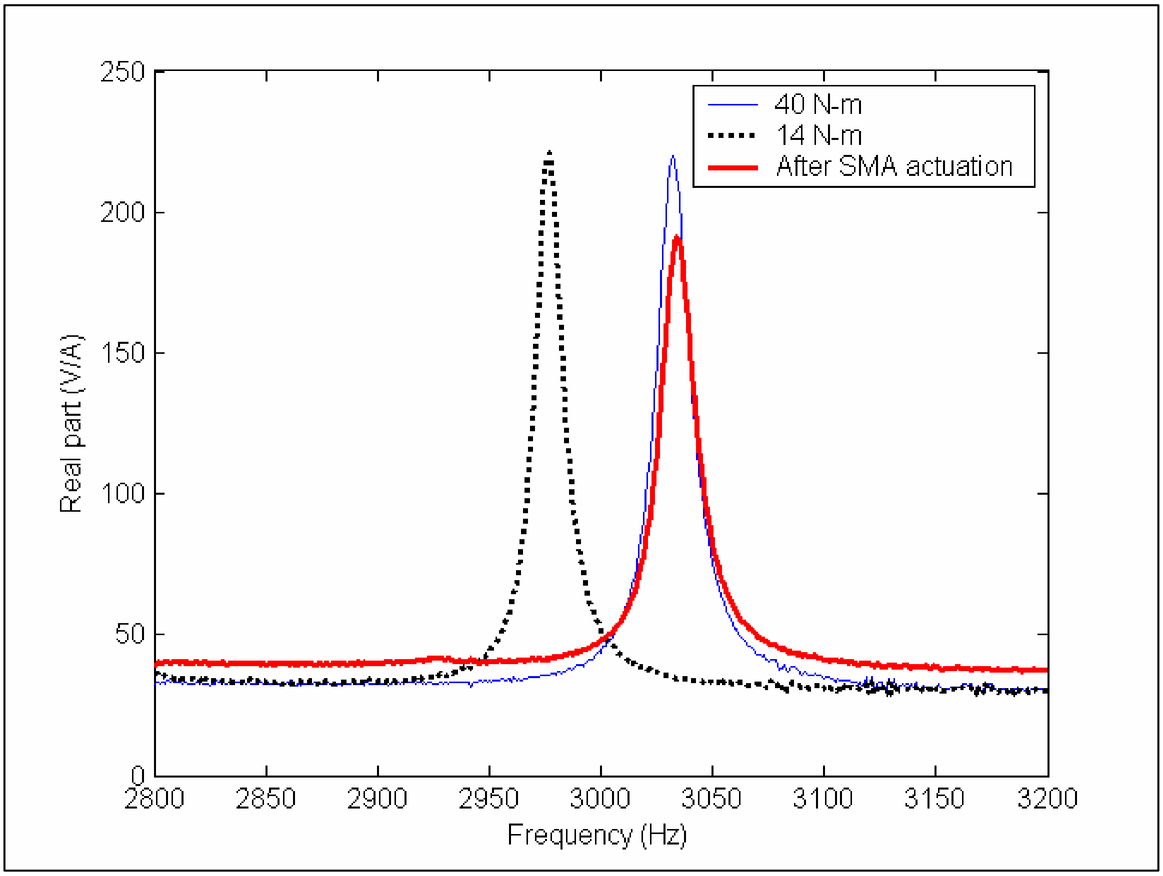
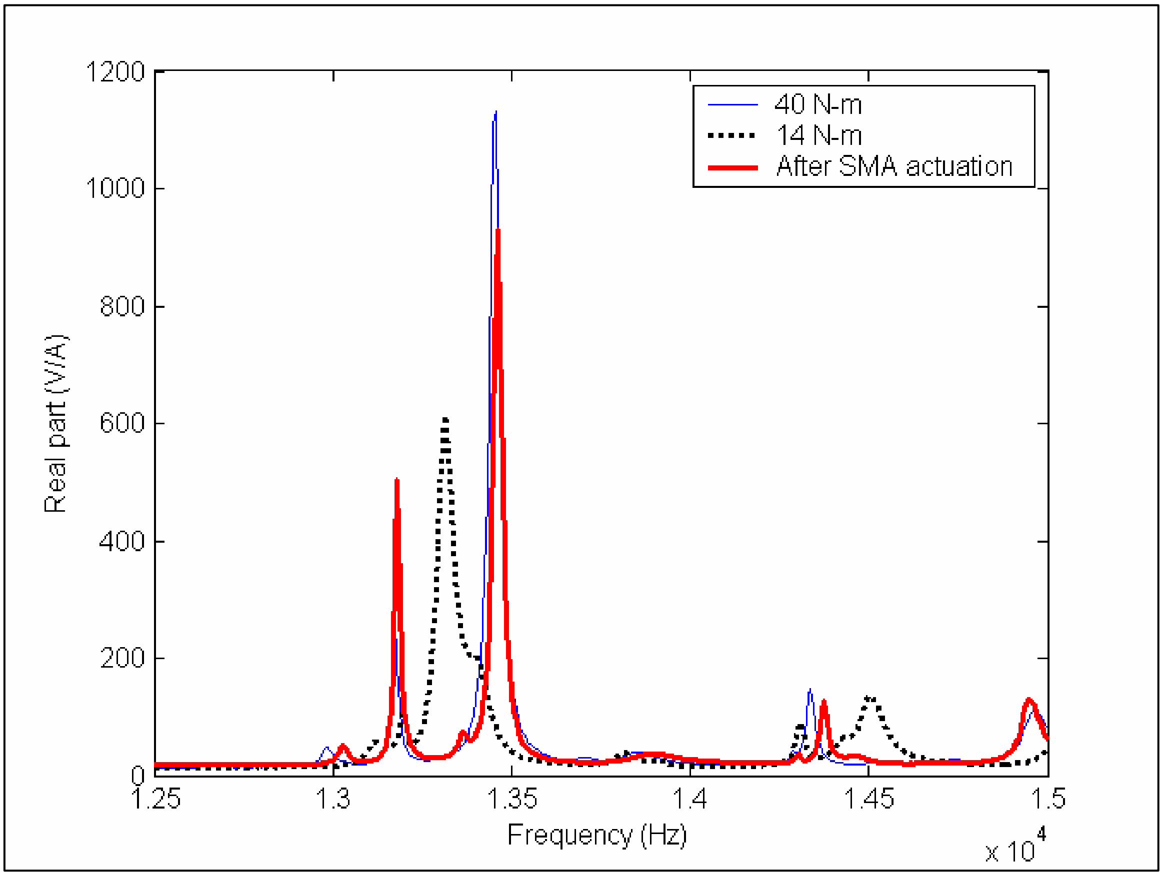

250
200
150
100
50
0
2800
2850
2900
2950
3000
3050
3100
3150
3200
Real part (V/A)
Frequency (Hz)
40 N-m
14 N-m
After SMA actuation

Figure 3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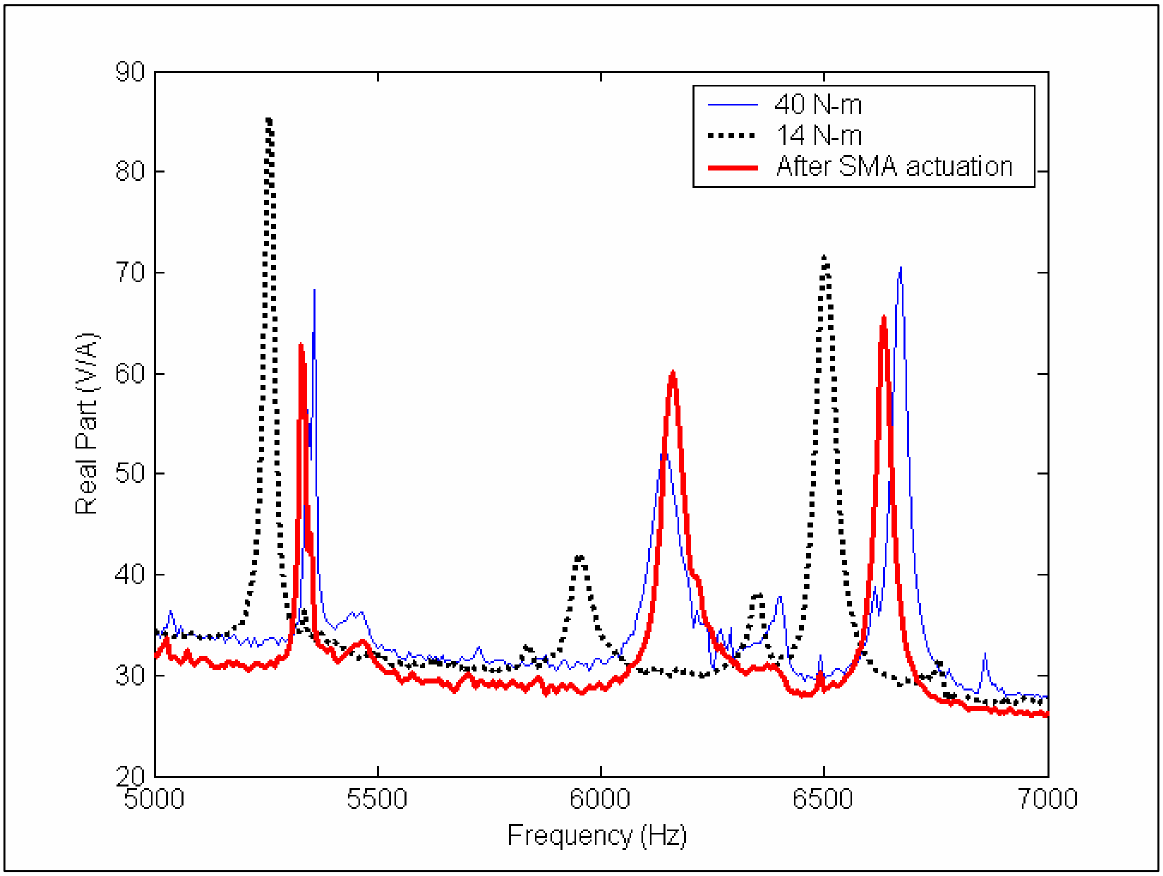
1000
800
600
400
200
0
Real part (V/A)
1.25
1.3
1.35
1.4
1.45
1.5
Frequency (Hz)
x 10^4
40 N-m
14 N-m
After SMA actuation

Figure 4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80
70
60
50
40
30
20
Real Part (V/A)
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5500
6000
6500
7000
Frequency (Hz)
40 N-m
14 N-m
After SMA actuation

Figure 5

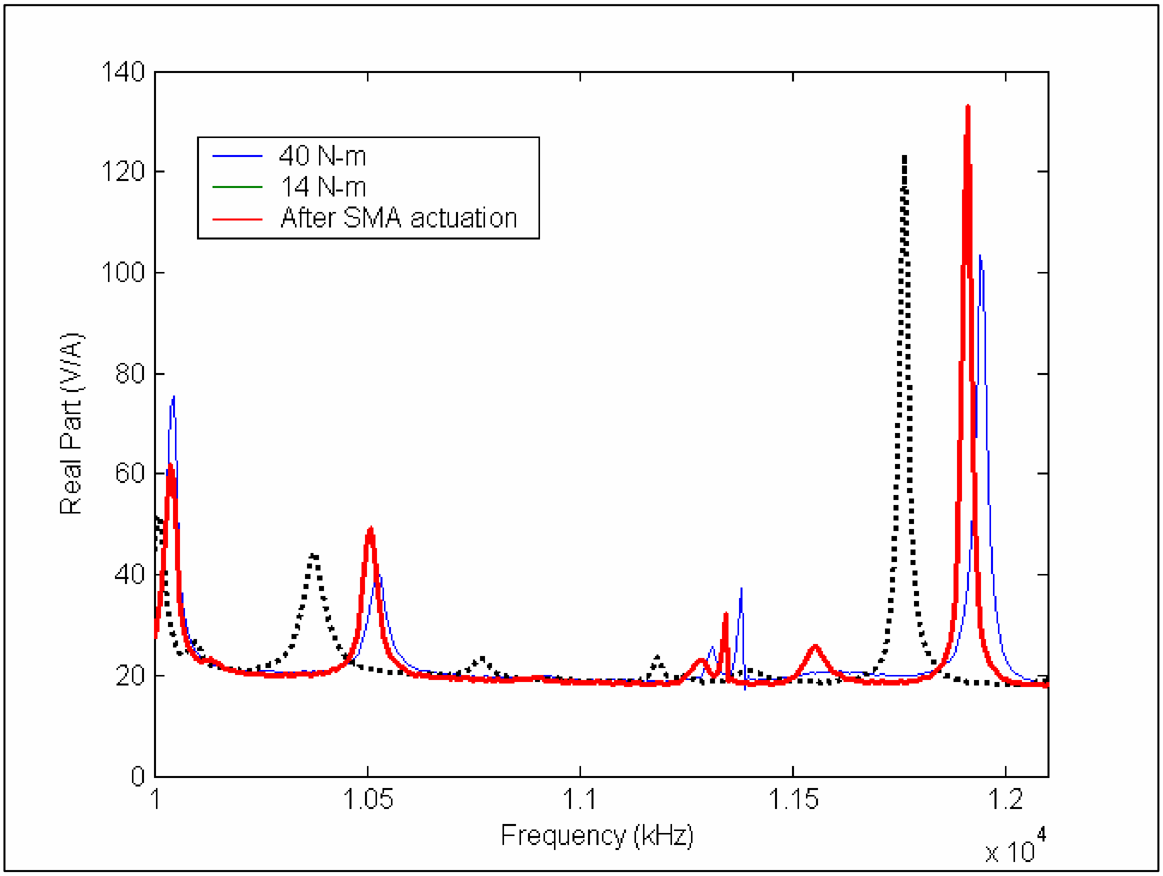
140
120
100
80
60
40
20
0
Real Part (V/A)
1
1.05
1.1
1.15
1.2
Frequency (kHz)
x 10^4
40 N-m
14 N-m
After SMA actuation

Figure 6

Part	Length	Width	Thickness	Diameter
Al 2024-T4 Bars	610	50	7	
Bolt	76.3 shaft; 7.9 head			12.5 shaft; 17.2 head
Nut	11			13.4 I.D.; 17.7 O.D.
AL Washers			2.85	14.4 I.D.; 35.25 O.D.

Table 1.

Washer / Dimension		Length	Thickness	Inner Diameter	Outer Diameter
First experiment	Before actuation	9.6901	1.2065	24.3586	26.7716
	After actuation	9.7917	1.3208	23.4950	26.2382
Second experiment	Before actuation	9.7028	1.3589	24.4602	27.1780
	After actuation	9.8044	1.4986	23.4315	26.4287

Table 2.