Damage Diagnostics of Metallic Structures using Magneto-Mechanical Impedance Technique

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ABSTRACT

The paper discusses application of a Magneto-Mechanical Impedance (MMI) technique for damage diagnostics in metallic structures. A magneto-elastic active sensor consisting of a coil and a permanent magnet is utilized for generation of elastic waves via the eddy current mechanism. The generated waves travel in the host structure and reflect off boundaries producing standing (modal) spatial patterns at respective resonance frequencies. Frequency dependent response to the applied excitation is obtained by the same sensor and is presented in terms of the dynamic impedance. It is shown that the impedance measured in the MMI technique reflects structural dynamic characteristics. Experimental studies involving simple and complex structural elements are presented that explore MMI spectral features for damage diagnostics. Comparison of the impedance data reveals shift and redistribution of impedance peaks in the MMI spectra associated with the damaged samples. We conclude that MMI technique can be employed for structural diagnostics in the embedded SHM or re-configurable NDE formats.

Keywords: damage diagnostics, magneto-mechanical, impedance, structural health monitoring, structural identification, active sensors.

1. INTRODUCTION

This paper discusses innovative Magneto-Mechanical Impedance (MMI) technique for structural diagnostics. The MMI diagnostics method is based on assessing structural integrity through measurement of the dynamic response of metallic structures. It has been shown by Zagrai and Çakan (2007) that magneto-mechanical impedance signature reflects sensor attributes and structural dynamic (mechanical) properties of a host structure. Structural damage modifies mechanical properties and hence structural dynamic characteristics. This modification is manifested in a dynamic signature inferred in MMI measurements. Therefore, MMI data can be used to determine presence and extend of damage in metallic structures.

In previous work on utilizing impedance measurements for damage diagnostics, two different methods have been used. Lange (1972) and Cawley (1984) reported impedance measurements by coupling an excitation source and measurement transducers. Liang et al. (1994), Giurgiutiu et al (1998) and Park et al (2000) employed thin piezoelectric wafers as active sensors for impedance measurements. In the Electro-Mechanical Impedance (EMI) method, electrical impedance of a permanently bonded piezoelectric sensor is measured to determine dynamic characteristics of a host structure. The presence of damage can be inferred from structural dynamic properties modified by damage. Park et al (1999) and Zagrai et al (2001) reported that EMI-based SHM is facilitated by mechanical coupling at the sensor/structure interface and the electro-mechanical transformation within the sensor. Therefore, the sensor/structure bond and its quality affect EMI signature and results of structural diagnostics. This was also studied in details by Bhalla and Soh (2004), who suggested that thickness of the bond needs specific attention in EMI measurements.

Information on structural damage can be also inferred through another impedance-based methodology - Eddy Current (EC) testing. This method utilizes electrical impedance measurements that reflect local changes in electrical characteristics of the experimental sample. An electro-magnetic coil is used to induce eddy currents on a surface of a test specimen; crack or inhomogeneity affects spatial distribution of eddy currents; finally, a difference between damaged and undamaged distributions leads to changes in the electrical impedance of EC coil. It is important to note that mechanical parameters and structural dynamic characteristics of the test specimen are not inferred in EC measurements. To enable reasonable amplitudes of electro-magnetically generated elastic wave, an additional piece of hardware, a permanent magnet, needs to be added to the coil setup. In other words, a magneto-mechanical impedance technique occupies a niche between electro-mechanical impedance measurements (because MMI measures structural dynamic responses) and eddy current testing (because in MMI, electro-magnetic means are used to generate an elastic wave).
In this paper, we provide experimental data supporting a connection between the MMI signature and structural dynamic characteristics. MMI utilizes a sweep excitation signal supplied to the Magneto-Elastic Active Sensor (MEAS) by an impedance analyzer. MEAS exploits the magneto-elastic transformation in conductive material to excite structural vibrations that, through a reverse process, are reflected in the impedance response of the active sensor. Hence, a result of MMI measurement contains a sensor contribution and a structural dynamic signature. In previous paper (Zagrai and Çakan, 2007), we have shown that MMI can be used as a structural dynamic identification tool. This contribution discusses details of experimental hardware, a theoretical model for MMI response and a set of structural diagnostic applications of magneto-mechanical impedance measurements.

## 2. MAGNETO-MECHANICAL IMPEDANCE AND STRUCTURAL DYNAMICS

### 2.1 Magneto-Elastic Active Sensors (MEAS)

A Magneto-Elastic Active Sensor (MEAS) consists of a coil and a permanent magnet. Presence of coil is essential for generating eddy currents within metallic test element and the permanent magnet is necessary for initiating the elastic wave via Lorentz force in non-ferromagnetic metals. Figure 7 illustrates the sensor configuration and shows details on the nickel plated neodymium magnet used as a part of the assembly. In our study we considered two sensors with slightly different characteristics. Table 1 reflects differences in dimensions of the electro-magnetic coil for MEAS-1 and MEAS-2. The neodymium magnet employed in all MEAS has a thickness of 3.2mm and a diameter of 19.1mm. Table 2 represents electrical characteristics of the sensors measured with a digital multi-meter.

<table>
<thead>
<tr>
<th>Active Sensor</th>
<th>Outer Dimensions (mm)</th>
<th>Inner Gap Dimensions (mm)</th>
<th>Thickness (mm)</th>
<th>Wire Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAS-1</td>
<td>25.3</td>
<td>22.4</td>
<td>9.8</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.9</td>
<td>0.25</td>
</tr>
<tr>
<td>MEAS-2</td>
<td>25.3</td>
<td>22.4</td>
<td>16.1</td>
<td>13.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.9</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 2 Electrical characteristics of MEAS-1 and MEAS-2.

<table>
<thead>
<tr>
<th>Active Sensor</th>
<th>Inductance (mH)</th>
<th>Resistance (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAS-1</td>
<td>1.9</td>
<td>9.7</td>
</tr>
<tr>
<td>MEAS-2</td>
<td>1.3</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Because one of major elements of MEAS is an electro-magnetic coil, characteristic impedance of MEAS is dominated by the inductive reactance $Z \approx i\omega L_{MEAS}$. Hence, representation of the sensor impedance on the amplitude vs. frequency plot follows a straight line with a slope proportional to coil inductance. Figure 2 illustrates self impedances of two MEASEs differing in number of windings in their electro-magnetic coils. For the presented sensors, impedance characteristics are rather smooth, without substantial deviation from a straight line. Therefore, this straight line may be subtracted from the general response to eliminate contribution of the magneto-elastic sensor. In practice, however, the impedance of a sensor is not perfectly smooth, especially at low frequencies, and fitting the curve with splines or polynomials is recommended. Subtraction of the fitted response from the impedance signature produces more effective removal of the sensor's characteristic.

Figure 2 Impedance characteristics of two MEASes in 0.5 kHz to 10kHz frequency range.

Figure 1 Illustration of Magneto Elastic Active Sensor.
Two independent setups were used for MMI measurements. The first setup involved a standard instrument – HP 4192A impedance analyzer. The impedance analyzer was controlled via a GPIB interface from a PC. A Labview® program was developed to communicate with the analyzer and to acquire impedance data. The second setup included a digital system based on 10 Ms/s multi-purpose DAQ card and National Instrument’s NI ELVIS virtual instrumentation. The structure of the digital impedance analyzer is presented in Figure 3. A harmonic frequency swept signal was generated using a signal generator in NI Sound and Vibration toolkit. The generated signal was supplied to MEAS via the analog output (DAC0). In digital impedance measurements, we utilized a standard methodology, in which a serial resistor $R_s = 2 \Omega$ is connected to device under test (DUT) and the current through DUT is determined from a voltage drop $V_{Rs}$ across resistor $R_s$ (Park et al., 2003).

$$I = \frac{V_{Rs}}{R_s} \tag{1}$$

The impedance of DUT is represented as

$$Z_{DUT} = \frac{V_{DAC0} R_s}{V_{Rs}} \tag{2}$$

where $V_{DAC0}$ is the amplitude of frequency swept signal. $V_{DAC0}$ and $V_{Rs}$ were transferred via analog input channels ACH0 and ACH1 into DAQ card for signal digitizing. In development of a digital impedance measurement system we followed a procedure reported by Xu and Giurgiu (2005). However, in contrast to an external sweep sine generator employed by these researchers, our setup included a DAQ card for both signal generation and data acquisition. Amplitude and phase of the impedance was calculated according to expressions for a cross-correlation method available in Xu and Giurgiu (2005). Upon subtracting MEAS’s contribution from MMI response of a thin aluminum beam, real impedances obtained with HP 4192A and a digital ELVIS system are presented in Figure 4. According to Figure 4, HP 4192A impedance analyzer furnishes more accurate measurements with less noise. It should be noted, however, that noise in a digital system based on NI ELVIS can be filtered out using an appropriate analog filter. The small difference between results on Figure 4 is due to approximate measurement of current in Equation (1). In addition, at low frequencies the electrical impedance of MEAS is close to $R_s$, which limits validity of the approximation. As excitation frequency increases, the error gets smaller because of more accurate approximation criteria. In experiments reported below, we focused on proof-of-concept tests with high accuracy. Hence, HP 4192A was used in most cases. However, for a practical realization of a fieldable system, validation experiments with digital NI ELVIS impedance analyzer were important.
Proof-of-concept experiments were conducted using magneto-elastic active sensors presented in Table 1 and an aluminum 2024T3 beam (length – 304.8 mm, width - 25.4 mm, thickness 1.587 mm). A beam was suspended using 0.16 mm thick fishing line to simulate free-free boundary conditions. The measurements were conducted in a non-contact mode by placing a MEAS underneath a beam as indicated in Figure 3. The gap between the MEAS and the specimen was kept approximately 1 mm. Results of MMI measurements conducted using two sensors are presented in Figure 5. Noticeable in a figure, the curves represent cumulative sensor/structure electrical characteristics “modulated” by a mechanical response of the aluminum beam. Although amplitude of peaks in MMI signatures may differ slightly from sensor to sensor, position of the peaks may be considered identical. In other words, using different MEASes we are able to obtain similar dynamic responses of the beam. Figure 6 clarifies this point by illustrating structural dynamic responses extracted using different MEASes. Also available in Figure 6 are theoretically calculated values of beam’s natural frequencies. Correspondence between calculated natural frequencies and position of peaks in the MMI response is remarkable. We attribute very small differences between theory and experiment to limitations of the simplified beam theory used to calculate natural frequencies and to deviation of material parameters from reported values.

Our experiments indicate that presence of peaks in the MMI signature depends on position of MEAS on a test structure. When a sensor is placed in the location of a modal node, amplitude of the peak approaches zero. Quite the contrary, for locations coinciding with modal maximums, we observed relatively large amplitudes. This observation supports a hypothesis that a structural signature obtained with MMI measurement is closely related to structural dynamic (mechanical) response. Another important experimental consideration is that in non-contact mode, amplitude of the dynamic response depends of the thickness of a gap between MEAS and a test structure. It is recommended that the gap must be kept constant throughout experiment and needs to be as small as possible to maximize energy transfer via electro-magnetic interaction between sensor and structure.
3. MAGNETO-ELASTIC ACTIVE SENSING

Magneto-elastic active sensing utilizes effect of electro-magnetic generation and reception of elastic waves in metals. This effect is thoroughly described by Banik and Overhauser (1977), and is used in Electro Magnetic Acoustic Transducers (EMATs) (Thompson, 1990). EMATs are relatively bulky and are designed for non-contact periodic inspections. MEAS explore the same transduction mechanism, but are optimized for embeddable SHM configurations and dual use of short-time and CW signals. In the case of CW excitation, continuous elastic wave are generated in the metallic structural element and reception is achieved via a reversed phenomenon. Depending on a type of metal (ferromagnetic or non-ferromagnetic) different transduction mechanisms are possible. In the following development, we consider generation of elastic waves in non-ferromagnetic metals via the Lorentz force.

3.1 An Analytical Model for Magneto-Mechanical Impedance

When a permanent magnet is placed above an electric coil, a magnetic field is produced with magnetic induction field lines extending into the metallic structure adjacent to MEAS. For the type of permanent magnet depicted in Figure 7, configuration of magnetic field is complex; field lines at the center of the sensor show distinct z component, but field lines further away from the center are primarily oriented along x direction. An electric current flowing in the sensor coil induces opposite eddy current in the specimen. Mutual orientation of the induced eddy current and vector of magnetic induction $B$ define the Lorentz force acting on electrons. This force is transferred to lattice ions and is responsible for generation of the elastic wave (Banik and Overhauser, 1977). Orientation of the Lorentz force depicted in Figure 7 suggests that both longitudinal and flexural waves can be excited in a thin-walled metallic structure. In one particular one-dimensional case, a thin elastic beam is considered with a forcing term containing contributions of the electric current $J$ and magnetic induction $B$.

$$\rho A \frac{\partial^2 w(x,t)}{\partial t^2} + EI \frac{\partial^4 w(x,t)}{\partial x^4} = F_L(x,t) \quad (3)$$

where $F_L(x,t) = (J \times B_n(x)) \cdot e^{i\omega t}$ represents harmonically varying Lorentz force acting on the metallic beam. In the vicinity of a sensor, $F_L$ is not uniform. However, if dimensions of a sensor are much smaller than dimensions of a structure, it is possible to simplify analysis by neglecting spatial distribution of $F_L$ and considering a single point excitation. Using this assumption, right-hand-side (RHS) of Eq. (3) becomes

$$F_L(x,t) = I \cdot B \cdot b_y \cdot \delta(x-x_a) \cdot e^{i\omega t}, \quad (4)$$

where $b_y$ is the y-axis dimension of the sensor equal to beam’s width, $\delta(x-x_a)$ is the Dirac delta function and $x_a$ is position of the active sensor. Modal expansion of displacement in Eq. (3) is

$$w(x,t) = \sum_{n=0}^{\infty} W_n(x) \cdot T_n(t) \quad (5)$$

where $T_n(t) = C_n \cdot e^{i\omega t}$ denotes a temporal component and

$$W_n(x) = A_n \left[ \cosh \gamma_n x + \cos \gamma_n x - \sigma_n \left( \sinh \gamma_n x + \sin \gamma_n x \right) \right] \quad (6)$$

is a spatial mode shape.

Parameters in a mode shape (6) depend on boundary conditions. For free-free boundary condition, a numerical procedure is needed to calculate $\gamma_n$ and $\sigma_n$ for $n < 5$. For larger $n$, $\gamma_n = (2n+1) \pi \sqrt{2L}$ and $\sigma_n = 1$. Parameter $\gamma_n$ is related to natural frequency $\omega_n = \gamma_n^2 c_w$, $c_w = \sqrt{EI/\rho A}$. Substitution of the modal expansion (5) into Eq. (3) allows for determining a modal participation factor,
where orthogonality condition for spatial modes $W_n(x)$ was taken into account.

Combining (4), (5), and (7) we arrive to

$$w(x,t) = \sum_{n=0}^{\infty} \frac{W_n(x) \cdot W_n(x_o) \cdot I \cdot b_n \cdot B}{\rho A \left( \omega_n^2 - \omega^2 \right)} \cdot e^{i \omega t}$$

(8)

Considering a reciprocal effect of inducing the electro-magnetic field due to the propagating elastic wave (Turner et al., 1969), displacement (8) can be used to determine the resultant voltage

$$V = \dot{w}(x_o,t) \cdot B \cdot \int_0^{b_o} dy = \dot{w}(x_o,t) \cdot B \cdot b_o,$$

(9)

where $\dot{w}(x_o,t)$ represents a velocity measured at location $x_o$. Equations (8) and (9) determine the dynamic magneto-mechanical impedance

$$Z_n(\omega) = \frac{V}{I} = \sum_{n=0}^{\infty} \frac{i \omega \cdot W_n(x_o) \cdot W_n(x_o) \cdot (b_n \cdot B)^2}{\rho A \left( \omega_n^2 - \omega^2 \right)}.$$ 

(10)

Notation $Z_n(\omega)$ is used in Eq. (10) to emphasize the dependence of the magneto-mechanical impedance on the excitation frequency $\omega$. The expression above describes dynamics of the undamped mechanical system due to electro-magnetic excitation. Damping may be introduced in the host structure by considering a damping ratio $\zeta_n$ for each vibration mode

$$Z_{str}(\omega) = \sum_{n=0}^{\infty} \frac{i \omega \cdot W_n(x_o) \cdot (b_n \cdot B)^2}{\rho A \left( \omega_n^2 + 2i \zeta_n \omega \omega_n - \omega^2 \right)}.$$ 

(11)

It needs to be mentioned that in deriving Eqs. (10) and (11) we considered the excitation force $F_L$ applied directly to the beam. Therefore, a contribution of the magneto-elastic active sensor and details of the magneto-elastic interaction via the mutual induction between the sensor and the metallic structure were not accounted for. These effects will be incorporated in the model using an equivalent electrical circuit.

Electro-magnetic interaction between a sensor coil and a test sample can be described using a transformer with mutual inductance $M$ (Cartz, 1999). An equivalent electrical circuit, which includes inductance of the sensor $L_{MEAS}$, resistance of the sensor $R_{MEAS}$, inductance of the metallic structure $L_s$, and the dynamic impedance $Z_{str}(\omega)$, is presented in Figure 8. In this circuit, generation of the elastic wave and the associated resonance phenomenon contribute into impedance across points A-A'. Under idealistic conditions, this impedance would uniquely represent structural dynamic (mechanical) characteristics manifested via a Lorentz force mechanism. In practice, the Lorentz force is inductively coupled to the test sample. The inductive coupling is accounted for by considering a contribution of the transformer depicted in Figure 8. Analysis of the transformer circuit leads to the following formulation for the cumulative impedance seen by the magneto-elastic sensor.

$$Z(\omega) = R_{MEAS} + i \omega L_{MEAS} + \frac{\omega^2 M^2}{i \omega L_s + Z_{str}(\omega)},$$

(12)

In Eq. (12) a parameter responsible for the electro-magnetic coupling is the mutual inductance $M$. This parameter depends on many factors including material composition, size of the air gap separating a sensor from the structure, coil configuration, etc. For modeling purposes, it is convenient to consider a coupling coefficient ranging from 0 (no coupling) to 1 (perfect coupling) rather than the mutual inductance. Theory of electro-magnetic coupling (O’Malley, 1992) suggests that electro-magnetic coupling coefficient, $k_C$, depends on inductance of the sensor, inductance of the test sample, and the mutual inductance.
\[ k_c = M \sqrt{L_S L_{\text{MEAS}}} \]  
\[ Z(\omega) = R_{\text{MEAS}} + i \omega L_{\text{MEAS}} + \frac{\omega^2 L_{\text{MEAS}} L_S}{i \omega L_S} + Z_{\text{str}}(\omega) \]  

Formulation (14) incorporates three distinct contributions: mechanical dynamic response via \( Z_{\text{str}}(\omega) \), electro-magnetic coupling, and sensor characteristics.

### 3.2 Experimental Validation of the Analytical Model

To verify the modeling approach presented in the preceding section, an experiment was conducted on a one-dimensional metallic structure. A test structure consisted of an aluminum 2024T3 beam with the following parameters: length = 304.8 mm, width = 25.4 mm, thickness = 1.587 mm, modulus of elasticity = 73.1 GPa, and density = 2780 kg/m³. During experiments, the beam was suspended using thin fishing line to simulate free-free boundary conditions. The magneto-elastic active sensor was placed underneath the beam with the air gap of approximately 1 mm. Actual contact of the sensor with the beam was avoided to eliminate contribution of the sensor mechanical characteristics into the measured dynamic response. The sensor consisted of a 1 inch electromagnetic coil and a neodymium magnet. MEAS impedance was measured using a standard instrument – HP 4192A impedance analyzer interfaced with a personal computer using a HPIB connector. NI Labview® software was utilized for processing and displaying data. Results of the experimental testing are presented in Figure 9 as a solid red curve.

The analytical model incorporated characteristics of the elastic beam presented above. In addition, \( L_{\text{MEAS}} = 1.9 \) mH and \( R_{\text{MEAS}} = 10 \) Ω were inferred from the measured self-impedance of the sensor. Parameters \( L_S \) and \( k_c \) were estimated as \( L_S = 0.1 \) µH and \( k_c = 0.4 \). Equations (11) and (14) were utilized to obtain theoretical magneto-mechanical impedance presented in Figure 9 as a solid blue line. Theoretically calculated MMI match well with the experimental data. In particular, a direct correspondence is noticeable between theoretically calculated and measured MMI peaks. A slight shift in frequency values is attributed to limitations of the Euler-Bernoulli beam theory employed for structural modeling. Amplitude of the theoretical MMI response shows values comparable to the experimental impedance. Idealizations related to the field distribution and electromagnetic coupling may contribute to minor differences between theoretical and practical frequency-dependent slopes. We conclude that presented modeling rather accurate describe the magneto-mechanical impedance response of metallic structures that support generation of elastic waves via Lorentz force mechanism.

### 4. Damage Diagnostics Using Magneto-Mechanical Impedance

In this section, we present results of utilizing MMI as a damage diagnostic technique. We have provided both experimental and theoretical evidences connecting structural dynamic characteristics and the MMI response. It is well documented (see LANL report LA-13070-MS and work of many other researchers) that damage causes changes in mechanical properties of a test object and modifies its frequency response. Therefore, by comparing dynamic characteristics of undamaged and possibly damaged parts it is feasible to infer information on presence and severity of damage. In the proposed magneto-mechanical impedance damaged diagnostic method, we compare structural dynamic responses obtained from MMI measurements.
4.1 Honeycomb panel

Aluminum honeycomb panels are among major structural elements of spaceships, satellites and aeronautical vehicles. To investigate performance of the MMI technique in monitoring complex structures, we conducted a set of experiments on an aluminum honeycomb panel. In these experiments the magneto-elastic active sensor was in physical contact with a specimen. Figure 10 shows results of MMI monitoring of a painted aluminum honeycomb panel with an edge disbond. In this experiment we utilized HP 4192A impedance analyzer and the \( Z_{\text{cond}} = R + i\omega L \) contribution was subtracted from raw MMI data. In Figure 10, MMI responses obtained from healthy (good bond) areas are labeled A and C, while a response of a damaged area (disbond) is labeled B. MMI signature of the damaged area shows different position of peaks and absence of spectral features inherent to responses of healthy areas.

One of concerns in honeycomb structures is damage caused by the presence of water inside the core. To address this interesting problem, we evaluated responses of a honeycomb panel with and without water in one of the combs. First, MMI data were taken from the damaged area of a panel. The panel response inferred from this data is depicted in Figure 10c as a solid green line. Second, 3 ml of water was added to the comb underneath MEAS using a medical syringe. After water was added, MMI response was measured in the same location. This response is indicated as a solid red line in Figure 10c. Although some features in “dry” and “wet” responses are similar, adding water clearly causes shifts of several peaks and amplitude changes. Therefore, MMI technique can be used not only to detect disbonds in honeycomb panels, but also to find hidden areas exposed to water.

4.2 Adhesive Joints

In recent years, there has been increasing use of adhesive joints in aeronautical and space structures. These joints are easy to fabricate and they are lightweight. However, inadequate application of adhesive or deterioration of the bond may cause areas of reduced strength. Subjected to high operational loads, such areas may trigger irreversible failure of the whole joint. In this section, we report results of utilizing MMI diagnostic method for examining adhesive joint specimens with three different bonds. Specimens consisted of two 12” long, 2” wide and 0.08” thick aluminum beams bonded together using Hysol™ EA 9309NA. One of the specimens represented a good bond, i.e. intact condition. The other two specimens represented inadequate bonds of different extend: 1” × ½” semi-circular disbond and 1” × 1” rectangular disbond. The MEAS in this experiment was employed in a non-contact mode with the gap between the specimen and the active sensor reaching 1 mm. Measurements were taken using HP 4192A impedance analyzer. The MMI spectra were processed in accordance to a procedure described in preceding sections of this paper; i.e. subtracting a trend line from raw data. The results are presented in Figure 11a for a selected frequency range. As it can be seen from the figure, responses obtained from degraded bonds show amplitude changes and frequency shifts. The amount of a frequency shift depends on extend of the disbonded area, but the dependence is likely nonlinear. Details on the frequency shift can be inferred from the zoomed-in spectra depicted in Figure 11b. We conclude that MMI can be used for diagnostics of the quality of adhesive bonds.
4.3 Bolted Joint

Bolted joints are employed in many mechanical structures. Loosening of the bolt may result in serious weakening of structural health and could further lead to catastrophic failure of the whole structure. Hence, monitoring of bolted joints is a critical issue for some structures. In this section we report results of MMI diagnostics of the bolted joint under different torque conditions. Geometry of the bolted joint is depicted in Figure 12a. The joint contains two 3/8-16 UNC steel bolts connecting 0.08” aluminum 2024T3 beams. MEAS was positioned on aluminum surface in the middle of a specimen and 60 mm away from bolts. Data was taken using HP 4192A impedance analyzer. The trend line was removed from original data for clarity of presentation. The MMI response was recorded for the first condition representing completely loosened bolts. For this case, we obtained relatively weak response as indicated in Figure 12b. The second condition corresponded to finger-tight bolts. The MMI signature representing this condition indicates distinctive peaks of relatively low amplitude. A torque wrench was used to tighten bolts to 28 ft-lbs. This value was used as a representation of the fully tight condition. As it can be seen in Figure 12b, the tight condition produced a MMI response showing additional peaks, frequency shifts and amplitude changes. In fact, amplitude of MMI peaks in the tight condition is considerably higher than in other cases. From data presented in Figure 12b it is evident that integrity of the bolted joint can be assessed using MMI measurements. Hence, we suggest considering MMI for monitoring bolted joints.
4.4 Large Panel with Simulated Cracks

Magneto-mechanical impedance diagnostics was applied to a large specimen representing a skin section of an aircraft wing. The material of the panel is aluminum 2024T3 and dimensions of the specimen are given in Figure 13a. The panel contained two 15 mm cracks simulated by narrow (0.7 mm) through-thickness cuts. In experiment, MEAS-1 was placed on a surface of the specimen 2 cm away from one of the cracks. The MMI response was measured and processed by subtracting the trend line. The MMI signature measured in the location next to a simulated crack is presented in Figure 13b as a solid blue line. The experiment was repeated in a symmetric location without a crack. Because of symmetry, we anticipated response in the symmetric location to be similar to response in the first location, but without a crack. Therefore, MMI response measured in the symmetric location was considered as a response of the healthy area and MMI response measured near the simulated crack represented the unhealthy (damaged) area. Comparison of these two responses is presented in Figure 13b. Noticeable in the figure, the MMI response measured near the simulated crack is considerably different from the response measured in the healthy area. The response measured near the crack reveals denser spectrum and higher amplitude of impedance peaks. This observation is in agreement with previous studies (Giurgiutiu and Zagrai, 2005) conducted for electro-mechanical impedance monitoring of aircraft panels. Therefore, the presented experiments show feasibility of the MMI technique for structural diagnostic of large aircraft panels with cracks.

5. CONCLUSIONS

In this paper, we discussed structural diagnostic applications of magneto-mechanical impedance technique. MMI differs from eddy current testing as its damage detection algorithm explores structural dynamic signatures rather than local electrical characteristics of structural material. At the same time, in contrast to electro-mechanical impedance method, MMI utilizes electro-magnetic means of generating the elastic wave in metallic specimen. Under CW excitation, this wave travels in a test structure and forms standing wave patterns at respective natural frequencies. Therefore, by sweeping the excitation frequency it is possible to obtain a structural dynamic response reflected in magneto-mechanical impedance signature.

A standard instrumentation for impedance studies – HP 4192A impedance analyzer was used in majority of tests.
reported in this paper. A digital version of the analyzer was created, but the results were less accurate due to limitations associated with a key resistor in a measurement circuit.

An analytical model was suggested to explain magneto-mechanical impedance response. The model is based on a Lorentz force actuation mechanism in non-ferrous metals. Theoretical predictions match well with results of experimental testing. We have shown that the resultant impedance depends on parameters of the MEAS and the test structure. In particular, electrical and physical characteristics of the sensor contribute in the MMI response in accordance with Eqs. (11) and (14). These equations show that MMI measurements may be improved by utilizing a larger sensor, more turns in a sensor coil (increases \( I_{\text{MEAS}} \)), stronger magnet (increases \( B \)), and augmenting the electro-magnetic coupling. The latter may be achieved either by reducing a gap between the sensor and a test structure in non-contact measurements or by considering a contact mode.

MMI diagnostics utilizes a fact that structural damage modifies mechanical parameters of the structural element and affects its dynamic characteristics. Because structural dynamic signatures are available through MMI measurements, changes in the MMI response may indicate presence and severity of damage. Structural diagnostic capabilities of the MMI technique were tested on a variety of experimental samples. We have shown that disbonds in adhesive joints lead to changes in position and amplitude of impedance peaks. In the bolted joint experiment, loosening of the bolts produced MMI response of relatively small amplitude. As the torque was changed to the finger-tight case, amplitude of the MMI response increased and well-defined impedance peaks appeared in the spectrum. Further tightening to 28 ft-lbs lead to additional impedance peaks and increased amplitude of the response. We conclude that MMI method can be used for assessing integrity of adhesive joints and qualifying condition of bolted joints. MMI detection of simulated cracks in a large aircraft skin panel has shown noticeable differences between MMI responses obtained from healthy and damaged areas. This observation is consistent with previous studies conducted using electro-mechanical impedance method. Hence, we suggest employing MMI for detection of cracks. MMI method has shown promising results in detecting disbonds and presence of water in a honeycomb panel. In this specimen, MMI signatures were obtained through a layer of paint. One of advantages of MMI diagnostics is that actual generation of the elastic wave occurs in the metal itself. Therefore, it suitable for through-paint (and thin layer of dirt) inspections and high temperature non-contact applications.

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7. REFERENCES


