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Health Monitoring of Welded Aluminum Beams

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Electro-Mechanical Impedance (EMI) testing with piezoelectric transducers is one among several methods used for Structural Health Monitoring (SHM). The present investigation focuses on the feasibility of EMI for detecting cracks in welded Aluminum beams which have been equipped with piezoelectric composites made from lead-zirconate-titanate (so-called Macro Fiber Composites, MFC). MFC transducers were chosen because of their thin planar design and their conformability. The beams have been subject to four-point bending fatigue loading under laboratory conditions. Crack formation in the welds has been detected with crack gauges. EMI-spectra taken before fatigue loading and after crack detection are empirically compared with a routine programmed in Matlab®. Preliminary EMI-testing had identified the frequency range between about 30 and 50 kHz as showing a number of distinct peaks with sufficient intensity (amplitude) in the impedance spectra. In all cases tested, the crack formation yielded distinct changes in the frequency position of the peaks in the real part of the impedance spectra. This provides a basis for further development of the EMI-method and automated analysis of the spectra towards application in an industrial test environment.

1 INTRODUCTION

Vibration-based modal analysis for defect diagnostics of structures or structural elements has been applied for a long time. It is a technique which measures and analyzes the dynamic response of structures when excited by a suitable input. Impact hammer and shaker excitation are most widely used for modal analysis. One example of this is the measurement of the vibrations of a car body that is attached to an electromagnetic shaker. One distinct disadvantage of modal analysis for structural health monitoring (SHM) is the low excitation frequency, typically in the range of a few Hz and the corresponding long wavelengths. This limits the detectability to relatively severe defects affecting a sufficiently large volume of the structure. Electro-Mechanical Impedance (EMI) testing is also a vibration-based modal SHM technique but uses higher frequency excitation. This allows the detection of defects on a smaller scale. However, EMI testing is limited to the volume of the structure sufficiently close to the piezoelectric transducer (the effective size will depend on the material properties).

The high-frequency excitation for EMI is provided by piezoelectric transducers coupled to the structure. Piezoelectric elements provide electro-mechanical coupling that allows using the same element as both, actuator and sensor. A coupled EMI analysis of adaptive systems driven by surface-attached piezoelectric elements was reported by Liang et al. (1994). Their one-

degree-of-freedom analysis aimed at determining the actuator power consumption and the energy transferred into the system. Sun et al. (1994) performed modal analysis of a structure with a surface bonded piezoceramic patch as collocated sensor-actuator. The effectiveness of the approach was shown by using a simple Aluminum beam. These two papers were among the first to apply EMI with piezoelectric transducers for SHM. Giurgiutiu (2008) described two experiments on defect detection with EMI and piezoelectric transducers. In one of them, four groups of circular Aluminum plates with artificial cracks at increasing distance from the edge are compared with one group without cracks. This showed the effect of different defect states (absence or presence of cracks at different locations) on the EMI-measurements. Peairs et al. (2004) reported EMI measurements for monitoring bolted joints. There, a low-cost electronic circuit was developed and used for the EMI-measurement with the piezoelectric element.

All the experiments reported above have been performed under laboratory conditions and on simple test objects with artificially introduced defects. In the present paper, EMI-tests were performed on hollow, square Aluminum beams with a welded seam on one side before and after crack formation. For this, the beams were fatigue loaded in a four-point bending test-rig until a crack was detected in the area of the weld by a crack gauge. Based on these results, the first aim of the paper was to investigate the feasibility of EMI-testing for detection of real fatigue cracks in Aluminum welds. The second aim was to investigate the effects of ambient conditions (mainly temperature variations). Even though the experiments have been performed under laboratory conditions, the ambient temperature during the EMI-measurements were not always constant. The third aim was to see whether automated signal processing could be applied for defect detection in the EMI-data. The latter two aims were considered crucial for developing applications of the EMI method in an industrial test environment.

2 STATEMENT OF PROBLEM

2.1 Electro-Mechanical Impedance Testing

The supply of a harmonically varying voltage V(t) to any piezoelectric element will produce a corresponding oscillating mechanical strain. If bonded to a structure, the piezoelectric element will induce a deformation in the structure according to the applied vibration. This results in a local dynamic response to the induced vibration. The coupled electrical and mechanical response for a piezoelectric element assuming a single-degree-of-freedom is described by

$$S_1 = s_{11}^E T_1 + d_{33} E_3 \tag{1}$$

$$D_3 = d_{33} T_1 + \varepsilon_{33}^T E_3 \tag{2}$$

where S_1 and T_1 are the mechanical strain and stress, respectively, D_3 the electrical displacement, E_3 the electrical field, s_{11}^E the complex mechanical compliance at zero electric field, ε_{33}^T the dielectric constant at zero mechanical stress, and d_{33} the induced electro-mechanical strain coefficient. Substituting equation (1) into (2) yields the electric displacement as a function of strain and electric field

$$D_3 = \frac{d_{33}}{s_{11}^E}\left(S_1 - d_{33} E_3\right) + \varepsilon_{33}^T E_3 \tag{3}$$

With the strain-displacement relation $S_1 = u_1^{'}$, where $u^{'} = \frac{\partial}{\partial x} u$, the electric displacement can be written as

$$D_3 = \varepsilon_{33}^T E_3 \left[1 - k_{33}^2 \left(1 - \frac{u_1^{'}}{d_{33} E_3} \right) \right] \tag{4}$$

where $k_{33}^2 = \frac{d_{33}^2}{s_{11}\varepsilon_{33}}$ is the electromechanical coupling coefficient. The electric current I(t) is obtained as the time derivative of the electric charge Q,

$$I = \dot{Q} = j\omega Q \tag{5}$$

where j is $\sqrt{(-1)}$ and ω is the angular frequency. The electric charge Q is calculated by integration with respect to the piezoelectric element area A

$$Q = \int_A D_3 dA \tag{6}$$

Substituting equation (5) into equation (6) leads to

$$I(t) = j\omega \int_A D_3 dA \tag{7}$$

The admittance Y, i.e., the inverse of the electromechanical impedance Z is defined as

$$Y(t) = \frac{I(t)}{V(t)} \tag{8}$$

where $V(t)$ is the supply voltage and $I(t)$ the resulting alternating current on the piezoelectric element. Liang et al. determined the admittance by using the mechanical impedance of the structure Z, the mechanical impedance of the piezoelectric element Z_A and the electromechanical coupling coefficient k_{33}^2 which leads to

$$Y(t) = j\omega C \left(1 - k_{33}^2 \frac{Z}{Z - Z_A} \right) \tag{9}$$

where $C = \varepsilon_{33}^T (A/h)$ is the capacitance of the piezoelectric element. The mechanical impedance Z of the structure is given by

$$Z(\omega) = c + m\frac{\omega^2 - \omega_n^2}{\omega} j \tag{10}$$

where c is the damping coefficient, m the mass, ω the excitation frequency and ω_n the n^{th} resonant frequency of the structure (assuming a one-degree-of-freedom spring-mass-damper system for simplicity). In the same way, the mechanical impedance Z_A of the piezoelectric element could be calculated. The resonance frequencies ω_n of the structure are then given by

$$\omega_n = \sqrt{\frac{K_s}{m}} \tag{11}$$

where K_s denotes the dynamic stiffness of the structure. Figure 1 shows the coupled electromechanical impedance, presented as the real and imaginary part of one Aluminum beam driven by a piezoelectric actuator. At the resonance frequencies of the electromechanical system, the piezoelectric element yields maximum current and power output (Liang, 1994). This results in the peaks at the corresponding frequencies in the impedance spectrum.

Therefore, if there is a change in the structure due to a defect, the value of K_s and consequently the electromechanical impedance Z or the admittance Y are changed. This can be seen as a peak shift to other frequencies in the real part of the electromechanical impedance spectrum (Fig. 2).

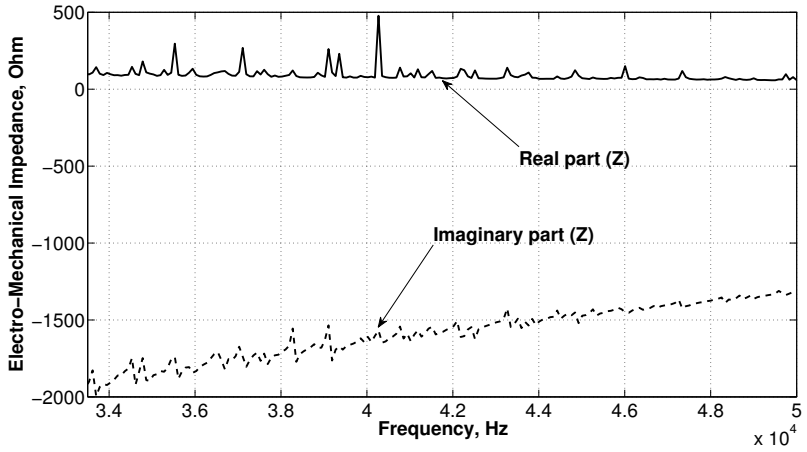

Figure 1: Real (solid line) and imaginary part (dotted line) of the electromechanical impedance spectrum of a welded Aluminum beam before fatigue loading in the frequency range between about 34 and 50 kHz, the spectrum has been measured with an MFC, the peaks indicate the resonance frequencies of the coupled electromechanical system.

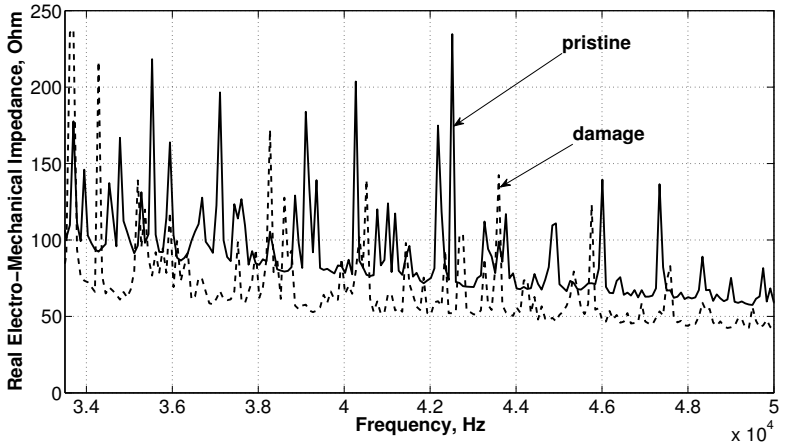

Figure 2: Comparison of the real part of the electromechanical impedance spectrum of a welded Aluminum beam before (solid line) and after fatigue loading (dotted line) in the frequency range between about 34 and 50 kHz; the spectra have been measured with an MFC.

2.2 Piezoelectric Composite Transducers

Piezoelectric transducers are commercially available in various shapes and sizes and with application specific properties (e.g., frequency range, sensitivity). The piezoelectric transducer chosen for the present investigation is a piezoelectric composite made from piezoelectric slabs (cut from lead-zirconate-titanate wafers) that are sandwiched between two polymer films with interdigitated electrodes (IDE), a so-called Macro-Fiber Composite (MFC, see www.smart-materials.com for details). The advantages of the MFC over other piezoelectric transducers are their flexibility and conformability, their thin, planar design and their polarization along the fiber direction (d_{33}-effect). A further advantage is that MFC elements can be easily cut to a

desired or required length. This will affect their frequency characteristic and sensitivity, as discussed, e.g., by Brunner et al. (2009).

3 EXPERIMENTAL

3.1 Material

The EMI-measurements were performed on a total of four hollow Aluminum beams with a wall-thickness of 2 mm and square cross-section (50 mm x 50 mm). On the bottom side, a slot of 3 mm width is milled and then welded (see Fig. 3 for a schematic drawing and dimensions).

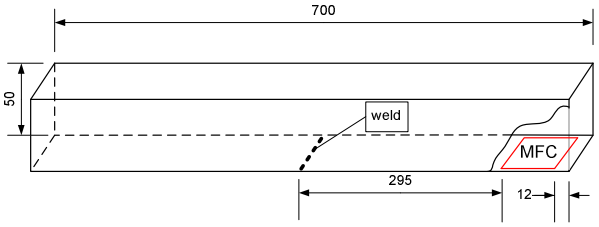

Figure 3. Schematic drawing of the test specimen and its dimensions (in millimeters), i.e., an Aluminum hollow beam with square cross-section and a weld across one side at the center location, the weld is monitored by a crack gauge, and the piezoelectric MFC is mounted inside the beam on the side with weld.

The piezoelectric element for the EMI measurements on the welded Aluminum beams was an MFC (type M 8528 P1 from Smart Materials Inc.). This element has a length of 85 mm and 28 mm width (active area) and is polarized along the fiber direction. For the application inside the Aluminum beams (Fig. 3), this MFC has been cut in half, resulting in a piezoelectric composite with about 42 mm length and first resonance frequency around 30 kHz (in the "free", i.e., uncoupled state). The MFC have been permanently mounted inside the beam by a commercial two-component adhesive (type Araldit® Standard from Vantico AG, Basel). Insulated wires (about 11 cm long) have been soldered to the contact points of the IDE of the MFC.

3.2 Test Set-up

The four-point bending fatigue tests for inducing crack formation in the welds of the Aluminum beams (Fig. 4) have been performed on a custom-made test-rig with a servo-hydraulic actuator. The fatigue tests have been performed under load control. The number of cycles has been recorded by the control unit and crack formation detected by a wire crack gauge placed across the weld zone.

The EMI measurements have been performed with a commercial data acquisition system (type PCI-6052E from National Instruments). As explained above, the input voltage $V(t)$, the resulting current $I(t)$ through the MFC and the phase difference between voltage and current have to be measured. The schematic for this is shown in Fig. 5. Data acquisition and storage on the hard-disk of a PC is controlled by a LabView® program. The circuit in Fig. 5 essentially constitutes a voltage divider. The output voltage is proportional to the current through the resistor R_M which, if R_M is sufficiently small (10000 Ω), is also the current through the piezoelectric MFC. The measured analogue values of $V(t)$ and $I_{MFC}(t)$ with their phase angles ϕ_U and ϕ_I, respectively, are converted from analogue to digital and then transmitted to the measurement PC. Finally, the impedance is calculated as a function of frequency and stored.

The initial and final frequency (within the range of about 10 Hz and 2 MHz), the number of data points per measurement (equivalent to the frequency step), the number of data points and measurement duration per frequency can be independently selected. The AC excitation voltage can be selected between 0.1 and 5.0 V. The frequency range for the EMI measurements has been determined in preliminary experiments on one Aluminum beam. In order to limit the duration of the measurement, the range between 100 Hz and 50 kHz and a total of 601 equidistant data points has been selected. The excitation voltage was set at 5 V.

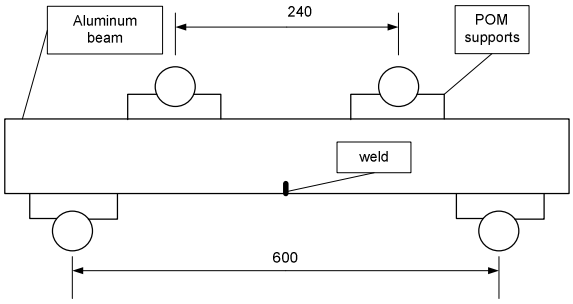

Figure 4. Schematic of the test set-up for four-point bending fatigue (dimensions in mm) that has been mounted inside a custom-made test-rig with servo-hydraulic actuators (type Instron Schenk PL36kN), the number of load cycles, the applied load and the resulting deformation have been recorded with control unit; a wire crack gauge has been applied across the weld (see Fig. 3).

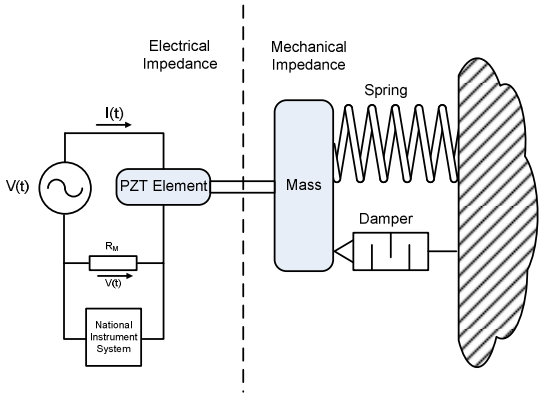

Figure 5. Schematic of the electrical circuit for the EMI measurement with the piezoelectric MFC, also showing the coupled mechanical system (simplified as a one-dimensional spring-mass-dashpot system) of which the electromechanical impedance is measured.

For the EMI measurements, the Aluminum beams have been dismounted from the test-rig, put on a foam plate, and the POM pads for the load introduction been removed. The ambient temperature during the EMI measurements has been determined with a digital thermometer.

3.3 Data Analysis

One drawback of piezoelectric transducers is their temperature-dependent behavior. Wang et al. (1998) showed that in a temperature range between -100°C and +100°C the piezoelectric strain d_{ij} which represents the mechanical properties shows a linear characteristic. Since the electromechanical properties vary linearly with temperature, the temperature drift of the impedance curves can be compensated by curve fitting using Matlab®. The impedance spectra (real and imaginary part, respectively) show clear peaks at the resonance frequencies (Fig. 2). The number of peaks used for the analysis is reduced by setting a lower limit for the peak

amplitude and a frequency range from 30 kHz to 50 kHz. The ten remaining peaks are organized in a feature vector where the feature corresponds to the resonance frequency. This data reduction is important for developing automated crack detection with electronic devices providing on-board signal processing placed next to the sensor.

The analysis of the data recorded by the electro-mechanical impedance measurement system has been performed with a Matlab® routine programmed at the authors' laboratory. This analysis was divided into two steps. The first was a compensation of the impedance spectrum for temperature drifts, and the second the detection of (significant) peaks and their center frequency in the real part of the impedance spectrum.

4 RESULTS AND DISCUSSION

The number of fatigue cycles necessary to induce the crack in the weld varied between about 40'000 and 1.5 millions for the four specimens (Table 1). This quite likely reflects the variation in the welds and their behavior under bending fatigue.

Table 1. Number of fatigue cycles until crack detection by wire gauge and number of EMI measurements

	Beam 1	Beam 2	Beam 3	Beam 4
Number of fatigue cycles until crack detection	1'523'030	154'020	41'507	1'010'475
Number of EMI measurements before fatigue	7	6	5	4
Number of EMI measurements after fatigue	2	2	2	2

The empirical comparison of the EMI-data is summarized in Table 2; six of ten identified peaks are listed. There are shifts in the frequency position of the peaks after crack formation. For an assessment of the results, additional information is required. Repeated measurements on the Aluminum beams before and after fatigue loading have indicated that the respective peak positions identified by the Matlab® procedure are reproducible within less than 1 Hz. This is much less than the frequency step size chosen for the experiments which, from the number of data points recorded in the measurement interval (100 Hz to 50 kHz), was 83 Hz.

Table 2: Frequencies of Peaks in the Real Part of the Electro-Mechanical Impedance Spectrum for four Welded Aluminum Beams tested before and after four-point bending fatigue, crack formation has been crack detected by a wire gauge.

Beam Number and State	Frequency 1 [Hz]	Frequency 2 [Hz]	Frequency 3 [Hz]	Frequency 4 [Hz]	Frequency 5 [Hz]	Frequency 6 [Hz]
1 pristine	34'781	35'529	35'945	37'109	39'105	40'270
1 cracked	33'699	34'282	35'196	39'274	40'519	43'596
2 pristine	34'697	36'610	37'525	38'773	39'188	40'602
2 cracked	34'032	34'864	35'695	36'527	39'272	41'517
3 pristine	33'783	34'697	35'529	36'610	37'525	39'272
3 cracked	34'864	35'779	38'274	40'602	41'184	-
4 pristine	33'783	34'032	35'196	36'527	37'691	45'509
4 cracked	33'949	35'363	35'695	37'359	37'608	38'773

The data in Table 2 indicate that the resonance frequencies before fatigue loading vary somewhat among the specimens. This could be attributed to slight variations in the geometry of the beams and/or in the size and properties of the weld zone. It has not been investigated whether the frequencies f_i (i = 1-6) identified by the Matlab®-routine do correspond to the same mode of vibration for each beam. For an identification of the modes, a model of the beam would have to be established, but this is not required for the empirical detection of changes reported here. The changes in the frequencies of the observed peaks due to fatigue crack formation also vary from specimen to specimen. Both, shifts to lower and higher frequencies (with respect to the initial value listed in Table 2) have been observed. All the frequency shifts are clearly larger than the resolution of the EMI-measurements determined by the step size (83 Hz). The Matlab®-routine only identified peaks, if the amplitude exceeded a certain minimum value. The different sign of the empirically observed frequency shifts may be related to different modes of vibration present in the frequency range scanned by EMI before and after fatigue loading. Peak frequencies listed under the same frequency identifier f_i in Table 2 may hence be from different modes. The resonance peaks before and after fatigue loading have not been evaluated with respect to changes in their amplitudes. Some changes were observed, but a quantitative evaluation of amplitudes would require EMI-measurements with higher frequency resolution.

It would be interesting to investigate whether crack initiation due to fatigue loading yields a gradual shift in the peak positions or a sudden change from one position to another. However, for this it would be advantageous if measurements could be performed during fatigue loading. There is also the question of the sensitivity of the EMI to fatigue crack formation. These questions will be investigated in further experiments on similar specimens.

5 CONCLUSIONS

The feasibility of Electro-Mechanical Impedance (EMI) tests for fatigue crack detection in welded Aluminum beams has been shown under laboratory conditions with piezoelectric Macro Fiber Composite transducers mounted about 300 mm from the weld. Cracks were detected with a Matlab® routine identifying frequency shifts of resonance peaks in the impedance spectra that also compensated for temperature shifts. EMI hence looks promising for empirically monitoring welded Aluminum parts in an industrial test environment or under service conditions.

Acknowledgments

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