EMILIA – A compact impedance analyzer for local integrity assessment

Mihail Lilov, Thomas Siebel
Fraunhofer Institute for Structural Durability and System Reliability LBF,
Bartningstr. 47, 64289 Darmstadt, Germany
email: mihail.lilov@lbf.fraunhofer.de, thomas.siebel@lbf.fraunhofer.de

ABSTRACT: A compact and integrated electronic node for local integrity assessment of a mechanical structure is presented in this paper. The electronic node is referred to as EMILIA (Electromechanical Impedance for Local Integrity Assessment). It consists of an electronic circuit that can be realized as a handheld impedance analyzer for local measurements or directly installed on a piezoelectric patch for performing of distributed monitoring applications.

The damage detection of the mechanical structure is based on the method of Electromechanical Impedance (EMI). The EMI requires only a single piezoceramic transducer for in order to monitor a local part of a structure in the vicinity of the transducer. The developed impedance analyzer can perform free adjustable impedance and optional temperature measurements of the observed structure. To verify the accurate operation of EMILIA, laboratory measurements with a high precision impedance analyzer as reference were performed and compared with measurements of the electronic node carried on an aerospace observed structure.

KEY WORDS: Electromechanical impedance; Impedance analyzer; Piezoceramic transducer; Structural health monitoring.

1 INTRODUCTION

The use of carbon fiber reinforced composites has found considerable attention in the construction of lightweight structures like aircrafts within the last decade. However, the advantageous mechanical properties of a high specific strength and fatigue durability comes along with a new class of damages, i.e. impact damages or delamination, that have to be paid enhanced attention compared to traditional metal-based construction materials. Oftentimes, these damages are invisible for the naked eye and have to be detected with non destructive inspection methods, because not detecting these damages possibly leads to fatal accidents [1]. Thus, structural health monitoring (SHM) systems for critical composite components is strongly demanded from the aeronautic industry. [2]

A proven approach for the detection of structural changes in a mechanical structure is the electromechanical impedance method. This method offers a reliable health monitoring procedure that can be realized with only a single piezoceramic transducer applied on the surface of the structure to be monitored. Due to the electromechanical coupling within piezoceramic materials, piezoceramic transducer bonded to a structure can be used to excite the structure to vibration. A simultaneously measured electrical impedance at the transducer reflects the mechanical characteristics of the host structure. Based on that, modifications of the host structure like stiffness loss, bolt-loosening or cracks are detectable. [3] Finite Elements modeling of the EMI also allows for the simulation of different damages, prediction of damage severity and laying-out EMI-based SHM-systems. [4]

SHM-systems for aerospace have to comply with numerous requirements. Besides the ability to perform intelligent monitoring, these systems should have available scalability, reliability, openness, flexibility, robustness and extendibility. Due to the huge dimensions of aeronautic structures, scalability plays an important role which has to be taken into account, when SHM-systems are developed. Also crucial is the choice of the system topology realization – centralized or distributed architectures. Both architecture kinds have contrary advantages and disadvantages, whereas for aeronautic applications the distributed one is the most appropriate one. [5]

Recent research activities are concerned with development of electronic nodes based on EMI for the detection of structure damages on different materials and for different cases. Exemplary, the realization of wireless SHM-nodes based on EMI for detection of condition of CFRP laminated concrete structures, using piezoceramic sensors, were performed. [6] Bolt-loosening within a metal fitting plug, which connects a composite aircraft wing to a fuselage under realistic environmental conditions, was also successfully realized with an EMI-based system, especially developed for this purpose. [7]

In this work, the development of two versions of a compact and flexible impedance analyzer, based on centralized and distributed architecture concept, is presented. Due to its small physical dimensions, a full integration into the laminated piezoceramic transducer and in this way the increase of the robustness of the whole SHM-system can be achieved. Completely replacing a bulky laboratory impedance analyzer, the introduced compact node can achieve high precision measurements and therefore realize a basis SHM-platform, which can be easily adapted to specific application requirements. In the performed study, a verification of the monitoring node is successfully achieved under laboratory conditions.
2 ELECTROMECHANICAL IMPEDANCE METHOD

The EMI-method is based on a single piezoelectric transducer applied to the structure to be monitored. Due to the electromechanical coupling inside the piezoceramic and the mechanical coupling between the piezo and the host structure, an oscillating excitation voltage at the transducer induces mechanical vibration in the host structure. The simultaneously measured electrical impedance at the piezo terminals is then a function of the piezo characteristics as well as of the mechanical characteristics of the host structure. The mechanical properties depend on e.g. stiffness, damping, mass, or geometric properties of the structure. If structure changes occur, shifts in the resonance frequencies of the measured impedance are accurately and immediately determinable. The practical implementation of the electromechanical impedance method is shown in Figure 1.

Figure 1. Principle of electromechanical impedance method.

The electrical impedance can be expressed as the relation of the input voltage $U$ and the resulting current $I$ in the piezo. A more precise description yields the following Formula (1). Here, $Z$ is the electrical impedance measured at the piezo coupled to the host structure, $C$ is the zero-load capacitance, $\kappa_{31}$ is the electromechanical cross coupling coefficient, $Z_{Sr}$ is the impedance of the host structure and $Z_A$ is the mechanical impedance of the un-bonded piezo. Due to the higher sensitivity to structural changes, only the real part of the complex electrical impedance is taken into account for monitoring purposes. [8, 9]

$$Z(\omega) = \left[ ioC \left( 1 - \kappa_{31}^2 \frac{Z_{Sr}(\omega)}{Z_{Sr}(\omega) + Z_A(\omega)} \right) \right]^{-1}$$  \hspace{1cm} (1)

If the imaginary part of the admittance (the inverse of the impedance) is taken into consideration, piezo health monitoring can be also performed with EMI. [11]

3 EMILIA - ELECTRO-MECHANICAL IMPEDANCE FOR LOCAL INTEGRITY ASSESSMENT

Alongside several investigations based on electromechanical impedance method and detection of host structure and piezoceramic damages, there is the requirement to replace the bulky, standard used, expensive laboratory impedance analyzer with a compact, lightweight and much cheaper impedance analyzer, which can be implemented into a networkable SHM-system on an airplane. For the development of the EMI-node, low weight and compact design are the two pivotal requirements. The realization of two versions of the node – one for centralized and a second for distributed topology, is taken into account during the node designing.

3.1 Electrical Characteristics

The electric specifications of EMILIA are mainly based on the core component in the node circuit, the impedance converter AD5933 from Analog Devices, and on the voltage regulator which is responsible for providing a stable supply voltage to the node (Table 1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
<th>Units/Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>3.20</td>
<td>12.00</td>
<td>V</td>
</tr>
<tr>
<td>Load Current</td>
<td>-</td>
<td>200</td>
<td>mA</td>
</tr>
<tr>
<td>Excitation Freq.</td>
<td>1</td>
<td>100</td>
<td>kHz</td>
</tr>
<tr>
<td>No. of Increments</td>
<td>1</td>
<td>511</td>
<td>-</td>
</tr>
<tr>
<td>Excitation Ampl.</td>
<td>0.19</td>
<td>1.98</td>
<td>V p-p</td>
</tr>
<tr>
<td>Imp. Meas. Range</td>
<td>1k</td>
<td>10M</td>
<td>Ohm</td>
</tr>
<tr>
<td>System Accuracy</td>
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<td>-</td>
<td>%</td>
</tr>
<tr>
<td>Temp. Sensor</td>
<td>-</td>
<td>-</td>
<td>on board</td>
</tr>
<tr>
<td>Temp. Range</td>
<td>-40</td>
<td>+125</td>
<td>°C</td>
</tr>
</tbody>
</table>

The compact impedance converter AD5933 is the heart of the developed EMI-node. It can precisely measure complex impedances connected to its output and input pins. Integrated on the chip are a frequency generator with 12-bit resolution and direct digital synthesizer, an internal clock and also a temperature sensor. For each measured frequency, the response of the measured impedance is calculated by an on board data signal processor, which computes the discrete Fourier transformation. As result, the real and imaginary part of the measured impedance is sent back via two-wire communication Inter-Integrated-Circuit (I2C) bus to the control unit, e.g. a microcontroller (MCU) or another I2C-compatible device, which drives the AD5933. The settings for the impedance measurements, e.g. measuring point, start frequency, output excitation range, etc., are submitted to the register of the I2C-converter. For a proper function, the AD5933 needs a feedback resistor on the receiving stage of the chip, which sets the gain of the transimpedance amplifier, followed by a programmable gain amplifier (PGA), antialiasing filter and Analog-Digital-Converter. It has to be selected cautiously to ensure that the ADC is working in its linear range to achieve high accuracy. For calibration of AD5933, a justification measurement of a calibration resistor with known value is connected to the output and input stage.
3.2 Function Diagram

Figure 2 illustrates the basic function topology parts of EMILIA. The control of the impedance analyzer is realized by a personal computer and a USB to I2C bridge. This conversion element also delivers the supply raw voltage of 5 V to the node.

![Function Diagram](image)

Figure 2. EMILIA Function Diagram.

EMILIA consists of three main circuits: the clock, impedance converter and the voltage regulator circuit. Despite the on board clock generator, for precise measurements under variable temperature the usage of an external clock is highly recommended. The function of the voltage regulator is to transform higher than the recommended 3.3 V operational voltage for AD5933 and to ensure stable voltage supply required for proper operation.

3.3 Stages of Development

In first step, a central configuration of the EMI-node named EMILIA-V01 is developed.

Due to the I2C-communication interface of the impedance converter, an external USB to I2C bridge from ELV Elektronik AG is used (Figure 3). This compact device utilizes CP210x USB to UART Bridge Virtual COM Port (VCP) Drivers from Silicon Labs and in this way provides a basic possibility to control the impedance node via COM-port implementation in Matlab or another programming environment. The bridge disposes three I2C connectors for external devices and can manage up to 128 nodes connected with a bus clock rate from 245 Hz until 400 kHz.

![USB-I2C Bridge from ELV](image)

Figure 3. USB-I2C Bridge from ELV.

The design of EMILIA-V01 is adapted to the dimensions and especially to the fixing of the I2C bridge, two drillings (Figure 4). Thus, a mount of EMILIA-V01 to the bridge can be realized by plugging it on the top of the bridge and in this way simple housing can be achieved.

In this first version, the voltage regulator circuit responsible for the supply of AD5933 with stable 3.3 V is placed on the bottom of a double sided printed circuit board (PCB). As shown in Figure 4, on the top of the node the clock generator circuit and the AD5933 circuit are located. Left, connections for the needed feedback resistor are designed. On the right side, the connections for the piezoceramic transducer or unknown impedance are placed. The size of EMILIA-V01 is 45 x 20 mm with weight of 2.8 g.

![Design of EMILIA-V01](image)

Figure 4. Design of EMILIA-V01.

Embedded into the housing of the USB-I2C (Figure 5), the developed EMI-node acts as a compact and central impedance analyzer which offers connection to multiple piezos consecutively. The control of EMILIA-V01 is realized in Matlab.

![Assembly of EMILIA-V01 with USB-I2C](image)

Figure 5. Assembly of EMILIA-V01 with USB-I2C.

In the next development stage, the impedance analyzer is realized by a flexible PCB named EMILIA-V02, which is designed and optimized for application on a piezoceramic module from PI Ceramic GmbH, series DuraAct, type SP-876.A13. This configuration allows for a distributed solution for structural health or piezo monitoring purposes (Figure 6). Due to the flexibility, given by this concept, no influences on the piezoceramic module from the EMI-node exist. An advantage of this concept is, that the temperature at the piezo can be measured by AD5933 directly and be used for...
temperature compensation issues of the temperature dependent piezo behavior. The concept of EMILIA-V02 provides positioning of all needed circuits on the top of the board. The size of the system is 58.5 x 30 mm with a weight of 1.5 g. The bottom of the PCB is kept free for later implementation purposes. At this realization status, short distance networks due to the used I2C-communication can be performed.

In the preparation of the system validation, impedance measurements with the system are realized and lead to following conclusions: a) the calibration resistor needed for the initial calibration of the system should have the same value like the feedback resistor; b) the calibration resistor should have the arithmetical average value of expected impedance; c) the smaller the measurement resolution is, the higher is the system accuracy; d) the usage of precise resistors as calibration and feedback resistor increase also the accuracy of the system especially at high frequencies.

4 EMILIA VERIFICATION
For accuracy system verification, a comparison between measurements conducted with a lab precision impedance analyzer, Wayne Kerr 6500B, and the developed EMI-node are performed (Figure 7). Here, measurements with both systems are performed at identical environmental conditions and on the same CFRP-panel. The measurements are performed with an excitation voltage of 1 Vp-p due to the limitation of the lab impedance analyzer excitation voltage.

Figure 8 shows the EMI-data comparison measured with the laboratory impedance analyzer (continuous line) versus EMILIA (dotted line) in the frequency range 20 kHz to 45 kHz. The average deviation between the measurements is less 2 % in the frequency range of 20 kHz to 45 kHz.

5 DETECTING OF STRUCTURAL CHANGE
After investigation of the developed system and factors responsible for the precise function, measurements on an airplane conform structure under laboratory environment are carried out. Here, all investigations are realized with the first, centralized version of the node EMILIA-V01.

5.1 Test Setup
For system verification, a setup consisting of control personal computer (PC), CFRP-panel with applied piezoceramic transducer and EMILIA is conducted (Figure 9).

The used CFRP-specimen has a size of 500 x 400 mm with a thickness of 2 mm and is manufactured of unidirectional prepreg material. Two stringers are bonded on the surface.

The measurement performed to detect a structural change, here adding of 27.4 g heavy mass 20 mm distant from the piezo was conducted in Matlab on the control PC (Figure 10). First, the entire measurement frequency range between 1 kHz and 100 kHz is measured. After data analysis, the most sensitive frequency band for the induced structure change detection is selected and a new set of measurements with higher frequency resolution within this frequency range are performed.
5.2 Experimental Results

In the following, the measured impedance analysis for the setup illustrated in Figure 9 and Figure 10 is introduced. The most dynamic frequency band is between 10 kHz and 15 kHz for the realized setup configuration and the raw data streams for the structure status without (continuous line) and with added mass (dotted line) are shown in Figure 11. Obviously, characteristic and amplitude changes of the resonance peak at 11.4 kHz are observed after modifying the structural mass. The same observation exists for the resonance peak at 10.8 kHz and for the run of curve at 14 kHz.

6 CONCLUSION

In this paper, the development of a compact impedance analyzer node is presented. Two versions of the node are implemented, one version is appropriate for realization of a local impedance analyzer (EMILIA-V01) and second version (EMILIA-V02) for the integration on the surface of a piezoceramic module (PI DuraAct SP-876.A13). Both designs offer different advantages of an EMI-system for realization of a monitoring system dependent of specific application requirements.

Successful detection of a mass modification on a CFRP structure is realized by the means of the developed EMI-node. The comparison of measurements conducted with a laboratory precision impedance analyzer and EMILIA is carried out. This investigation reveals that the developed node offers precise measurements of a complex unknown impedance. The presented compact impedance analyzer can be used for structural heath monitoring and also for piezo health monitoring purposes.

In future steps, an implementation of a MCU on the PCB of EMILIA-V02 is planned. In this way the realization of SHM-network for large scale structures can be achieved.

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