Experimental Analysis of Piezoelectric Transducers for Impedance-Based Structural Health Monitoring

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Outline

• Structural Health Monitoring (SHM)
• Electromechanical Impedance (EMI) Method
• Piezoelectric Transducers
• Damage Detection – Damage Indices
• Experimental Setup
• Results
• Conclusions
Structural Health Monitoring (SHM)

Objective: monitoring and detection of structural damage

Application: various types of structures
Structural Health Monitoring (SHM)

Benefits

- Reduction of maintenance costs
- Improved safety
- Increased lifetime
Electromechanical Impedance (EMI) Method

Damage detection

- Acoustic Emission
- Comparative vacuum
- Eddy current
- Lamb waves
- Electromechanical impedance (EMI)

The electromechanical impedance (EMI) method stands out from the other methods by its simplicity and by using low-cost, lightweight and small piezoelectric transducers.
Electromechanical Impedance (EMI) Method

Principle

\[
Z_E(\omega) = \frac{1}{j \omega C_0} \| jZ_T \left( \frac{s_{11}}{d_{31} \ell} \right)^2 \left[ \frac{1}{2} \tan \left( \frac{k \ell}{2} \right) - \frac{1}{\sin(k \ell)} + \frac{Z_s}{j2Z_T} \right]
\]

Electrical impedance Transducer  
\[Z_E(\omega)\]

Mechanical impedance Structure  
\[Z_s\]
Piezoelectric Transducers

PZT (lead zirconate titanate) piezoceramic
Type: 5H
Size: 15 x 15 x 0.267 mm

MFC (macro-fiber composite)
Type: M2814-P2
Size: 37 x 18 mm

Piezoelectric diaphragm – “Buzzer”
Size: 27 mm (external diameter)
Damage Detection – Damage Indices

- Comparison of two electrical impedance signatures: **healthy condition** and **damaged condition**

- We used the real part of the electrical impedance

### RMSD

Root mean square deviation

\[
RMSD = \sqrt{\frac{1}{\omega_f - \omega_i} \sum_{k=\omega_i}^{\omega_f} \left[ Z_{E,D}(k) - Z_{E,H}(k) \right]^2}
\]

### CCDM

Correlation coefficient deviation metric

\[
CCDM = 1 - \frac{\sum_{k=\omega_i}^{\omega_f} \left[ Z_{E,H}(k) - \bar{Z}_{E,H} \right] \left[ Z_{E,D}(k) - \bar{Z}_{E,D} \right]}{\sqrt{\sum_{k=\omega_i}^{\omega_f} \left[ Z_{E,H}(k) - \bar{Z}_{E,H} \right]^2} \sqrt{\sum_{k=\omega_i}^{\omega_f} \left[ Z_{E,D}(k) - \bar{Z}_{E,D} \right]^2}}
\]
Experimental Setup

Structures

Aluminum beams
500 x 38 x 3 mm

The transducers were placed on the beams using cyanoacrylate glue

Damage was simulated by placing a small steel nut
11 x 0.5 mm, 1 g
Experimental Setup

Measurement System

**Configuration**

- Sampling rate: 2 MS/s
- Excitation voltage: 1 V
- Frequency range: 0 – 500 kHz
- Frequency step: 2 Hz

**Measurement System**

**Auxiliary Circuit**

- PZT
- Rs

**DAQ Device**

- DAC
- ADC
- USB

**Calibrated Signal Pattern**

- Excitation
- Windowing
- DFT

- FRF
- Averaging
- Calculation of Z

**NI USB-6361**

**ni.com**
Experimental Setup
Results – Impedance Signatures – 5H PZT patch
Results – Impedance Signatures – MFC transducer
Results – Impedance Signatures – **Buzzer**

Piezoelectric diaphragm, “buzzer”

- **Damaged**
- **Healthy**

![Graph](image-url)
Results – Impedance Signatures

According to the electrical impedance signatures:

• There are resonance peaks in the signatures related to the natural frequencies of the structures;

• Structural damage (nut) causes variations in frequency and amplitude in these peaks, which can be quantified by indices of damage;

• The peaks are more significant at low frequencies and tend to decrease as the frequency increases;

• The PZT patch has provided impedance signatures with higher amplitude;

• Impedance signatures with lower amplitude were obtained using the MFC transducer;

• The piezoelectric diaphragm provided impedance signatures with intermediate amplitude between the other two transducers.
Results – Damage Indices – **5H PZT Patch**

- RMSD

- CCDM

**5H PZT patch**
Results – Damage Indices – MFC transducer

RMSD

MFC transducer

0 10000 5000 0

Frequency (kHz)

CCDM

MFC transducer

0 1 0.5 0

Frequency (kHz)
Results – Damage Indices – **Buzzer**

Piezoelectric diaphragm, “buzzer”

**RMSD**

**CCDM**

**Frequency (kHz)**
Results – Damage Indices

According to the damage indices:

• The PZT patch and the diaphragm provided the highest indices for low frequencies around approximately 10-70 kHz;

• The MFC transducer provided higher indices at high frequencies;

• The piezoelectric diaphragm showed a reasonable sensitivity to detect damage, although the indices were lower compared to other transducers. However, this device has the advantage of having a very low cost.
Conclusions

- The experimental results indicate that the transducers have different sensitivities to detect damage;

- The sensitivity varies significantly with the frequency range;

- It is important to note that this study does not consider an important feature of the transducers for the EMI method, which is to provide repeatable and consistent impedance signatures.
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Questions?

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