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Structural health monitoring of aluminium structure with piezopatches

Petr Sadílek[1] , Robert Zemčík[2] , Jan Bartošek[3]

Abstract: Frequency analysis with an impact hammer on an aluminium structure was performed and a finite element model was created and evaluate eigenfrequencies. Consequently further sensing was done on the structure, this time with piezo sensor and actuator. Following experiments were performed on the same aluminium structure with predefined damages with different types of excitation to find out, whether a damage can be identified.

Keywords: piezoelectric, finite element method, experiment, simulation, damage

1. Introduction

Today's demands on the material properties are reaching the limits, which calls for the usage of embedded sensors and actuators, such as piezoelectric transducers. These complex mechatronical systems [1] are usually called smart or adaptive structures because they can respond to varying conditions in real time.

The piezoelectric effect describes the relation between mechanical loads and electrical voltage in solids. It is reversible: applied mechanical stress will generate voltage and applied voltage will cause change of the shape. The advantage of piezoelectric materials is their quick response and high efficiency compared to other smart materials.

The piezoelectric phenomenon can, therefore, be used for example for the analysis of spectral characteristics of given structure. If a change in the characteristics is found it means that the structure was modified for example by local damage of material or loosening of a joint etc. This is the first step in structural health monitoring (SHM) and it can be followed by damage localization or residual strength prediction.

The first finite element implementation of the piezoelectric phenomenon was described by Allik and Hughes [2] in 1970. Since then many researches have equipped the standard structural finite elements with the piezoelectric capability. Cen et al [3], for example, developed a four-node plate element for laminated structures based on first-order shear deformation theory while Lee et al. [4] introduced a nine-node assumed strain element allowing, unlike other elements, for variable thickness.

[1] *Ing. Petr Sadílek; Department of Mechanics, Fac. of Applied Sciences, University of West Bohemia; Univerzitní 22, 306 01 Plzeň, Czech Republic; psadilek@kme.zcu.cz*
[2] *Ing. Robert Zemčík, Ph.D.; Department of Mechanics, Fac. of Applied Sciences, University of West Bohemia; Univerzitní 22, 306 01 Plzeň, Czech Republic; zemcik@kme.zcu.cz*
[3] *Ing. Jan Bartošek; Department of Mechanics, Fac. of Applied Sciences, University of West Bohemia; Univerzitní 22, 306 01 Plzeň, Czech Republic; bartose4@kme.zcu.cz*

The pure mechanical stress-strain law for piezoelectric material is extended with piezoelectric coupling [5]. This can be then written as

$$\begin{aligned} \boldsymbol{\sigma} &= \mathbf{C}\,\boldsymbol{\varepsilon} - \mathbf{e}^{\mathrm{T}}\,\mathbf{E}\,, \\ \mathbf{D} &= \mathbf{e}\boldsymbol{\varepsilon} + \boldsymbol{\epsilon}\,\mathbf{E}\,, \end{aligned} \tag{1}$$

where $\mathbf{D}$ is the vector of electric flux density, $\boldsymbol{\epsilon}$ is the dielectric permittivity matrix, $\mathbf{e}$ is the piezoelectric coefficient matrix and $\mathbf{E}$ is the electric field vector. The permittivity matrix $\boldsymbol{\epsilon}$ and the piezoelectric matrix $\mathbf{e}$ are defined as

$$\boldsymbol{\epsilon} = \begin{bmatrix} \epsilon_{11} & 0 & 0 \\ 0 & \epsilon_{22} & 0 \\ 0 & 0 & \epsilon_{33} \end{bmatrix}, \tag{2}$$

$$\mathbf{e} = \begin{bmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{24} & 0 & 0 \\ e_{31} & e_{32} & e_{33} & 0 & 0 & 0 \end{bmatrix}. \tag{3}$$

Based on previous research with piezoelectric patches [6], an aluminium structure with piezoelectric actuator and piezoelectric sensor was created. The structure was tested for eigenfrequencies and the results were compared to experiments with an impact hammer and an accelerometer and consequently with results from finite element method software – MSC.Marc. Number of different failures was simulated and examined. Results were mutually compared again, the method of testing was verified and prepared for further experiments.

2. Modal characteristics of aluminium structure

An aluminium structure was used for the first experiments as a free-end body. Aluminium beams with thickness of 3 mm, width of 20 mm and total length of 220 mm were prepared. Aluminium connectors, steel screws and steel nuts were used for connecting. Two different configurations were examined, a symmetrical one with 17 beams and an asymmetrical one with 16 beams.

2.1. Experimental analysis using impact hammer

Analysis of modal characteristics of the structure was performed. The measurement was carried out on both configurations to demonstrate the change of the characteristics. The structure was loose hanged on a frame and slightly damped with rubber lines (see Fig. 1). An impact hammer and an accelerometer (Brüel&Kjær) bonded to one of the connectors were used. The eigenfrequencies and eigenmodes were determined using Pulse software. It was difficult to distinguish between the higher eigenfrequencies that were close to each other and collapsed in one peak. Selected eigenfrequencies are shown in Fig. 2.

2.2. Finite element analysis

Simplified finite element models of the two configurations were created. All elements were defined as solids (see Fig. 3). Material properties were defined as in Table 1 and were verified for both previous experiments through modal analysis.

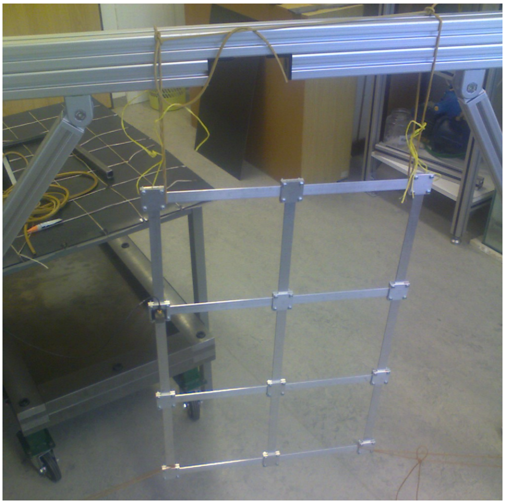

Figure 1: Photograph of experiment arrangement.

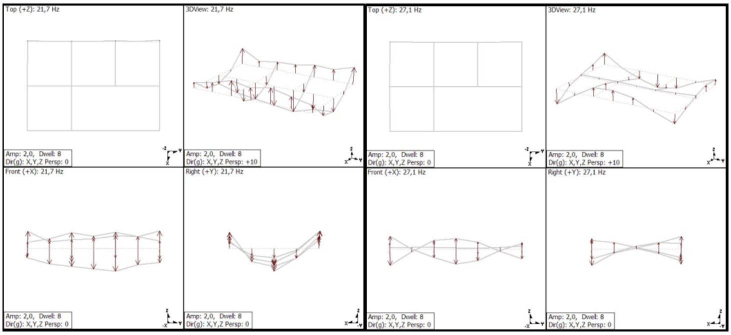

Figure 2: Third and fourth eigenfrequency from experiment with one beam removed.

	ρ [kg/m^3]	E [GPa]	ν [-]
Beam	2679	63	0.35
Connector	3050	70	0.3

Table 1: Material properties of aluminium structure.

Results of numerical model revealed two additional lower eigenfrequencies that were not obvious from the experiment. Values from the experiment and FEM analysis did not differ in more than 5% in the latter eigenfrequencies. The resulting data are compared in Table 2.

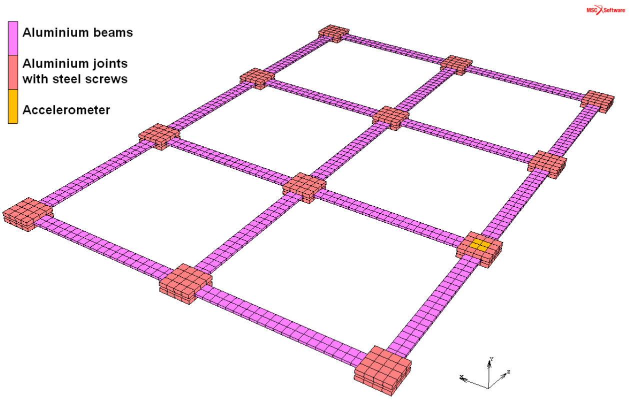

Figure 3: Simplified model of the structure with accelerometer in MSC.Marc.

2.3. Experimental analysis using piezoelectric patches

Another method for investigation of modal characteristics was employed. Two piezoelectric patches P-876.SP1 (active area of a piezoelectric material was 10×10 mm), one as a sensor and the latter as an actuator, were glued to the central connector of the original configuration with 17 beams. Since the patches are very sensitive, shielding with an aluminium foil (Fig. 4) was needed to supress the unwanted electric 50 Hz hum from the power line.

Arrangement of the experiment is shown in Fig. 5. The experiment was controlled by a computer, connected to National Instruments CompactDAQ unit with 9263 output module and 9215 input module. The output module converts the digital signal generated to an analog signal. This signal is amplified by a driver. The amplified signal goes to the actuator glued to the beam. The applied voltage contracts and stretches the piezoelectric patch, which excites the beam. The oscillation is than

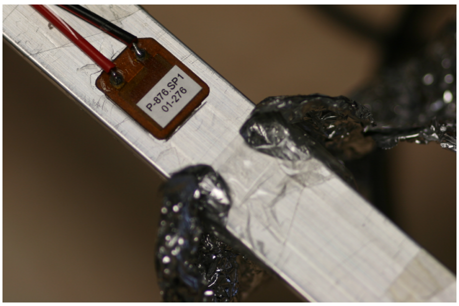

Figure 4: Detail of one patch attached to the beam and shielding foil.

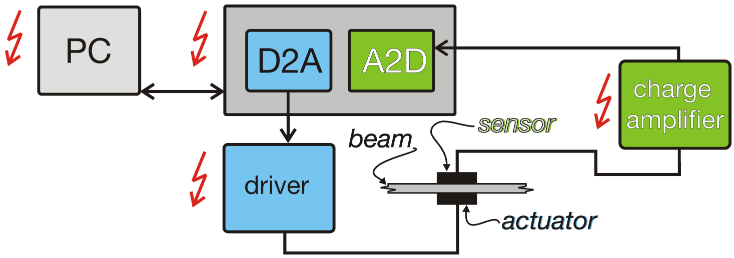

Figure 5: Apparatus scheme.

captured by the second piezoelectric patch. The sensor sends the signal through a charge amplifier to the input module, that converts analog signal **U** to a digital signal.

The experiment was carried out with a software in National Instruments LabView. Several excitation pulses were tested. The results obtained did not differ strongly. Therefore, only six basic excitation pulses (one peak of 100 Hz triangular wave, 10 Hz, 50 Hz, 100 Hz, 200 Hz, and 350 Hz square wave) were used. A whole period of chosen signal was tested in the first experiments, later mainly a section of square wave was used, as it showed clearer border between the end of excitation signal and the beginning of free oscillations. Eigenfrequencies were found using Fourier transform in Matlab.

As shown in Table 2 the values of eigenfrequencies found using piezoelectric patches also did not reveal all eigenfrequencies clearly, but the results show good similarity with results from sections 2.1 and 2.2.

Frequency	1	2	3	4	5	6	7
Symmetrical							
Exp. impact [Hz]	-	-	25.33	29.24	36.41	40.81	55.59
MSC.Marc [Hz]	13.04	13.26	25.30	28.69	36.40	38.07	52.55
Exp. piezo[Hz]	12.21	13.30	-	27.47	35.10	37.38	50.35
Asymmetrical							
Experiment [Hz]	12.7	-	21.7	27.1	34.1	38.1	47.8
MSC.Marc [Hz]	12.5	13.2	22.0	27.7	34.9	39.1	48.8

Table 2: Comparison of eigenfrequencies of both configurations.

3. Analysis of damaged aluminium structure

The structure examined in previous sections was changed to investigate its behavior for purposes of SHM. A beam divided in half was chosen as a case of representative damage. There are six possible cases of such damage (Fig. 6), they are highlighted with a magenta line. Other 11 cases are only symmetrical types of mentioned six cases.

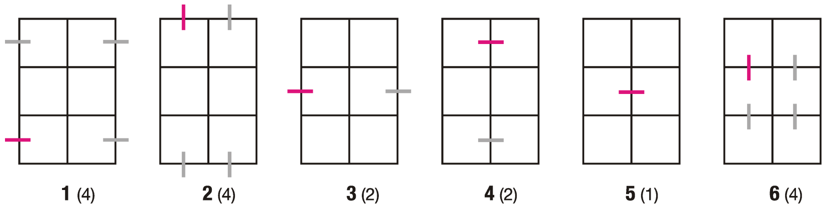

Figure 6: Six cases of damaged structure with one damaged beam (magenta lines). Numbers in brackets denote the number of symmetrical cases (grey lines).

Numerical models of all six cases with appropriate damage were created by modal analysis. Eigenfrequencies were found out for following confrontation with experiment. The six abovementioned excitation signals were used (as in the previous section with undamaged structure) and all six cases of structure with artificial damage were examined accordingly. Results are compared in Table 3 to 8. Based on the comparison it can be concluded that the excitation signal does not have significant influence on the results. Fig. 7 shows the response of damaged case 1 and the corresponding spectrum of both damaged and undamaged configurations.

4. Conclusion

The work focused on application of piezoelectric materials on an aluminum structure in order to perform damage detection by analysing spectral characteristics. Based on previous research, experiments with an impact hammer were performed and consequently verified with FEM software MSC.Marc. Testing of the same structure with piezoelectric patches was performed. Testing with piezoelectric equipment showed close results to values obtained from FEM and also to the experiment with an impact hammer. Different excitation signals were investigated with no substantial difference in results.

To simulate damage of the structure six cases were proposed and investigated. The results agreed with corresponding results from MSC.Marc and differed among the six cases of damage and undamaged structure.

Presented research showed, that piezoelectric patches can be used for the excitation and response measurement of structure. This approach can be used for structural health monitoring to detect damage. Following research will focus on monitoring composite materials, where a failure is difficult to recognize.

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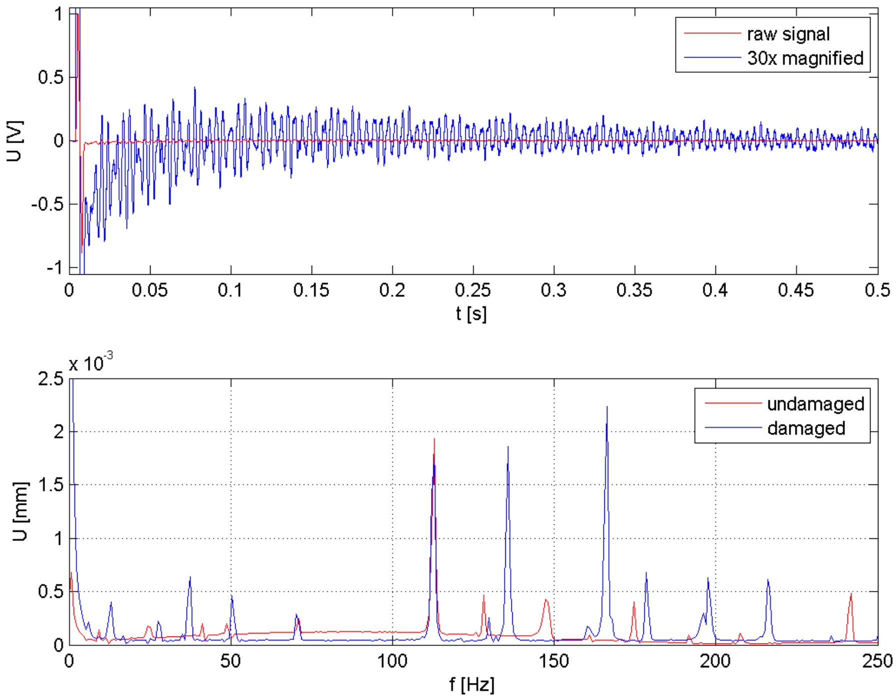

Figure 7: Signal from piezoelectric sensor (top) and comparsion of spectra of damaged (case 1) and undamaged structures.

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Frequency	1	2	3	4	5	6	7	8	9	10
MSC.Marc [Hz]	9.421	12.08	19.77	25.29	32.54	34.79	42.74	50.86	66.37	73.64
Experiment [Hz]	9.155	12.21	19.84	25.18	-	-	41.2	49.59	64.09	70.95
Difference [%]	1.03	0.99	1.00	1.00	-	-	1.04	1.03	1.04	1.04

Table 3: Comparison of results from experiment with results from MSC.Marc - case 1.

Frequency	1	2	3	4	5	6	7	8	9	10
MSC.Marc [Hz]	9.749	13.03	17.53	24.16	30.86	38.02	44.44	51.47	66.67	73.25
Experiment[Hz]	9.918	12.97	17.55	23.65	-	37.38	42.72	49.59	64.09	70.19
Difference [%]	0.98	1.00	1.00	1.02	-	1.02	1.04	1.04	1.04	1.04

Table 4: Comparison of results from experiment with results from MSC.Marc - case 2.

Frequency	1	2	3	4	5	6	7	8	9	10
MSC.Marc [Hz]	9.064	10.52	22.09	25.30	26.92	34.48	43.50	52.56	67.44	96.29
Experiment [Hz]	-	10.68	21.36	-	26.70	34.33	41.96	49.59	64.85	94.60
Difference [%]	-	0.99	1.03	-	1.01	1.00	1.04	1.06	1.04	1.02

Table 5: Comparison of results from experiment with results from MSC.Marc - case 3.

Frequency	1	2	3	4	5	6	7	8	9	10
MSC.Marc [Hz]	11.96	12.66	25.27	27.28	31.80	35.56	45.72	51.84	64.56	88.33
Experiment [Hz]	11.44	12.21	-	26.70	31.28	35.1	44.25	49.59	62.56	85.45
Difference [%]	1.05	1.04	-	1.02	1.02	1.01	1.03	1.05	1.03	1.03

Table 6: Comparison of results from experiment with results from MSC.Marc - case 4.

Frequency	1	2	3	4	5	6	7	8	9	10
MSC.Marc [Hz]	10.89	12.36	25.29	27.57	28.69	36.50	51.51	52.09	60.25	98.74
Experiment [Hz]	10.68	12.21	-	26.70	-	35.10	49.59	-	58.75	97.66
Difference [%]	1.02	1.01	-	1.03	-	1.04	-	1.05	1.03	1.01

Table 7: Comparison of results from experiment with results from MSC.Marc - case 5.

Frequency	1	2	3	4	5	6	7	8	9	10
MSC.Marc [Hz]	12.51	13.04	21.16	27.23	34.49	38.00	46.11	51.61	65.32	87.47
Experiment [Hz]	-	12.97	-	26.70	36.62	-	44.25	49.59	62.56	99.95
Difference [%]	-	1.01	-	1.02	0.94	-	1.04	1.04	1.04	0.88

Table 8: Comparison of results from experiment with results from MSC.Marc - case 6.