SENSITIVITY SPREAD OF PIEZO ELECTRIC FILMS USED AS SENSORS FOR MACHINE AND STRUCTURAL MONITORING

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Abstract. The importance of integrated diagnostic systems grows, increasing safety and reducing the cost of operating machines and structures. For serially manufactured machines and structures inexpensive monitoring systems are needed. One of the developed solutions could be the replacement of the calibrated accelerometers with piezoelectric films. Such configuration of the system implies the methods that allow monitoring and diagnostic with uncalibrated sensors. As the film sensitivity parameters are not specified, it is necessary to determine experimentally the characteristics of individual piezo films. The experimental study has been completed by testing a batch of 50 piezo films. Each tested film was glued to a thin metal specimen, which is dynamically loaded with tensile and compressive stresses at a fixed frequency and amplitude. The sensitivity factor of the piezo film was evaluated using dynamic tests followed by temperature control. The testing setup and testing methods are described. Data processing techniques with results of development are performed. The study allowed establishing the dependence of sensitivity of piezo-film sensors on temperature, the confidence interval for the linear regression coefficient for the investigated temperature range. The results allow recognizing the piezo electric films (PVDF) as the sensors acceptable for use in vibration diagnostics and structural monitoring systems.

Keywords: piezo electric films, sensitivity to temperature, monitoring system, modal passport method.

Introduction

To improve the safety of operation and to reduce the cost of maintenance and repair of complex machines and structures, the use of vibration monitoring and diagnostic systems is increasingly expanding. Systems for monitoring the condition of rotating machines can detect defects in bearings and gearboxes [1]. Monitoring systems using modal analysis technologies are able to detect damages or changes in mechanical properties. For operating objects, the methods of Operational Modal Analysis (OMA) [2] are used, which provide an assessment of modal properties applying a number of vibration sensors. Trial samples of structural monitoring systems use expensive equipment, including calibrated accelerometers and multichannel measuring equipment [3; 4]. Due to the high cost, such systems remain inaccessible for mass-produced machines and structures used in industry, agriculture and transport. For wider applications, fundamental solutions are needed to create compact and inexpensive monitoring systems. For example, the prototype of the onboard monitoring system [5] foresees replacement of calibrated accelerometers with cheap film sensors, as justified in [6]. The above approach allowed reducing the number of measuring channels due to the switches use. The modal passport (MP) application [5], which for monitoring combines typical modal properties with individual ones makes it possible not only to reduce the cost, but also to simplify monitoring systems for serial structures.

The use of piezoelectric sensors is one of the ways to reduce the cost and dimensions of monitoring systems for serial objects due to their negligible weight (0.06 g), scanty thickness (less than 0.11 mm) and no balancing required. Along with the advantages, piezo films have limitations due to the lack of calibration (from manufacturer) and the dependence of their sensitivity on temperature [7-9]. Also, there is sensitivity spread between sensors affecting the system error.

The applications of structural monitoring with MP methods and of some methods for machine vibration diagnostics use the normalized parameters only, so the absence of calibration for piezo films is not an obstacle. Other monitoring techniques require absolute vibration values, therefore the sensitivity of piezo films can be determined by calibrating some samples from a batch. For any case, to use piezo films for monitoring or diagnostics, it is necessary to take into account the sensitivity spread among the sensors. Most potential monitoring objects (windmills, aircrafts, and infrastructure objects) operate in a wide range of temperatures that affect the properties of structures and sensors. This influence on the properties of the structure may be taken into account by the MP influence functions, provided by the dependence of the films' sensitivity on temperature.

The objective of this work is to study the influence of the sensitivity of piezo films on the measured vibration diagnostic parameters. The tasks of the study include the development of a technique for

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measuring the sensitivity of piezo films and its spread between sensors, as well as the effect of temperature on the sensitivity.

Materials

A batch of 50 *DT*1-028*K* type piezo films produced by *TE connectivity* [9] was used as an object of the study. The basis of this type of sensors is a polarized fluoropolymer - polyvinylidene fluoride film (PVDF), on which silver electrodes are printed on both sides. The characteristics and main overall dimensions of these sensors in Fig. 1a, according to the manufacturer’s technical documentation, are shown in Table 1.

Table 1

Specifications of type *DT*1-028*K* sensors

Parameter	**Value**	**Unit**	**Notes**
Sensor Model Number	DT1-028K	---	-
Film Thickness	28	μm	-
Dimension A (Film)	16	mm	-
Dimension B (Electrode)	12	mm	-
Dimension C (Film)	41	mm	-
Dimension D (Electrode)	30	mm	-
Total Thickness	40	μm	-
Cap	1.38	nF	-
Minimum Impedance	1	MΩ	-
Preferred Impedance	10	MΩ	and higher
Output Voltage	0.01 ÷ 100	V	depending on force and circuit impedance
Storage Temperature	-40 ÷ + 70	ºC	-
Operating Temperature	0 ÷ + 70	ºC	-

After the delivery of a batch of piezo films as in Fig. 1b, the work was carried out to prepare them for testing. The set of works consisted in gluing conductors (copper, varnished wire “*Wire Copper Enameled*” Ø 0.25 mm) 150 mm long to the sensor electrodes using a special two-component epoxy adhesive “*Silver Conductive Epoxy*”. After that, the sensor was pasted with a protective film on one side, and, to ensure the possibility of fixing it to the test sample, with double-sided adhesive tape on the other, Fig. 1c. This procedure was carried out with all 50 piezo films before testing.

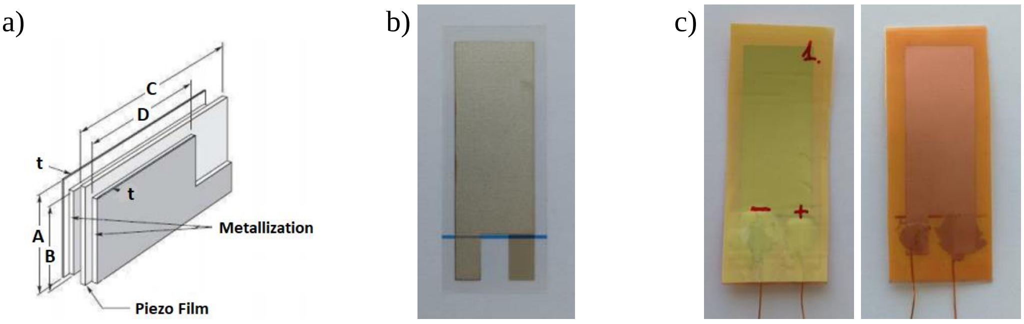

Fig. 1. **Sensor dimensions (a), sensor supplied by the manufacturer (b), sensor prepared for testing, both sides shown (c)**

Testing methods

A dynamically deformed piezoelectric film generates an electric charge on its electrodes. For this study, the way of linear deformation of the piezo film due to periodic tension-compression was chosen for calibration. The sensitivity of the piezo film is estimated by the ratio of the voltage measured at the sensor contacts to the linear deformation mean that causes this voltage. Thus, the determined sensitivity of the piezo film corresponds to the conversion coefficient of the linear deformation of the piezo film into electric current voltage. In order to ensure identical test conditions and bring them closer to the operating conditions, the piezo films were tested while glued serially to the test sample (specimen). The specimen was a duralumin plate with a cross section of 25 x 2 mm and the length of 250 mm, which was installed in the clamps of the *INSTRON* testing machine (Fig. 2).

Fig. 2. **Testing machine INSTRON E3000**

The general scheme of measurement during testing is shown in Fig. 3. The lower clamp 3 of the testing machine is stationary, the upper one 2 vibrates in vertical direction. The tested piezo film 6 is glued on the surface of the specimen 5, and when the machine operates the piezo film is deformed together with the specimen, experiencing tensile-compressive stresses 7 in vertical direction. The amplitude of the upper clamp 2 vibrations is limited by the condition of the absence of specimen buckling. The 3-axis accelerometer *AP*2022 4 is fixed on top of the force sensor 1 fixed to the movable clamp 2 for displacement measurement. On the backside of the specimen 7 the temperature sensor *DS*18*B*20 8 is located to provide monitoring the specimen temperature.

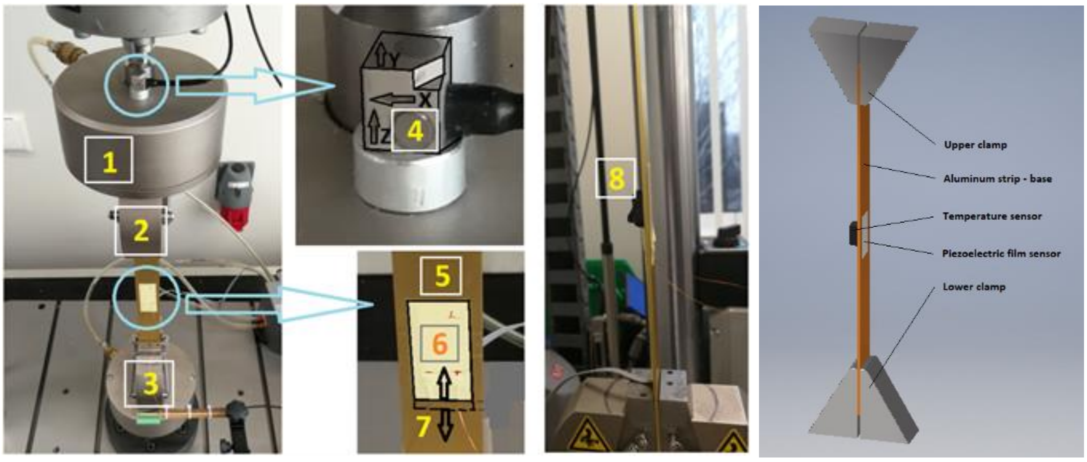

Fig. 3. **Placement of the accelerometer and piezofilm on the elements of the testing machine and the test sample**

The signals from the piezo film, accelerometer and temperature sensor are transmitted through connecting cables to the input of a 12-channel measurement unit *Brüel & Kjær Type* 3053-*B*-120. The measured and digitalized signals are sent to the computer that provides data processing. The control and management of the testing machine operation, including the frequency and amplitude of excitation, are carried out by the control unit. All tests of piezo films were conducted with a fixed frequency of 45 Hz and the load amplitude of 2000 N. It should also be noted that the 2000 N pretension of the specimen was provided for buckling prevention.

The testing procedure for each film included four stages. At the first stage the sensor was made from each tested piezo film; the procedure for this stage is described earlier. The second stage considered gluing the sensor on the specimen. The third stage was testing the sensor at a given temperature, including control, measurement and registration of the signals from five channels for 10 seconds, and the data files formation. Removing the sensor and cleaning the sample surface for the next test was the last stage.

The tests of all piezo films were carried out at three fixed temperature grades for specimen with the tested film: 25 ºC, 45 ºC, and 70 ºC. Additional tests were performed to determine the sensitivity of one sensor in low temperature zone 9 to 25 ºC.

Data processing methodology

Data files with the test results for each sensor were processed in accordance with the data analysis methodology. The sensitivity k_i of i^{th} piezofilm is calculated as the ratio of the parameter of the electrical signal voltage generated by the piezo film at the excitation frequency U_i to the RMS of the variable value of the relative elongation δl_i of the piezo film

$$K_i = \frac{U_i}{\delta l_i}. \tag{1}$$

Parameter U_i is defined as the magnitude of the signal spectrum component of the piezoelectric film with the excitation frequency (45 Hz), which corresponds to the RMS of the measured voltage at this frequency. The relative elongation parameter δl_i was used because piezo films of different sizes can generate a different signal with the same excitation. Variable deformation of a specimen S_i along the vertical axis occurs due to the reciprocating movement of the testing machine's upper clamp. The relative elongation of the sample was estimated by the ratio of the RMS S_i to the length L of the stretched part of the sample

$$\delta l_i = \frac{S_i}{L}. \tag{2}$$

The Z-axis of the accelerometer coincides with the reciprocating movement of the upper clamp, which movement $S_i(t)$ is calculated by double integrating the acceleration signal $a_z(t)$

$$S_i(t) = \int\int_0^T a_Z(t) d(t) \cdot \tag{3}$$

The value of S_i is defined as the amplitude of the displacement spectrum component $S_i(t)$ at the excitation frequency. Based on the results of data processing of 50 samples, the average value of $\bar{K}_t$ of sensitivity and the standard deviation (STD) of sensitivity σK_i are calculated for each of the three temperature values

$$\bar{K}_t = \frac{1}{50} \sum_{i-1}^{50} S_i^t , \tag{4}$$

$$\sigma K_t = \sqrt{\frac{1}{50}\left[\sum_{i-1}^{50} \left(S_i^t - S_t\right)^2\right]}. \tag{5}$$

To assess the dependence of the sensitivity of piezo films on temperature based on linear assumption, a linear regression coefficient is used, determined by the Least Mean Square method

$$\sum_{i-1}^{50} \left(S_i^t - S_t\right)^2 \to \min . \tag{6}$$

The scatter in the sensitivity of the sensors can distort the shapes of the modes calculated from their signals but does not affect the assessment of the state of the structure. The fact is that MP evaluates the state of the structure by comparing the modal parameters with the threshold values that are set for the reference conditions. In reality, the modal parameters of the structures are measured under arbitrary conditions, and in order to compare them with the threshold, MP provides recalculation of the parameters to the reference conditions. For this purpose, influence functions are predetermined for typical structures, for example, the temperature function $F_m^s(t)$. Using the linear regression coefficient, the eigenvector S_m^t of m-th mode estimated at temperature t can be recalculated to the reference t_0

$$S_m^0 = S_m^t - F_m^S\left(t - t_0\right). \tag{7}$$

Since the position of the sensors on the structure does not change, the influence of the scatter on the measured eigenvector S_m^t will remain the same for the linearly transformed S_m^0.

Discussions and results

Using the data files recorded during the tests, the sensitivity coefficients of each of the 50 sensors for three temperature values were calculated according to formulas (1-3). The diagram in Fig. 4. illustrates that sensitivity of the sensors is falling with temperature rise. It can be seen from the diagram that the dependences of all tested sensors are close to linear origin and fit into a "corridor" limited by the spread. The sensitivity means averaged over all sensors and their standard deviation calculated by formulas (4,5) are shown in Table 2. Using formula (6), the generalized sensitivity linear regression coefficient was calculated, which is -0.524 V/%/ºC (in the right column of Table 2). The above coefficient value was confirmed also for lower temperature (9...25 ºC) using additional tests of randomly selected sensors.

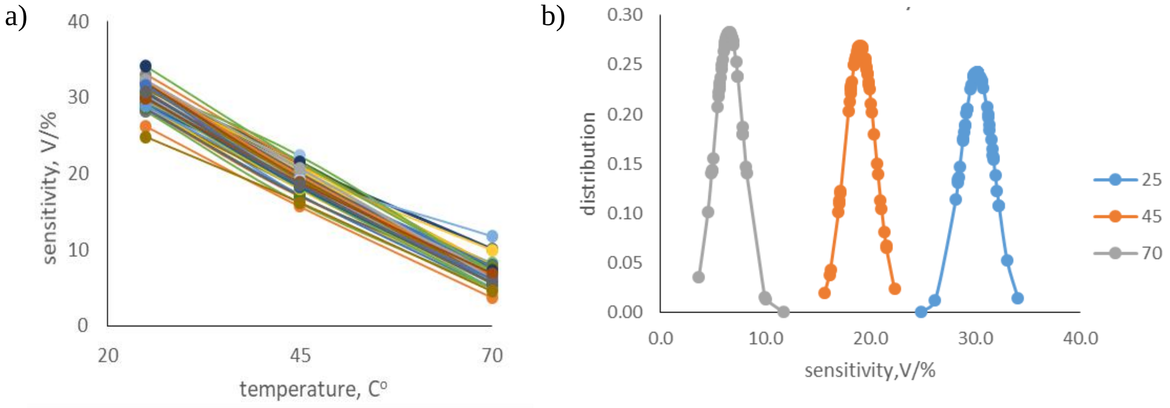

Fig. 4. **Diagram of sensitivity estimates: dependence on temperature for 50 films (a), distribution (b)**

Table 2

Spread of the sensor sensitivity

Parameter	***t*, ºC**			**Trend, V/%/ºC**
	25 ºC	45 ºC	70 ºC	
Mean. V/%	30.2	19.1	6.57	-0.524
STD. V/%	1.64	1.48	1.41	0.036
CI (99.7%)	4.93	4.44	4.24	0.107
% (CI/mean)	16%	23%	65%	20%

As it can be seen from Table 2, although the sensors' sensitivity decreases with temperature rise, STD between sensitivity means remains almost unchanged. The distribution of sensitivity estimates showed the origin close to normal (Fig. 4b) at all three temperature steps. Considering the normal distribution, the confidence interval (CI) of sensitivity with a probability of 99.7% was estimated as triple STD for each temperature. Also STD and CI were calculated for linear regression coefficients. The bottom row of Table 2 shows the confidence interval as percentage to the mean for each temperature and for the regression coefficient. For the reference conditions (25 ºC), the distribution area was limited to 16% and increased up to 65% at (70ºC). For the linear regression coefficient, the CI level was limited to 20%, which corresponds to the manufacturer's information.

Conclusions

According to the results of the study, it was established:

- the calibration technique applied for piezoelectric sensors makes it possible to evaluate the sensitivity coefficient by tensile-compression strains,
- the sensitivity of piezo films falls dramatically with temperature growth demonstrating the linear dependence of piezo films' sensitivity on temperature,

- the limited (20%) confidence interval of linear regression coefficients allows using the sensitivity dependence on temperature for recalculation of the modal parameter of structures,
- the measurement uncertainty lies in + /- 1.5% of the parameter values.

The study results allow recognizing the piezo electric films (PVDF) as the sensors acceptable for use in vibration diagnostics and structural monitoring systems.

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Author contributions

Methodology, A.M. and A.S.; validation, P.D.; investigation, A.S., P.D., V.K.; data curation, A.S., and A.M.; writing – original draft preparation, A.S.; writing – review and editing, A.M and P.D...; visualization, A.S. All authors have read and agreed to the published version of the manuscript.

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