THE USE OF INTELLIGENT MATERIALS AS COMPONENTS IN THE CONSTRUCTION OF MACHINES

Andrzej Wróbel

Silesian University of Technology, Faculty of Mechanical Engineering, Institute of Engineering Processes Automation and Integrated Manufacturing Systems, Konarskiego 18A, 44-100 Gliwice, Poland

Corresponding author: Andrzej Wróbel, andrzej.wrobel@polsl.pl

Abstract: In recent years, the methods of active vibration damping in the construction and exploration of machines are often taken up issue. Most vibrations occurring in technical devices have a negative impact on their technical condition and on the immediate surroundings. There are many well known methods of reducing the vibration; generally they can be divided into passive methods and active methods. Intelligent materials are more often used for active vibration damping. They can be defined as a group of materials that have the ability to change their physical properties in an appropriate way as a result of external influences. One of the most popular materials in this group are piezoelectric materials. They are used where it is necessary to reduce vibrations with small amplitudes of μm and work in high frequency ranges. They are the most popular and at the same time the oldest intelligent materials. Piezoelectrics are most often used in automatics, micromanipulation, measuring technology and medicine, used as actuators or sensors. One of the disadvantages of this kind of sensors is the small displacement, which can be increased by using so-called bimorphic systems - complex systems, used to increase the relative elongation of the piezoelectric system, and thus obtain greater mechanical displacements.

The correct identification of the characteristics of the studied piezoelectric systems should be carried out both by theoretical analysis and laboratory tests. In the presented article, the author attempts to detail analyze the longitudinally vibrating piezoelectric plate examine the possibility of use it as subassemblies or assemblies in machine construction.

Key words: intelligent materials, pzt, smart element, complex system, analysis

1. INTRODUCTION

Nowadays, the issues of the use of the intelligent materials working as the sub-assemblies and/or machine assemblies should be considered in terms of the fourth industrial revolution called "Industry 4.0". This revolution assumes very close integration of devices on production lines and entire control systems in order to increase production efficiency and flexibility. In addition, it is assumed that digital networks will supervise every stage of production starting of design, construction, implementation through exploitation and service and ending with recycling.

So what are the foundations of the Industry 4.0. The first step towards industrialization was made by introducing mechanization so the replacement of manual work by the machine [12]. A good example is the replacement of horses used to drive agricultural machinery by a steam engine. A steam engine is now regarded as the first machine of the Industry 1.0. The next big industrial step called the Industry 2.0 was the electrification of the industry. The introduction of electric motors replacing steam engines allowed to increase production, creating so-called mass production, using assembly lines and a strict division of labor by individual employees.

The Industry 3.0 is colloquially speaking the digitization of enterprises, i.e. the dissemination of digital technology, the introduction of the production of high-performance computing units and control systems allowing for more flexible production, and quick changes in the operating parameters of machines and entire production lines. Software development also had an important role in the Industry 3.0, which was the basis for the introduction of automation. Currently still implemented the concept of the Industry 4.0 - is the integration of intelligent systems based on industrial networks and the Internet. In this concept, machines not only communicate with IT systems, but also exchange data with each other.

However, to introduce the concept of the Industry 4.0 into real industrial applications, it is necessary to realise and implement technologies from previous stages of development. Without digitization and full automation of the enterprise, it will not be possible to implement assumptions of the Industry 4.0. The future of modern technical engineering is associated with intelligent materials, so it is difficult to imagine the current industrial revolution without the sub-assemblies and/or the assemblies in which intelligent materials are not implemented. In the literature, there are often found various synonymous terms: "intelligent materials, smart materials or adaptive materials". Of such a large group of the intelligent materials, piezoelectric wafers are very often used in the industry:

• simple piezoelectric phenomenon, depending on generating tension after deformation of the material,

• reverse piezoelectric phenomenon, depending on changing the dimensions after applying voltage to the piezoelectric cladding.

The piezoelectrics are most often used in automatics, micromanipulation, measuring technology and medicine, used as actuators (the reverse piezoelectric phenomenon) or sensors (the simple piezoelectric phenomenon). One of the disadvantages of this kind of sensors is the small displacement, which can be increased by using so-called bimorphic systems - complex systems, used to increase the relative elongation of the piezoelectric system, and thus obtainig greater mechanical displacements.

The main purpose of the article is to present the piezoelectric plate tests working as the sub-assemblies of the vibration sensor presented in article [22, 23]. The correct identification of the characteristics of the studied piezoelectric systems should be carried out both by theoretical analysis and laboratory tests. The article includes verification of the correctness of mathematical models derived in advance by the author [6, 7, 9, 10, 11, 15, 16, 19, 25], both the individual plates and complex systems or often undertaken by other authors on piezoelectric effect [4, 5, 13, 14, 18].

2. OBJECT UNDER EXAMINATION

The subject of the research is a piezoelectric plate or plates in the form shown in Figure 1, which are used in vibrating level sensors (Figure 2). The main idea of the operation of such a sensor used e.g. to detect presence, relies on: detecting the presence of powder when the vibrated sensor element, so-called fork, comes into contact with powder or liquid and the vibrational forks have been covered. The described sensor has both oscillations plates and plate working as sensors, for this reason it uses both the simple and the reverse piezoelectric effect. Output signal is a binary signal, transmitted to the automation systems via a relay.

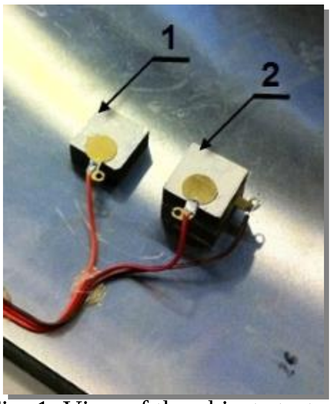

Fig. 1. View of the objects tested

The presented sensor is shown in Figure 2. The sensor is composed of several receiving elements and several elements that generate vibrations. The voltage connected to the supply plates causes thickness vibrations proportional to the applied voltage. This causes vibrations of mechanical elements so-called sensor forks. If the sensor forks are covered, the vibrations of the receiving plates are much smaller, which allows you to detect the state of the sensor (filled or unfilled). When designing level sensors, the important is chose of parameters such as overall dimensions or the number of plates in the stack.


Fig. 2. View of the level sensor

The examined objects there were the individual piezoelectric plates glued together with an electrically conductive adhesive. The parameters of the test plates are shown in Table 1.

Table 1. The geometrical parameters of the test plates

PZ_27	
Party number	F4270074
Shape	Plate
Thickness *[m]*	0.01
Length *[m]*	0.03
Width *[m]*	0.03
Type of material	Pz_27

The actuators and sensors in the presented sensor are piezoelectric ceramic plates. The author also attempted to apply PVDF piezoelectric films in the article [23]. In another article, the author presents the use of piezoelectrics as sensors for the condition of the railway wagon plating [17, 20].

Table 2. The material parameters of PZ_27 plates

Thickness	ρ	7700	$\left[\frac{kg}{m^2}\right]$
Piezoelement elasticity module	$E=C_{33}$	84.25·E^9	[Pa]
Surface area of the plate	A	0.0009	[m^2]
Height of the piezoelectric plate	d	0.01	[m]
Electric capacity	C	1437	[pF]

The parameters characterizing the piezoelectric material were also included in the mathematical model, which was described in detail in previous publication of the author [24, 25]

3. MEASURING EQUIPMENT AND APPEARANCE OF THE LABORATORY STAND

The chapter attempts to validate the results of theoretical considerations on the analysis of vibrations of the piezoelectric plates with the conducted experiment. The autor will try to focus on the existence of resonant areas in the frequency domain. These areas for the single piezoelectric plate and the piezoelectric stacks were stimulated in other publications of the author [19, 25].

In order to conduct research on the piezoelectric plates, there was created a test stand. The main problem occurring in the research concerned vibrations from an external source, and recorded by sensitive measuring instruments, e.g. derived from vibrations of the building, floors.

To minimize vibrations, there was used a heavy steel plate, placed on rubber feet damping vibrations. To stimulate the vibrations of the piezoelectric plates with the appropriate frequency, there was used an Agilent 33210A generator (Figure 3), capable of generating frequencies from 1MHz to 10MHz and obtaining sinusoidal and rectangular courses.

Fig. 3 Measuring instrument used during the experiment – a function generator

In order to obtain a higher voltage, there were connected two power supplies, model ATTEN PPS3205T-3S and model TTi CPX400D.

Fig. 4. Measuring instrument used during the experiment – a power supply

The scheme of connecting the measuring sub-assemblies is shown in Figure 5, and as a result of device configuration, there was received the supply voltage 162V and current 0.17A.

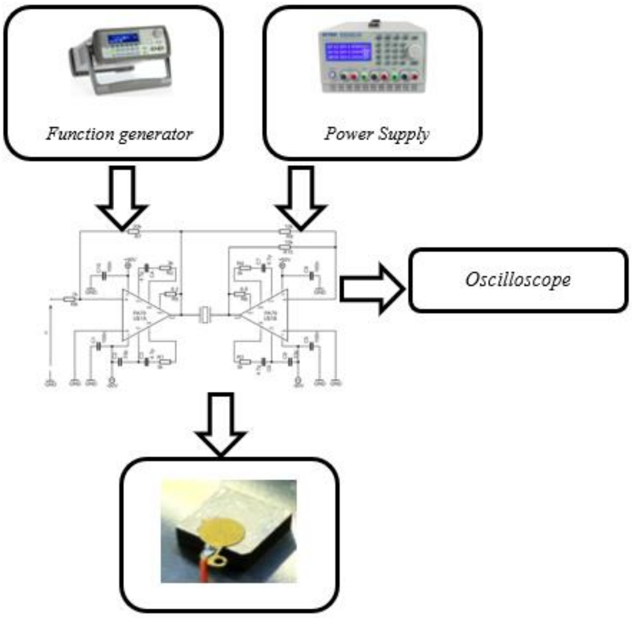

Fig. 5. Connection scheme for measuring instruments

In order to measure such small displacements, there was used a laser vibrometer with a controller: OFV-2570HF and a sensor head marked as OFV-534 Compact Sensor Head (Figure 6). The technical data sheet is shown in Table 3.

Fig. 6. Measuring instrument used during the experiment - a laser vibrometer

Table 3. Data sheet of Compact Sensor Head

Laser type:	Helium neon (Hene),
Laser protection class:	Class 2, <1 *mW*
Laser wavelength:	633 *nm*,
Diameter of aperture`s hole $1/e^2$	6.2 *mm* – 5.2 *mm*
The maximum spot size:	1.5 μm
Video camera (optional)	Type – 1/4" CCD color, resolution (H x V) 510 x 492, lens F 4.5, automatic snapshot speed from 1/60 to 1/100000.

There were carried out the measurements on the test stand shown in Figure 7. The obtained measurement data were subjected to Fast Fourier Transform (FFT) to illustrate the amplitude of displacements in the frequency domain.

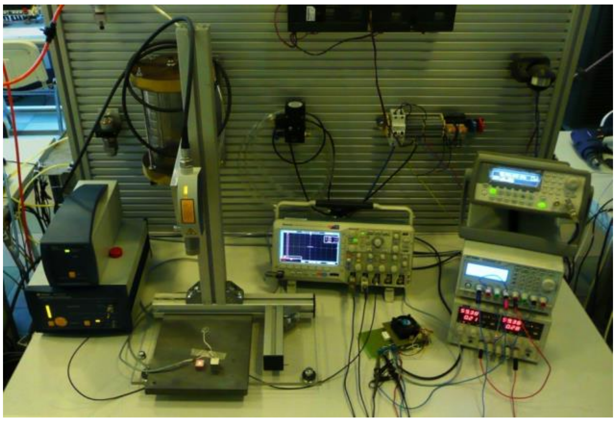

Fig. 7. View of the test stand with the test object

The piezoelectric plates were glued with an electrically conductive adhesive to the heavy plate as shown in Figure 8.

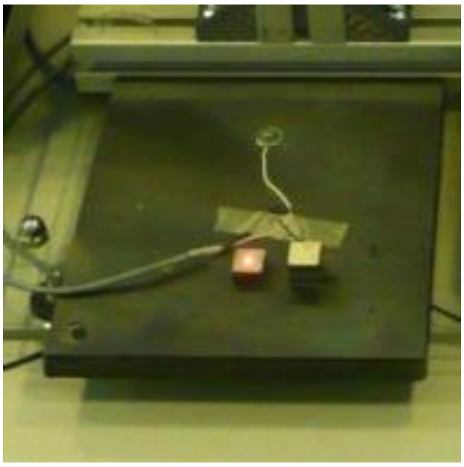

Fig. 8. View of the plates glued to the heavy plate

The research object prepared in this way has caused elimination of external disturbances and allowed to provide voltage to the plates.

4. RESEARCH AND ANALYSIS OF THE RESULTS OBTAINED

During generating the characteristics determining the displacement of the piezoelectric stack in the frequency domain, there was used spectral analysis, which main assumption is the distribution of the examined signal into elementary components and determination of the amplitudes of these components. The spectral analysis shows that each compound signal is the sum of elementary signals called sinusoidal signals, each element has an individual frequency, amplitude and phase. The basis for determining the spectral analysis of vibrations is the Fourier series. The Fourier series allows the correct distribution of a function describing periodic vibrations into an infinite number of elements, each of which represents the elementary vibrations. There were carried out tests using the laser vibrometer and the generated signal was recorded using the oscilloscope. The analyzed courses derived from the laser vibrometer registered the courses of the piezoelectric system, while to read the final data there was used the fast Fourier transform. This analysis allowed to read data in the frequency domain and to read the amplitude at a given frequency excitation.

Determination of the signal spectrum using digital analysis systems is based on fast Fourier transform (FFT) calculations. By carrying out the mentioned calculations, there were obtained resonance frequency graphs as a result of algebraic analysis and experimental tests of the piezoelectric elements. The graph also shows a comparison of previously mentioned data with the data contained in the product card.

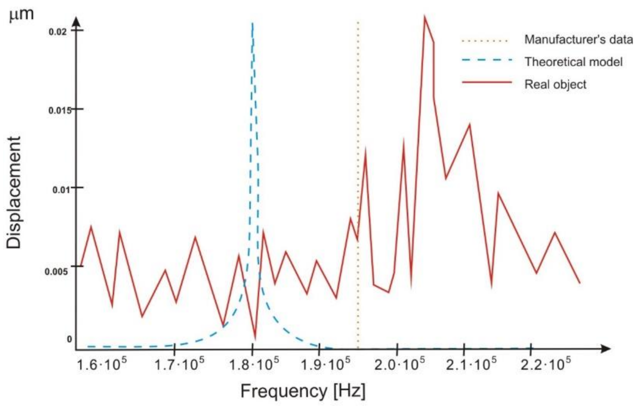

Fig. 9. Comparison of resonant frequencies of the algebraic method and research on the piezoelectric element

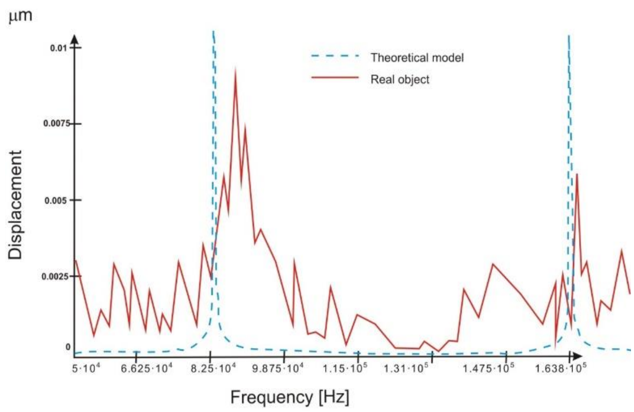

Fig. 10. Comparison of resonance frequencies obtained with algebraic methods and the method of laboratory tests of two connected plates

On Figure 9 there were presented algebraic comparison method presented in the previous chapters of this monograph and the results of laboratory tests of the

piezoelectric stacks. The tests were performed on single elements and the piezoelectric. Analyzing the graphs presented in Figure 9, it was found that the percentage error in relation to the research performed on the real element is not greater than 12%. In the next step, there were compared the results of experimental and mathematical models with the data contained in the piezoelectric plates manufacturer's card. The cataloged values of the frequency of vibrations of the tested elements differ about 8% from the values obtained as a result of testing, and about 7% in reference to the models calculated using the algebraic method.
The article also compares the results of the piezoelectric stack research, i.e. two glued plates forming a bimorphic system (Figure 10). The resonance frequency error generated based on mathematical formulas compared to the results of the laboratory test is about 5%. It can therefore be concluded that increasing the number of plates reduces the measurement error. A larger number of plates causes a larger displacement and it can be assumed that a larger displacement is recorded by the used measuring instruments with greater accuracy. It should be noted that during the tests the impact of external interference and background noise is of great importance. Another element significantly affecting the emergence of differences in the values of various methods of analysis is a certain limitation of the mathematical model (e.g., in the mathematical model there were not taken into account the thickness of the adhesive layer connecting the plates and the thickness of the power supply electrodes). In future studies, it is proposed to determine the displacement of plates by gluing a piezoelectric voltage meter, sticked to the side walls of the piezoelectric stacks. It can be assumed that such a system will be more convenient compared to tests using the laser sensor.

5. CONCLUSIONS

In the construction and operation of machines, assemblies and sub-assemblies are very often used, the operation of which involves the use of intelligent materials.
Modeling and testing of the simple and complex piezoelectric systems is associated with a multitude of phenomena occurring in them, and thus it is a difficult task requiring the implementation of complicated mathematical calculations. Their correct implementation is, however, a key element in the design process of the technical measure, in which the piezoelectric converter is used as a sensor or actuator. In order to develop a functional system containing the piezoelectric converters, it is necessary to select physical and geometrical parameters, which in the case of examined piezoelectric plates are, among others, geometric dimensions of individual plates, the number of the plates in a stack, as well as electrical parameters [24].
In this article, the author took into account the use of intelligent materials as components in the construction of machines including modeling and testing of piezoelectric plates.
The utilitarian goal of the article was to propose a measuring station and to conduct piezoelectric plate tests, whose mathematical models were analyzed in previous author's works.
One of the practical examples of application of the presented mathematical models is their use in vibrating level sensors. The implementation of a functional piezoelectric system, acting as a sensor and actuator, involves the appropriate selection of geometric dimensions of a plate, the number of plates in the stack and their basic material parameters. So far, the choice of system parameters in such sensors has been made by means of subsequent tests, checking whether the achieved results meet the assumptions made. This type of procedure increased the sensitivity of the built piezoelectric converter, until achieveing the satisfactory effect.
The author, as a result of realisation of research tasks carried out on real objects, confirmed the correctness of the mathematical model determined in his previous publications.
The author did not re-analyze piezoelectric systems [22] in the article by classical and non-classical methods [1, 2, 3, 8, 21] that are the basis for comparative analysis of theoretical models and practical studies. Checking the correctness of the obtained results of mathematical models and the results of experimental research, the correctness of the thesis was demonstrated: it is possible to model piezoelectric systems by classical and non-classical methods.
The presented problematic aspects do not fully cover the issues related to modeling and testing of the piezoelectric elements, however, they open up new possibilities and they are a base for further research works.
As part of future research, it is proposed to include a layer of glue connecting individual elements of the piezoelectric stacks, hysteresis analysis of the piezoelectric circuits, creation of a computer program supporting analysis of the studied systems, including material damping and external electrical components, and conducting and formalizing the problem of synthesis of the complex piezoelectric systems.

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