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A NEW PROTOTYPE OF PIEZOELECTRIC BENDING RESONANT TRANSDUCER FOR ANALYSIS OF SOFT TISSUES PROPERTIES

NOWY PROTOTYP REZONANSOWEGO PRZETWORNIKA PIEZOELEKTRYCZNEGO DO ANALIZY WŁAŚCIWOŚCI TKANEK MIĘKKICH

A b s t r a c t

This paper is devoted to a new piezoelectric bending resonant transducer prototype dedicated to the characterization of the mechanical properties of soft tissue. A general description of the actuator's structure is presented including the basic principles of the measurement. The chosen geometry of the prototype is discussed and compared with the existing version. Constitutive equations are presented for the active and passive layer of the cantilever transducer. The prototype is verified by means of finite element method analysis. Results of the static and modal analysis are presented and discussed.

Keywords: *piezoelectric transducer*, *sensor*, *actuator*, *resonant transducer*, *finite element method*

S t r e s z c z e n i e

W niniejszym artykule opisano nowy prototyp rezonansowego przetwornika piezoelektrycznego przeznaczony do pomiaru właściwości mechanicznych tkanek miękkich. Przedstawiono ogólny opis struktury aktuatora wraz z wyjaśnieniem podstawowej zasady pomiaru. Podano cechy geometryczne projektowanego prototypu, a następnie porównano go do już istniejącego. Sformułowano równania konstytutywne dla warstwy aktywnej oraz pasywnej przetwornika. Prototyp zweryfikowano metodą elementów skończonych. Zaprezentowano oraz skomentowano wyniki symulacji statycznej i modalnej.

Słowa kluczowe: *przetwornik piezoelektryczny*, *sensor*, *aktuator*, *przetwornik rezonansowy*, *metoda elementów skończonych*

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1. Introduction

From the time of their discovery in 1880, piezoelectric materials have found applications in various fields of industry and services. Piezoelectric transducers are used for measuring a wide variety of mechanical and thermal parameters including: effort; pressure; acceleration; weight; angular speed; moments; deformations; temperature etc. Considering accuracy, in many cases these devices surpass transducers based on other detection principles. Nowadays, piezoelectric transducers are used in medicine and bioengineering for ultrasonic tomography, pulse measurements, tone measurements, urology, ophthalmology, etc. This work describes the continuation of research activities dedicated to a piezoelectric resonant transducer intended for dermatological application. Details of the measurement system as well as state of the art can be found in [1, 2].

This paper is organized as follows: section 2 presents the problem under research in a qualitative manner; basic requirements for the designed transducer are shown, as well as the main differences between the prototypes; section 3 describes the measurement system in a more quantitative way; constitutive equations are presented for the cantilever sensor/actuator; the principle of operation is described; section 4 presents the numerical model of the transducer and the results of finite element method analysis; section 5 presents remarks and conclusions on the investigated prototype.

2. Description of piezoelectric sensor actuator

The main objective of the project is the design and analysis of a piezoelectric resonant, bending sensor/actuator intended for measuring the mechanical properties of soft tissues, such as their rigidity, flexibility and viscosity.

A dynamic indentation method for the measurement of mechanical properties is used in this study. This technique is based upon registering the force applied on the surface of the material as a function of the displacement imposed by the indenter. In addition to a static force, vibrations are injected on the surface of the tested sample. A spherical indentation device is located at the free end of the developed piezoelectric cantilever sensor/actuator working in resonance conditions.

A resonant piezoelectric sensor is a device with an element vibrating at resonance which changes its output frequency, i.e. the mechanical resonance frequency, as a function of a physical parameter – this is proved to have major advantages over other physical resolution principles. Resonant sensors with various excitation and detection techniques have been reported in the literature and each one has its own advantages and disadvantages. Smart materials, in particular piezoelectric materials for excitation and detection, have numerous advantages like strong force, low actuation voltage, high energy efficiency, linear behavior, high acoustic quality, high speed and high frequency. In the design of resonance piezoelectric sensors, a sensor/actuator in collocation is usually used and provides a stable performance [5]. A new prototype of a developed piezoelectric sensor/actuator should meet a number of requirements based on the analysis of human skin properties:

- stimulation method with sufficient sensitivity for measuring mechanical quantities, such as stiffness and elasticity (e.g. indentation method),
- the maximum deflection at the free end of the actuator, which corresponds to the depth of skin's penetration, should be less than 5 mm,
- the maximum force applied to the tested tissue should not exceed 1 N,
- the frequency of the stimulation should be in the range perceivable by the skin receptors – that is below 1500 Hz,
- simple electromechanical structure with compact dimensions,
- possibility of implementation of the structure on a stylus [6].

Firstly, to better fulfill the compact dimensions condition, the new prototype is 40% smaller than the first transducer. The total active length is now only 60 mm, the width is 10 mm for the piezoelectric ceramics, and is only 1.5 mm thick. On the other hand, the indentation device (a rigid sphere) is now bigger, with a diameter of 16 mm, which contributes to better sensitivity for measured quantities. Material for the active layer had been changed to PZT-401 ceramic, due to its better electro-mechanical coupling and lower dielectric losses. Also, the area for the electrodes has been rearranged. Thanks to the sectorization of the ceramics, there are five areas dedicated to sensing and actuating at a desired resonance frequency. The middle three are dedicated to sensing/actuating the first and the third mode, while the other two are dedicated for the second resonant mode. The new prototype is located in Fig. 1.

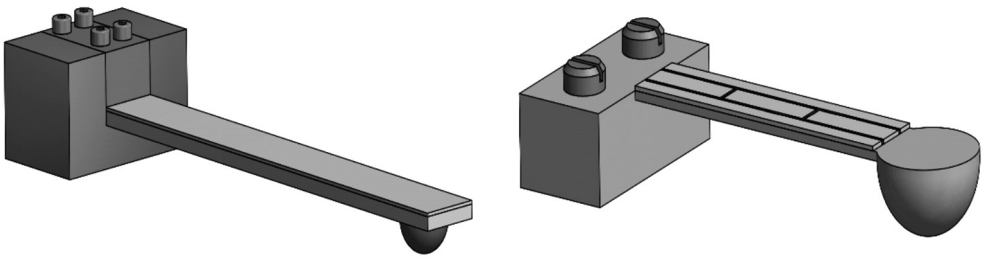

Fig. 1. Comparison of two prototypes of cantilever sensor/actuator. Right – first prototype; left – newest prototype (size is not scaled)

3. Analytical description of the transducer

General constitutive equations for piezoelectric material can be presented in the form of a matrix, describing the relationship between the following pairs of quantities: (***S***, ***E***); (***S***, ***D***); (***T***, ***E***); (***T***, ***D***). Choosing ***T*** and ***E*** as independent variables, constitutive relations take form of:

$$\begin{aligned}(S) &= \left[s^E\right]\cdot(T) + [d]^t\cdot(E)\\ (D) &= [d]\cdot(T) + \left[\varepsilon^T\right]\cdot(E)\end{aligned} \tag{1}$$

where:

($\boldsymbol{S}$) – the six-dimensional strain vector,
($\boldsymbol{T}$) – the vector of stresses,
($\boldsymbol{D}$) – the three-dimensional electric displacement vector,
($\boldsymbol{E}$) – the electric field vector,
[$\boldsymbol{s}^E$] – the six by six compliance matrix evaluated at constant electric field,
[$\boldsymbol{d}$] – the three by six matrix of piezoelectric strain coefficients,
[$\boldsymbol{\varepsilon}^T$] – the three by three dielectric constant matrix evaluated at constant stress.
T – represents the stress induced by the combined mechanical and electrical effects [3].

Before writing the constituent equations for the piezoelectric cantilever (bending transducer), it is necessary to adopt the following convention for the crystal axes of the piezoelectric material: the polarization vector defines 3rd or z direction; the 1st and 2nd directions (x, y directions) are mutually perpendicular to the 3rd direction; the z direction is perpendicular to the large surface of the piezoelectric element. When an external voltage, V, is applied across the electrodes such that the external electric field, E_3, is anti-parallel to the polarization of the piezoelectric element, the piezoelectric material will expand in the plane perpendicular to E_3 and contract in the direction of E_3 if $d_{31} < 0$ and $d_{33} > 0$. Taking the above assumptions into consideration; the constitutive equations for the piezoelectric cantilever sensor/actuator (1), with polarization along the 3rd direction, can be reduced from matrix form into the following:

$$\begin{aligned} S_1^a &= s_{11}^{E,a} T_1^a - d_{31} E_3 \\ -D_3^a &= d_{31} T_1^a - \varepsilon_{33}^T E_3 \end{aligned} \tag{2}$$

For the passive layer, a non-piezoelectric, elastic material can be used. For this layer, it can be written:

$$S_1^p = s_{11}^p T_1^{\mathrm{p}} \tag{3}$$

where s_{11} represents compliance under mechanical stress. Both T_1^a and T_1^p are transverse stresses acting on the y-z planes of the elements and are linear functions of the distances from the neutral axis, z_a and z_p, as given in the following:

$$\begin{aligned} T_1^a &= -\Gamma^a z_a \\ T_1^p &= -\Gamma^p z_p \end{aligned} \tag{4}$$

where Γ^a and Γ^p are proportionality constants. The neutral axis of the bender doesn't coincide with the joined surface [3].

The active, piezoelectric layer (superscript a) is bonded to a passive, elastic layer (superscript p). When the voltage is applied across the thickness of the active layer, a longitudinal and transverse strain appears. The elastic layer opposes the transverse strain and the asymmetry of the whole structure leads to a bending deformation. A basic rectangular cantilever transducer under deformation is located in Fig. 2. To benefit from the indentation function, a small rigid sphere (an indentation device) is glued to the free end of the sensor/actuator.

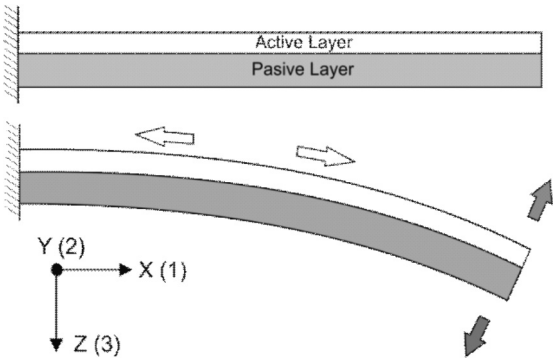

Fig. 2. Principle of operation: piezoelectric material extension resulting in the bending movement of cantilever actuator

The total deflection of the free end of the transducer is a function of material characteristics (piezoelectric and elastic properties), the supply voltage and the geometric dimensions. Without the force acting at the free end, the total deformation can be expressed as follows:

$$\delta_0 = -3L^2 \frac{\beta\eta(1+\eta)}{h_s(1+4\beta\eta+6\beta\eta^2+4\beta\eta^3+\beta^2\eta^4)} d_{31}E_3 \tag{5}$$

where:
E_a, E_p – Young modules of piezoelectric and the elastic layer in [N/m^2],
h_a, h_p – thicknesses of the piezoelectric and the elastic layer in [m],
L – length of the transducer in [m],
d_{31} – piezoelectric coefficient in [m/V],
E_3 – electric field in [kV/m],
with $\beta = E_a/E_p$ and $\eta = h_a/h_p$.

The piezoelectric sensor/actuator is equipped with a spherical rigid probe – the indentation device (Fig. 3). Such a design grants the possibility of verification of the obtained results (by means of an electromechanical impedance analysis, which is explained in detail in [1] and [2]) with the classic Hertzian contact mechanics theorem. Knowing the normal force acting on an elastic surface, as well as the properties of the spherical indenter, it is possible to assess the Young modulus of the elastic material as well as the stiffness of the contact

$$\delta = \sqrt[3]{\frac{9}{16}\frac{F_N^2}{RE^{*2}}} \tag{6}$$

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \approx \frac{1-\nu_2^2}{E_2} \tag{7}$$

Where:

δ – the penetration depth,

F_N – the normal force acting on the surface,

R – the radius of the sphere,

E_1, E_2, ν_1, ν_2 – Young and poisons coefficients for the rigid sphere and the elastic material surface respectively.

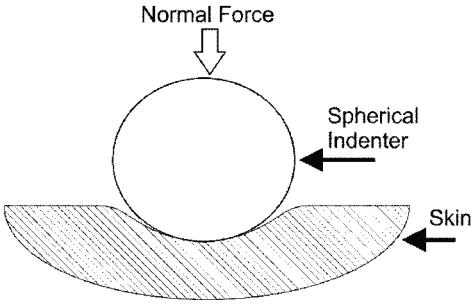

Fig. 3. Schematic description of the indentation method: rigid sphere acting on a soft tissue with the normal force F_N

4. Simulation analysis

In this paragraph, we will present results of the verification of the proposed piezoelectric transducer by means of the finite element method. This analysis will include a short description of the numerical model of the sensor/actuator, as well as results of static and modal simulations aiming to check if the performance of the designed prototype is up to the required level. Computations were made using a user-defined numerical model and boundary conditions in a finite element method package ANSYS.

The definition of piezoelectric material requires permittivity (or dielectric constants), the piezoelectric matrix and the elastic coefficient matrix to specify the properties of the material [7]. The permittivity matrix specifies the relative permittivity values. The permittivity values represent the diagonal components ε_{11}, ε_{22}, ε_{33} respectively of the permittivity matrix ε^s. The superscript S indicates that the constants a2re evaluated at a constant strain. The piezoelectric matrix can be defined as a piezoelectric stress matrix **[*e*]** or a strain matrix **[*d*]**. Matrix **[*e*]** is usually associated with the input of anisotropic elasticity in the form of the stiffness matrix **[*c*]**, while **[*d*]** is associated with the compliance matrix **[*s*]**. The elastic coefficients matrix (6x6 symmetric matrix) specifies the stiffness **[*c*]** or compliance **[*s*]** coefficients [4].

The numerical model of the cantilever transducer can be divided into two main parts – the passive layer of the bender and the indentation device (hemisphere), which are created from one solid block of steel. The second part of the transducer includes the active layer built from sectorized piezoelectric ceramics. For this part, hard PZT-401 ceramics were chosen due to their high resistance to depolarization and low dielectric losses under high electric drive. This type of material is especially suited for high power transducers and power generating bending systems. The meshed geometry of the transducer is provided in Fig. 4.

Table 1

Properties of materials used in the FEM model

Layer	Passive	Active
Material	Steel	PZT-401
Height	$h_p = 1$ mm	$h_a = 0.5$ mm
Density	$\rho = 7850$ kg/m^3	$\rho = 7600$ kg/m^3
Young modulus	$E_p = 21 \cdot 10^{10}$ N/m^2	$E_a = 12.89 \cdot 10^{10}$ N/m^2
Poisson Coefficient	$\nu_p = 0.3$ [–]	$\nu_a = 0.31$ [–]
Piezoelectric strain coefficients	–	$d_{33} = 315$ pm/V $d_{31} = 132$ pm/V $d_{15} = 511$ pm/V
Dielectric constant	–	$K^T_{33} = 1395$ [–]

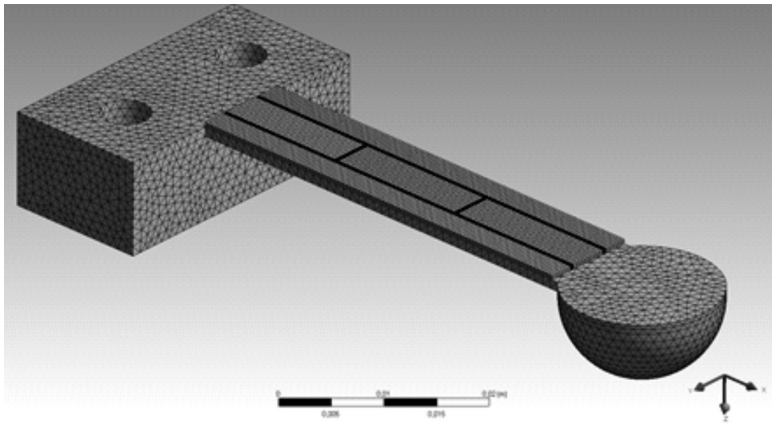

Fig. 4. Meshed numerical model of cantilever transducer. Piezoelectric layer is sectorized into five regions for sensing and actuation

During the static analysis, piezoelectric ceramics were supplied with a DC voltage of 200 V. The structure was fixed at the bottom of the base. The deformation was measured along the *z* axis, and it corresponded to the normal excitation of the material's surface. Depending on how many sectors of the active layer were supplied with voltage, the deformation of the transducer ranged from 21.99 µm to 49.79 µm. Those values could be related to a maximal deflection at the state of resonance using the quality factor *Q*. Considering the fact that the described sensor/actuator has a *Q*-factor below 100, its maximal deformation meets the requirements described in section 2. The static, bending deformation is illustrated in Fig. 5.

The other design requirements were tested with modal analysis. The aim of which was to determine the vibration characteristics of a structure, including its natural frequencies, mode shapes and participation factors (the amount of a mode participates in a given direction). Three basic natural frequencies were extracted. Each of those corresponded to a deformation in a different direction (axis). First resonant mode was the bending movement in the *z* axis, which is normal to the tested material. The second was the torsion deformation (the tip of

spherical indenter – probe is moving in the *y* axis). The third natural frequency was linked to a 'wave' movement of the transducer, which caused the probe to move in the direction aligned with the *x* axis (Fig. 6).

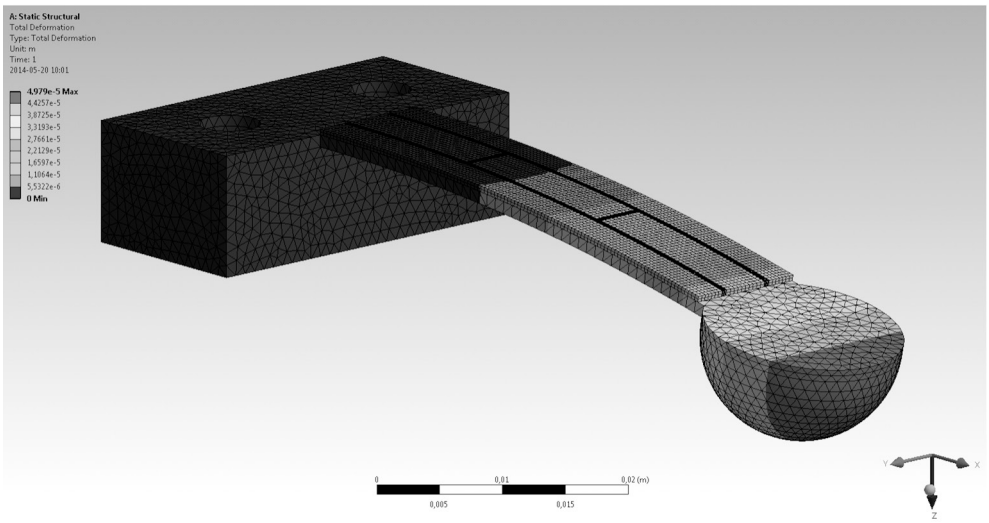

Fig. 5. Results of static simulation: cantilever sensor/actuator supplied with 200 V DC. Basic bending deformation

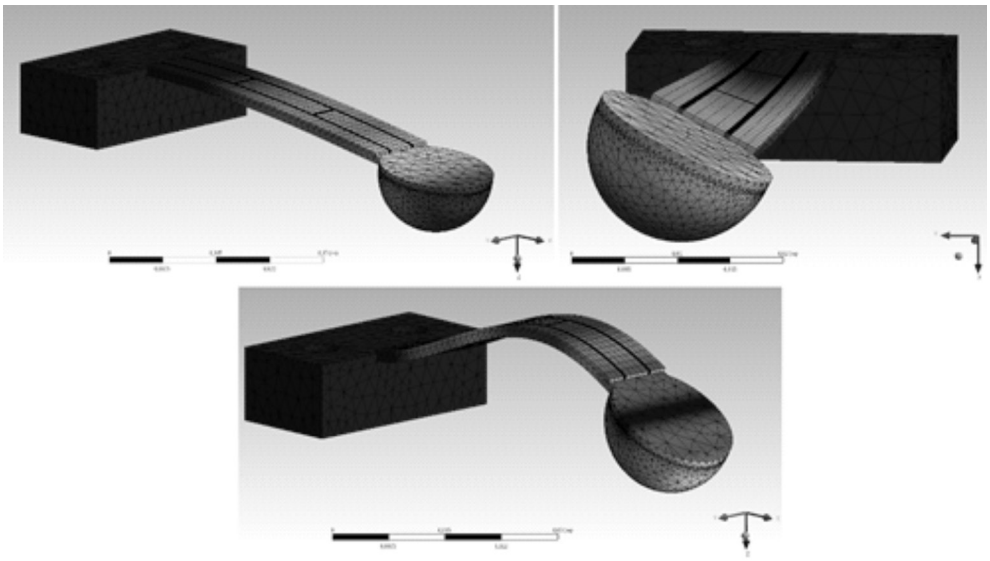

Fig. 6. Results of modal simulation: first three natural frequencies and corresponding deformations of the cantilever transducer. Upper left: first mode – bending movement; upper right: second mode – torsional movement; lower: third mode – 'wave' movement. The amplitude of deformations **is not** to scale

Moreover, for each natural frequency of the actuator, the indentation sphere and tested material create different contact surfaces. This contributes to varying conditions of friction and sliding between the spherical indenter and sample to be characterized. Piezoelectric actuators, generally characterized by a low amplitude of vibration, work in the area of partial slip, since the contact area is often greater than the vibration amplitude. Under those conditions, the coefficient of friction of the sphere/surface contact may change depending on the mode in question. This property can serve as a way to tune the deformations of the transducer to meet the specific requirements of the measurement of mechanical properties of materials.

To establish frequency values of resonance and anti-resonance for each mode of the transducer, boundary conditions of the model had to be defined accordingly:

- Resonance – electromechanical impedance becomes minimum; $Z \rightarrow 0$; short-circuit: voltage on both electrodes set to 0.
- Anti-resonance – electromechanical impedance becomes maximum; $Z \rightarrow \infty$; open circuit; voltage not defined [4].

Table 2

Results of modal analysis: resonance and anti-resonance frequencies for the first three working modes of the sensor/actuator

Mode number	Resonance frequency [Hz]	Anti-resonance frequency [Hz]
1	133.91	135.84
2	772.91	775.83
3	1337.4	1358.7

Deformations corresponding to frequencies listed above are illustrated in Fig. 5. Depending on the frequency of the supply voltage the cantilever sensor/actuator can produce movement in each axis. This property is quite interesting considering the characterization of the mechanical properties of soft materials, where different kinds of movement can be used in extracting different quantities. Moreover, the highest value of resonant frequency is well below the required threshold of 1500 Hz (Table 2).

5. Conclusions

The aim of the paper was to present a new prototype of the piezoelectric cantilever transducer with improved geometry and electromechanical properties, while comparing with the first one. The presented analysis has proved that such a design has met most of the requirements specified for the measurement system of mechanical quantities describing soft tissues. Those are: compact dimensions and the simple electromechanical structure welcome in a portable device; adequate levels of produced deformation; force and operating frequency; most importantly, sufficient sensitivity for measurement of mechanical properties of viscoelastic materials (at the current stage of research – soft polymers; ultimately – human skin tissue).

Furthermore, the described prototype profits from the dynamic indentation method described in the literature, used for the measurement of elastic and viscous properties of human skin.

The presented considerations in the paper have proved the importance of choosing the resonance mode of the actuator on the mechanical contact between the indenter and the sample. Therefore, the right choice of working mode of the sensor/actuator will allow or greatly facilitate the measurement of mechanical properties of soft tissues.

In further works, it is planned to fabricate the considered prototype and to carry out experimental verification by an impedance measurement and a comparison with the existing prototype.

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