# FEM MODELING OF PIEZORESISTIVE FORCE SENSOR FOR MEDICAL RETRACTOR AND DESIGN VERIFICATION

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**Abstract**

In this paper the numerical modelling of medical retractor for lumbar discectomy is presented. Lumbar discectomy is the most common operative procedure performed by neurosurgeons. During the surgery the retractor is used to alter the position of spinal nerve root in order to optimize surgical exposure. The force and time of retraction monitoring is the essential step in the improvement of surgical procedure. The medical retractor was equipped with silicon based piezoresistive sensors and the prototype was manufactured. The numerical analysis done with ANSYS Finite element analysis software was used to evaluate the design, characterize force sensor used and provides design modifications to improve the retractor usability. The characterization method is explained and the numerical model of the retractor is built using the measured values for mechanical and electrical properties. The mechanical properties were measured and compared with calculated values. The optimal position of piezoresistive force sensors is determined by stress distribution in the retractor, where the uniformity of stress and the stress magnitude was under the consideration. The numerical model also serves as a basis for extending force measurement in two dimensions. The 2-axis force measurement is required to sufficiently monitor the force during the surgery and it is thus essential in the design.

**Keywords: force sensor, stress, strain, ANSYS, finite element method, retractor, medical application, piezoresistivity, modeling, silicon**

## Presenting Author's Biography

Samo Penič was born in 1980 in Celje, Slovenia. In 2006 he received his B. Sc. degree at the Faculty of Electrical Engineering, University of Ljubljana and became a junior researcher at the Faculty of Electrical Engineering in the Laboratory for microsensors structures and electronics (LMSE). He is continuing his postgraduate studies. He is interested in coupled-field modeling of MEMS structures, especially sensors and actuators.

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# 1 Introduction

Lumbar discectomy is the most common operative procedure performed by neurosurgeons. During lumbar discectomy, a nerve root retractor is used to alter the position of the involved spinal nerve root in order to optimize surgical exposure. The rate of success of such surgery depends, among others, on the force and time the force is applied on the nerve. Careful monitoring of force is thus essential step towards improved surgical procedure. In our laboratory we developed and manufactured force sensor attached to retractor for medical use as described by [1] and [2].

In this paper piezoresistive coefficient in longitudinal direction of sensor chip were determined. In order to characterize piezoresistive sensor properties, piezoresistor was bonded to stainless steel prismatic shape testing cantilever. Investigation results serve as input data of ANSYS finite element analysis software (FEA). The exact material properties of the stainless steel cantilever, like Young's modulus was crucial for numerical model and were measured independently by two methods – the indentation method and by analysing modal frequencies. Simple shape of the cantilever allowed analytical verification of numerical model.

The geometric model of the actual retractor (D'Errico, MDE, Frittlingen, Germany) was used to verify the stress concentrations at points where the sensor was mounted in the first prototype, prior to the numerical modelling. On the basis of simulation, the design improvement is suggested. The retraction during the surgery is done by applying force in two direction – transverse and longitudinal to the retractor length. With additional sensor, the retractor for lumbar discectomy could perform a 2–axis measurement of force applied to the nerve, which is closer to satisfy surgeon's requirements.

Existing designs reported in the literature [3, 4] includes force sensors at the tip of the retractor where sensor and retractor are in direct contact with the nerve during the surgery. The proposed design in this article provides an essential advantage, the elimination of the sensor from the operative area.

# 2 Numerical model preparation

Silicon has piezoresistive properties thus it is suitable for indirect force measurement through stress in material that the force induces. Mechanical stress in silicon chip can be detected as a change in resistance in comparison with unstressed material. Any force applied on structure results in mechanical stress in accordance to material Young's modulus, given by equation

$$\{\sigma\} = [E]\{\epsilon\}, \tag{1}$$

where $\{\sigma\}$ denotes stress and $\{\epsilon\}$ is strain. $[E]$ is the Young's modulus and is material depended. The equation 1 is valid in the range of elasticity. If the force is too great, the permanent change in material occurs and the linearity of material behaviour is lost. It is also worth noting, that stresses and strains are vectors written using a simplified notation by ANSYS, whereas Young's modulus is a matrix representing a tensor.

The governing equation of the piezoresistive effect is

$$\left\{\frac{d\rho}{\rho}\right\} = [\pi]\{\sigma\}, \tag{2}$$

where $[\pi]$ represents matrix with stress coefficients of piezoresistivity and $\{\frac{d\rho}{\rho}\}$ relative change in resistivity.

Mechanical properties and geometry of the structure define its modal frequencies. For modal analysis a clamped prismatic shaped stainless steel beam was used, since the analytical relation for its modal frequency is known. The Euler-Bernoulli theory was used to solve the model of clamped bar analytically[5], resulting in equation 3.

$$\omega_i = \frac{\beta_i^2 h}{l^2}\sqrt{\frac{E}{12\rho_v}}, \tag{3}$$

In the equation 3, $h$ represents beam height, $l$ its length, $E$ Young's modulus of the material and $\rho_v$ its density. The index $i$ denotes the i-th modal frequency. The constant $\beta_i$ corresponds to boundary conditions and to the mode of vibration. For clamped bar the constant for the first modal frequency is indeterminable, for higher frequencies the values are given in tabular form (see table 1). The values for modal frequencies are close approximates, since the Euler-Bernoulli theory do not take into account the rotational inertia of the cross section and shear deformation.

Tab. 1 Values for constant $\beta_i$ for beam clamped at single side.

| $i$ | $\beta_i$ |
|---|---|
| 1 | $1,875$ |
| 2 | $4,694$ |
| 3 | $7,855$ |

Analytical expressions for strain and stress are straightforward only for basic structures like prismatic bars, cantilevers etc., and are analytically indeterminable for more complicated structures like cantilevers with nonuniform cross-section. Latter structures are the most commonly occurring in the real world, so another approach is needed for calculating the stress. Numerical analysis provides the answer to the problem. There are numerous software packages available on the market that can perform mechanical and even multiphysics coupled field analysis. Numerical modelling is usually performed using finite element method (FEM), since it is the method that can be used on various structures due to its adaptable meshing.

## 2.1 ANSYS input model

For modeling piezoresistor properties, elements named SOLID227 were used. These elements have the capability to model piezoresistive effect in three dimensional space. Stress or strain can result in the change of the resistivity of the material

$$[\rho] = [\rho_0]([I] + [r]), \tag{4}$$

where $[\rho]$ is the resistivity of mechanically loaded material, $[\rho_0]$ is resistivity of unloaded material, $[I]$ is identity matrix and $[r]$ is relative change of resistivity $[\frac{d\rho}{\rho}]$. Brackets are used by ANSYS to denote, that the variables are in fact matrices.

Relative change of resistivity (the elements of the matrix $[r]$) is calculated according to equation 2. Equations 1 and 2 combined results in another material properties matrix called the piezoresistive strain matrix ($[m]$) that takes into the consideration piezoresistivity matrix $[\pi]$ and Young's modulus $[E]$ thus relating $\{r\}$ directly with strain $\{\epsilon\}$.

$$\{r\} = [m]\{\epsilon\} \tag{5}$$

Braces are by ANSYS semantics signaling that $\{r\}$ and $\{\epsilon\}$ are vectors of elements used to build up the corresponding matrix – for example, vector $\{r\} = \{\frac{d\rho}{\rho}\}$ consists of components that are used to build up the matrix with the same name $[r]$.

$$[r] = \begin{bmatrix} r_x & r_{xy} & r_{xz} \\ r_{xy} & r_y & r_{yz} \\ r_{xz} & r_{yz} & r_z \end{bmatrix} \tag{6}$$

where $\{r\} = [r_x \; r_y \; r_z \; r_{xy} \; r_{yz} \; r_{xy}]^T$

ANSYS uses the relation 5 to solve coupled-field finite element problem with with equation 7

$$\begin{bmatrix} [M] & [0] \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} \{\ddot{u}\} \\ \{\ddot{v}\} \end{Bmatrix} + \begin{bmatrix} [C] & [0] \\ [0] & [0] \end{bmatrix} \begin{Bmatrix} \{\dot{u}\} \\ \{\dot{v}\} \end{Bmatrix} + + \begin{bmatrix} [K] & [0] \\ [0] & [K^V] \end{bmatrix} \begin{Bmatrix} \{u\} \\ \{v\} \end{Bmatrix} = \begin{Bmatrix} \{F\} \\ \{I\} \end{Bmatrix}, \tag{7}$$

where is $[K^V]$ conductivity matrix that includes piezoresistive effect, $\{u\}$ is displacement, $\{v\}$ is electric potential, $[M]$ is mass matrix, $[C]$ is damping matrix and $[K]$ is stiffness matrix that represents Young modulus. Loads are described with vectors $\{F\}$, which is force and $\{I\}$ that represents electric current[6].

### 2.2 Mesh

The geometry is modelled in 3D space, taking into account the symmetry of the structure where possible. The ANSYS SOLID227 built in elements were used to model silicon piezoresistors and SOLID92 elements were used for stainless steel cantilever and retractor. The meshed models are shown on figures 1 and 2.

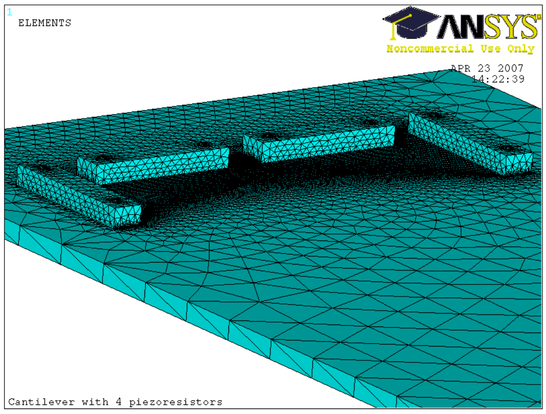


Fig. 1 Meshed model of piezoresistor chips on stainless steel cantilever used to determine coefficients that build up $[\pi]$ matrix. Due to the symmetry only half of the model must actually be solved.

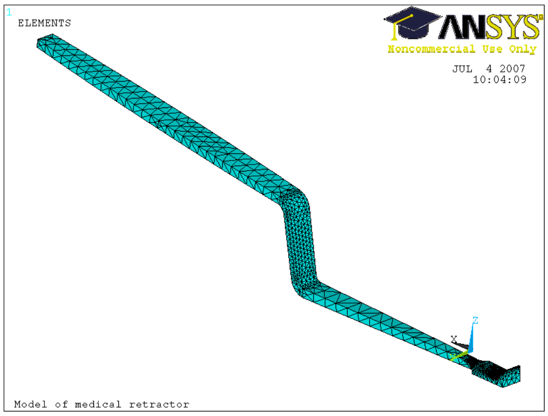


Fig. 2 Meshed model of medical retractor. Stresses in the retractor are important for piezoresistor placement.

### 2.3 Material properties

The material properties were largely unknown before the modelling and the experiment was matched with numerical solution with parameter variation until the results were matched. Since the prismatic shape cantilever was used, the analytical solutions were useful to predict material properties from measurements.

Silicon Young's modulus and density were taken from literature [7, 8] and are listed in table 2. The piezoresistive coefficient in longitudinal direction of the chip dimensions were determined by experiment and its value is presented under results.

Testing cantilever used for characterization was made of the cold rolled Austenitic 14310 stainless steel. Its Young's modulus was determined with the measurement of modal frequencies and microindentation technique. The same properties were assumed for medical retractor.

Tab. 2 Mechanical properties of silicon

| Property | Value |
|---|---|
| $E_1 1$ | 165.7 GPa |
| $E_1 2$ | 63.9 GPa |
| $E_4 4$ | 79.6 GPa |
| $\rho_v$ | 2330 $\mathrm{kg/m^3}$ |

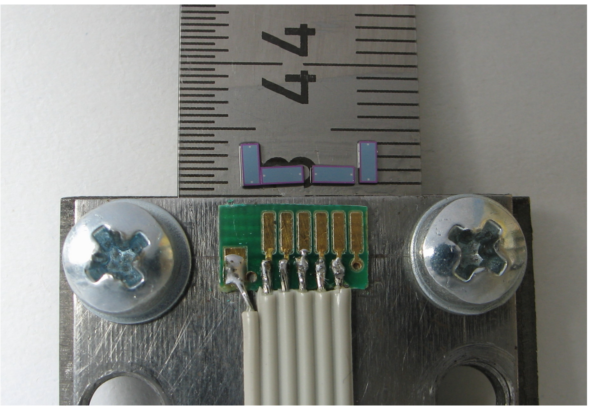

Fig. 3 Stainless steel cantilever with four piezoresistors prepared to operate in bridge circuit.

## 3 Experimental setup

Piezoresistors were made on 4-inch, 380$\mu$m thick n-type silicon wafer with $\langle 100 \rangle$ orientation and resistivity of 800$\Omega$cm. Sheet resistance of piezoresistor is 23k$\Omega$/sq at non uniformity over the wafer better than 2.5%.

The characterization of piezoresistors was split into two stages. Firstly the mechanical properties of stainless steel cantilever were determined using microindentation technique. The results of multiple measurements proved to be largely dependent on the location of the indentation, thus an integral method needed to be used to confirm the measured values.

After the Young modulus for stainless steel cantilever was determined, the piezoresistors were bonded 1 mm from the cantilever support. Cantilever was displaced by known force and change in resistance was measured. In ANSYS the same force was applied and the measured change in resistance was mached with calculated stress in cantilever. The piezoresistive coefficient was calculated according to equation 2.

The acquired $\pi_L$ coefficient in longitudinal direction was used in a model of retractor to allow the calculation of resistance change on load.

The modulus of elasticity of stainless steel cantilever was determined by two methods. The first was microindetation method [9, 10] which provided scattered values for Young's modulus. More integral measurement method of modal frequencies was used to get additional results. The cantilever vibration was initiated with mechanical deflection and release. The vibration was observed by pointing a laser source to the tip of the cantilever, where it reflected. The reflected ray was directed to the photodiode which was connected to the HP4155A semiconductor parameter analyser. The parameter analyser logged the response, which was transfered to the computer and the FFT was applied. The modal frequencies were extracted and compared with simulated values and analytical values. When the modulus of elasticity was known, the characterization of bonded piezoresistor chips was possible by loading the cantilever.

Piezoresistors were glued to the retractor and stainless steel cantilever with "UHU plus endfest 300" epoxy adhesive that was cured at the highest recommended temperature of 180°C at which it achieved a bonding strength of 3000N/cm$^2$. After bonding, the piezoresistor contact pads and cable interface were connected with standard microelectronics golden wire with 25$\mu$m diameter.

Stainless steel cantilever (Figure 3) was used to characterize piezoresistive parameter of manufactured piezoresistors in longitudinal direction $\pi_L$. The equation 2 is simplified assuming that the transversal stresses do not contribute to the overall change in resistivity.

$$\frac{d\rho}{\rho} = \pi_L \sigma_L \tag{8}$$

The four resistors are setup for bridge measurements, whereas for characterization only one resistor was measured.

The cantilever was loaded with known force and the response of the piezoresistor was measured with Semiconductor Parameter Analyzer HP 4155A. The parameter analyzer was measuring the voltage on the piezoresistor while providing the constant current through the resistor. The same response under the same load was achieved with simulation at while piezoresistivity matrix was varied.

Piezoresistor is temperature depended as well as sensitive to light. Temperature dependency was minimized with usage of two identical piezoresistors in voltage divider circuit [1]. To mask all incoming light, to protect golden wiring to the substrate and to protect piezoresistor from mechanical and chemical damage, both piezoresistors in the retractor prototype design were covered with epoxy casting compound TRACAST 3103. Used epoxy compound is non-toxic and medical compatible.

Glue bonding and epoxy casting was not used in numerical model, since its influence was estimated to be negligible. Some additional simplifications were made in preparation of the model, since the model was too complex to manually enter it into the simulation software. The shape of the model corresponds to the actual retractor, but there were some minor differences mostly at the corners. Namely, retractor smooth corners were replaced with model sharp edges. The influence of this simplification was estimated to be of no importance far

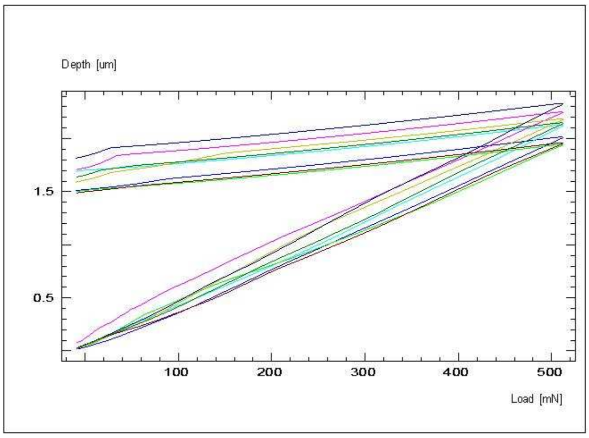


Fig. 4 Depth–load diagram determined by the indentation method. (From the slopes of the curves and starting and ending load point the Young's modulus is calculated by the method described in [9].)

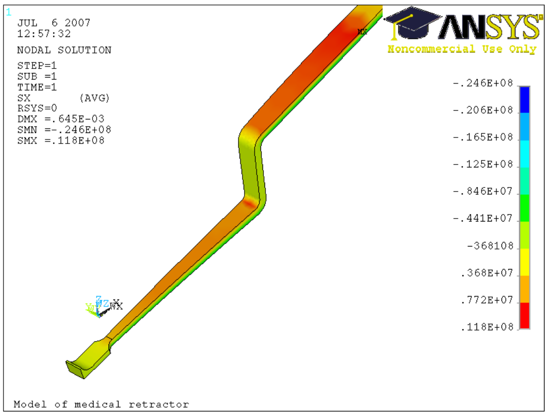


Fig. 5 Stresses in longitudinal ($x$) direction in loaded retractor.

from the physical borders where all the measurements were done.

With numerical model the optimal position of the piezoresistors was determined, taking into account several requirements, such as high sensitivity to the stimulus and high uniformity of stress on the piezoresistor surface. The final location of sensor was also conditioned with surgeon requirements such as the fact that it should not block the view in the operative field.

## 4 Results and discussion

With indentation method the Young's modulus was determined. The measured Young's modulus for stainless steel cantilever was averaged on the basis of 8 measurements as $E = 167,56$ GPa, whereas the maximum and minimum values were scattered over the range of $12\%$ of average value. Difference in measurements were assigned to non-uniform surface of stainless steel cantilever.

Using the Equation 3 and Young's modulus determined by microindentation method the same value was used as input for the ANSYS model and modal analysis was done. In Table 3, there is a list of modal frequencies acquired by measurement, numerical model and analytical solution. Due to low sampling rate of parameter analyser and due to the fast decay of higher modal frequencies, only two modal frequencies were extracted from measurements using FFT.

Tab. 3 Modal frequencies of stainless steel cantilever in longitudinal mode

| $i$ | Measurement | Simulation | Analytical solution |
|---|---|---|---|
| 1 | 75, 68 Hz | 80, 91 Hz | 79, 71 Hz |
| 2 | 492, 8 Hz | 507, 92 Hz | 496, 23 Hz |

Values acquired by numerical model are higher than measured values, but still confirm the measured Young's modulus. The Euler–Bernoulli theory provides good agreement to measured frequency at given Young's modulus. We have thus confirmed the indentation method measurements of Young's modulus with analytical and numerical tools.

In characterization of piezoresitors, the piezoresistivity coefficient $\pi_L$ was calculated from resistance measurements. Resistance was measured with loaded and unloaded cantilever. Load was matched in ANSYS model and the average stresses on resistors were readout. From the stress in the resistor and the resistance change, the coefficient $\pi_L$ was calculated. All measurements were done at 23° C. The results are listed in table 4.

Tab. 4 Measured resistances under various loads on cantilever beam and average stresses on piezoresistors active area.

| $F$[mN] | $R_x$[kΩ] | $\sigma_x$[MPa] |
|---|---|---|
| 0 | 8, 1637 | 0 |
| 78 | 8, 1822 | 6 |
| 441 | 8, 2587 | 31 |
| 696 | 8, 2805 | 37 |
| 1010 | 8, 3847 | 69 |
| 1138 | 8, 4116 | 78 |
| 1452 | 8, 4725 | 100 |
| 1707 | 8, 5350 | 117 |

Using the data from table 4 the piezoresistive coefficient $\pi_L$ was calculated to be $38,3 \cdot 10^{-11}\mathrm{Pa}^{-1}$ and it's value is in good agreement with published results [11]. The $\pi$ coefficients are important as they influence the final sensitivity of the device. The cantilever characterization of sensor is now superseded with simulation of medical retractor. Calculated stresses with color scale are shown on figure 5. Longitudinal stress is strongest at the retractor support – at the point where the retractor is hand held. The point of support is not uniquely defined and it strongly varies with different fingers position during the retractor usage. Another interesting

 

(a)

(b)

Fig. 6 Two prototype retractor for force measurement. Piezoresistors are covered with black epoxy cast. (a) Sensors bonded on back side. (b) Sensors bonded on front side.

area, where the stresses are of similar magnitude, is the section where the retractor is curved in S-shape. The curvature acts as a partial support for the long retractor arm of the retractor and it is thus the region of increased stress.

The uniformity of the stress is also of importance, since the resistors bonded on the retractor will always have some variance in position. Thus small deviation from designated position should have no major influence on the sensor performance.

## 5 Conclusion

Simulation and mechanical characterization of stainless steel cantilever was shown. In combination with numerical analysis software the longitudinal piezoresistive coefficient $\pi_L$ was determined. Results from cantilever analysis were then applied in the case of retractor. Using ANSYS simulations it was determined that retractor response is insensitive to piezoresistors position variation because of good uniformity of stress distribution on retractor arm.

The final prototype retractor was built on the basis of practical aspects and surgeon requirements. The back side of the retractor (Figure 6) was used for the first prototype. Later on this was discarded, because the sensor blocked the view into the operative field. Therefore the sensors were mounted at the front side. In addition the sensor was still mounted on an area with large stress. Sensitivity was thus maximized by optimal sensor position.

The proposed method of retraction force measurement has an advantage in comparison with published designs, since it doesn't involve force measurement in operative field. Removing the sensor away from the biological systems provides protection from interference, such as electrical voltages, that could potentially result in neural response.

The numerical simulation provided invaluable results in terms of design verification and design improvement. Numerical results enable insight into mechanical stress distribution of loaded retractor and represent the basis for improvement of design.

The retraction is not applied only in one direction, but is usually combined or it can shift from one direction to another. Additional sensors on such a retractor will provide further improvements in dual-axis force measurements. With additional software the influence of orthogonal stress components in cantilever, which are result of forces acting in different directions, could be evaluated resulting in total force vector acting on a nerve.

## 6 Acknowledgment

We would like to acknowledge prof. Peter Panjan from IJS, Slovenia for providing the microindentation measurements.

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