Characteristics Improvement of Conductivity Microsensors Basing on FEM Simulation

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Abstract: - Microsensors have already become components in various macrotechnical systems. One of significant problems, impeding application of such type of sensors, is their reduced characteristic stability for longer periods of time. This one arouses basically from the biofouling processes on their active surface.

The application possibilities of compound base structure consisting microsensor mounted on circuit board, piezoactuator and piezosensor for cleaning of active sensor surfaces are investigated in the following. Basing on the two-step analyses on the structure - modal followed by harmonic - have been made significant practical conclusions for the optimal working conditions. Here is presented a method of frequency range choosing for the piezoactuator stimulating voltage, based on the well known FEM error estimation procedure presented in the most of commercial FEM software packages.

Key Words: - Microsensors, conductivity sensor, piezoactuator, environmental control, modeling, FEM analysis, error estimation.

1 Introduction
Technology advances in micromechanics and thin-micromechanical structure realization should be considered as one of significant achievements in the field of mechanical engineering in our decade. This new technology allows new measurement applications, which require modern computer-aided methods to solve the metrological problems.

Microsensors have been already consisting part of macrotechnical systems in numerous of scientific areas. Reaching a micro-dimensions offers opportunity to use fundamentally different methods for signals converting. Surface process prevailing, dynamics of energy exchange and transformation, as well as, high module density, give opportunity of development of new measuring devices [9,10].

The problem putting in front most difficulties to approach is connected with stability of microsensor characteristics. Whereas, application of microsensors in lab-conditions have already reached the stage of classical measuring devices replacement, then application of microsensors in environment investigations is in the stage of scientific survey. In real conditions, microstructures work under non-deterministic influence of different factors, which reduce reliability far and away than admissible conventional measuring devices [11]. The fundamental bad-influence factor here is biofouling.

The results in the following, are part of investigations, in which the aim was improvement of metrological characteristics of microsensors with the help of finite elements modeling and simulation.

There are two different directions toward improving, have been made:
- Optimization of constructive parameters.
- Integration of additional components (sensors and actors).

An important aspect in this integration is searching of possibilities to reduce the influence of natural environment upon micro-technological developed sensors, using conventional low-cost piezoactuator structures.
2 Conductivity microsensors

The investigated sensors – family of Si-based microsensors for conductivity measurement, with four titanium nitride coated electrodes. Fig.1 shows two basic structures and their pin-out.

The two outside electrodes (FOR1, FOR2 are connected to voltage. Within the field, generated of these electrodes, another two “voltage electrodes” (SEN1, SEN2) are placed [3].

![Fig. 1. Conductivity microsensors – basic structures](image)

Electrodes of microsensor are high chemically resistant. The chip is mounted on FR4 - type board (fig.2).

![Fig. 2. Microsensor on FR4 - type board (all dimensions are in mm).](image)

3 Finite element analysis

Finite element analysis (FEA) is frequently used for characterizing of the mechanical, thermal and electrical behavior of microsensors. FEA is a flexible and efficient tool to analyze the performance of complex microstructures, increasing the reliability of microsensors, and reducing development time and cost [4].

3.1 Modeling of Microsensors

Various effects should be considered throughout the design and evaluation process of a microsensor. Both, static and dynamic analysis may be necessary to investigate the mechanical behavior. Thus, composite three-dimensional structures with geometrical nonlinearities (large deflection/rotation, stress stiffening, et.c.) and complex material data (in general anisotropic material) have to be considered.

For the aims of present investigation FEM – simulation has been developed on the next different stages:
- Electrical field simulation – aims optimization of constructive parameters;
- Modal and harmonic analyses – aims consequently: determination of frequency range, and choice of appropriate frequency in previously selected range.

At the stage of conceptual design of microsors FEA - simulations have been performed to determine the electrical field distributions generated by outer electrodes in order to optimize shape, dimensions and placement of the inner electrodes.

The results allowed us, to summarize direct conclusions about some of significant constructive requirements [3, 7].

In the following main attention is placed to modal and harmonic analyses of structure, which consists: mounted on a circuit board microsensor, piezactuator and piezosensor.

For structure building we choose 3D-geometrical model, represented by solid finite elements.

3.2 Modal and Harmonic analyses

Specific dimensions of piezactuator and piezosensor take in consideration particularities of microsensor board geometry, and additional requirements of high frequency working range.

Here:
- Modal analysis – aims specification of optimal (lowest-cost) energy frequency range;
- Harmonic analysis – is connected with choosing of appropriate frequency in previously defined frequency range.
  
  Aims and particularities of the stage “Modal analysis” could be separated in the next set of criteria for frequency range defining:
  
  - Frequency range, have to includes a segment of supersonic frequency bend – a consideration enforced by physical conditions come into being water cavity;
  
  - Frequency range, have to be with boundary frequencies, whose equivalent stresses resulting amplitudes do not overlap yield stress value.
  
  In the same manner, we have build criteria for frequency choosing in the stage of harmonic response analysis:
  
  - In the boundaries of previously build frequency range, it should be selected a frequency, guaranteeing minimal value of harmonic vibration – this is strength invoked requirements.
  
  - Selected frequency should be in supersonic range – a cavity requirement;
  
  - The frequency should be releasable with the help of available electronic devices and also should take in consideration the properties of piezomaterial.

### 3.2.1 Modal analysis

Specific feature of the stage is considering both, the strain energy and energy of piezoelectrical response.

The last one adds in the energy equation two different terms: piezomechanical and piezoelectrical. Piezomechanical term describes growing of electrical field, due to mechanical stresses (strict piezoelectrical effect: “strains – potential difference”), and could be represented by:

\[
U_{cm} = \frac{1}{2} \int_{V} \{\sigma\}^T \{\varepsilon\} dV .
\]  

(1)

Second term considers strain energy due to opposite piezoelectrical effect (“potential difference – strains”). It reads:

\[
U_{e} = \frac{1}{2} \{u^T\}K\{u\},
\]

(2)

in admission that electrical field and material are homogeneous.

Here \(K_e\) is stiffness matrix of the FEM structure.

For appropriate numerical description of energetic components it is necessary to know permittivity, piezoelectrical and stiffness matrices of considered material. These quantities usually are placed in disposal by piezomanufacturer [9, 10].

Take in mind terms (1) and (2) in Lagrange – equation, we obtain the following representation of structural behavior:

\[
[M]\{\ddot{u}\} + [K]\{u\} = \{0\}, \quad (3)
\]

where \([M]\) is mass matrix, and \([K]\) - stiffness matrix.

Solution of (3) holds the form:

\[
\{u\} = \{u_o\}\cos \omega t .
\]

(4)

Substitute (4) in (3), the problem could be transformed to eigenvalue – equation solving, namely:

\[
([K] - \omega^2[M])\{u_o\} = \{0\}
\]

(5)

Here it have been considered, sensor to be ideal (sensor resistance and input resistance of amplifier used by the measurement goes to infinity), but in actor the stimulating voltage is dominant and no sensor effect is considered.

For the numerical solution of (5) an iterative QR – Housholder method has been used. It follows the sequence:

- Stiffness matrix \([K]\) is transformed in upper triangular form by so called master degrees of freedom

- By QR-iterations the whole set of eigenvalues is obtained

- By inverse iteration, are expanded necessary subset of eigenvalues and eigenvectors.

### 3.2.2 Harmonic analysis

In this investigation, we accept that all of acting loads change your magnitude according to some sinusoidal low (this one argues usage of harmonic response analysis). We have no aim to describe specific theoretical considerations of harmonic response analysis, but it should be mentioned that, for solving of non-homogeneous set of differential equation we use so called reduced method (performed in similar manner as Housholder method), following the next advantages:

- Lower cost measured in evaluation cycles;
- A possibility to define master degrees of freedom, i.e. user defined reduction of stiffness matrix.
- Smaller number of iterations, which guarantees converged solution. This advantage allows reducing of round-errors [1].

Simulated behavior of conductivity sensor CLFF-1 and the piezo-plates is shown in fig.3. Fig.3 a), b) show modes in frequencies of 5 kHz and 20 kHz respectively.

3.3 An approach for frequency range defining based on error estimation of FEM solution

The criterion for frequency range defining is founded on proposed by Zenkiewicz ? Zhu [8] error-estimation procedure. In general, this procedure is based on observation of discontinuity in the field of stresses upon the boundaries of finite elements. In other words, as uniformly is distributed field of displacements (so-called equilibrium distribution), as uniformly is distributed the field of stresses and opposite. We aim frequency range with similar equilibrium distributions, i.e. such a piece of error distribution diagram with strongly decreasing character.

The essence of error estimation procedure is described in the following:

In displacement based FEM requirements of compatibility hold only displacement filed. Field of stresses generally said, is discontinued through the element boundaries. Thus for each node of given finite element could be defined a vector, called error stress vector, which reads:

$$ \{ \Delta \sigma^i_m \} = \{ \sigma^a_m \} - \{ \sigma^i_m \}, \quad (6) $$

where:
- $\{ \sigma^a_m \}$ - mean stress vector in node “m” of element „i” ($\{ \sigma^a_m \} = \sum_{i=1}^{N} \{ \sigma^i_m \} / N$);
- $\{ \sigma^i_m \}$ - vector of stresses in node „m” of element „i”;

Thus for each of elements we could write:

$$ e_i = \frac{1}{2} \int_{V} \{ \Delta \sigma \}^T [D]^{-1} \{ \Delta \sigma \} dV, \quad (7) $$

where:
- $e_i$ - is energy error in element „i”;
- $V$ – volume of element;
- $[D]$ - strain displacement matrix of element;
- $\{ \Delta \sigma \}$ is error vector of considered points of element (as usual in the centroid of element).

A total error in FEM solution in this case holds:

$$ e = \sum_{i=1}^{N} e_i, \quad (8) $$

where $N$ - number of elements.

Hereby percentage error in energy norm follows the expression:

$$ E = 100 \sqrt{ \frac{e}{U + e} }, \quad (9) $$

where $U$ - strain energy for the structure.
4 Conclusion

The measurement tasks on the field of environmental monitoring produce a unique complex of requirements to the necessary measuring equipment. For the solving of such a kind of tasks, and especially in-vivo and in-situ measurements microsensors are widely applicable. The fields of their application can be widening by the use of efficient methods for prevention of biofouling the active sensor surfaces.

In this work we represent two-level approach for modeling and FEM - simulation of piezostructures. This approach includes:

- Modal analysis – specifying lowest-cost energy frequency range, based on the error estimation procedure;
- Harmonic analysis – specifying appropriate frequency in previously defined frequency range.

And as a result with the help of finite element method an optimal working conditions for the given structure, were invoked.

References: