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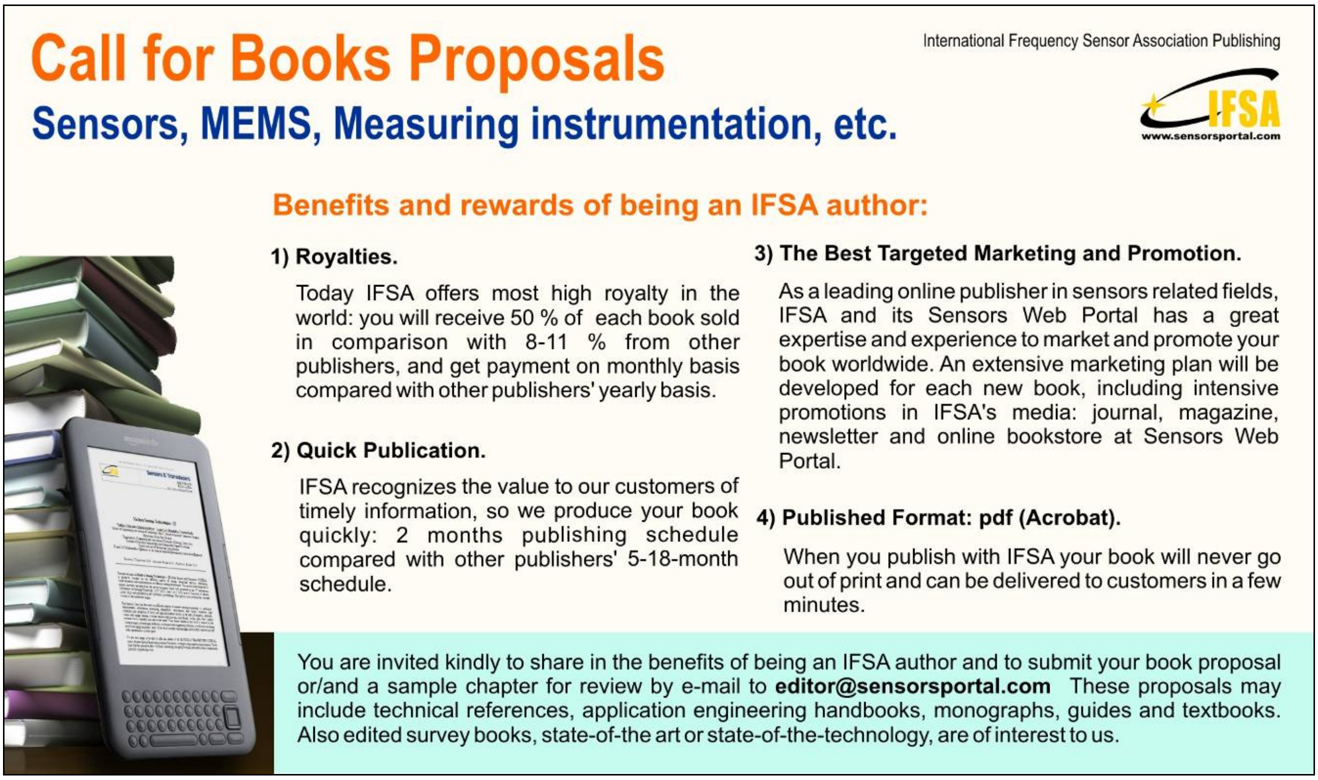
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An Analytical Method to Determine the Response of a Micro Capacitive Pressure Sensor

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Abstract: The response of a capacitive pressure sensor is generally represented by a fourth order partial differential equation which is complex to solve and does not possess an exact solution. Several attempts have been made earlier through various techniques such as the Galerkin method, Finite Difference Method etc. In this paper an attempt has been made to develop a simple approximate analytical approach to determine the response of a capacitive pressure sensor whose diaphragm is designed to undergo very small deflections (typically less than 25 % of the thickness). The non-uniform gap between the electrodes is mathematically expressed as a combination of the initial gap between the electrodes (in the undeformed state) and a displacement function in (x, y). The proposed displacement function is then utilized in evaluating the capacitance as a function of the applied pressure. The results obtained from the analytical approach are benchmarked against those obtained from COMSOL Multiphysics®, a popular Finite Element Analysis tool in the MEMS industry. It is observed that the results obtained from COMSOL Multiphysics® and those from the analytical approach are in good agreement with a maximum deviation of about 3.38 %. *Copyright © 2011 IFSA.*

Keywords: Non-uniform gap, Simple approximate approach, Displacement function, COMSOL Multiphysics®.

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1. Introduction

Pressure sensing is one of the most established and well-developed areas of sensor technology. One reason for its popularity is that it can be used to measure indirectly various real-world phenomena like flow, fluid level and acoustic intensities, in addition to pressure [1]. Pressure sensors invariably use a thin elastic member such as a diaphragm which acts as the primary transducer. Application of pressure on the diaphragm results in the change of one or more physical attributes of the diaphragm like displacement, stress, strain, etc. However these quantities have a very small magnitude and cannot be read out directly. In view of this difficulty various transduction techniques are adopted such as piezoresistive, piezoelectric, capacitive, optical, resonance etc.

Piezoresistive sensing has been widely studied during the past 20 years and has become one of the most popular sensing mechanisms [2, 9]. These sensors exhibit excellent linearity but suffer on account of temperature dependence of the piezoresistive coefficients [2, 9]. Resonant pressure sensors have the advantage of excellent linearity, low cost on-chip electronics, easy interface to external electronics, immunity to electronic effects such as noise etc… but are complicated in terms of design and manufacturing [11, 12]. Capacitive sensing on the other hand provides significant advantages such as very high pressure sensitivity, low power, low noise, large dynamic range and low temperature sensitivity, immunity to hazardous environments, lower cost and hence are preferred candidates in many emerging high-performance applications [2, 10]. Capacitive Micromachined Ultrasonic Transducers (CMUTs) are gaining a lot of popularity and are expected to replace traditional piezoelectric transducers for high frequency ultrasonic imaging due to the flexibility offered by the microfabrication, wide bandwidth, CMOS compatibility, very high level of integration and mass production.

The literature available suggests a fourth order Partial Differential Equation (PDE) for the sensor behavior which does not possess an exact analytical solution [1, 9, 14]. Several attempts have been made earlier to arrive at an approximate solution using various techniques such as the Galerkin method, Finite Difference Method etc., [8, 10, 13, 14]. Keeping these in mind, in the present work, modeling of a capacitive pressure sensor is attempted with a simple approximate displacement function for the diaphragm deflection to estimate the response of the sensor.

2. Modeling of the Micro Capacitive Pressure Sensor

Capacitive pressure sensors are essentially simple devices that rely on applied pressure altering the distance between the electrodes. This results in a value of capacitance that varies as a function of the applied pressure [3].

A capacitive absolute pressure sensor with a square diaphragm as shown in Fig. 1 is considered for the analysis with structural and material properties as given in Table 1. Since $h = \frac{a}{10}$, the diaphragm can be analyzed as a thin plate undergoing small deflections [5, 7].

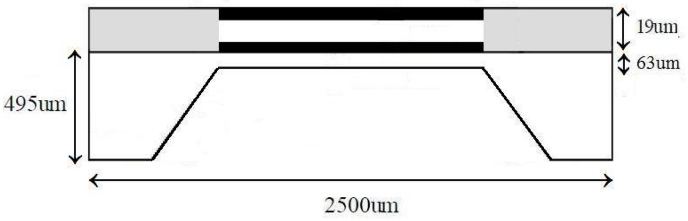

Fig. 1. Sectional view of an absolute pressure sensor with capacitive transduction.

Table 1. Structural and Material Properties of the Diaphragm.

Parameters	Values
Side of the square diaphragm (a)	783 um[4]
Thickness of the diaphragm (h)	63 um
Initial gap between electrodes (g_0)	19 um
Max. pressure (P_{max})	100 MPa
Poisson's ratio(ν)	0.27
Young's modulus (E)	131.9 GPa
Density (p)	2330 kg/m^3

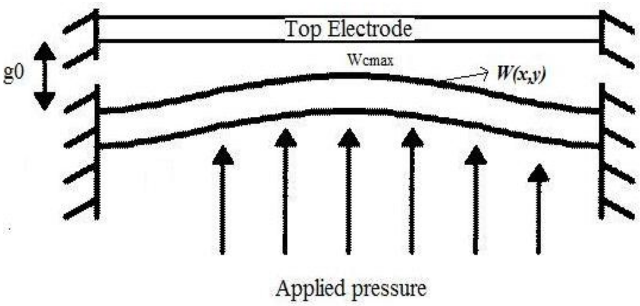

Fig. 2. Schematic showing the non-uniform gap between the electrodes.

2.1. Theoretical Analysis of the Sensor Response

Change in the capacitance between the electrodes of the sensor is a function of the diaphragm deflection.

$$C(x,p,P_i)=\int_0^a\int_0^a \frac{\varepsilon_0\varepsilon_r dxdy}{g_0-W(x,y)} \tag{1}$$

The standard double integral used in the evaluation of the capacitance of the sensor in Cartesian co-ordinate system is given by (1) where P_i is the applied pressure, $\varepsilon_0 = 8.854\times10^{-12} F/m$ is the permittivity of free space and ε_r is the relative permittivity of the medium between the electrodes. It is assumed that air is the dielectric medium between the electrodes and hence $\varepsilon_r = 1$. The term *W(x, y)* in (1) is the instantaneous deflection at any point on the diaphragm. This needs to be evaluated from the theory of plates.

A detailed study of the literature concerning theory of plates in the design of pressure sensors reveals the usage of two terms namely "thin plates" and "small deflections". A "thin plate" is one for which $h \simeq \frac{a}{10}$ [5, 7] and "small deflection" condition is expressed mathematically as $W_{\max} < \frac{h}{4}$ where is the maximum central deflection [8, 16]. The linearity in the relation between the maximum deflection $W_{\max}$ and the applied pressure P_i for $W_{\max} < \frac{h}{4}$ in such a structure is suitable to be used as a sensor [8, 16]. Thus in this work, a pressure sensor structure meeting the above conditions is considered for analysis.

Fig. 3 represents the boundary conditions for a diaphragm clamped at all edges. These are mathematically expressed as [5]

$$W(x,y)=0 \text{ and } \frac{\partial W(x,y)}{\partial x}=0 \text{ at } x=0 \text{ and } x=a \tag{2}$$

$$W(x,y)=0 \text{ and } \frac{\partial W(x,y)}{\partial y}=0 \text{ at } y=0 \text{ and } y=a \tag{3}$$

$$\frac{\partial^2 W(x,y)}{\partial^2 x}\neq 0 \text{ at } x=0 \text{ and } x=a \tag{4}$$

$$\frac{\partial^2 W(x,y)}{\partial^2 y}\neq 0 \text{ at } y=0 \text{ and } y=a \tag{5}$$

where W (x, y) is the instantaneous deflection. Equations (4) and (5) clearly indicate the presence of a finite bending moment about the x, y as well as the x-y direction which is a characteristic of a perfectly clamped plate.

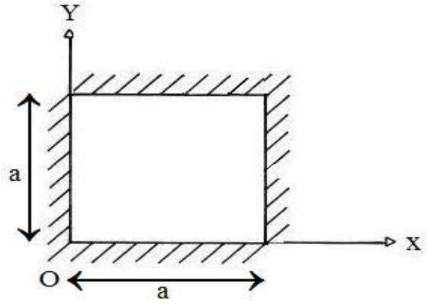

Fig. 3. Definition of co-ordinate system and the boundary conditions for the diaphragm.

The displacement function W(x, y) for the above is an infinite trigonometric series [5, 14] and difficult to use in the evaluation of the capacitance of the sensor with respect to the applied pressure.

Further it has been established experimentally that large discrepancies appear near the diaphragm edges due to improper clamping and the real world boundary conditions are very difficult to predict. Results of the experimentation reveal that $\frac{\partial W(x,y)}{\partial x}=0, \frac{\partial W(x,y)}{\partial y}=0$ are strictly non-zero at the edges [15] and for very small deflections $\frac{\partial^2 W(x,y)}{\partial^2 x}\neq 0, \frac{\partial^2 W(x,y)}{\partial^2 y}\neq 0$ could be very small and thus neglected for the purpose of analysis without contributing significant error.

In view of the above mentioned approximations, the spatial variation of the displacement function for the pressure sensor diaphragm could resemble that of a simply supported plate. The displacement function in this condition could be represented as

$$W(x,y)=W_{\max}\sin\left(\frac{\pi x}{a}\right)\sin\left(\frac{\pi y}{a}\right), \tag{6}$$

where $W(x,y)$ is the displacement function of the diaphragm with realistic boundary conditions and $W_{\max}$ is the maximum central deflection of the diaphragm.

The value of $W_{\max}$ is given by [5]

$$W_{\max} = \frac{0.00126 P_i a^4}{D}, \tag{7}$$

where P_i is the applied pressure and D is the flexural rigidity of the diaphragm given by [5]:

$$D = \frac{Eh^3}{12\left(1-\nu^2\right)} \tag{8}$$

with usual terms as described earlier.

The inner integral I1 is evaluated using (6) in (1) which gives

$$I_1 = \frac{2a\varepsilon_0\varepsilon_r}{\pi\sqrt{d_0^2 - \beta^2 W_{\max}^2}}\left[\frac{\pi}{2} + \arctan\left(\frac{\beta W_{\max}}{\sqrt{g_0^2 - \beta^2 W_{\max}^2}}\right)\right], \tag{9}$$

where is $\beta = \sin\left(\frac{\pi y}{a}\right)$ and all other terms have their usual meaning.

Capacitance is evaluated using (9) in (1) which yields

$$C\left(x, y, P_i\right) = \int_0^a I_1 dy \tag{10}$$

The complex integrand in (10) is evaluated using trapezoidal rule for numerical integration in MATLAB® to estimate the output capacitance corresponding to different input pressures [6].

In case of MEMS devices such as pressure sensors, accelerometers etc., design verification is generally done virtually through modeling the device in a design-analysis package as physical prototyping is very cost intensive. In the subsequent section, an attempt is made to model this pressure sensor using COMSOL Multiphysics® Version 3.2.

3. COMSOL Multiphysics® Model:

COMSOL Multiphysics® is an equation based multiphysics Finite Element Modeling (FEM) tool widely used in the analysis and design of MEMS structures. The software package comes with a wide variety of predefined multiphysics coupling modules which can be used to analyze real-time systems involving more than one engineering domain simultaneously.

A 3D model of the diaphragm and the sensing structure is built in COMSOL Multiphysics® with structural and material properties given in Table 1. Only one-fourth of the geometry is considered for modeling owing to symmetry. The model is subjected to various mesh sizes to check for convergence until the difference between two successive values of deflection are about 1%. ‘Predefined Mesh Size’ feature with ‘Coarser’ resolution based on free tetrahedral mesh element is used for meshing of the geometry .The meshed geometry consists of 1225 elements.

This problem is solved using three application modes: one plane stress application mode, one mesh deformation application mode, and one electrostatic application mode. The latter two are defined in a frame to allow the mesh to move. It is necessary to select a nonlinear solver to compute the solution. The plane stress application mode solves for the diaphragm deflection [7].

Next, the recalculation of the mesh is done with the COMSOL Multiphysics® mesh deformation application mode. Then the boundary conditions for the mesh deformation are solved with the plane stress application mode dependent variables. These conditions correspond to the deformation when the sensor is pressurized [7].

For solving the electric field, the electrostatics application mode is used. This application mode is added to the frame which was created when the mesh deformation application mode was added. The electrostatics application will then take account of the deformed geometry to calculate the capacitance [7].

Fig. 4 shows the Finite Element mesh and Fig. 5 the deformed diaphragm along with top electrode modeled using COMSOL Multiphysics®.

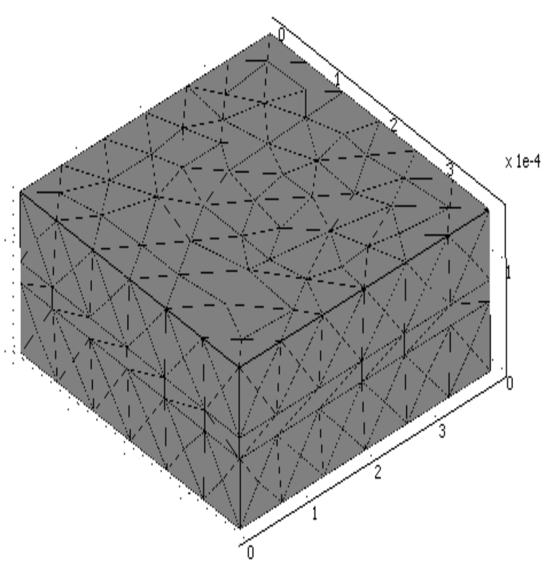

Fig. 4. Meshing of the geometry in COMSOL Multiphysics®.

4. Results and Discussion

The variation of central deflection of the diaphragm with the applied pressure is shown in Fig. 6. Results from the theoretical analysis and COMSOL Multiphysics® model illustrate that the central deflections are linear functions of the applied pressures as expected of a sensor with thin diaphragm and small deflection.

Fig. 7 and Table 2 present comparison of the results obtained using approximate analytical approach and COMSOL Multiphysics®.

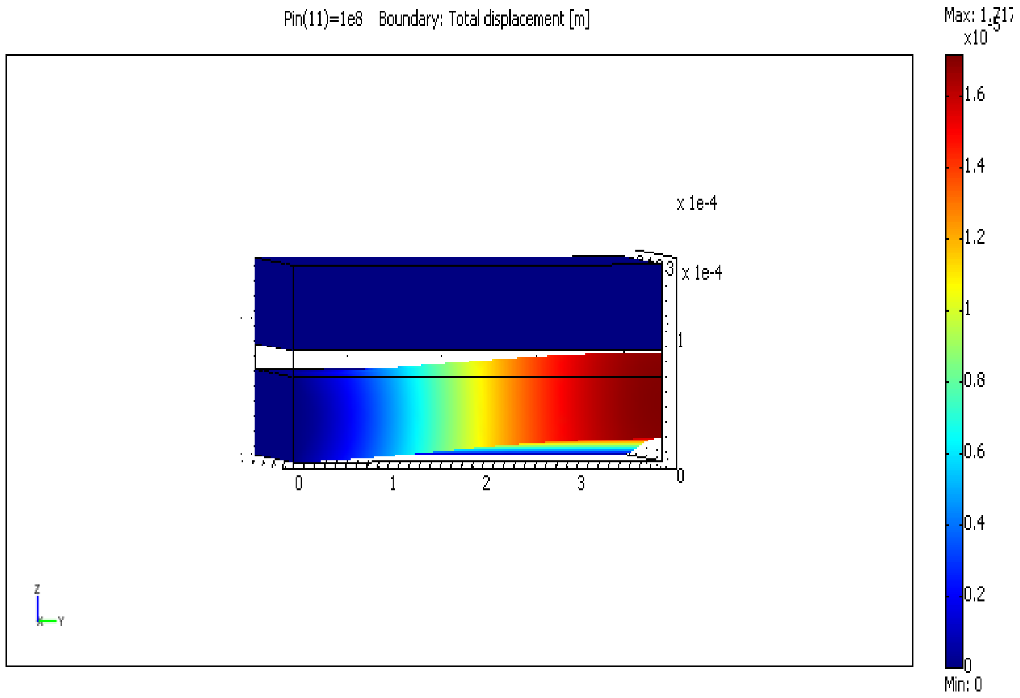

Fig. 5. One-fourth of the diaphragm modeled using COMSOL Multiphysics®.

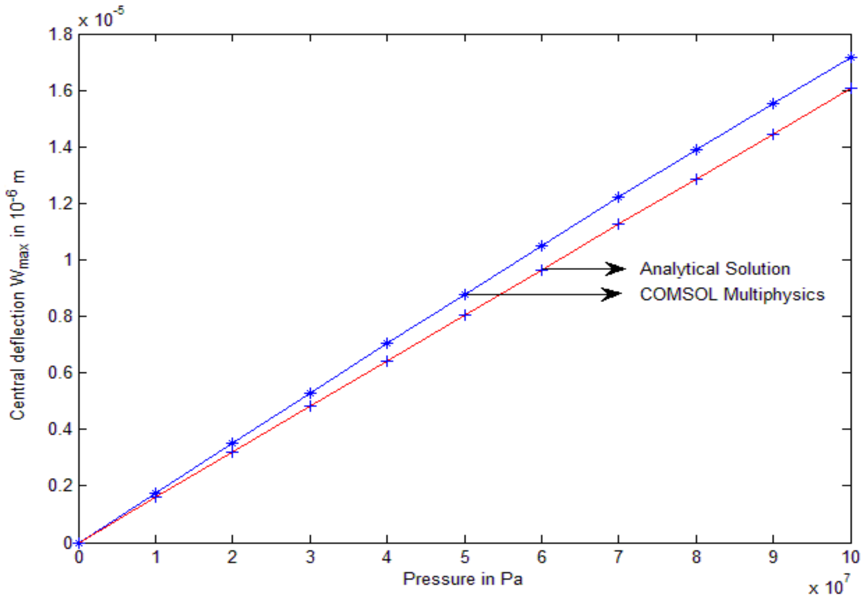

Fig. 6. Central Deflection of the Diaphragm.

It is observed from Table 2 that the values of capacitance obtained from approximate analytical method are in good agreement with the solution obtained from COMSOL Multiphysics® package. The values of the capacitance suggested by COMSOL Multiphysics® are conservative compared to the approximate analytical approach proposed in this work. Further it is interesting to note the non-linear variation of the capacitance at higher pressures. This non-linearity could be justified by visualizing the diaphragm as a cascade/concatenation (parallel electrical connection) of two non-parallel plate capacitors, one sloping towards the left and the other towards the right from the central plane of the diaphragm and whose overlapping areas change as a function of the slope of the diaphragm.

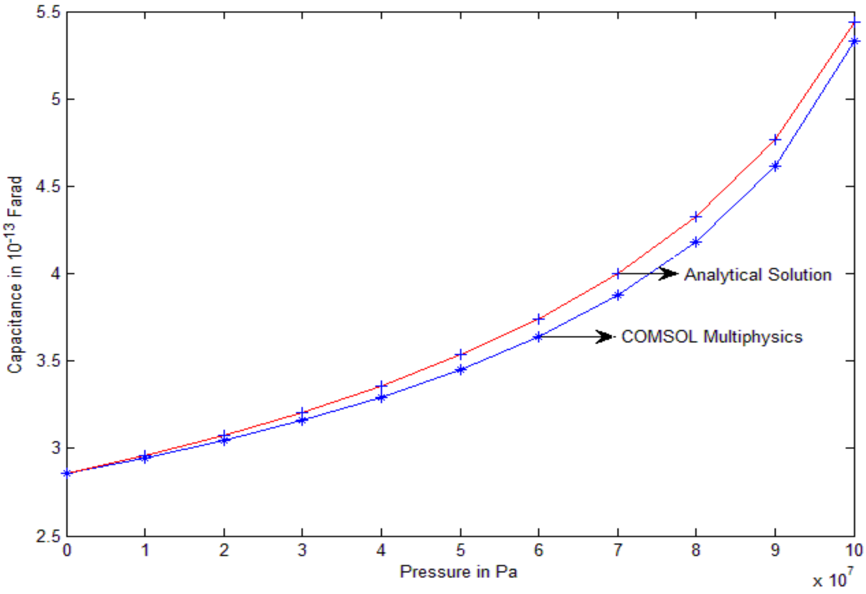

Fig. 7. Comparison of the results.

Table 2. Comparison of Results.

P_i in MPa	COMSOL Multiphysics® Capacitance (10^{-13} F)	Analytical Solution Capacitance (10^{-13} F)
0	2.8570	2.8580
10	2.95	2.9619
20	3.047	3.0770
30	3.162	3.2080
40	3.295	3.3590
50	3.452	3.5340
60	3.640	3.7430
70	3.874	3.9990
80	4.180	4.3260
90	4.612	4.7680
100	5.329	5.4350

5. Conclusions

A simple approach for modeling a pressure sensor with thin diaphragm is proposed in the present work. Further the proposal is compared with the commercially available Finite Element Analysis (FEA) tool COMSOL Multiphysics®. The maximum deviation observed between the results of capacitance from analytical approach and the FEA approach is around 3.38 % which could be attributed to the approximation of the boundary conditions and the numerical approach to the problem adopted by COMSOL Multiphysics®. Considering the magnitude of deviation observed, the proposed approximation could be acceptable for all practical purposes. Thus a preliminary evaluation of the pressure sensor response could be based on the results obtained from the approximate analytical method proposed for a thin diaphragm sensor with small deflections.

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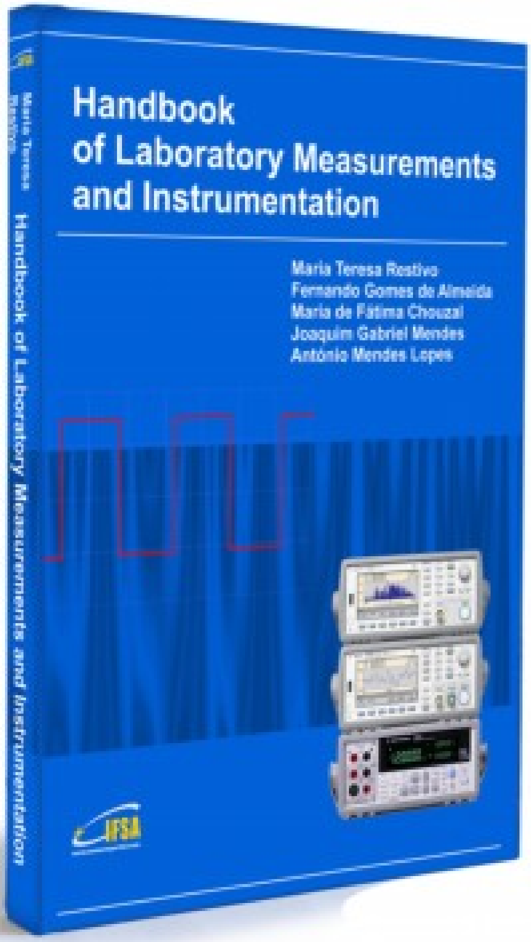

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