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Sergey Y. Yurish

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Lumped Parameter Modeling of Absolute and Differential Micro Pressure Sensors

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Abstract: Mechanical systems may be modeled as systems of lumped masses (rigid bodies) or as distributed mass (continuous) systems. The latter are modeled by partial differential equations, whereas the former are represented by ordinary differential equations [1]. In this paper a lumped parameter model of absolute and differential pressure sensors are developed, whose diaphragm is designed to undergo very small deflections (typically less than 25 % of the thickness). A simple approximate model with proper assumptions are considered and analyzed first. A more appropriate model with refined approximation is considered later. Estimation of various parameters like mass, spring constant and damping of the diaphragm & fluid are done and used to estimate the transfer function. The transfer function is then used to understand the frequency and stability analysis of the system. A square, rigidly fixed diaphragm pressure sensor is considered in this work. By limiting the maximum deflection to one-fourth of the thickness, the analysis has been done for a maximum applied pressure of 100 MPa. MATLAB® is used as a tool to carry out the analysis. *Copyright © 2012 IFSA.*

Keywords: Lumped parameter model, Absolute pressure sensors, Differential pressure sensors, Micro electro mechanical systems (MEMS), Modeling.

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 [2]. 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.

Most pressure sensors today use sealed gas or vacuum filled cavities. The basic operation of such a sensor is to couple the pressure to be measured to one surface of a membrane and to measure its deflection. The Fig. 1 shows the different type of pressure sensor designs commonly implemented in micromachined form. Pressure sensors can be built to measure pressure relative to a sealed reference cavity or differentially using two input ports. For sealed cavity designs a vacuum is preferred since there will be no temperature dependent pressure changes in the reference pressure [3].

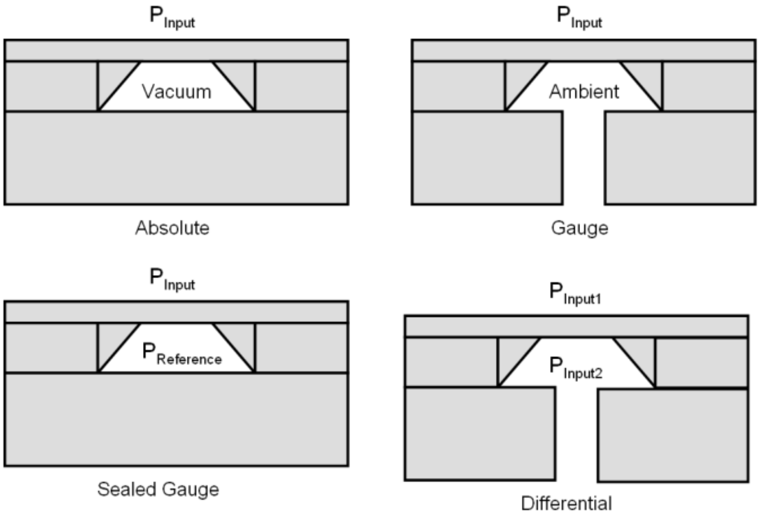

Fig. 1. Commonly used Pressure sensors.

2. Mechanical Lumped Model

A 100 mm diameter wafer with a thickness of 500 μm is considered in this work. The sensor geometry and dimensions are taken as listed in the Table 1 and the side view of a bulk micromachined pressure sensor is shown in Fig. 2. The thickness is considered as 495 μm for practical reasons, where there will be a reduction in thickness due to cleaning and smoothening of the surface.

Table 1. Geometry and Dimensions of Silicon Pressure Sensor.

Diaphragm geometry and wafer thickness	Flat square silicon(100) and 500 mm
Side of the diaphragm (a)	783 um [4]
Thickness of the diaphragm (h)	63 um
Max. central deflection of the diaphragm (w_{max})	15.75 um(limited to h/4 for linearity) [5]
Young's modulus (E)	131 GPa
Poisson's ratio (γ)	0.27
Yield strength of silicon(100) (S_y)	7 GPa
Input pressure range (P)	0 – 100 MPa
Density of silicon (ρ)	2300 kg/m^3

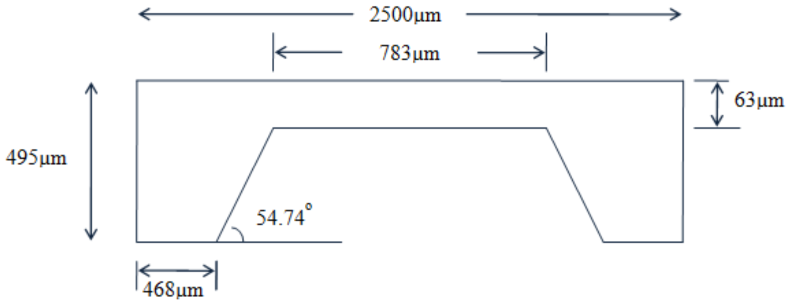

Fig. 2. Dimensions of Silicon Die.

3. Lumped Model of an Absolute Pressure Sensor

A 3 Degree of Freedom with respect to the fluid, diaphragm and the air between diaphragm and casing is considered in this model. The model and its parameters are described in the Fig. 3.

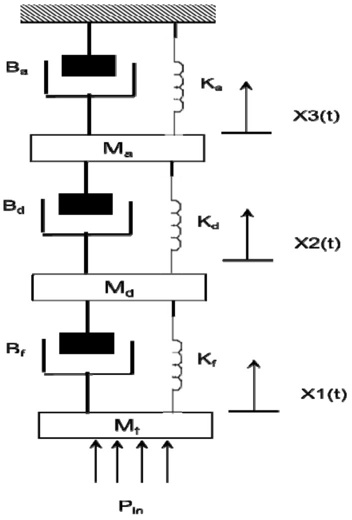

Fig. 3. Complete 3 DOF model of the pressure sensor.

Description of Symbols:
M_f = mass of the fluid in the chamber in kg;
K_f = stiffness contributed by the fluid in the chamber in N/m;
B_f = damping introduced due to fluid-structure interaction at the fluid-diaphragm boundary in Nm/s;
M_d = Mass of the diaphragm in kg;
K_d = stiffness of the diaphragm in N/m;
B_d = damping introduced by diaphragm in Nm/s;
M_a = Mass of the air in the cavity in kg;
B_a = damping introduced due to interaction between the diaphragm and air in Nm/s;
K_a = stiffness constant of air in N/m.

3.1. Computation of B_f, K_d, M_d and M_f Values

Using the values in Table 1 and the standard formulas, the following parameters are calculated and given below.

1. Stiffness of the diaphragm (K_d)

$$K_d = \frac{Eh^3}{0.0138a^2} = 4.26\times10^6\left(\frac{N}{m}\right) \tag{1}$$

2. Squeeze film damping introduced due to fluid-structure interaction [6] at the fluid-diaphragm boundary

$$B_f = \frac{96\eta a^4}{\pi^4 h_i^3}, \tag{2}$$

where H_i is the height of the inlet chamber. Referring to Fig. 2 H_i = 432 um. Thus

$$B_f = 2.065\times10^{-22} \text{ Ns/m}$$

3. The mass of the fluid is given by

$$M_f = p_f V, \tag{3}$$

where, p_f is the density of the fluid admitted in kg/m^3; $V_f = a^2H_i$ is the volume of the fluid in m^3.

Assuming the fluid admitted is water with p_f = 1000 kg/m^3.

$$M_f = 2.68\times10^{-7} \text{ kg}$$

4. The mass of the diaphragm is given by

$$M_d = \rho Vd \tag{4}$$

Using the values in Table 1 yields

$$M_d = 8.105\times10^{-8} \text{ kg}$$

3.2. First Approximate Model

Several parameters in the model can be assessed only experimentally or via complex mathematics involving more than one physical phenomenon at a time. To overcome this difficulty only those parameters which can be readily estimated are considered as a first approximation along with the following assumptions:

- The effect due to air friction between the diaphragm and the casing is not considered;
- The material damping associated with the diaphragm B_d is ignored since silicon does not exhibit mechanical hysteresis;
- Squeeze film damping contributes to the value of B_f and B_d;
- Liquids are incompressible. Hence K_f is very high and is not considered;
- Slope in the walls of the cavity due to anisotropic etching of silicon is not accounted.

After considering the above assumptions, the model is redrawn as given in Fig. 4.

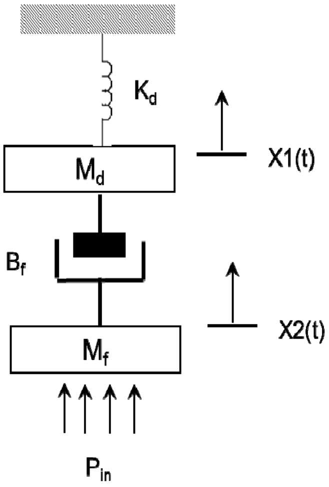

Fig. 4. First Approximate Lumped Model.

The governing equations for the above system in Fig. 4 are [1]:

$$M_d \ddot{x}1 + K_d x1 = B_f\,(\dot{x}2 - \dot{x}1) \tag{5}$$

$$F_{in} = M_f \ddot{x}2 + B_f (\dot{x}2 - \dot{x}1) \tag{6}$$

Rearranging equations (5) and (6) and taking Laplace transformation yields

$$(M_d s^2 + B_f s + K_d)x1(s) - B_f\, s x2(s) = 0 \tag{7}$$

$$-B_f\, s x1(s) + \left(M_f\, s^2\ + B_f\, s\right)x2(s) = F_{in}(s) \tag{8}$$

Representing equations 7 and 8 in matrix form and solving using Cramer's rule,

$$\begin{bmatrix} M_d\, s^2 + B_f s + K_d & -B_f s \\ -B_f s & M_f\, s^2 + B_f s \end{bmatrix} \begin{bmatrix} x1(s) \\ x2(s) \end{bmatrix} = \begin{bmatrix} 0 \\ F_{in}(s) \end{bmatrix} \tag{9}$$

$$\frac{x1(s)}{F_{in}(s)} = \frac{sB_f}{M_d M_f\ s^4 + M_d B_f\ s^3 + M_f B_f\ s^3 + M_f K_d\ s^2\ + K_d B_f\ s} \tag{10}$$

Using Final Value Theorem,

$$x1(t) = \lim_{s \to 0} s x1(s) \tag{11}$$

$$x1(t) = \lim_{s \to 0} \frac{F_{in}\, s B_f}{s(M_D M_f\, s^3 + M_D B_f\, s^2 + M_f B_f\ s^2 + M_f K_D\, s^1\ + K_D B_f\,)} \tag{12}$$

$$x1(t) = \frac{F_{in}}{K_d} \tag{13}$$

The fact that equation (13) was arrived at using final value theorem successfully verifies that the governing equations are derived in proper sense. Using the values of the parameters obtained from (1) to (4) and substituting into (10), the transfer function of the system is obtained as

$$\frac{x1(s)}{F_{in}(s)} = \frac{2.065e^{-022}}{2.174e^{-014}\,s^3 + 7.213e^{-029}s^2 + 1.144\,s + 8.807e^{-016}} \tag{14}$$

3.3. Refined Model

It can be recognized that different fluids can enter the pressurizing chamber of the sensor. In view of this, the parameters B_f, K_f and M_f associated with the fluid entry are eliminated in the refined model. The parameters B_a and B_d are introduced just to check that it can be possible to establish any comparison in the magnitudes between the various parameters of the model. The model shown in Fig. 4 is redrawn to satisfy the condition shown in refined model is shown in Fig. 5.

Again using the concept of free body diagrams and Newton's second law the following equations are established for the nodal equilibrium of forces at the two nodes.

$$M_d \ddot{x1} + K_d(x1 - x2) = B_f\,(\dot{x1} - \dot{x2}) \tag{15}$$

$$M_a \ddot{x1} + B_a\,\dot{x2} + K_a x2 = K_d(x1 - x2) + B_d\,(\dot{x1} - \dot{x2}) \tag{16}$$

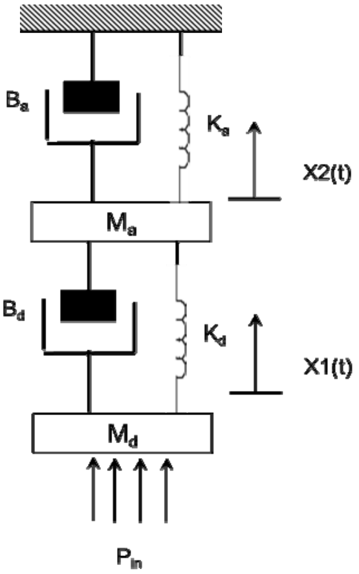

Fig. 5. Refined Model.

Taking Laplace transform and rearranging equations (15) and (16) in matrix form yields

$$\begin{bmatrix} M_d s^2 + B_d s + K_d & -(K_d + B_d s) \\ -(K_d + B_d s) & M_a s^2 + (B_a + B_d)s + (K_a + K_d) \end{bmatrix} \begin{bmatrix} X_1(s) \\ X_2(s) \end{bmatrix} = \begin{bmatrix} 0 \\ F_{in}(s) \end{bmatrix} \tag{17}$$

Solving by Cramer's rule gives,

$$\frac{X1(s)}{F_{in}(s)} = \frac{M_a\,s^2 + (B_a + B_d)s + (K_a + K_d)}{M_d M_a\,s^4 + (M_d B_d + M_d B_a + M_a B_d)s^3 + (M_d K_d + M_d K_a + B_d B_d + M_a K_d)s^2 + (K_a B_d + K_d B_a)s + K_a K_d} \tag{18}$$

For a step input of amplitude ‘F’, $F_{in}(s) = F/s$,

Using Final Value Theorem,

$$x1(t) = \lim_{s \to 0} s\,x1(s) \tag{19}$$

$$x1(t) = \frac{F\left(K_a + K_d\right)}{K_a K_d} = \frac{F}{K_a \text{ Series } K_d} \tag{20}$$

4. Lumped Model of a Differential Pressure Sensor

A 3 Degree of Freedom with respect to the high pressure fluid, low pressure fluid, and diaphragm is considered in this model. A simple back to back diaphragm type pressure sensor is considered in this work. The parameters with the values listed in Table 1 are used. The model is shown in the Fig. 6.

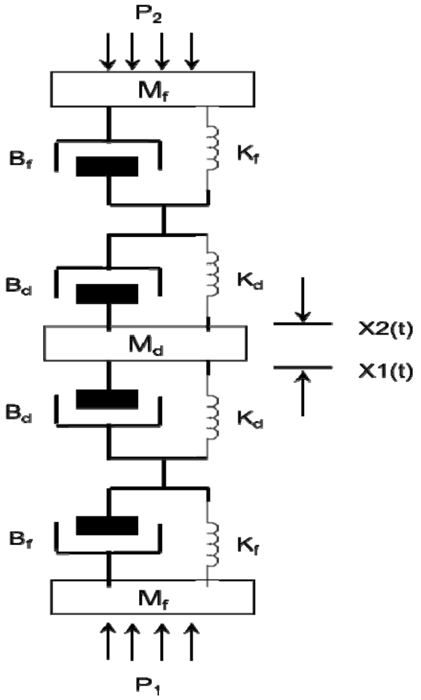

Fig. 6. Complete 3 DOF model of a differential pressure sensor.

4.1. Approximate Lumped Model

The assumptions listed in section 3.2 are considered in this case also. If the concept of free body diagrams and Newton’s second law is used then, we will get six set of equations and solving for transfer function will be very difficult. To avoid complications, the equivalent circuit using force-voltage analogy is drawn as shown in Fig. 7 and the governing equations are given below.

The governing equations for the above system are:

$$P_1 = \left(sM_f + B_f + sM_d + \frac{K_d}{s}\right) I_1 - \left(sM_d + \frac{K_d}{s}\right) I_2 \tag{21}$$

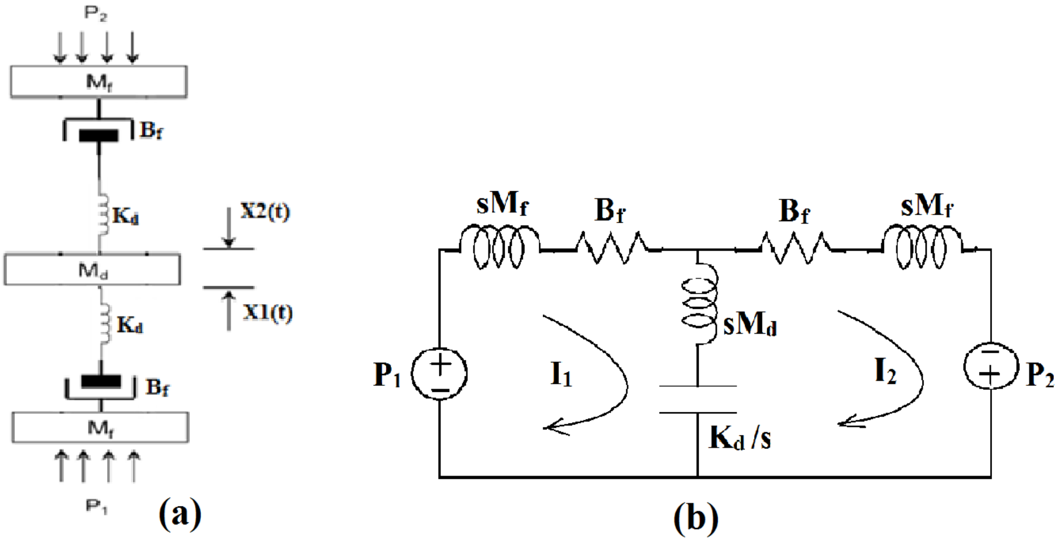

Fig. 7. (a) Approximate lumped model and (b) its equivalent circuit

$$P_2 = \left(sM_f + B_f + sM_d + \frac{K_d}{s}\right)I_2 - \left(sM_d + \frac{K_d}{s}\right)I_1 \tag{22}$$

Then,

$$\Delta P = P_1 - P_2 = \left(sM_f + B_f + 2sM_d + 2.\frac{K_d}{s}\right)(\Delta I)\ ;\ \Delta I = I_1 - I_2 \tag{23}$$

Now, $\Delta P = \Delta F$ and $\Delta I = s\Delta X$ (Force-Voltage Analogy), then the required transfer function can be obtained as:

$$\Delta F = \left\{sM_f + B_f + 2sM_d + 2.\frac{K_d}{s}\right\}.s\Delta X \tag{24}$$

or,

$$\frac{\Delta X}{\Delta F} = \frac{1}{\left\{sM_f+B_f+2sM_d+2.\frac{K_d}{s}\right\}.s} = \frac{1}{s^2\left(M_f+2M_d\right)+sB_f+2K_d} \tag{25}$$

Using Final Value Theorem,

$$\Delta x(t \to \infty) = \lim_{s\to 0} \frac{s.\Delta F(s)}{s^2(M_f+2M_d)+sB_f+2K_d}, \tag{26}$$

where, $F_{in}(t)=F.u(t)$. Taking Laplace Transform, $\Delta F(s)=\Delta F/s$, Then,

$$\Delta X = \frac{\Delta F}{2K_d} \tag{27}$$

4.2. Computation of B_f, K_d, M_d and M_f Values

1. Stiffness of the diaphragm (K_d)

$$k_d = \frac{Eh^3}{0.0140a^2} = 5.6153\times10^6\ \text{N/m}$$

2. Squeeze film damping introduced due to fluid-structure interaction at the fluid-diaphragm boundary *(B_f)*

$$B_f = \frac{96\eta a^4}{\pi^4 h_i^3} = 4.0894\times10^{-6}\ \text{Ns/m},$$

where, h_i is the height of the inlet chamber. Referring to Fig 2, h_i = 432um

3. The mass of the fluid is given by

$$M_f = 2.6485\times10^{-7}\ \text{kg}$$

4. The mass of the diaphragm is given by

$$M_d = 8.999\times10^{-8}\ \text{kg}$$

Using the values of the parameters obtained, the transfer function of the system is obtained as

$$\frac{\Delta X}{\Delta F} = \frac{1}{4.440e^{-07}s^2 + 4.009e^{-06}s + 1.123e^{07}} \tag{28}$$

5. Results and Discussion

5.1 Absolute Pressure Sensor

5.1.1. Frequency Analysis of First Approximate Model

The bode plot for the transfer function of the first approximate model absolute pressure sensor is given in equation (14) is shown in Fig. 8. It can be concluded that the resonant frequency of the system is $(7.25\times10^6)/(2\pi)$ = 1.138 MHz. This is in agreement with the theoretical results given by

$$f_r = \frac{\sqrt{\frac{K_d}{M_d}}}{2\pi} = \frac{\sqrt{\frac{4.26\times10^6}{8.1\times10^{-8}}}}{2\pi} = 1.153\ \text{MHz} \tag{29}$$

The fact that the amplitude at resonance being high and phase changing by an angle -180 degrees very rapidly indicate that the damping caused by the fluid B_f is negligible provided the inlet cavity of the height h_i is sufficiently high.

5.1.2. Root Locus Plot of First Approximate Model

Root locus analysis is done to assess the stability of the above system. Since the parameter of interest is the correct estimation of B_f, which characterizes the flow of different fluids at different velocities, the equation (10) can be rearranged as,

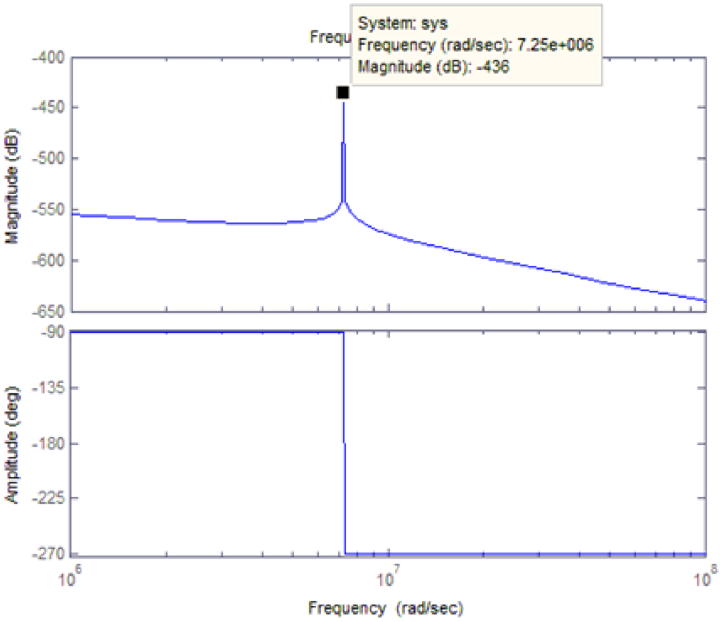

Fig. 8. Magnitude – Phase plot of equation.

$$\frac{x1(s)}{F_{in}(s)} = \frac{B_f}{1+\frac{B_f\left((M_d+M_f)s^2+K_d\right)}{M_f M_d s^3+M_f K_d s}} \tag{30}$$

which represents the closed loop transfer function of a non-unity negative feedback control system. The denominator of equation (30) is defined as the characteristic equation of the form $1 + G(s)H(s) = 0$.

$$1 + G(s)H(s) = M_f M_d s^3 + (M_d B_f + M_f B_f)s^2 + M_f K_d s + B_f K_d = 0 \tag{31}$$

Rearranging equation (31) and let $B_f = K$, gives

$$1 + K\frac{\left(M_d + M_f\right)s^2 + K_d}{M_f M_d s^3 + M_f K_d s} = 0 \tag{32}$$

$$G(s)H(s) = K\frac{\left(M_d + M_f\right)s^2 + K_d}{M_f M_d s^3 + M_f K_d s} \tag{33}$$

The rootlocus plot of the equation in (33) is shown in Fig. 9.

Referring to Fig. 9 the gain term K is nothing but B_f. It can be concluded that the system is stable since the entire root locus plot is on the left half of the s-plane. Also with respect to equation (10) the order of the system is 3. It is observed from the above plot that the value of B_f = *0.656* the only value resulting in minimum overshoot of the response. But this value of B_f is nowhere closer to the value predicted using squeeze film damping model. Also the value of B_f obtained from the root locus plot is extremely high compared to the typical values found in microsystems which are of the order of 10^{-6} Ns/m. The third order system can be further decomposed into one first order and one second order system. The evaluation of B_f requires the understanding of fluid structure interaction and Computational Fluid Dynamics and hence will be refined further.

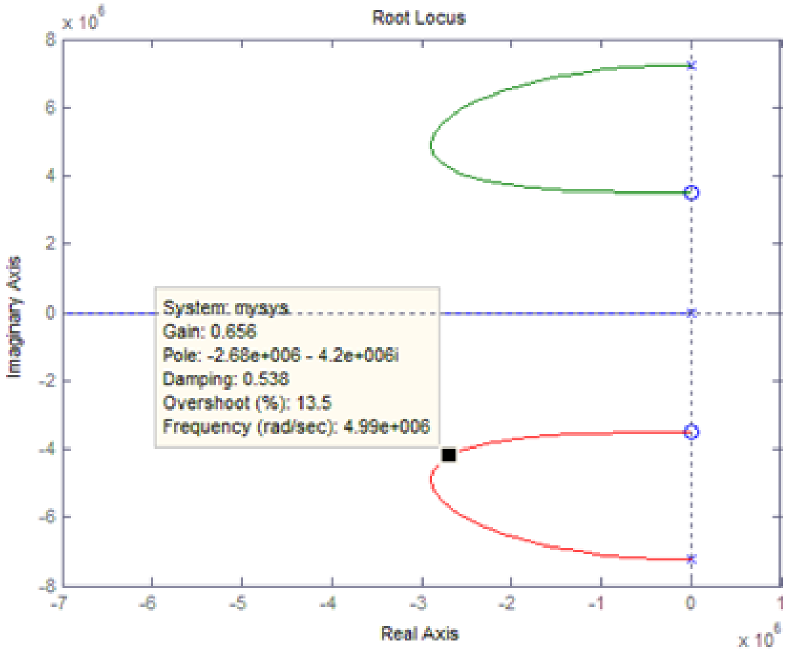

Fig. 9. Rootlocus plot for equation (33).

5.1.3. Frequency and Stability Analysis of Refined Model

Fig. 10 to Fig. 13 shows the step response of the sensor for P_{in} = 100 MPa and the frequency domain plot of the open loop transfer function derived in (18) as the refined model for different values of B_d. Four different values of B_d are considered to show different cases namely B_d=100B_a, B_d=10B_a, B_d=B_a and B_d=0.1B_a. By observing the phase changes in the frequency domain plot for different cases, we immediately conclude that as the value of B_d decreases, the slope of the phase curve increases rapidly at resonance which indicates a decrease in the damping ratio/damping factor of the system. This is accompanied by an increase in the overshoot of the step response as can be observed from the plots. It is also worthwhile to observe that the settling time increases as the damping factor reduces which is consistent with our understanding on basic Control Theory.

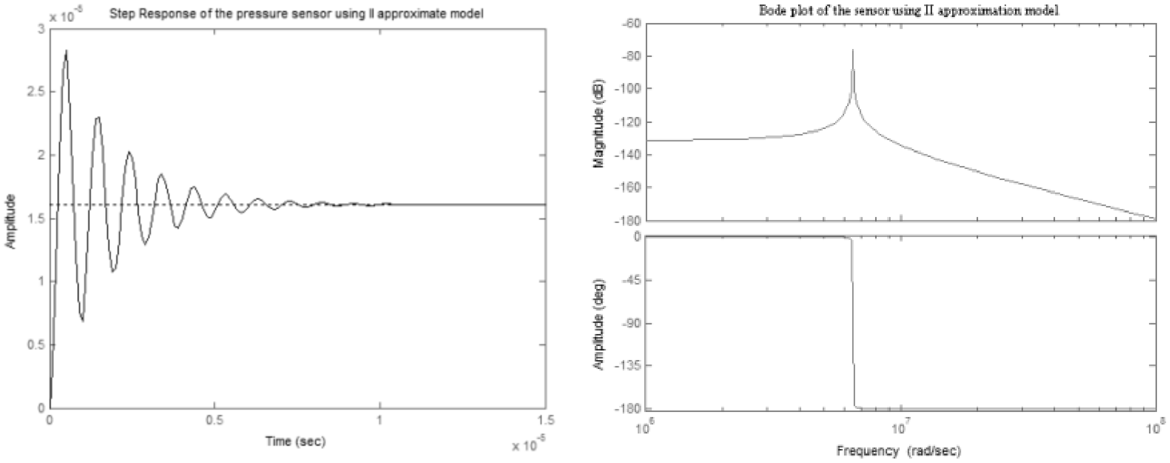

Fig. 10. Step and frequency response of the sensor B_d = 100 B_a.

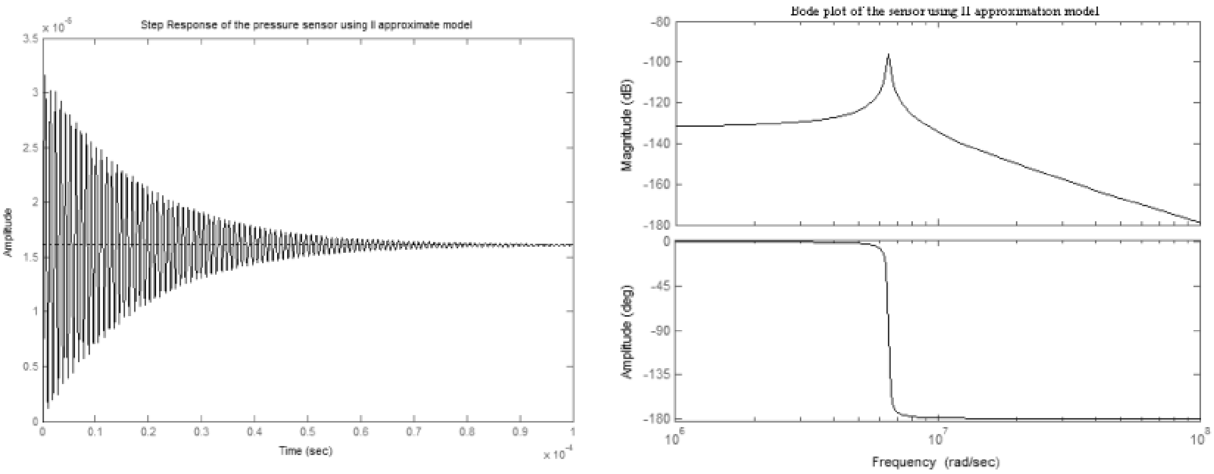

Fig. 11. Step and frequency response of the sensor $B_d = 10B_a$.

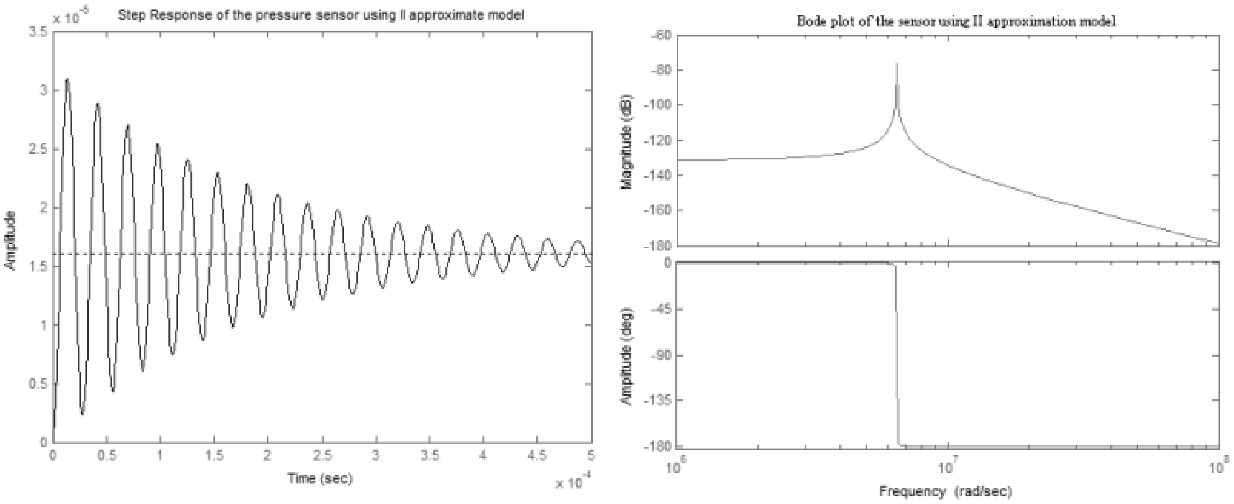

Fig. 12. Step and frequency response of the sensor $B_d = B_a$.

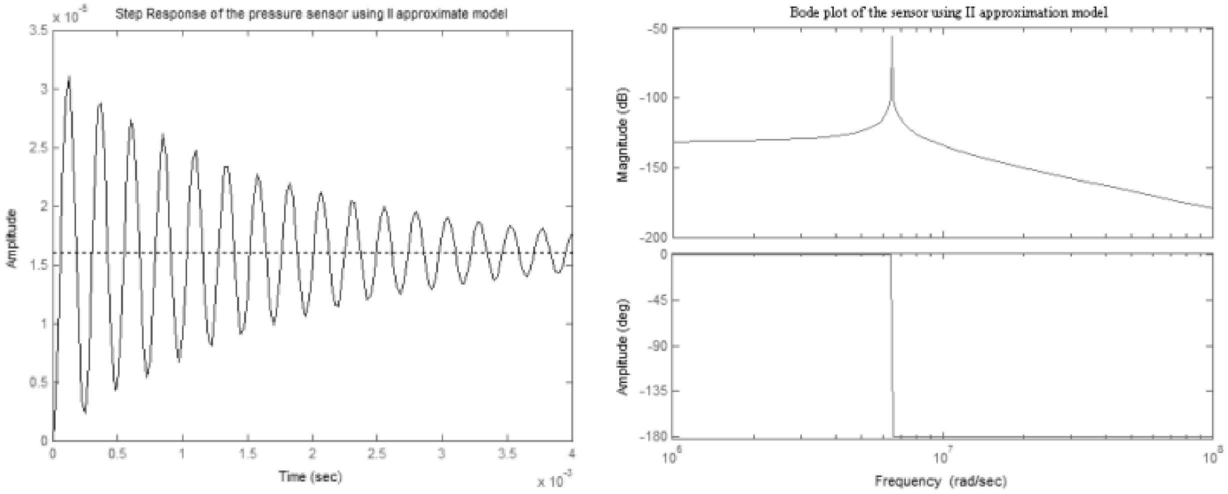

Fig. 13. Step and frequency response of the sensor $B_d = 0.1B_a$.

5.1.4. Effect of K_a on the Static Deflection of the Diaphragm

The magnitude of K_a relative to K_d can have a considerable effect on the static deflection of the diaphragm. From Eqn. (20) it is readily seen that for $K_a >> K_d$, the value of x_1 (t) depends only on the stiffness of the diaphragm and the force F_{in}. If the magnitude of K_a is comparable to K_d, there will be an appreciable change in the value of x_1 (t). The same is depicted by Fig. 14 for a fixed value of $B_d=100B_a$ and two cases namely $K_a=100K_d$ and $K_a=K_d$. The former yields a value of the static deflection much closer to the true value (~16 μm) while the latter results in a much higher value of about (32 μm).

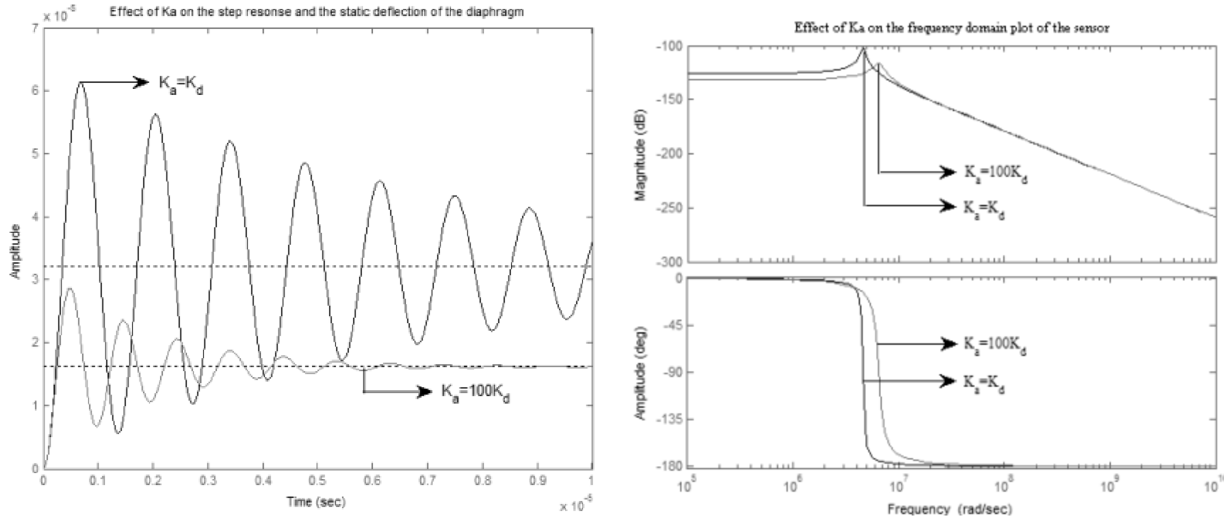

Fig. 14. Effect of K_a on the step and frequency response (B_d =100B_a).

Fig. 14 (b) shows the effect of the magnitude of K_a relative to K_d on the frequency domain plot of the sensor. When K_a =100K_d the magnitude plot indicates that the damping factor is lower than that for $K_a=K_d$. This implies a much lesser settling time for $K_a=100K_d$ which is evident from the step response of Fig. 14. It is also to be noted that when $K_a=K_d$ (or Ka has a magnitude comparable to K_d), the effective value of the stiffness K series is higher than that for $K_a=100K_d$ and hence a shift in the resonant frequency is observed in the increasing/positive direction.

5.2. Differential Pressure Sensor

5.2.1. Frequency Response Analysis

From Fig. 15, it can be concluded that the actual resonant frequency of the system is 0.80 MHz, which is almost closer to the theoretical result given by:

$$f_r = \frac{\sqrt{\dfrac{K_d/2}{M_d}}}{2\pi} = \frac{\sqrt{\dfrac{4.26\times10^6}{2\times8.105\times10^{-8}}}}{2\pi} = 0.816 \text{ MHz} \tag{34}$$

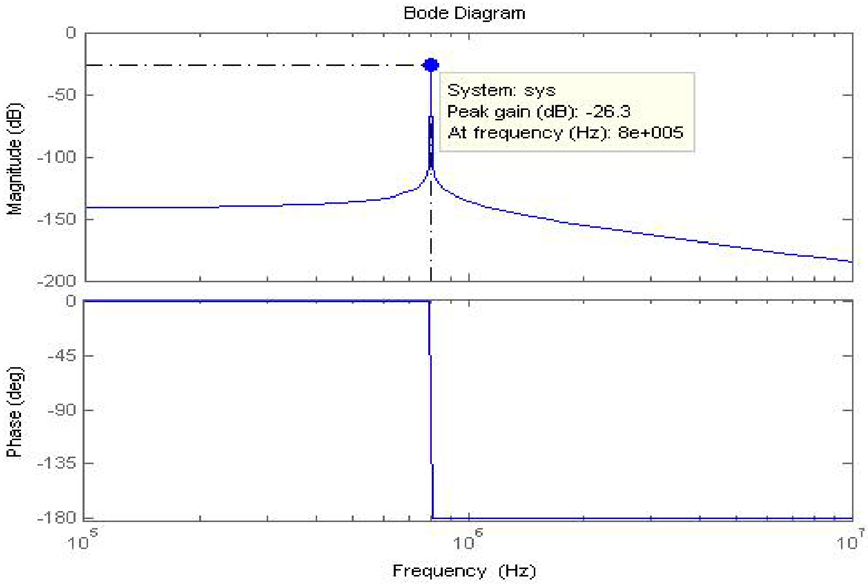

Fig. 15. Magnitude – Phase plot of equation (28).

5.2.2. Root Locus Plot

B_f can be set as the parameter K in the equation for plotting the root-locus diagram, which represents the closed loop transfer function of a non-unity negative feedback control system as shown in Fig. 16. The denominator of equation (25) is defined as the characteristic equation of the form

$$1 + G(s)H(s) = s^2(M_f + 2M_d) + sB_f + 2K_d = 0 \tag{35}$$

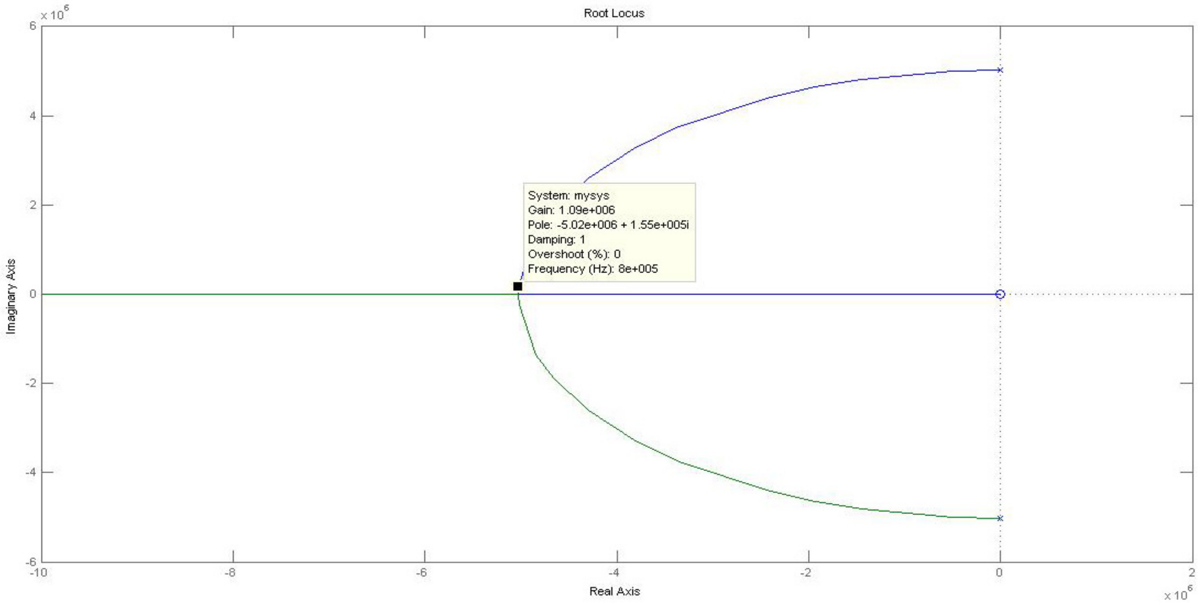

Fig. 16. Rootlocus plot for equation 4.10.

Since the entire root locus plot is on the left half of the s-plane, and it is a stable system. Also with respect to equation (25) the order of the system is 2. It is observed from the above plot that the value of

$B_f = 1.09\times10^6$ the only value resulting in minimum overshoot of the response. But this value of B_f is nowhere closer to the value predicted using squeeze film damping model. Also the value of B_f obtained from the root locus plot is extremely high compared to the typical values found in microsystems which are of the order of 10^{-6} Ns/m. The evaluation of B_f requires the understanding of fluid structure interaction and Computational Fluid Dynamics and hence will be refined further.

The step response of the equation given (28) is given below. It is evident from the step response that, for differential pressure, the diaphragm will oscillate back and forth and then settles. The oscillation is in the order of 10^{-7}, which again agrees the deflection properties of micro structures.

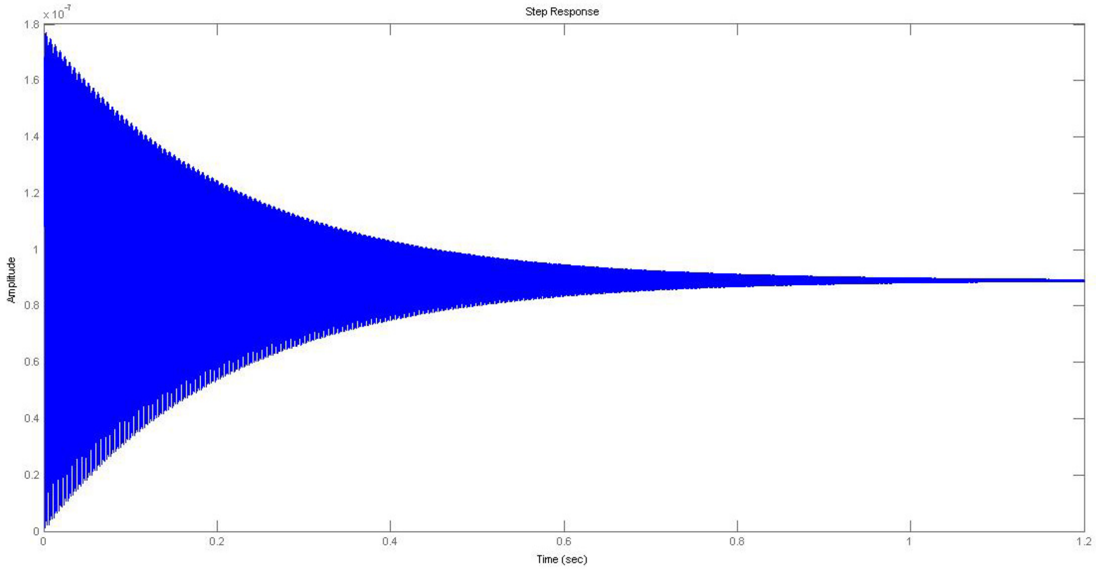

Fig. 17. Step response of the transfer function given in eqn. (28).

6. Conclusion

Thus the lumped parameter model of absolute and differential micro pressure sensors are developed, whose diaphragm is designed to undergo very small deflections. A 3 Degree of Freedom with respect to the fluid, diaphragm and the air between diaphragm and casing is considered. A simple approximate model with proper assumptions are considered and analyzed first. The transfer function obtained from the model is analyzed for its frequency and stability. The analytical natural frequency is found matching with natural frequency obtained from the model with a small difference.

A more appropriate model with refined approximation is considered later. The effect of diaphragm stiffness is compared with stiffness of air in casing. Also various ratio of damping of the fluid with damping of diaphragm is considered and analyzed.

Later the first approximation is applied to the differential pressure sensor and the stability and frequency of the model is analyzed and found to be more appropriate.

The analytical value of B_f is not matching with the value predicted using squeeze film damping model. The evaluation of B_f requires the understanding of fluid structure interaction and Computational Fluid Dynamics and hence will be refined further.

The refined model of the differential pressure sensor and analysis about the mismatch of damping of fluid are left as future work.

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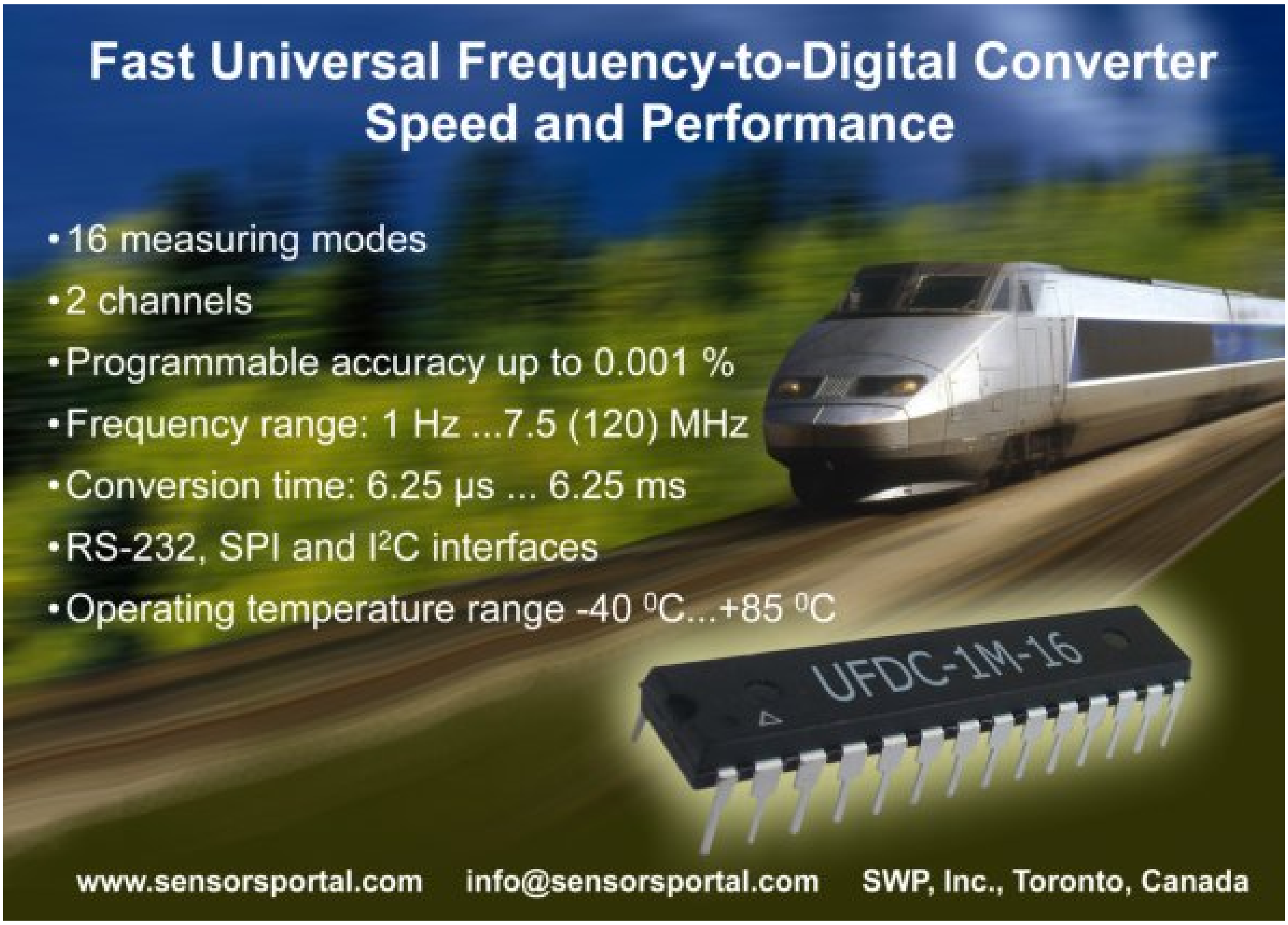

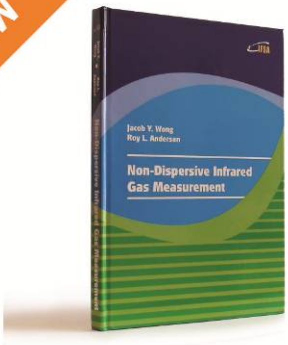
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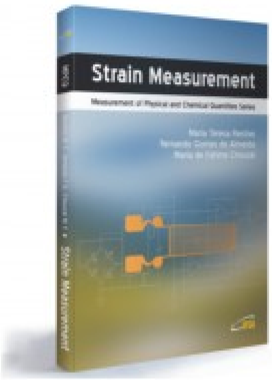
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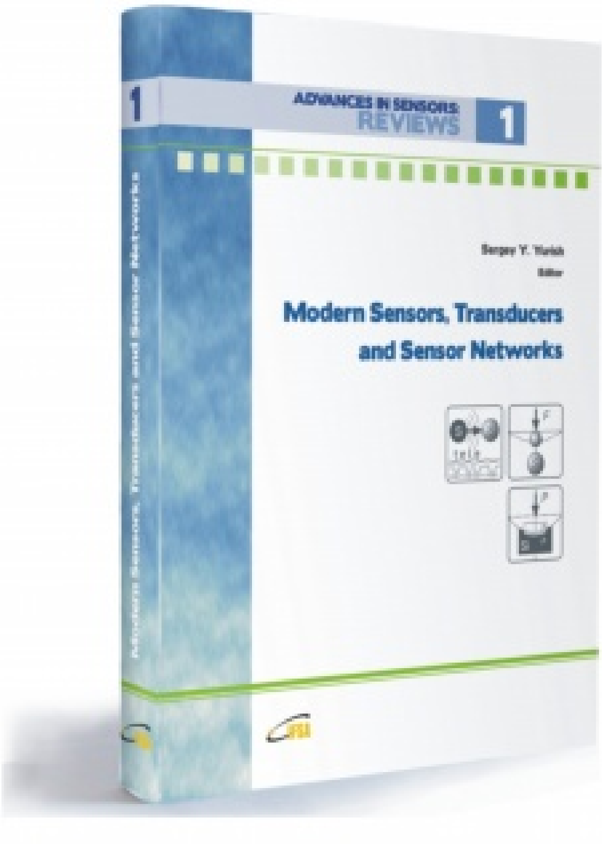

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