Received March 15, 2013, accepted April 30, 2013, published May 10, 2013.

Digital Object Identifier 10.1109/ACCESS.2013.2262012

Increasing the Sensitivity of Vibrating Wire Pressure Sensor

AKIN CELLATOGLU (Member, IEEE)[1] AND KARUPPANAN BALASUBRAMANIAN[2]
[1]Computer Engineering Department, European University of Lefke, Turkish Republic of Northern Cyprus, Lefke 010000, Turkey
[2]Faculty of Architecture and Engineering, Electrical and Electronics Engineering Department, European University of Lefke, Turkish Republic of Northern Cyprus, Lefke 010000, Turkey
Corresponding author: K.Balasubramanian (kbala@eul.edu.tr)

ABSTRACT The design of a sensitivity improved dual diaphragm based vibrating wire transducer for sensing pneumatic pressure is proposed. The improvement achieved in sensitivity of a dual diaphragm structure over the single diaphragm category is verified through experiments. An experimental setup for efficiently assessing the dynamic performances of the pressure transducers is presented. Eventually, the improved sensitivity concedes improvement in precision and resolution of the instrument. While the vibrating wire transducer based pressure sensors always show better dynamic performances over others, the present dual diaphragm structure offers improved sensitivity, which adds to their dynamic performances and overall performance characteristics.

INDEX TERMS Diaphragm structure, dynamic pressure sensor, sensitivity improvement, time constant measurement.

I. INTRODUCTION

Pressure sensors and acoustic transducers working on the elastic properties of metallic diaphragms were reported in the past [1]–[2]. Appropriate pickup devices were linked with the diaphragms and the signals were sensed and calibrated for the pressure acting on the diaphragms [3]–[8]. As a further extension of the work on this line the stress induced in the diaphragm due to application of pneumatic pressure was transformed into vibrations on a wire stretched to the vertex of a diaphragm and its frequency was measured to calibrate for the pressure acting on the diaphragm [9]–[11]. The vibrating wire transducer was claimed to offer improved dynamic performances over the conventional strain gauge types of elements clamped to the diaphragm. We now propose a dual diaphragm structure holding a tightly stretched wire at the vertices of the diaphragms as to increase the sensitivity of the pressure transducer. The enhancement in sensitivity improves further the dynamic performance of the pressure transducer and is quite suited in applications measuring relatively low changes in the magnitude of applied pressure. Also, an experimental setup to assess efficiently and precisely the dynamic performances of the dual diaphragm vibrating wire transducers are presented. This test setup can be used for determining the dynamic performances of other pressure sensors as well. For measuring pneumatic pressure, diaphragm based cantilever excited pressure cell was proposed in the past [12]. Later, its performance was improved by considering dual diaphragm structure [13] which could measure differential pressure as well. Furthermore, dual diaphragms incorporating spherical corrugations in the diaphragm structure linked to appropriate pickup was also reported [14]. These dual diaphragm structures were showing improved performances over single diaphragm structures. Nevertheless, as these devices are not involving vibrating wires they have limited dynamic performances. Now we consider dual diaphragm structure with vibrating wire for improving its sensitivity and other performance characteristics.

II. DUAL DIAPHRAGM ACTUATED VIBRATING WIRE PRESSURE SENSOR

The single diaphragm based vibrating wire pressure sensor reported earlier [10]–[11] is presently extended to dual diaphragm structure.

A. CONSTRUCTIONAL FEATURES

Fig.1 shows the schematic of the pressure transducer having two symmetrically spaced metallic diaphragms with their vertices facing each other. The vibrating stainless wire is bonded at the vertices of the diaphragms. The diaphragms

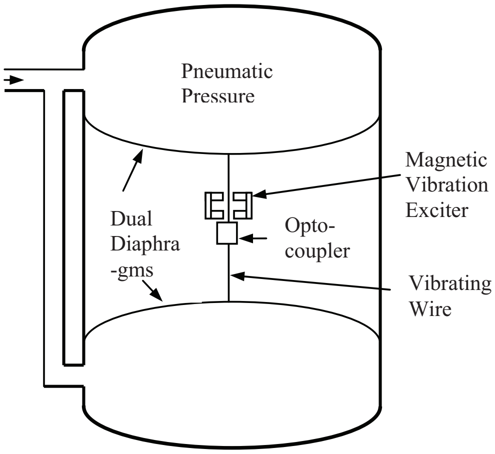

FIGURE 1. **Simplified Schematic of Dual Diaphragm Implanted Vibrating Wire Pressure Transducer.**

are brazed rigidly inside a metallic hollow cylinder at an estimated spacing between them.

The wire is set into vibration by mechanical force exerted onto it magnetically. As the wire vibrates, the frequency of the vibration is measured by an opto-coupler fixed around the wire. The light projected from an LED of opto-coupler falling on its photocell is interrupted by the vibrating wire. The waveform of the sensed signal is processed and frequency is determined. Then the frequency is calibrated for the pressure acting on the diaphragms. In order to maximize the output the directions of the magnetic vibration exciter and the opto-coupler are kept mutually orthogonal to each other.

B. RELATIONSHIP BETWEEN FREQUENCY AND PRESSURE

The frequency of the vibrating wire stretched between the diaphragms depends on the pressure acting on the diaphragms. As the pressure induces stress on the wire it influences the nature of vibrations and its frequency. The relationship between the frequency and applied pressure is established as follows.

A tightly stretched string of length L (Fig.2) at the extreme ends is subject to set into vibration by small force acting on it. The forces experienced on the string in orthogonal directions are given below.

$$Fy = T.Sin\,(\theta + \Delta\theta) - T.Sin\,\theta \tag{1}$$

$$Fx = T.Cos\,(\theta + \Delta\theta) - T.Cos\,\theta \tag{2}$$

where T is the tension involved.

As the transverse displacement y is small and $\theta\&\ \theta + \Delta\theta$ are also small in magnitudes the above expressions become

$$Fy = T.\Delta\theta \tag{3}$$

$$Fx = 0 \tag{4}$$

As reported before [9], the partial differential equations concerning the transverse motions in terms of space and time as

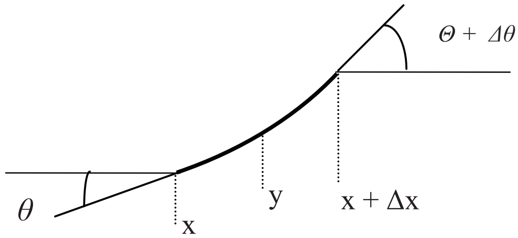

FIGURE 2. **A Portion of the Vibrating String.**

follows.

$$\frac{\partial^2 y}{\partial x^2} = \frac{\xi}{T}\frac{\partial^2 y}{\partial t^2} \tag{5}$$

where

$$\xi = \frac{m}{L} \tag{6}$$

in which m is mass of the wire in Kg and L is length in meters.

The solution of the partial differential equation (5) is

$$y\,(x, t) = r(x).Cos\,(\omega t) \tag{7}$$

The second derivative in terms of time and spatial distance are

$$\frac{\partial^2 y(x,t)}{\partial t^2} = -\omega^2 r(x) Cos\,(\omega t) \tag{8}$$

$$\frac{\partial^2 y(x,t)}{\partial x^2} = \frac{\partial^2 r(x)}{\partial x^2} Cos\ (\omega t) \tag{9}$$

Using (8) and (9) in (5) we get

$$\frac{\partial^2 r(x)}{\partial t^2} = -\frac{\omega^2 \xi}{T} r(x) \tag{10}$$

The solution of the above equation is

$$r(x) = K.Sin\left[\omega.x\sqrt{\left(\frac{\xi}{T}\right)}\right] \tag{11}$$

Applying boundary conditions at $x = 0$ *and* $x = L$ we get

$$\omega.L\sqrt{\frac{\xi}{T}} = n\pi \tag{12}$$

As $\omega = 2\pi f$, we get

$$f = \frac{n}{2.L}\sqrt{\frac{T}{\xi}} \tag{13}$$

The fundamental frequency of oscillations would be

$$f_1 = \frac{1}{2.L}\sqrt{\frac{T}{\xi}} \tag{14}$$

With the use of two diaphragms experiencing vector added tensions *T1 and T2* the frequency f_1 becomes

$$f_1 = \frac{1}{2.L}\sqrt{\frac{(T1 + T2)}{\xi}}ax \tag{15}$$

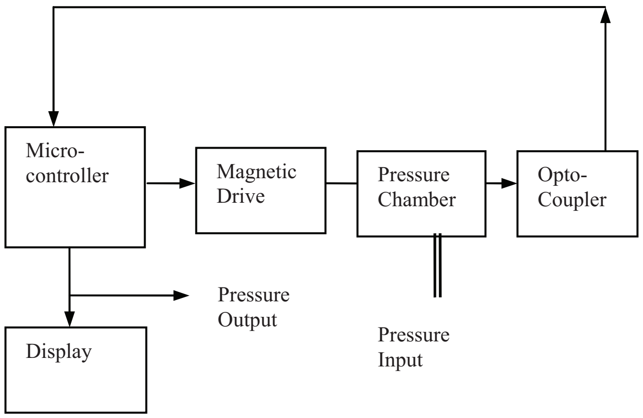

FIGURE 3. Block Schematic of the Pressure Transducer.

where *ax* is the alignment factor concerning fixing the two diaphragms whose magnitude would be slightly less than unity.

If A is the area of the diaphragm then tension acting on the diaphragm is

$$T = p.A \tag{16}$$

where *p* is the pressure acting on the diaphragm.

With *T1 and T2* remaining the same, the *frequency* f_1 becomes

$$f_1 = \frac{1}{2.L}\sqrt{\frac{2.p.A.ax}{\xi}} \tag{17}$$

The frequency f_1 has a magnitude $\sqrt{2}$ times greater than the single diaphragm structure. This therefore increases the sensitivity accordingly.

C. BLOCK SCHEMATIC OF PRESSURE SENSOR

A simplified block diagram of the pressure transducer with the dual diaphragm vibrating wire structure is shown in Fig.3. The microcontroller has standard features such as I/O ports EPROM, RAM memory, keyboard and display interface. Through one of its output port a programmed magnetic exciting pulse train is sent to the pressure transducer. The vibrating wire is an alloy made of Tungsten, Silver and other few elements [9]. At selected portion falling in the midway of wire is coated with magnetic sensitive ferrous elements required for producing magnetic excitation. The electromagnetic core surrounds this part of the wire and attracts it on one side and opposite side successively and periodically due to the pulsating current excitation. This sets the wire into vibration and its frequency would depend on the pressure acting on the diaphragm.

The diaphragm used is a medium strength Al alloy of 5cm radius, 1mm thickness and 1cm of height for the spherical shell with Young's modulus 200GN/m^2 and Poisson ratio 0.3. The range of pressure input for this cell is worked out to be 20KPa to 100KPa. The opto-coupler fixed orthogonal to the direction of vibration picks up the electrical signal proportional to the interruptions given to the light beam and it

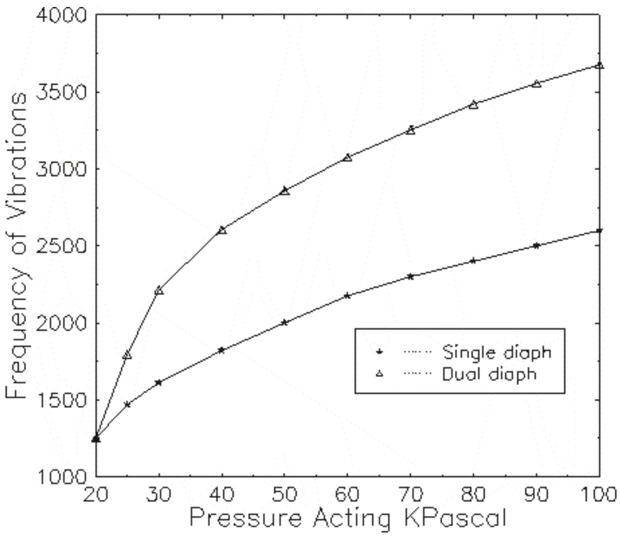

FIGURE 4. Frequency Sensed vs Pressure Applied.

is digitized and read by the microcontroller. From the stream of data of opto-coupler the frequency is evaluated both in time domain and in frequency domain.

Time domain determination of the frequency is based on the zero crossing instants of the opto-coupler signal. The frequency domain determination of f_1 of the vibrating wire depends on the application of FFT. The FFT also gets the harmonics of the vibrating wire, but we use only the fundamental component of the frequency. In both computation techniques, the frequencies are estimated on five trials basis and the medians are estimated first and these two medians are averaged finally to get the frequency of vibration.

A lookup table providing the relationship between the frequency and pressure is saved in EPROM memory. After determining the frequency the pressure acting on the diaphragm is obtained from the lookup table and it is sent external to the microcontroller both in digital form and in analog form. The relevant data is also displayed in LEDs as desired. The data of pressure thus obtained are also saved in FIFO (First In First Out) organized in RAM memory. Therefore, when the device is set into action, the frequency is continuously monitored and the pressure is delivered to output.

The relationship between the frequency measured from the wire and pressure acting on the diaphragm is shown in Fig.4 for single diaphragm structure and dual diaphragm structure holding vibrating wires. This shows nonlinear behavior of the frequency of vibrations against the pressure.

III. CONDUCTING EXPERIMENTS

Fig.5 shows a simple block diagram for conducting practical experiments for the pressure sensor. With the block schematic of the pressure sensor shown in Fig.3, only an I-to-P converter is included in the setup as shown in Fig.5. With this inclusion the microcontroller facilitates performing wide ranges of experiments by driving the appropriate electrical signal

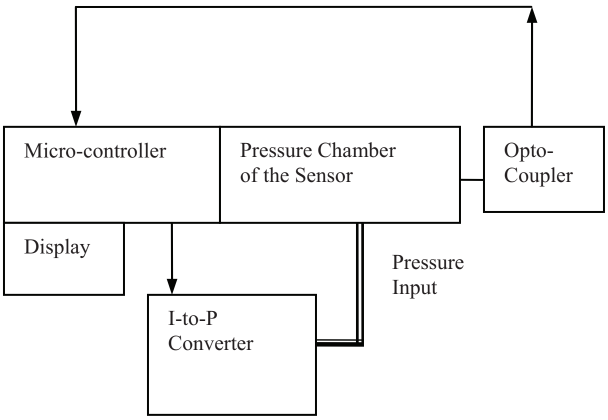

FIGURE 5. **Simplified Block Schematic of the Experimental Setup.**

waveform to I-to-P converter. The analogue output delivered from the microcontroller to the I-to-P converter produces an equivalent pressure applied to the pressure cell. As before, the vibrations of the wire are picked up from the opto-coupler and the signal are processed in the microcontroller for determining the measured pressure. The nonlinearities present in the characteristics shown in Fig.4 are linearized appropriately by programming the EPROM bearing the lookup table of frequency and pressure.

It is to be noted that the I-to-P converter is an important device connecting microcontroller to the pressure chamber of the pressure cell. It works on force balance principle with a coil suspended in a magnetic field on a flexible mount [15]. A flapper valve connected at the lower end of the coil operates against a precision ground nozzle to create a backpressure on the servo diaphragm of a booster relay. The input current flows in the coil and produces a force between the coil and the flapper valve, which controls the servo pressure and the output pressure.

A. STATIC TEST

The static test is performed with constant pressure applied relatively for longer time and the responses are tested. Static test is mainly meant for assessing the accuracy and precision of the pressure sensor in its operating range. The difference between the applied pressure and the response of the cell should be negligibly small as to have high accuracy. Static tests for single diaphragm vibrating wire pressure sensor, dual diaphragm vibrating wire sensor and single diaphragm strain gauge wire pressure sensor are performed and the responses are plotted in Fig.6.

The dual diaphragm vibrating wire transducer is sensing precisely the low pressure applied since the frequency of vibrations generated in dual diaphragm case are always greater than the single diaphragm case of vibrating wire transducer. For higher pressures applied the measurements shown by all three transducers are almost similar but always precision results closer to the applied pressure is shown invariably by dual diaphragm vibrating wire transducer. Table I shows

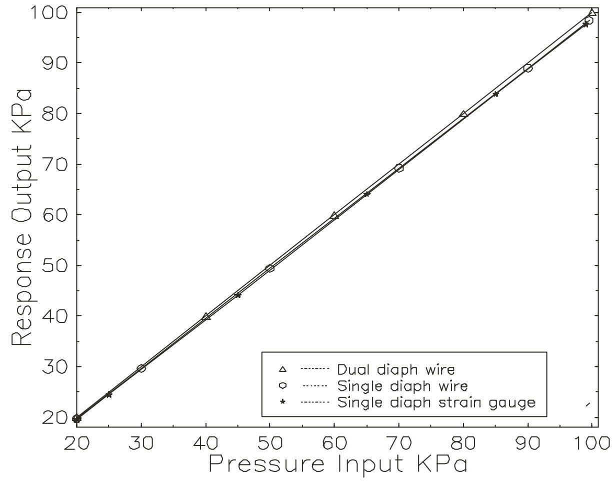

FIGURE 6. **Response to Static Test.**

the data taken from EPROMs of the three sensors for selected applied pressures in the set measurement range.

TABLE 1. **Lookup table data in eproms at selected pressures.**

Pressure Applied KPa	Pressure Sensed Single Diaph Vibrating Wire KPa	Pressure Sensed Dual Diaph Vibrating Wire KPa	Pressure Sensed Single Diaph Strain Gauge KPa
20	19.990	19.998	19.851
40	39.991	39.999	39.855
60	59.992	59.999	59.856
80	79.992	79.999	79.857
100	99.992	99.999	99.857

B. MEASURING THE TIME CONSTANT

The time constant of a pressure cell might be required to be measured in several occasions. The geometry and the materials used for the diaphragm and the wire would decide the system order of the instrument and the time constant. It might fall into the category of a first order system or an over damped second order system.

For a first order instrument time constant is determined by applying unit step input and marking the time it takes for the response to reach 63.2% of the step size. This is ascertained by the following.

The transient response of the pressure cell for the step input is given by

$$eo\,(t) = \left(1 - e^{-t/\tau}\right) \tag{18}$$

where τ is the time constant.

At the instant when time t reachesτ, the response $eo(t)$ would be $(1 - 1/e)$ and this value is 0.632.

When the microcontroller sends the pressure input as a step a software counter organized in memory is initialized. As the response rises exponentially the microprocessor reads it successively to mark the instant of reaching 63.2% level. The software counter is incremented until this marking level

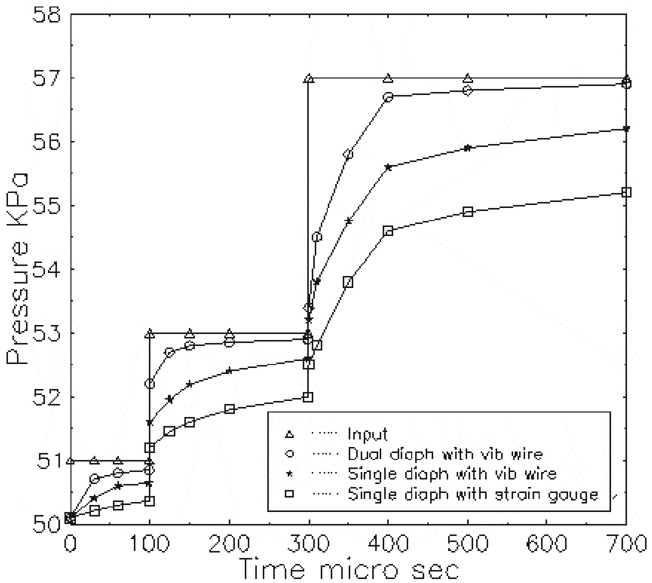

FIGURE 7. Dynamic Response of Pressure Cell.

is reached and then it is terminated. Therefore, the software counter data provides a measure of the time constant of the pressure sensor. A lookup table in EPROM is made available with the microcontroller for providing readily the time constant whenever the software counter data is driven to it. It is to be noted that the elastic properties of the material would decide mainly the value of the time constant.

The over damped second order model has the transient response to step input resembling the first order system. It is well known that the differential equation characterizing the second order system is given by

$$\ddot{y} + 2\zeta\omega_n\dot{y} + \omega_n^2 y = f(t) \tag{19}$$

where y: response in time, ζ: damping factor, ω_n: natural frequency of oscillations and $f(t)$: forcing function.

The step response of the over damped ($\zeta > 1$) second order system is given by [16]

$$y_s(t) = \frac{1}{\omega_n^2}\left[1 - \frac{\omega_n}{2\sqrt{\zeta^2 - 1}}\left(\tau 1.e^{-t/\tau 1} - \tau 2.e^{-t/\tau 2}\right)\right] \tag{20}$$

where $\tau 1$ and $\tau 2$ are the time constants. The largest of these two is known as dominating time constant and this can be determined as in first order system.

C. PERFORMING DYNAMIC TESTS

Dynamic response of a pressure cell depicts the characteristics of the pressure cells under dynamically varying pressure inputs. Standard test signals such as decayed sine wave input, triangular and square wave inputs are usually applied to pressure cell to see its response. Here, we give more sophisticated dynamic input of staircase waveform with varied step size and duration and the responses are obtained. The pressure sensors of single diaphragm vibrating wire, dual diaphragm vibrating wire and single diaphragm strain gauge are taken for the experimentation and the responses are plotted as in Fig.7. The step magnitude in pressure is progressively changed from 1KPa, 2KPa and 4KPa and the duration of the steps is kept successively as 100μs, 200μs and 400μs. The steps are issued from the starting level of 50KPa. As seen in the response, the dual diaphragm based vibrating wire offers better performance compared to others.

IV. CONCLUSION

The improved performance of the dual diaphragm based vibrating wire pressure cell in its sensitivity encourages us to replace the single diaphragm vibrating wire pressure transducers used in practice. The cost factors involved in dual diaphragm cell and single diaphragm cell are comparable as only a meagre increase in cost is encountered in dual diaphragm cell.

The deflection characteristics of the diaphragm depend on the elastic properties of the material used for wire and for diaphragms and on the physical dimensions of the materials employed. Therefore, the material for the diaphragm are so chosen as to have the elastic properties that offer only the first order deflection on the surface of the diaphragm. For measurement of extremely high pressures, the thickness need be relatively larger as to withstand the pressure and offer reasonable durability. Depending upon the range of measurement of the pressure the materials for the diaphragm and wire should be chosen accordingly for the different application ranges. Under the circumstances of measuring dynamic variations in pressure the diaphragm would adjust itself to the varying loads causing no permanent deformation in the physical and mechanical geometry of the diaphragm.

REFERENCES

[1] D. Maier-Schneider, J. Maibach, and E. Obermeier, "A new analytical solution for the load-deflection of square membranes," *J. Microelectromech. Syst.*, vol. 4, no. 4, pp. 238–241, 1995.

[2] H. E. Elgamel, "Closed-form expressions for the relationships between stress, diaphragm deflection, and resistance change with pressure in silicon piezoresistive pressure sensors," *Sens. Actuators A, Phys.*, vol. 50, nos. 1–2, pp. 17–22, 1995.

[3] K. Balasubramanian and A. Cellatoglu, "An inductive pickup for pneumatic pressure transducer developed over thin metallic spherical diaphragm," in *Proc. Int. Conf. Math. Comput. Sci.*, 2008, pp. 19–26.

[4] K. Balasubramanian and A. Cellatoglu, "Precision pneumatic pressure measurement with diaphragm based mechatronic devices," *Int. J. Electron.*, vol. 97, no. 1, pp. 45–62, 2010.

[5] K. Balasubramanian and A. Cellatoglu, "Exploiting the inflation characteristics of thin metallic spherical diaphragm for designing pneumatic pressure transducer," in *Proc. Int. Conf. Digit. Factory*, 2008, pp. 1828–1834.

[6] H. Camur and K. Balasubramanian, "Fluid pressure measurement while filling a rectangular cavity by a pressure cell of opto-electronic arrangement embedded on a diaphragm," *Proc. SPIE*, vol. 4902, pp. 124–133, Nov. 2002, DOI:10.1117/12.467349.

[7] J. A. Voorthuyzen, A. J. Sprenkels, A. G. H. Van Der Donk, P. R. Scheeper, and P. Bergveld, "Optimization of capactive microphone and pressure sensor performance by capacitor-electrode shaping," *Sens. Actuators A, Phys.*, vol. 26, nos. 1–3, pp. 331–336, 1991.

[8] A. Cellatoglu and K. Balasubramanian, "LVDT pickup for improved sensitivity in diaphragm based high-pressure measuring mechatronic device," in *Proc. Int. Conf. Converg. Sci., Eng. Educ. Res., a Global Perspect. New Millennium*, Bangalore, India, Apr. 2010, pp. IT_1–IT_5.

[9] V. Liviu, C. Ioan, D. Mrcea, and P. Seftimiuu, ''Using an embedded microcontroller system to excite vibrating wire transducers,'' in *Proc. 27th IEEE Int. Spring Seminar Electron. Technol., Meeting Challenges Electron. Technol. Progr.*, May 2004, pp. 1–4.
[10] K. Balasubramanian, K. Guven, and Z. G. Altun, ''Microprocessor based new technique for measuring pneumatic pressure using opto-coupler controlled vibrating wire transducer,'' in *Proc. IEEE Instrum. Meas. Technol. Conf.*, May 1994, pp. 464–467.
[11] K. Balasubramanian, Z. G. Altun, K. Guven, and T. Yalç, ''A novel pneumatic pressure measuring device,'' *CU J. Faculty Engg. Arch*, vol. 7, no. 2, pp. 65–74, 1992.
[12] K. Balasubramanian, Z. G. Altun, and K. Guven, ''A cantilever operated vibrating thin strip for sensing pneumatic pressure,'' in *Proc. IEEE Instrum. Meas. Technol. Conf.*, Apr. 1995, pp. 139–143.
[13] A. Cellatoglu and B. Karuppanan, ''Vibrating cantilever transducer incorporated in dual diaphragms structure for sensing differential pneumatic pressure,'' *Int. J. Soft Comput.*, vol. 2, no. 4, pp. 95–109, Nov. 2011.
[14] A. Cellatoglu and K. Balasubramanian, ''Pneumatic pressure cell with twin diaphragms embedding spherical corrugations in a dual diaphragm structure,'' *Int. J. Comput. Sci. Issues*, vol. 1, no. 1, pp. 1–6, Nov. 2011.
[15] Omega Engineering Inc. (2013, Apr.). *Catalogue*, Stamford, CT, USA [Online]. Available: http://www.omega.com/Pressure/pdf/IP210.pdf
[16] (2013, Apr.). *Advanced System Dynamics and Control; Review of First and Second Order System Response* [Online]. Available: http://web.mit.edu/2.151/www/Handouts/FirstSecondOrder.pdf

AKIN CELLATOGLU (M'13) received the Bachelor's degree in electronics and communication engineering from Eastern Mediterranean University, Turkish Republic of Northern Cyprus, Lefke, Turkey, in 1996, and the M.Sc. and Ph.D. degrees from the University of Surrey, Surrey, U.K., in 1998 and 2003, respectively. He has been with the Computer Engineering Department of European University of Lefke, Turkish Republic of Northern Cyprus, Lefke, since September 2003. His fields of specialization are in video codec systems, multimedia, and communication networks.

KARUPPANAN BALASUBRAMANIAN received the Bachelor's degree in electronics and communication engineering from Madras University, Chennai, India, in 1971, and the Master's and Ph.D. degrees from the Indian Institute Technology, Madras, in 1976 and 1984, respectively. He was with Calicut University, Calicut, India, from 1972 to 1990 and from 1995 to 1998 in various positions, including as an Lecturer, an Assistant Professor, and a Professor. In 1988, he was a Post-Doctoral Researcher with Tennessee Technological University, Cookeville, TN, USA, under a Fulbright Indo-American Fellowship Program. He joined Cukurova University, Adana, by June 1990, as a Professor, until 1995. By 1996, he was granted the Best College Teacher's Award from the University of Calicut. Since 1998, he has been with the Faculty of Architecture and Engineering of European University of Lefke, Turkish Republic of Northern Cyprus, Lefke, Turkey. He is a Life Member of the Instrument Society of India and the Indian Society for Technical Education. His fields of specialization are in 3-D imaging and microprocessor based systems.