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Microcontroller based split mass resonant sensor for absolute and differential sensing

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Abstract. Two degrees of freedom resonant systems are employed to improve the resonant property of resonant sensor, as compared to a single degree of freedom resonant system. This paper presents design, development and testing of two degrees of freedom resonant sensor. To measure absolute mass, cantilever shaped two different masses (smaller/absorber mass and bigger/drive mass) with identical resonant frequency are mechanically linked to form 2 - Degree-of-Freedom (DOF) resonator which exhibits higher amplitude of displacement at the smaller mass. The same concept is extended for measuring differential quantity, by having two bigger mass and one smaller mass. The main features of this work are the 3 - DOF resonator for differential detection and the microcontroller based closed loop electronics for resonant sensor with piezoelectric sensing and excitation. The advantage of using microcontroller is that the method can be easily extended for any range of measurand.

Keywords: resonant sensor; 2 DOF resonator; piezoelectric and split mass.

1. Introduction

A resonant sensor is a device with an element vibrating at resonance, which changes its output frequency i.e., mechanical resonance frequency, as a function of the physical parameter. The frequency domain sensor output is digital in the sense that it is basically independent of analog levels and can be connected to digital circuitry. The conversion from the measurand to the resonance frequency of the vibrating element can be accomplished by means of a change in stress, mass, or shape of the resonator. Advantages of the resonant sensor are its high stability, high resolution and quasi digital output. The mechanical resonator structure has to be brought into vibration and the vibration has to be detected, excitation and detection techniques can be seen in Goran Stemme (1991). A variety of resonant sensors have been investigated and some of them have been commercialized. However, so far resonant sensors are rarely seen among commercial sensor products due to, possibly, the complexity of operational electronics and the design aspect considered for high quality factor (Hahimoto, *et al*. 1995).

The damping seriously degrades the intrinsic Q value of silicon resonator. As a result of this lowered Q value, silicon micro-resonators sometimes display inadequate resonant amplitude, thus, cannot adequately meet the requirements of applications. With a certain actuation force and Q value, a 2-DOF resonant system is proposed for much larger resonant amplitude by the use of a mechanical coupling amplification effect. In certain applications of a micro-machined resonator, the resonant bandwidth

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becomes more important. In normal one-degree-of-freedom resonating system, there is a tradeoff between the resonating amplitude and bandwidth (Xinlin, *et al*. 2000). However, with properly designed parameters of the 2-DOF resonator, a very broad bandwidth can also be achieved by overlapping the two split modes. 2-DOF resonator consists of a big mass-spring- damping unit and a small mass-spring-damping unit with identical resonant frequency and great disparity in mass, mechanically linked together. As the resonant energy in the system is distributed equally between the two units with strong mechanical coupling that results in much enlarged resonant amplitude of the small mass compared to the big mass, which facilitates higher sensitivity for sensing when it is used as resonant sensor (Xinlin, *et al*. 2003, Uma, *et al*. 2007). In this paper a two Degree-of-Freedom (DOF) and three Degree-of-Freedom (DOF) resonator structures are designed to measure the absolute and differential quantity using micro controller based closed loop electronics. The proposed measurement systems use the piezo electric excitation and detection. The authors believe that the measurement system proposed for absolute and differential quantity and the closed loop electronics is first of its kind.

2. Resonator structure design

2.1. Design for absolute quantity

The two Degree-of-Freedom (DOF) resonant sensor for absolute quantity measurement is realized by means of cantilever structure as shown in Fig. 1. In Fig. 1, section 1 represents the big mass unit (drive mass) and section 2 represents small mass unit (absorber mass) and section 3 represents the link between section 1 and section 2 which has negligible mass in comparison to drive and absorber mass unit. The section 2 is mechanically linked to section 1 which is fixed at the other end. The drive and absorber mass units are identical in length and thickness. The ratio between the width of the drive mass unit and the absorber mass unit gives the desired mass ratio for the 2 DOF resonators. As the length of the units is same, the two units will have identical resonance frequency. The properties and the

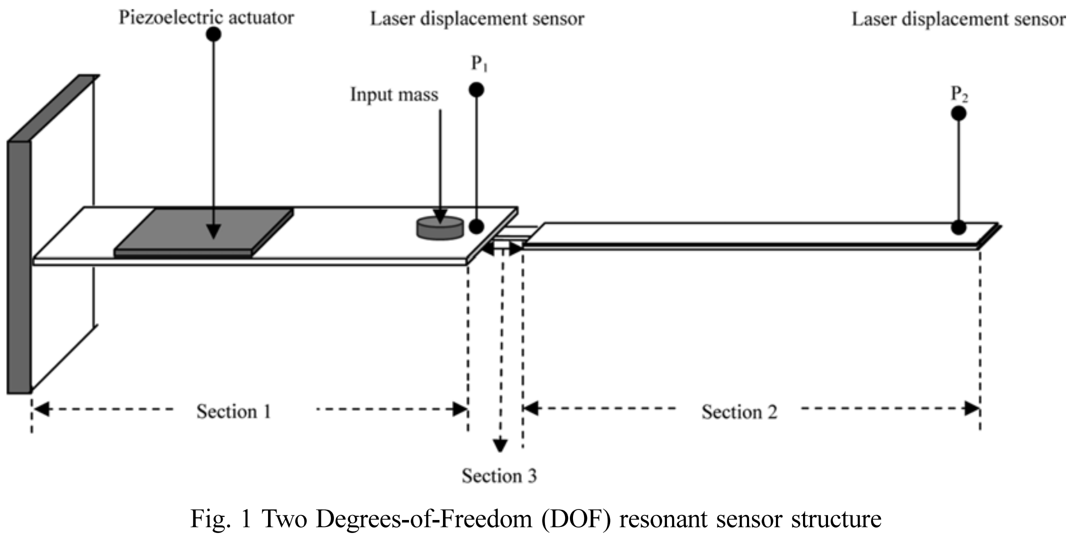

Fig. 1 Two Degrees-of-Freedom (DOF) resonant sensor structure

Table 1 Properties and dimensions of resonator structure

	Driver mass (M_1)	Absorber mass (M_2)	Coupling unit
Length (mm)	190	190	5
Width (mm)	15	5	2.5
Thickness (mm)	1	1	1
Young's modulus (Gpa)	71	71	71
Density kg/m^3	2700	2700	2700

Table 2 Properties and dimensions of piezoceramic sensor/actuator

		Actuator	Sensor
Length (mm)	l_p	76.5	25.0
Width (mm)	b	12.7	6.5
Thickness (mm)	t_a	0.5	0.5
Young's modulus (Gpa)	E_p	47.62	47.62
Density (kg/m^3)	ρ_p	7500	7500
Piezoelectric strain constant (m V^{-1})	d_{31}	-247×10^{-12}	-247×10^{-12}
Piezoelectric stress constant (V m N^{-1})	g_{31}	-9×10^{-3}	-9×10^{-3}

dimensions of the resonator structure and piezo ceramic patch are given in the Table 1 and 2.

The mass (M_1) of the driver mass unit (section 1) is 7.695×10^{-3} Kg, its first mode frequency is 22.94 Hz and its spring constant (K_1) is 160 N/m. The mass (M_2) of the absorber mass unit (section 2) is 2.565×10^{-3}Kg, its first mode frequency is 22.94 Hz and its spring constant (K_2) is 53.33 N/m. The mass (m) of coupling unit (section 3) is 0.03375×10^{-3}Kg and its spring constant is 3.55×10^5 N/m. The mass ratio ($\alpha = M_1/M_2$) is 3 and the split mode frequencies of the 2 DOF system are 13.7 Hz and 45.5 Hz. The frequency response of resonator was experimentally obtained by sweeping the drive signal frequency applied to the piezoceramic patch bonded on the top surface of the drive mass unit. The displacement of

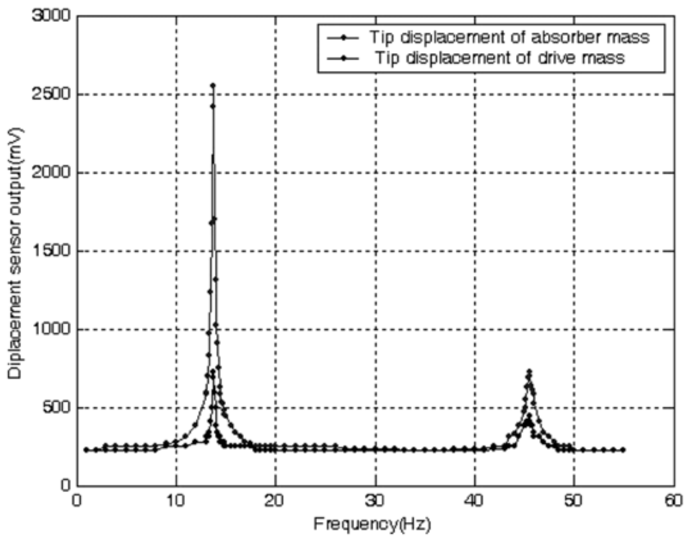

Fig. 2 Frequency response of 2- DOF resonant sensor structure

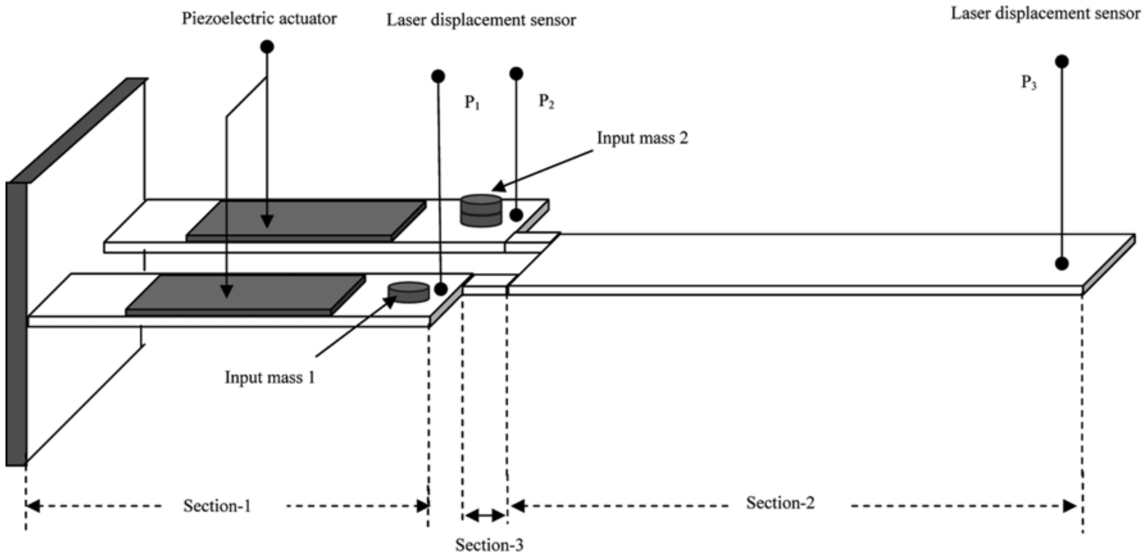

Fig. 3 Three degrees-of-freedom (DOF) resonant sensor structure

drive mass and absorber mass was measured using laser displacement sensor (Micro Epsilon - ILD 1400) at point P_1 and P_2 respectively. The amplitude of the drive signal is 10 Volts peak to peak and the frequency is varied from 1 Hz to 50 Hz. The frequency response of the resonator obtained experimentally is shown in Fig. 2. As the resonance magnitude is higher in the first split mode frequency, the same is used for the design of the resonant sensor.

2.2. Design for differential quantity

To measure the differential quantity three Degree-of-Freedom (DOF) resonant sensor is realized by having dual beam cantilever structure for drive mass as shown in Fig. 3. In Fig. 3, section 1 represents the drive mass units and section 2 represents absorber mass unit and section 3 represents the mechanical link between absorber and drive mass units. The drive mass section and absorber mass sections are identical in length and thickness, the ratio of the width between the drive and absorber mass sections presents the mass ratio of the 3 DOF resonators. As the length of the units is same, the three units will have identical resonance frequency. The properties and the dimensions of the resonator structure and piezo ceramic patch are given in the Tables 3 and 4.

The mass (M_1 & M_3) of the driver mass units (section 1) are equal and it is 44.8×10^{-3} Kg, its first

Table 3 Properties and dimensions of resonator structure for differential quantity

	Driver mass (M_1 & M_3)	Absorber mass (M_2)	Coupling unit
Length (mm)	190	190	5
Width (mm)	30	10	2.5
Thickness (mm)	1	1	1
Young's modulus (Gpa)	210	210	210
Density kg / m^3	7860	7860	7860

Table 4 Properties and dimensions of piezoceramic sensor/actuator for differential quantity

		Actuator	Sensor
Length (mm)	l_p	76.5	25.0
Width (mm)	b	25.0	6.5
Thickness (mm)	t_a	0.5	0.5
Young's modulus (Gpa)	E_p	47.62	47.62
Density (kg/m^3)	ρ_p	7500	7500
Piezoelectric strain constant (m V^{-1})	d_{31}	-247×10^{-12}	-247×10^{-12}
Piezoelectric stress constant (V m N^{-1})	g_{31}	-9×10^{-3}	-9×10^{-3}

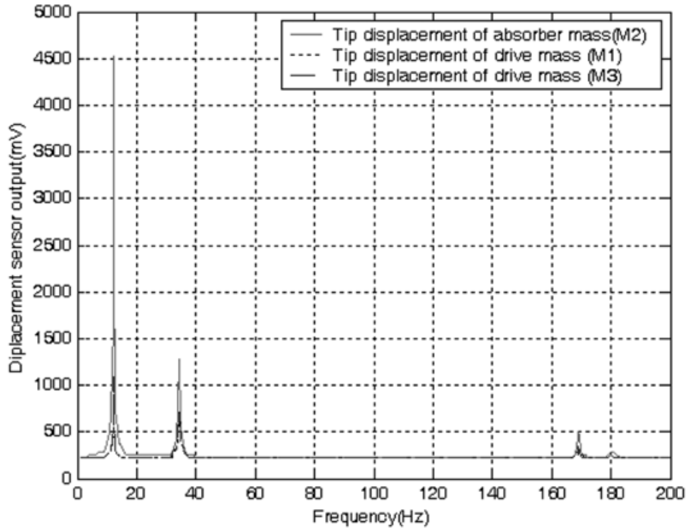

Fig. 4 Frequency response of 3- DOF resonant sensor structure

mode frequency is 22.94 Hz and its spring constant (K_1 & K_3) is 956 N/m. The mass (M_2) of the absorber mass unit (section 2) is 14.93×10^{-3}Kg, its first mode frequency is 22.94 Hz and its spring constant (K_2) is 318.5 N/m. The mass (m) of coupling unit (section 3) is 0.0982×10^{-3}Kg and the spring constant is 1.05×10^6 N/m. The mass ratio ($\alpha = M_1/M_2 = M_3/M_2$) is 3 and the split mode frequencies are 12.2 Hz, 34.3 Hz and 169.1 Hz. The frequency response of resonator was experimentally obtained by sweeping the drive signal frequency applied to the piezoceramic patches bonded on the top surface of the drive mass units (M_1 & M_3). The displacement of drive mass units and absorber mass units was measured using laser displacement sensor (Micro Epsilon - ILD 1400) at point P_1, P_2 and P_3 respectively. The amplitude of the drive signal applied is 10 Volts peak to peak and the frequency is varied from 1 Hz to 50 Hz. The frequency response of the resonator obtained experimentally is shown in Fig. 4.

3. Measurement system design

3.1. Principle

Two degree-of-freedom cantilever resonator designed in Section 2 is used to measure the absolute

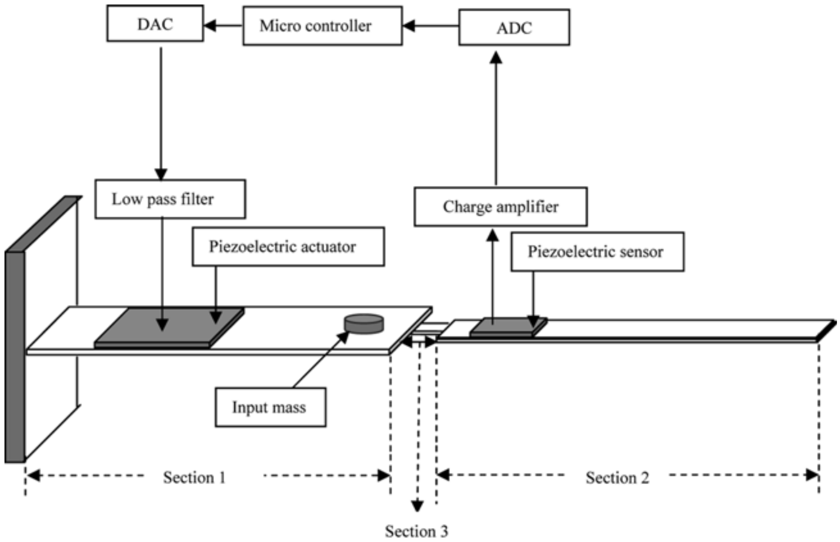

Fig. 5 Schematic diagram of measurement system for absolute quantity

quantity (mass), by bonding a piezoceramic patch as an actuator on the drive mass at a distance of 10 mm from the fixed end. For sensing a piezoceramic patch is surface bonded on the absorber mass at a distance of 160 mm from the free end. The mass to be measured is placed at the free end of the bigger mass (marked as input mass in Fig. 1) and the change in the resonance frequency is traced by microcontroller based closed loop electronics. The mass is measured by sensing the change in the resonance frequency, using microcontroller based closed loop electronics. The measurement system is shown in Fig. 5.

The microcontroller is programmed to excite the beam by sourcing an ac signal through a DAC to the piezo actuator, the frequency of which is swept from the maximum to minimum value. The output of the piezo sensing patch is conditioned using charge amplifier and acquired by the microcontroller through ADC. The magnitude of the acquired signal is compared with the magnitude of oscillation obtained at resonance frequency of the 2 DOF system. Whenever the magnitude of the acquired signal equals to the magnitude of the signal obtained at first split mode frequency, the microcontroller stops sweeping the excitation frequency and continues to excite the beam at that frequency. When the measurand i.e. mass changes the mismatch between the magnitude of acquired signal and the magnitude at resonance occurs, the microcontroller starts sweeping the frequency until they are equal. The shift in the resonance frequency is linear with the change in measurand.

Three degree of freedom resonator designed in Section 2 is used to measure the differential quantity (difference in mass) by bonding a piezoceramic patch as an actuator on each drive mass unit at a distance of 10 mm from the fixed end. For sensing a piezoceramic patch is surface bonded on the absorber mass at a distance of 160 mm from the free end. Two different masses are placed at the free end of the driver mass units and the difference in mass is measured by means of sensing the change in resonance frequency using microcontroller based closed loop electronic. The measurement system is shown in Fig. 6. The closed loop electronics function is similar to the one proposed for the absolute quantity.

3.2. Microcontroller based electronics

In the microcontroller a Look Up Table (LUT) consisting of 72 data was used to generate one cycle of

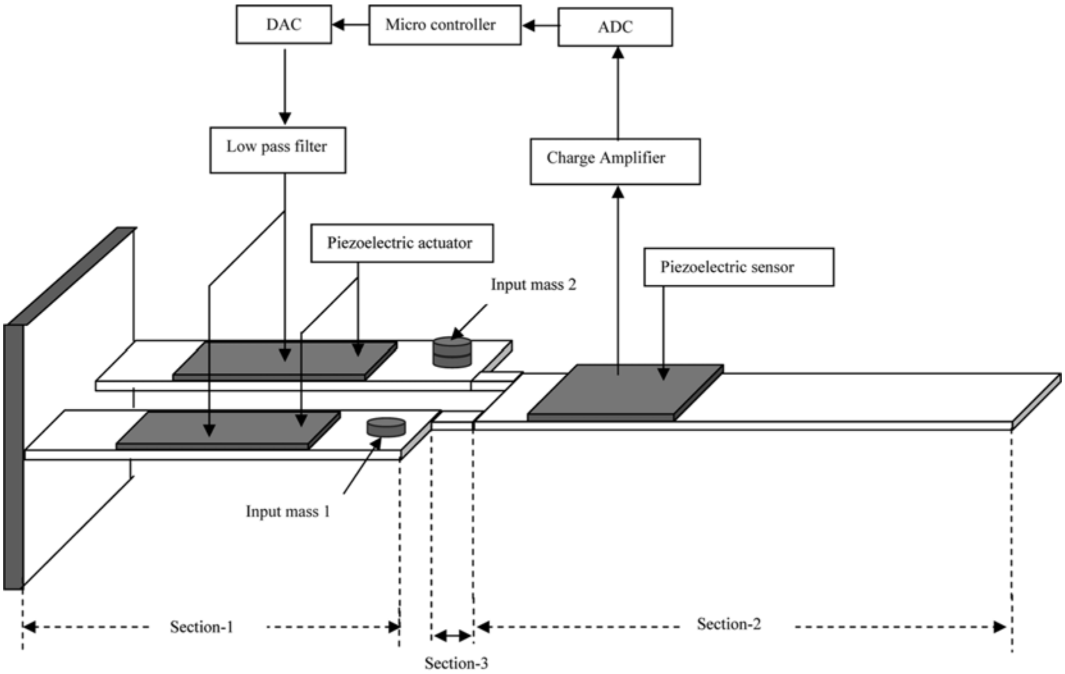

Fig. 6 Schematic diagram of measurement system for differential quantity

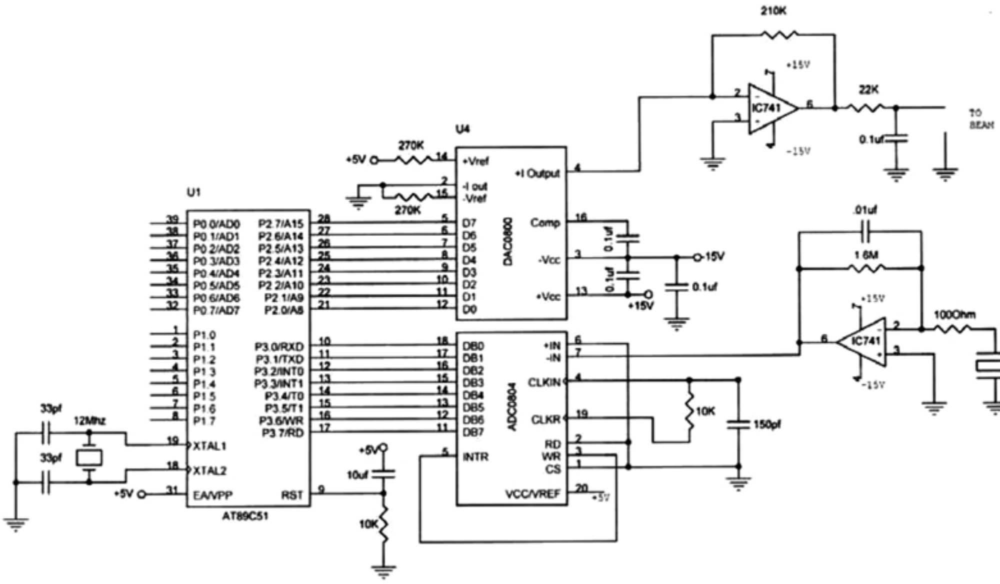

Fig. 7 Integrated hardware with microcontroller

sine wave with fixed amplitude, which is fed to the piezo actuator through a DAC 0800 and current to voltage converter. The current to voltage converter output is fed to a low pass filter. Five such cycles of fixed amplitude are generated and fed to the actuator which makes the beam to vibrate at a particular frequency. The beam vibration is sensed by a piezo sensor, with charge amplifier and is fed to the microcontroller through ADC 0804. The complete integrated hardware with microcontroller is shown in Fig. 7.

For each output from the DAC to the actuator the microcontroller reads the ADC output at its input port 3 and stores the value in register R0. The present value in port 3 is compared with the previous value and the larger value is stored in register R0. Thus, the peak value of the signal from the sensor is stored in a digital form in R0 for every five cycles of particular frequency. This peak value is compared with the magnitude of the signal at resonance. If the value in R0 is lesser than the peak value at resonance, the excitation frequency is varied, by varying the delay between successive fetches from LUT, until the magnitude of the acquired signal equals the magnitude at resonance. This procedure is repeated to identify the resonance whenever there is a change in the measurand (mass). Since the resonant frequency of 2DOF resonator is 13.7 Hz the microcontroller is programmed to source a maximum frequency of 20 Hz which is programmable. The sine wave is generated using 72 data; the delay between successive data is varied to vary the frequency of excitation. Simple calculation can reveal that the time delay between each fetches is sufficient to acquire a data through ADC; the conversion time of ADC is 125 μs. The magnitude at resonance was found as 001Fh using open loop operation and it is compared with the peak value stored in R0 to identify the resonance. The delay between successive fetches from LUT is varied to have a frequency variation of 0.3 Hz. The same procedure is repeated for the 3-DOF resonator proposed for differential quantity measurement.

4. Testing and results

4.1. For absolute mass measurement

The 2DOF resonate measurement system designed and developed is shown in Fig. 8. Tests were conducted in open loop configuration as shown in Fig. 9 and it was observed that the magnitude obtained at resonance frequency for the input range of 0-10 grams remains constant. Hence this magnitude is used as a reference in the closed loop measurement system. The input-output characteristic of the measurement system with closed loop electronics is shown in Fig. 10. The resonance frequency change with mass was found to be linear and the maximum inaccuracy in comparison with input output characteristics obtained with open loop configuration was 1.639%. The resolution was

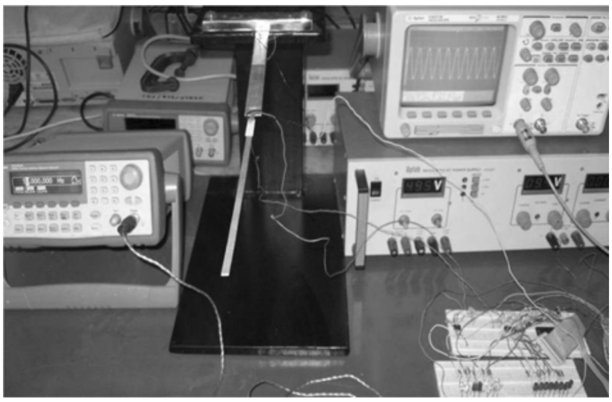

Fig. 8 Photograph of measurement system for absolute quantity

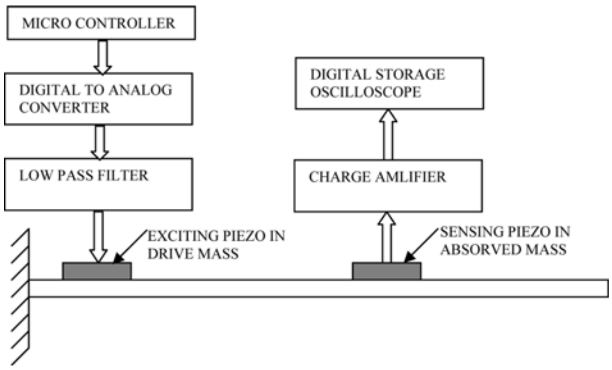

Fig. 9 Measurement system in open loop configuration

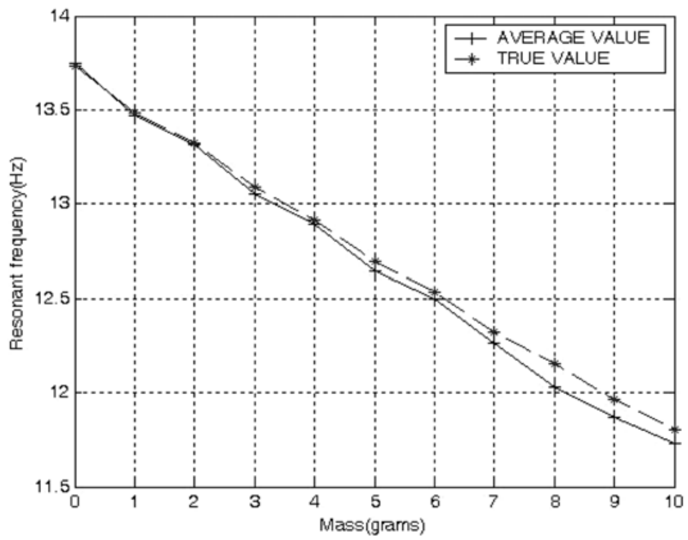

Fig. 10 Input-output characteristics showing accuracy of 2-DOF

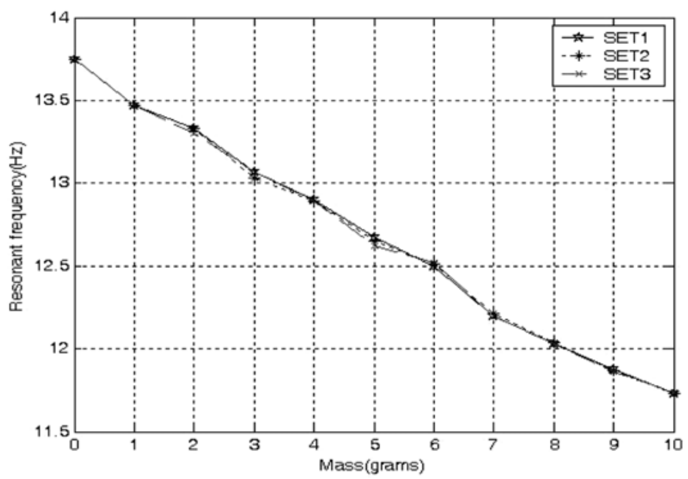

Fig. 11 Input-output characteristics showing repeatability of 2-DOF

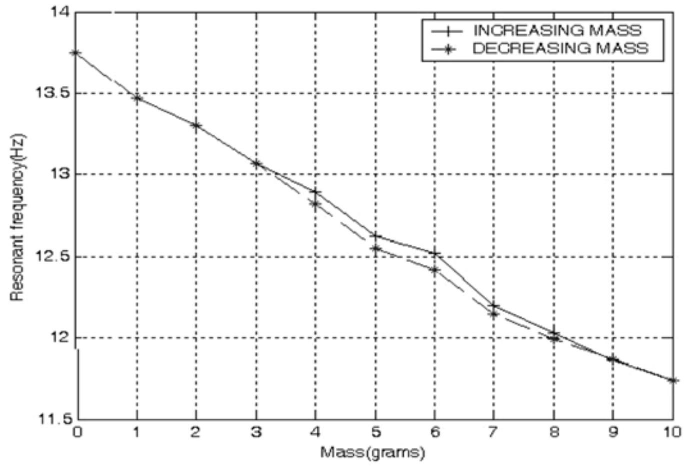

Fig. 12 Input-output characteristics showing hysteresis of 2-DOF

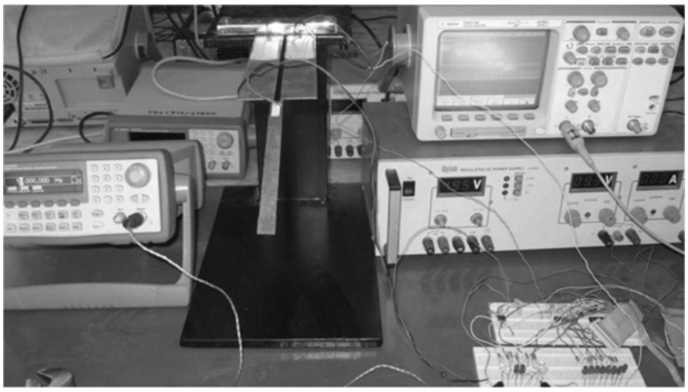

Fig. 13 Photograph of measurement system for differential quantity

found to be 0.5 grams with closed loop electronics. Test was also conducted to find the repeatability of the sensor and the graph in Fig. 11 shows that the results are highly repeatable. The sensor was subjected to loading and unloading to test the hysteresis effect and it was observed from the test result shown in Fig. 12 that it was minimal.

4.2. For differential mass measurement

The 3DOF resonate measurement system designed and developed is shown in Fig. 13. Tests were conducted in open loop configuration and it was observed that the magnitude obtained at resonance for the input range of 0-20 grams remains constant. Hence this magnitude is used as a reference in the closed loop measurement system. Similar to absolute measurement system test were conducted for accuracy, repeatability and hysteresis. The maximum inaccuracy was found to be 0.5434% and it was found that results are highly repeatable and hysteresis effect was minimal and results are shown in Figs. 14, 15 and 16 respectively.

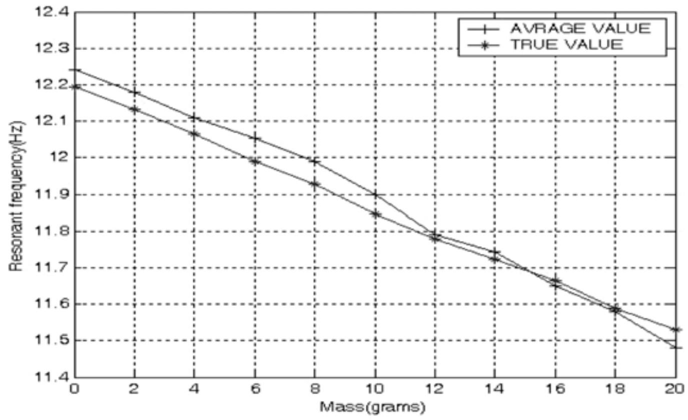

Fig. 14 Input-output characteristics showing accuracy of 3-DOF

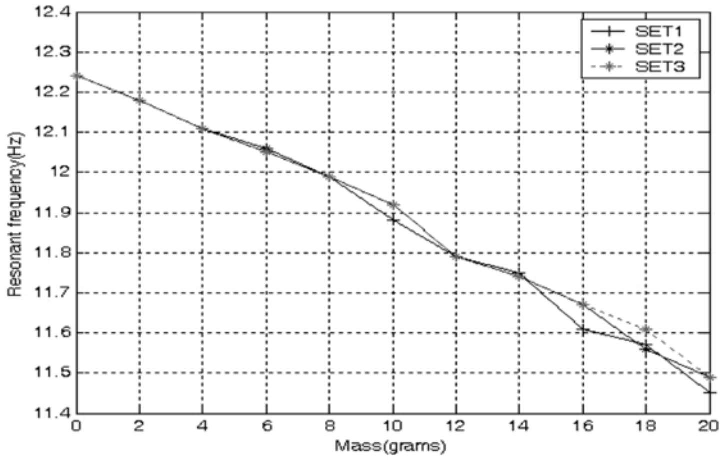

Fig. 15 Input-output characteristics showing repeatability of 3-DOF

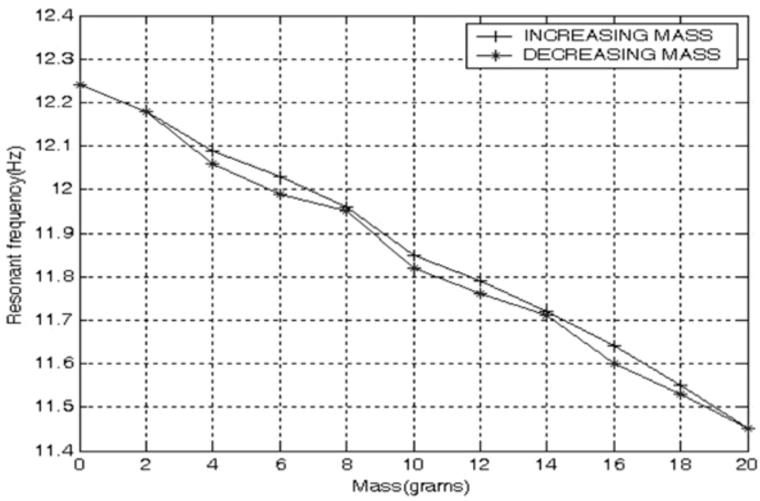

Fig. 16 Input-output characteristics showing hysteresis of 3-DOF

5. Conclusions

Using 2 DOF and 3 DOF cantilever beam resonators a measurement system with microcontroller in feedback is designed to measure the absolute and differential mass. Piezoceramic was used for driving and sensing. The 2 DOF and 3 DOF measurement systems were tested for the measurement of absolute and differential mass respectively and the input output characteristic was found to be linear. The sensor was tested for accuracy, repeatability and hysterisis. The results are so promising that the same can be implemented in micro domain for chemical sensing, where the mass of the sensitive film coating varies on absorption of the testing chemical. The proposed differential detection arrangement can be used to avoid any common sources of error. The proposed feedback electronics with microcontroller is simple and can easily be modified to measure different range of masses.

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