Readout Interfacing Circuit for Natural Frequency Detection of MEMS Resonator

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***Abstract*— This paper presents the readout interfacing circuit (ROIC) for natural frequency detection of MEMS resonator. It is reported that the MEMS Resonator vibrate at specific natural frequency under different condition. Therefore, the main aim of this research is to design the interfacing circuit to capture the current in order to analyze resonator frequency behavior. The work is focused on the development of ROIC prototype design with the MEMS resonator emulator included. The architecture of ROIC is mainly based on two blocks: transimpedance and instrumentation amplifier where this design is simulated using Multisim and implemented on PCB level. Simulation result of MEMS Resonator emulator model shows, it produces a current of 2.89nA at 22kHz natural frequency which is close to published works. Simulation result of ROIC with MEMS emulator model produces 10.7mVrms at 21kHz with 10 gain. The ROIC hardware implementation with practical values of RLC produces 0.624Vrms as compared in simulation process produces 1.46Vrms at the same 1.5kHz natural frequency even though the theoretically produces 1.6KHz natural frequency. As conclusion, it is shown that the ROIC is able to capture the natural frequency with 95.5% accuracy compared to the theoretical value.**

Keywords-component; Readout circuit, MEMS Resonator, Architecture, natural frequency

I. Introduction

Nowadays, the Micro-Electro-Mechanical System technology has changed the world especially manufacturing technology in small scale. MEMS actually are combination between mechanical structure, sensors and actuators with micrometer scale sizing[3]. They have quietly used in many application such as inertial sensor, mass sensor, charge sensor, microfluidics, oscillator and filter [1]. Micromechanical system (MEMS) silicon resonant or MEMS Resonator is one type of the MEMS application is quietly used in communication system and mass MEMS sensor because it has high performance device with small size and high potential for integration with CMOS electronic circuit as well as low cost batch fabrication [1][4][6][8]. Before the MEMS resonator is introduced in the electronic application, the Quartz crystal oscillator have been used as a resonator especially in timing device and communication application because it has ability to determine the long range frequency such as MHz as well as high quality factor[1][5][6]. Unfortunately, the quartz crystal oscillator is not compatible with the IC fabrication [1][8].

Recently, MEMS resonator is suitable for chemical sensing application due to the sensitivity and selectivity performance. A shift in air pressure or chemical concentration will cause change of the mass in MEMS Resonator. It will be affect to the natural frequency where this natural frequency will be shifted from the origin position. Under the capacitive technique, it is reported that MEMS resonator vibrates at the specific natural frequency when there is forces exists and produces a maximum current. Unfortunately, this frequency of current is difficult to capture directly with laboratory equipment since most of the equipment are measuring in a voltage signal. Therefore, an electronic device is required to capture this current signal and convert to voltage signal for assisting measurement in order to characterize the MEMS Resonator behavior.

There are several circuit architecture and measurement technique are to perform the characterization of MEMS resonator. The read-out interfacing circuit is one type of the circuit architecture and the measurement device that can be used to analyze the performance and characteristic of MEMS resonator. Therefore, the objective of this research is to design the readout interfacing circuit using the general operational amplifier to capture the current from MEMS resonator in order to analyze the resonator frequency behavior. The main function of this Read-Out circuit is to convert and amplify the output electrical signal of MEMS resonator. Since, the MEMS resonator produces smallest current. There are specification performance and requirement need to be considered will be discussed in this paper.

This project focuses on development of readout interfacing circuit prototype and MEMS Resonator emulator. The series RLC equivalent circuit is used to emulate the MEMS resonator behavior. The modeling MEMS resonator will be discussed further in this paper. Fig. 1 shows general overview connection between readout circuit and MEMS resonator.

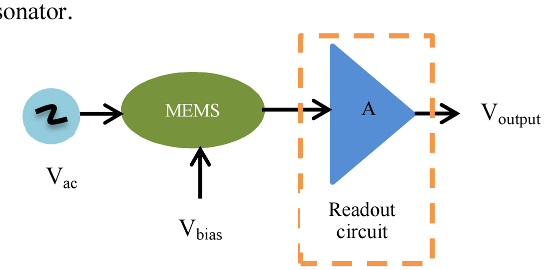

Fig. 1 general overview connection between readout circuit and MEMS resonator

The architecture this readout circuit consists of two blocks which is Transimpedacnce and Instrumentation Amplifier. The conversion between the current to voltage signal and amplification process for better measurement is main functions of doing this prototype circuit.

II. METHODOLOGY

A. Microresonator Emmulator

Normally, the MEMS resonator is use the concept of mass-spring-damper system as a model [3]. For better understanding behavior of MEMS resonator concept, this device is modeled by using simple equation of motion [1-4][6];

$$mx''+b x' + k(x)x = F e (x) \tag{1}$$

Where the x is displacement, Fe is the driving force, m, b, and k is refer to mass, damping and spring respectively. The driving force or known as electrostatic force can be derived as[6];

$$Fe(x) = \frac{dC}{dx} VdcVac\ sin(\omega t) \tag{2}$$

Where the $\frac{dC}{dx}$ is small displacement of the capacitance between the two fingers interdigitated of MEMS resonator while the excitation voltage refer to two types voltage such as Vdc and Vac components. Moreover, the DC bias also refers to Vdc Component. The electromechanical coupling coefficient can be defined as DC bias multiply by the small displacement of capacitance on the comb driver [1][4][6];

$$\eta = \frac{dC}{dx} Vdc \tag{3}$$

Substitute the equation (2) and (3) into equation (1);

$$m\, x'' + b\, x' + k(x)x = \eta Vac\ sin(\omega t) \tag{4}$$

By using the electromechanical coupling coefficient, the relation between the mechanical velocity and the electrical current can be defined as $ix = \eta x'$. Substitute this relation into the equation (4) and divided by electromechanical coupling coefficient, η. As a result;

$$\frac{m}{\eta^2}\frac{di_x}{dt} + \frac{b}{\eta^2} i_x + \frac{k}{\eta^2}\int i_x\, dt = Vac\ sin(\omega t) \tag{5}$$

The equation (5) can be rewrite as a harmonically excitation series RLC circuit;

$$L_x \frac{di_x}{dt} + R_x i_x + \frac{1}{C_x}\int i_x\, dt = Vac\ sin(\omega t) \tag{6}$$

Where the motional inductance, motional resistance and motional capacitance are defined as;

$$L_x = \frac{m}{\eta^2}, \quad R_x = \frac{b}{\eta^2} = \frac{\sqrt{k.m}}{\eta^2.Q}, \quad C_x = \frac{\eta^2}{k} \tag{7}$$

The series RLC equivalent circuit can be used in simulation with the readout interfacing circuit such as LTspice and Multisim. The electromechanical coupling coefficient η is directly dependent on the bias voltage, V_{dc}. Therefore, the value of motional resistance R_x, motional, Capacitance, C_x and motional inductance, L_x must be calculated based on value of V_{dc}[1]. At the same time, from the equation (7) it can be seen that, the second order of motional equation will cause the values of electrical parameter are more inconvenient. Therefore, to solve this problem is by reducing order behavioral modeling for better simulation.

$$L_x = \frac{m}{\eta}, \quad R_x = \frac{b}{\eta} = \frac{\sqrt{k.m}}{\eta\ .Q}, \quad C_x = \frac{\eta}{k} \tag{8}$$

Furthermore, the total output current from this circuit is defined;

$$I_0 = I_f + I_x \tag{9}$$

$$I_O = \frac{dQ}{dt} = \frac{d(CV)}{dt} = C_0\frac{dV_{AC}}{dt} + V_{dc}\frac{dC}{dt} \tag{10}$$

I_f is the current flow through a parasitic capacitive feedthrough C_0 in MEMS resonator. Ideally, this capacitance does not exist. Therefore, the total current is equal the motional current is given by;

$$I_O = I_X = V_{DC}\frac{dC}{dt} = V_{dc}\frac{dC}{dx}\frac{dx}{dt} \tag{11}$$

Substitute the equation (3) and into (11), thus the electromechanical coupling coefficient also can be defined as;

$$I_X = \eta\omega \quad Or \quad \frac{I_X}{\omega} = \eta \tag{12}$$

The motional current also can be defined using the R-L-C equivalent circuit;

$$I_X = \eta\sqrt{\frac{\eta^2}{C_X\ \eta^2\ L_X}} \tag{13}$$

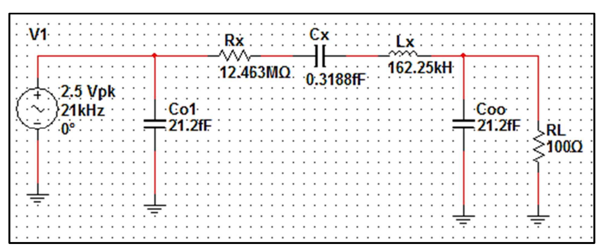

Fig. 2 Series RLC equivalent circuit to represent as MEMS Resonator

Fig. 2 shows the series RLC equivalent circuit to emulate the MEMS resonator. The values of motional inductance L_X, motional capacitance C_X, and motional resistance R_X were calculated based on values mechanical parameters[2] by using the modeling of MEMS resonator formula. 12.463MΩ, 0.3188fF and 162.25kH values were used to represent the values of MEMS resonator emulator. Both of the capacitance values which is C_{OI} and C_{OO} are represent the static capacitance between the input and the output of the MEMS resonator since MEMS resonator uses the capacitive technique to generate the electrostatic force. In previous reference shows that these value of static capacitances are approximately 21.2fF respectively with 2.09fF small displacement $\frac{dC}{dx}$ at $5V_{PP}$ input voltage.

B. Interfacing Circuit Design And Operation

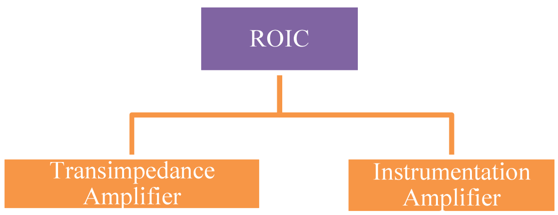

Fig. 3 Readout interfacing circuit architecture

Readout interfacing circuit design consists of two parts which is transimpedance amplifier and instrumentation amplifier. These amplifiers were developed by using the general operational amplifier. As mention early, the MEMS resonator is vibrate when the drive frequency is equal to the natural frequency and produce the maximum current signal. This current will be captured by the transimpedance amplifier to convert to the voltage signal by using ohm's law equation.

$$V_o = iR \tag{14}$$

Equation above shows the conversion of electrical signal between the current and voltage signal with the external feedback resistor of transimpedance amplifier.

The output voltage signal produced by transimpedance amplifer was fed to the input of instrumentation amplifier to amplify this voltage signal. The Instrumentation Amplifier (IA) is one of the operation amplifier applications where it has used to amplify the small differential input with strong common mode voltage [10] which means, it will cancelling out the same potential both input. It has an excellent performance to amplify the small signal because the highest input impedance compare to the basic amplifying circuit. The good Instrumentation Amplifier must have a good characteristic such as very high common rejection ratio with high bandwidth, very high input impedance, very low DC offset, very low noise, and very high open loop gain. The Instrumentation Amplifier is actually improvement of Subtractor Amplifier within two additional buffers at the inputs.

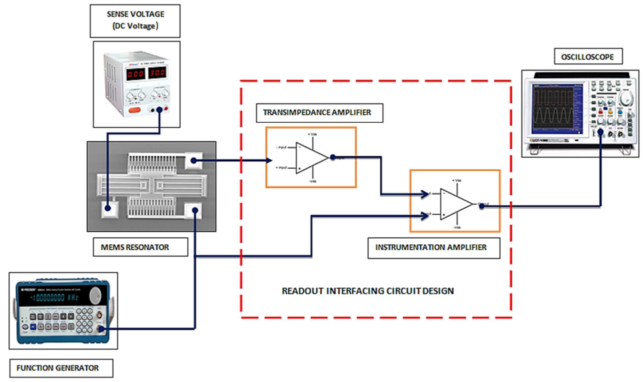

Fig. 4 Measurement setup for readout interfacing circuit

Fig. 4 shows the measurement setup for readout interfacing circuit to characterize the MEMS resonator behavior. The output of the function generator was connected to the MEMS resonator and a voltage divider circuit (not shown in fig. above) before this signal fed into the one inputs of instrumentation amplifier in readout circuit. Both inputs of instrumentation amplifier must receive a same frequency to produce smooth sinewave otherwise it will produce a distortion sinewave. The voltage of the function generator was set to a fix value while the frequency was swept with the particular ranges. The oscilloscope was used to measure and observe the change of the amplitude as well as frequency. Form the equation (4) and (11) show that The DC voltage was used to activate the MEMS resonator and produce the motional current. Otherwise it will produce zero output.

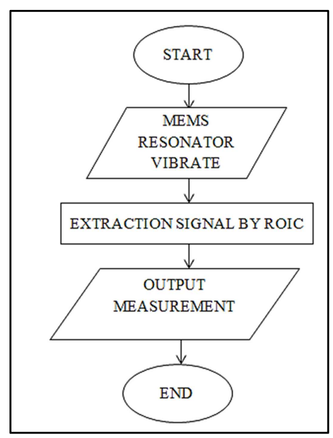

Fig. 5 Circuit operation of identifying MEMS resonator characterization

Fig. 5 shows the circuit operation of readout interfacing circuit to determine behavior of MEMS resonator. For this project, the MEMS resonator emulator which is consists of RLC components used to emulate the MEMS resonator behavior. The excitation voltage is used to generate electrostatic force since MEMS resonator is uses the capacitive technique (interdigitated comb). The capacitive technique means the MEMS resonator was using the capacitive actuation at the input to convert the electrical signal from the function generator to the mechanical movement in which the MEMS resonator start to vibrate. At the same time, the capacitive transducer was placed at output of MEMS resonator to convert the mechanical movement to the electrical signal which is a maximum peak of current signal. This current signal will be extracted by Readout interfacing circuit for the conversion to the voltage signal and amplification process. The oscilloscope is used to measure changing of voltage amplitude as well as the frequency of MEMS Resonator.

TABLE 1. TYPICAL MAXIMUM VOLTAGE AND GAIN AMPLIFIER FOR MEMS RESONATOR EMULATOR

Parameter	value	Unit
Gain (IA)	10	-
V_{DC}	8	V
V_{AC}	5	V_{PP}
R_F (TA)	1	MΩ

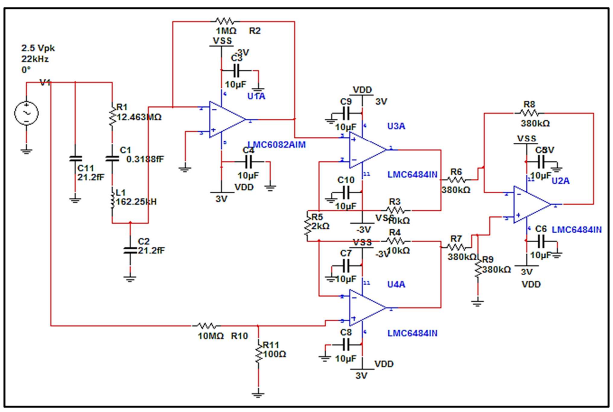

Fig. 6 Readout interfacing schematic circuit with MEMS Resonator emulator

Table 1 shows the typical maximum voltage excitation, gain amplifier of instrumentation amplifier and feedback resistance of transimpedance amplifier were applied in fig. 6 readout interfacing circuit. The characteristic performance of these operation amplifiers were choose based on the comparison data sheet and simulation performance which is discussed in result and discussion chapter. LTspice software was used to characterize these operation amplifiers. Fig. 6 shows that the MEMS resonator emulator produces smallest current where this current was be captured by transimpedance amplifier to convert to the voltage signal. This voltage signal further will be amplified using the Instrumentation Amplifier. The Instrumentation Amplifier is suitable used for sensing application because of involving the small signal as well as reject the common mode noise and interference signal. It can be seen that there are three combination of operation amplifier was used to form the instrumentation amplifier. Also, 10uF was connected to the each supply voltage of the operation amplifier as shown in fig.6. The functions of these capacitors are to prevent this circuit from oscillation and voltage spike where noise was introduced.

Unfortunately, to implement these MEMS resonator emulator on prototype design is impossible because it was require smallest value for capacitance and biggest value for inductance at least one fantom farad (1fF) and Kilo Hanry(KH) respectively. These values are not available in the market. Therefore, these values need to change to the practical values that available in the market. Table 2 shows the practical values parameter was choose to represent MEMS resonator emulator as well as readout interfacing circuit;

TABLE 2. PRACTICAL VALUES PARAMETER OF MEMS RESONATOR EMULATOR AND READOUT CIRCUIT

Parameter	value	Unit
Gain (IA)	3	-
V_{DC}	8	V
V_{AC}	1.5	V_{PP}
R_F (TA)	100	Ω
C_X	0.1	µF
L_X	0.1	H
R_X	100	Ω

Note that the values of this MEMS Resonator emulator are not actual values and theoretically, this circuit produces 1.6kHz resonant frequency.

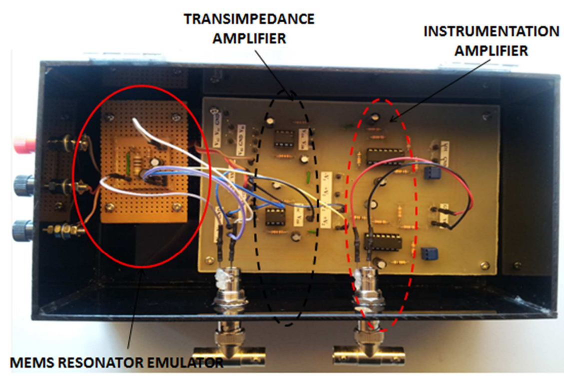

Fig. 7 readout interfacing circuit prototype

After obtaining the simulation results, ROIC schematic will be implemented using discrete device on the Printed Board circuit (PCB) as shown in fig. 7. Comparing the behavior of discrete device on the PCB and simulation process is to prove and verify the functionality of this readout interfacing circuit. The troubleshooting process is required to make sure all the components are functionally. Any components are damaged when soldering and installation process need to be replaced.

III. Result and Discussion

TABLE 3. Comparison And Analysis Two Op Amp Acting As Transimpedance Amplifier

Parameter	datasheet		Simulation		unit
	TLC 2262	LMC 6082	TLC 2262	LMC 6082	
Power supply VDD	±2.5V	±2.25V-7.75V	±2.5V	±2.5V	V
Open Loop Gain	103	130	106	117	dB
Offset Voltage	Typ : 300	Typ: 350	381	350	µV
Gain Bandwidth	0.82	1.3	0.913	1.1	MHz
Phase Margin G=1(RL=50kΩ,CL=100 Pf)	56	50	60	25	^{0}Deg
Slew Rate	Typ:0.5 5	Typ : 0.6	0.015	0.025	V/µS
CMRR	Typ : 70	Typ : 85	86	92	dB
ICMR	Typ: -0.3 to 4.2	Typ : -0.4 to 1.9	--	--	V
PSSR(+/-)	----	85/94	90	220	dB

Table 3 shows the characteristic comparison and analysis between two operation amplifier which is TLC2262 and LMC6082. The characteristic analysis through the simulation process such as Open Loop Gain, Offset Voltage, Gain Bandwidth, Phase Margin, Slew Rate, Common Mode Rejection Ratio and Power Supply Rejection Ratio has been done to both these operational amplifier with ±2.5V power supply. From the table 1, it can be seen that LMC6082 is much better than TLC 2262 in term of high open loop gain, low offset voltage, high gain bandwidth, as well as high common mode rejection ratio. Low voltage offset was means more accurate output value will be achieved and the high value of CMRR shows the ability of Op Amp to reject any common mode signal(noise). The other characteristic where not mention in table above is LMC6082 has ultra-low input bias current compare to TLC2262. Therefore, LMC 6082 is suitable operational amplifier to represent transimpedance amplifier for this project.

TABLE 4. Comparison And Analysis of two Instrumentation Amplifier

Parameter	Simulation		Unit
	LMC6484	TLV2252	
Voltage	±2.5	±2.5	V
Offset voltage	1500	98.93	µV
CMMR (G=1)	92	84	dB
Slew rate	0.018	0.019	$V/\mu s$

Table 4 shows two types instrumentation amplifier was constructed using three general Operation Amplifiers. These instrumentation Amplifiers was simulated and characterized based on the offset voltage, common mode rejection ratio and slew rate performance. From the table above, LMC6484 is better than TLV2252 in term of the Common Mode Rejection Ratio, CMRR. The higher CMRR is required especially in eliminate the common mode noise, as well as interference signal. Even though the offset voltage is high, placing the voltage source at the input terminal of instrumentation Amplifier is alternative ways to reduce the offset voltage's value.

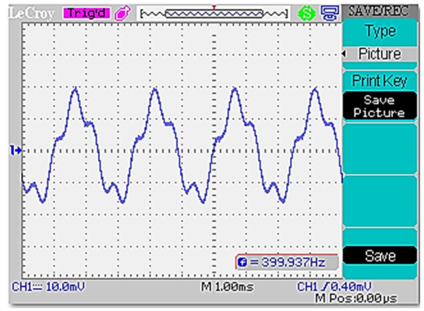

Fig. 8a. Distortion sine wave at the output of instrumentation amplifier

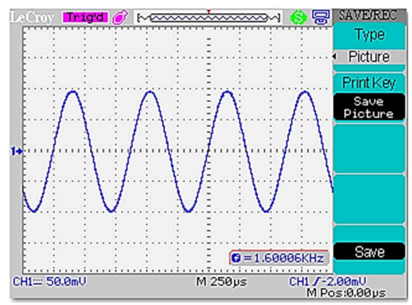

Fig. 8b. Smooth sine wave at the output of instrumentation amplifier

Fig. 8 shows the sinusoidal wave was measured at the output of the instrumentation amplifier. From fig. 8(a) shows that the distortion waveform was produced when the both inputs of instrumentation amplifier are not receive the same frequency. Otherwise, it produces smooth sinusoidal wave as shown in fig. 8 (b). The purpose of doing this observation is to proof the functionality of instrumentation amplifier.

TABLE 5. Simulated Output Current Irms Versus Frequency of MEMS Resonator Emulator

Frequency (KHz)	Irms(A)	Frequency (KHz)	Irms(A)
12	61.6E-12	22	2.89E-9
13	72.2E-12	23	741E-12
14	85.2E-12	24	413E-12
15	102E-12	25	288E-12
16	124E-12	26	223E-12
17	154E-12	27	183E-12
18	201E-12	28	156E-12
19	279E-12	29	136E-12
20	440E-12	30	121E-12
21	954E-12	31	110E-12

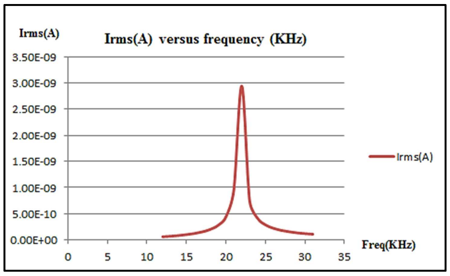

Fig. 9 Frequency response simulation of MEMS Resonator emulator

Fig. 9 shows the graph frequency response simulation for output current Irms versus Frequency of MEMS resonator emulator as shown fig.2. $5V_{PP}$ voltage input was set as fix voltage to generate the electrostatic force[2]. The frequency of AC excitation voltage was swept between 12KHz until 31KHz with 1KHz interval. The current was measured at the Load Resistor R_L and recorded at every swept frequency as shown in table 5.

From fig. 9 and table 5, it can be seen that the MEMS resonator emulator was produces 2.89nA maximum peak at 22KHz natural frequency. This value is approximately similar that produced by fixed-fixed beam resonator [2] in previous reference. Therefore the MEMS resonator emulator are successful emulate the MEMS resonator.

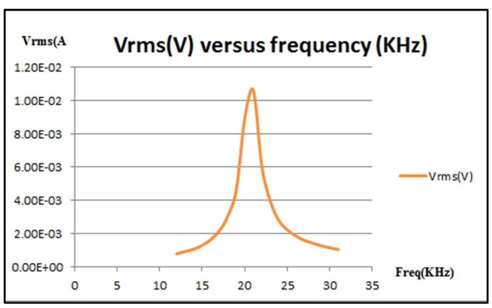

Fig. 10 Frequency response simulation of readout interfacing circuit with MEMS Resonator emulator

Fig. 10 shows the frequency response simulation MEMS resonator emulator was measured at the output of readout interfacing circuit as shown in fig. 6. It can be seen that, the natural frequency was dropped 1kHz from the original natural frequency of modeling MEMS resonator (graph on fig. 9). 4.5% percentage error was calculated and this unexpected effect is quietly small. This value more significant because the resonant frequency is normally stable when the bias voltage remain constant[3]. Also, fig. 10 shows that 10.7mVrms maximum peak at 21kHz natural frequency was produced.

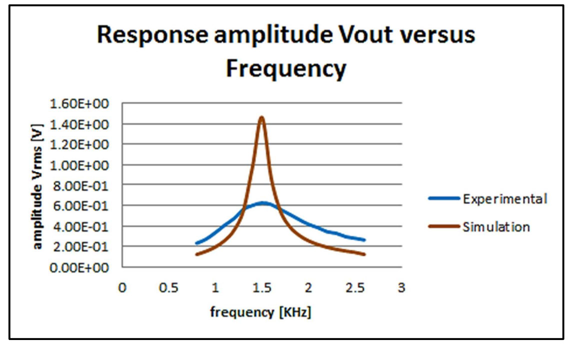

Fig. 11 Frequency response curve between the simulation and experimental result

Fig. 11 shows the comparison frequency response curve between the simulation and experimental analysis using practical values of MEMS Resonator emulator (refer to table 2). This result was measured at the output of readout interfacing circuit. Brown and blue colors were representing the simulation and experimental curve respectively. $1.5V_{PP}$ was set at the function generator and the frequency was swept between 800Hz until 3kHz frequency with interval 100Hz. From this figure, the simulation curve is much sharper than the experimental curve. The amplitude of simulation and experimental analysis also different are 1.46Vrms and 0.624Vrms respectively. Based on the ohm law equation, it shows that, the voltage drop will be increases when the resistance is increases. Since the copper layer on the PCB board will affect the increasing of resistance in this system, it will increase the value of voltage drop on board. Thus, the voltage output will be reduced.

TABLE 6 : COMPARISON ANALYSIS BETWEEN THEORETICAL, SIMULATION AND EXPERIMENTAL

	Theoretical	Simulation	Experimental
Natural frequency	Rx = 10Ω Lx=0.1H Cx = 0.1μF $\omega_0 = \frac{1}{\sqrt{LC}}$ $f_0 = \frac{1}{2\pi\sqrt{LC}}$ $f_0 = \frac{1}{2\pi\sqrt{0.1H \times 0.1\mu F}}$ $f_0 = 1.59KHz$	Natural frequency, f_0= 1.5KHz	Natural frequency f_0= 1.5KHz
Quality factor	$Q = \frac{\omega_0 L}{R}$ Q =100	$Q = \frac{f_0}{BW}$ Q= 80	$Q = \frac{f_0}{BW}$ Q=2.5

Table 6 shows the comparison between the theoretical, simulation and experimental analysis. Theoretically, the MEMS resonator emulator produces 1.6 kHz natural frequency in which slightly different between the simulation and experimental analysis. This shows that, the readout interfacing circuit was able to detect and capture the natural frequency with 95.5% accuracy compared to the theoretical values. The quality factor between the theoretical and simulation analysis is slightly different because difference of natural frequency. The simulation and experimental analysis show significant distinction of the quality factor.

$$Q = \frac{\omega_0 L}{R} \tag{15}$$

From equation(15) it can be seen that quality factor is inverse proportionality with resistance value. It shows that, when the value of resistance in MEM resonator is increase, the quality factor will be decreased. The copper layer on the PCB board also act as resistance at which it will increase the value of resistance in MEMS resonator emulator. Thus, it will reduce the value of quality factor.

IV. CONCLUSION

The readout interfacing circuit prototype design for natural frequency detection of MEMS resonator were proposed and discussed. Transimpedance and Instrumentation Amplifier in readout interfacing circuit prototype were selected based on their specification requirement and characteristic performance. The series RLC equivalent circuit was used to emulate the MEMS resonator behavior. Further, the readout interfacing circuit with and without MEMS resonator emulator were simulate and analyze. Implement this schematic circuit on the PCB level is to proof the functionality of this circuit. The prototype result shows the difference output voltage and quality factor values compared to the simulation result due to the effect resistance of the copper layer on PCB board. Noise and interference also give impact of the performance of Readout interfacing circuit. The result also shows that, this readout interfacing circuit is able to detect and capture the natural frequency with 95.5% accuracy compared to the theoretical values. In future work, by using the prototype of MEMS resonator to implement on the prototype readout interfacing circuit will give more precise values and convenience in analyze the MEMS resonator characterization.

ACKNOWLEDGEMENT

This project has been selected finalist in innovate Malaysia competition 2013 under guidance by Dr. Wan Fazlida Hanim Abdullah as supervisor.

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