NAVAL POSTGRADUATE SCHOOL

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THESIS

DESIGNING AN ELECTRONIC READOUT FOR A DIRECTIONAL MICRO ELECTRO-MECHANICAL (MEMS) SOUND SENSOR

by

Choon Wee Lim

December 2011

Thesis Advisor:	Gamani Karunasiri
Second Reader:	Roberto Cristi

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13. ABSTRACT (maximum 200 words)

Locating sound sources has been of interest to the military, especially in locating sniper fire in an unconventional operational theater. Today, there are such systems to localize snipers, but they are bulky, heavy and do not employ networking, which can greatly improve the performance in terms of accuracy and reliability. Hence, there is a need to design a system that is small, compact, distributed, and reliable. In this project, an electronic readout system was designed and integrated for a directional Micro Electro-Mechanical (MEMS) sound sensor that is being developed in Naval Postgraduate School, Physics department. It is composed of the hardware and software components to process sensor signals such as amplitudes and frequencies, to aid in determining the direction of the sound. To keep the system small and compact, the electronics readout was integrated to the sensor system on the same platform. Such electrical and mechanical system integration minimizes the parasitic capacitances and enhances the sensitivity. The measured sensor response using the integrated electronics showed an improvement of nearly a factor of four larger as compared to that using an external circuit board.

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DESIGNING AN ELECTRONIC READOUT FOR A DIRECTIONAL MICRO ELECTRO-MECHANICAL (MEMS) SOUND SENSOR

Choon Wee Lim
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Beng, Nanyang Technological University, Singapore, 2006

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December 2011**

Author: Choon Wee Lim

Approved by: Gamani Karunasiri
                 Thesis Advisor

                 Roberto Cristi
                 Second Reader

                 Andres Larraza
                 Chair, Department of Physics

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ABSTRACT

Locating sound sources has been of interest to the military, especially in locating sniper fire in an unconventional operational theater. Today, there are such systems to localize snipers, but they are bulky, heavy and do not employ networking, which can greatly improve the performance in terms of accuracy and reliability. Hence, there is a need to design a system that is small, compact, distributed, and reliable. In this project, an electronic readout system was designed and integrated for a directional Micro Electro-Mechanical (MEMS) sound sensor that is being developed in Naval Postgraduate School, Physics department. It is composed of the hardware and software components to process sensor signals such as amplitudes and frequencies, to aid in determining the direction of the sound. To keep the system small and compact, the electronics readout was integrated to the sensor system on the same platform. Such electrical and mechanical system integration minimizes the parasitic capacitances and enhances the sensitivity. The measured sensor response using the integrated electronics showed an improvement of nearly a factor of four larger as compared to that using an external circuit board.

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I.   INTRODUCTION

A.   OBJECTIVE

The objective of this project is to design and integrate an electronic readout to a directional MEMS sound sensor. It focuses on the techniques and procedures to optimize the electronic readout for the sensor.

B.   BACKGROUND

The MEMS sound sensor design is made with electrical readout in consideration. It consists of two wings that are coupled in the middle and attached to the surrounding substrate by two legs. Interlaced fingers are designed at the edges of the wings to allow capacitance change when the wings are oscillating due to an acoustic pressure wave (see Figure 1). Electrical connections are also made on the sensor and its chip carrier to allow external interface circuitry to be connected to the capacitance readout.
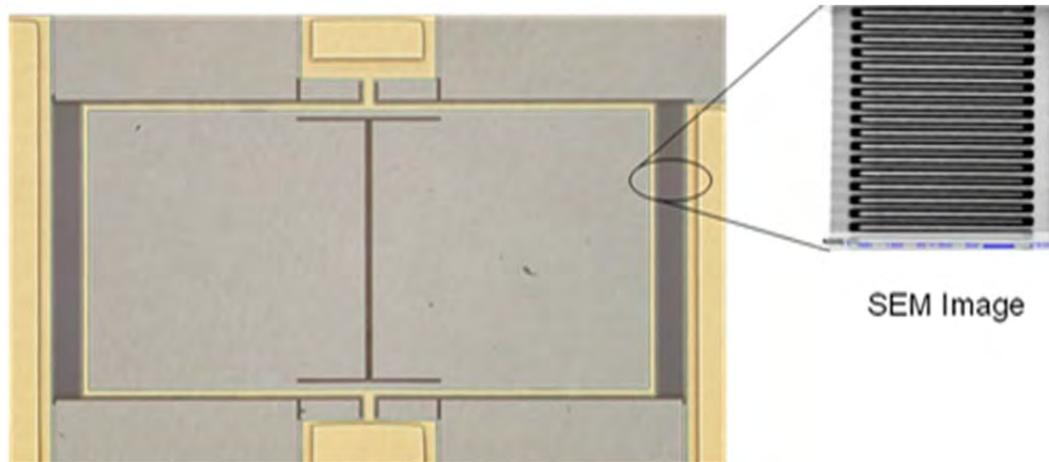
Figure 1.   MEMS sound sensor showing interlaced fingers.

The MS3110 IC from Irvine Sensors has been used in its evaluation board to function as the electronic readout. Figure 2 shows an overview of the MS3110 IC when used in the (Zero Insertion Force) ZIF socket of its evaluation board.

Figure 3 is the corresponding sketch that describes the board. In the circuit, Jumper J3 pins are used to make connections from the IC to the sensor. A computer is also used to program the IC during the experiments via the parallel port connector.
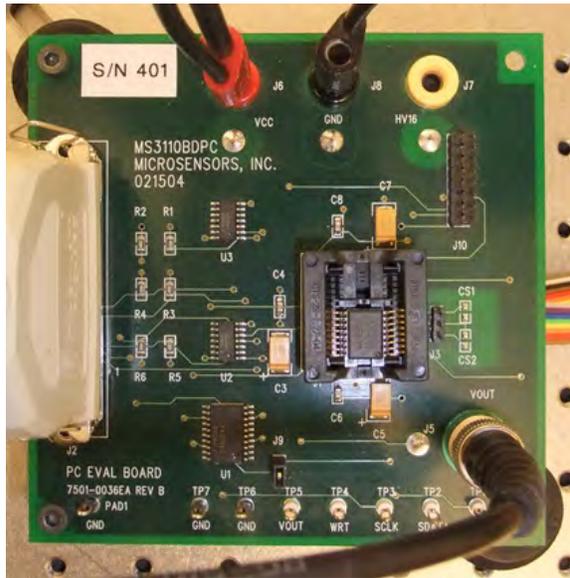
Figure 2.   MS3110 evaluation board (and a dime for scale reference).
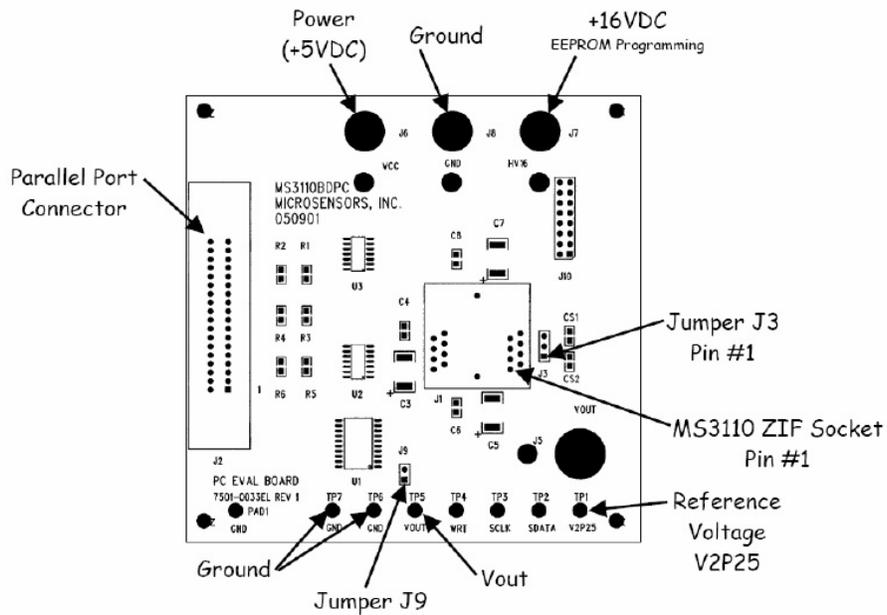
Figure 3.   Sketch of MS3110 evaluation board showing various test points.

To aid in the development, the MS3110 evaluation board includes many test points to measure several of the operating parameters, such as the reference voltage (V2P25) and the output signal (V0). Additional test points have been provided for monitoring of the programming signals to the MS3110 IC. The evaluation board software includes volatile register read-back, the ability to store programming settings, and hard-copy generation (printing). The board operates from a single +5Vdc supply. A second source (+16Vdc) is necessary for programming the MS3110 EEPROM [1].

In previous works [2, 3], it was shown that such an electrical readout is possible by connecting sensor output to the evaluation board. Research on MEMS accelerometers and gyroscopes for inertial measurement units [4] has demonstrated the use of MS3110 IC as the readout circuitry as a hybrid system. Research on integrating capacitive pressure sensors with read-out circuitry [5] has demonstrated the use of the MS3110 die integrated by wirebonding directly to the microfabricated pressure sensors. The main advantage of bringing the readout electronics closer to the MEMS sound sensor is the reduction of parasitic capacitances, which enhances the signal.

C.   THESIS ORGANIZATION

Chapter II gives an overview of the sensor system. It describes design considerations of integrating MEMS sound sensor and the MS3110 IC/die on the same platform. It also describes experiments carried out to verify the functionality of the sensor and procedures taken to integrate the MS3110 IC/die to the sensor.

Chapter III discusses the integration of the MEMS sound sensor and the MS3110 IC/die on the same platform. It also discusses the problems encountered and solutions adopted.

Chapter IV presents the results of the experiments carried out in the laboratory. A summary of findings and conclusions are drawn. Recommendations and future works are also discussed.

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II.   SYSTEM OVERVIEW

A.   SENSOR MODEL

Studies on the *Ormia ochracea* fly showed that it uses a unique mechanically coupled ear system, which consists of two identical wings hinged at the center to determine the direction of sound. Modeling the combined structure as two coupled, damped harmonic oscillators, Miles et al., [6] showed that the motion is a combination of two fundamental modes. One mode, in which the two sides oscillate 180 out-of-phase, can be envisioned as a rocking motion similar to a see-saw. In the second mode, the coupling structure bends in the middle and the two sides oscillate in-phase, generating a bending-like motion.

With the model in place, a software simulation using COMSOL is performed on a Gen.7 Dev#1 MEMS sound sensor to show how the sensor would response as sound pressure is applied. The structure of the Gen.7 Dev#1 sensor is shown in Figure 4. Figures 5 and 6 shows the corresponding bending and rocking modes of the sensor respectively, as perceived in the model. Figure 7 shows the simulated frequency response (bending mode at about 3.5 kHz and rocking mode at about 2 kHz).

Figure 4.   Structure of Gen.7 Dev#1 sensor.
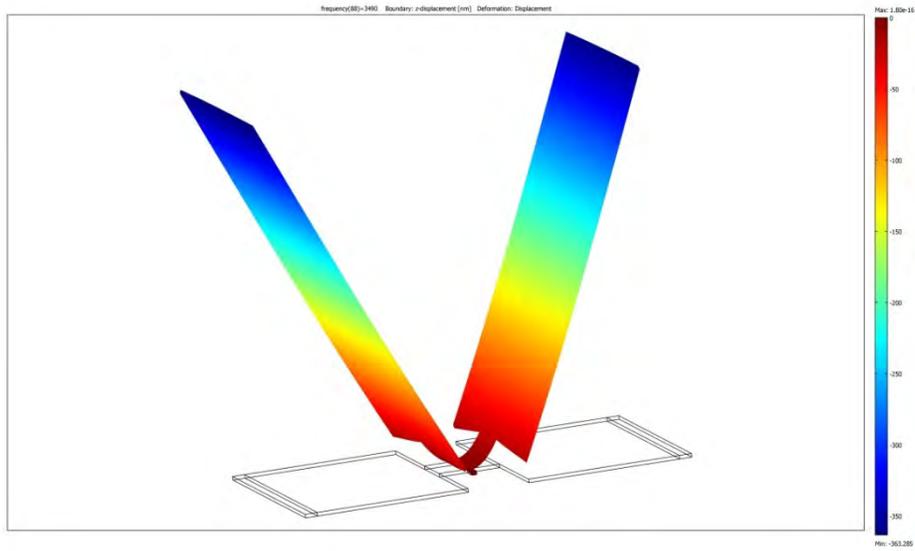
Figure 5.   Bending mode of Gen.7 Dev#1 sensor.
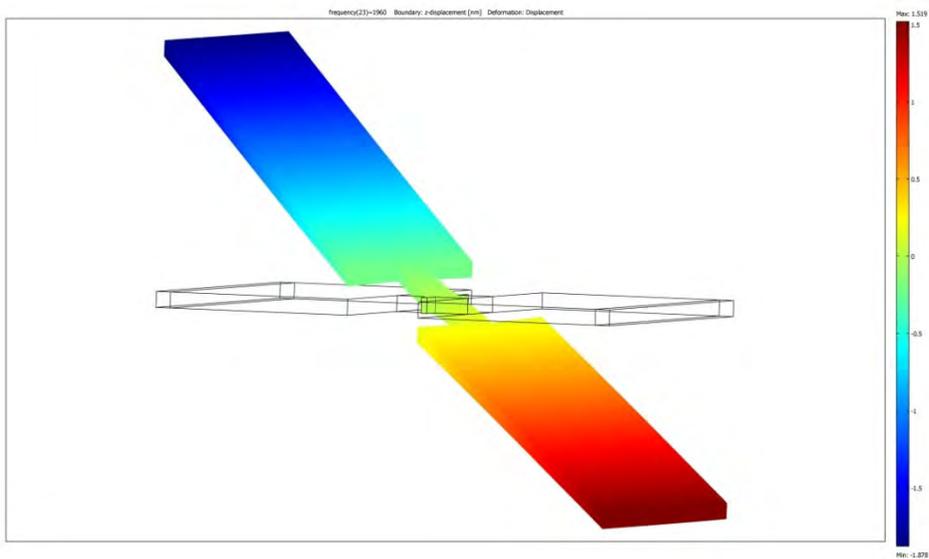
Figure 6.   Rocking mode of Gen.7 Dev#1 sensor.
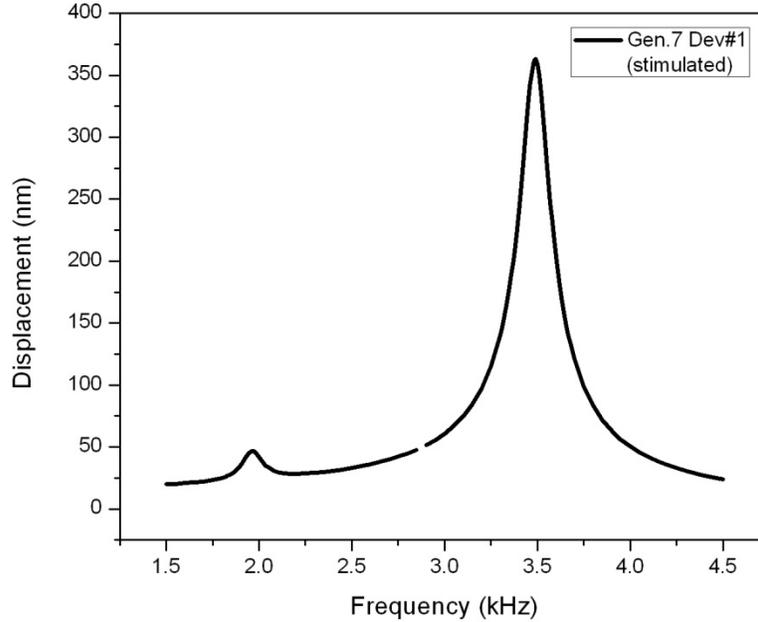
Figure 7.   Simulated frequency response of Gen.7 Dev#1 sensor.

With the design in place, the MEMS sound sensor is fabricated. The sensor consists of two wings that are coupled in the middle and attached to the surrounding substrate by two legs. The design incorporates interlaced comb fingers on the wings, which enables electrostatic capacitive readout. The design also included a reference capacitor for balancing the bridge readout architecture used by the MS3110 IC/die. The reference capacitor is internally connected to the common terminal of the sensor providing three outputs terminals DEVICE, COMMON & REFERENCE that are used as inputs to the electronic readout circuit.

In addition, the functionality of the sensor should be tested, and this is done by monitoring the displacements of the wings. It is suggested that the displacements should be large enough, at least of a few nanometers so that the output signal from the electronic readout has a reasonable signal-to-noise ratio. The experiment is carried out in the laboratory using a laser vibrometer, where

the Gen 7 sensor is subjected to a sound source of 50 mV, corresponding to a sound pressure of about 0.2 Pa (equivalent of about 80 dB) from the reference microphone. Figure 8 shows the measured frequency response of the sensor. The dominant response at 3.5 kHz is due to the bending mode, which drives both sides of the wings with the full sound pressure incident on the device, causing much larger amplitudes. In subsequent measurements, the sensor is excited using a sine wave at this frequency to achieve the highest signal. The rocking mode is barely visible around 1.7 kHz as the rocking mode amplitude is governed by the very small pressure difference at the two wings [3].
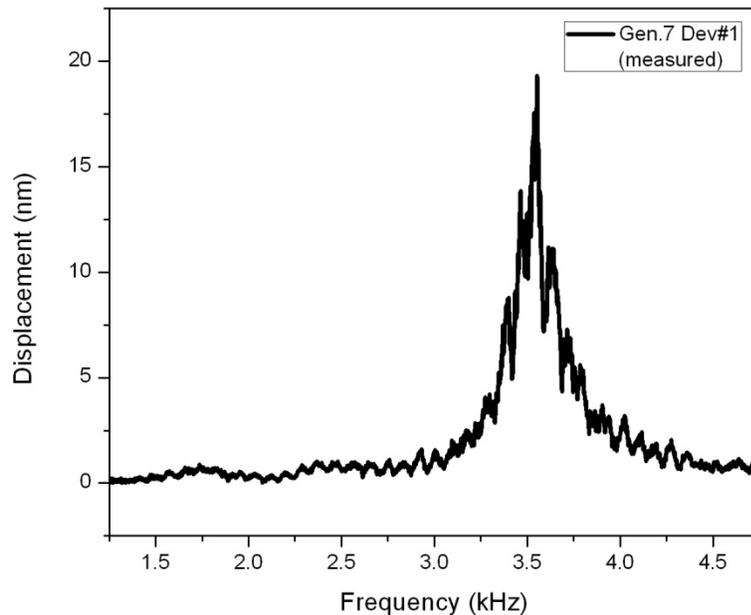
Figure 8.   Plot of sensor wing displacement against frequency.

B.   MS3110 UNIVERSAL CAPACITANCE READOUT

The MS3110 is a general purpose, ultra-low noise CMOS IC intended to support a variety of MEMS sensors that require a high resolution capacitive readout interface [1]. Typically, it is capable of sensing capacitance changes down to 4.0 aF/rtHz. It can be used to interface either a pair of capacitors

differentially or to read a single capacitor. The output is in the form of a range of voltages proportional to the difference of input capacitances.

The output voltage (V_0) can be obtained from the block diagram of the MS3110 as shown in Figure 9. It is given by the transfer function as [1]

V_0 = GAIN * V2P25 * 1.14 * ($CS2_T$ - $CS1_T$) / CF + VREF

where Gain = 2 or 4 V/V

V2P25 = 2.25 VDC

$CS2_T$ = CS2IN + CS2

$CS1_T$ = CS1IN + CS1

CF is the adjustable feedback capacitance to optimize sensor input sense capacitance range

VREF is selecTable 0.5/2.25V output offset voltage
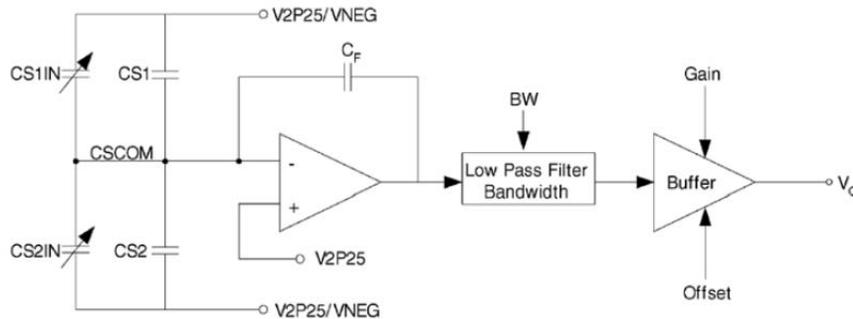
Figure 9.   Block diagram of MS3110 electronic circuit.

Figure 10 shows the MS3110 IC along with the description of the terminals. Figure 11 shows the corresponding microscopic view of MS3110 die and Table 1 shows the pin-out descriptions.
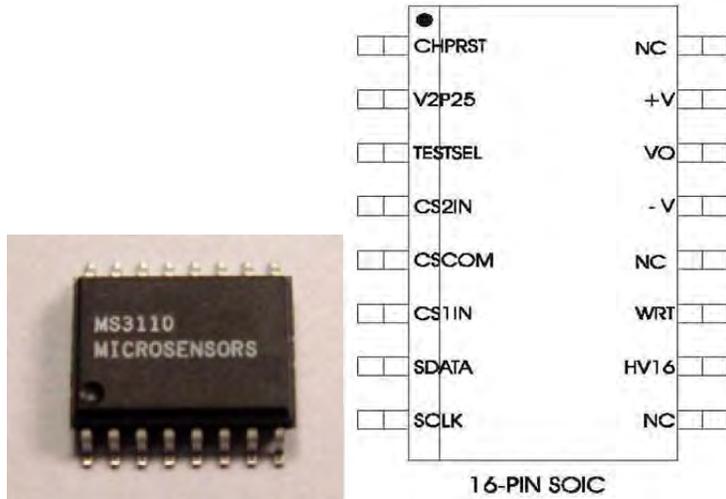
Figure 10.   MS3110 IC and description of terminals.
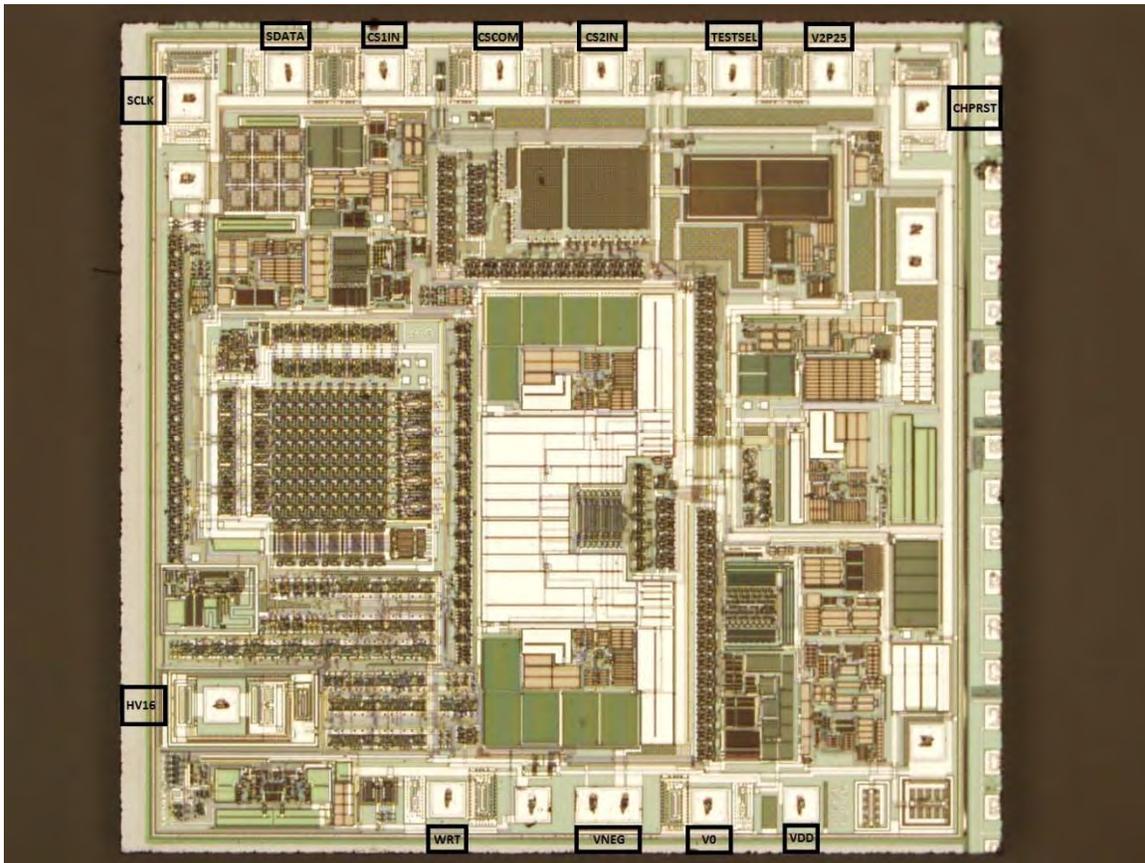
Figure 11.   Microscopic view of the MS3110 die.

SOIC Pin No.	Name	Description
1	CHPRST	ASIC Reset, internally pulled up. Normally 4.0V
2	V2P25	2.25V DC Reference.
3	TESTSEL	Test Select. Enables the user to bypass the on-chip EEPROM and program the ASIC directly.
4	CS2IN	Capacitor sensor input 2, to be connected with the upper electrode.
5	CSCOM	Capacitor sensor common, to be connected to the common sensor node.
6	CS1IN	Capacitor sensor input 1, to be connected with the upper sensor electrode.
7	SDATA	Serial Data Input, used for the serial data input port for programming the EEPROM or the ASIC registers directly. This node is internally pulled down.
8	SCLK	Serial Clock Input, serves as the strobe which the ASIC latches the serial data. This node is internally pulled down.
9	NC	No Connect.
10	HV16	16V DC input port, tied to 16V when writing to EEPROM and Grounded otherwise.
11	WRT	Write Select. Enables the user to program the on-chip EEPROM.
12	NC	No Connect
13	-V	Negative Voltage Rail, usually 0V.
14	VO	ASIC Signal Path Voltage Output.
15	+V	Positive Voltage Rail, usually +5V.
16	NC	No Connect

Table 1.   MS3110 pin-out descriptions.

In the integration, pins CS2IN, CSCOM & CS1IN should be connected to the sensors (DEVICE, COMMON & REFERENCE terminals). Pins CHPRST, V2P25, TESTSEL, SDATA & SCLK are required for data comunications from the computer to the MS3110 IC/die and pins VDD & GND are required for the power supply to the MS3110 IC/die. Pins V2P25 & V0 provide a means to monitor signal response. Details on the connections are provided in the system integration portion of the thesis.

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III. SYSTEM INTEGRATION

A. INITIAL DESIGN

1. Setup

The MS3110 die is used as the electronic readout and integrated to the sensor on a chip carrier. A hole on the chip carrier is drilled to keep the backside open when mounted to prevent squeezed film damping as the wings oscillate. In addition, the sound entering from the backside provides the cosine dependence to the response at the bending frequency [3]. The layout of the integrated sensor and die is shown in Figure 12. Three output terminals from the sensor, namely, the DEVICE, the COMMON, and the REFERENCE, are directly wirebonded to the MS3110 die's CS2IN, CSCOM & CS1IN pads. In addition, wirebonds are also made between pads on the die and chip carrier for the power supply (VDD & GND) and data communication (CHPRST, V2P25, TESTSEL, SDATA & SCLK). To monitor the signal response, output voltages (V2P25 & V0) are wirebonded from the MS3110 die to the chip carrier. Figure 13 shows the set-up of the integrated system and its various connections via J10 and J1, the ZIF socket of the MS3110 evaluation board.
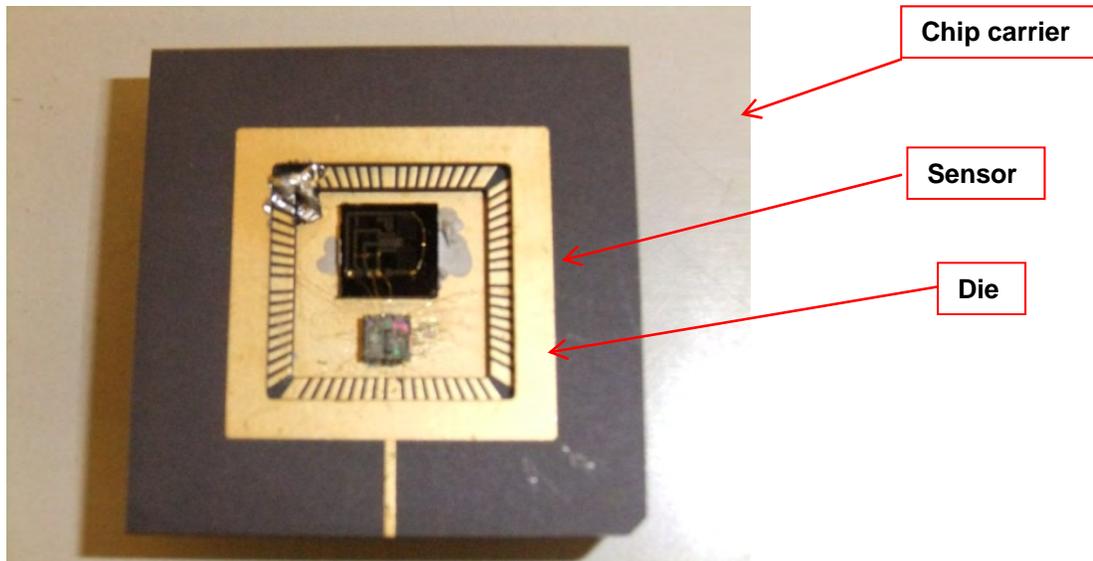
Figure 12.   Initial integration of sensor (top) and die (bottom).

**Chip carrier
(Back view)**
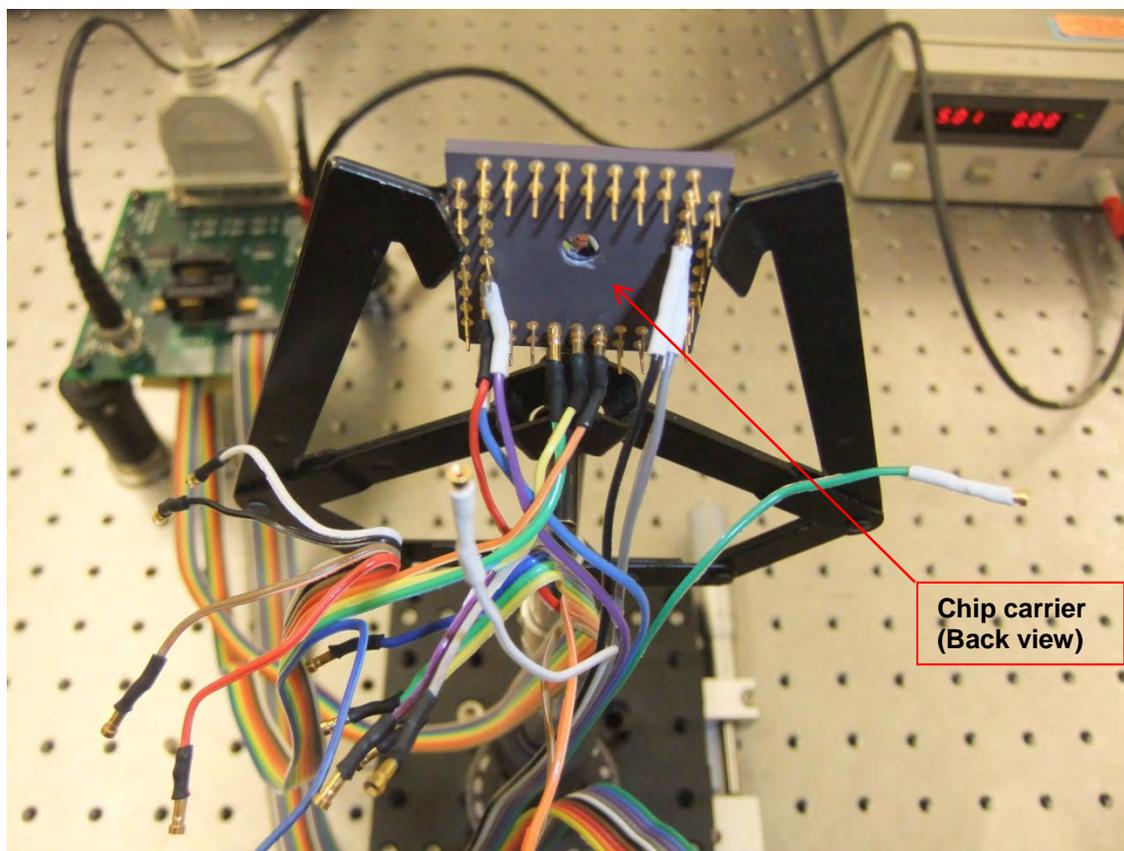
Figure 13.   Initial system set-up for readout.

In the setup, J10 of the evaluation board is used for data communication between the computer and the MS3110 die. J10 consists of six outputs, namely, SDATA, WRT, SCLK, TESTSEL, CHPRST and GND as shown in Figure 14. However, only four outputs, that is, SDATA, SCLK, TESTSEL and CHPRST are required from J10. Hence, these signals are tapped from J10 to the MS3110 die mounted on the chip carrier itself. In addition, there is a need to send V2P25 signal from another port, that is, J1, the ZIF socket of the evaluation board, to the MS3110 die mounted on the chip carrier, to complete the connections for data communication.
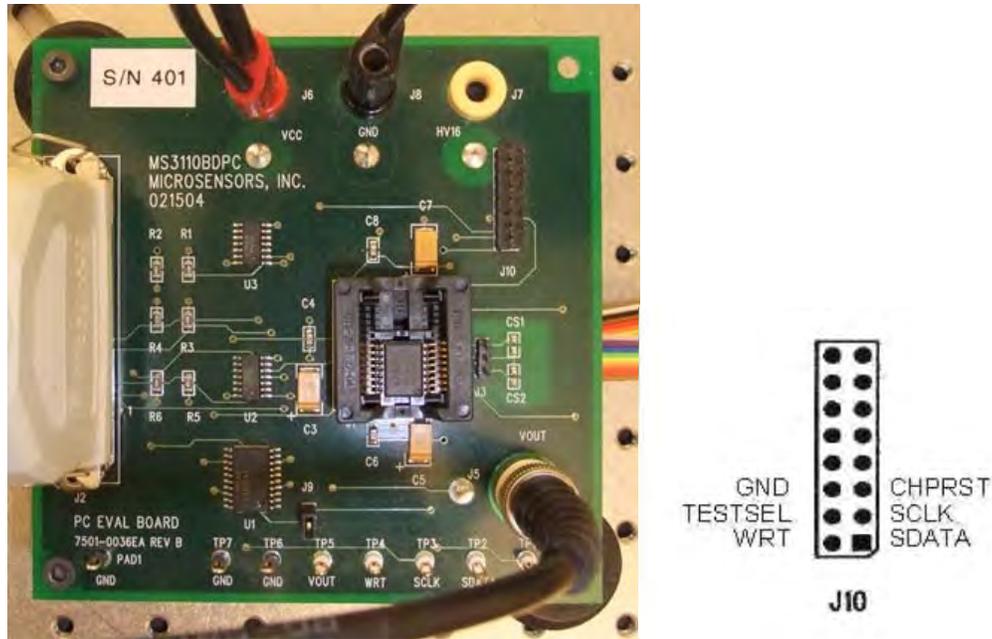
Figure 14.   J10 of MS3110 evaluation board.

A power supply of 5 volts is supplied, via VDD & GND, to the MS3110 die though J1, the ZIF socket of the evaluation board. Alternatively, power could be supplied directly and separately to the die from an external source.

Output voltages (V2P25 & V0) are tap from the MS3110 die via J1, the ZIF socket of the evaluation board, and monitored on the oscilloscope. Alternatively, output voltages could be read directly from the die. It is noted that V2P25 should have a voltage of 2.11 V to 2.45 V for proper operation of MS3110 die [1]. To ensure that the entire circuit is connected correctly, V2P25 should be adjusted to 2.25 V ± 0.01 V via the MS3110 software program. With V2P25 as 2.25 V, the next step is to observe output voltage, V0 and balance the capacitance bridge via the MS3110 software program.

2.   Capacitance Bridge Balancing

With the circuit connected, the MS3110 IC is reset via its software program to write the initial register settings into the memory. Generally, the process begins by setting the feedback capacitance to approximately 10 pF, and

the balancing capacitors to zero. Raising the value of CS1 to its maximum value should bring the output signal from 0 to 5 V or vice versa. Failing to do so would mean that the maximum internal capacitance is less than that required to balance the entire bridge and the leads should be switched between the device and reference capacitors (CS1 and CS2 terminals). The CS1 values are then adjusted until the output signal is approximately 2.25 V. Based on the voltage output equation, it could be concluded that reducing the feedback capacitance would increase the amplitude of the output signal. However, setting the feedback capacitance too low may cause distortion. Hence, setting the feedback capacitance at 1 pF is reasonable compromise between signal strength and distortion.

3. Observations

It is observed that V2P25 is correctly indicated as 2.25 V, which means that the circuit is correctly connected. However, the circuit could not be balanced as V0 could not be adjusted to 2.25 V, hence no response from the sensor is observed. A step-by step approach to troubleshoot the system is then adopted.

B. COMPONENT TESTING

1. Analysis

With knowledge from prior work [2], [3] about the MS3110 IC and its evaluation board, it could be concluded that the sensor, MS3110 die and its wirebonds, mounted on the chip carrier, are components in the new system that needs to be troubleshooted and tested. Nonethesless, quick check is done on the connections from the existing MS3110 evaluaution board to ensure that the same signals from J10 are obtained as from J1, the ZIF socket, with the MS3110 IC siting in its evaluation board.

Furthermore, with the sensor operation, which has been verified earlier, it could be further concluded that the MS3110 die and its wirebonds should be

checked. Hence, the first step is taken to cut the wirebonds between the sensor and the MS3110 die, which isolates the sensor so that the MS3110 die and the wirebonds could be verified.

The next step is attempted to balance the circuit, without the sensor, via J10 on the evaluation board. The circuit should be balanced, even without the sensor. Failing to do so would mean that the MS3110 die is faulty, not working correctly or the wirebonds are not connected properly. In addition, the internal resistances between various terminals of the standalone MS3110 die mounted on the chip carrier and the standalone MS3110 IC should be checked and compared to ensure consistency.

2. Observations

With the sensor disconnected from the system, it is observed that V2P25 is correctly indicated as 2.25V, which means that the circuit is correctly connected. However, the circuit could not be balanced as V0 could not be adjusted to 2.25V, hence no response from the sensor. In addition, there are inconsistencies in the internal resistance values across various terminals of the MS3110 die when compared to that of the MS3110 IC. These observations would sum up to mean that the MS3110 die is faulty, not working correctly or its wirebonds may not be connected precisely.

C. HYBRID DESIGN

1. Setup

The integration of the MEMS sound sensor and the MS3110 die proves to be challenging, in terms of uncertainty of the die performance and its connections. The MS3110 die needs to be sufficiently studied and tested to ensure that it is working correctly and its wirebonding needs to be precisely made. Hence, faced with a short amount of time left, the MS3110 IC is used in place of the die. The MS3110 IC would be integrated, in close proximity, with the sensor as shown in Figure 15. Figure 16 shows the set-up of the integrated

system (sensor on the chip carrier is connected to its readout on another chip carrier) and its various connections via J10 and J1, the ZIF socket of the MS3110 evaluation board. In the final design, Gen.7 Dev#1 MEMS sound sensor is used.
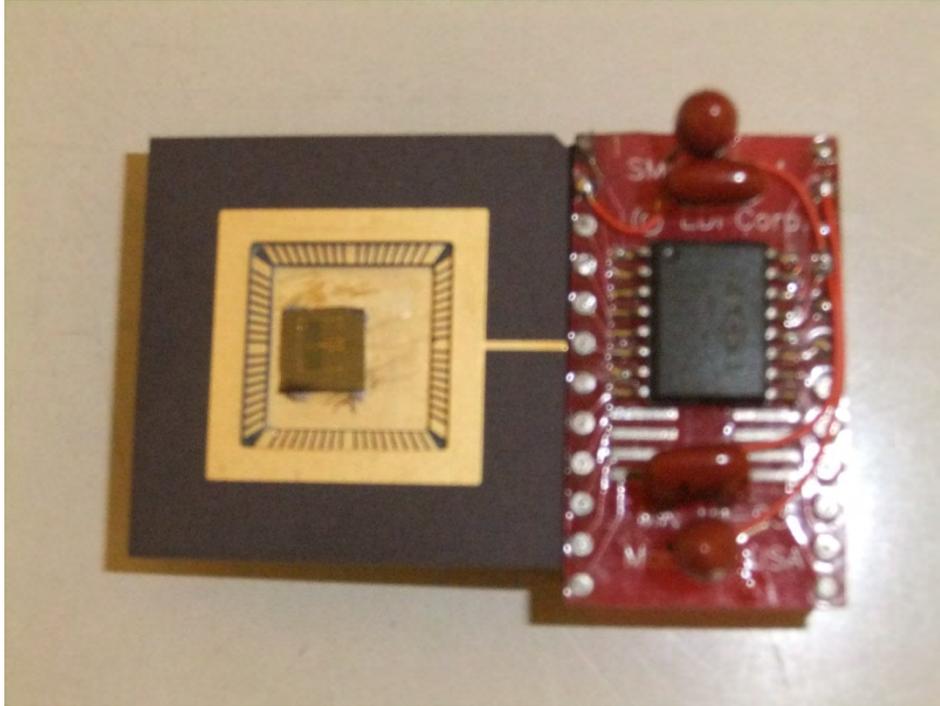
Figure 15.   Hybrid integration of sensor (left) and MS3110 IC (right).
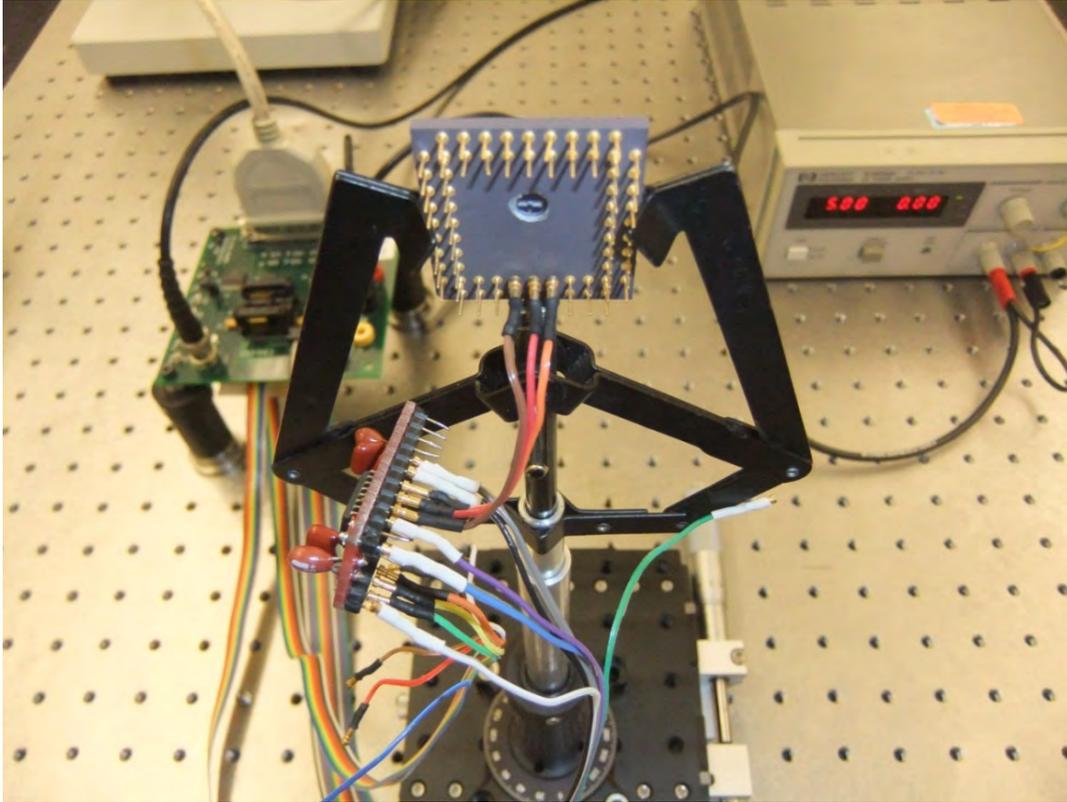
Figure 16.   Hybrid system wired to perform electronic readout.

In the set-up, three output terminals from the sensor, namely, the DEVICE, the COMMON, and the REFERENCE voltages, are connected to the MS3110 IC (CS2IN, CSCOM & CS1IN). In addition, the MS3110 IC gets its communication signals, namely, SDATA, SCLK, TESTSEL and CHPRST from J10. This is basically the same approach when the MS3110 die is used earlier. However, there is no need to connect the V2P25 signal to the MS3110 IC as the required 10 µF and 0.1 µF capacitors are connected as shown in Figure 17.
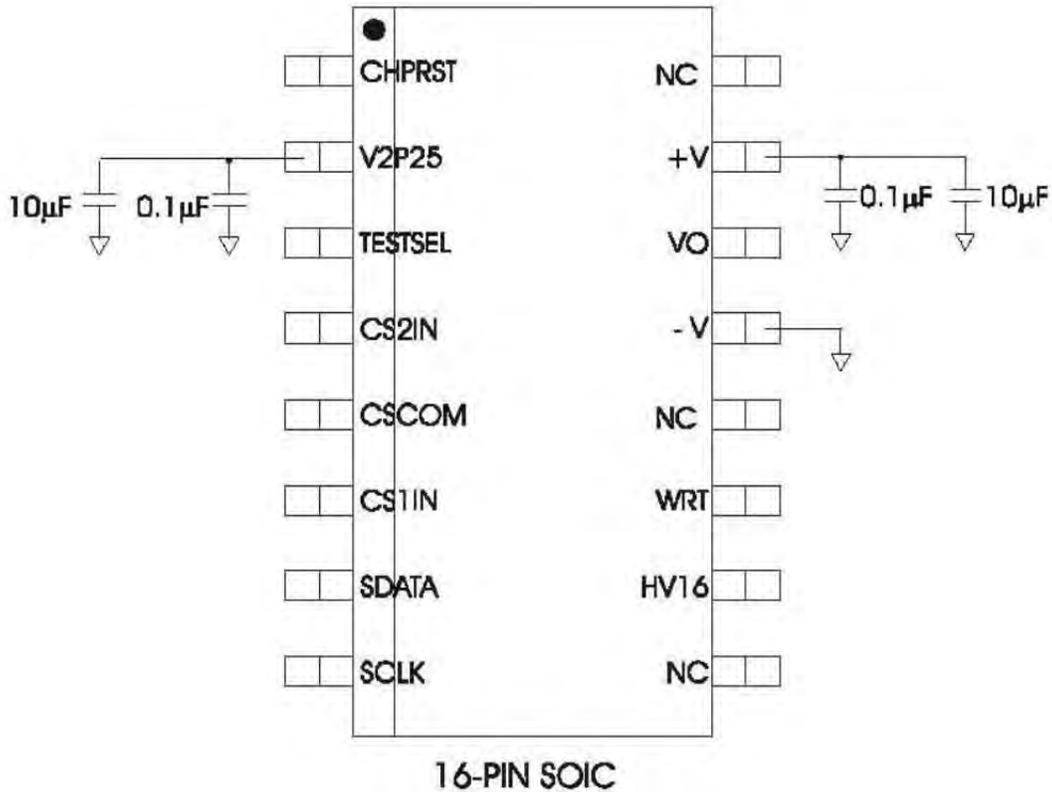
Figure 17.   MS3110 IC connected with 10 µF and 0.1 µF capacitors.

Similiarly, a power supply of 5 volts, via VDD & GND, is supplied to the MS3110 IC though J1, the ZIF socket of the evaluation board. Alternatively, power could be supplied directly and separately to the IC from an external source. Output voltages (V2P25 & V0) are tapped from the MS3110 IC via J1, the ZIF socket of the evaluation board, and monitored on the oscilloscope. Alternatively, output voltages could be read directly from the IC. Again, it is mandated that V2P25 should have a voltage of 2.11 V to 2.45 V if the MS3110 die is operating correctly. To ensure that the entire circuit is connected correctly, V2P25 should be adjusted to 2.25 V ± 0.01 V via the MS3110 software program. With V2P25 as 2.25 V, the next step is to observe output voltage, V0 and balance the circuit via the MS3110 software program.

2.   Observations and Further Testing

With the circuit balanced with output voltage, V0, equal to 2.25 V DC, the next step is to look at its AC component. This requires a sound source, operating at the bending frequency of the sensor (3.5 kHz) being directed at the sensor. The signal from the sensor can be measured using the hybrid configuration and compared against the original set-up where the MS3110 IC sits in its evaluation board. The same Gen.7 Dev#1 sensor is used for the comparison purposes. In addition, the sensor should be verfied again to ensure that it is functioning correctly and its performance is consistent in both cases, so as not to introduce any variables in the experiments.

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IV.   RESULTS, CONCLUSION AND RECOMMENDATIONS

A.   WING DISPLACEMENT

The hybrid approach is tested and compared against the original set-up where the MS3110 IC sits in its evaluation board. The main difference in this case is the use of relatively long wires to connect the sensor output to the evaluation board. Results from the vibrometer experiment where the sensor is verfied again to ensure that it is functioning correctly, in terms of wings displacements, are noted to be similar in both cases as shown in Figure 18. Hence, it could be concluded that the sensor is functioning correctly and its performance is consistent in both cases. It should also be noted that these results are essentially the same as the results obtained when the sensor is being verified earlier.
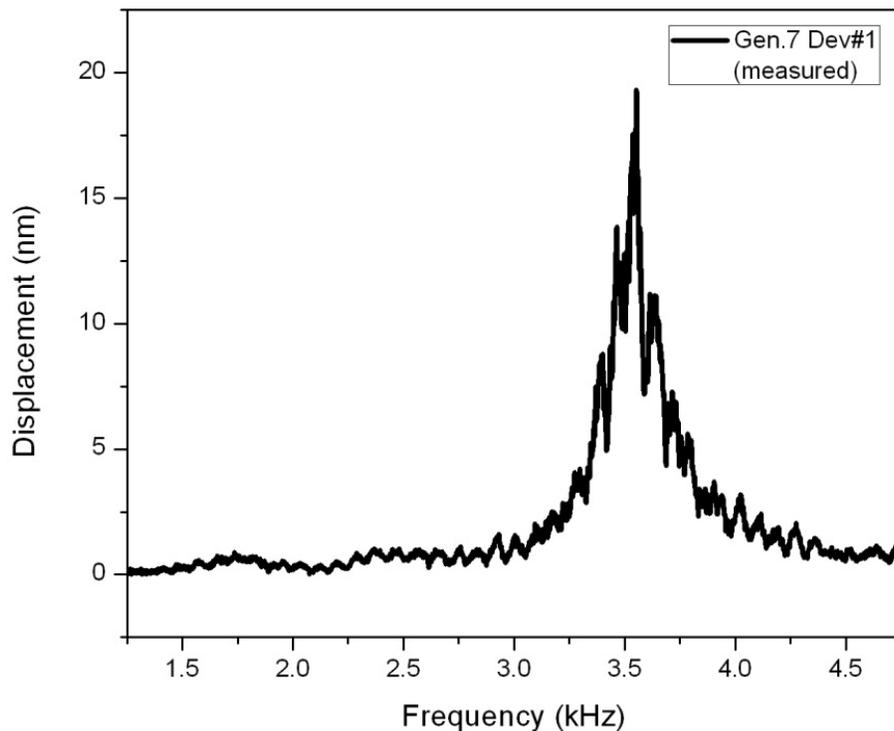
Figure 18.   Plot of sensor wing displacement against frequency.

B. OUTPUT SIGNAL

The output signal of the sensor was first measured by connecting it to the evaluation board. The speaker generated a sine wave at 3.5 kHz (bending frequency of the sensor) and incident on the sensor at around 10°. The sound pressure was about 0.2 Pa (an equivalent of about 80 dB), corresponding to a setting of 50 mV on the laser vibrometer software. Figure 19 shows the recorded output voltage on the oscilloscope. It can be seen that it is relatively small with substantial distortion and jitter. The peak-to-peak voltage signal is approximately 15 mV.
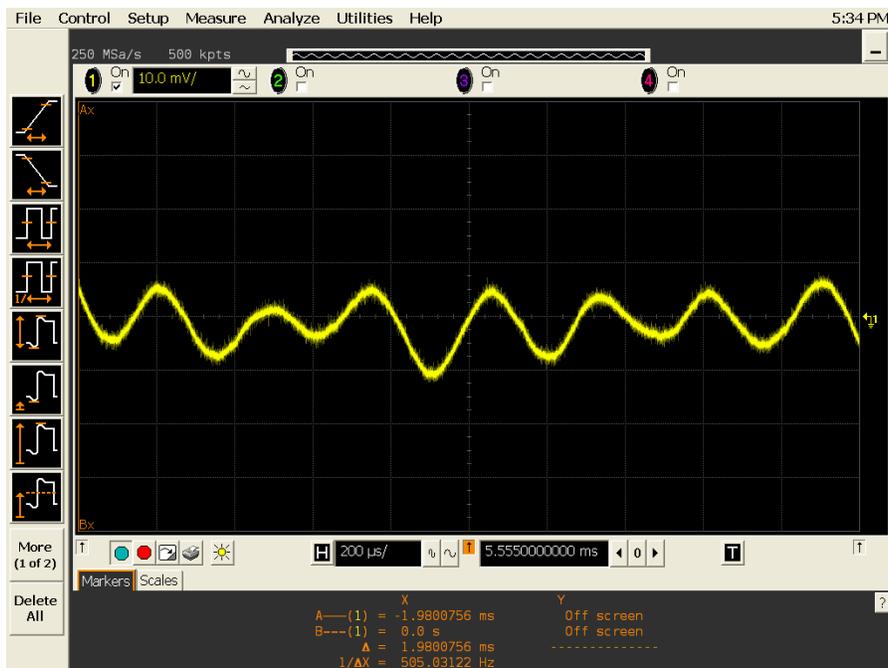
Figure 19.   Output signal using original set-up.

Figure 20 shows the recorded signal on the oscillascope using the hybrid setup that we have constructed (see Figure 16). The peak-to-peak voltage is found to be about 65 mV, which is over a 4-fold increase compared the recordings shown in Figure 19. In addition, the output voltage is well-defined sine wave as compared to the distortions seen with the measurement done using the evaluation board.
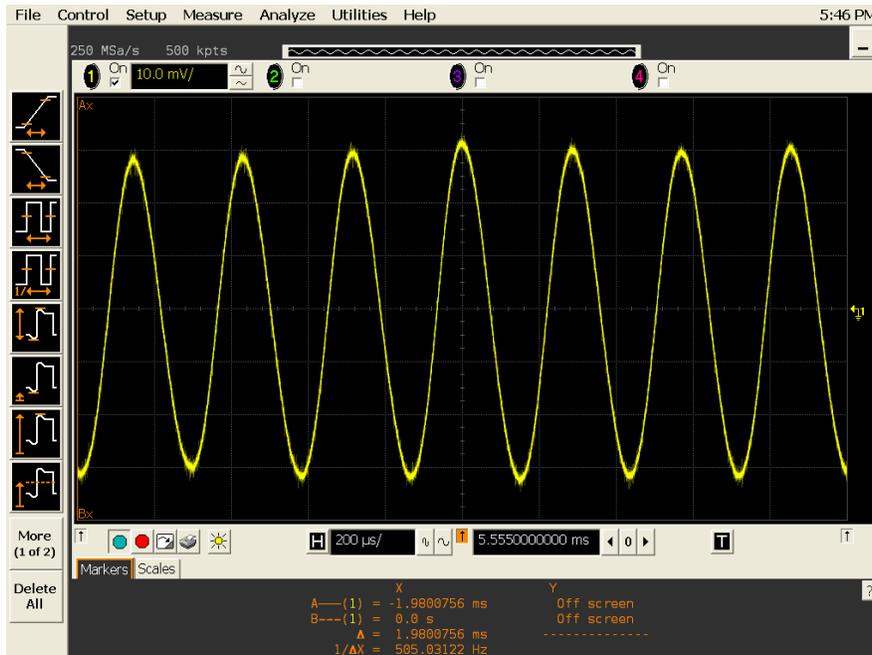
Figure 20.   Output signal using hybrid readout electronics.

The enhancement of the signal can be qualitatively understood by considering the capacitance readout bridge including the parasitic capacitances (see Figure 21) introduced by the long wired employed for connecting the evaluation board to the sensor as follows.

Considering parasitic capacitances, we can derive these two equations.

$V_0' = -V + Q/(CS2_T + C_P)$ _____(1)

$2V = Q/(CS1_T + C_P) + Q/(CS2_T + C_P)$ _____(2)

where Q is the charge on the capacitor

C_P is the parasitic capacitance

$CS2_T = CS2IN + CS2$

$CS1_T = CS1IN + CS1$

Combining these two equations, we obtain

$$V_0' = V(CS1_T - CS2_T)/(2C_P + CS1_T + CS2_T)$$

Clearly, the value of V_0' would drop as parasitic capacitances increase and this explains the enhancement of the signal using the hybrid setup, as compared to the original set-up using the evaluation board with long wires.
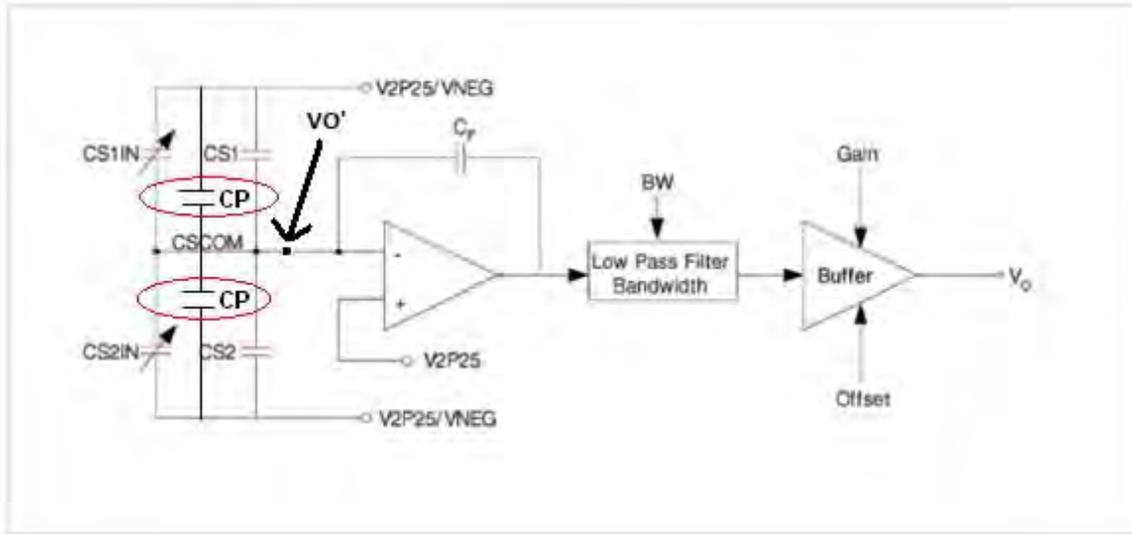
Figure 21.   Block diagram of MS3110 electronic circuit considering parasitic capacitances (circled).

C.   OUTPUT SIGNAL VS. ANGLE OF INCIDENCE

The angle of incidence of the sound source is varied to determine the directional response of the sensor using the hybrid readout electronics. Figure 22 shows the measured normalized amplitude of the electrical signal as a function of incident direction of sound along with the expected cosine dependence. The data is normalized with respect to the maximum amplitude of the electrical signal.

The cosine dependence of the directional response can be qualitatively understood by combining the interaction of sound waves on the top and bottom sides of the wings using the approach described by Kinsler et al., [7] for pressure-gradient microphones. When the sound wave hits the top surface of the sensor it is diffracted and reaches the bottom side with a time delay

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corresponding to an effective path length, *L*. Thus, the net sound pressure at the sensor can be written as a linear combination of the incident and diffracted components

$$P = P_0 (1 - exp(jkL\cos\theta)),$$

where *k* is the wavenumber and P_0 is the amplitude of the incident sound wave. Since the wavelength of the incident sound is much longer than the sensor dimensions, that is, *kL* << 1, it can be easily seen from the equation that the net pressure is proportional to cosθ. As mentioned earlier, the amplitude of the bending motion is proportional to the net sound pressure at the sensor, so its directional response is expected to have a cosine dependence as observed experimentally.

The results show a reasonably good cosine dependence considering the contributions from unwanted sound reflections from the walls of the laboratory. This can be avoided by carrying out the experiment in an anechoic chamber [3]. On the other hand from the original set-up (using the evaluation board with long wires), the output signal fluctuates from 10–15 mV range and is rather unresponsive with a change in angle.
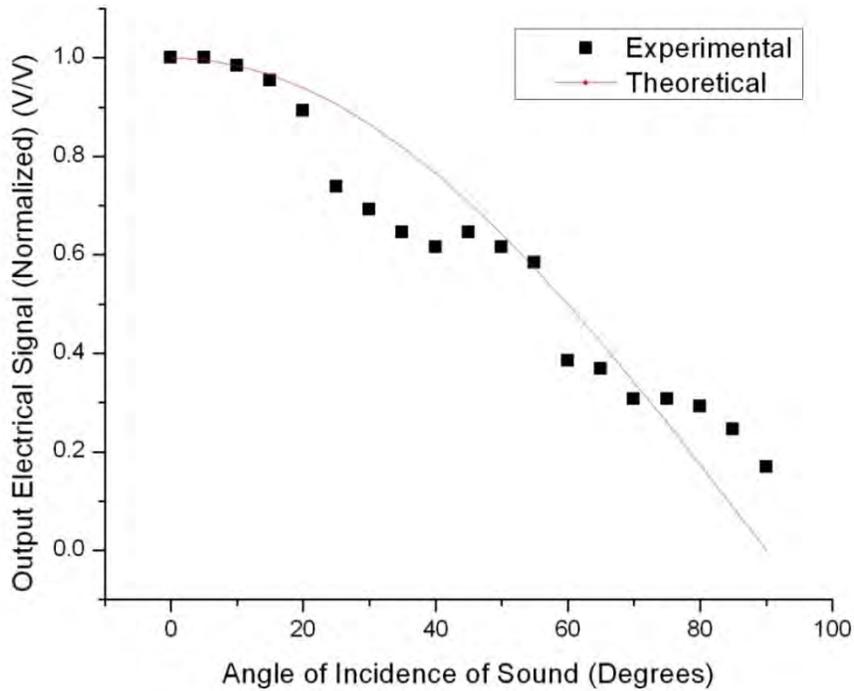
Figure 22.   Plot of output electrical signal against angle of incidence of sound
(solidline shows the expected cosince dependence).

D.   CONCLUSION

In this thesis, the integration of readout electronics with MEMS directional sensors was performed. Initially, the use of the MS3110 die directly connected to the sensor was explored to minimize the parasitic effects. It was found that the die could not be properly programmed to extract the electronic signal from the sensor. This may be either due to difficulty in wirebonding to the relatively small pads on the die without shorting the wires running closer to them or ambient light causing the circuit to malfunction. Initial measurement of the impedance of the die at various terminals indicates that the light is disturbing the circuit characteristics. This led us to use the MS3110 IC and position it closer to the sensor to reduce the parasitic effects.

The circuit functioned properly and the output response from the system was much stronger than that obtained using the evaluation board provided by the manufacturer (Irvine Sensors). It can be concluded that both noise and parasitic capacitances has been successfully suppressed and the performance was much improved in terms of accuracy. The enhancement of the signal was about 4-fold, which can be attributed to the reduction of parasitic capacitance due to longer wires needed when the evaluation board is used for extracting the electrical signal from the sensor.

E. RECOMMENDATIONS AND FUTURE WORK

Much progress has been made in this project to bring the MEMS sound sensor into a military application, which could leads to the ultimate goal of designing with a practical system that could be deployed in the operational theater. This section discusses some of recommendations that could bring us closer to the goal.

The hybrid approach where the MEMS sound sensor is integrated to its MS3110 IC electronics readout has been shown to be feasible. This reignites the idea in using the MS3110 die as the electronic readout for further improving the signal-to-noise ratio. Hence, it is recommended that the integration of the MS3110 die should be revisited by packaging the MS3110 die along and step-by-step programming it for getting the required functionality.

In terms of wirebonding the die, it is recommend that a better control of placing the bonds on the pads can be achieved to avoid the unexpected circuit malfunctioning.

It is also recommended that future experiments to be conducted in an anechoic chamber to ensure the measurement is not affected by the unwanted reflections of sound in a laboratory environment.

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