

Deployment of Piezoelectric Disks in Sensing Applications

by

Mohamed Abdelrahman

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

This thesis builds on and encompassing the following contributions made by collaborators and colleagues:

- Mr. Mohd Faiz developed the relationship between output voltage and exerted force described in Eq. (2.6).
- Mr. Ayon Kumar Das fabricated the glass wafer for the interface circuit.
- The research group of Professor Helene Debede-Hickel, University of Bordeaux, fabricated and provided the piezoelectric disks used to implement the gas sensor described in Chapter 3.
- The research group of Professor University of Waterloo, synthesized and provided the sensitive materials used to implement the gas sensor described in Chapter 3.

Abstract

Micro-electromechanical Systems (MEMS) have revolutionized the way we approach sensing and actuation, offering benefits like low power usage, high sensitivity, and cost efficiency. These systems rely on various sensing mechanisms such as electrostatic, piezoresistive, thermal, electromagnetic, and piezoelectric principles. This thesis focuses on piezoelectric sensors, which stand out due to their ability to generate electrical signals without needing an external power source. Their compact size and remarkable sensitivity make them highly attractive. However, they're not without challenges—their performance can be affected by temperature changes, and they can't measure static forces. These limitations call for advanced signal processing and compensation techniques. Piezoelectric sensors, which operate based on the direct and inverse piezoelectric effects, find use in a wide range of applications, from measuring force and acceleration to detecting gases.

This research zooms in on two key applications of piezoelectric sensors: force sensing and gas detection. For force sensing, the study focuses on developing smart shims that measure forces between mechanical components, which helps prevent structural failures. The experimental setup includes an electrodynamic shaker, a controller, and custom components like a glass wafer read-out circuit and a 3D-printed shim holder. During tests, the system underwent a frequency sweep from 10 Hz to 500 Hz, and a resonance was detected at about 360 Hz, matching the structural resonance. Some inconsistencies in the sensor's output were traced back to uneven machining of the shim's holes and variations in circuit attachment. To address these issues, the study suggests improving the machining process and redesigning the shim holder for better circuit alignment. Future work will include testing for bending moments, shear forces, and introducing a universal joint in the design to study moment applications more effectively.

On the gas sensing side, the research examines a piezoelectric disk with a Silver-Palladium electrode for detecting methane. Using the inverse piezoelectric effect, the sensor's natural frequency was found to be around 445 kHz. When coated with a sensitive material—PANI doped with ZnO—the disk exhibited a frequency shift of 2.538 kHz, indicating successful methane detection. The setup for this experiment included a gas chamber with precise control over gas flow and displacement measurements. Interestingly, after methane was replaced with nitrogen, the natural frequency returned to its original value, demonstrating the sensor's reversible detection capability. Future research will expand to test other gases and sensitive materials, broadening the scope of applications.

In summary, this thesis pushes the boundaries of piezoelectric MEMS sensors by tackling key design and performance challenges. Through detailed experimental methods, results, and suggested improvements, it lays a solid foundation for further research aimed at enhancing the reliability and versatility of piezoelectric sensors in real-world applications.

Acknowledgements

First and foremost, all praise is due to Allah for granting me the strength, guidance, and patience to complete this research.

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Chapter 1

Introduction

Micro-electromechanical Systems (MEMS) can act as both sensors and actuators. They have proven their importance and major role in sensing applications. With their low power consumption, miniaturization, high precision, high sensitivity, and cost-effectiveness, they are now used in lots of sensitive devices. MEMS has a variety of sensing mechanisms such as electrostatic, piezoresistive, thermal, electromagnetic, and piezoelectric. Each with its own advantages and disadvantages is suitable for a different application [3].

Piezoelectricity is a phenomenon where certain materials generate electrical energy in response to mechanical stress and vice versa. This unique property has been extensively explored for various technological applications. Piezoelectric materials function in one of two ways: either through the direct piezoelectric effect or the inverse piezoelectric effect. The direct piezoelectric effect involves the generation of an electric charge on specific surfaces of the material when it is subjected to mechanical stress (such as compression, tension, or bending). This effect is utilized in applications like force and acceleration sensing. Conversely, the inverse piezoelectric effect refers to the mechanical deformation (expansion or

contraction) of the material when an electric field is applied across it, which is used in applications such as ultrasonic transducers, and gas sensing [4, 5]. The first people to discover the direct piezoelectric effect were Jacques and Pierre Curie in 1880. In 1881, Gabriel Lippmann mathematically predicted the inverse piezoelectric effect [6]. However, The first significant applications of piezoelectric devices emerged during World War I. In 1917, P. Langevin and his team developed an ultrasonic submarine detector using a transducer made from thin quartz crystals sandwiched between steel plates, with a resonant frequency of 50 kHz. By the end of the war, they successfully used high-frequency sound waves to measure underwater depth [7]. The most commonly used materials in the sensor technologies are lead zirconate titanate (PZT), quartz, and polyvinylidene difluoride (PVDF). PZT is a piezoelectric ceramic known for exhibiting both direct and inverse piezoelectric effects, offering excellent high-temperature stability and superior electromechanical coupling coefficients compared to quartz. On the other hand, piezoelectric polymers like PVDF have lower piezoelectric performance and reduced stability for various applications. Consequently, despite its lead content, PZT remains the primary material used in most piezoelectric transducers. [8, 9]

1.1 Piezoelectric force sensing

Since the piezoelectric materials are reversible electromechanical converters, the material could be used as mechanical stress sensing element because of the direct piezoelectric effect. When a force is applied to the material (mechanical energy), an electrical charge distribution develops on its surfaces (electrical energy). Piezoelectric material-based sensors are extensively utilized due to their excellent linearity, high sensitivity, and broad frequency response range. They are also active sensors because, in theory, no external energy is re-

quired for obtaining the output signal, since the sensing element and the transduction element are usually the same. This also makes the piezoelectric sensors the best options for force sensing because despite all force sensors need an elastic sensing element whose deformation is dependent on the acting force, there's no need to measure this deformation in piezoelectric sensors, but there's a need to measure the deformation in the other sensors. The direct piezoelectric effect found its initial applications after World War I, with the development of the first sensors for measuring force, pressure, and acceleration—primarily in the context of shock and vibration. These sensors were initially created solely for research purposes, serving specific laboratory experiments. Pressure and acceleration were the first quantities to be measured using piezoelectric sensors, while force sensors were introduced later. Under the quasi-static assumption, which disregards the device's dynamic behavior at resonance, the device can be represented using linear, frequency-independent equations, expressed in equations 1.1 and 1.2, Where ∂ is the deflection or displacement of piezoelectric device, Q is the charge on the terminals of the piezoelectric device, F is the force exerted on the device, V is the voltage across the electrodes, S^V is the compliance under constant voltage, d is the piezoelectric coefficient, and C^F is the capacitance under constant force. Since the piezoelectric materials response depends on the orientation, the piezoelectric coefficient is one of the most important factors to consider for choosing the piezoelectric device because it represents the behavior under mechanical and electrical coupling. The piezoelectric coefficient is usually followed by two subscript number d_{xy} , where x represents the direction of the electric field or the polarization and y represents the direction of the mechanical strain or deformation. For example, d_{33} means that both the electrical field and the strain are in the same direction which is the z-direction in this case. However, d_{31} indicates that the electric field is in the z-direction but the strain is in different direction (in-plan). This shows that the piezoelectric material can be suitable for measuring forces

in different directions and different applications depending on the piezoelectric coefficient [10, 11, 12].

$$\partial = S^V F + dV \quad (1.1)$$

$$Q = dF + C^F V \quad (1.2)$$

1.2 Piezoelectric gas sensing

Piezoelectric sensors have demonstrated exceptional performance in gas detection applications. Gas sensors consist of two primary components: a physical transducer and a selective sensitive material. Piezoelectric gas sensors are highly sensitive to mass changes because the selective material they contain targets specific gases. When exposed to a particular gas, the material absorbs it, leading to an increase in its mass. The natural frequencies are discussed thoroughly in the next subsection with equation 1.6 showing the effect of the mass on the natural frequency. Since, the mass and the natural frequency are inversely proportional, this means that the increase of the mass due to the gas added mass will shift the natural frequency. Thus, the relation between the mass sensitivity (S_m) and the frequency response is shown in equation 1.3 [8].

$$S_m = \Delta f / \Delta M \quad (1.3)$$

The advantages of using the piezoelectric sensors for gas detection are the relatively easy fabrication and use, the low cost, the high quality factor. It also has a wide range for

sensing with the natural frequencies going to up to 5 MHz.

1.2.1 Oscillators and mode shapes

Resonance takes place when a system oscillates at its natural frequency in response to an external force of the same frequency. Every physical system possesses one or more natural frequencies, which are determined by its mass, stiffness, and damping characteristics. When the frequency of the applied force aligns with the system's natural frequency, the amplitude of oscillation increases significantly, potentially leading to intense vibrations. This phenomenon can be advantageous, as seen in musical instruments, or detrimental, causing structural failures in bridges or machinery. To control the effects of resonance and maintain system stability, damping mechanisms are commonly employed. In MEMS, however, resonance proves beneficial, as many sensing applications rely primarily on identifying the resonance due to its high signal-to-noise ratio and the ease of pinpointing the natural frequency. Resonance also corresponds to a specific mode shape, which can be utilized for various sensing purposes. The quality factor and mode shape are critical in determining which natural frequency to target for optimal performance [13, 14]

The equation used to calculate the quality factor Q is given in equation 1.4, where f_0 represents the natural frequency, and Δf is the bandwidth between f_1 and f_2 . The frequencies f_1 and f_2 are determined using equation 1.5, which provides an effective method for evaluating the quality factor Q in linear systems [15].

The quality factor Q is defined as:

$$Q = \frac{f_0}{\Delta f} \tag{1.4}$$

The half-power bandwidth is given by:

$$\text{Half-power bandwidth} = \frac{\text{Peak displacement}}{\sqrt{2}} \quad (1.5)$$

Each natural frequency corresponds to a unique pattern of motion, known as the mode shape. While similar structures share the same mode shapes, their corresponding natural frequencies may differ. Piezoelectric disks exhibit standard disk mode shapes, which are characterized by two numbers (x, y) . The first number (x) represents the number of nodal diameters (lines with no motion), while the second number (y) indicates the number of nodal circles (regions with no motion).

For instance, the first mode shape $(0, 1)$, shown in Figure 1.1(a), has no nodal diameters and one outer nodal circle at the edge, as the entire surface moves up and down with the center having the highest displacement. In contrast, the second mode shape $(1, 1)$, depicted in Figure 1.1(b), has one nodal diameter. Comparing these two modes with Figure 1.1(c), it becomes increasingly difficult to identify the mode shapes at higher natural frequencies.

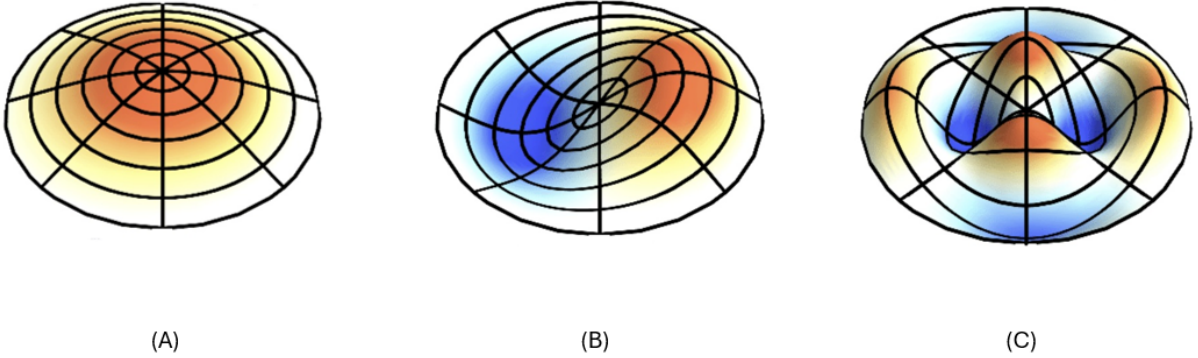


Figure 1.1: (a) Mode $(0,1)$ - (b) Mode $(1,1)$ - (c) Mode $(2,2)$ [1]

The natural frequencies for a simple harmonic oscillator f is given by:

The natural frequency of a simple harmonic oscillator, f , is expressed as:

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad (1.6)$$

similar to that of a mass-spring system, where k is the spring constant and m is the mass. This relationship indicates that the natural frequency is inversely proportional to the mass. Therefore, any additional mass applied to the piezoelectric disk will result in a downward shift in its natural frequency [16, 17].

Chapter 2

Force Sensing

This sensing apparatus deploys commercially available piezoelectric disk elements to measure pressure forces applied to the face of a shim. The aim of the apparatus is to create smart shims that can sense the interaction forces between two mechanical components where the shim serves as their interface. The apparatus can serve as either an independent safety measure for the mechanical integrity of the structural parts on either side of the shim, by detecting instances where the applied forces exceed their safe load limits, or as a part of an integrated health monitoring system for the parent structural system.

2.1 Apparatus

The apparatus is made of a solid aluminum shim equipped with four circular seats, Figure 2.1. Identical piezoelectric elements, Physik Instrumente's PIC 255 [2], are fitted into those seats. The physical properties of the sensor elements are listed in Table 2.1. The electrodes on the piezoelectric elements are completely separated, with one located on top and the

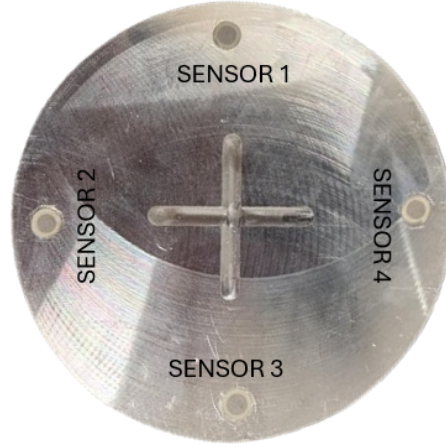


Figure 2.1: Aluminum shim fitted with 4

other on the bottom.

Table 2.1: Properties of PIC 255 [2]

Property	Symbol	Unit	PIC 255
Density	ρ	kg/m ³	7800
Curie temperature	T_c	C	350
Piezoelectric charge coefficient	d_{33}	pC/N	400
Elastic stiffness coefficient	C_{33}^D	GPa	161
Mechanical quality coefficients	Q_m		80
Temperature coefficient ϵ_{33}^T	TK ϵ_{33}	1/k	3×10^{-3}

The sensor elements, PI PIC255 [2] sensors, have a diameter of 5 mm and a thickness of 0.5 mm. They are shown fitting inside their seats within the shim in Figure 2.1. The sensors are made of lead zirconate titanate. They exhibit a high coupling factor.

The shim is grounded and serves as a part of the read-out circuit. It comes into contact with the bottom electrode of each sensor element. An interface interface circuit comes

into contact with the top electrodes to close the circuit on the sensor elements. The shim diameter is $D = 76$ mm. Each sensor seat is less than 0.5 mm deep to ensure that the sensors protrude above the shim’s face as shown schematically in Figure 2.6.

Using three sensors instead of four can simplify the alignment of the shim and sensor elements with the interface circuit by creating a single contact plane. However, this can create misalignment between the front and back surfaces of the shim assembly thereby undermining its functionality as a reference aligner between the parent mechanical components.

2.2 Experimental Setup

A schematic of the experimental setup designed to test and demonstrate the apparatus is shown in Figure 2.2(a). A picture of the realized and assembled test rig is also shown Figure 2.2(b). In this setup, a closed loop controlled electrodynamic shaker applies a commanded acceleration signal, with a known amplitude and frequency, to the shim-interface circuit assembly. The shim is mounted to a holder for alignment and support purposes. In turn, the shim holder is mounted to a pair of parallel linear guides allowing it to move freely under forces applied by the shaker. Four springs separate the back plane of the shim holder from a fixed reaction wall, thereby turning the commanded acceleration signal into a pressure force on the shim face. The experimental setup, shaker, linear guides, and reaction backplate, is securely mounted to a common rigid platform to prevent relative motion except for that of the shim holder along the linear guides.

An electrodynamic shaker (Labworks Inc. ET-126B-1 [18]), shown in Figure 2.3, was used to apply force to the experimental setup. This model supports frequencies up to

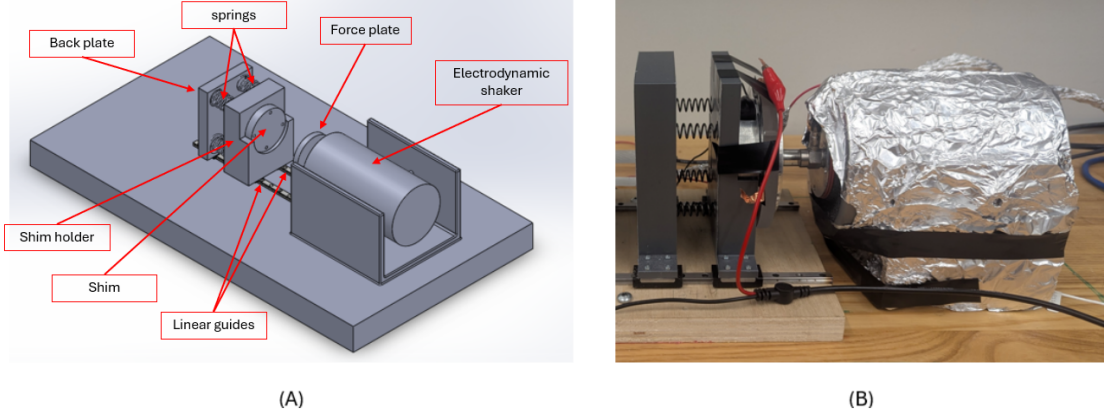


Figure 2.2: (a) A schematic and (b) a picture of the experimental setup.

8.5 kHz, significantly exceeding the frequencies range of the experimental apparatus (10–1000 Hz). The shaker can apply peak forces up to $F_p = 57.8 \text{ N}$ with a stroke length of up to $x_u = 19 \text{ mm}$ and acceleration amplitudes up to $A_u = 125g$. A power amplifier (Labworks Inc. PA-138) [19] drive the shaker with an output of 25 V (RMS) and 20 A (RMS).

The shaker is driven in close loop mode. An accelerometer mounted on the shaker head provides the feedback signal to the drive controller. The accelerometer (Dytran 3055B3) [20] shown in Figure 2.3 has a sensitivity of 500 mV/g, measurement range of $\pm 10 \text{ g}$, and a frequency range of 1 Hz – 10 kHz. The controller (VR9500) [21] provides control over the acceleration, frequency, and sweep duration. It allows for both single frequency and frequency sweep test modes.

A force plate made of aluminum, Figure 2.4, is attached to the shaker head to apply forces uniformly to the shim-interface circuit assembly. Its diameter matches that of the shim. It acts on the interface circuit, which consists of a glass wafer mounted on an acrylic backplate both with a diameter of 100 mm. This acrylic backplate serves as a support to prevent to protect the brittle glass interface circuit during testing.



Figure 2.3: electrodynamic shaker (Labwork Inc. ET-126B-1) and Accelerometer (Dytran 3055B3)

The interface circuit is made of a glass wafer 0.5 mm thick. Four rectangular pads, made by depositing 1 μm thick aluminum (AL) on the wafer, are equally distributed around the perimeter to serve as contact pads with the sensor's top electrodes, Figure 2.5. They are labeled in the figure as Sensor 1 to 4. Copper tape is attached to each contact pad to act as bonding ribbon and facilitate connection to the oscilloscope's probes. The diameter of the interface circuit is larger than that of the shim to allow access for the bonding ribbons into the contact pads. A schematic side view of the assembled shim (apricot), sensor elements (navy blue), and interface circuit (gray) is shown in figure 2.6

The shim holder is 3D printed out of polylactic acid (PLA). The holder features a rectangular shape. The front face of the holder features a semi-circular shelf extending outward from its surface, with a thickness less than that of the shim. The shim rests on the shelf while its face remains exposed to the interface circuit. It also ensures that the centers of the force plate, the interface circuit, and the shim are aligned. The assembly is

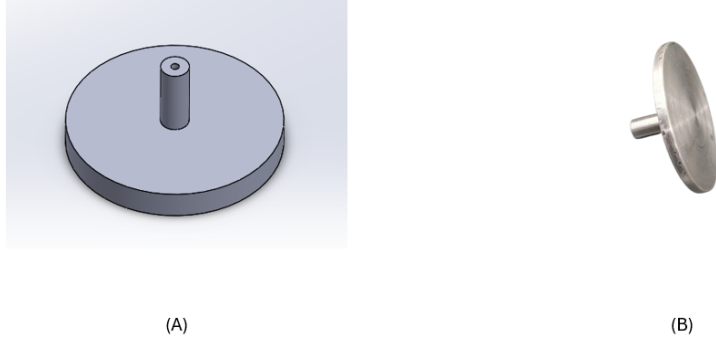


Figure 2.4: (a) A 3D Model and (b) the fabricated shaker head

shown in Figure 2.2.

Four spring seats are built into the back of the shim holder, as shown in Figure 2.7. These spring holders are positioned such that the intersection point of the lines connecting diagonally opposite springs C_{sh} aligns with the center of the shim. The shim holder is mounted on two linear guides (CPC, MR7MLSUV0N-300-7.5-7.5) to maintain alignment and eliminate friction forces as the shim holder moves during testing.

Four springs are inserted into the spring seats at the back of the shim holder and the counter seats on the front face of the fixed backplate as illustrated in Figure 2.2. This design with the springs supporting the shim holder as it moves along the linear guides enforces continuous contact between the force plat and the shim-interface circuit assembly and completes the mechanical circuit of the reaction wall. Springs with a linear stiffness of $k = 0.7605 \text{ N/mm}$ were acquired to construct the reaction wall. Their effective stiffness is $k = 3.042 \text{ N/mm}$ which is consistent with the ratio of the peak force F_p to the maximum stroke x_u of the shaker at $F_p/x_u = 3.034 \text{ N/mm}$. To keep the shim face under compressive stresses throughout the motions of the shim holder as the shaker head

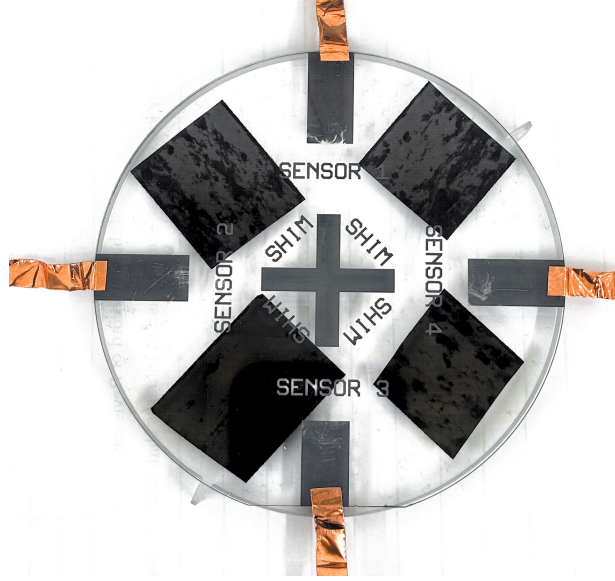


Figure 2.5: The interface circuit mounted to its acrylic backplate

oscillates, the backplate is placed to create a pre-compression force F_c along the mechanical circuit while the shaker is stationary.

2.3 Experimental procedure

2.3.1 Debugging of the experimental setup

A three-axis accelerometer (Analog Devices, ADCMXL3021BMLZ) [22] is mounted at point C_{sh} on the back face of the shim holder to measure the realized accelerations. It is set such that the z-and x-direction are aligned with the actuation direction and gravity, respectively, while its y-direction remains passive. The acceleration components were discretized and recorded using the acceleroameter's native hardware (ADCMXL-BRKOUT/PCBZ) and software interfaces (ADCMXL Evaluation Software). Typical accelerometer output

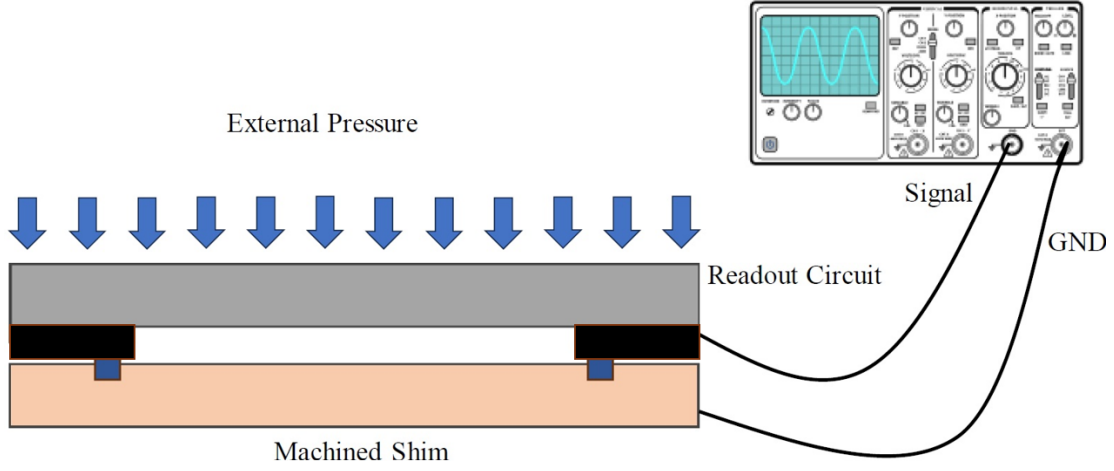


Figure 2.6: A schematic of the read out circuit

when the experimental setup is aligned correctly is shown in Figure 2.8. In this case, the shaker was commanded to supply an acceleration amplitude of $A = 0.05$ g and frequency of $f = 1.5$ Hz after 7.1 s of the start of data collection.

The x-component's mean and standard deviation are found to be $a_x = -0.9810 \pm 0.0016$ g, the y-component's mean and standard deviation are $a_y = 0.0106 \pm 0.00166$ g and the z-component's mean and standard deviation are $a_z = 0.0089 \pm 0.0421$ g (evaluated only over the commanded portion of the time-history). It can be seen that the standard deviations of the acceleration components along the unactuated x- and y-directions are negligible (on the order of 10^{-3} g) compared to the actuated z-direction indicating minimal feed-through signal (cross-talk) into those directions. Any deviation from this signature, an elevated level of standard deviation in the x- and y-directions on the order of 10^{-2} g, would indicate misalignment. The setup should be revised in such a case to bring them to levels similar to those shown above. The mean of the y-component, which indicates misalignment with respect to the gravitational field, is two orders-of-magnitude less than that of the x-component, which is another indicator of correct alignment with respect to

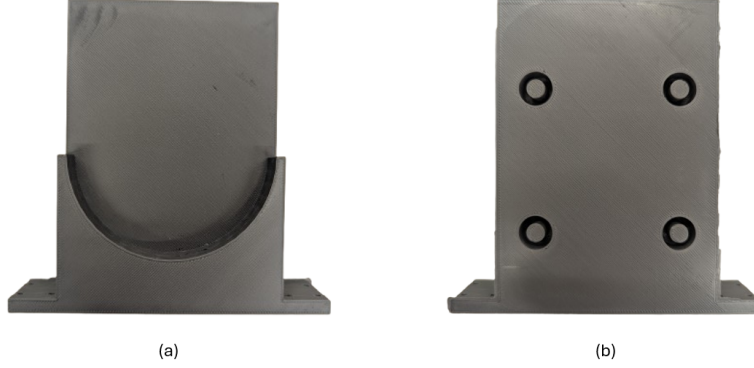


Figure 2.7: (a) Front view and (b) back view of the shim holder

the gravitational field. Finally, the mean of the z-component indicates minimal zero-bias in the actuation signal. A similar procedure and should be used to check for proper alignment, actuation, and minimal feed-through before commencing with test and calibration of the sensing apparatus.

It was found that the power amplifier of the electromagnetic shaker used to implement the reaction wall has a feed-through signal at 60 Hz. This signal results in residual vibrations of the shaker head as soon as the amplifier is powered, irrespective of the presence or absence of an actuation signal. An accelerometer was placed on the shaker head and used to measure its acceleration while the power amplifier was powered on and the commanded output signal was set to zero ($A = 0$). Figure 2.9 shows the FFT of the measured acceleration magnitude. The RMS of the feed-through acceleration at $f = 60$ Hz was found to be $a = 0.0831$ g. This ‘zero bias’ should be noted in all results reported in this thesis.

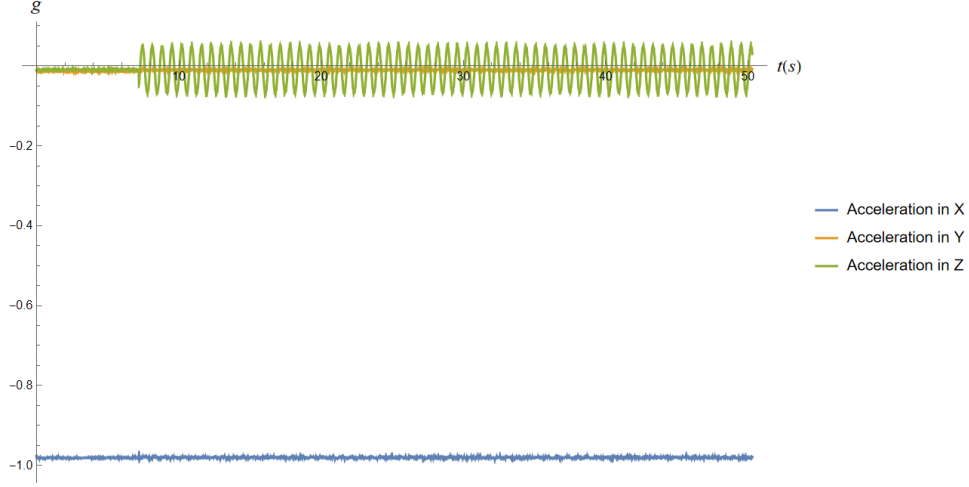


Figure 2.8: The measured acceleration components of the shim holder

2.3.2 Data collection

The sensor output signal was amplified using a voltage amplifier (Tabor Electronics 9200) at a gain of $\times 15$, then discretized at a sampling rate of 5 kHz and recorded using a digital oscilloscope (Keysight DSOS204A). Each sensor output was measured independent of the others under identical test conditions. The time-history and FFT of the measured output signal of Sensor 2 under forcing with an acceleration amplitude of $A = 1g$ and a frequency of $f = 500$ Hz are shown in Figure 2.10. The measured signal that the commanded reaction force at $f_1 = 500$ Hz has been modulated with a lower uncommanded signal at $f_2 = 60$ Hz. This can be seen clearly in the FFT. Although most of the signal power resides in the commanded signal and its harmonics, the modulating signal is not negligible.

While the feed-through acceleration described above forms a part of this signal, we investigated whether the background electromagnetic radiation of the electrical mains contributed to the electrical noise of the readout circuit at this frequency.

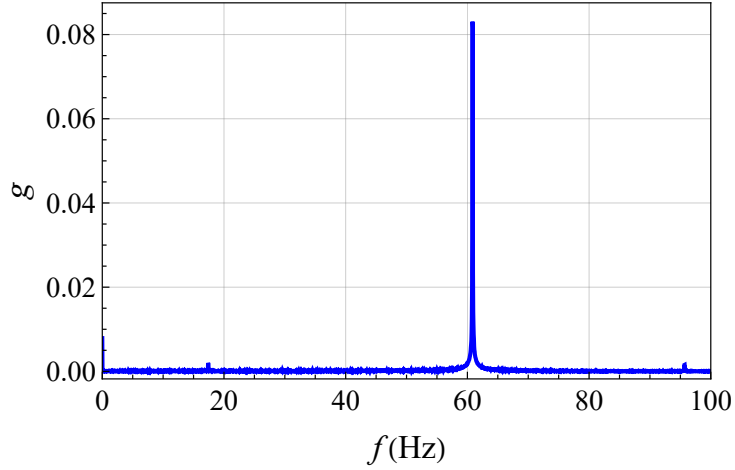


Figure 2.9: FFT of the shaker head feed-through acceleration

To reduce electromagnetic radiation in the vicinity of the experimental setup, additional insulation was added to the shaker body and power cords of the experimental setup by wrapping them in aluminum foil, as shown in Figure 2.2(b). The foil, the force plate, and the shim were grounded. As a result, the RMS of the power in the modulating signal dropped from 1.23 V to 0.274 V, Figure 2.11, indicating electrical background noise was a major contributor in that signal. Therefore, experimental test and calibration in a lab environment should take into account reduction of this noise source.

2.3.3 Configuring the experimental setup

To prepare the experimental setup, the sensor elements are first placed in their designated seats within the shim face. The shim is then placed into the shim holder. The interface circuit is placed on top of the shim such that its contact pads are in direct contact with the top electrodes of the four sensor elements and secured in place using adhesive tape. A compressive pre-load force of 52 N is then applied to the springs between the shim holders

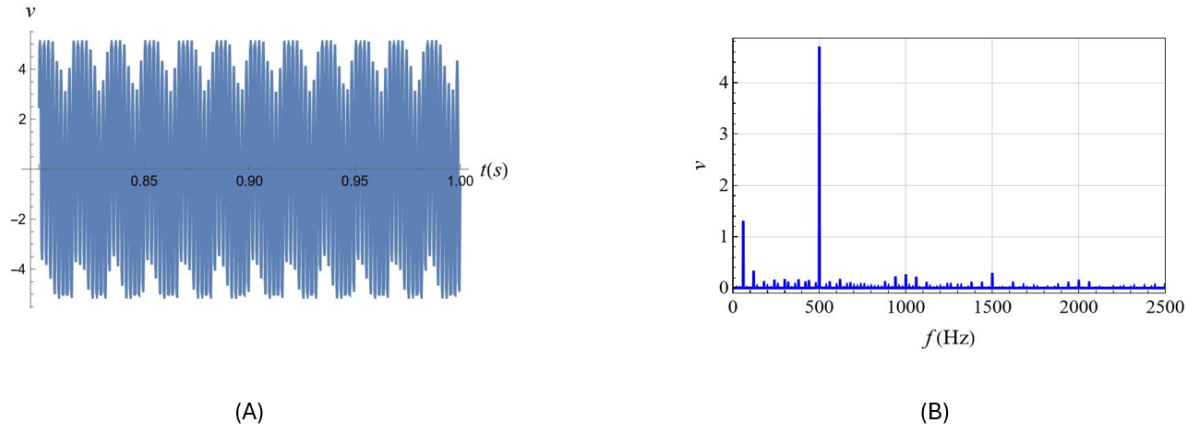


Figure 2.10: (a) The time-history and (b) FFT of Sensor 2 output signal

and backplate pushing the backplate until the shaker head moves to the beginning of its stroke from the neutral (mid-stroke) point. This pre-load is set to maintain the sensor elements under compressive load throughout the load cycle and to guarantee continuous contact between the force plate and the interface circuit throughout the cycle.

We note that the experimental setup constitutes a reaction wall. The forces exerted by the wall are proportional to the spring compression. This in turn will vary with frequency and approach maxima at the setup natural frequencies. We found its fundamental (lowest) natural frequency using equation (1.6). The system mass was found to be $m = 0.5 \text{ kg}$. Using the effective spring stiffness listed in section 2.2, the frequency was found to be $f = 26 \text{ Hz}$.

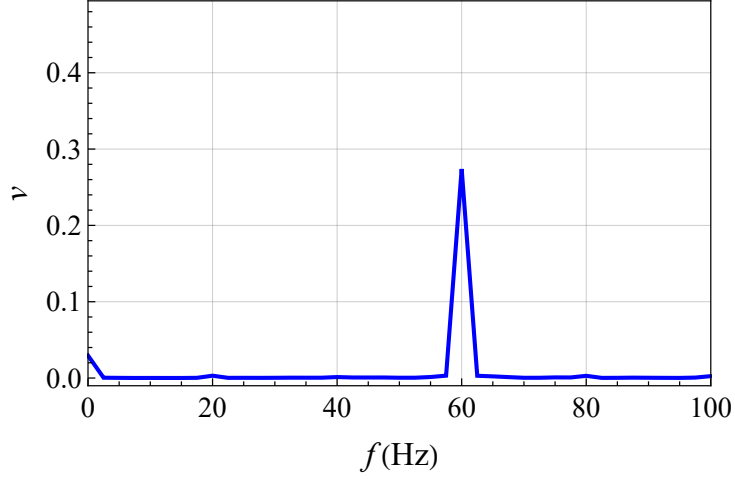


Figure 2.11: FFT of Sensor 2 output after electromagnetic shielding and grounding

2.4 Results

2.4.1 Frequency-response curves

The shaker was commanded to supply a frequency up-sweep from 10 Hz to 500 Hz over one minute, corresponding to a slew rate of 8.17 Hz/s. Previous testing has shown that measurements are stationary under slew rates less than 10 Hz/s. The sampling rate of the digital oscilloscope was set to 5 kHz. Independent tests were conducted for three levels of reaction forces resulting from acceleration levels of $A = 1$ g, 1.5 g, and 2 g. The recorded time histories for the measured signal output were then processed to calculate the RMS of the time-domain signal as a function of frequency [23]. The frequency-response curves of Sensors 1–4 obtained via this method are shown in Figures 2.12–2.15, respectively.

The sensor output increases monotonically with the pressure force. It also increases with frequency up to a peak at $f = 360$ Hz before dropping again. This peak is a result of the experimental setup encountering a resonance at that frequency. Various structural

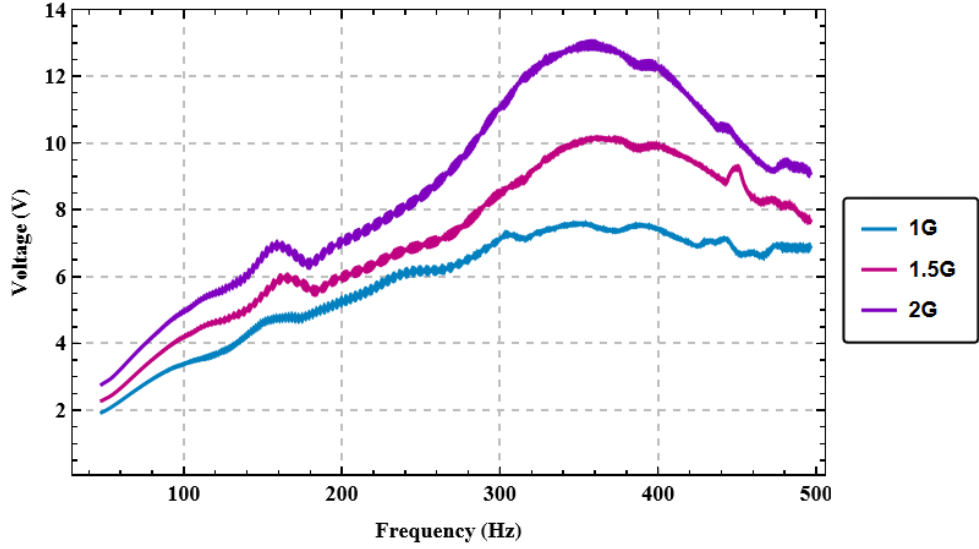


Figure 2.12: The frequency-response curves of Sensor 1 for forces produced by a reaction wall under acceleration levels of $A = 1\text{ g}$, 1.5 g , and 2 g

components will have their distinct resonances which, in general, will not match that of the experimental setup or be the same for various shims. Integrating smart shims into an overall health monitoring system for the parent structure will, therefore, require a training phase where the system ‘learns’ the locations of those resonances for the healthy structure. It can then use this learned signature and then changes it experiences over time, in the locations and amplitudes of the resonant peaks as well as overall changes in the frequency response curve shape and level, as indicators of structural degradation and structural faults.

Variations are observed among the four sensors' frequency-response curves in both their shape and peak. Sensors 1 and 2 have the same functional relationship and their peaks are close to each other at 13.1 V and 13.5 V , respectively. Similarly, Sensors 3 and 4 have the same functional relationship and the same peak at 8 V . The consistency of each pair of sensors compared to the other pair is evidence that the underlying cause of these differences is due to the interface circuit lying at an inclination with respect to the shim face.

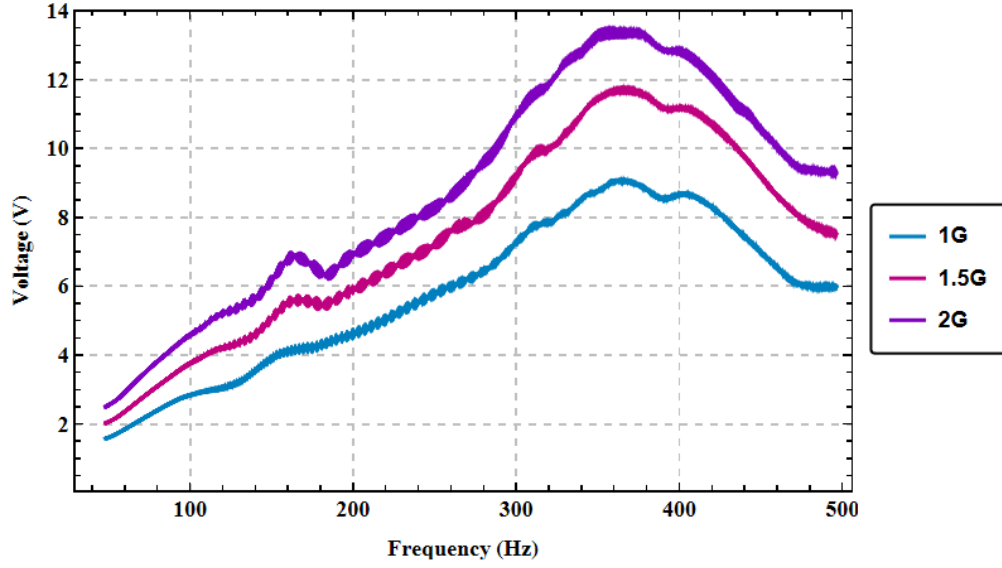


Figure 2.13: The frequency-response curves of Sensor 2 for forces produced by a reaction wall under acceleration levels of $A = 1\text{ g}$, 1.5 g , and 2 g

Two factors lie at the root of this inclination. The first is the inconsistency between the depth of the sensor element seats. Given that the standard tolerance of commercial shims is on the order of $100\text{ }\mu\text{m}$, this factor is irreducible. Instead, the variation among the frequency-response curves of the sensors need to be ‘learned’ as a part of the initial calibration of the smart shim.

The second factor is related non-repeatability of the method used to attach the interface circuit to the shim. The circuit is manually attached to the shim face by tapping the circuit backside to the shim holder backside. This results in the application of inconsistent compression forces across the shim face. A proposed solution to address this factor is described in Chapter 4.

To verify the absence of hysteresis in the sensing apparatus, a comparison between sensor 2 to forward and backward frequency sweeps was done. The frequency-response

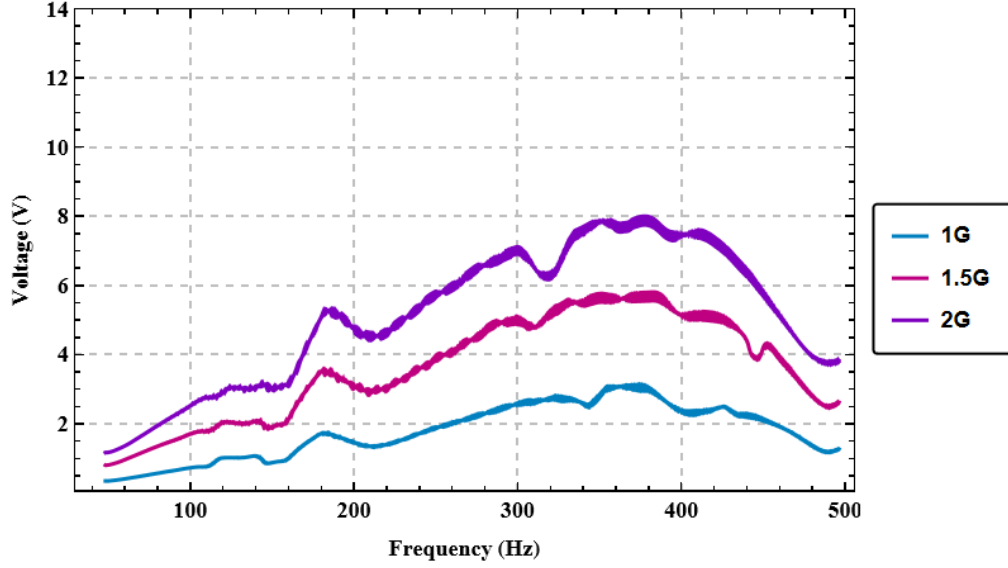


Figure 2.14: The frequency-response curves of Sensor 3 for forces produced by a reaction wall under acceleration levels of $A = 1\text{ g}$, 1.5 g , and 2 g

curves of both sweeps are shown in Figure 2.16. The results show that while the response has similarity in the curve shape, there's difference in the magnitude between both of them.

2.4.2 Voltage-force relationship

To interpret the measured signal, we develop here the relationship between the signal, voltage across the piezoelectric element leads, and the force acting on the element surface. The charge Q developing across the electrodes of a piezoelectric element is related to the force F acting on the element by

$$Q = dF$$

where d is the element charge sensitivity. The electrodes across the element form a capacitor and the charge collect on the electrodes (capacitor plates is related to the to the voltage

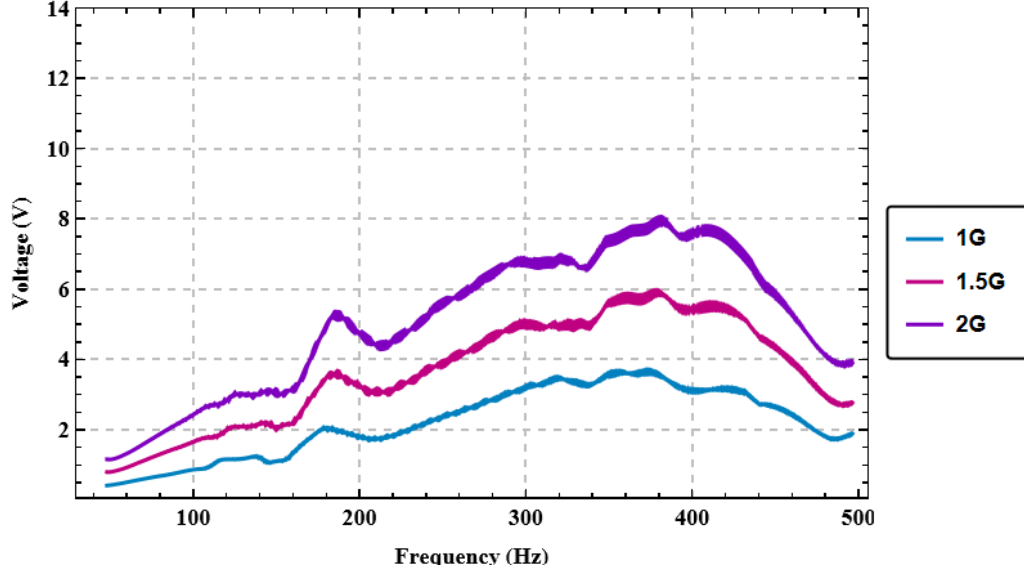


Figure 2.15: The frequency-response curves of Sensor 4 for forces produced by a reaction wall under acceleration levels of $A = 1\text{ g}$, 1.5 g , and 2 g

across them by

$$Q = CV$$

where C is its capacitance. Therefore, we can write that

$$VC = dF \tag{2.1}$$

where V is the output voltage and C is the capacitance. Given a common electrode area A and an element thickness (distance between the electrodes) of t , we can write the capacitance as

$$C = \frac{\epsilon A}{t}$$

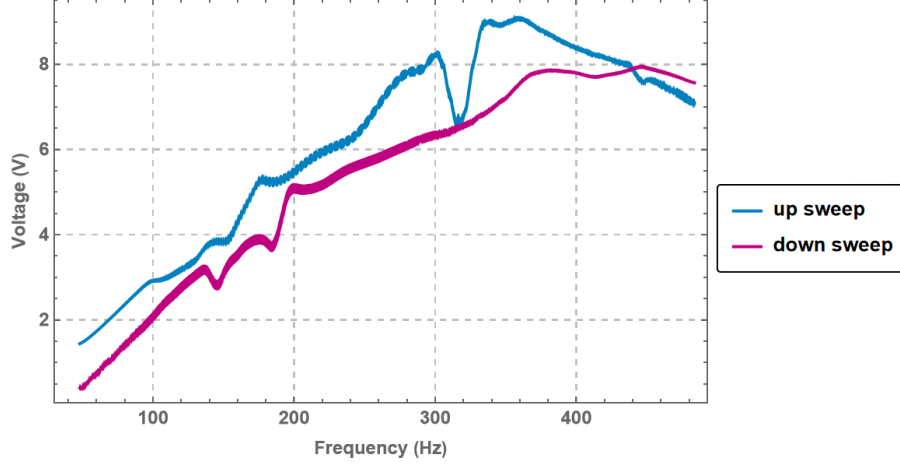


Figure 2.16: The frequency-response curve of Sensor 2 during forward and a backward frequency sweeps in the range of 10–500 Hz

where ϵ is the piezoelectric absolute permittivity. Using this expression in equation (2.1), we can write the output voltage as

$$V = \frac{dFt}{\epsilon A} \quad (2.2)$$

Under a compressive force F , the piezoelectric element will deform from an unstressed thickness of t_0 to

$$t = t_0 \left(1 + \frac{F}{A'Y} \right) \quad (2.3)$$

where A' is the element cross-sectional area and Y is Young's modulus. The change in the electrode area can be expressed as

$$A = A_0 + \frac{\pi}{4} (\Delta D)^2 + 2D_0(\Delta D)$$

where D_0 is the electrode undeformed diameter.

The change in the diameter can be written as

$$\Delta D = -\frac{vF}{A'Y}D_0 \quad (2.4)$$

where v is Poisson's ratio. Therefore, the deformed electrode area can be written as

$$A = \frac{\pi}{4}D_0^2\left[1 + \frac{v^2F^2 - 2A'YvF}{A'^2Y^2}\right] \quad (2.5)$$

Substituting with Eqs. (2.3) and (2.5) in Eq. (2.2), the relationship between the applied force and the output voltage can be expressed as

$$V = \frac{dF}{\epsilon} \frac{Yt_0(A'Y + F)}{Y^2A'^2 + v^2F^2 - 2A'YvF} \quad (2.6)$$

Chapter 3

Gas Sensing

In this test, a Lead Zirconate Titanate (PZT) piezoelectric disk with a Silver-Palladium electrode and a diameter of 4 mm was used. The disk has an electrical conductance of 50.6 mS. Before characterization, the expected natural frequency was approximately 460 kHz. The method used to fabricate the disk is screen-printing method.

The method used in this test is the inverse piezoelectric as there was an electric field applied on the disk, and then its motion was observed. The theory behind this gas testing is already discussed in the introduction chapter. The advantages of using this method is cost-effectiveness, scalability, material efficiency, thickness control, customization patterns [8].

3.1 Preparation and characterization

3.1.1 Preparation of disks

The disk was received with two wires welded to its top and bottom electrodes, which were connected on the other ends to another two electrodes for electrical connections purposes. As a result, the disk itself was suspended in the air without any support as shown in Figure 3.1. Since the measurements in this experiment are done optically, it was essential to secure the disk to a support structure to eliminate any unintended movement and ensure that all motion originated solely from the electrical excitation. A rectangular acrylic piece 2 cm x 3 cm was used as the platform for the disk. The 2 electrodes for electrical connections were welded to conductive tape and attached to the acrylic piece which also made it easier for electrical connection. The disk was mounted on a small acrylic piece to ensure it was no longer suspended in the air. This configuration is shown in Figure 3.2. A check of the electrical conductivity between the tape and the wires showed good conductivity.



Figure 3.1: Piezoelectric disk as received

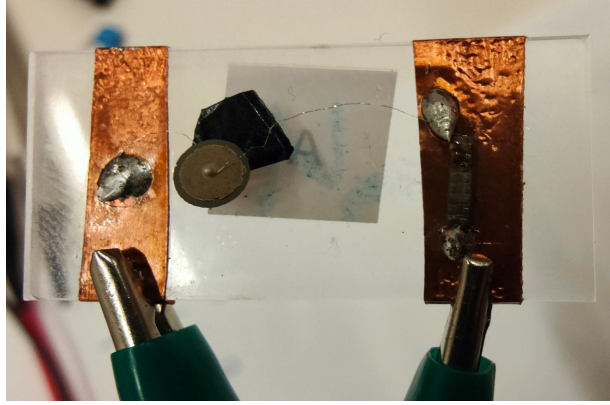


Figure 3.2: Sensor with acrylic support

3.1.2 Characterization of the piezoelectric disk

To characterize the piezoelectric disk, a frequency sweep analysis was conducted from 1 kHz to 1 MHz with an excitation voltage of 20 V PK-PK and a duration of 0.01 s. The analysis was performed using the PICOSCALE Vibrometer [24] with a sampling frequency of 5 MHz. The results, shown in Figure 3.3, reveal multiple natural frequencies, with the highest response occurring around 480 kHz.

To further investigate the nature of these natural frequencies, a mode shape analysis was carried out, focusing on the frequencies below 100 kHz and those between 400 kHz and 600 kHz, which exhibited the highest amplitude response.

The first modal analysis was performed on the natural frequency at 24.1 kHz, which corresponds to the first clear peak. This analysis revealed that the mode is the second-order flexural mode (2,1), characterized by two nodal diameters and one nodal circle at the edge. This can be identified from the amplitude and the phase in Figure 3.4. This is a non-axisymmetric mode since there's no rotational symmetry.

The second natural frequency analyzed was at 32.9 kHz. The mode shape for this

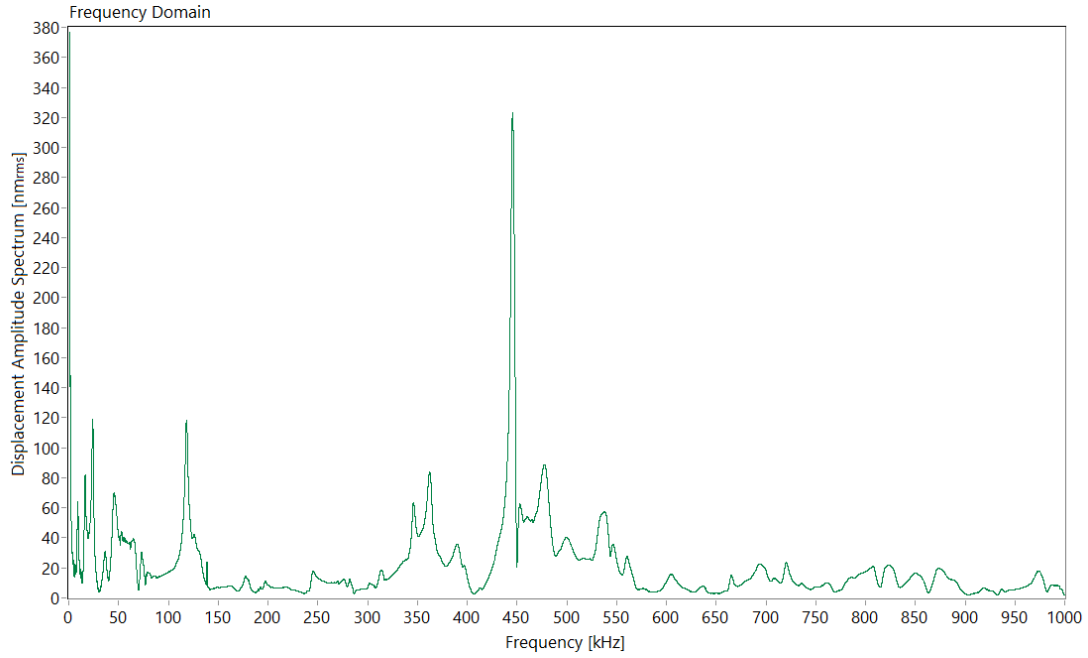


Figure 3.3: Displacement response to a frequency sweep from 1 kHz to 1 MHz

frequency, shown in Figure 3.5, was identified as the second radial mode, characterized by two nodal circles. Although the mode shape was not as distinct as that of the first mode, the amplitude still indicates a second nodal circle in addition to the one at the edge, with no nodal lines present, and this proves it's the (0,2) mode.

To analyze the higher natural frequencies between 400 kHz and 600 kHz. A second frequency sweep, shown in Figure 3.6, revealed three distinct peaks at 445 kHz, 463 kHz, and 474 kHz. The peaks at 463 kHz and 474 kHz interfere with each other due to their proximity, making it challenging to accurately identify their mode shapes and quality factors. However, the natural frequency at 445 kHz exhibited a strong amplitude and a narrow bandwidth, indicating a high quality factor.

Since the mode shapes include both nodal lines and nodal circles—where no movement

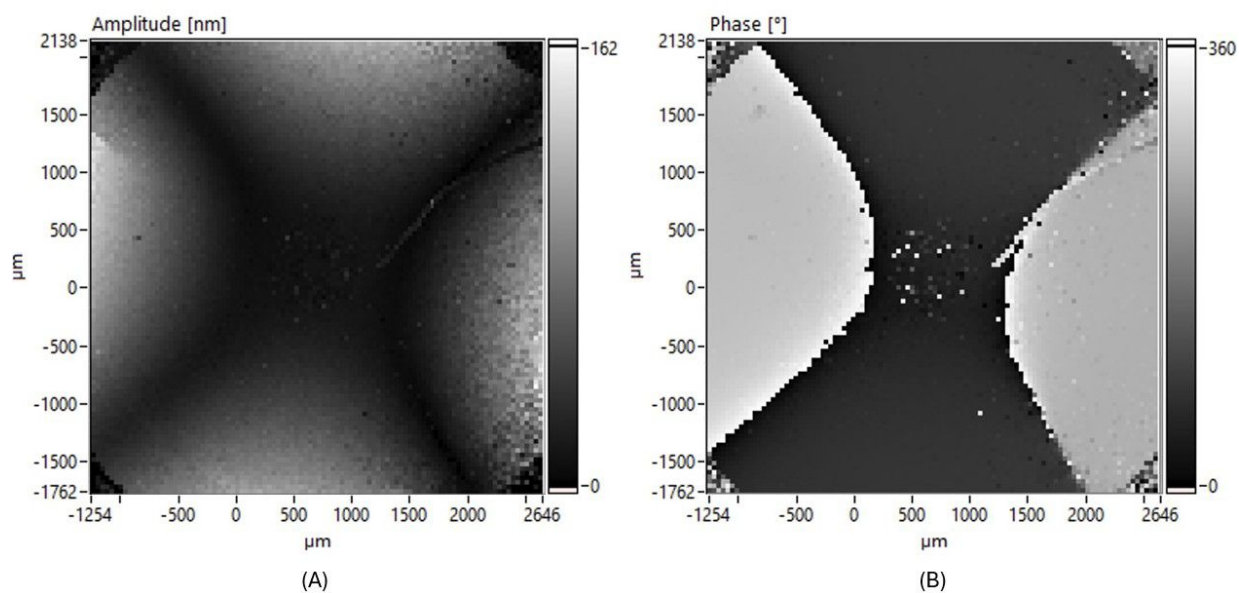


Figure 3.4: (a) Amplitude response (b) Phase

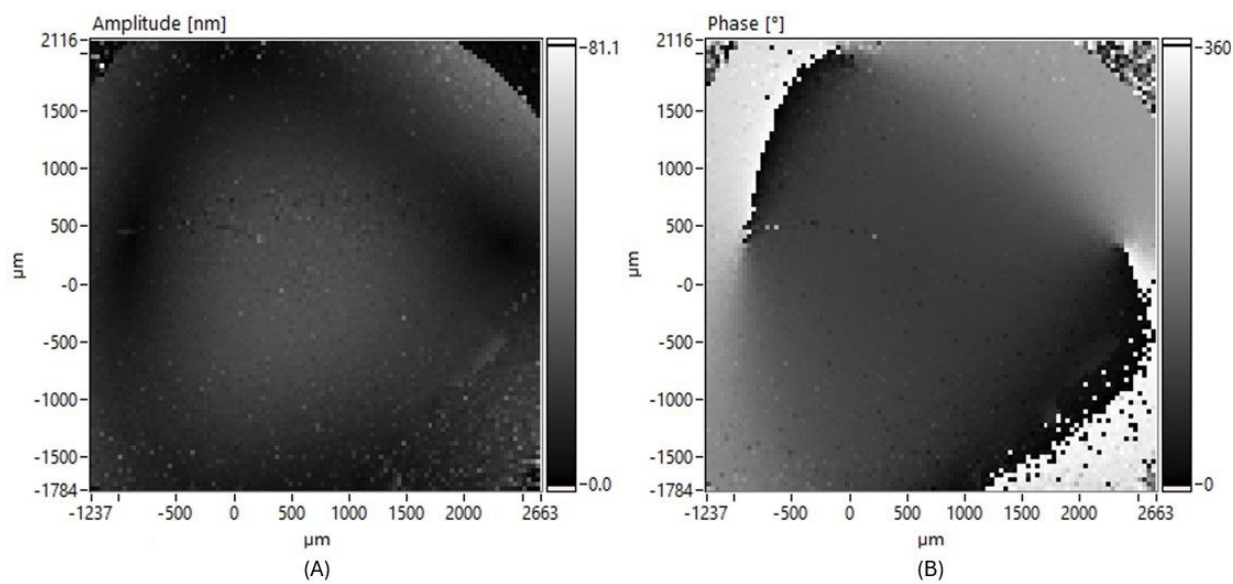


Figure 3.5: (a) Amplitude response (b) Phase

occurs—it is crucial to carefully position the vibrometer’s laser spot. To address this, the laser was moved from its initial position (A) to a new position (B), as shown in Figure 3.7.

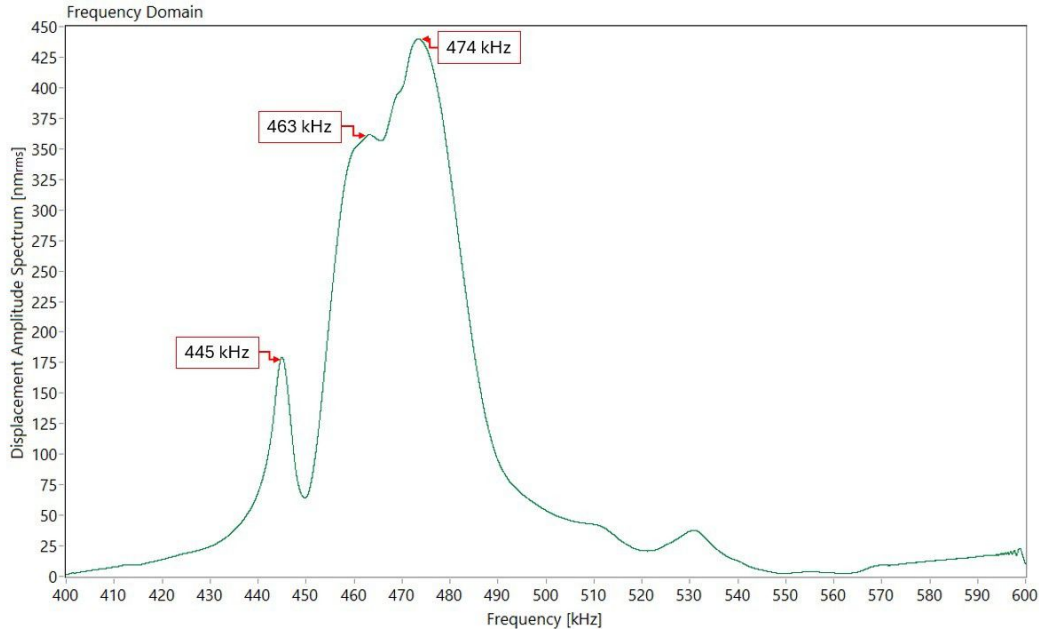


Figure 3.6: Displacement response to frequency sweep from 400 kHz to 600 kHz (first position)

With the change in laser position, the first natural frequency at 445 kHz showed a higher displacement amplitude, the second natural frequency at 463 kHz exhibited a significantly lower displacement amplitude (with the laser near a node), and the third natural frequency at 474 kHz displayed no displacement at all (with the laser positioned at a node), as shown in Figure 3.8. A new peak appeared at 477 kHz, but it was of little interest compared to the strong response at 445 kHz.

The natural frequency was more precisely identified as 445.329 kHz, with a displacement amplitude of approximately 324 nm RMS. Its mode shape was subsequently analyzed. As shown in Figure 3.9, this mode shape was more challenging to identify than the first few

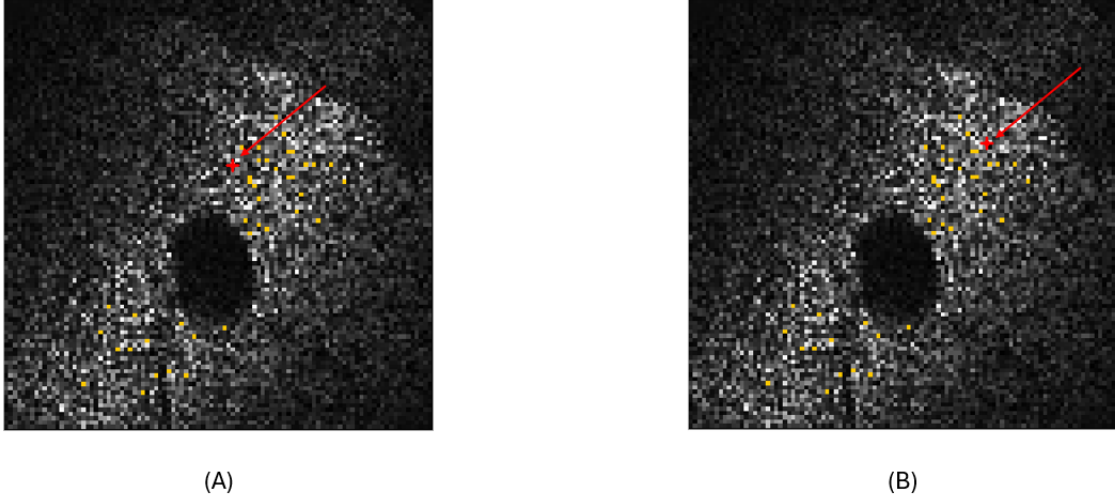


Figure 3.7: (A) First position of the laser spot. (B) Second position of the laser spot

modes, making the use of animation essential for accurate identification. This mode shape features four nodal lines and two nodal circles, classifying it as the (4,2) or fourth-order flexural mode.

The quality factor of the natural frequency's peak was calculated using the half-power level which is determined using 324 nm as the peak displacement in Equation 1.5, yielding f_1 and f_2 at 444 kHz and 447 kHz, respectively. By substituting f_1 , f_2 , and 445 kHz as f_0 into Equation 1.4, the quality factor is calculated to be approximately 148. This value indicates that the system exhibits a relatively sharp resonance peak, a characteristic of a high-quality factor, which is advantageous for sensing applications.

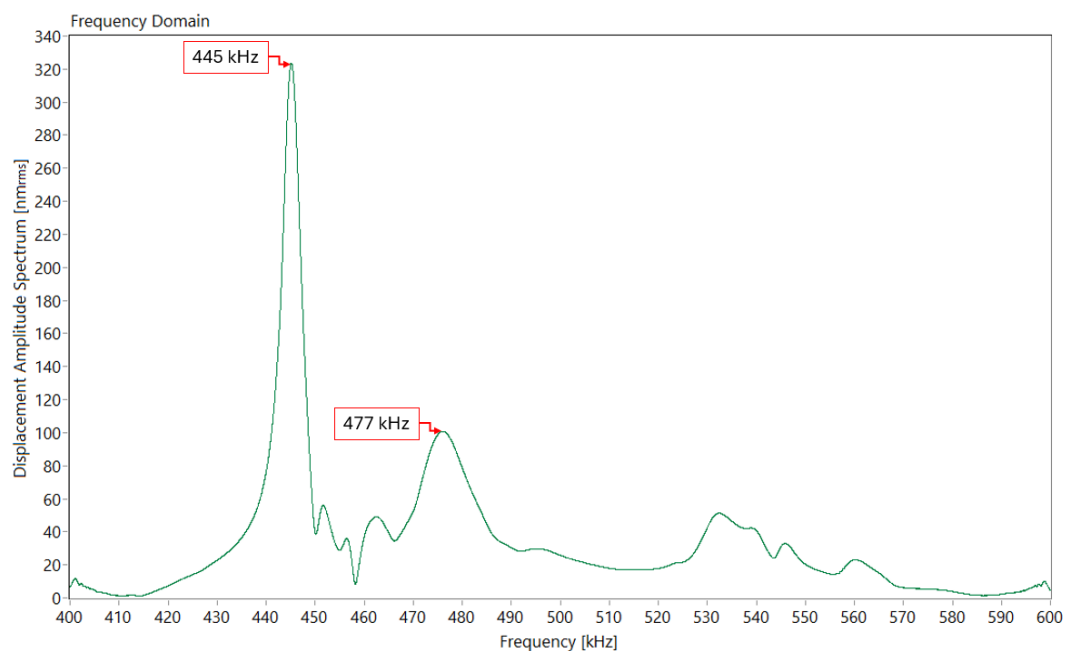


Figure 3.8: Displacement response to frequency sweep from 400 kHz to 600 kHz (second position)

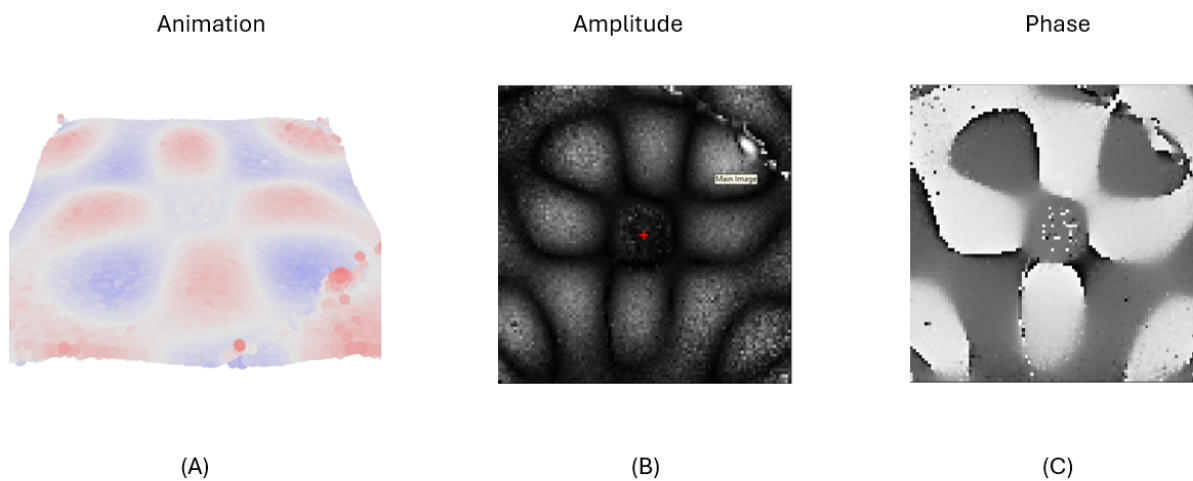


Figure 3.9: (a) Screenshot of Animation. (b) Amplitude response. (c) Phase

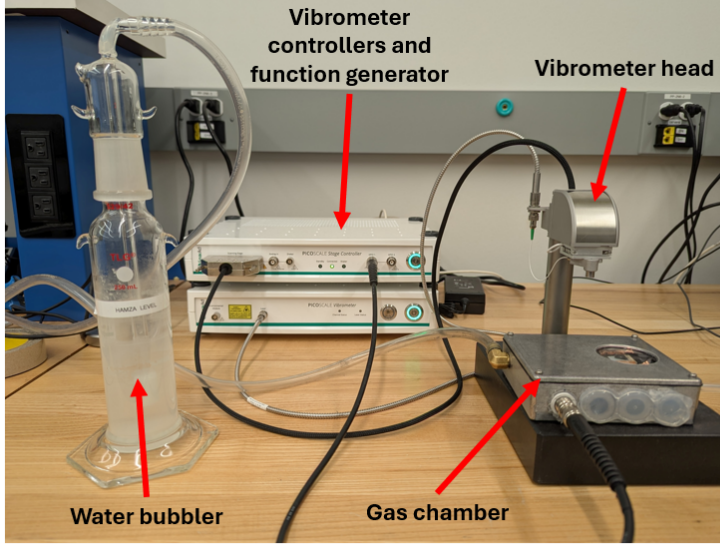
3.2 Testing and results

3.2.1 Experimental setup

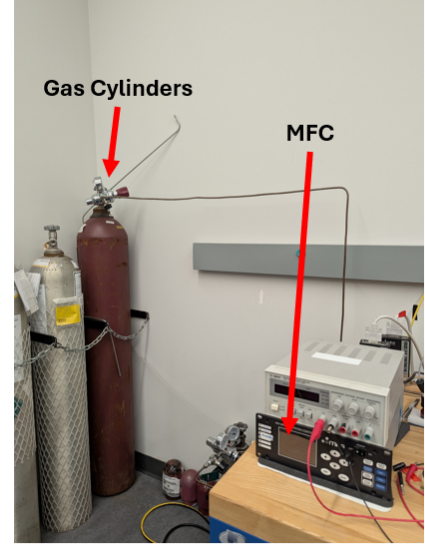
The experimental setup utilized in this test, which is shown in Figure 3.10 has a lot of similarities with the one used by Shama et al. (2024) [25]. for test enclosure, a custom made chamber with anti-reflective glass port that provides optical access, two ports for gas flow, and an electrical port for the actuation signal. This electrical signal was provided using the built-in function generator of the PICOSCALE vibrometer. A mass flow control system (MFC), MKS series 946 [26] was used to precisely control the flow coming from the nitrogen and methane cylinders used in the test. To prevent possible backflow, the outlet port is linked to a water bubbler. Measurements of the sensor's displacement response was done using the PICOSCALE vibrometer [24]

3.2.2 Test procedure and results

A solid powder form of PANI doped with 5% ZnO was mixed with ethylene glycol, a carrier fluid, at a concentration of 10–15% by weight. This mixture acted as a medium for delivering the powder to its intended application. The material, previously used by Shama et al. (2024) [25, 27, 28, 29], exhibits an affinity for various volatile substances, including methane, which was utilized in this test. However, the deposition method differed due to the size disparity between the two devices. A single drop of the mixture, approximately 30 μL in volume, was deposited onto the top surface of the disk using a pipette. The disk was then left for 24 hours to allow the ethylene glycol to evaporate naturally, leaving behind the solid doped PANI. This process, performed only once, provided sufficient material for the sensing test, as illustrated in Figure 3.11.



(A)

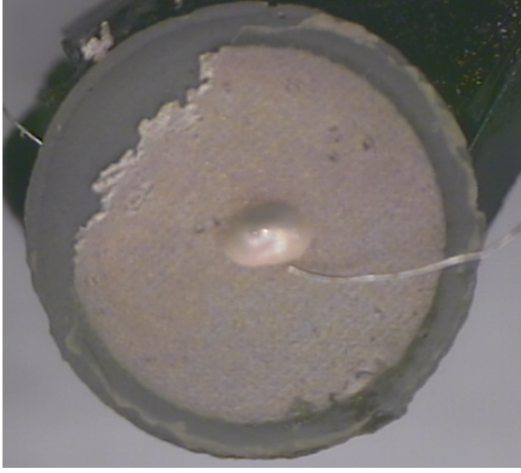


(B)

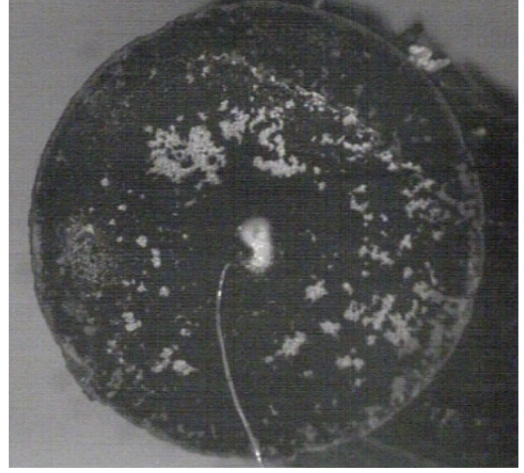
Figure 3.10: (a) Measuring part of the experimental setup (b) Gas cylinders and flow control unit

The sensor was securely placed inside the chamber to start testing. Nitrogen was introduced into the chamber at a flow rate of 100 sccm and left for approximately 15 minutes to ensure stability of the conditions inside the chamber such as temperature, humidity, and pressure. A measurement of the sensor's displacement response was done to evaluate the effect of the deposited material on the sensor's response. When we compare the new peak, which was found to be at $f_{\text{after deposition}} = 442.791$ kHz with the original $f_{\text{original}} = 445.329$ kHz, this means a frequency shift of 2.538 kHz. The mode shape was reanalyzed to confirm that this is the original mode's natural frequency shifted and not the natural frequency of a different mode.

The methane was released into the gas chamber replacing the nitrogen inside at a flow rate of 100 sccm as well, and it was also left for 15 minutes before conducting any measure-



(A)



(B)

Figure 3.11: (a) The piezoelectric disk before deposition (b) The piezoelectric disk after deposition

ments for stabilization of internal conditions of the chamber and to ensure absorption of the gas by the sensitive material. After that, a new measurement was taken to check again for the shift before and after the gas. The shifted peak was found at $f_{\text{After gas}} = 442.098$ kHz with a shift of $\Delta f = 0.693$ kHz between before and after methane. The drop of the peak amplitude of the displacement response to approximately half of the original value is another way of detection as well.

The methane in the chamber was replaced with nitrogen once again to check if the natural frequency will return to $f_{\text{after deposition}} = 442.791$ kHz. At a flow of 100 sccm, the nitrogen was released back inside the chamber and left for 15 minutes to ensure the stability of the internal conditions once again. The natural frequency went back to $f_{\text{after deposition}} = 442.791$ kHz the same frequency before the methane gas was introduced inside the chamber. This proves that the piezoelectric disks can be used for gas detection.

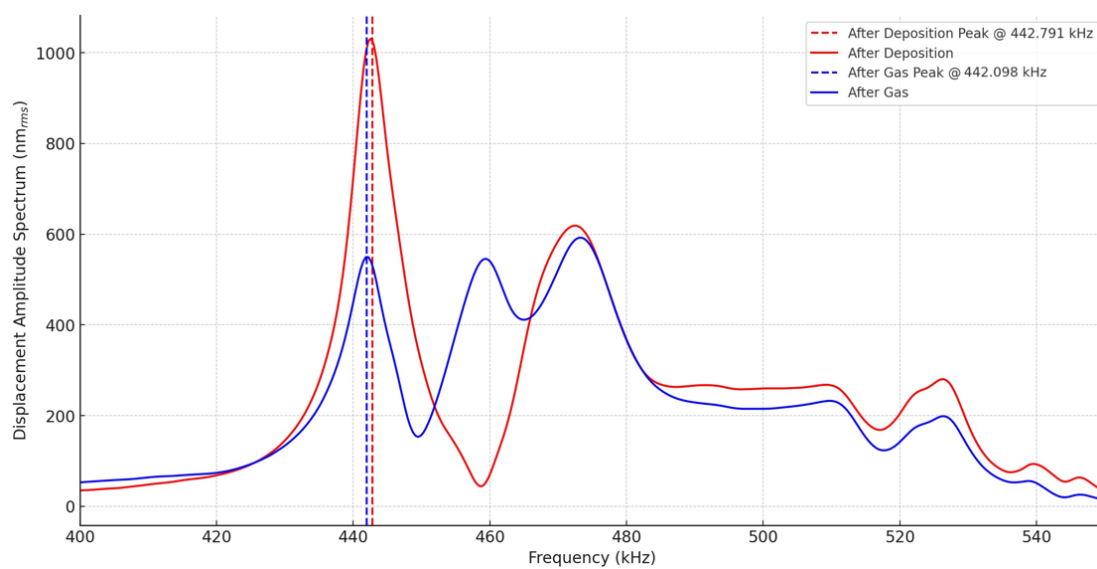


Figure 3.12: Displacement response before and after releasing the gas

Chapter 4

Conclusions and future work

4.1 Force Sensing

4.1.1 Experimental setup design

Two solutions are proposed to improve the repeatability of the attachment of the interface circuit to the shim, discussed in section 2.4.1:

1. The first solution is straightforward: reducing the machining tolerance of the sensor element seats to ensure better planarization of the sensor element top surfaces.
2. The second solution calls for a new shim holder, Figure [4.1](#), featuring shelf designed to securely hold the interface circuit during attachment. The shelf incorporates a central channel to provide a route for wiring of Sensor 3.

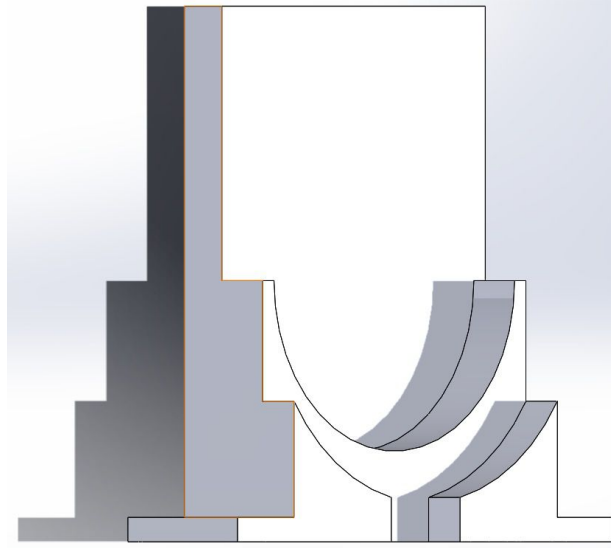


Figure 4.1: A 3D schematic of the improved pressure force experimental rig

4.1.2 Deployment of the sensing apparatus

As previously mentioned, different structural components exhibit unique resonance frequencies, which typically do not align with those of the experimental setup and are not the same across various shim placements. A training phase would be required in order to integrate one or more smart shims into a comprehensive health monitoring system for the parent structure. During this phase, the system would "learn" the locations of the resonance frequencies characteristic of a healthy structure. It can then use this baseline 'signature' to detect structural degradation and faults by monitoring shifts in the locations and amplitudes of the resonant peaks, as well as overall variations in the shape and level of the frequency-response curve over time.

4.1.3 Future work

To implement a fully functional sensor apparatus, future work should include construction and proof of experimental rigs to measure and calibrate the apparatus response under moment, torque, and shear forces. The conceptual design for experimental rig to test for the two moments around the shim face axes has been completed and fabricated. It involves using two pairs of springs with different spring constants: one pair with the same spring constant as the that of the pressure force experimental rig and the other with a lower spring constant. This configuration will create a difference in reaction forces between the two pairs. This force imbalance will generate a moment on the shim face. Additionally, allows the shim holder to rotate around an axis at the bottom of the shim holder under the the applied moment, thereby acting as a moment multiplier.

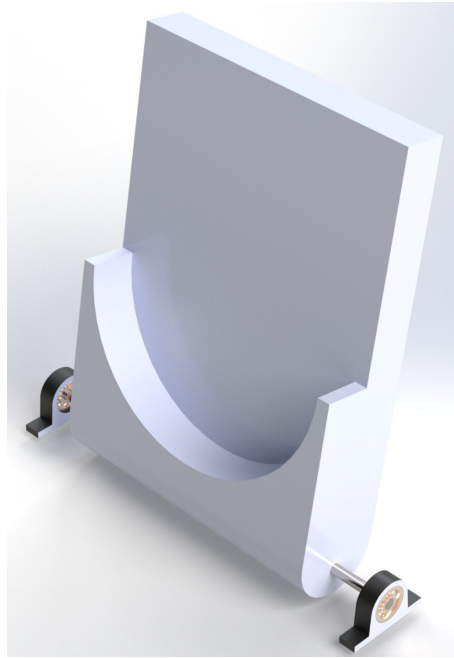


Figure 4.2: A 3D schematic design for moment experimental rig

The new shim holder, shown in Figure 4.2, includes bearings and bearing seats, a metal rod serving as the axis of rotation, and a shim seat. A new shaker head, equipped with a universal joint that allows it to follow the shaker linear oscillations while rotating to maintain continuous contact with the shim, has also been designed and fabricated.

4.2 Gas Sensing

The primary challenge encountered in implementing those sensors was in mounting the piezoelectric disks onto the acrylic platform. Designing a chip carrier to serve as interface between the disk and the test platform would increase the signal-to-noise ratio and improve the repeatability of experiments.

Future work for gas sensing using piezoelectric disks involves testing for other gases and sensitive materials, comparison of results to identify the most sensitive and selective materials as well as the limit of detection for each material. It is also important to compare the sensitivity of this sensor class to other classes of inertial sensors.

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