Structural Health Monitoring (SHM) Using Liquid Metal Antenna with Wireless Sensor Network (WSN) via Zigbee Technology

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Abstract**—**This study develops a Structural Health Monitoring system that will track the strain imbued within the concrete. The system is comprised of the liquid metal antenna as the strain sensor, a sensing unit, microcontroller, and a computer application. Resonant frequency is the main input of this study, and it comes from the behavior of the sensor attached below the structure. The data will then be processed by the sensing unit to convert the frequency to voltage pulses for easier data reading. The acquired resonant frequency undergoes a Harmonic Termination Matching Network and an RF-DC converter to turn it into a more readable data. Half-wave rectifier is also added to convert the output into pulsating DC. In this system, Wireless Sensor Network with star topology using Zigbee Technology is implemented for easier data acquisition from the sensor nodes. A computer application is also developed to generate reports of the strain detected by the sensors, displaying the short- and long-term predictions, map diagram and sensor settings. Other factors, such as stretching, submerging underwater, and variation of wire length, that can affect the behavior of the liquid metal antenna is observed through experimentation. To the test the validity of the system, the resonant frequency of the liquid metal antenna acquired by the NanoVNA is compared to the data gathered by the system.

Experiments showed that there is a direct relationship between the voltage and the resonant frequency of the LMA in the system, as the resonant frequency decreases the voltage decreases. Hence, there is an inverse relationship between voltage and strain applied, as the LMA resonance frequency decreases due to the increasing strain imbued resulting to its elongation, the voltage decreases as well.

Keywords—liquid metal antenna, resonant frequency, harmonic termination network, wireless sensor network, Zigbee protocol, sensor node

I. INTRODUCTION

Structures such as roads and bridges are susceptible to experiencing heavy loads everyday which induces stress on them and thus causes strain. Since the country is in the Pacific Ring of Fire, it is important that the Philippines must have an excellent Structural Health Monitoring. The Structural Health Monitoring (SHM) done in the Philippines was based only on the physicality of the structures and can be considered inaccurate, which is the reason why buildings, roads, and bridges are still at risk whenever disasters occur. Technology advancements on Structural Health Monitoring includes strain gauges, sensor nodes, and automated monitoring [7].

Liquid Metal Antenna (LMA) is a promising technology that can be a better placement to strain gauges in SHM due to its size, light-weightiness, non-complex design, flexibility, and its self-healing properties. Liquid Metal Antenna can detect strain by its resonant frequency being inversely proportional to its displacement [3].

Implementation of RF-DC Converter Circuit in a Wireless Network System is efficient since it has a simple circuitry and combining it with Harmonic Termination Matching Network ensures an improved performance of the converter circuit [4]. In this study, The Sensing Unit shall read the output frequency of the Liquid Metal Antenna and convert the data to its voltage equivalent for easier data reading.

IEEE 802.15.4 standard implemented Zigbee that specifies high level communication protocol mainly used for wireless data transmission up to 100 meters at a fixed speed at 250 kbps [8]. Wireless links under this standard operate in license free frequency bands accommodating 250 kbps in the 2.4 GHz band in most jurisdictions worldwide. Zigbee is a RF protocol that belongs to the Zigbee Alliance which targets the application domain of low power, low duty cycle and low data rate requirement devices and its network has adopted three topologies, namely star, cluster, and mesh topology [9]. Using this protocol, wireless SHM will be obtained, and the strain in specific points can be detected by the multiple nodes of strain sensor which provide better accuracy of readings.

The Zigbee receiver interprets the data sent and displays it to the computer. The Arduino has an embedded code which provide the text information of the Graphic User Interface. A Java application text scroll of the current readings was used as the Graphic User Interface of the proponents [11]. On the other hand, Firmata enables the communication of microcontroller and the computer software. It is open and scalable, allowing it to work in any programming environment, as well as easy to implement on both the microcontroller and the host machine, allowing for a wide variety of applications [6].

The elements used for analyses are based on the experimental setups for Liquid Metal Antenna equipping NanoVNA and the sensing unit as a tool for acquiring data. It is crucial for this study to compare the results of two different tools, NanoVNA and Sensing Unit because it strengthens the validity and precision of the developed Structural Health Monitoring System.

II. METHODOLOGY

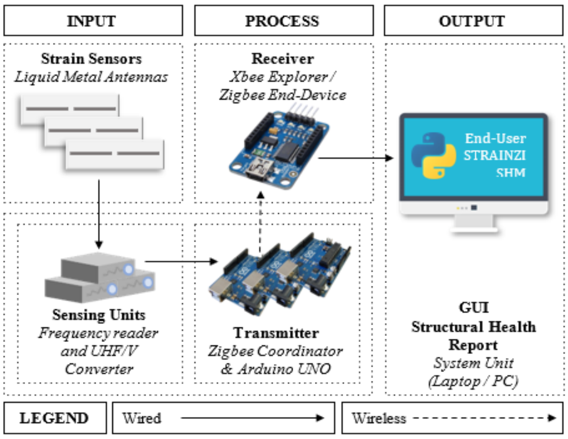

Figure 1. System Architecture

The overall system of this study is shown in Figure 1. It consists of wired and wireless connections between devices from the input to the output. The system consists of three major parts: input system, data processing, and output system. The system starts with equipping the liquid metal antenna as a strain sensor which acquires their respective resonant frequency. Then, the circuits of sensing units are designed to obtain the input from liquid metal antenna and convert it to voltage pulses and these are connected to Arduino UNO. The location of sensing units and Arduino UNO modules are on the structure side and considered as the sensor node of the network. The relevant information acquired is sent to the master node operated by the system unit, through wireless communication using Zigbee end-device and Zigbee coordinators. The Arduino UNO of each sensor node consists of a storage device module for saving data when sensors are temporarily disconnected to the master node. The master node consists of a Zigbee module with Zigbee explorer connected directly to the system unit for graphical user interface (GUI) which is located at the end-user side. Lastly, the Structural Health Monitoring System computer application shows the integrity of the structure in terms of strain with diagrams, warnings, and predictions.

A. *Liquid Metal Antenna*

This device is designed to act as a strain sensor for the SHM system and it is fabricated using Soft Lithography. Eutectic Gallium Indium is the liquid metal used and the substrate is the QSIL 216 which is a type of polydimethylsiloxane. The space between the two branches is 5 mm and the total length and width of the antenna with the substrate is 145 mm x 25 mm x 5 mm. The size of the microfluidic channel is 1600 um which is based on the thickness of the solid wire. The theoretical maximum value for resonant frequency is 603.5 MHz based on the given formula from the study of Kubo, et. al. [9],

$$f = \frac{143}{l}\ x \frac{1}{\sqrt{\varepsilon_{eff}}} = 603.5\ MHz$$

$$l = 145\ mm$$

$$\varepsilon_{eff} = 2.67$$

The adhesive used to attach the liquid metal antenna and the sensing unit under the bridge is the El Heneral all-purpose epoxy because it exhibits strong adhesion in all types of weather.

Figure 2. Liquid Metal Antenna and Sensing Unit attached under the bridge

B. *Sensing Unit Architecture*

The Sensing Unit design was based on the design made by Au & Seo [10] and Schauwecker [1]. The circuit starts off with the Harmonic Termination Matching Network (HTMN), which had two purposes: (1) for impedance matching and (2) harmonic suppression. This part of the circuit was based on the stub matching concept for transmission lines and microstrip filters. To construct the HTMN, the proponents used Keysight Advanced Design System software for its *Line Calculation Feature* that helped in getting the dimensions of HTMN.

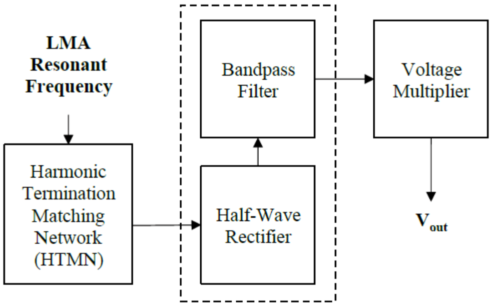

Figure 3. Sensing Unit Block Diagram

After HTMN was a two-diode configuration half-wave rectifier using HSMS-2850 Schottky diode which was suitable for low-power applications. After the rectifier was a T-section bandpass filter whose computations were based of on [21]. After the T-section bandpass filter, the proponents added a voltage multiplier circuit to quadruple the data.

Sensing Unit T-Section Bandpass Filter Computations:

$$f_{center} = \sqrt{f_L f_H}$$
$$f_{resonant} \approx f_{center}$$

$$C_1 = \frac{f_H - f_L}{4\pi f_H f_L Z_0}$$
$$C_2 = \frac{1}{\pi Z_0 (f_H - f_L)}$$
$$L_1 = \frac{Z_0}{\pi (f_H - f_L)}$$
$$L_2 = \frac{Z_0 (f_H - f_L)}{4\pi f_H f_L}$$

The substrate used for the circuit was FR4 substrate as it was the material suitable for microwave circuit applications and was locally available in the Philippines. As the sensing unit operates on the microwave frequency range, its components were all surface mounted since there were little to none through-hole components found by the proponents that could be used for the Sensing Unit.

C. Wireless Sensor Network

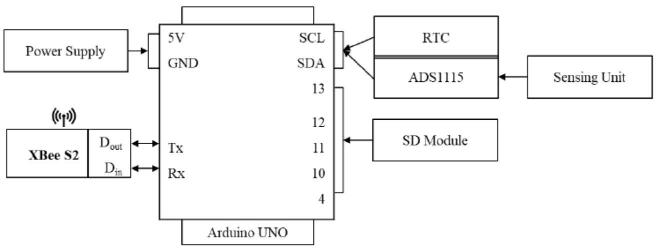

Figure 4. Sensor Node for Wireless Communication System

The sensor nodes consisted of the sensing unit connection, Arduino Uno, Zigbee wireless modules, SD card module, Real-time clock module, ADC Bit converter, and power supply are responsible for acquiring data from the sensing unit and sending measured values to the master node.

The microcontroller utilized for sensor nodes was the Arduino Uno module with ATMEGA328P and its main purpose was to acquire voltage pulses from the sensing unit and process data that would be prepared for delivering to the Zigbee wireless module. ADS1115 is utilized to have higher resolution output data with 16-bit ADC, which allows it to read milli to microVolts. XBee Shield was used for seamless interface between the Arduino module and the XBee S2. It can also store data in the micro-SD card and to have reliable time indication of data acquired, RTC module DS3231 was used to record the time occurrence of data. The power supply used was a Lithium Polymer (Li-Po) battery which was rechargeable connected to the 5V pin of the Arduino module.

The master node consisted of an XBee Explorer module with XBee S2 Mesh C module connected via USB communication interface to the system unit is responsible for wirelessly receiving data from the sensor nodes and transporting measured values to the system unit for GUI and its base module is FTDI device which aims to have a simple transceiver device to recognize data received by the XBee S2 and send commands to the sensor nodes.


Figure 5. Wireless Sensor Network device installed on the bridge

D. Computer Application

In this study, a python-based computer program aided with API libraries such as PyQT5 for the GUI building aspect and, pySerial and Arduino's Firmata for the serial port connection and communication between the computer and Arduino. PyQT5 is a GUI (Graphical User Interface) that is more versatile than the de-facto standard Tkinter. pySerial is a module that encapsulates the access for the serial port [5]. Firmata is a communications protocol fully implemented on Arduino for communicating between the microcontroller and the computer [2]. The features included in the computer application are:

1. *Sensors Report* which is comprised of the short- long-term reports. It also includes prediction reports that uses Regression analysis to predict the trend of sensor's reading.
2. *Graph (Live-view/Free-view)* for plotting a set range of data gathered by the GUI. When in real-time mode, it will automatically plot and update at each new data instance.

3. *Sensor settings* is also included to give space for customization of threshold appropriate for its placement on the structure. In here, you can also add and remove sensors when needed along with the configurations in Zigbee connection.

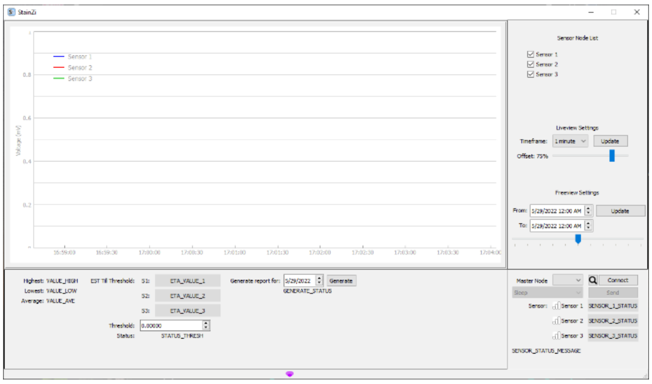

Figure 6. Graphic User Interface

E. Testing Procedures

To evaluate the efficiency and accuracy of the project study, four experimental setups were conducted. The liquid metal antenna is stretched up to 0% of its original length, elongating it at every 2 mm using a clamp. Its resonant frequency will be measured by the network analyzer and the sensing unit to have a comparison of results. The sensor is also tested under varying temperature conditions and varying wire length from the device to the sensing unit. Furthermore, its behavior is also observed when submerged under water.

III. RESULTS AND DISCUSSION

The data analysis and results were categorized and presented in four sections: 1) Data Collection 2) Simulation Data 3) Actual Data and 4) Data Results from Computer Application. The data were collected and interpreted in response to the objective that is mentioned in Chapter 1. The objectives were to develop the feasibility of the Liquid Metal Antenna as a sensor in Structural Health Monitoring. This also included the justification of data in case no statistical results were found.

A. Data Collection

It has been proven from the study of E. Fernandez et al., that the resonant frequency of the Liquid Metal Antenna is inversely proportional to its length, therefore, as the Liquid Metal Antenna stretches, its resonant frequency would decrease. The theoretical value of the resonant frequency from the Liquid Metal Antenna at rest is critical for the design of the system. From the study of Kubo et al., the equation is used to obtain the theoretical value of the Liquid Metal Antenna's resonant frequency:

$$f_{MHz} = \frac{143}{l} x \frac{1}{\sqrt{\varepsilon_{eff}}}$$

LMA	Resonant Frequency (Rest)	Resonant Frequency (Submerged)
04	652 MHz	632 MHz
05	656 MHz	612 MHz
06	744 MHz	712 MHz

Where:

L = Length of the Liquid Metal Antenna

ε_{eff} = Effective Dielectric Constant (PDMS = 2.67)

NanoVNA for this study to record and measure the resonant frequency of the antenna. The maximum length that the Liquid Metal Antenna can be stretched is 159 mm or an additional 14 mm to the length of LMA at rest which is 145 mm. The inversely proportional relationship of LMA length and its resonant frequency is proven and shown in Figure 7.

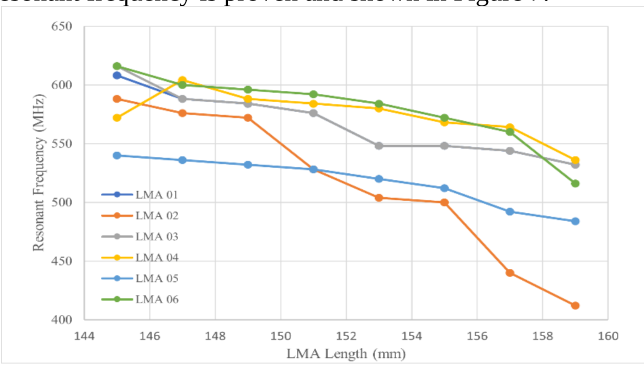

Figure 7. Graph of Liquid Metal Antenna Resonant Frequency vs Length (mm)

An experiment was also conducted to measure the respective resonant frequency each time the wire would be cut by 20 mm. It was observed and shown in Figure 8 that the resonant frequency of the Liquid Metal Antenna increases as the length of the conductor decreases, therefore, there is an inverse relation between the conductor's length and the antenna's resonant frequency.

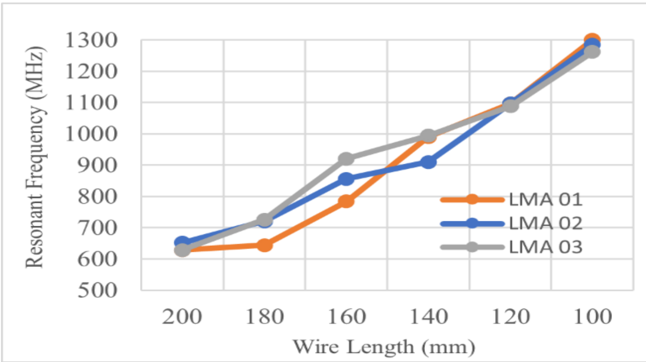

Figure 8. Graph of Liquid Metal Antenna Resonant Frequency vs Wire Length (mm)

It was taken into consideration the possibility of the Liquid Metal Antenna to be submerged underwater since it would be deployed under the bridge. In this experimental set-up, the LMA is submerged under 300 mL of normal temperature tap water. In Table 1, it can be seen that there is no significant effect to LMA resonant frequency when submerged underwater.

Table 1. LMA Resonant Frequency when Submerged Underwater

To determine the possible threshold that the Liquid Metal Antenna can be stretched before it can reach its limit and to determine the minimum possible resonant frequency the Liquid Metal Antenna can produce. This will serve as the basis for the values of resonant frequency that the Liquid Metal Antenna would acquire during the actual deployment. From the Table 2, depending on the sensitivity of the LMA, its resonant frequency can decrease by 35 MHz to 153 MHz.

Table 2. Threshold of LMA when stretched

LMA	Resonant Frequency at Rest	Resonant Frequency at Threshold	Threshold Stretch (per mm)	LMA Status
01	702 MHz	666 MHz	145 - 165	Active
02	783 MHz	648 MHz	145 – 165	Active
03	738 MHz	585 MHz	145 - 165	Damaged

B. Simulated Data

The PCB layout of sensing unit was made using KiCAD. To test its resulting voltage, the whole circuit was simulated under varying frequencies from 800 MHz to 100 MHz, with 10 MHz decrements. The range was determined as 800 MHz was the theoretical resonant frequency when the Liquid Metal Antenna was designed. In figure 9, it shows the plotted data gathered from said simulation.

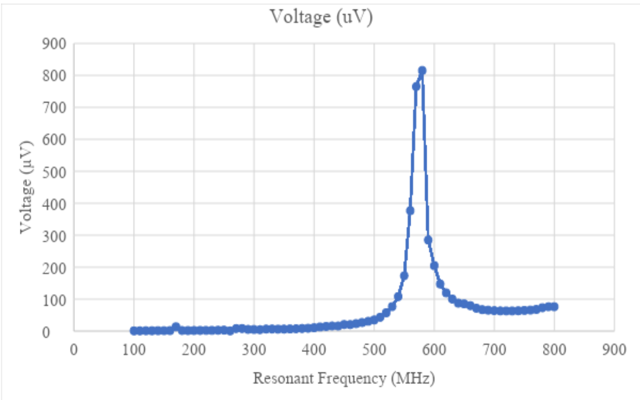

Figure 9. Plotted Data of Sensing Unit Simulation

There was a positive spike of data recorded in 580 MHz, this was due to the design of the Harmonic Termination Matching Network (HTMN) as it was designed for the 580 MHz frequency since it is the average frequency of all the fabricated LMAs. In addition, the voltage data recorded in 580 MHz was the highest possible theoretical value for the voltage output, which was 816 µV. As observed in the plot, voltage decreases as resonant frequency decreases.

C. Actual Data

The resonant frequency decreases when there is an increase of length with the Liquid Metal Antenna [7]. To determine the behavior of the antenna with regards to voltage, three antennas that were deployed in the bridge are tested by elongating the

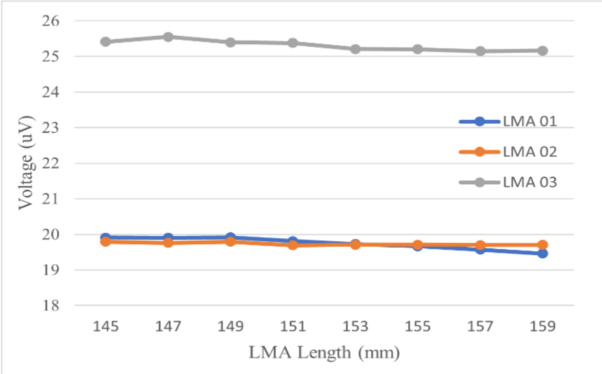

Figure 10. Graph of Voltage acquired by the Sensing Unit vs LMA Length

antenna and recording the Average Voltage through the system

From the data gathered and the graph shown in Figure 10, as the Liquid Metal Antenna elongates, the average output voltage read by the system decreases. Therefore, since the resonant frequency decreases as the antenna elongates, and the average output voltage read by the system also decreases, there is a direct relationship between the antenna's resonant frequency and output voltage. When strain is applied to the antenna, it is expected that there will be a decrease of output voltage that will be read by the system.

D. Data Results from Computer Application

Figure 11 shows the data gathered of the system using the STRAINZI computer application from the deployment in the actual bridge. Based on the confirmation of the end-user between real-time and user-time operation, the history of data saved in the computer is shown by adjusting the date and time of the map diagram. The blue line indicates sensor node 1, the red line for sensor node 2, and the green line for sensor node 3. As shown in the map diagram, the voltage decreases from certain times indicating a vehicle arrived at the bridge.

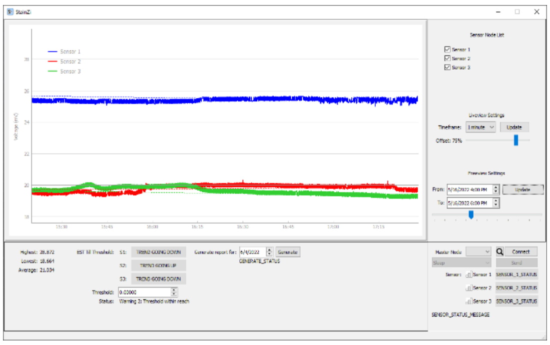

Figure 11. Screenshot of the Computer Application containing the data from bridge deployment

IV. CONCLUSION

Based on the results of the study, the following conclusions were drawn, the resonant frequency of the Liquid Metal Antenna decreases as the length of it increases, therefore, there is an inverse relationship between the antenna's length and resonant frequency. Moreover, the conductor's length is critical in designing a Liquid Metal Antenna as the resonant frequency of the antenna increases when there is a decrease on the conductor's length. Also, there is a decrease of resonant frequency when the Liquid Metal Antenna is submerged underwater. It can be also drawn out from this study that the resonant frequency of the Liquid Metal Antenna has a direct relationship with the output voltage. From the deployment it was observed that the heavier the vehicle that passes by the bridge, the greater the voltage difference was detected by the system. All in all, with the data acquired while utilizing the liquid metal antenna as sensor and establishing wireless sensor network alongside with a computer application for data visualization, a structural health monitoring system that monitors the strain imbued in a structure in terms of voltage can be developed.

V. RECOMMENDATION

To further improve the study, future researchers may consider developing and designing a Sensing Unit circuit that would yield DC Voltage rather than Voltage pulses for easier data readings. It is also advisable to use other wireless mediums for data gathering. Also, it is also recommendable to use better types of adhesives that would not affect the Liquid Metal Antenna's sensitivity in sensing strain in concrete beams. For the deployment, it is better if there would be more disciplines involved such as electrical engineering, mechanical engineering and civil engineering. The electrical wirings in the deployment must also be more secured and it is recommended to use conduit system for it.

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