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Design and Characterization of the Liquid Metal Antenna Optimally Embedded in Concrete Beam Prototype as an Alternative Strain Sensor

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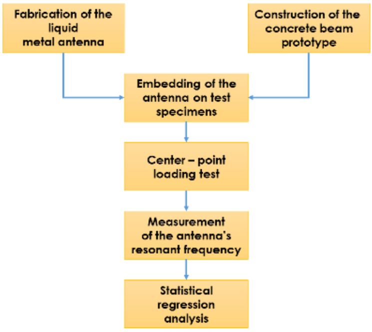
Graphical abstract



Abstract

This paper presents the implementation of the novel dipole liquid metal antenna as an alternative strain sensor when embedded in the optimal location of a concrete beam prototype. The antenna is made up of eutectic Indium Gallium, a fluid metal alloy, encased in a microfluidic channel, namely, polydimethylsiloxane (PDMS) elastomer fabricated using McGyver-esque technique to microfabrication. The fluidic dipole antenna being highly flexible, stretchable, and reversibly deformable mimics the basic characteristics of the strain sensor where its resonant frequency is inversely related to its length. The concrete specimen was subjected to center – point loading tests where the resonant frequency of the liquid antenna embedded in it was measured simultaneously. Statistical analysis of the results show that there is a significant relationship between the displacement of the concrete specimen and the resonant frequency of the embedded antenna.

Keywords: Liquid metal antenna; center-point loading test; concrete beam prototype

1.0 INTRODUCTION

In the recent years, a higher frequency of devastating earthquake incidents are experienced not only in the country but also in other parts the world. Due to these incidents, a critical importance on structural health monitoring should be highlighted. The underestimation of small cracks in concrete beams or columns could result to progressive collapse of infrastructures that can be easily avoided through early detection systems. Such detection systems could help minimize the loss of lives, livelihood, and properties.

The process of employing a damage identification strategy for civil engineering infrastructures like the buildings, bridges, and roads for reparation and prevention of potential danger of collapse is referred to as structural health monitoring (SHM). While the damage in structures are changes to the material and/or geometric properties on it such as cracks and breakages which adversely affect the structure's performance. The presence of this damage situates civil structures to serious condition which endangers the safety and lives of the users. Structural health monitoring involves the observation of structure over time using periodically spaced measurement, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current condition of the structure [1].

The common method of monitoring the health of structures is by using strain gauges where its electrical resistance changes proportionally to its amount of strain. This converts mechanical deformation in a concrete under stress to electrical signals [2]. These signals are then fed to either wired or wireless systems for analysis to determine the condition of the concrete structures [3]. Various methods have been developed to replace the conventional strain sensors such as using patch antennas [4, 5], oscillator circuits and resonators [6] that mimic the behavior of the concrete under stress namely, the vertical or horizontal movements, depending on the material's orientation with the concrete and which converts its deformation to certain measurable quantity. Patch antennas changes its resonant frequency in inverse proportion to its electrical length. On the other hand, strain changes parameters in oscillator circuits which eventually change its resonant frequency. Resonators are also frequency shifting based strain sensors that uses elastic materials such as carbon fibers and metamaterials. These sensors are usually incorporated in wireless systems for structural health monitoring. Among these alternative strain sensors, antenna sensors are more advantageous in terms of its design simplicity, size and weight, and power supply reliance [6].

In addition to antenna sensors, recent publications used liquid alloys as a fluidic antenna that can change its shape, and therefore the frequency at which it resonates, in response to applied stress in a controlled and predictable manner [7, 8]. Liquid-metal antenna was initially characterized as flexible, self-healing, and reversibly deformable material where its resonant frequency is inversely related to its length [9]. Shape-changing antennas like this one could also be used as another alternative strain sensor for structural health monitoring.

This paper focuses on characterizing the novel liquid metal antenna as a strain sensor by embedding it in prototype concrete beams in optimal location and subjected it to center-point loading test and simultaneously measured its changes in resonant frequency in every applied pressure on the specimen. The results were analyzed statistically to determine the consistency of the inverse relationship between the antenna's resonant frequency and the displacement of the concrete as initially characterized in previous researches. Mathematical models were also developed relating the resonant frequency and the displacement on the specimen

2.0 METHODOLOGY

Materials characterization technique was the method employed in this research. Characterization of materials focuses on determining the interrelationships and interdependence between processing, structure, properties and performance [10]. In this paper, the performance of the test specimens, namely, the concrete beam and the embedded liquid metal antenna under continuous application of stress were analyzed. The research began by developing a hypothesis regarding the outcome of the characterization of the mentioned materials by conducting a series of experiments. The experiment was repeated for certain number of specimens to further investigate and validate the developed hypothesis.

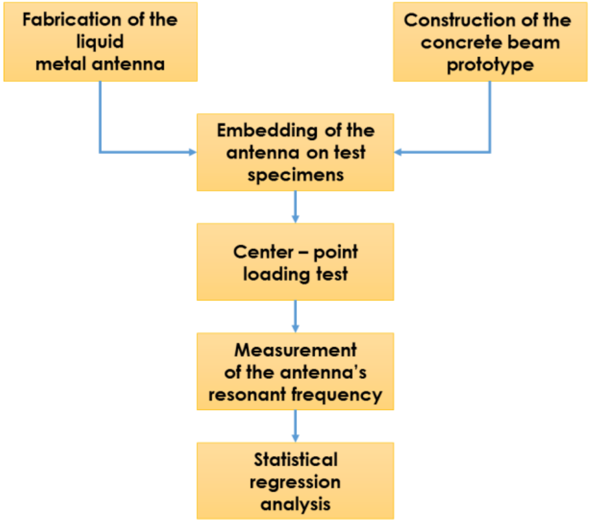


Figure 1 Process flow chart of the characterization of the liquid metal antenna as strain sensor

Figure 1 shows the process flow chart in characterizing the liquid metal antenna. It starts with the fabrication of the antenna and the construction of the concrete beam prototype. Then the fabricated antenna is embedded in the optimum location of the concrete and was subjected to center – point loading test. The applied stress will cause crack and deformation on the prototype specimens which in turn will elongate the embedded antenna that changes its resonant frequency according to its physical length.

The resonant frequency of the antenna was measured in real-time using vector network analyzer to monitor the change in deformation or crack width of the concrete. These data is then processed by an interface on the personal computer from which the network analyzer is interfaced to.

Regression was used to analyze the collected data and to statistically determine whether there is significant relationship between the deformation of the test specimens and the resonant frequency of the antenna. The result is then concluded using a mathematical equation obtained using the regression analysis showing the relationship between the antenna's resonant frequency and strain.

2.1 Fabrication of the Liquid Antenna

The dipole liquid metal antenna is fabricated by injecting the eutectic Gallium Indium (EGaIn, 75% Ga, 25% In by weight) alloy in a microfluidic channel composed of polydimethylsiloxane (PDMS), a silicone elastomer. The fluidic channel is fabricated by providing a McGyver-esque approach to microfabrication which is simpler as compared to the normal fabrication of microfluidic devices that employs soft lithography requiring expensive cleanrooms and user expertise. This method is based on replicating a master mold made of electrical tape which can be used without any chemical treatment as detailed in [11]. Figure 2 shows the microfluidic channel master mold made of glass slide with electrical tape with a uniform height of 160µm.

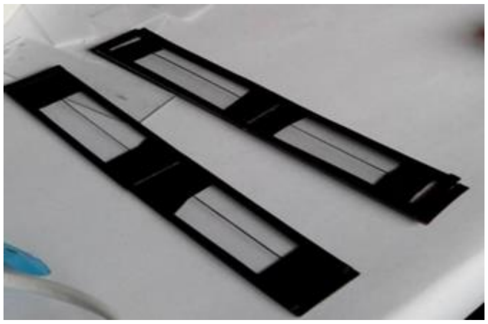


Figure 2 Microfluidic channel master mold made of glass slide with electrical tape

Figure 3 shows the resulting dipole antenna. It consists of two conductive microfluidic alloy of eutectic Gallium Indium of equal length that are aligned along their long axis and separated by an insulating gap. The EGaIn alloy was injected using 1 cc syringe.

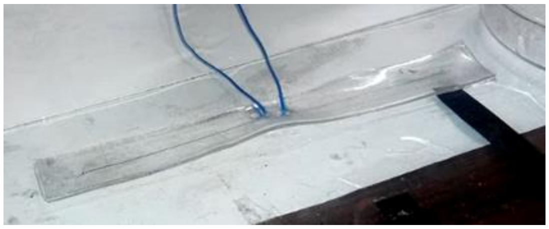


Figure 3 Liquid metal antenna

As preliminary study on the liquid metal antenna, the authors chose to fabricate antennas with length between 100mm to 180mm where the resonant frequency is limited to less than 1GHz which simplifies the antenna design and characterization. The length of the antenna is computed using the formula in Equation 1, while its thickness is based on the study done by [7].

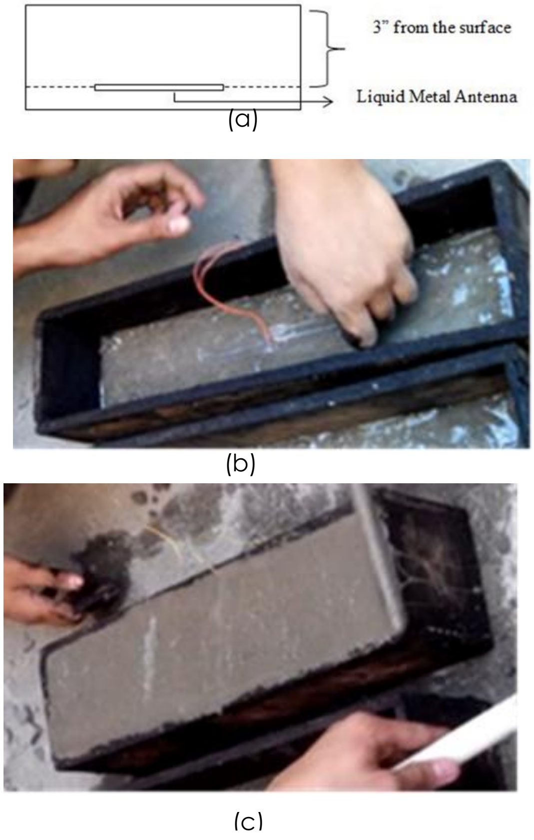
$$l = \frac{c}{2f\sqrt{\epsilon_r}} \qquad (1)$$

Where l is the length, c is the speed of light (3×10^8 m/s), f is the frequency and ϵ_r is the relative permittivity.

2.2 Embedding the Antenna in Test Specimens

In this study, the researchers opted to embed the fabricated liquid antenna in unreinforced concrete beams and focused only on determining its performance characteristics. This method streamlines the approach on characterizing the liquid antenna by not considering the effects of the steel bars on the resonant frequency of the antenna present in reinforced concrete beams. The standard 40 cm by 10 cm by 10 cm mold with 1:2:3 mixture of cement, sand, and gravel is used constructing the concrete beam prototype. The concrete is then demolded by submerging in water and allow curing for 7 and for 21 days to increase the flexural strength of the concrete.

The antennas were embedded in the concrete beams 3 inches from its surface as shown in Figure 4a since it is near the bottom that the optimum displacement can occur with respect to the antenna. Two concrete specimens were provided for each curing time to determine if the varying strength of the concrete beams can affect the performance of the embedded liquid antenna when subjected to stress.



(a)

(b)

(c)

Figure 4 Liquid metal antenna: (a) embedded 3 inches from the surface; (b) embedding prior to pouring of cement; (c) embedded in concrete beam

Figures 4b and 4c show the photographs of an antenna before the concrete mixture was poured and after embedding. A pair of stranded copper wires were inserted as well to the antenna where the probes of vector network analyzer were tapped in measuring its resonant frequency.

However, a sample antenna was initially tested by elongating it at every 1 mm increment until it reach 40% of its original length using a plastic clamp where its corresponding resonant frequency was measured simultaneously. This limit of antenna elongation was based in [7]. The researchers also characterized an antenna prior to embedding in the concrete by gluing it on an acrylic strip with a dimension of 400 mm by 21 mm. It was subjected into center point loading to resemble the way it would behave inside the concrete.

2.3 Subjecting the Antenna to Center – Point Loading Test

After the 4000 cm^3 prototype concrete beams completely cured, these then were subjected to center-point loading test using the Universal Testing Machine (UTM) according to the American Society for Testing and Materials (ASTM) C293 standard [12]. The internal deformation and cracks that occur in the test specimens causes the embedded antenna to deform and elongates to certain strain resulting to a change on its resonant frequency. The corresponding resonant frequencies of the antenna are measured simultaneously through a network analyzer based on its lowest reflection coefficients obtained for every additional load applied by the machine on the beam. The applied load was also measured simultaneously at every displacement of the beam. The measured load was used to calculate the flexural strength of the beam. All specimens are subjected to the tests until the concrete breaks. Figure 5 shows the photograph of one of the tests conducted. The collected data are then evaluated using Regression analysis.

3.0 RESULTS AND DISCUSSIONS

Table 1 shows the summary of result of the Regression Analysis on the gathered data. The obtained coefficients of correlation for all test specimens range between 0.64 to 0.75 indicating a very strong but negative relationship between the displacement of the concrete beam and the resonant frequency of the liquid metal antenna. These findings is shown to be statistically significant based on the resulting null p-values using 95% level of confidence as indicated on the table below.

Figure 6 shows the plot of the flexural strength of the four concrete beam prototypes with respect to its displacement cured in 7 and 21 days. It indicates that both specimens cured in 21 days exhibits higher initial flexural strength compared to the specimens cured in 7 days.

Figure 5 Concrete beam under center-point loading test and resonant frequency measurement using a network analyzer

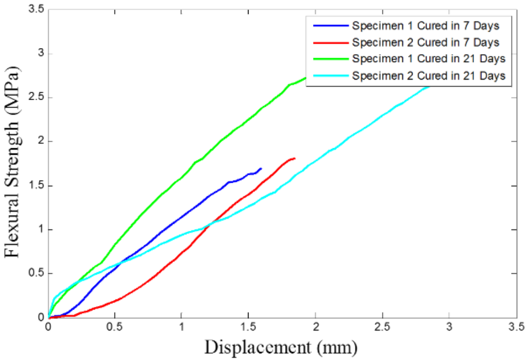


Figure 6 Graph of displacement vs flexural strength of the four antenna embedded in concrete specimens cured in 7 and 21 days

It can also be observed that the Specimen 2 has the lowest flexural strength. This means that Specimen 2 bend less easily compared to the other three. Another indication that can be observed is that Specimen 1 though cured in 7 days has a higher latter flexural strength compared to Specimen 2 cured in 21 days. While Specimen 1 cured in 21 days has exhibited a consistently high flexural strength.

Figure 7 shows the plot of the relationships between the displacement and the resulting resonant frequency of the antenna stretched using plastic clamp and the antenna attached acrylic using center-point loading test. The graph indicates a very strong negative relationship between the displacement of the concrete beam and the resonant frequency of the antennas. The unembedded antenna has a coefficient of correlation of 0.9919 with almost null p-value. The antenna glued in acrylic has 0.6831 correlation coefficient and a very minimal p-value. Both indicated statistical significance. These initial findings validates the basic property of the liquid metal antenna.

Table 1 Summary of findings using regression analysis

Cure Time	Specimen Number	Number of Samples	Coefficient of Correlation	P-value	Remarks
7 days	1	32	0.7539	4.07036E-07	Reject H0
	2	38	0.6691	4.38282E-06	Reject H0
21 days	1	40	0.7099	2.89693E-07	Reject H0
	2	68	0.6439	3.16101E-09	Reject H0
Antenna in acrylic		50	0.6831	4.60876E-08	Reject H0
Antenna stretched in clamp		39	0.9919	9.7873E-35	Reject H0

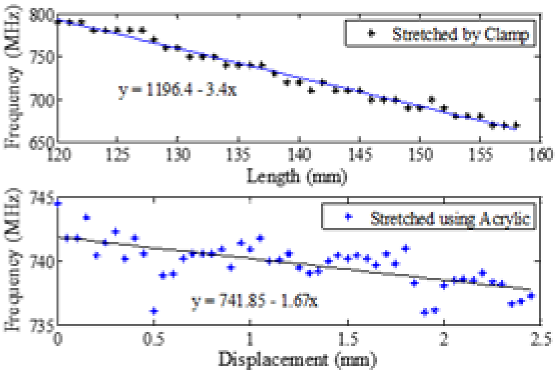


Figure 7 Graph of displacement vs the frequency of the antenna stretched using a plastic clamp and acrylic beam

Figure 8 demonstrates a strong and very strong negative relationships between the displacement of the concrete beam cured in 7 days and the resulting resonant frequency of the antenna. The embedded antenna has a coefficients of correlation of 0.6691 and 0.7539 with very minimal p-values which indicates statistical significance. Specimen 1 which has higher resonant frequency exhibited wide variance as can be seen to its outliers above the regression line. These outliers are the points in which cracks in the concrete specimen began to appear until it reach breakage.

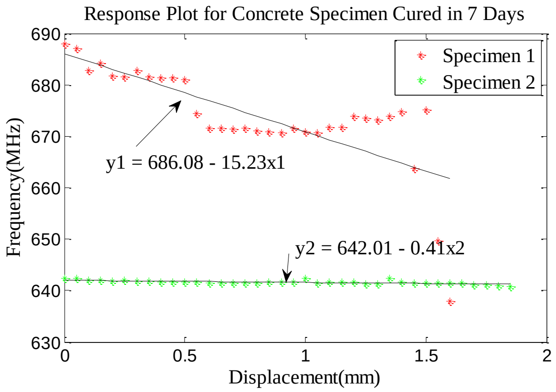


Figure 8 Graph of displacement vs the frequency of the antenna embedded in concrete specimen cured in 7 days

Figure 9 also shows a strong and very strong negative relationships between the displacements of the concrete beam cured in 21 days and the resulting resonant frequency of the antenna. The embedded antenna has a coefficients of correlation of 0.64391 and 0.7099 with very minimal p-values which also indicate statistical significance. As indicated in the slopes of the regression lines, it is noticeable that Specimen 2 exhibited higher change of frequency compared to Specimen 1 since the former has a higher initial resonant frequency.

Although it is expected that both of these specimens should demonstrate high slope of regression line since these have higher flexural strength, it is apparent that a higher initial resonant frequency prior to center-point loading test results to a higher change in frequency. This is also evident for concrete specimens cured in 7 days as Specimen 1 exhibited a higher regression slope compared to Specimen 2.

As can be observed on the results, the resonant frequency of the embedded antenna changes significantly for highly flexural concrete beam prototypes and for antennas with higher initial resonant frequency, that is, for shorter dipole antennas.

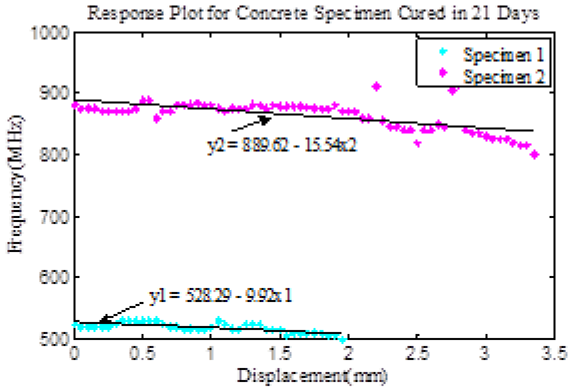


Figure 9 Graph of displacement vs the frequency of the antenna embedded in concrete specimen cured in 21 days

3.1 Comparison to Existing Works

As cited earlier in the Introduction section, antenna sensors are more advantageous in terms of its simplicity of design, smaller size, lighter weight, and non-reliance to external power supply. Aside from these properties, the use of the novel liquid metal antenna holds promise as a better alternative for strain sensors since it is not only capable to measure strain but the flexural strength of the material as well, in this case, the concrete. This enhances the existing antenna strain sensors.

3.2 Future Works

The implementation of the novel liquid metal antenna as an alternative strain sensor could also be incorporated in wireless systems in structural health monitoring such as wireless interrogation or wireless multiple nodes sensor. Further development of this liquid antenna could be utilized as strain sensor for a more advanced method in monitoring health of structures.

4.0 CONCLUSIONS

The authors designed and characterized the novel liquid metal antenna embedded in concrete beam prototype using the standard center – point loading test as an alternative strain sensor. The novel liquid metal antennas were fabricated using also a novel approach of electrical-tape lithography. These antennas were embedded in optimum location in concrete beam prototypes and were subjected to center-point loading test. Resonant frequencies and flexural strengths were successfully measured during the test for each concrete specimen.

The presented statistical results using Regression Analysis reject the null hypothesis thereby arriving to a conclusion that significant relationships between the displacement of the concrete beam and the resonant frequency of the embedded antenna occur. The concrete specimens cured in both 7 and 21 days and subjected to loading tests yields very significant and strong negative relationships between its displacements and corresponding resonant frequencies.

However, the regression line varies for each test specimens depending on the flexural strength of the concrete and the resonant frequency of the antenna.

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