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# Determination of Optimum Placement of the Liquid Metal Antenna Design Embedded in Concrete Beam Prototype Under Center – Point Loading Test

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***Abstract*—This study describes the application of dipole liquid metal antenna as a possible sensor of crack when embedded in a concrete beam prototype on several locations. The approach to the fabrication of antenna is based on McGyver-esque approach to microfabrication. The antenna consists of Eutectic Gallium Indium (EGaIn), a fluid metal alloy injected into microfluidic channels comprising a silicone elastomer composed of polydimethylsiloxane (PDMS). While the fluidic dipole antennas are highly flexible, stretchable, and reversibly deformable, changing its length through stretching the elastomeric channel also changes its resonant frequency. Experiments show that increasing the length of the antenna (not embedded in concrete), decreases its resonant frequency. This relationship becomes the basis of the study whether the antenna behaves in the same manner when it is already embedded in prototype concrete beams. Simultaneous testing using center-point loading machine and network analyzer for the three embedding locations of antenna are conducted to gather the necessary data that would best adapt to the inverse relationship of antenna's resonant frequency and displacement due to loading.**

***Index Terms*—Dipole liquid metal antenna, microfluidic channel, resonant frequency, lowest reflection coefficient, concrete beam prototype**

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## I. Introduction

The civil structures are often exposed to severe loadings during their lifetime, especially at extreme events like earthquake and typhoon, which causes serious concerns on the integrity of the structures that, is closely related to the public safety. Tragic disasters on the civil structures, like collapses of bridges or buildings, often accompany a large number of casualties as well as social and economic problems, thus most of the industrialized countries are on the verge of increasing their budget for structural health monitoring of their major civil infrastructures [1].

The use of concrete as a primary structural material in complex structures such as tall buildings, submerged structures, bridges, dams, liquid and gas containment structure has increased in the recent past. Proper understanding of the structural behavior of reinforced and unreinforced concrete is absolutely necessary in designing complex concrete structures. The presence of little cracks and other inherent flaws in concrete act as potential sources of crack propagation and fracture under external loadings. On the other hand, due to the application of repeated loads or due to a combination of loads and environmental attack, these cracks will grow in time causing the original strength of the structure to decrease progressively [2].

The damage condition of a concrete structure can be assessed through the detection and monitoring of cracks. Studies about crack detection applying different technologies like the use of fiber optics sensors, and image processing have been a popular and interesting topic of research at present times [3,4]. New technologies are hoped to be utilized as sensing elements for crack detection system. Such technologies include the liquid metal antenna which is determined to be a good sensor of strain through its resonant frequency whenever it is stretched or elongated [5]. The flexibility of the antenna might be exploited to make stress-detectors for civil-engineering projects such as dams and bridges [6].

As the incidents about building failures and bridge collapses increase, there is a need for thorough study of crack detection. The main goal of the study is to provide another sensing technology in crack detection by using liquid metal through finding its optimum placement embedded in concrete beam under center point loading test. This experimental study characterizes the capability of liquid metal antenna to detect cracks in concrete beam specimens using its property to change in resonant frequency every time it increases its length. A mathematical equation, relating the resonant frequency of the liquid metal antenna to its displacement under loading has been devised.

## II. RESEARCH DESIGN

The study is a developmental research which employs characterization technique. Characterization is a method of verifying the various attributes or qualities of a certain product or innovation by making a simulation and series of tests. The data gathered will be used to conclude the characteristics of the novel liquid metal antenna.

Figure 1 shows the steps in characterization of the liquid metal antenna. It involves fabrication of the antenna, construction of concrete beam and insertion of the antenna on the concrete. It also includes the measurement in real time of the resonant frequency for various effects of strain on antenna. This system will be monitored through the use of a system interface connected to the network analyzer. The accumulated results will be summarized using a mathematical model.

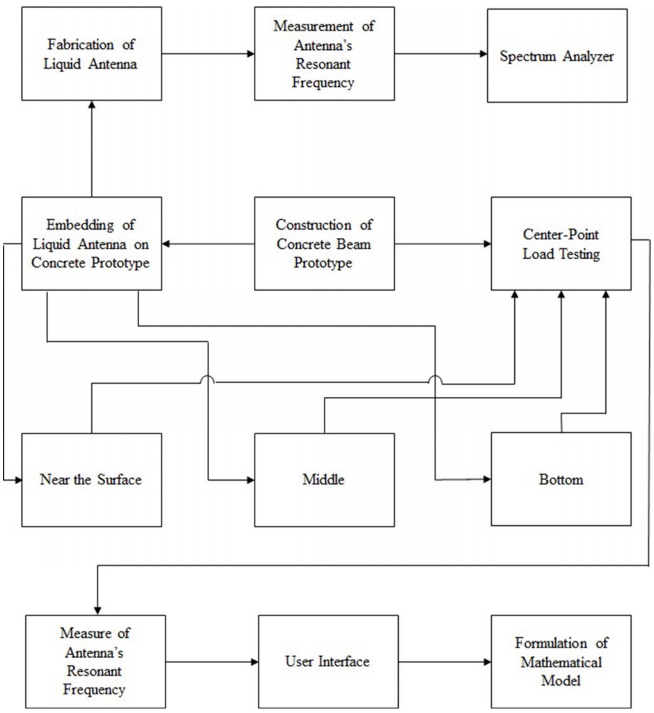


Fig.1 Block diagram of the determination of optimum placement of the liquid metal antenna embedded concrete beam prototype under center – point loading test

### *A. Fabrication of Antenna*

The researchers choose to fabricate a dipole antenna shown in Fig. 2. It consists of two conductive rods (Eutectic Gallium Indium) of equal length that are aligned along their long axis and separated by an insulating gap.

Fig.2 Liquid metal antenna

The length of the antenna is determined by using the formula as in Eq. 1. The thickness is based on the study done by [5].

$$l = \frac{c}{2f\sqrt{\epsilon_r}} \tag{1}$$

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

In order to cope with the complex methods of making microfluidic channel such as etching and soft lithography, requiring expensive facilities and user expertise, the researchers provide a McGyver–esque approach to micro fabrication. The simple method for fabricating PDMS microfluidic device is based on replicating a master mold made of electrical tape. Figure 3 shows the microfluidic channel master mold made of glass slide with electrical tape used in this study. The patterned electrical tape can be used (without the need of any chemical treatment) as a master mold for soft lithography yielding microfluidic channel with a uniform height of 160µm.

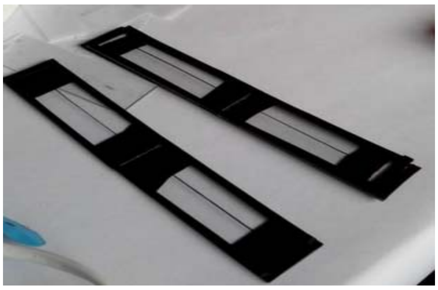

Fig.3 Microfluidic channel master mold made of glass slide with electrical tape

### *B. Embedding the Antenna in Concrete*

As a preliminary study for the characterization of the liquid metal antenna, the researchers opted to embed the antenna in unreinforced concrete beams. Reinforced concrete beam prototypes vary in both the concrete and steel bar dimensions requiring lots of factors to consider which are more difficult to test using center-point loading method since it require larger and heavy-weight machines and longer dipole liquid metal antennas. This approach simplifies the method by disregarding the effects of the steel bars on the resonant frequency of the antenna considering only the effect of the applied stress on the concrete to the resonant frequency of the embedded antenna.

The concrete beam prototype is constructed by using a standard 40 cm by 10 cm by 10 cm mold where the mixture of the cement, sand, and gravel at a 1:2:3 ratio is poured. Then, demolding is done for the concrete to be submerged in water and allow curing for 21 days. The antennas are embedded in the concrete beams as shown in Fig. 4 for the following locations: on the surface, in the middle and at the bottom which are 1 inch, 2 inches, 3 inches, respectively, from the top of the prototype beam.

Fig.4 Liquid metal antenna embedded in concrete beam prototype

### *C. Testing using Center-Point Loading Test*

The 4000 $cm^3$ concrete beam prototype is subjected to center-point loading using a testing machine to form cracks. The internal cracks are then responsible for the embedded antenna to stretch to certain length increase causing it to change its resonant frequency. The resonant frequencies of the antenna are measured through a network analyzer based on their corresponding lowest reflection coefficients obtained for every additional load applied by the machine on the concrete.

Simultaneous testing using center-point loading machine and network analyzer for this three embedding locations of antenna are conducted. This testing is shown in Fig.5. The data gathered are then analyzed using Pearson's correlation analysis.

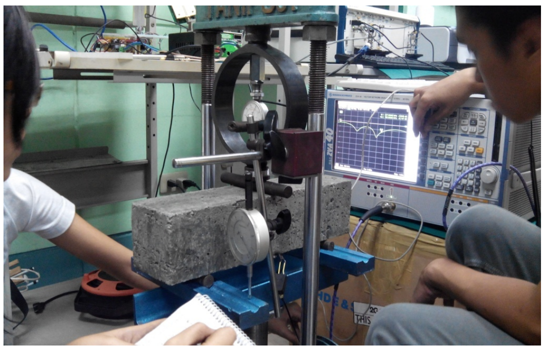

Fig.5 Concrete beam under center-point loading test and resonant frequency measurement with network analyzer

## III. ANALYSIS OF RESULTS

Necessary data such as the antenna's resonant frequencies with corresponding displacements on concrete beam due to loading were gathered and then analyzed statistically through Pearson's correlation analysis.

After the experiments, the samples which demonstrated the expected response were the concrete prototypes with antennas embedded at the bottom part. The findings in this paper show significant relationships between the displacement of the concrete beam prototype due to applied load and the resulting resonant frequency of the embedded liquid metal antenna.

The antenna was embedded 3 inches from the surface. An example of this is shown in Fig.6.

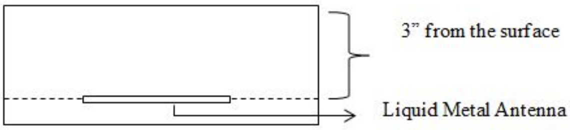


Fig.6 Sample figure of antenna embedded 3" from the surface

Figure 7 showed the significant relationship between the displacement and frequency of specimen 1. The graph also showed the linear equation formed from its given values.

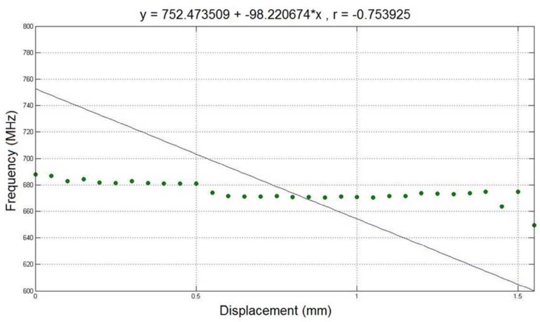


Fig.7 Graph of Displacement vs Frequency of Specimen 1 of 7 days curing with liquid metal antenna embedded 3" from the top surface

Also, extracting the square root of the coefficient of Determination ($R^2$) to get the coefficient of correlation (R) which was – 0.753925 (the negative sign indicates negative correlation), it showed that frequency and displacement have strong negative correlation.

Figure 8 showed significant relationship between the displacement and frequency of specimen 2. The graph also showed the linear equation formed from its given values. Also, extracting the square root of the coefficient of Determination ($R^2$) to get the coefficient of correlation (R) which was – 0.669079 (the negative sign indicates negative

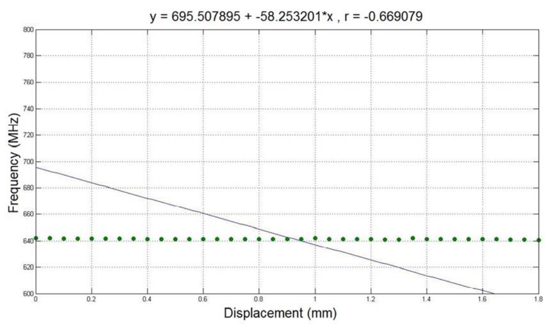


Fig.8 Graph of Displacement vs Frequency of Specimen 2 of 7 days curing with liquid metal antenna embedded 3" from the top surface

correlation), it showed that frequency and displacement have moderate negative correlation.

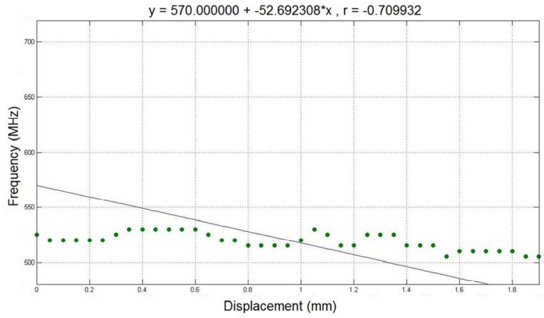


Fig.9 Graph of Displacement vs Frequency of Specimen 1 of 21 days curing with liquid metal antenna embedded 3" from the top surface

Figure 9 above showed significant relationship between the displacement and frequency of specimen 1. The graph also showed the linear equation formed from its given values. Also, extracting the square root of the coefficient of Determination ($R^2$) to get the coefficient of correlation (R) which was – 0.709932 (the negative sign indicates negative correlation), it showed that frequency and displacement have strong negative correlation.

Figure 10 showed significant relationship between the displacement and frequency of specimen 2. The graph also showed the linear equation formed from its given values. Also, extracting the square root of the coefficient of Determination ($R^2$) to get the coefficient of correlation (R) which was – 0.643870 (the negative sign indicates negative correlation), it showed that frequency and displacement have strong negative correlation.

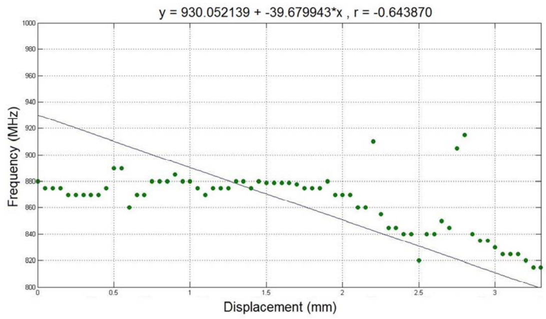


Fig.10 Graph of Displacement vs Frequency of Specimen 2 of 21 days curing with liquid metal antenna embedded 3" from the top surface

The graph in Fig.11 showed approximately a normal distribution of residuals since it passed the "fat pencil" test. It was a bit likely of a positively-skewed curve.

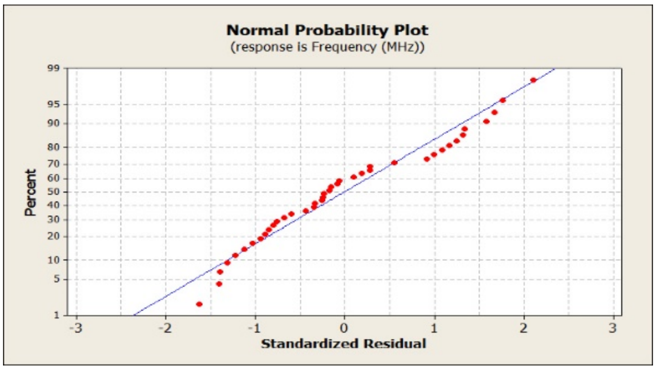


Fig.11 Normal Probability Plot of Specimen 1 of 21 days curing with liquid metal antenna embedded 3" from the top surface

The plot in Fig.12 shows how the variance of the residuals varies over time. It showed approximately minimal trend which implied a constant variation all throughout the data.

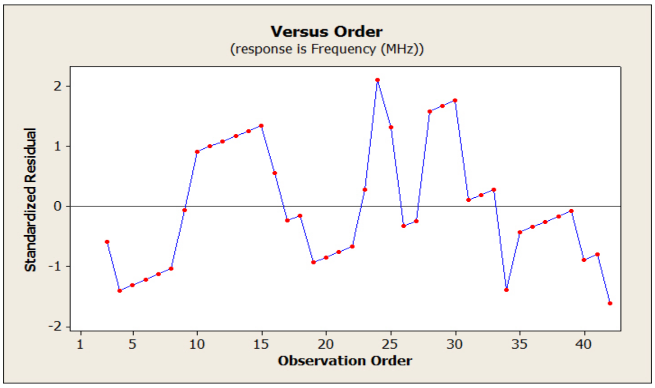


Fig.12 Residual Plot of Specimen 1 of 21 days curing with liquid metal antenna embedded 3" from the top surface

Figure 13 showed approximately a normal distribution of residuals since it passed the "fat pencil" test. It was more of a "bell-shaped" curve with few outliers to the right of the distribution.

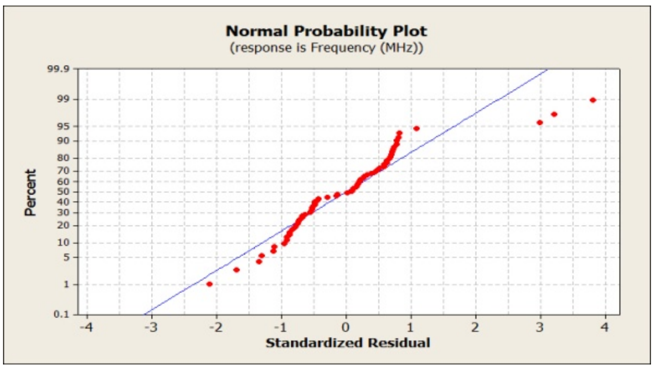


Fig.13 Normal Probability Plot of Specimen 2 of 21 days curing with liquid metal antenna embedded 3" from the top surface

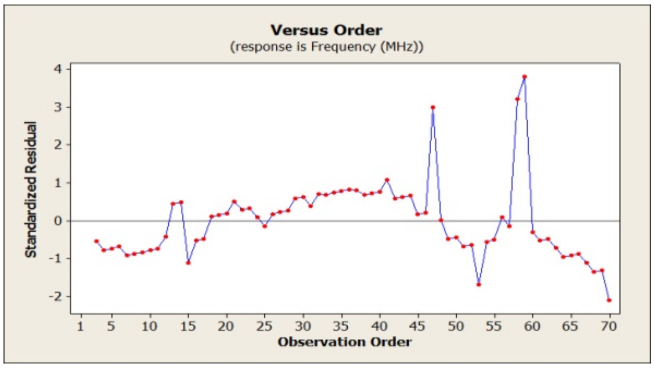


Fig.14 Residual Plot of Specimen 2 of 21 days curing with liquid metal antenna embedded 3" from the top surface

The plot in Fig.14 showed how the variance of the residuals varies over time. It showed approximately minimal trend with a few sudden increase in variance which implied a constant variation all throughout the data.

Based on the summary of findings of Regression Analysis in Table 1, among the three placements of antenna in concrete beams namely, on the surface, in the middle and at the bottom which are 1 inch, 2 inches, 3 inches, respectively, from the concrete's top surface, the antenna was most sensitive to change its resonant frequency when it was placed at the bottom.

TABLE I

SUMMARY OF FINDINGS OF REGRESSION ANALYSIS

| Cure Time | Specimen | Number of Samples | T0 | T(0.05, n-2) | Remarks | R | Confidence Interval on Slope | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | *Lower Limit* | *Upper Limit* |
| 7 days | ENS 1A | 31 | 3.26 | -1.699 | accept H0 | -0.5088 | 0.2004 | 0.7371 |
| | ENS 2A | 21 | -3.07 | -1.792 | reject H0 | -0.3481 | -0.8071 | -0.1924 |
| | EM 1A | 23 | -1.58 | -1.721 | accept H0 | 0.3535 | -0.6505 | 0.1 |
| | EM 2A | 43 | -5.71 | -1.683 | reject H0 | -0.2275 | -0.805 | -0.4565 |
| | EB 1A | 32 | -6.39 | -1.796 | reject H0 | -0.7539 | -0.873 | -0.5494 |
| | EB 2A | 38 | -5.4 | -1.689 | reject H0 | -0.6691 | -0.8147 | -0.4448 |
| 21 days | ENS 1B | 24 | -1.49 | -1.717 | accept H0 | -0.4428 | -0.6297 | 0.1141 |
| | ENS 2B | 40 | -1.97 | -1.687 | reject H0 | -0.2217 | -0.5605 | 0.0108 |
| | EM 1B | 26 | -0.65 | -1.711 | accept H0 | -0.0979 | -0.4926 | 0.271 |
| | EM 2B | 61 | -7.3 | -1.672 | reject H0 | -0.6879 | -0.8014 | -0.5283 |
| | EB 1B | 40 | -6.21 | -1.6866 | reject H0 | -0.7099 | -0.8364 | -0.5115 |
| | EB 2B | 68 | -6.84 | -1.6697 | reject H0 | -0.6439 | -0.7651 | -0.4794 |
| Antenna in Acrylic 1 | | 50 | -4.98 | -1.6788 | reject H0 | -0.6831 | -0.9207 | -0.4973 |
| Antenna Stretched by Clamp | | 39 | -49.94 | -1.6879 | reject H0 | -0.9919 | -0.9961 | -0.9856 |

The following observations were drawn:

*1)* The relationship between resonant frequency and strain was analyzed by Pearson's correlation analysis using a Matlab program that extracts the raw data (.csv file format) obtained from the network analyzer and outputs the graph of resonant frequency vs. displacement.

*2)* A mathematical equation was devised by determining first the optimum position at the concrete beam where the dipole liquid metal antenna was most sensitive to change in resonant frequency which is at the bottom. Then linear regression equations of each sample were obtained using Minitab. Finally, a Matlab program was created to average these equations to come up with one approximate linear regression equation:

$$y = -10.273993x + k, \quad (2)$$

where $x$ is the displacement in mm and $y$ is the resonant frequency in MHz, and $k$ is the initial resonant frequency. Thus, the model shows an explicit linear relationship between resonant frequency and displacement. It contains a negative slope which implies an inverse proportionality between the two.

## IV. CONCLUSION

According to the resonant frequency vs. displacement graphs that has been previously shown, it clearly showed that the optimum position at the concrete beam where the dipole liquid metal antenna was most sensitive to change in resonant frequency was at the bottom. It is also in accordance to the testing of hypothesis through t-test, using a 95% confidence.

Based on Table 1, for the samples of concrete beams with 7 and 21 days of curing, both the null hypothesis were rejected under such specimens where liquid metal antenna were embedded at the bottom unlike from the other samples where the antenna were embedded on the surface and in the middle. Moreover, the correlation coefficients under the said specimens proved to be the highest among the other samples which implies that antennas embedded at the bottom have the strongest negative correlation between the resonant frequencies and displacements.

The findings of this novel approach of characterizing liquid metal antenna by embedding it in a concrete indicate the high feasibility of using the liquid antenna as a sensing element for detecting concrete deformation such as cracks. For more accurate results, this suggests a further study on the characterization of the liquid antenna by embedding it in reinforced concrete considering the effects of steel bars in the antenna's resonant frequency.

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