

# PZT Based Smart Aggregate for Unified Health Monitoring of RC Structures

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## Abstract

The most familiar civil engineering structure is reinforced concrete (RC) structure. Performance of structure undergoes changes during their service life with time. Thus, it is of great concern to monitor the health of RC structure. Structural health monitoring (SHM) is the art of detecting the changes in structure that influences its performance. Various techniques to monitor the health of structure are broadly studied worldwide. PZT based smart aggregate can play an effective role as an advanced tool in the development of structural health monitoring. This research work contributes for proposing a more generous Non-Destructive Evaluation (NDE) technique for structural health monitoring by using smart materials. If performance of a structure deviates from the design parameters with time, appropriate and effective maintenance is required. Considering the relevant need of RC structures, a more sensitive and cost-effective approach by using Electro-Mechanical Impedance (EMI) technique has been proposed for implementation in real-life situations. In general, surface bonded PZT transducer is used for SHM. Since PZT transducers are of very small dimension and brittle in nature, for consistent characteristics, they should be protected from severe environmental condition and other external interruptions. For this reason, PZT transducer is embedded in structure at the time of construction and manufacturing of the embedded transducer is simple. The proposed EMI technique assesses the health of RC structures more rationally by embedding PZT transducer in the structure, whose health is to be monitored over the user specified preset frequency range. The conductance and susceptance signatures are acquired by using LCR meter. At any future point of time, when it is desired to assess the health of structure, the conductance and susceptance signatures are acquired and further utilized for damage detection and quantification. The Root Mean Square Deviation (RMSD) is used to specify damage severity.

## Keywords

Concrete, Impedance, Piezoelectric Materials, Sensors, Smart Aggregates

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## 1. Introduction

Structures consist of an assembly of various members like columns, beams, slabs, etc. Piezoceramic transducer has been playing an important role in structural health monitoring. Any damage of the host structure reflects changes in its properties. Major damages to structures can lead to failures, causing inconvenience and safety problems. Therefore, continuous monitoring of structure is essential. Numerous structural engineers drew attention towards developing modern sensor technology for making structures, smart enough to warn the concerned authorities before their failure in the recent decade years.

Sensors like accelerometers, strain gauges, Piezo based Lead Zirconate Titanate (PZT) patches, etc. can be used to monitor the health of the structures. As compared to other sensors, piezo based sensors are becoming more popular because of their efficiency of monitoring. Smart materials are widely used in Structural Health Monitoring (SHM) systems due to the viability of them in host structures; to act as sensors and/or actuators to assess the continuous health of a structure.

Among all the health monitoring methods, Electro-Mechanical Impedance (EMI) based health monitoring using piezoelectric materials is extensively acknowledged. The conductance signature is acquired with the help of EMI active sensor which serves as an indication of damage in structure. Kaur, Gupta, Jain and Bhalla [1] presented the integrated application of the global vibration technique and the low-cost EMI technique for damage detection and severity assessment. Shanker [2] experimentally investigated the possibility of an embedded PZT as a sensor by using impedance based method over concrete beams and steel beams. Annamdas, Yang, and Soh [3] proposed a double protection wrap method employing both metal and non-metal of embedding PZT sensor in concrete for monitoring either fresh or cured concrete using embedded piezoelectric transducer (PZT) via EMI technique. Negi, Kaur, Bhalla and Chakraborty [4] presented the responses of PZT patches while embedded in host structure in three different configurations after embedding in a prototype RC beam. Dumoulin, Karaiskos and Deraemaeker [5] studied the embedded transducers to detect and follow the crack propagation in a reinforced concrete beam subjected to a three-point bending test. Song, Gu and Mo [6] proposed the multi-functionality of smart aggregates for early-age concrete strength monitoring, impact detection and structural health monitoring. Feng, Dandjekpo and Zhou [7] detected the post-earthquake damage in concrete dams by using embedded electro-mechanical impedance (EMI) sensors. Visalakshi and Bhalla [8] compared the sensing capabilities of surface bonded and embedded piezoceramic (PZT) patches in diagnosing chloride-induced corrosion for RC structures. Yoo, Khatibi and Kandare [9] reported a study on the degradation of embedded PZT transducers under cyclic loadings.

Damage identification is carried out by comparing the signature of structure in healthy state with the signatures obtained after a damage. The specific objective of the present study is to carry out the structural health monitoring of structures using indigenously prepared embedded PZT patches.

## 2. Electro-Mechanical Impedance (EMI) Technique

The Electro-Mechanical Impedance (EMI) technique using piezo elements is relatively a new technique for SHM. The EMI technique employs PZT patches as a sensor. A PZT patch is surface bonded or embedded inside the structures to be monitored, as shown in **Figure 1**. The sensing zone of PZT patch is limited to 0.4 to 2 m.

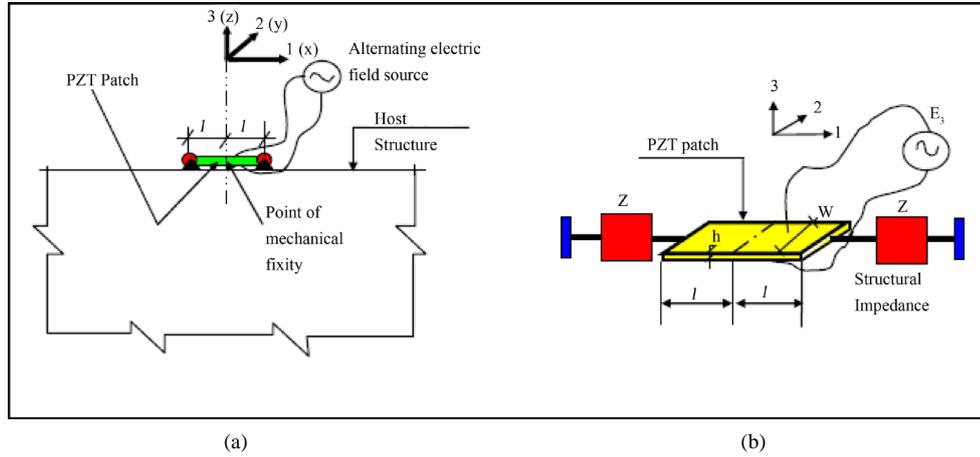
The patch (length  $2l$ , width  $w$  and thickness  $h$ ) behaves as thin bar undergoing axial vibration. When an alternating electric field is applied to the patch; it expands and contracts dynamically in direction "1". Two end points of the patch can be assumed to encounter equal impedance  $Z$  from the host structure. An electro-mechanical model of the system is shown in **Figure 1(b)**, where the structure has been replaced by two equal mechanical impedances  $Z$ .

$$Y = 2\omega j \frac{wl}{h} \left[ (\epsilon_{33})^T + \left( \frac{Z_a}{Z + Z_a} \right) (d_{31})^2 \bar{Y}^E \left( \frac{\tan kl}{kl} \right) - (d_{31})^2 \bar{Y}^E \right] \quad (1)$$

Equation (1) represents the complex electro-mechanical admittance  $Y$  of the coupled system.

Where,  $Z_a$  is mechanical impedance of the PZT patch,  $\omega$  is angular frequency and  $kl$  is the wave number,  $d_{31}$  is the piezoelectric strain coefficient of the PZT material,  $\bar{Y}^E$  is the complex Young's modulus under constant electric field,  $(\epsilon_{33})^T$  is the complex electric permittivity at constant stress.

The mechanical impedance  $Z$  of the host structure is the function of the structural parameters, *i.e.*, as stiffness, damping and mass. Any damage to the structure will cause these parameters to change, and hence changes the



**Figure 1.** Modeling PZT-structure interaction [2]. (a) A PZT patch bonded to structure under electric excitation; (b) Interaction model of PZT patch and host structure.

drive point mechanical impedance  $Z$ . As a result, the electro-mechanical admittance  $Y$  will change and this serves an indicator of the state of health of the structure. Equation (1) is utilized in EMI technique for damage detection. The electro-mechanical admittance  $Y$  consists of the real and the imaginary component called conductance and susceptance respectively. Hence, the magnitude of complex admittance can be calculated as given in Equation (2):

$$Y = \sqrt{G^2 + B^2} \quad (2)$$

where,  $G$  = Conductance; real part of admittance,

$B$  = Susceptance; imaginary part of admittance.

There are several techniques available to quantify damages in structure. In the present work, to quantify damage in structure Root Mean Square Deviation (RMSD) technique is used which is given as:

$$M = \sqrt{\frac{\sum (G_2 - G_1)^2}{\sum G_1^2}} \times 100 (\%) \quad (3)$$

where,  $M$  = Damage metric (Root Mean Square Deviation),

$G_1$  = Conductance before damage,

$G_2$  = Conductance after damage.

### 3. Experimental Investigation

#### 3.1. General

In order to perform structural health monitoring of concrete structures using EMI technique, a model RC beam and smart aggregate was cast. The experimental investigation is carried for damage identification and crack detection. The instrument used is digital Impedance Analyzer (LCR meter E4980A) of frequency range of 20 Hz to 2 MHz and its connecting fixture, and a USB cable and VEE Pro 9.32 for data acquisition. To monitor the health of a structure experiment was performed in two stages *i.e.* firstly for the healthy state of host structure and then for damaged state of structure.

#### 3.2. Materials and Specimen

The test was carried out on reinforced concrete beam. The PZT sensor was fabricated and embedded inside the RC beam. To prepare the embedded sensor SMart AGgregate (SMAG), both the surfaces of naked PZT patch with the dimensions of 10 mm × 10 mm × 0.2 mm are welded to coaxial cable wires, respectively, and the bare PZT impedance sensors is formed. The form work of card board with 20 mm diameter was first filled with ce-

ment mortar of proportion (1:2) to the half depth. After 7 days curing, the PZT (5 H) patch was bonded on the top of the surface of the cement block using epoxy (Araldite). After 24 hours, the card board was filled to full depth with the cement mortar. After 7 days of curing, the card board was removed from cement block and was ready to use in any structure under construction as shown in **Figure 2**.

The performance of sensor was studied on the R.C. beam structure whose dimensions and properties are shown in **Table 1**. The typical block diagram of RC beam with SMart AGgregate (SMAG) is shown in **Figure 3**.

### 3.3. Experimental Set-Up

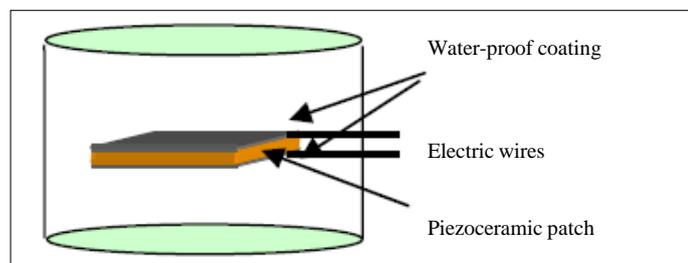
This experiment essentially involves a simply supported RC beam with embedded SMAG at 100 mm distance from right support and 30 mm distance from bottom of beam as shown in **Figure 4**. The instrument required to obtain signatures are digital Impedance Analyzer (LCR meter E4980A) and its connecting fixture and a USB cable and VEE Pro 9.32 for data acquisition. This test was performed in two stages *i.e.* in the first stage signatures for healthy condition of the beam and in second stage for the damaged condition of beam is obtained.

In the first stage, the soldered PZT patch in the form of SMAG was wired to Impedance Analyzer through Connecting Fixture of LCR meter. Then the frequency was swept through 100 kHz to 400 kHz *i.e.* the PZT patch transfers this vibrations to the structure through adhesive bond layer. These vibrations are transferred to structures and reflected back from the same PZT patch through waves, which will indicate the health of the structure. The required parameter *i.e.* Conductance (G) is directly measured through LCR meter for all the values of frequency. From the obtained data, the graph of Conductance versus Frequency is plotted. These graphs are said to be the Conductance Signature or just a signature shown by particular sensor for specimen. This data is saved in excel format and can be available as and when required. The assembly for the experiment of EMI technique is as shown in **Figure 5**.

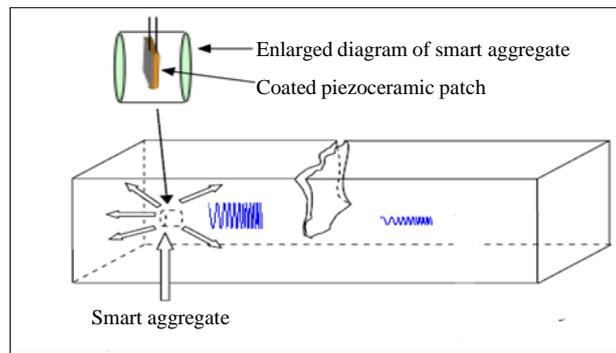
In the second stage, damage was introduced in the form of significant visible crack by loading the specimen under Universal Testing Machine (UTM) as shown in **Figure 6** and then the same damaged specimen with PZT patch was reanalyzed for damaged state by using the same procedure as previously adopted. The PZT patch again acts as an actuator and sensor. Then the data for healthy state and damaged state was compared.

**Table 1.** Material properties and dimensions of RC beam.

Dimensions/Properties	Value
Length (L)	410 mm
Cross-section	100 mm × 100 mm
Grade of cement (OPC)	43
Grade of steel	Fe 415
Reinforcement bars	2#8 mm dia at top and bottom
stirrups	6 mm dia @80 mm c/c
Characteristic strength of concrete	20 N/mm <sup>2</sup>
Curing period	7 days



**Figure 2.** Typical SMart AGgregate (SMAG).



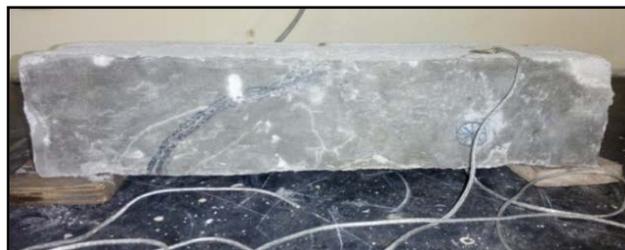
**Figure 3.** Block diagram of RC beam with embedded SMAG.



**Figure 4.** RC beam with embedded SMAG.



**Figure 5.** General configuration of set-up and instrument using E4980A impedance analyzer.



**Figure 6.** Damaged RC beam.

## 4. Results and Discussions

### 4.1. Response for Healthy Condition of Embedded SMAG

For the first stage, the healthy structure response is taken, with the SMAG embedded in simply supported RC beam. Piezoelectric patch was connected via cable to LCR meter and corresponding response was recorded. The beam was subjected to frequency range of 100 to 400 kHz. In this range, corresponding conductance values

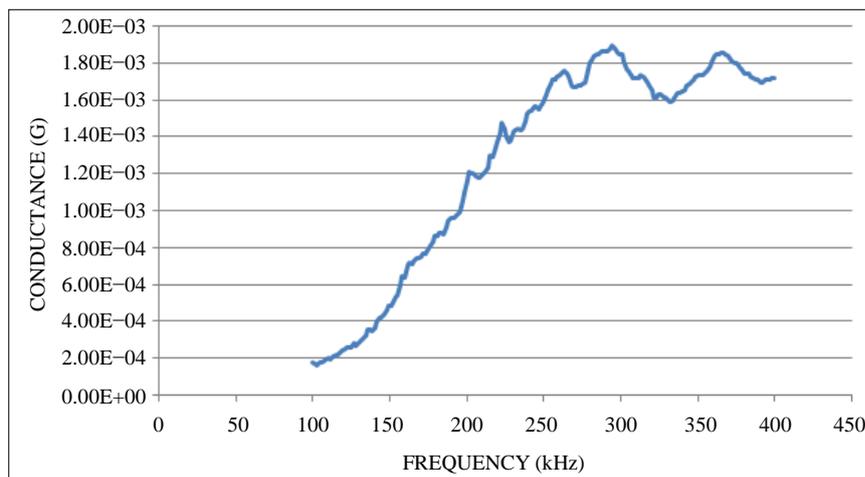
were recorded by LCR meter. The conductance graph is shown in **Figure 7** and susceptance graph is shown in **Figure 8**. The conductance graph shows abundant peaks where the susceptance graph is comparatively flat.

## 4.2. Response for Damaged Condition

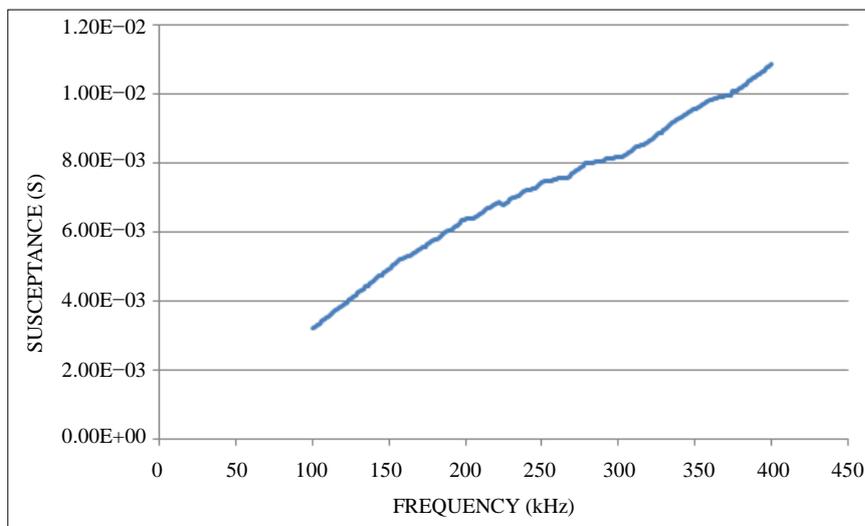
In the second stage, the beam is laterally loaded on Universal Testing Machine until significant visible crack is seen. The same beam with embedded SMAG was connected via cable to LCR meter and corresponding response in term of conductance and susceptance was recorded as shown in **Figure 9** and **Figure 10** respectively.

By comparing the results obtained for both the stages as shown in **Figure 11** and **Figure 12**, it can be said that the responses for RC beam is different for healthy and damaged conditions. Changes in the responses are the indications of damages. The effectiveness of embedded PZT is evident from the fact that there is clear shift in vertical as well as lateral direction in the recorded conductance response. The absence of peaks in the original susceptance response in **Figure 8** and **Figure 10** and lesser deviation from original curve in **Figure 12** makes susceptance signature a weak candidate for flaw detection. Structural health monitoring with embedded piezoelectric patches proves to be effective tool for damage detection.

The damage index recorded by embedded SMAG using root mean square deviation technique (RMSD) is found to be 5.0014% in frequency range of 100 - 400 kHz.



**Figure 7.** Conductance graph for healthy beam by embedded SMAG.



**Figure 8.** Susceptance graph for healthy beam by embedded SMAG.

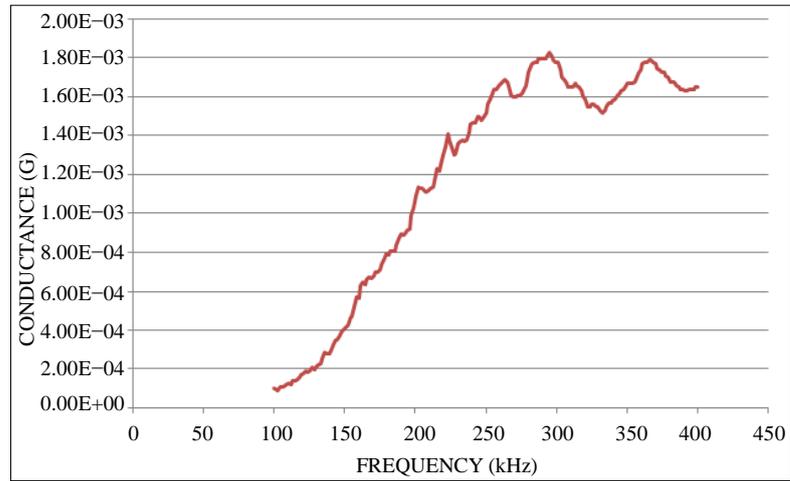


Figure 9. Conductance graph for damaged beam by embedded SMAG.

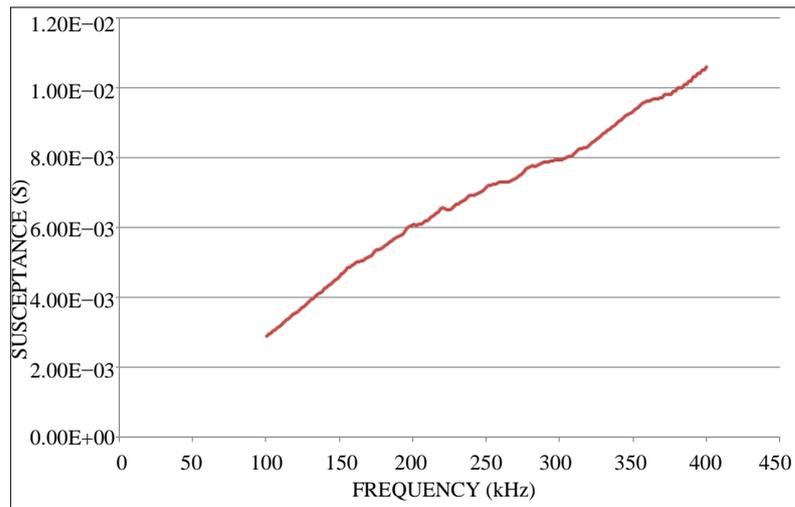


Figure 10. Susceptance graph for damaged beam by embedded SMAG.

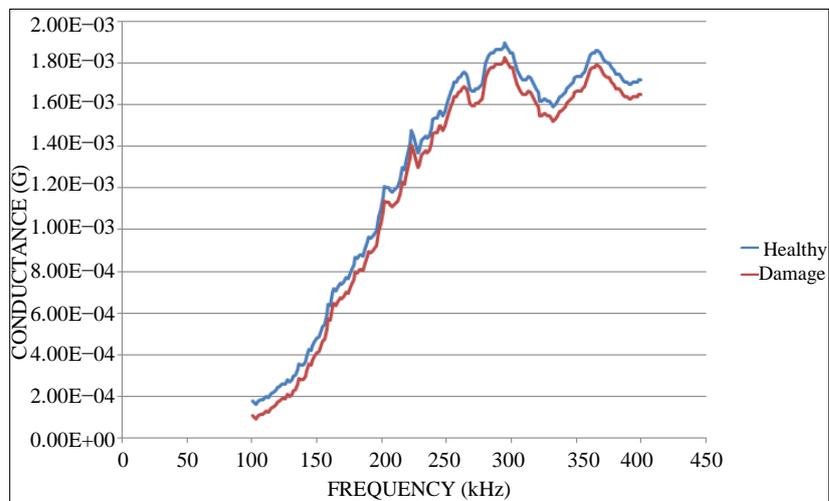
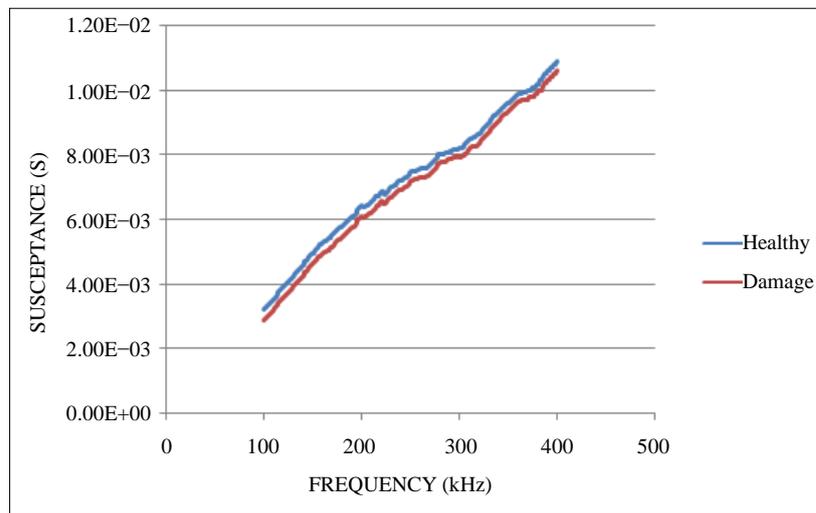


Figure 11. Conductance graph for healthy and damaged beam by embedded SMAG.



**Figure 12.** Susceptance graph for healthy and damaged beam by embedded SMAG.

## 5. Conclusion

It is concluded from the above experimental work that continuous health monitoring of structure is possible using proposed simple low cost technique. Instead of surface bonded PZT patches, structural health monitoring with embedded PZT patches is very effective and easy to implement and the record data can be available as and when required. For health monitoring of RC structure, it is a challenging task to detect incipient damages. It is found that the incipient level damages are very quickly and effectively detected by using present EMI technique. It is again established that the conductance signature is more effective in damage detection than susceptance signature.

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