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Investigation of strain-sensing materials based on EM surface wave propagation for steel bridge health monitoring

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ABSTRACT

This paper describes the exploration of a sensor concept for use in structural health monitoring. The sensor is based on the principle of electromagnetic (EM) surface wave propagation, and consists of a thin-layer of wave-guiding media attached to a metal base (e.g., steel bridge elements) and an EM wave emitter and receiver. Targeting at a low-cost and practical solution, various dielectric materials that facilitate EM wave propagation were examined. Low-density polyethylene was determined to have the most suitable dielectric properties and was selected for laboratory tests using tension coupon specimens. The tests of steel coupons with a low-density polyethylene strip indicated that the parameters of an EM wave (e.g., amplitude and phase) changed as the coupon specimens deformed. Therefore, the proposed sensor concept based on EM surface wave propagation can be a viable option for monitoring steel bridges.

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1. Introduction

Bridges represent significant investment within the highway transportation network that supports commerce, economic vitality, and personal mobility. These expensive structures must operate in an environment that is not favorable to their durability. Defining service levels and prioritizing maintenance budgets based only on analytical/numerical computations and/or periodic inspections may result in inaccurate diagnosis and inefficient use of resources. Stress detection in structural materials has recently become of significant interest for bridge engineers and transportation agencies throughout the United States. In 2007, the I-35W bridge, which spans the Mississippi River in Minneapolis, Minnesota, collapsed and killed 13 people [31]. The collapse of the bridge sparked the need to improve or renew the bridge infrastructure of the nation [21]. Rather than spending trillions of dollars to replace every aging bridge structure, one solution is the real-time monitoring of the state of a bridge to determine the scale and propagation of any defects for timely decisions on bridge operation and maintenance [26].

This paper describes the exploration of an innovative sensor concept based on the principle of electromagnetic surface wave propagation, for potential use as a cost effective bridge health monitoring system. The proposed sensor consists of a thin layer of EM wave-guiding material applied on a steel member, an EM wave transmitter and a signal receiver. The fundamental concept of the sensor is similar to that of fiber optic sensors, except that fiber optic sensors usually detect the phase change of an optical wave (i.e., high-frequency EM wave at several hundred THz) [12] while lower frequency (e.g., around 40 GHz) EM wave was used in the proposed technique. The advantage is that with a much lower frequency, the well-established technology developed for wireless communication may be used to detect the disturbance of the EM wave caused by strains in the base steel. Importantly, the amplitude of the EM wave rather than the phase changes can be used for strain detection, thus leading to an economical and practical solution [33]. The envisioned application of such sensor technology is schematically shown in Fig. 1 for monitoring a deck truss bridge: a layer of EM wave-guiding material is applied to steel members (both primary members and secondary members) in a manner similar to their anti-corrosive paint; and EM wave transmitters and receivers are located at the joints to emit/receive the EM wave and detect changes. The obtained information may be sent to engineers via wireless communication devices.

2. Literature review

The conventional method to monitor the status of a bridge is dominated by visual inspection though technologies for bridge evaluation have been rapidly advancing since the collapse of the Silver Bridge [9] in Point Pleasant, West Virginia, on December 15, 1967. Visual inspection is labor consuming, subjective and not always effective for observing the damage of a bridge in real-time [19]. Numerous methods of structural health monitoring, including nondestructive testing of structures, have been developed to

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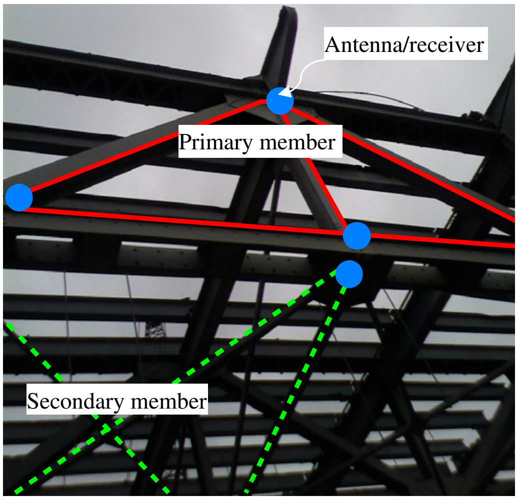

Fig. 1. Schematic of electromagnetic wave sensors on deck truss bridge.

provide an estimate of bridge status (e.g., [1,5,6,10,11,13,14,17,18,29,32].

Monitoring bridge vibration is among global inspection techniques, which detect critical local failures through monitoring the global bridge responses [18,5]. Bridge vibration (i.e., overall dynamic response) excited by truck loads can be affected by local member damage such as cracking, and the change in the dynamic response can be detected using accelerometers and GPS-based devices. However, using this technique it is difficult to determine the failure locations because many different local failures may cause similar changes in the global bridge response. Strain detecting devices, such as resistance-type strain gages, can be installed on bridges to monitor the condition of critical bridge elements. To minimize the impact of an adverse environment on conventional strain gages, fiber optic sensors have been explored [6,12]. In addition to strains, fiber optic sensors are capable of detecting surface cracks perpendicular to the sensor line through sensing the disruption of the optic waves. A disrupted optical wave could also provide the means for determining the location of a crack. The optical wave involved in fiber optic sensors is actually a high-frequency EM surface wave, and expensive signal demodulators are usually needed to detect the change in the EM wave and correlate the change with the strain of the base material [30].

The use of eddy currents and acoustic emission can detect local failures (e.g., cracking in structural members) [8,18]. The eddy current inspection technique is based on a principal of electromagnetism: when a source of alternating current is supplied to a conducting material, a magnetic field develops in and around the material. The presence of a crack in the material/structure affects the flow pattern of the eddy current, which can be detected. Small defects such as near-surface cracks can be detected, providing early warnings for structural failure. Eddy current technology has been implemented for the detection of surface-breaking cracks in welded connections [8]. The advantages of eddy current inspection techniques include portability of sensor equipment, minimum part preparation, and non-contact evaluation. However, scanning through an entire structure using eddy current or acoustic emission techniques can be labor intensive and requires accessibility of the structure that is often not accessible. In addition, Zoughi and Kharkovsky [33] have utilized microwaves (300 MHz–30 GHz) and millimeter (30–300 GHz) waves for detecting cracks. In the reported application, a layer of dielectric paint was placed on a steel member with a preformed defect, and EM waves were emitted and received by two closely placed antennas. The normal EM wave transmited is disturbed near the defect in the base metal. Again, the disturbance of the EM wave needs to be detected in the frequency domain, thus requiring specialized equipment.

The proposed sensor is based on the principles of EM surface wave propagation with a wave frequency of around 40 GHz. In this respect, the proposed sensor is different from fiber optic sensors in that millimeter waves rather than optical waves are used. With a lower frequency, it is expected that the amplitude of the EM wave can be used for the targeted measurement with an expectation to eliminate the need for expensive specialized equipment for phase detection.

3. Dielectric material selection

Electromagnetic (EM) waves are created by the vibration of an electric charge by application of an energy input. The mechanism of EM wave propagation through a medium involves the absorption and reemission of the wave energy by the atoms of the material [7,25]. Materials with more closely packed atoms have smaller distances between atoms, thus affecting the propagation of the EM wave [22]. Materials that facilitate EM wave propagation are mainly dielectric materials, including ceramic, mica, glass, plastics, and the oxides of various metals [30]. An ideal dielectric material does not exhibit electrical conductivity. The ability of a dielectric material to facilitate EM propagation is measured by the amount of energy dissipated and transformed into heat energy. The lower the dielectric loss tangent, the lower the proportion of energy lost (i.e., the lower the absorption). Another material characteristic is the dielectric constant, the extent to which a substance concentrates the electrostatic lines of flux. Substances with a low dielectric constant include a perfect vacuum, dry air, and most pure, dry gases such as helium and nitrogen. Materials with moderate dielectric constants include ceramics, distilled water, paper, mica, polyethylene, and glass. Metal oxides in general have high dielectric constants [30].

Permittivity is a physical quantity that describes how an electric field affects and is affected by a dielectric medium to reduce the total electric field inside the material. The material to be used as the wave-guiding medium in the proposed concept sensor is required to have exceptional dielectric properties for practical implementation on bridges: the material should have very low absorption characteristics, and a relatively high permittivity. For example, a loss tangent around 0.001 and a dielectric constant of around 10 are desired. This requirement of high permittivity and low loss for the wave-guiding material results from the concept of the proposed sensor: the EM wave needs to travel a distance equaling the length of the steel bridge elements; energy needs to be confined to the vicinity of the material (suggesting high permittivity), and the low absorption is required by the large distances involved. This is different from the sensors described by Zoughi and Kharkovsky [33], in which the EM waves were required to travel the short distance between the sensor heads that were located on the two sides of the crack in the base metal. In addition, the wave-guiding material should have a near-perfect bond with the base metal and minimal creep properties.

In this study, various materials with different dielectric, adhesion and mechanical properties were tested. The application of the media to the specimen required the media to have strong adhesion properties along with a viscosity capable of being applied in a thin layer. Two systems of media were investigated: the use of an epoxy coat and the use of a pre-manufactured media adhered to the structural element using a pre-manufactured adhesive. A variety of epoxies were tested for viscosity, curing rate, and, most importantly, permittivity. A split post resonator (shown in Fig. 2) was used to measure the permittivity of materials at a frequency

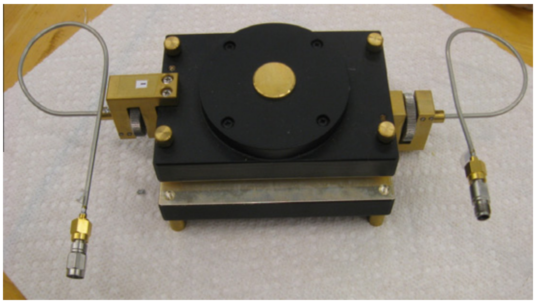

Fig. 2. Cross-section of split post dielectric resonator.

of 2.67 GHz [2]. With details shown elsewhere [20], the dielectric properties of various materials were determined and listed in Table 1.

Among the epoxies tested, MT-13 had the highest dielectric constant (3.54) and EA-40 had the lowest loss tangent (0.012). Comparing with the aforementioned desired values, both materials were deemed inadequate for the project needs. Besides epoxies, the dielectric properties of solid materials were also examined. The materials explored were known through a literature review [4] to have exceptional dielectric properties. The dielectric properties of the solid materials were tested in a similar fashion as the epoxy. Quartz was found to have exceptional dielectric properties as shown in Table 1. The extremely low loss tangent indicates the material will lead to very low energy absorption.

With a hope to enhance the dielectric properties of the epoxy (i.e., EA-40), different materials of known low loss tangents were mixed with epoxy resin to create a designable dielectric media. Although MT-13 provided the highest dielectric constant of all the epoxies tested, the EA-40 was considered the better material due to the lower loss tangent. Powdered glass and silicon dioxide (both with known low loss tangents) were introduced into the epoxy systems at various quantities. Powdered glass was mixed in with the EA-40 at ratios of 1%, 5% and 10% by mass and silicon dioxide was mixed in at ratios of 10% and 25% by mass. The measured dielectric properties of the composite materials are shown Table 2. With the addition of silicon dioxide into the EA-40 epoxy matrix, the dielectric constant increased by 7.5% for the mixture with both a 10% and 25% SiO_2 powders by mass. However, the dielectric loss tangent increased by 33%. Similarly, the addition of glass particles into the epoxy media caused the dielectric constant to remain the same as plain EA-40, but the loss tangent also significantly increased by 79%. This increase in loss tangent indicates that the composite materials with arbitrarily dispersed dielectric particles would not improve the EM wave propagation characteristics. It is thus envisioned that composite materials with structured dielectric particle distributions may be appropriate. The design of structured dielectric composites was not further explored in this study due to a limited particle dispersion capability.

If energy absorption is high, the signal transmitter and receiver need to be placed close together, as in the study by Zoughi and Kharkovsky [33]. Hence, low-density polyethylene (LDP) was used to demonstrate the concept of the proposed sensor. Low-density polyethylene was found to have desirable characteristics (i.e., although the dielectric constant of 2.2 is somewhat low, the extremely low loss tangent of 0.00065 indicates very low absorption) and high ductility. This may have been due to the fact that the LDP material has a high degree of short and long chain branching, which means the chains do not pack into a crystal structure [28]. In addition, the high degree of branches with long chains gives molten low-density polyethylene unique and desirable flow properties, thus it may be used in the designable composite material in the future as discussed by Hong et al. [15].

Table 1
Dielectric properties of various materials.

Epoxy type	Dielectric constant	Dielectric loss tangent
EA-1	2.83	0.1837
MT-13	3.54	0.0295
EA-40	2.8	0.0115
EP30	2.97	0.0392
EP21LV	2.83	0.0400
C-1509	2.8	0.0284
URE Bond	2.18	0.0386
PCM 121/30	2.59	0.0794
PMC 744	2.27	0.0676
Plasti-paste	2.58	0.0286
Quartz	4.55	0.000094
Polyethylene	2.2	0.00065

Table 2
Dielectric Properties of EA-40 with additional glass and silicon dioxide.

Composite material	Dielectric constant	Dielectric loss tangent
EA-40	2.8	0.0115
EA-40 with 10% SiO_2	3.01	0.0153
EA-40 with 25% SiO_2	3.01	0.0151
EA-40 with 1% Glass	2.71	0.0200
EA-40 with 5% Glass	2.8	0.0206
EA-40 with 10% Glass	2.8	0.0180

The decision to use low-density polyethylene as wave propagation media resulted in a secondary challenge of how to adhere the low-density polyethylene to steel. To achieve this, a variety of techniques were explored. Double-sided tape with acrylic adhesive was found to be able to provide secure bonding even under high temperature conditions [27]. Applications of such adhesive materials include mounting plates in the automotive industry, self-adhering mounting of rubber and EPDM materials and decorative trim in the furniture industry. Application of the Killer Red tape manufactured by CS Hyde Company produced satisfactory adhesion between the low-density polyethylene and the steel coupon.

4. Verification tests

The laboratory verification tests for the sensor concept were conducted on steel coupons with low-density polyethylene adhered to the steel using acrylic adhesive. The coupon specimens were sized proportional to that of the standard tension coupons per ASTM standards as shown in Fig. 3. A wider specimen was used because of the required width of EM wave-guiding medium (i.e., larger than 25 mm). The thickness of the specimen was chosen accordingly to ensure the ultimate coupon load within the capacity of the INSTRON load frame shown later in Fig. 5. An extensometer was used to measure the strain of the steel coupons, which was assumed constant within the 230-mm LDP length as shown in Fig. 3. The LDP layer was 0.6 mm in most tests while the thickness of the LDF medium was varied to 1.4 mm in some tests. To effectively transmit and receive the EM wave, a patch antenna was developed. A patch antenna capable of focusing the EM surface wave in a certain direction was designed using the Yagi-Uda antenna concept [24] and [23]. The 40-GHz patch antenna manufactured for this research project is shown in Fig. 4 (details of the antenna are shown elsewhere [20]). Because of the directionality of the patch antenna, exact linear arrangement between the two patch antennas (transmit and receive) would provide the optimum measured signal strength. However, the geometry of the testing specimen shown in Fig. 3 restricted exact alignment, thus both patch antennas were rotated approximately 3° to produce the maximum sensitivity.

The amplitude and phase of the EM surface wave were measured using a network analyzer [3] as shown in Fig. 5 at this stage of sensor development. Using this system, the strain (and the applied load) measurements cannot be recorded simultaneously with the EM wave amplitudes. Therefore, the applied load increased stepwise with a load interval of 1.1 kN (the specimens yielded at a load around 5.6 kN from separate material tests). While the load applied to the coupon held, the EM surface wave was recorded and analyzed for its amplitude and phase using the network analyzer for three times, and the average amplitude was used in later figures of results. Each measurement taken by the network analyzer provided the amplitude of the EM wave at frequencies ranging from 2.67 GHz to 60 GHz, and the amplitude at a frequency of 43.8 GHz was used.

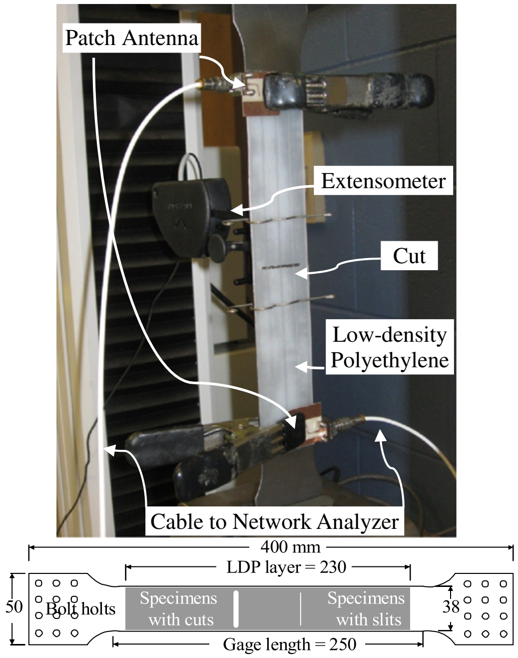

Fig. 3. Coupon specimen with EM wave-guiding medium.

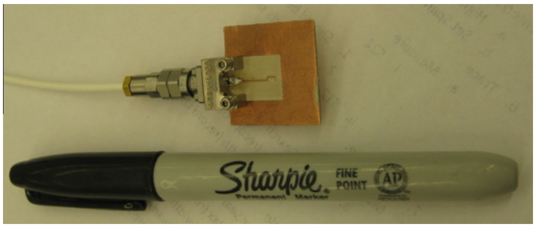

Fig. 4. Yagi-Uda slot-array antenna.

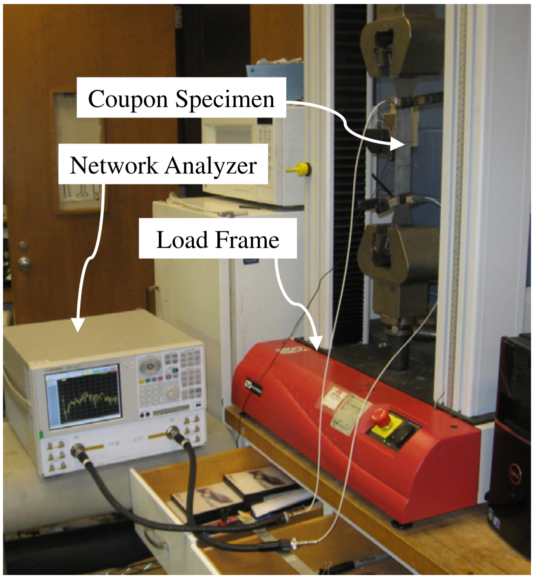

Fig. 5. Experimental test setup.

Tests of coupon specimens with a LDF layer indicated that the amplitude of the EM surface wave was not sensitive enough to the change of the strains in the base metal, although the phase changes were found more sensitive. Note that the sensor development is targeted at measuring the EM wave amplitude change, such that an expensive network analyzer in Fig. 5 can be eventually replaced with existing wireless communication technologies. It was thus envisioned that a discontinuity may be needed to magnify the disturbance to the EM wave propagation by the deformed base steel. To demonstrate the effect of such a discontinuity, a simple cut perpendicular to the EM wave propagation was made through the entire width of the material and the gap width varied in 2-mm increments. Fig. 6 illustrates the strength of the wave in dB's against the width of the gap. The increase in the gap size caused significant decrease in the magnitude of the EM surface wave, yet the magnitude was high enough (compared with that of the noise) to be detected. As the gap width increased to the 12 mm distance, the energy bridging the gap increased. This increase can be explained by the wavelength being the exact gap width to allow the wave to "jump" from one side of the gap to the other via a resonance set up in the gap. When the gap increased to a space of 14 mm the wave again refracted and reflected, causing a decrease in the energy transferring through the system. This phenomenon is similar to that observed for diffraction gratings in fiber optic sensors [16].

In further studies using steel coupons, discontinuities (i.e., gaps and slits) were introduced in the layer of low-density polyethylene.

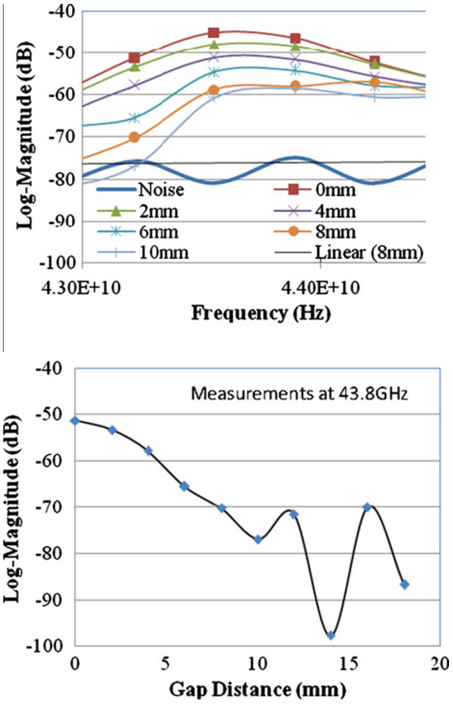

Fig. 6. EM wave amplitude vs. increasing gap widths (43.8 GHz).

Specimens were created with the following characteristics: (1) One slit in the center of the LDP layer, (2) Two slits spaced at 2.5 mm on center of the LDP layer, and (3) Three slits spaced at 2.5 mm on center of the LDP layer. A second group of tests was conducted with similar configurations of 2.5-mm gaps. Selected tests results are discussed below to represent the numerous exploratory tests in this study.

Fig. 7 shows the EM wave amplitude against the strain applied to the specimen with one slit in the center. The EM wave amplitude generally decreases with an increase in the strain applied to the specimen up to a strain of 0.035%. The EM wave energy (represented by the amplitude of the EM wave) transmitted through the system kept almost unchanged as the strain further increased as shown by the oscillating amplitudes. The sensitivity range was very low, indicating that the simple cuts with LDF materials at both sides of the slit still in contact is not an option for magnifying the effect of base metal deformation.

The results of tests with 2.5-mm gaps are shown in Fig. 8. The EM wave amplitude again decreases with an increase in the strain applied to the specimen. The specimen with a plain low-density polyethylene showed an energy loss up to a strain of 0.01%. The EM wave energy (represented by the amplitude of the EM wave) transmitted through the system increased as the strain further increased and the measured amplitudes oscillated afterwards. This might have been due to the fact that the thickness of the low-density polyethylene medium decreased as the coupon specimen was loaded, and the thinning of the wave-guiding medium may have changed the behavior of the EM wave. The specimens with 2.5-mm cut(s) in the LDP medium shows more pronounced changes as the specimen was loaded. Specifically, the EM wave amplitude decreased almost proportionally by 6 dB's when the strain the coupon specimen was 0.04%. The rate of the amplitude decrease reduced as the specimen was further loaded. This may be explained by the theory that a change of boundary conditions (i.e. discontinuities) likely caused the EM wave to reflect and refract, thus affecting the measured signal intensity.

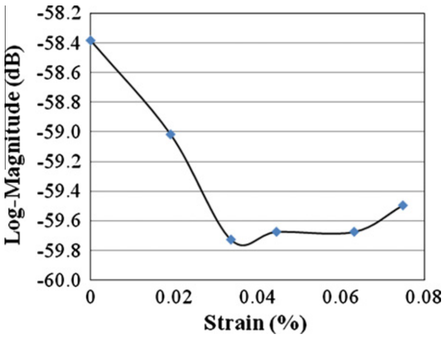

Fig. 7. EM wave amplitude vs. strain (specimens with 1 slit).

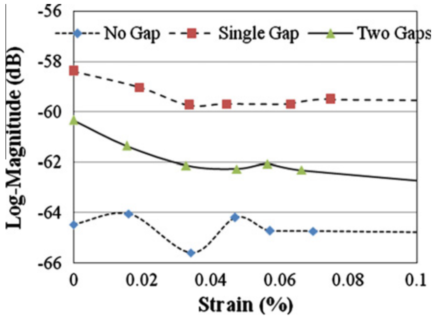

Fig. 8. EM wave amplitude vs. strain (specimens with gaps).

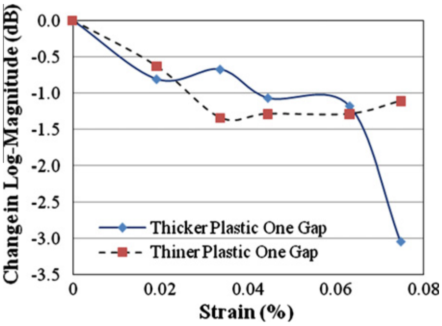

Fig. 9. Comparison between different thicknesses of low-density polyethylene.

The impact of 2.5-mm gaps on the EM wave transmission through a thicker (1.4-mm) layer of LDP medium is more outstanding as shown in Fig. 9. Although the change in the EM wave amplitude was not linear as desired, the large drop in EM wave amplitude at strains larger than 0.06% indicates that the thickness of the wave-guiding medium is an important designable parameters for future studies.

5. Conclusions

In this study, the use of electromagnetic (EM) surface waves within the millimeter wave range in sensing strains in steel members was proved viable. The proposed sensor consists of a thin layer of dielectric material adhered to steel members. As the EM surface wave is propagating through the dielectric material, the change in the amplitude of the wave, representing the energy being transmitted, can be detected and correlated with the strains of the base metal. Such application requires wave-guiding materials with low dielectric losses. After testing numerous materials, including composite materials with epoxy and various amounts of SiO_2 and glass particles, the epoxy-based composites with randomly dispersed particles were found not appropriate for the proposed sensor application due to their high dielectric loss tangent. The dielectric properties of such composite materials were found to be strongly influenced by the dielectric properties of the worst dielectric component in the composite material. Other materials such as low-density polyethylene may be used as the matrix material in future developments.

Low-density polyethylene was used as the dielectric media in the demonstration tests of steel coupons. Applied strain in the base metal and the strip of low-density polyethylene would alter the propagation of EM surface waves and the energy transmitted through the system. The change in transmitted energy, represented by the amplitude of the measured EM wave, was enhanced by adding 2.5-mm gaps at a spacing of 2.5 mm in the wave-guiding material. Hence, the measurable amplitude of the EM surface wave can be used for stress detection. The developed sensor can be an innovative and practical method for potential use in structural health monitoring of steel bridge structures.

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