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Microwave sensor technologies for structural health monitoring of infrastructure

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ABSTRACT: The existing standard sensors such as strain sensors and accelerometers may not always be capable of sensing critical parts of infrastructure. Microwave sensor technologies may provide wireless passive (unpowered) strain sensors in addition to wireless sensor networks. This paper provides a review of novel microwave sensor technologies developed for structural health monitoring of infrastructure including bridges and building. It focuses on passive wireless sensor systems and microwave sensors that provide the measurement of strain and displacement in civil infrastructure members operating without other power sources such as batteries.

1 INTRODUCTION

Several papers related to wired and wireless sensors for structural health monitoring have been recently published. They presented many different classifications of sensors depending on measured/sensed physical parameters such as displacement and moisture, on functional principles such as mechanical and electrical, and on the applications such as civil infrastructure, aircraft and maritime structures. The existing standard sensors used in civil infrastructure such as strain sensors and accelerometers may not always be capable of sensing critical parts of infrastructure. For instance, strain is one of the most important physical parameters that provide information about loading, boundary, fatigue and material conditions. Traditional strain gauges are reliable, practical and inexpensive, however, they require a wired physical connection and this is not suitable for structural health monitoring of large scale civil infrastructure systems. Microwave sensor technologies may provide wireless passive (unpowered) strain sensors in addition to wireless sensor networks. They based on the interaction between materials and electromagnetic waves at frequency range from 300 MHz to 30 GHz with corresponding wavelength range from 1m to 10 mm. In some cases, microwave sensors may be the only viable solution or can be used in combination with other sensors to reveal a more comprehensive picture of structural health monitoring problem. This paper introduces wireless microwave sensor technologies for structural health monitoring of infrastructure. It focuses on passive wireless sensor systems and microwave sensors that provide the measurement of strain and displacement in civil infrastructure members such as bridges and building. These sensors include resonant cavity, microstrip patch antenna and dielectric-loaded waveguide sensors that can be mounted on or embedded in the members.

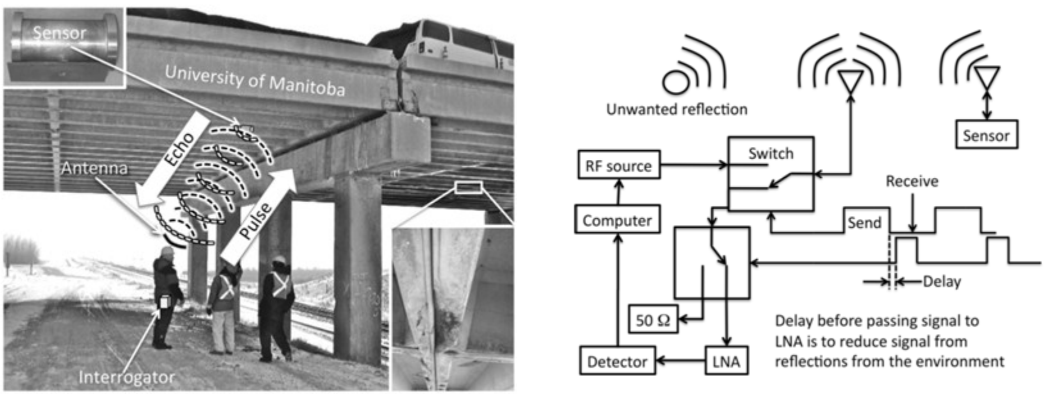
2 MICROWAVE WIRELESS SENSOR SYSTEMS

2.1 Active wireless sensor systems

Active wireless sensing devices usually contains an analog-to-digital converter for data sampling, a microprocessor for data processing, and a wireless transceiver for communication Lynch & Loh (2006). Most of these devices acquire data from associated traditional sensors such as a metal foil strain gage and MEMS (Micro-Electro-Mechanical Systems) and are primarily utilized to transmit the digitized sensor data. Many types of active wireless sensors require battery or local power for electronics on the sensor. This negates many of the advantages of wireless sensors, as the batteries require frequent replacement. Research is in progress on wireless sensors operating from scavenged or radiated power, but it is not yet clear if the accuracy, stability, and cost requirements for monitoring civil infrastructure can be met Thomson et al. (2009).

2.2 Passive wireless sensor systems

Passive wireless sensor systems are an emerging alternative, where the sensor is a passive device, and hence, there is no requirement for local power. For example, a passive wireless sensing system with a resonant cavity sensor mounted on a bridge and its schematic Thomson et al. (2009) are shown in Fig. 1. The sensor is a passive device, often constructed using copper cylinders and a simple antenna. The interrogator transmits a radiofrequency pulse from an antenna to the antenna on the sensor and then into the cavity. After a specified time, the transmitter turns OFF and the interrogator switches to a receiving mode. The RF cavity sensor (RFCS) emits an echo that contains energy that has been stored in the cavity. An external antenna needs to be connected with the cavity sensor for interrogation, and an interrogation distance of 8 m is achieved by using high-gain antennas. A Radio-Frequency ID (RFID) antenna-based passive wireless sensor system was developed and applied for measuring strain on the surface of metallic structures by Yi et al. (2011) as shown in Fig. 2. The system utilizes the principle of electromagnetic backscattering and adopts a low-cost off-the-shelf RFID chip to reduce the design and manufacturing cost. The RFID-based technology allows the sensor to be passive, i.e. operate without other power sources such as batteries.



(a)

(b

Figure 1. A passive wireless sensing system with a resonant cavity sensor (a) testing a bridge, and (b) its schematic, Thomson et al. (2009).

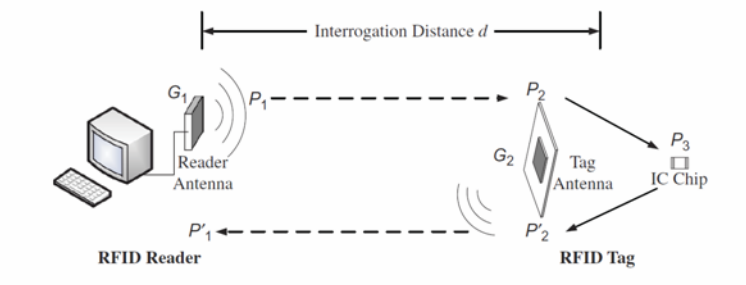
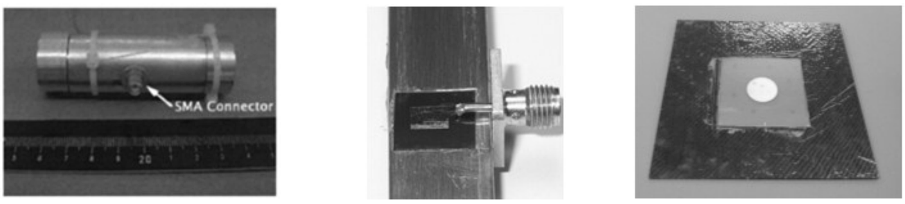


Figure 2. A passive RFID tag-reader system, Yi et al. (2011).

3 MICROWAVE SENSORS

3.1 Strain measurement sensors

Microwave strain measurement sensors exploite the strain-dependent behavior of the electromagnetic waves in microwave components as the sensing mechanism. The basic concept is that when the microwave component such as an antenna and a resonator is under strain/deformation, its resonant frequency may change accordingly. For example, a radiofrequency cavity sensor, using a 25.4-mm diameter copper tubing with length of 90 mm and end plates as the strain or displacement sensing element was proposed and presented by Chung et. al (2005) as shown in Fig. 3a. Microstrip patch antennas for measuring strain and detecting cracks in metallic structures were developed and presented in Tata et al., (2009) (Fig. 3b) and Daliri et. al. (2011), (Fig. 3c) and Yi et al. (2011), (Fig. 2).



(a) (b) (c)

Figure 3. Microwave strain measurement sensors: (a) a resonant cavity sensor, Chung et. al (2005), (b) a rectangular microstrip patch antenna sensor with a width-direction elongation, Tata et al., (2009) , and (c) a circular microstrip patch antenna sensor attached to carbon fibre composite, Daliri et. al. (2011)

3.2 Dielectric-loaded waveguide sensors

Microwave dielectric-loaded waveguides and resonators have been successfully used for detecting surface damage such as tight surface cracks or tiny pits in metal substrates. Recently, the applications of these waveguides and resonators to the measurement and monitoring of displacement, Kharkovsky & Zoughi (2011), and gap between concrete and metal surfaces, Kharkovsky & Tao (2012), have been initiated for the purpose of increasing sensitivity of microwave displacement sensors.

3.2.1 Measurement of wall displacements

A quarter-wavelength resonator sensor has been proposed for the displacement measurement, Kharkovsky & Zoughi (2011). The resonator consists of an empty rectangular waveguide section, a metal plate and a dielectric slab inserted inside the waveguide and centered along the waveguide broad wall as shown in Fig. 4. The resonator is terminated by a movable metal plate with a displacement *d*, and connected to measurement device such as a reflectometer through a waveguide-coaxial line connector and an antenna (not shown here). The magnitude and phase of reflection coefficient was measured and analyzed as the sensor response to wall displacement. The dielectric slab has specific dimensions and shapes suitable for a given application. Such dielectric slab tends to concentrate the electromagnetic fields in it, thereby improving the sensitivity of this approach.

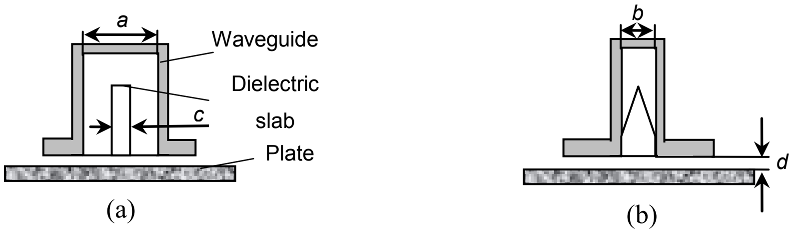


Figure 4. Cross-section schematic of the dielectric-slab-loaded waveguide resonator with a movable metal plate: (a) top view and (b) side view (not-to-scale), Kharkovsky & Zoughi (2011).

It has been shown that the resonant frequency of this resonator is ~10 times more sensitive to the plate displacement than the resonant frequency of a conventional half-wavelength resonator such as that used by Chung et. al (2005) and Thomson et al. (2009). The latter resonator was created between the waveguide and the plate and was fed by an empty or the dielectric-loaded waveguide. For instance, Fig. 5 shows a resonant response of the proposed and the half-wavelength resonator. It can be seen from Fig. 5a that the resonant frequency of the proposed resonator gradually increases when the displacement increases.

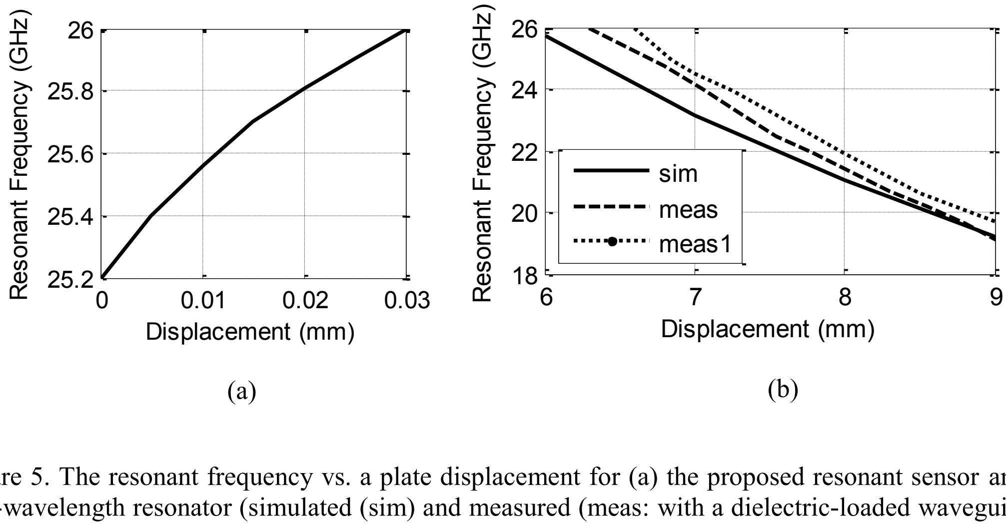


Figure 5. The resonant frequency vs. a plate displacement for (a) the proposed resonant sensor and (b) a half-wavelength resonator (simulated (sim) and measured (meas: with a dielectric-loaded waveguide feed and meas1: with an empty waveguide feed)).

This behavior of the resonant response of the resonator to wall displacement is different than that due to increasing of the length of the half-wavelength resonator which causes decreasing of the resonant frequency as shown in Fig. 5a. In addition, an average value of sensitivity can be estimated from Fig. 5 to be of ~27 GHz/mm and 2.5 GHz/mm for the proposed and the half-wavelength resonators, respectively. The simulation results of this investigation were verified by the measurement results. The proposed resonator can be used to construct efficient sensors for nondestructive evaluation of metal surfaces and for measurements of their displacements.

3.2.2 Monitoring of gap in concrete-metal structures

The capability of near-field microwave dielectric-filled waveguide sensors for the purpose of measurement and monitoring of gap between concrete and metal surfaces has been studied Kharkovsky & Tao (2012). This work is in the response of concrete-metal bond problem in structures used in infrastructure engineering such as concrete-filled steel tubes (CFST) and columns. It was shown that a microwave dielectric-loaded waveguide sensor provides higher sensitivity to the gap than a conventional open-ended waveguide sensor. The performances of the dielectric-loaded waveguide sensor have been studied and optimised. The proposed near-field dielectric-loaded waveguide sensor for measurement and monitoring of a value of gap between metal and concrete surfaces is shown in Figs. 6a-b. It consists of a rectangular waveguide, installed in metal wall of the structure under inspection. A dielectric insert is installed inside the waveguide to provide good impedance match between the empty and the dielectric-filled sections of the waveguide, and to prevent penetration concrete (when it is fresh) or its obstacles inside the waveguide. Fig. 6c shows a reflectometer that consists of the microwave sensor, a microwave circuit, a conditioning circuit and an indicator. The microwave waveguide sensor aperture is used to illuminate the interface between metal wall and concrete in a CFST and to receive the reflected signal.

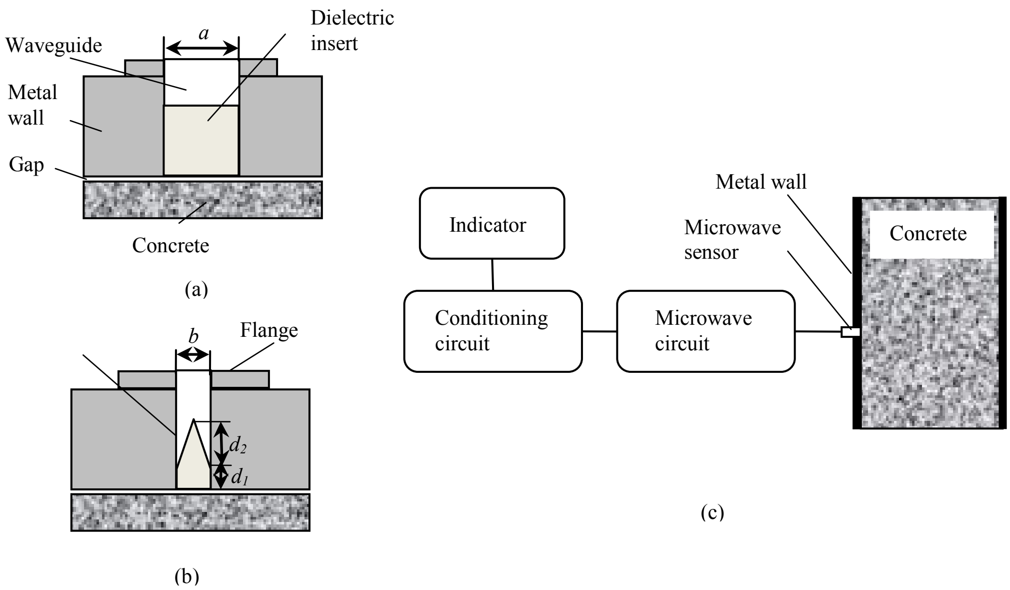


Figure 6. Schematic of the microwave dielectric-loaded waveguide sensor: (a) top view and (b) side view, and (c) a reflectometer with the microwave sensor testing a CFST (not-to-scale), Kharkovsky & Tao (2012).

The measurement system is designed to produce information about the magnitude and/or phase of the reflected signal and to convert this information in data for a gap value. The capability of monitoring of a gap by four microwave waveguide sensors at single frequency is demonstrated in Fig. 7. The results shown in Fig. 7 indicate that microwave waveguide sensor DI3 provides near optimal conditions for this purpose. Its reflection coefficient magnitude increases in proportion of the gap value and this proportion is almost linear.

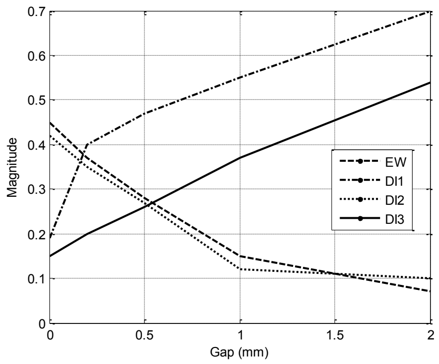
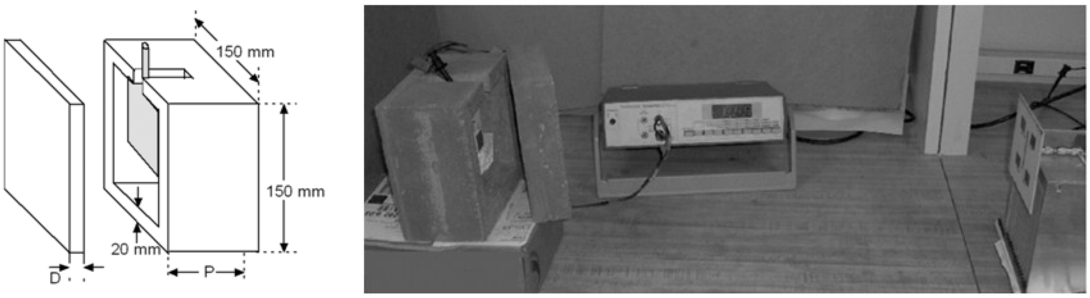


Figure 7. Simulated magnitude of reflection coefficient vs. value of gap for a sensor with empty waveguide (EW) and three dielectric inserts with different dielectric constant and dimensions *a*, *b* (DI1: 9.8 – j0.002, 2.5 mm, 7.5 mm; DI2: 2.01-j0.0002, 10 mm, 2.5 mm; DI3: 4 – j0.002, 5 mm, 7.5 mm) at frequency of 21.2 GHz, Kharkovsky & Tao (2012).

3.3 Embedded sensors and antennas

As mentioned above, microwave sensors for structural health monitoring have been mounted on and embedded in infrastructure members. Microwave embedded sensors such as resonators and antennas can be useful for many applications. Some of these applications are material characterization, defect detection, strain measurement and . For example, a novel modulated dipole scatterer loaded by two diodes, has shown a great promise as an embedded sensor for material characterization and flaw detection, providing real-time measurements of the dielectric properties of a host structure in the vicinity of the sensor, Donnell et al. (2011). An embeddable wireless strain sensor based on a resonant cavity was proposed and presented in Chuang et al. (2005). Another application is wireless power transmission to sensors embedded in civil engineering materials such as concrete. Microstrip patch antennas have been used for the wireless power transmission in concrete and for material characterization due to their conformability and relatively small size Shams & Ali (2007). Fig. 8a shows a schematic of microwave patch antenna buried in concrete. A photograph of the wireless power transmission measurement setup is shown in Fig. 8b. In the transmitter side, the 5.7 GHz input signal from the signal generator and a power amplifier was radiated by the transmit microstrip patch array. In the receiver side, wireless microwave power was received by the antenna buried in concrete. The received microwave power was 18.62 mW for a transmit power of 7 W at a distance of 600 mm, Shams & Ali (2007).



(a) (b)

Figure 8. (a) Schematic of microwave patch antenna buried in concrete, and (b) photograph of the wireless power transmission measurement setup, Shams & Ali (2007).

It should be noted that this work is still at research stage since several problems must be addressed for its application in practice. One of these problems is the undesired influence of the surrounding material on the performance of embedded antennas. Recently, the design an embeddable antenna module for civil engineering applications has been proposed in Salama & Kharkovsky (2012). The module consists of a rectangular microstrip patch antenna, a microstrip inset feed, electronic components such as a rectifier circuit and a dielectric housing. The housing was optimised to protect the module from the physical, chemical and electromagnetic influence of the surrounding material. The feasibility of a two-antenna approach with the embeddable antenna module for a wireless microwave power transmission in concrete member has been demonstrated. The simulation and measurement results for transmission coefficients obtained with early-age concrete block are in good agreement.

4 CONCLUSIONS

Microwave wireless sensor systems have great potential for structural health monitoring of infrastructure. Their advantages may provide decreasing complexity and weight of sensor systems and increasing reliability of structural monitoring systems. This paper briefly introduced some microwave wireless sensor systems while focusing on passive wireless systems and sensors. There has been an increase in scientific investigation and hardware development in this area in the past 10 years. One of the most important advantages of microwave sensor technologies is the ability of many different sensors. The microwave sensors presented in this paper are not all-inclusive in terms of the areas of applicability and the investigating groups that are involved in these areas. The application of microwave sensor technologies for structural health monitoring of infrastructure will be wider in the future since materials technology has produced new composite materials and microwave technology has developed new advanced components and devices.

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