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Advanced microwave sensors for the detection of gap in concrete-filled steel tubes

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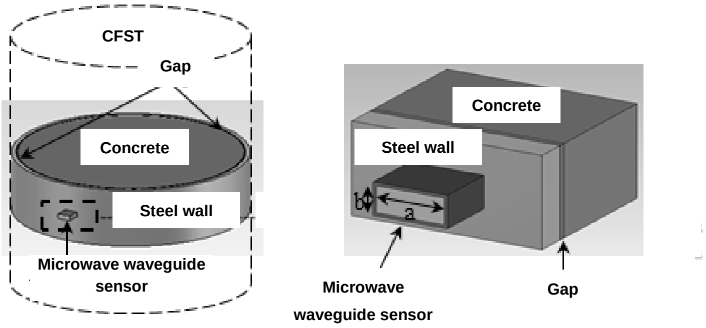
ABSTRACT: Concrete-metal composite structures have been widely used in infrastructure engineering. Concrete-filled steel tubes (CFSTs) are examples of these structures. For CFSTs, there is a requirement on the shear force transfer between the concrete and steel tubes. However, gap between concrete and steel surfaces may occur due to natural shrinking of concrete and imperfections of concrete and steel caused by not proper manufacturing process. A few methods have been applied for detecting the gaps. Microwave sensor techniques have shown a great potential for this purpose demonstrating the highest sensitivity to the gap. In this research work advanced microwave embedded sensors have been proposed and applied for two cases: 1) early-age concrete when its natural shrinking may lead to gap between steel and concrete surfaces and 2) hardened dry concrete when gap may occurs during service of a CFST. For the first time the feasibility of microwave sensors for the detection and monitoring of gap between the early-age concrete and steel surfaces has been considered taking into account the changes of dielectric constant of concrete during its hydration. It is shown that the sensitivity of the magnitude of reflection coefficient to the changes of gap value is higher with the K-band sensor than with the X-band sensor while these sensors demonstrate the same sensitivity to the changes of dielectric constant and it is significantly lower than the sensitivity of the magnitude to the changes of gap. The results also demonstrate that microwave waveguide sensors with dielectric inserts can be optimized by changing geometrical and electrical properties of the inserts, and they are the best candidates for the application in practice to detect and monitor gaps in CFST at different stages of its life.

1 INTRODUCTION

Composite structures such as concrete-filled steel tubes (CFSTs) have been widely used in infrastructure structures such as bridges, high-rise buildings and off-shore platforms in harsh environment. For CFST there is a requirement for the shear force transfer between concrete and steel surfaces. It was shown that steel imperfections and/or imperfections of concrete caused by not proper manufacturing process and/or its natural shrinking may lead to gap between steel and concrete surfaces of CFST which reduced compressive and flexural behavior of CFST members Liao et al. (2011), Tao et al. (2009) and Xu et al. (2013). Therefore, the existence of possible gaps should be detected to avoid failure of structures. A few methods have been applied for detecting the gaps. They include conventional acoustic methods (sonic, ultrasonic and acoustic emission technique), guided wave techniques Na and Kundu (2002) and piezoelectric technologies using wavelet packet analysis Xu et al. (2013) and Zhu et al. (2013). However all these techniques demonstrated low sensitivity in detecting the gap in CFSTs. To overcome this problem the application of microwave sensor technique has been proposed by Kharkovsky and Tao (2012). Preliminary investigations into feasibility of this technique for the detecting and monitoring of gap in CFSTs have demonstrated promising results. However, for the application of this technique in practice several issues should be addressed including the development of optimized sensors to be used at different stages of CFST's life. In this investigation, rectangular microwave waveguide sensors at two frequency bands namely, X-band (8.2 – 12.4 GHz) and K-band (18.0 – 26.5 GHz), have been designed and applied for the monitoring of CFSTs with early-age concrete as well as with hardened dry concrete for the purpose of the detection and evaluation of gap between steel and concrete surfaces at different stages of CFST's life. These sensors have different dimensions and their signals may penetrate at different depths inside concrete.

2 MODELLING OF MICROWAVE WAVEGUIDE SENSORS AND MEASUREMENT APPROCH

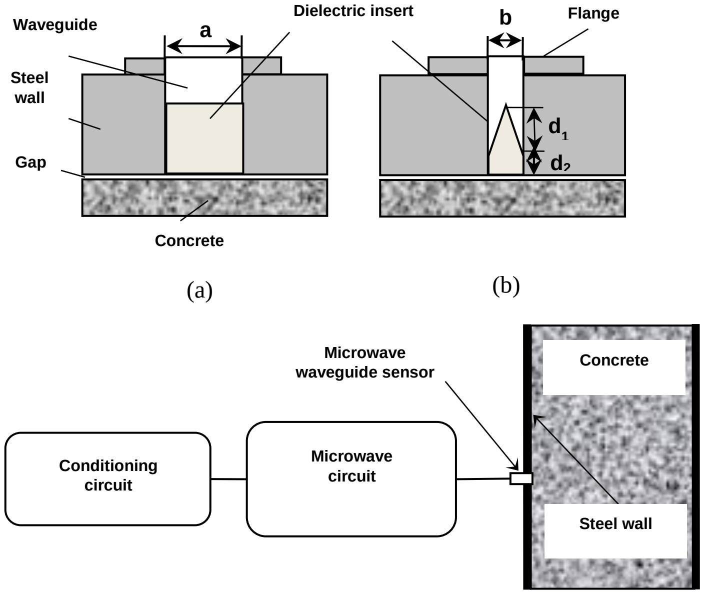
To detect the gap between concrete and steel surfaces in CFST a model of CFST and a microwave sensor embedded in its steel wall has been created using modern computational software package CST Microwave Studio. In this CST model concrete, steel wall and gap have been arranged as shown in Figure 1 to provide a similar interpretation of a large-scale composite structure such as a cylindrical CFST by setting suitable boundary conditions i.e., steel wall and concrete filling are infinite along length of CFST.



(a) (b)

Figure 1. CST model of CFST-microwave waveguide sensor arrangement: (a) a general view of a CFST section and (b) zoom-view of the area around the sensor.

Schematic of a microwave waveguide sensor for measurement and monitoring of gap between metal and concrete surfaces is shown in Figures 2a,b. It consists of a rectangular waveguide with dimensions of *a* and *b*, embedded in a steel wall of the CFST under inspection Kharkovsky and Tao (2012). In this investigation standard X-band (*a* = 22.86 mm, *b* = 10.16 mm) and K-band (*a* = 10.7 mm, *b* = 4.3 mm) microwave waveguides dimensions were used. A dielectric insert, with a height of *b* and a width of *a*, is installed inside the waveguide. The dielectric insert prevents penetration concrete (when it is fresh) or it obstacles inside the waveguide. In addition, the insert is tapered along its height at one end, providing good impedance match between the empty and the dielectric-filled sections of the waveguide. The other end of the insert is ended at the aperture of waveguide that is attached to the concrete surface. The empty waveguide sensor is built by a removal of the dielectric insert. A flange at the open end of waveguide shown in Figures 2a,b is used to provide the connection of the waveguide to a measurement system such as a reflectometer or a commercial vector network analyzer. For example, Figure 2c shows a reflectometer that consists of a microwave waveguide sensor, a microwave circuit and a conditioning circuit. The microwave waveguide sensor aperture illuminates the interface between steel wall and concrete in a CFST and receives the reflected signal. The reflectometer is designed to produce information about the magnitude and/or phase of the reflected signal.



(a) (b)

(c)

Figure 2. Schematic of a cross-sectional (a) top and (b) side view of a microwave waveguide sensor and (c) a reflectometer with this sensor testing an CFST.

The investigation into capability of the proposed sensors for the detection and monitoring of gap in CFST has been performed for two cases: 1) early-age concrete when its natural shrinking may lead to gap between steel and concrete surfaces, and 2) dry concrete when gap occurs during service of a CFST. Electrical properties of concrete such as the complex dielectric permittivity at microwave frequencies are different for these cases. Moreover, they change during hydration of concrete and it is more complex case than the case of dry concrete. The values of the complex dielectric permittivity of concrete for both cases were taken from literature. Steel was modeled as a perfect conductor.

3 RESULTS AND DISCUSSION

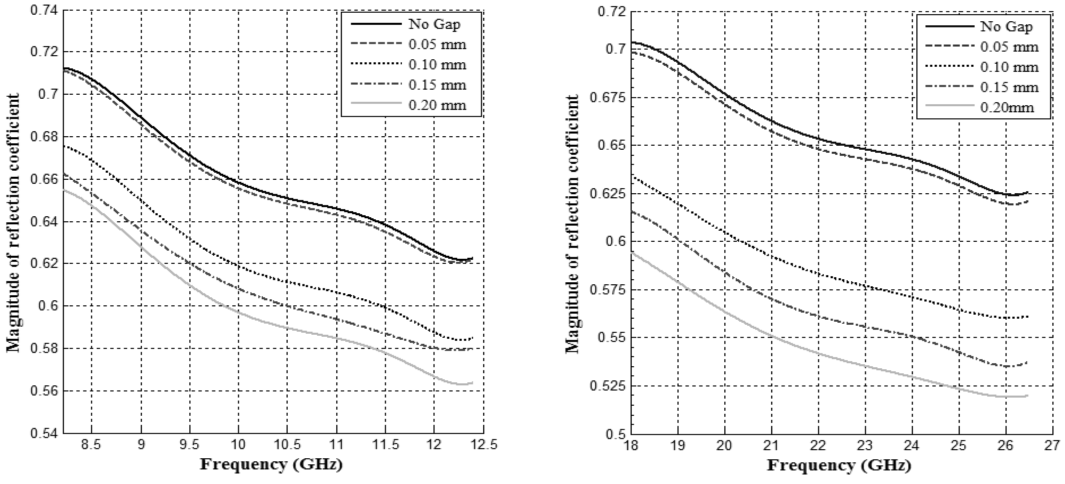
3.1 Early-age concrete

Data for the complex dielectric permittivity of early-age concrete are still not well-established since it depends on several parameters including concrete mixture design, measurement conditions and the influence of environment. Five references for early-age concrete are shown in Table 1. The results of this investigation show that the magnitude of reflection coefficient for the proposed sensors is sensitive to changes of the real part of dielectric permittivity (referred to as dielectric constant) while it is practically insensitive to changes of its imaginary part (referred to as loss factor). One of the main goals of this investigation is to compare the influence of change of gap and dielectric constant values on the magnitude of reflection coefficients for the proposed sensors. Figure 3 shows the magnitude of reflection coefficient vs frequency at different gap values with X-band and K-band microwave waveguide sensors without dielectric inserts. In this investigation concrete had the complex dielectric permittivity of ε_{rc} = 14.0 – j1.47 (where j indicates the imaginary part of complex dielectric permittivity). Several important observations can be made from Figure 3. First of all, the results clearly demonstrate the capability of the microwave sensor technique to measure and monitor a gap between concrete and steel surfaces at a wide frequency range. An optimal frequency can be selected and a relatively simple magnitude-sensitive reflectometer can be used. The results also demonstrate that at both the X-band and the K-band the increase of the value of gap reduces the magnitude of reflection coefficient. However, the sensitivity of the magnitude of reflection coefficient to the changes of gap value is higher with the K-band sensor than with the X-band sensor. For instance, at the value of gap from 0.1 mm to 0.2 mm sensitivity is ~0.45 mm^{-1} at 22.5 GHz (K-band) while it is ~0.2 mm^{-1} at 10 GHz (X-band). However, there is a relatively large change of the magnitude when the value of gap changes from 0.05 mm to 0.10 mm. To explain this effect an extensive simulation on the performance of sensors has been performed.

Table 1. Complex dielectric permittivity of early-age concrete from literature

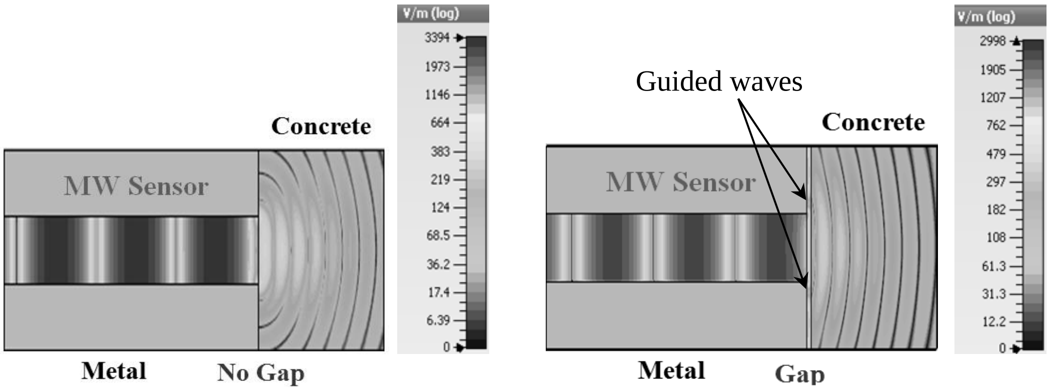
Real Part	Imaginary Part	Measurement Conditions	Reference
9.7 – 10.8	1.05 – 1.35	At 1.0 GHz frequency, several hours after casting, open-ended co-axial line.	Daout et al. (2014)
9.8 – 10.0	2.1 – 2.2	At 1.0 GHz frequency, 3 days after fabrication, co-axial line method.	Robert (1998)
14.5 – 14.8	1.7 – 1.8	At 2.0 GHz frequency, wet concrete, open-ended co-axial probe method.	Rhim and Buyukozturk (1998)
7.2 – 7.5	0.7 – 0.8	At 2.0 GHz frequency, saturated concrete, open-ended co-axial probe method.	Rhim and Buyukozturk (1998)
9.0 – 9.5	---	At 2.0 GHz frequency, wet concrete with 6.3% moisture, open-ended co-axial probe method.	Grantham et al. (2009)

The most critical information was obtained from the analysis of electromagnetic field distributions in the structure under investigation. For instance, Figures 4 and 5 show the electric field intensity distribution in the sensor and concrete without gap and with 0.1-mm gap at 10.3 GHz (X-band) and at 22.25 GHz (K-band), respectively. Figures 4 and 5 clearly show changes in electric field intensity distribution at the interface between steel wall and concrete due to the gap. Animation version of these distributions (not shown here) showed the propagation of electromagnetic waves between steel and concrete surfaces (referred to as guided waves) at 0.1-mm gap. These guided waves lead to losses in electromagnetic energy of the incident wave as well as the reflected wave. As a result, the magnitude of reflection coefficient decreases faster at the value of gap of ≥ 0.1 mm.



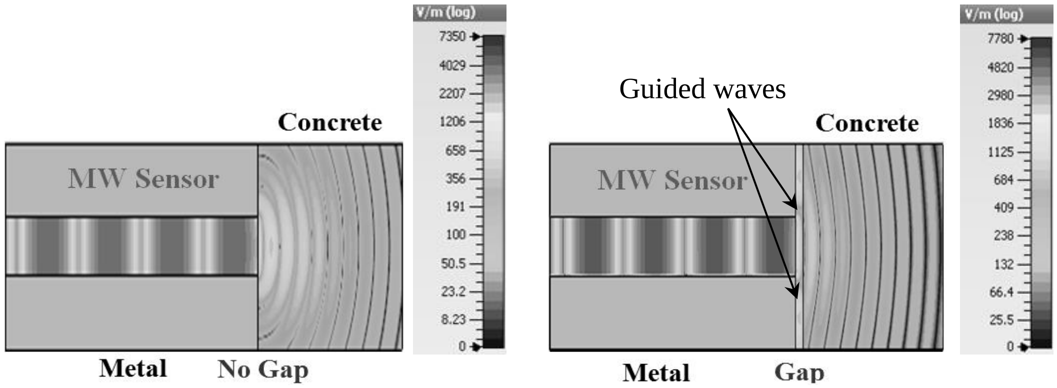
(a) (b)

Figure 3. Magnitude of reflection coefficient vs. frequency over (a) X-band and (b) K-band for the sensor without dielectric insert for different gaps.



(a) (b)

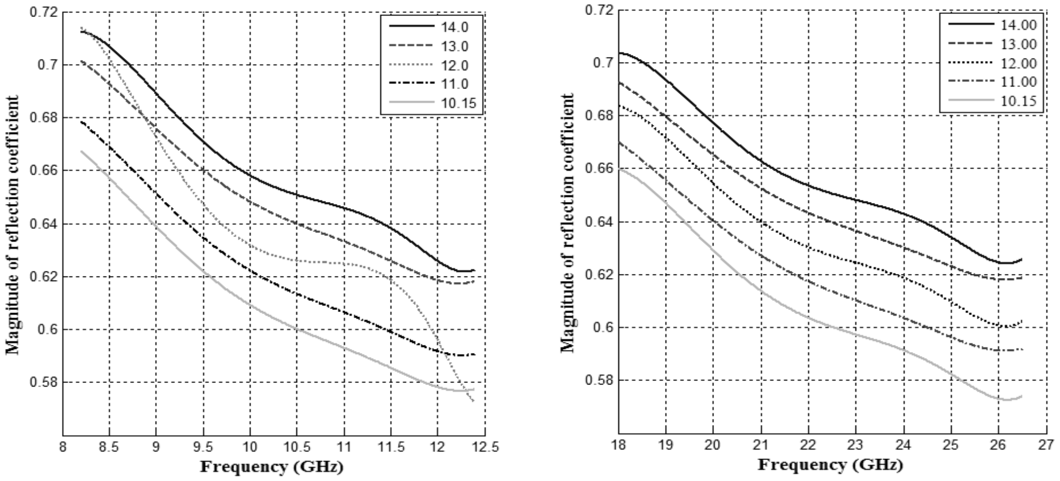
Figure 4. Side view of electric field intensity distribution in the sensor and concrete (ε_{rc} = 14.0 – j1.47) at frequency of 10.3 GHz: (a) without gap and (b) with 0.1-mm gap.



(a) (b)

Figure 5. Side view of electric field intensity distribution in the sensor and concrete (ε_{rc} = 14.0 – j1.47) at frequency of 22.25 GHz (a) without gap and (b) with 0.1-mm gap.

Figure 6 shows the magnitude of reflection coefficient vs. frequency at different dielectric constants of concrete without any gap between concrete and steel surfaces. The range of concrete dielectric constants (14.0 – 10.15) were chosen considering the dielectric constant value of early-age concrete during shrinking. Figure 6 illustrates that the magnitude of reflection coefficient decreases with the decrease of dielectric constant. For example, at frequency of 10 GHz (c.f. Figure 6a) and 22.5 GHz (c.f. Figure 6b) the magnitude of reflection coefficient decreases from 0.66 to 0.61 and from 0.65 to 0.60, respectively, when dielectric constant decreases from 14.0 to 10.15; i.e. sensitivity of the magnitude of reflection coefficient to the changes of dielectric constant of concrete is ~0.01 for both the X-band and the K-band.



(a) (b)

Figure 6. Magnitude of reflection coefficient vs. frequency over (a) X-band and (b) K-band at different dielectric constants of concrete (no gap between sensor and concrete).

It should be noted that the change of magnitude of reflection coefficient due to the change of dielectric constant is significantly lower than the change of magnitude of reflection coefficient due to the change of gap value at K-band (c.f. Figure 3b). This is a very important observation since the main goal of this investigation is the detection and monitoring of the gap.

3.2 Dry concrete

For this case the K-band sensor is selected since it showed the higher sensitivity than the X-band sensor at the case of early-age concrete. Figure 8 shows the magnitude of reflection coefficient of this sensor vs. frequency for the value of gap of 0.2 mm, 0.5 mm, 1 mm and 2 mm as well as for the structure without gap (0) as a reference. Concrete material in this case had the complex dielectric permittivity of ε_{rc} = 4 – j0.0125 Roqueta et al. (2012). The dielectric insert was made of material with the complex dielectric permittivity of ε_{rd} = 4 – j0.002 and length of d_1 = 5 mm and d_2 = 7.5 mm (c.f. Figure 2b). The results clearly demonstrate the capability of the microwave sensor techniques to measure and monitor a gap between dry concrete and steel surfaces. The results shown in Figure 8 indicate that the proposed microwave waveguide sensor provides near optimal conditions for this purpose at ~22 GHz. Its reflection coefficient magnitude increases in proportion of the gap value and this proportion is almost linear. The sensitivity of the magnitude of reflection coefficient to changes of gap from 0 to 0.2 mm in this case (~0.75 mm^{-1}) is slightly higher than an average sensitivity in the case of early-age concrete (~0.6 mm^{-1}).

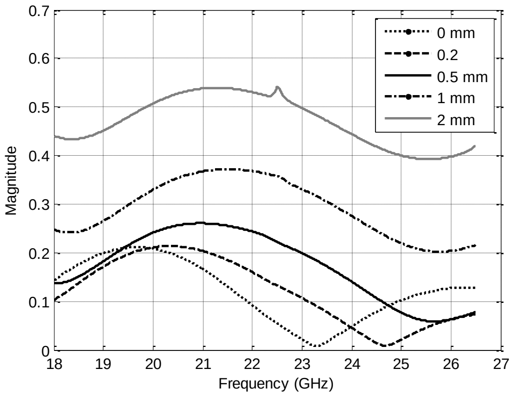


Figure 8. Magnitude of reflection coefficient vs. frequency over K-band for different gaps in the sensor with a dielectric insert Kharkovsky and Tao (2012).

4 CONCLUSIONS

The investigation into capability of the proposed sensors for the detection and monitoring of gap in CFST has been performed for two cases: 1) early-age concrete when its natural shrinking may lead to gap between steel and concrete surfaces and 2) dry concrete when gap occurs during service of a CFST. The results can be summarized as follows:

1) The proposed microwave sensors along with a relative simple magnitude-sensitive reflectometer can detect a very small gap (~0.1 mm) between concrete and steel surfaces in a CFST and monitor its value up to a few millimeters at different stages of its life;

2) The magnitude of reflection coefficient for the proposed sensors is sensitive to changes of dielectric constant of concrete while it is practically insensitive to changes of its loss factor.
3) The physical cause of the changes of the magnitude is the effect of guided waves that are generated between concrete and steel walls when the gap occurs. These guided waves lead to losses of electromagnetic energy of the incident wave as well as the reflected wave.
4) The sensitivity of the magnitude of reflection coefficient to the changes of gap value is higher with the K-band sensor than with the X-band sensor while these sensors demonstrate the same sensitivity to the changes of dielectric constant and it is significantly lower than the sensitivity of the magnitude to the changes of gap.
5) The K-band sensor can be selected for the further research and application since it is smaller and has higher sensitivity to gap value in a CFST than the X-band sensor.

The further research will include experimental verification of the simulated results.

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