Three-dimensional printed asymmetric biconical antenna for borehole concrete sensing application

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Abstract: An asymmetric biconical antenna is proposed to be used for a borehole radar system to inspect the corrosion of reinforcing bar inside a concrete structure. First, the antenna is designed by considering the hole needed for the borehole diameter. Then, the antenna is fabricated using a three-dimensional printer with polylactic acid plastic and coated with copper tape. Finally, the antenna is tested in free space and concrete environment. The diameter of the antenna is 20 mm and a length of 34 mm, with the usable frequency in free space is 2.4 GHz (2.1 GHz in concrete) to 8 GHz.

Keywords: biconical antenna, three-dimensional printer, concrete sensing, borehole radar system

Classification: Antenna and Propagation

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1 Introduction

A non-destructive inspection by utilizing ground penetrating radar provides the possibility to inspect the corrosion of the reinforcing bar inside the concrete structure without exposing the reinforcing bar to the environment. Nishimoto et al. demonstrated the possibility to use an ultra-wideband impulse signal with the frequency range of 2 GHz to 9 GHz to inspect a corroded metal bar from 10% to 30% corrosion rate [1]. By using a multi-gigahertz electromagnetic wave, a higher spatial resolution can be observed from the target [2] and could differentiate a thin layer of iron oxide formation on the surface of the reinforcing bar [3]. However, the penetration of the electromagnetic wave inside the concrete is limited due to the high conductivity characteristic of the concrete [4]. The borehole radar system can be utilized to reduce the distance between the reinforcing bar and the antenna by creating a hole near the observed reinforcing bar in the concrete. However, the effect of the core drilling in the concrete beam could impact the concrete strength. This was demonstrated by Vona et al. with a 30% concrete strength reduction for a 100 mm hole on a 200 mm concrete beam [5].

In this paper, we propose a coaxial feed biconical antenna for borehole concrete sensing with a small diameter and ultra-wideband characteristics to transmit an impulse signal with the bandwidth of 2 GHz to 8 GHz. The antenna is designed to be printed using a three-dimensional (3D) printer and coated by using conductive tape. The antenna has been tested on the free space and concrete environment, and both of the simulated and measured results of the antenna design are presented.

2 Antenna design

We conducted parameter studies to determine the optimal diameter of the antenna and the optimal ratio between the length of both arms of the biconical antenna with EMPro finite-difference time-domain simulator from Keysight Technologies. Fig. 1(a) shows the antenna shape used in this study. The permittivity of the polylactic acid (PLA) plastic used in this study is based on [6], with relative dielectric permittivity of 2.72 and loss tangent of 0.008 (for 100% infill). The antenna is assumed to be matched to a 50Ω system and simulated without considering the coaxial cable and connector used later in the fabrication process.

The parameters studies begin with the choice of the diameter $D$, and the ratio of top-section length $Lt$ and bottom-section length $Ld$ while using the plastic thickness of 2 mm and the antenna gap of 1.5 mm. The parameters are
Fig. 1. Design of the antenna for borehole concrete sensing. (a) The diagram and rendered view of the antenna’s plastic core. (b) Simulation results of varied diameter from 15 to 20 mm with \( Ld/Lt \) ratio = 1. (c) Simulation results of varied length ratio from 0.3 to 1 with \( D = 20 \) mm. (d) The radiation pattern of the simulated antenna with diameter = 20 mm and ratio = 1.

determined by choosing the best simulations results so that the bandwidth of the 10 dB return loss becomes as wide as possible. Based on [5] which describes the effect of the core drilling in the concrete beam on the concrete strength, we decided to reduce the diameter to be as small as possible (less than 20 mm) to reduce the hole’s diameter needed for the borehole sensing while maintaining the ultra-wideband characteristics.

The simulated return loss of the different antenna diameters and lengths ratio is shown in Fig. 1(b) and (c). Based on the simulation, the final geometrical parameters are as follows: \( D=20 \) mm, \( Din=2.3 \) mm, \( Lt=25 \) mm, \( Ld=7.5 \) mm, \( g=1.5 \) mm, \( Tp=2 \) mm, \( Tc=0.06 \) mm. From the simulation results, the bigger the antenna diameter the better the frequency response on the lower frequency. We decided to choose the 20 mm diameter because it has a better characteristic when the asymmetric configuration is applied, and also the asymmetric configuration has the best bandwidth compared with the equal length of the antenna arm. We also simulated the radiation pattern for the free space and inside the concrete, the results are shown in Fig. 1(d).
Overall, the antenna has an omnidirectional radiation pattern for both the free space and inside the concrete simulation.

3 Fabrication process

The 3D printer can deposit material in three-dimension space with high precision and can produce a complex geometrical object with rapid prototyping time and low manufacturing cost. The inner plastic core is printed by using Creality Ender 3 3D printer with PLA plastic. The overall dimension of the antenna is shown in Fig. 2(a). Also, another two cones are printed (see Fig. 2(b)) for attaching conductive tape on the inside surface of the plastic core. The 3D printer we used has a 0.4 mm extruder diameter and using 1.75 mm standard PLA filament. We decided to build the antenna with a 0.6 mm layer height and 40 mm/s print speed to improve the surface roughness of the printed parts.

After the parts are printed (see Fig. 2(b)), the antenna was coated by a conductive spray made from silver and copper. However, the spray method was proven difficult to solder due to the thinness of the cured conductive layer and the inner plastic core is deformed by the high temperature due to low insulation between the conductive layer and plastic core. Even though we successfully make one prototype using this method, the conductive layer is fragile and easily flakes if the surface of the plastic core is not primed with enamel paint before sprayed with conductive spray.

Fig. 2. Antenna fabrication with a 3D printer. (a) Antenna dimension. (b) 3D printer results of the plastic core. (c) RG405 coaxial cable connection. (d) Fabricated antenna.
To circumvent these difficulties, we decided to use conductive tape with 0.06 mm thickness made from copper foil and conductive adhesive backing. The conductive tape is coated to the surface of the parts and a rigid coaxial cable (see Fig. 2(c)) is soldered into the antenna, we are using ITT RG405 for the coaxial cable and Radiall SMA for the connector. By using this tape, the soldering process can be done without deformed the inner plastic and the bonding between parts is strong and able to hold the two-part antenna in place. The fully fabricated antenna is shown in Fig. 2(d).

Fig. 3. Measurement of the antenna characteristics. (a) Return loss in free space. (b) The measurement model of the concrete environment (size is in mm). (c) Return loss in the concrete model.
4 Antenna characterization

We characterize the frequency behavior of the proposed antenna by using an Advantest R3768 vector network analyzer to measure the return loss of the antenna. Both the measured and simulated return loss of the antenna is shown in Fig. 3(a). From the measured data, it can be seen that the usable bandwidth is from 2.4 GHz to 8 GHz in free space. The characteristic of the fabricated antenna is agreed well with the simulation result in free space. In addition, the return loss of the measurement results is better from 5.5 GHz to 8 GHz.

We also try to measure the return loss of the antenna in a concrete environment. In order to simulate the environment in concrete, 66 liters of sand and 1 liter of water were mixed and packed into a rectangular container with a 30 mm diameter hollow pipe penetrating in the center as a borehole for measurement (see Fig. 3(b)). The fabricated antenna was inserted into the center of the pipe and the characteristics were measured. Fig. 3(c) shows the measurement results of the concrete model. The simulation result is also shown in the figures. The lower frequency limit of the antenna in concrete is reduced to 2.1 GHz, which increases the available bandwidth. In addition, the return loss of the measurement results is slightly worse from 3.5 GHz to 4.8 GHz but is practically acceptable. From these results, we can confirm that the characteristics of the proposed antenna in the concrete model agree well with the simulation results.

5 Conclusion

We proposed a biconical antenna for borehole concrete sensing with small and ultra-wideband characteristics. For insertion into a borehole with a small diameter, the antenna was designed with a diameter of 20 mm and a length of 34 mm. In the simulation, the usable bandwidth was from 2.4 GHz to 8.0 GHz in free space and 1.9 GHz to 8.0 GHz in concrete. Next, we fabricated the designed antenna using a 3D printer with PLA plastic and measured its characteristics in free space and in a concrete model. As a result, we confirmed that the fabricated antenna had almost the same characteristics as the simulation results and it was available for inspection of reinforcing bar in concrete.