A Non-destructive Radar Device for Detecting Additive Materials in Concrete

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ABSTRACT

The use of electronic devices based on electromagnetic waves is promising for inspecting additives in structural concrete. However, the existing commercial devices are high-cost and do not publicly provide circuit design information. To overcome this issue, this study designed a low-cost nondestructive testing device with a radar sensor, using an HB-100 radar sensor module to generate and receive the radar wave. A suitable bandpass filter was used to suppress electrical noise in the received signal, an Arduino board was used for signal processing, and the measured data were displayed on a computer. The output at the IF pin of the sensor module presents the Doppler frequency and absorbance of the target materials. The device was tested to detect additives inside the concrete. An additive material can be recognized by the fact that the obtained signal magnitudes are different with different additive materials. The findings in this study can contribute to making a low-cost nondestructive testing device based on radar technology for structural concrete inspection.

Keywords-HB 100 radar sensor; active bandpass filter; nondestructive testing; structural inspection

I. INTRODUCTION

Concrete is one of the most important components used in civil engineering infrastructures. Unwanted additive materials in concrete can cause cracks over time due to dopants, corroding steel rods, or environmental factors [1-8]. Ensuring the structural integrity of concrete is very important for the longevity and safety of infrastructures [9-10]. Currently, infrared thermography, ultrasonic-echo, and radars are conventional technologies for detecting internal additive materials [1-8], with radar being widely used. In this method, when the waves are transmitted through concrete, they are partially attenuated and reflected depending on the dielectric properties of the concrete material. The comparison to the initial wave provides useful information about the materials inside the concrete [1]. On the other hand, existing commercial radar testing devices have high costs and limitations in the information of circuit design, which could be due to industrial secret policies [1-2].

The HB 100 Doppler radar sensor is widely used for motion detection thanks to its low cost and high reliability [11-12]. Recently, the HB 100 sensor was used for additional functions such as underground metal detection [13] or wooden pole inspection in forests [14]. Unfortunately, up to now, there are very few studies on the use of the sensor for detecting additive materials in concrete. This study designed a nondestructive testing device with the HB-100 radar sensor. The output of the Intermediate Frequency (IF) pin of the sensor module presents the Doppler frequency and the absorbance of the target materials. The IF signal was enhanced by a band-pass active filter before going to the microcontroller. The final measured signal on a computer can adequately distinguish the additives in the concrete.

II. SYSTEM DESIGN OF THE NONDESTRUCTIVE TESTING DEVICE

The proposed system was based on the HB100 Miniature Microwave Sensor, an X-Band Doppler transceiver module speed sensor radar commercially available by ST Engineering

Electronics Ltd, Singapore [15]. The module has the features of low current consumption and a long detection range of about 20m. An effective isotropic radiated power of 15dBm was transmitted at the frequency of 10.525GHz. Table I presents the parameters of the sensor.

TABLE I. RADAR SENSOR'S DEVICE PARAMETERS

No	Specification	Parameters
1	Working voltage	5V±0.25V
2	Operating Current	50mA max., 30mA typical
3	Emission parameters	2-16m
4	Helium emission frequency	10.525GHz
5	Frequency setting accuracy	3MHz
6	Output power	13dBm
7	Harmonic emission	<-10dBm
8	Pulse width	5uSec
9	Sensitivity	-86dBm
10	Vertical 3dB beam width	36°

Figure 1 shows the structure of the nondestructive testing device system. The microwave motion detector continuously transmits the signal within its range, and when the signal hits the target object it receives the reflected signal. The reflected signal is mixed with the transmitted and then the IF or Doppler frequency f_D signal can be given by [13]:

$$f_D = \frac{2v\cos\theta F}{C} \quad (1)$$

where *v*, *θ*, *F*, and *C* are the target speed, the angle between the trajectory of the concrete target and the radial line joining the target and the radar, the transmitted frequency, and the speed of light, respectively. The f_D is typically below 100Hz [15]. The radiation patterns of the antenna and their half-power beam width can be seen in [15]. The antenna patches were mounted on the module facing the desired detection. When measuring, the orientation of the module can be directed to get the best coverage. Fundamentally, the amplitude of the IF signals is very low and it is easy to attach electrical noise. To overcome that issue, an instrument amplifier based on a Texas Instruments LM324 was designed, as shown in Figure 2. The IF signal was amplified in the first stage by a noninverting amplifier and then by an inverting active bandpass filter [16]. The low- (f_L) and high-cutoff (f_H) frequencies were calculated to be 3.38 and 72.38Hz, using the following equations:

$$f_L = \frac{1}{2\pi R_6 C_7} \quad (2)$$

$$f_H = \frac{1}{2\pi C_5 R_7} \quad (3)$$

The amplified signal was connected to an analog pin on an Arduino board. The microcontroller has a built-in ADC that processes the signal, converts it to a digital value, and sends it to a computer via a USB cable with a serial communication protocol. The amplitude of the signal can be observed in computer software. Figure 3 shows a photo of the completed non-destructive testing device with the HB100 radar sensor. For convenient use of the device, the radar sensor was separated from the PCB by a 50cm long cable.

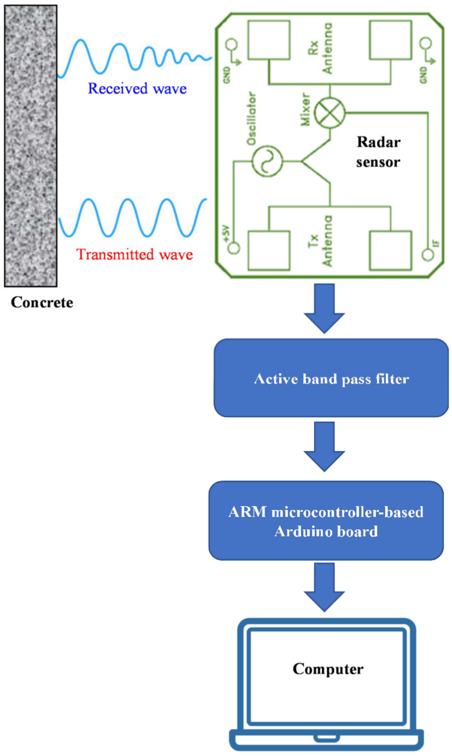

Fig. 1. The design of the nondestructive testing device system.

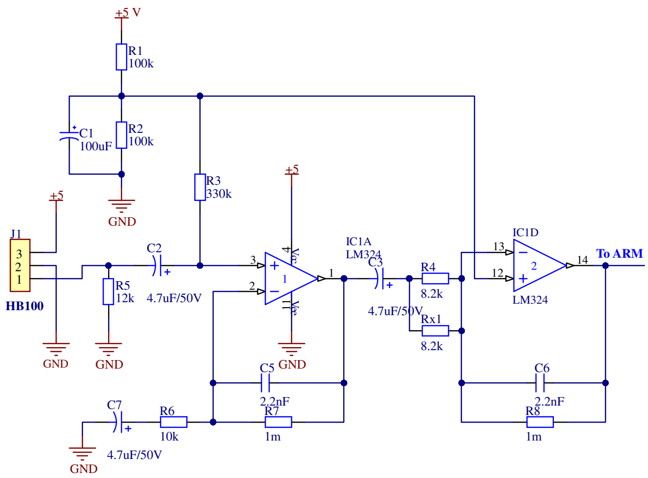

Fig. 2. Design of the active band-pass filter for the HB100 sensor.

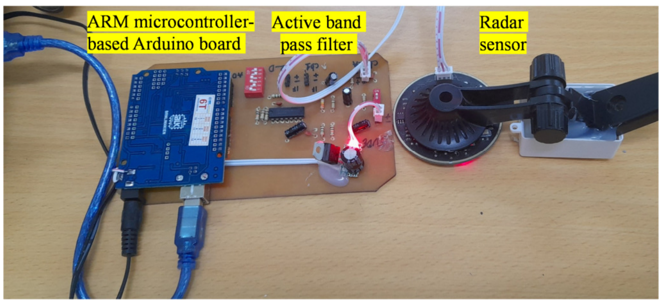

Fig. 3. The hardware implementation of the non-destructive testing device.

III. RESULTS AND DISCUSSION

Figure 4 shows the test procedure, where wooden, steel, and plastic bar objects were placed inside a hole in the concrete sample. The distance between the surface and the hole was approximately 5cm. In this experiment, the target was stationary, thus, to make HB 100 detect the Doppler effect, the radar sensor needed to move toward the target. The radar sensor was manually controlled to gradually move at a constant speed of about 0.45m/s and then touched the surface of the concrete sample. That generates a constant frequency of a certain amplitude. The amplitude levels of the reflected beat frequency were recorded at room temperature by a computer. Figure 4 also presents the data measured from the concrete sample with different additives. It can be noted, that while the frequency values were not significantly altered, the magnitude or data volume depended on the additive materials. Sensed data were further analyzed. The maximum values of the data volume in nominal units extracted from the examples in Figure 4 were 466, 468, 478, and 482 for solid concrete, wood inside the concrete, steel inside the concrete, and plastic inside the concrete, respectively. Figure 4 demonstrates that the designed device system could clearly distinguish the different materials.

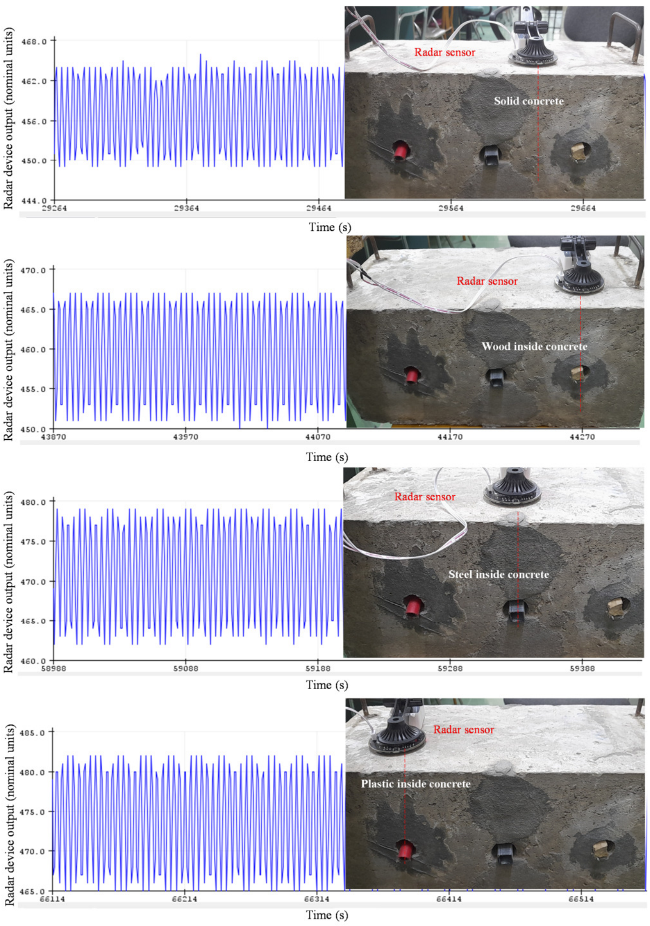

Fig. 4. Obtained signals measured from solid concrete with different additive materials.

The amplitude of the received signal can be expressed as [17]:

$$A = A_0 e^{-\alpha Z} \quad (4)$$

where A_0, α, and Z are the initial amplitude, attenuation factor, and travel distance, respectively. The value of a can be given by [17]:

$$\alpha = 2\pi F \left[\frac{\varepsilon\mu}{2}\left(\sqrt{1+\left(\frac{\sigma}{\varepsilon\omega}\right)^2} - 1\right)\right]^{1/2} \quad (5)$$

where μ is the magnetic permeability of the material, ε is the dielectric permittivity of the material, and σ is the electric conductivity.

TABLE II. MATERIALS' DIELECTRIC PERMITTIVITY

No	Tested material	Dielectric permittivity ε
1	Concrete	4.5
2	Wood	4.0
3	Steel	3.5
4	Plastic	3.1

Table II shows the dielectric permittivities of the tested materials [18-19]. The a in (5) strongly depends on the dielectric permittivity of the material. Therefore, (4) implies that the amplitude of the received signal is decreased with increasing dielectric permittivity. Figure 5 shows the relation between the maximum data volume of the received signal and dielectric permittivity. As can be noted, a material with higher dielectric permittivity results in a lower amplitude of the received signal, i.e. it absorbs more of the transmitted signal. That is consistent with the theoretical relationships (4) and (5). The amplitude levels in Figure 5 also confirm that the additive materials in concrete can be clearly identified. In previous studies on non-destructive radar inspection devices [1, 7, 8, 11-13], the measured data were visualized and could be exported in several aspects, such as additive materials, defects, and scanned mapping. However, these devices had a complicated structure with a special radar sensor and an elaborated signal processing system. This study used a simple design with a low-cost commercially available motion radar sensor and a popular microcontroller. Although the device needs to be further improved, integrating data analysis or visual mapping, it can be realized that the advantages of the proposed design are its low cost and simplicity.

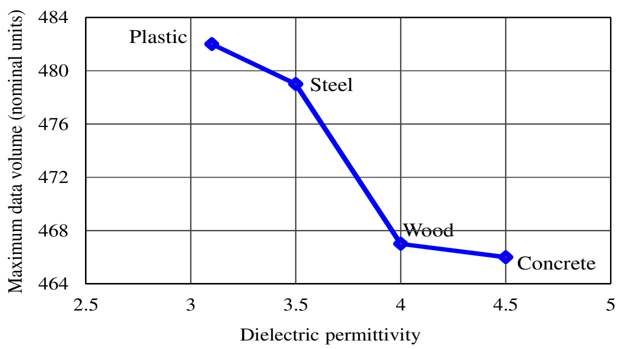

Fig. 5. Dielectric permittivity and maximum data volume of the received signal obtained from different additive materials inside the concrete.

IV. CONCLUSION

This study demonstrated an electronic device based on electromagnetic waves to inspect additive materials in structural concrete, based on the HB-100 sensor module to generate and receive the radar wave. A band-pass active filter was designed to suppress electrical noise from the received signal. The output at the IF pin of the sensor module presents the Doppler frequency and absorbance of the target materials. An Arduino microcontroller was used for signal processing and the measured values were displayed on a computer. The proposed device was used to detect additives inside a concrete sample, and the obtained signal magnitudes were different for different additive materials. This design used a low-cost commercially available motion radar sensor and a popular low-cost microcontroller. The results of this study show the feasibility of designing and implementing a low-cost nondestructive testing device based on radar technology for structural concrete inspection.

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