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Development of a capacitive sensor for concrete structure health monitoring

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HIGHLIGHTS

- A novel low-cost capacitive transducer (CT) is developed for reinforced concrete.
- Relationship between CT output & rebar size is established for the first time.
- Developed CT is effective for structure health monitoring, with great accuracy.
- Numerical simulations are done to substantiate the experimental results.

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ABSTRACT

A novel low-cost capacitive transducer (CT) using capacitance signals, which has the potential to provide accurate health assessment and damage prediction for reinforcement concrete structures, is developed in this study. Two designs of capacitive transducers are discussed for condition assessment of rebar and concrete, respectively. Both of them consist of a supporting structure and a pair of corresponding parallel electrode plates. In order to verify the effectiveness of the designed capacitive sensor, a series of preliminary experiments are conducted. The results show that the detected CT signals rise with the increasing rebar size. Pure cement paste and fiber-reinforced concrete have demonstrated a stable dielectric constant under the same fabrication conditions. To simulate the real reinforced concrete case, various sizes of rebars were placed in fiber reinforced concrete. It is found that monitoring the CT signals is an effective way to assess the rebar diameters inside concrete. Experiments results also showed that CT signals could be applied to predict rebar positions inside the concrete. Finally, FEM simulations were implemented for the last experiment, and comparison results have well verified the effectiveness of the developed capacitive sensor. The whole work has demonstrated a promising application of the capacitive sensor in NDT of reinforced concrete in the future.

1. Introduction

Since the last few decades, a great wave of interest has been raised in non-destructive testing in reinforced concrete [1]. Currently, certain amounts of large-scale infrastructures have reached their design life. For damage detection in large-scale and distributed systems, employing large number of sensors is a popular trend as the thorough information can be obtained by densely implementing sensors in the structures [2]. Thus, developing an economical, flexible while accurate sensor is vital to the success of structure health assessment.

Conventional non-destructive testing (NDT) techniques can provide very useful information for both rebar reinforcement corrosion and concrete hydration process. Cover meters is a well-developed traditional magnetic induction sensor that can provide key information in rebar localization and cover measurement [3,4]. But significant error can be made when there are iron oxide content or aggregates with magnetic properties in the concrete. Acoustic and ultrasonic techniques are also very common for [5–8] assessing concrete structures, however, the techniques are quite

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expensive and cumbersome, limiting their practical applicability on site. Besides, significant ultrasonic scattering and surface preparation before each time of testing remain an inevitable problem [9,10]. Electrochemical methods, such as half-cell potentiometer [11], has also been mainly adopted in the rebar corrosion estimation by measuring the electrochemical potential. However, it can only provide a qualitative or semi-quantitative results of the corrosion status and normally require other complicated statistical surveys. Electrical impedance methods such as electrical resistivity method have also been used to monitor the hydration process of concrete as well as the corrosion status of the rebar [12–14]. Some researchers also coupled the resistivity method with ultrasonic [9] and/or acoustic [5] method for the hydration monitoring process, while the interpretation of the measured signals in different frequencies could be very complex in both non-contact [14,15] and contact way [16,17]. Most of the time, concrete covers need to be broken for connecting the rebar in the impedance testing process. Ground Penetration Radar (GPR) [18,19] is also quite common in delamination detection in concrete and currently the application has been expanded to hydration monitoring [20], rebar position testing [21,22], and water content testing in concrete [23,24]. However, the equipment for GPR techniques is specialized and licensing is often required and the interpretation of results is complex and needs high technical skill. Moreover, the extensive signal processing may be quite expensive and one should compromise between penetration and resolution most of the time [25], hindering the real application of this technique. Most of these sensors are not flexible or economical, while the resulting interpretation of the results is also very complex, thus making these not suitable for densely implementing along the structures.

In this decade, a series of reports on the capacitive principle adopted sensors have attracted a lot of interests in NDT on the reinforced concrete. Perhaps, the most popular case is electrical capacitive tomography (ECT) technique [26–28], a kind of imaging method which is originally adopted in oil pipeline monitoring. The technique has been adopted for rebar position testing, hidden void measurement as well as concrete surface crack testing. However, the resolution of the testing results remains a big problem. Another meaningful application combines the capacitive and GPR techniques together for the evaluation of concrete cover [29]. Although it is reported that an embedded capacitive sensor is used to measure corrosion potential (E_{corr}) to monitor the corrosion status of reinforcement bar [30], it is indeed an electrochemical method instead of testing the rebar property through directly testing electrical field variation. None of these methods have built a direct relationship between the capacitance value and the rebar properties directly, not to mention the expensive and complex device as well as the complicated data acquisition and interpretation method.

Considering of the shortcomings of the aforementioned sensors, a novel cost-effective capacitive transducer that can provide accurate quantitative estimation of rebar size and positions through direct capacitance outputs is proposed for the first time. The construction of the capacitive sensor is simple yet effective. It consists of an in-house fabricated polymer isolated supports and two corresponding electrodes, forming a parallel capacitor. Such flexible design has paved the way for mass production and numerous employment of the sensors along the large-scale infrastructures.

2. Methodology

2.1. Capacitive sensor design and assembling

In view of the basic but useful principle of capacitive sensor and the different electric property of concrete and steel, two parallel-capacitive sensors were designed for reinforcement testing (Type I) and concrete testing (Type II), respectively. Both of the developed sensors included a specially designed polymer insulated support and their corresponding electrode pairs. The design configurations of the developed capacitive sensors only require minimal cost and the whole setup is very economic. Copper electrodes are adopted in the initial stage. Detailed dimensions of each sensor are illustrated in Fig. 1.

Type I capacitive sensor was fabricated using 3D printing technique with PET (polyethylene terephthalate) material in order to reserve a centric half-cylindrical channel for rebar property testing. Considering that cement or concrete pastes are usually in a rectangular shape, Type II capacitive sensor was made of PMMA (polymethyl methacrylate) plates to ensure a flat base between the two electrodes, which is convenient for concrete and cement pastes testing. Also, in order to investigate the influence of different testing positions, electrode spacing of Type II capacitive sensor was designed greater as comparing to Type I. Photos of both sensors are shown in Fig. 2.

Such designs of the capacitive sensors are quite flexible, since the electrodes and sensor supports are unattached. The capacitive electrodes and their corresponding sensor supports can be adjusted according to the real size of the tested rebar and concrete samples in order to get higher measure sensitivity, which will be discussed in the future work. As shown in Fig. 3, different sizes of capacitive electrodes with their corresponding sensor supports have been fabricated respectively for conducting future comparative study.

After assembling the developed capacitive sensor, a stationary electrical field is generated between the two parallel electrodes when they were charged by a power generator. When the properties of the reinforced concrete between the two electrodes change slightly, the electrical field will change as well. The electrical field change will be directly converted to capacitance signal (CT output).

2.2. Preliminary experimentation

2.2.1. Experimental conditions

After design and assembly, the two parallel-plate electrodes, serving as the test cell for capacitance sensing, were connected to a commercially available capacitance meter through a special test fixture. In order to ensure the stability of the whole setup and to minimize the stray capacitance as well, the two fixtures were placed in symmetrical positions. Except for the electrodes, other metallic parts such as the supporter and the axles were insulated.

Experiments were conducted to verify the effectiveness of the designed capacitive sensor. The preliminary experimental results could help to optimize the sensor design. In all the experiments, the angular frequency of the capacitance meter was set as 10 KHz, and the applied voltage on the two electrodes was 1.0 V. The output of the capacitance value was then recorded and the data was logged in the computer.

Other detailed conditions including electrodes material and gap, original capacitance value C_0, measured specimens as well as the measured positions between the two electrodes are listed in Table 1.

2.2.2. Materials preparation

Rebar used in the preliminary experiments follows the China national standard [31]. 6 mm rebar to 20 mm rebar with a diameter increment of 2 mm were selected. Ordinary Portland cement (OPC) type 52.5 was from Green Island, HK. For pure cement paste used in this project, the w/c ratio was set as 0.3 and specimens of size 80 mm × 30 mm × 8 mm were cast. For the fiber reinforced concrete samples, mix proportions are listed in Table 2. The PVA