Measurement 67 (2015) 84–91

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Corrosion monitoring of the RC structures in time domain: Part II. Recognition algorithm based on fractional derivative theory

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ARTICLE INFO

Article history:
Received 27 July 2014
Received in revised form 18 November 2014
Accepted 23 December 2014
Available online 8 January 2015

Keywords:
RC structures
Corrosion monitoring
Recognition algorithm
Time domain
Fractional derivative theory

ABSTRACTS

To identify the corrosion status of reinforced concrete (RC) structures, the fractional derivative (FD) theory is used to establish the integrated recognition algorithm. The electrochemical corrosion characteristics including dispersion and diffusion effects can be directly obtained in time domain. The effectiveness and accuracy of FD algorithm are verified numerically based on the results of complex-function-approximation algorithm. Furthermore, the robustness of FD algorithm is tested by the interference experiments of the white noise. The results indicate that the recognition algorithm established based on FD can successfully identify the corrosion status of RC structures in time domain.

1. Introduction

Reinforced concrete (RC) structures the most important structural type in civil engineering, have been tremendously constructed worldwide in the past few decades, e.g., super dams, long-span bridges and skyscrapers, etc. Unfortunately, corrosion of reinforcing steel has been one of the most important factors which lead to the premature deterioration of concrete infrastructures, especially the structures located in the areas with de-icing salt and coastal marine environment [1]. The most important causes of corrosion initiation are the ingress of chloride ions and carbon dioxide to the steel surface. When sufficient chloride ions penetrates to the reinforcement or the pH value of the pore solution drops to low values due to the carbonation, the protective film is destroyed and the reinforced steel is depassivated. Corrosion results in the damage of the RC components with subsequent enormous costs for maintenance, restoration and replacement, or even the collapse of the RC structures, and eventually leads to the huge losses of life and economic [2,3]. With the development of global warming and further deterioration of the environment, the service ambient of RC structures is being much more atrocious than that of before. Therefore, it is very urgent to pursuit the effective corrosion monitoring and control methods for RC structures.

Currently, the concept of smart community, smart city, or even smart planet is being pushed forward with the development of internet of things. Large numbers of sensing techniques based on the ultrasonic, light, electricity, heat and magnetism phenomena, etc., have been developed and applied in civil engineering [4–6]. Structural health monitoring and control (SMC) is able to provide the vital basis for the safety assessment, maintenance, reinforcement and life-circle design, etc [7–11]. As far as the corrosion monitoring and control concerned, the corrosion monitoring provides the scientific basis for the

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http://dx.doi.org/10.1016/j.measurement.2014.12.048
0263-2241/

corrosion control, and the corrosion control paves the way to prolong the service life and enhance the safety of structures. In the past few decades, the scientists and engineers worldwide have carried out extensive researches on the corrosion from the perspectives of building materials, structural elements and even structures themselves [12,13]. These investigations have established the key database to bridge the corrosion status and structural performance. The corrosion monitoring sensors have also been developed [14–18]. These corrosion sensors provide the hardware to carry plenty of corrosion measurement methods to measure the corrosion status of RC structures in the field. On the other hand, the active corrosion prevention approaches including corrosion inhibitors and cathodic protection (CP), etc., and the passive corrosion control methods including electrochemical realkalisation (ERA) and electrochemical chloride removal (ECR), etc., have been developed to alleviate or prevent the corrosion of RC structures [19–21]. The current trend of SMC is to realize the integration of real-time and online corrosion monitoring and control. Specifically, the corrosion monitoring system should be able to determine whether the RC structures have been corroded and which kind of corrosion has occurred, to provide the key information to instruct the corrosion control program, and to evaluate the effectiveness of corrosion control methods. The corrosion control program should also be able to regulate real-time and online to optimize the control effects.

Generally, there are four parts in SMC system for the corrosion of RC structures, i.e., corrosion monitoring sensors and corrosion controllers, data acquisition and transmission module, status evaluation and model updating module and control optimization module. Considering the entire system, corrosion recognition methods which provide the vital information for the corrosion control system are the most important theoretical foundation to guarantee the effectiveness and accuracy of the corrosion control techniques. Essentially, the corrosion process of the most of RC structures is a series of electrochemical reactions. In the past few decades, plenty of characterization methods for the corrosion of RC structures have been developed based on the electrochemical theory in frequency domain or in time domain [22–24]. Among all of these methods, the electrochemical techniques in time domain, such as Transient Galvanostatic Decay (TGD) and Transient Potentiostatic Decay (TPD), have attracted many attentions for their significant advantages, e.g., fast measurement and low cost of equipment, etc [25]. We hope to rapidly obtain the same amount of information in time domain as that of the frequency domain. This is very important for SMC of corrosion in the practical scenarios. Generally, there are large amounts of measuring points in the RC infrastructures. So, the SMC system should be able to quickly implement the corrosion monitoring duty and to promptly regulate the corrosion control tactics.

Recently, the simple equivalent circuit (EC) with clear physical meaning including the concrete resistance, the electrochemical reaction resistance, the constant phase element and the Warburg impedance has been successfully established to simulate the features of the steel–concrete system [26,27]. This EC provides the important baseline for the corrosion characterization and recognition of RC structures. The mathematical expression of the equivalent circuits developed here could be seemed as the corrosion transfer function of the concrete-steel system. Therefore, the corrosion recognition process of RC structures is transferred to extract the characteristic parameters of the EC mentioned above from its responses stimulated with TGD or TPD, etc., in time domain. Traditionally, the response expressions of linear systems with given stimulation could be achieved by the inverse Laplace or FFT transform, and then the parameters of the transfer function could be determined by fitting the experimental results to the explicit or implicit expressions of the response in time domain. However, the biggest obstacle to realize the corrosion parameters identification of the EC mentioned above is that the exponent of the transfer function contains the parameter $\beta \in (0, 1]$ which just needs to be recognized. The parameter β derived from the constant phase element (CPE) reflects the deviation degree of the capacitive characteristic of the double layer from the pure capacitance. Considering this obstacle, some modified algorithms have developed [25,28,29]. However, the accuracy of the parameters identified by the algorithms mentioned above, especially the Warburg impedance, directly depend on the time length of the response. Also, the time duration used to fit the response expressions are artificially selected. This could lead to the considerable errors or even mistakes. Considering the unique characteristic of the EC, a significant and brilliant algorithm based on fractional derivative operator has been explored to obtain the numerical solution of the response [30]. However, only the concrete resistance, the electrochemical reaction resistance and the constant phase element have been considered in this algorithm.

Considering the complexity of the corrosion process and the urgent needs of SMC for RC structures, we attempt to establish the overall and fast corrosion recognition method in time domain based on the FD theory. The contents are conducted as follows. The FD module for the universal EC is established in Section 2. In Section 3, the accuracy of the recognition algorithm is verified numerically based on the results of complex function approximation algorithm. We also discuss the influence of the noise to the recognition algorithm in Section 3. Finally, we conclude this investigation in Section 4.

2. Recognition methods based on FD theory

The electrochemical transfer function of RC structures, e.g., the admittance function of the universal equivalent circuit $R_c((R_{ct}Z_w)Z_{CPE})$, can be expressed as follows:

$$G(S)=\frac{I(S)}{U(S)}=\frac{Y_{OQ}(S)^{\beta}\left[R_{ct}Y_{OW}(S)^{1/2}+1\right]+Y_{OW}(S)^{1/2}}{R_cY_{OQ}(S)^{\beta}\left[R_{ct}Y_{OW}(S)^{1/2}+1\right]+R_cY_{OW}(S)^{1/2}+R_{ct}Y_{OW}(S)^{1/2}+1} \tag{1}$$

where $G(S)$ is the admittance function; $U(S)$ and $I(S)$ are the potential excitation applied to the electrochemical corrosion system of RC structures, respectively; Z_{CPE}, Z_w, R_{ct} and R_c are the impedance of constant phase element caused by the dispersion effect of the interface zone,