Measurement 67 (2015) 78–83

Contents lists available at ScienceDirect

Measurement

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

Corrosion monitoring of the RC structures in time domain: Part I. Response analysis of the electrochemical transfer function based on complex function approximation

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ARTICLE INFO

Article history:
Received 27 July 2014
Received in revised form 7 November 2014
Accepted 2 December 2014
Available online 18 December 2014

Keywords:
RC structures
Corrosion monitoring
Time domain
Equivalent circuit
Complex function approximation

ABSTRACT

To finally obtain the overall and fast recognition method for the electrochemical corrosion of reinforced concrete (RC) structures, the complex function algorithm is established to approximate the corrosion transfer function in frequency domain, and then the influence of Z_{CPE}, Z_W, R_{ct} and R_c in the universal equivalent circuit (EC) $R_c((R_{ct}Z_W)Z_{CPE})$ on the time response is discussed in detail. The results indicate that the polynomial complex function can successfully approximate the corrosion transfer function with the given accuracy. The response of $R_c((R_{ct}Z_W)Z_{CPE})$ in time domain can be achieved by the inverse Laplace transform of the polynomial complex approximation function.

1. Introduction

Reinforced concrete (RC) structures are the most important structural type all over the world. Compared with other factors including freeze–thaw, action of physical and chemical ambient, etc., corrosion of reinforcing steel, generally caused by the carbonation or Cl^-, is the most important factor which severely degrades the durability of RC structures in the presence of oxygen and water (humidity). Especially, Cl^- from the deicing salt or oceanic environment can lead to the corrosion with very high (up to 1 mm/y) that can quickly result in a remarkable reduction in the cross section of the reinforcing steel [1–3]. The durability deterioration of RC structures has finally resulted in very high repair costs, sometimes much greater than the initial construction cost, and in some extreme situations, has leaded to collapse of the structure in the past few decades. According to the statistics of World Corrosion Organization (WCO) in 2009, the overall economic losses caused by the corrosion worldwide have been up to 2.2 trillion per year [4]. With the development of global warming, extreme weather conditions and further deterioration of the environment, the service condition of RC structures is bound to much harsher than that of before [5]. Corrosion of RC structures is attracting the highly close attention worldwide.

Considering the serious damage of the corrosion, researchers and engineers are exploring the measurements methods used to identify the corrosion status of RC structures in laboratory or fields [6–8]. Essentially, the corrosion process in most of RC structures is a series of electrochemical reactions. Therefore, most of the corrosion measurement methods are based on the electrochemical theory. According to the different excitation mechanism, these methods fall into two main categories, i.e., active

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http://dx.doi.org/10.1016/j.measurement.2014.12.018
0263-2241/

measurement techniques (AMTs) and passive measurement techniques (PMTs) [9]. The AMTs mean to actively excite the electrochemical corrosion system of RC structures by using the external signals, and then to obtain the corrosion characteristics by analyzing the response of the corrosion system. The major AMTs applied extensively in corrosion measurement include Electrochemical Impedance Spectrum (EIS), Electrochemical Frequency Modulation (EFM), Harmonic Analysis (HA), Transient Galvanostatic Decay (TGD), Transient Potentiostatic Decay (TPD), Potentialdynamic Scan, Linear Polarization and Coulostatic Method. For the pitting corrosion caused by Cl^-, Electrochemical Emission Spectrum (EES) in PMTs is the most effective technique to recognize the corrosion status of the reinforcing steel. Essentially, electrochemical noise (EN) reflects the intrinsic information of the initial, metastable, repassive and stable stages during the pitting corrosion process. The pitting corrosion status can be identified via analyzing the EN data in time domain [10], frequency domain [11], wavelet domain [12] or chaos domain [13].

From the perspective of practical engineering, the characteristics of corrosion measurement are very important in the field, e.g., rapid measurement, accurate results and lower cost of the equipment, etc. Compared with the AMTs in frequency domain [14,15], the AMTs in time domain, such as LPR, TPD and TGD, have attracted many attentions for their huge advantages [16,17]. According to the numerous experiments results, a universal EC with clear electrochemical meaning has been successfully established to simulate the characteristics of the steel-concrete system [18,19]. There are four simple elements in the universal EC, i.e., the impedance of the constant phase element (CPE) Z_{CPE} which reflects the dispersion effect caused by the multiphase and heterogeneous characteristics of the concrete/reinforcing steel interface, the Warburg impedance Z_W which embodies the diffusion effect resulted by the diffusion process of oxygen around the cathodic zone, the reaction resistance R_{ct} and the concrete resistance R_c. In fact, the mathematical expression of EC is the transfer function of the electrochemical corrosion system of RC structures. Therefore, the corrosion status of RC structures could be recognized by extracting Z_{CPE}, Z_W, R_{ct} and R_c from the response data corresponding to the EC excited by the AMTs in time domain. However, the presented AMTs in time domain, regardless of the amplitude of the applied excitation, are complicated by the fact that the reinforcing steel/concrete electrochemical corrosion system does not usually reach a steady-state of potential or current shift within a given time [20,21]. This phenomenon could lead to the considerable error or even mistake. Therefore, how to effectively extract the valuable parameters in the EC mentioned above in time domain is the key point to accurately identify the corrosion status of RC structures.

To finally establish the overall and fast recognition method for the electrochemical corrosion of RC structures, we attempt to apply complex function approximation theory to analyze the influence of the elements in $R_c((R_{ct}Z_W)Z_{CPE})$ equivalent circuit on the response in time domain in this part, and then we presents the corrosion recognition algorithm based on the fractional derivative theory in the next part. It must be point out that the purpose of the complex function approximation established in this part is not only to present the influence of the four elements in the EC, but also to provide the precise numerical experiment conditions for the corrosion recognition algorithm in the next part. The contents of this paper are conducted as follows. The complex function approximation theory is introduced in Section 2. In Section 3, we discuss the influence of Z_{CPE}, Z_W, R_{ct} and R_c on the response in time domain in detail. We conclude this investigation in Section 4.

2. Complex function approximation algorithm

2.1. Electrochemical transfer function of RC structures

Fig. 1 illustrates the electrochemical transfer function model, i.e., the universal equivalent circuit, which can be used to simulate and characterize the electrochemical features of the steel/concrete system.

The coarse interface of the steel-concrete, isolated reaction region and the heterogeneous nature of concrete are the most important factors which could cause the dispersion effect. This phenomenon is depicted by the constant phase element. The CPE is expressed as follows:

$$Z_{CPE} = \frac{1}{Y_0 Q}(j\omega)^{-\beta} = \frac{1}{Y_{0Q}}\omega^{-\beta}\left(\cos\frac{\beta\pi}{2} - j\sin\frac{\beta\pi}{2}\right) \quad (1)$$

where Y_{0Q} is the basic admittance, β is the constant in the range of (0, 1], and ω is the angular frequency (rad/s).

$$Y_{0dl} = \frac{\omega^{-\beta}}{|Z_{CPE}|} \quad (2)$$

According to Eq. (1), the value of $\beta < 1$ implies that the capacitive characteristic of the double layer deviates from the pure capacitance.CPE will change to a pure resistance or a pure capacitance as $\beta = 0$ or 1, respectively.

The diffusion of the oxygen in the concrete around the cathodic region results in the Warburg impedance Z_W. Warburg impedance exhibits smearing phenomenon in

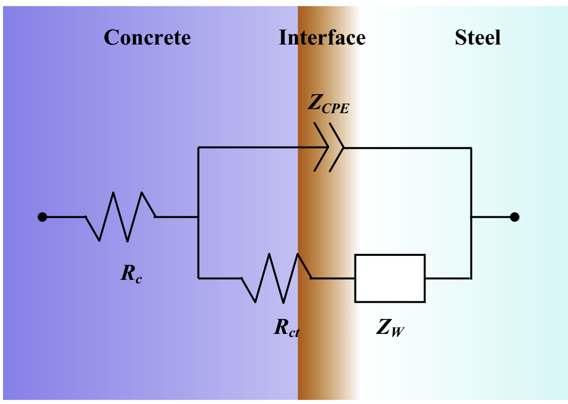

Fig. 1. The universal equivalent circuit $R_c((R_{ct}Z_w)Z_{CPE})$ of RC structures. Z_{CPE}, Z_W, R_{ct} and R_c are the impedance of constant phase element caused by the dispersion effect of the interface zone, Warburg impedance caused by the diffusion process of oxygen, electrochemical reaction resistance and the resistance of concrete, respectively.