Characterization of Impact Test Response of PCCP with System Identification Approaches

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Abstract

In this study, impact test was carried out to assess the condition of prestressed concrete cylinder pipe (PCCP). The impulse response of the test is modeled with system identification approaches. The model of the impulse response can be further used to characterize the deterioration of PCCP. This paper presents preliminary results on the comparison of different models for the response of impact test for the purpose of evaluating PCCP.

Keywords: impact test, prestressed concrete cylinder pipe, system identification, feature extraction.

1. Introduction

Prestressed concrete cylinder pipe (PCCP) is widely used throughout the world. In the USA and Canada, there are an estimated 30,000 miles of this product installed[1]. The installed PCCP will undergo various deterioration stages and there are a number of reasons that cause the failure of PCCP pipelines. The deterioration may include the corrosion and breakage of wires, loss of wire prestress, delamination of the outer mortar, delamination of steel cylinder and concrete core interface, crack growth and strength loss of concrete core. The final stage comes the catastrophic failure[2]. Non-destructive inspection/testing (NDI/NDT) techniques provide tools for pipe inspection and condition assessment[3]. Different technical solutions have been proposed so far. However, none of them can reveal all the information about the pipe at all stages. The combination of multiple NDI techniques could be a potential solution.

Impact test, which is also known as impulse response test, implements a fast evaluation of PCCP structures and has been applied to large concrete structure, like floor slabs, pavements, bridge decks, etc.[4, 5] The impact test uses a rubber-tipped hammer to send a low-strain impact propagating stress waves to the PCCP. The response of the PCCP is measured by accelerometers attached to the pipe surface and is characterized by a transfer function, which describes a dynamic system with the ratio of response and impact force spectrum. When any discontinuities (cracks/flaws) are present in the pipe, there will be an associated reduction in spectral amplitude[6]. Therefore, the transfer function contains the information related to the structures. However, the use of such information for quantitative analysis or characterization of a PCCP has not been reported so far.

In this study, we evaluated different system identification approaches to model the response of PCCP to the impulse generated by a rubber-tipped hammer. The system parameters determined by the dynamic model can be used characterize pipe condition. Different models are compared based on the accuracy. Preliminary experimental results are presented.

2. Impact Test for PCCP

The impact test measures the response of the tested material to the impact. A 198cm long PCCP segment as shown in Figure 1 was used and the setup for the impact test is illustrated. The inside diameter of the PCCP segment is about 42cm. Four accelerometers were placed at stations A, B, C, and D. The impact force was applied to the edge of pipe. Three different impact locations are marked in Figure 1 with numbers 1, 2, and 3. A WaveSurfer oscilloscope was used to record the impact force and the readings from the four accelerometers. The sampling rate in the following experiments was set as 5ks/s.
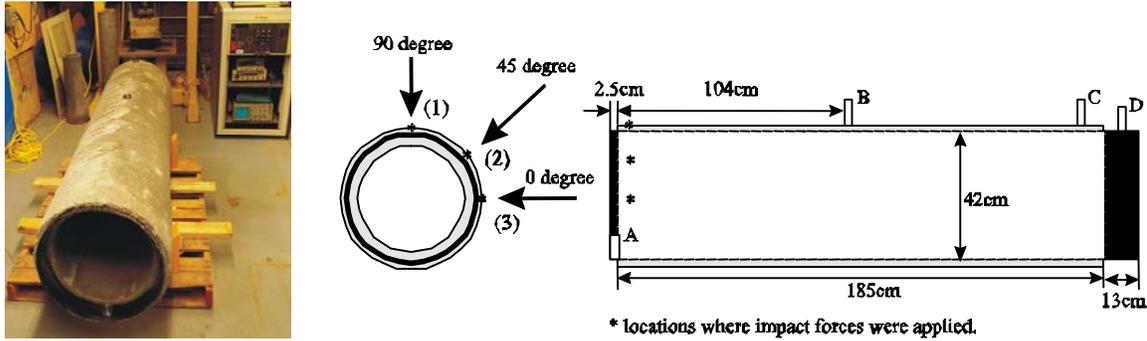

Figure 1. The impact test of a PCCP.

3. Modeling with System Identification Approaches

Dynamic models corresponding to the four locations (A to D) can be built from the measured data with system identification approaches. Four models were considered in this study. These include 1) linear model, 2) auto-regressive exogenous input model, 3) black-box state-space model, and 4) Hammerstein-Wiener Model. The detailed theoretical descriptions of the these methods are available in the literature[7].

3.1 Linear Model Using Steiglite-McBride Iteration

The first model is to find an IIR (infinite impulse response) filter to describe the time-domain impulse response. This parametric model is implemented with Steiglitz-McBride iteration algorithm, which minimizes the error between the predicted output and the observed output[8]. The transfer function is written as:

$$H(z) = \frac{B(z)}{A(z)} = \frac{b(1) + b(2)z^{-1} + \cdots + b(nb+1)z^{-b}}{a(1) + a(2)z^{-1} + \cdots + a(na+1)z^{-a}} \tag{1}$$

where $b(i)$ and $a(i)$ are the corresponding coefficient ($i = 1,2,\cdots,b+1; j = 1,2,\cdots,a+1$) of $B(z)$ and $A(z)$. The coefficients of this transfer function can be used to model the response of the test. In our application, we set $a = 4$ and $b = 3$ respectively.

3.2 Auto-Regressive Exogenous Input Model

Parametric modeling is to minimize the model's simulated output and the measured output. A parametric model can be expressed with difference equations. Auto-Regressive eXogenous input (ARX) model is commonly used for modeling dynamic systems[7]. The equation for ARX can be written as:

$$y(t) + a_1 y(t-1) + \cdots + a_{n_a} y(t-n_a) = b_1 u(t-n_k) + \cdots + b_{n_b} u(t-n_k-n_b+1) + e(t) \tag{2}$$

where $y(t)$ is the output signal at time t; $u(t - n_k)$ is the input signal at time $t - n_k$; $e(t)$ is the noise; a_{n_a} and b_{n_b} are the model parameters; n_a and n_b indicate the order of the respective polynomials and n_k is time delay from input to output. Equation (2) can be written as:

$$A(z)y(t) = B(z)u(t - n_k + 1) + e(t) \tag{3}$$

where there are:

$$A(z) = 1 + a_1 z^{-1} + \cdots + a_{n_a} z^{-n_a} \tag{4}$$

$$B(z) = b_1 z^{-1} + \cdots + b_{n_b} z^{-n_b} \tag{5}$$

A least-squares method that uses QR-factorization for overdetermined linear equations is applied to estimate the parameters of the ARX model[7]. The $e(t)$ is assumed to be white noise. In the experiment, n_a and n_b were set as 4 and 3 respectively.

3.3 Black-Box State-Space Models

In a state-space model, a system is characterized with state variables in a set of first-order differential equations. The general state-space model structure is:

$$x(t + 1) = Ax(t) + Bu(t) + Ke(t) \tag{6}$$

$$y(t) = Cx(t) + Du(t) + e(t) \tag{7}$$

where $y(t)$ represents the output at time t, $u(t)$ represents the input, $x(t)$ is the state value, and $e(t)$ is white noise. The matrices A, B, C, D, and K are the state-space matrices. A non-iterative subspace method is used to estimate the state-space model[7]. The order of the model was estimated as four.

3.4 Hammerstein-Wiener Model

A Hammerstein-Wiener (HW) model consists of one or two static nonlinear blocks and a linear block as illustrated in Figure 2[7].
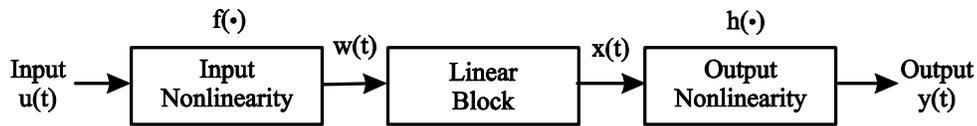

Figure 2. The diagram of Hammerstein-Wiener model.

The HW model is described by the equations below:

$$w(t) = f(u(t)) \tag{8}$$

$$x(t) = \frac{B(q)}{F(q)} w(t) \tag{9}$$

$$y(t) = h(x(t)) \tag{10}$$

where the input and output are $u(t)$ and $y(t)$ respectively. Nonlinear function f and h correspond to the input and output nonlinearities. $w(t)$ and $x(t)$ are internal variables. $B(q)$ and $F(q)$ are polynomials in the backward shift operator[10].

4. Experimental Results

In this study, we used the data sets obtained at the 90° (location 1) with a sampling rate of 5kHz. The pulse applied to the PCCP and its spectrum are shown in Figure 3. The test was applied twice. The first set of the data was used to estimate the models while the second set of data was used to validate the models.

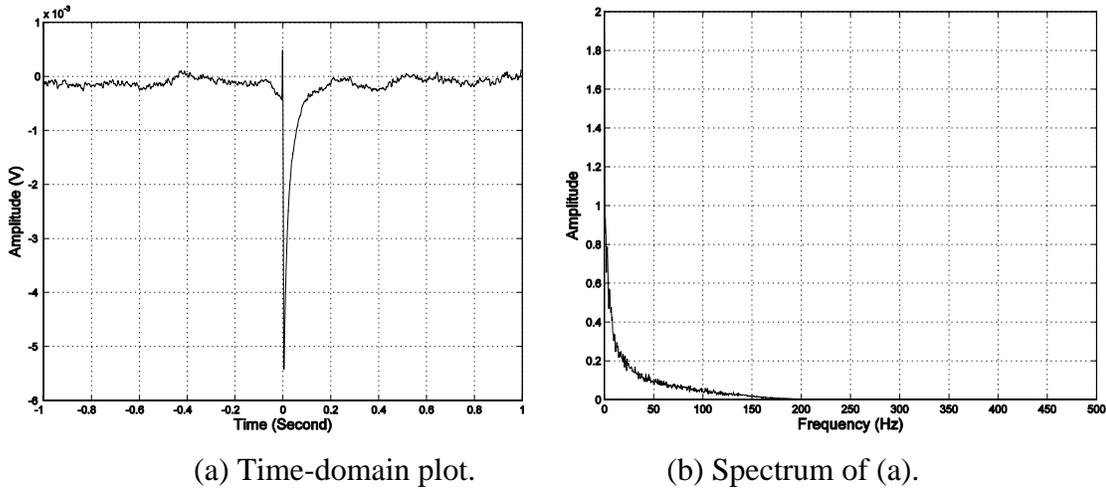(a) Time-domain plot.   (b) Spectrum of (a).

Figure 3. The pulse applied to PCCP at location (1).

Figure 4 shows the echo signal and spectrum plot at location B. It is observed from Figure 4(b) that a peak happens at 30Hz. This is from the pipe support[9]. Therefore, a FIR (finite impulse response) high-pass filter is designed to filter the echo signal. The cutoff frequency is set at 200Hz. The filtered signal and its spectrum plot are given in Figure 4(c) and 4(d) respectively. The filtered signal is used in model estimation.

We used the algorithms presented in section 3, which are implemented in Matlab® and its system identification toolboxes to build the models from measurement data. Two sets of measured data acquired at location B were used. The percentage of the output variation is computed as[10]:

$$fit(\%) = 100 \times \left(1 - \frac{\sqrt{\sum_i (\hat{y}_i - y_i)^2}}{\sqrt{\sum_i (y_i - \bar{y}_i)^2}} \right) \tag{11}$$

where y_i is the ith measured value and $\hat{y}_i$ is the ith computed value from the model. The average of the measurement is $\bar{y}$. A perfect model gives a result of 100%. Table 1 shows the results of four selected models and Figure 5 gives the corresponding outputs of the models. The Hammerstein-Wiener model achieved the best result.

(a) Time-domain response.

(b) Spectrum of (a).

(c) High-pass filtered time-domain response.
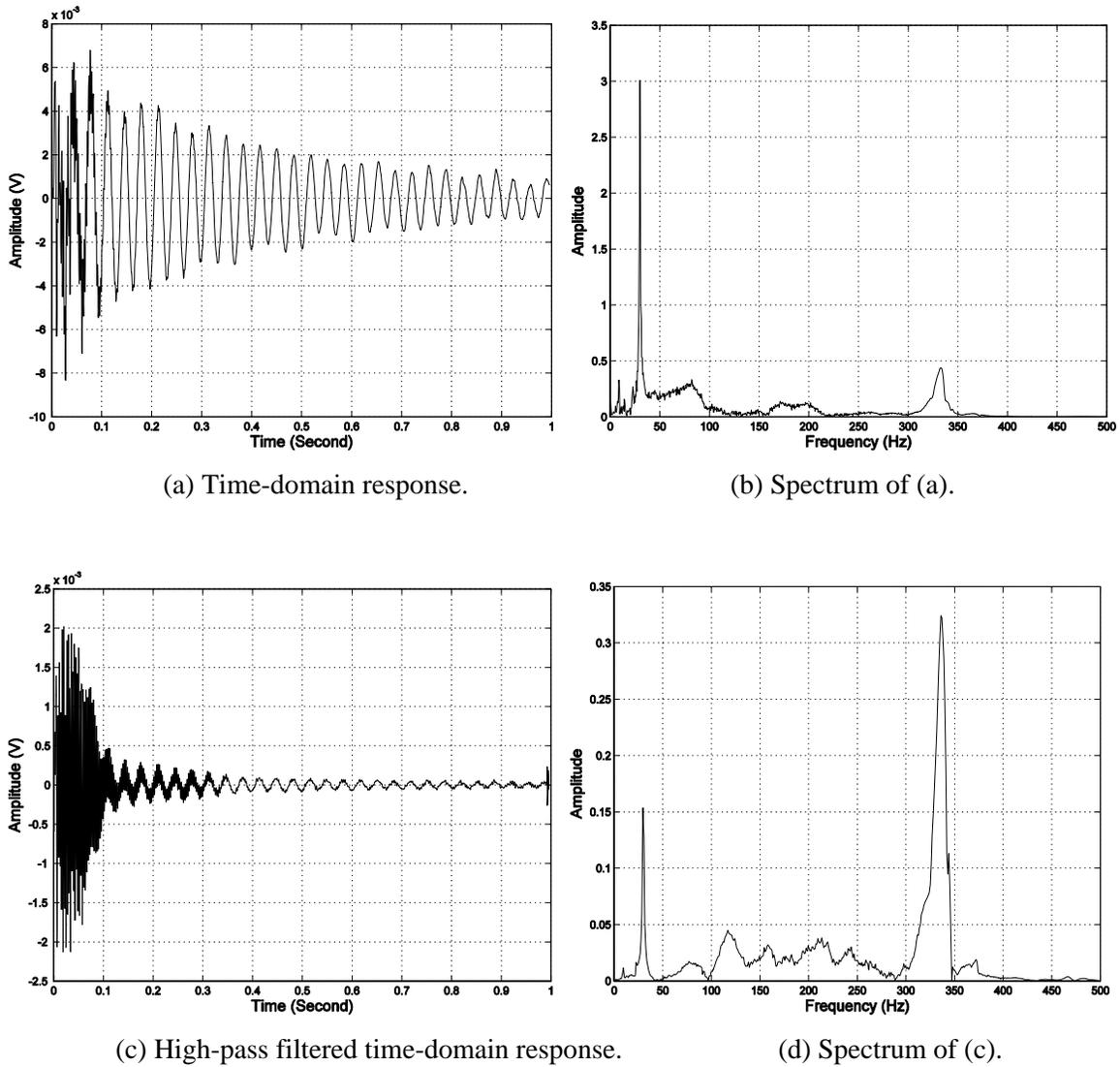
(d) Spectrum of (c).

Figure 4. The impact test results acquired at location (B).

As illustrated in Figure 2, there are two non-linear blocks in a HW model. In the experiment, we used dead-zone and saturation nonlinearity estimator for the input and output respectively. However, the saturation is not obvious in the actual response in Figure 5(a), although such configuration gives a better result in term of the output variation. The output variation may not be the only criterion to evaluate the performance of the proposed models.

Table 1. The evaluation of the estimated models with fitting rate.

SI method	Linear model	ARX model	Black-box state space model	Hammerstein-Wiener model
Fit (%)	13.84	26.24	47.69	53.91
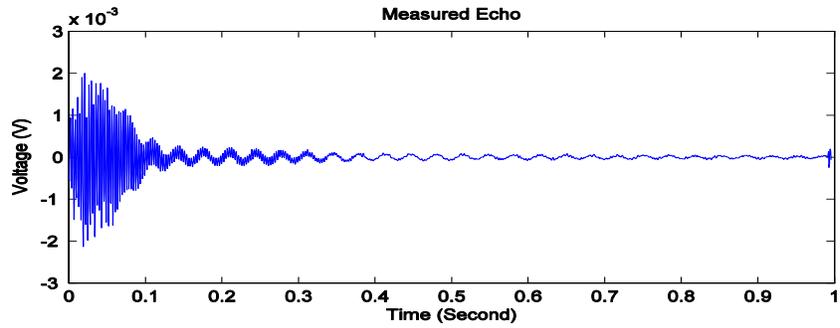
(a) Time-domain response of the second test.
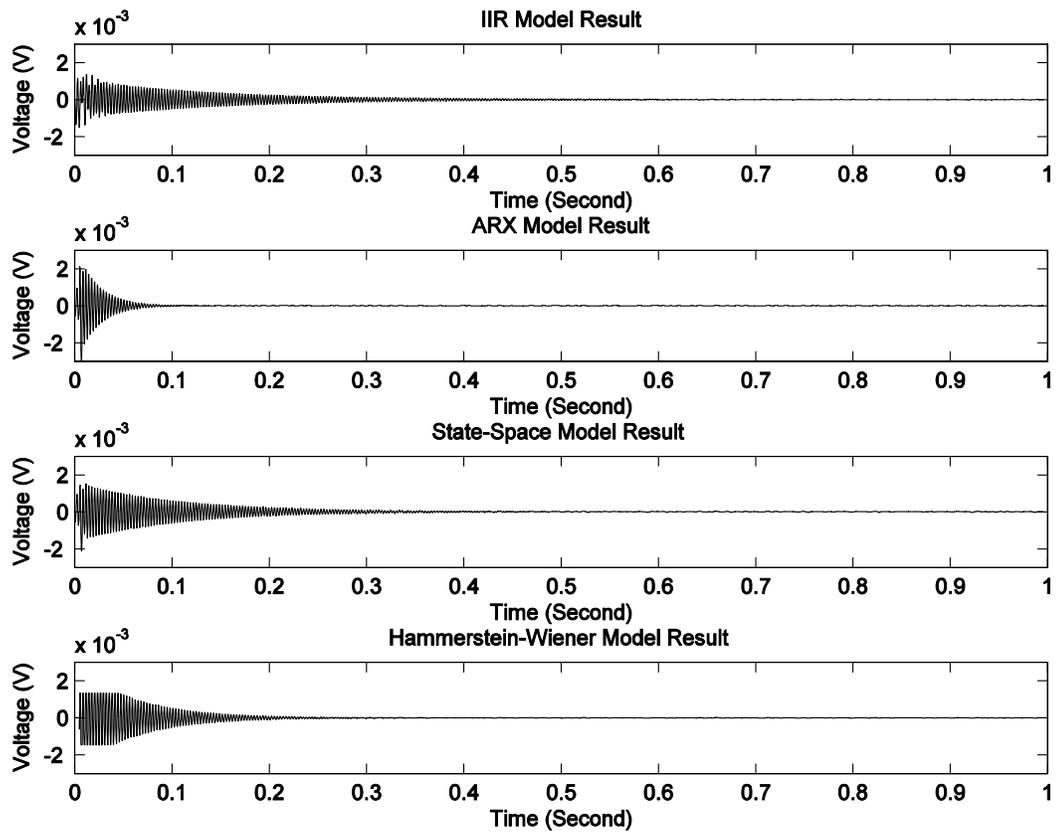
(b) The simulated outputs from different models.

Figure 5. Original response (a) and model outputs (b).

5. Summary

In this paper, we presented the results of applying system identification approaches to model the impact test of PCCP. Among the selected models, Hammerstein-Wiener model achieved the best result. The deterioration of PCCP is complicated and varies at different stages. The acquired response signal is affected by a number of factors even in a laboratory environment. The model parameters may reflect the deterioration at different stages. The most prominent factor needs to be identified. How system parameters change with the deterioration is not clear yet. A straightforward method to identify the deterioration of a PCCP is through comparing the signature with a reference. To fully characterize the condition of PCCP, multiple-site modeling remains a topic for our future research.

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