Modeling of environmental influence in structural health assessment for reinforced concrete buildings

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Abstract: One branch of structural health monitoring (SHM) utilizes dynamic response measurements to assess the structural integrity of civil infrastructures. In particular, modal frequency is a widely adopted indicator for structural damage since its square is proportional to structural stiffness. However, it has been demonstrated in various SHM projects that this indicator is substantially affected by fluctuating environmental conditions. In order to provide reliable and consistent information on the health status of the monitored structures, it is necessary to develop a method to filter this interference. This study attempts to model and quantify the environmental influence on the modal frequencies of reinforced concrete buildings. Daily structural response measurements of a twenty-two story reinforced concrete building were collected and analyzed over a one-year period. The Bayesian spectral density approach was utilized to identify the modal frequencies of this building and it was clearly seen that the temperature and humidity fluctuation induced notable variations. A mathematical model was developed to quantify the environmental effects and model complexity was taken into consideration. Based on a Timoshenko beam model, the full model class was constructed and other reduced-order model class candidates were obtained. Then, the Bayesian modal class selection approach was employed to select the one with the most suitable complexity. The proposed model successfully characterizes the environmental influence on the modal frequencies. Furthermore, the estimated uncertainty of the model parameters allows for assessment of the reliability of the prediction. This study not only improves the understanding about the monitored structure, but also establishes a systematic approach for reliable health assessment of reinforced concrete buildings.

Keywords: Bayesian inference; model selection; reinforced concrete building; structural health monitoring; temperature and humidity effects; Timoshenko beam

1 Introduction

Structural health monitoring (SHM) has attracted a tremendous amount of attention from research communities throughout the world in last few decades. The integrity of civil infrastructures can be assessed by extracting information from their dynamic response measurements. The ultimate goal of SHM is to diagnose structural damage at the earliest possible stage so that human life can be protected. Modal frequency is a widely adopted indicator for this purpose since the squared modal frequency is proportional to the structural stiffness. As a result, a substantial reduction of this indicator is regarded as loss of structural integrity (Salawu, 1997; Sohn et al., 2003). However, results obtained from long-term health monitoring in-field applications demonstrated that this indicator is sensitive to fluctuating environmental conditions, e.g., temperature, humidity, wind excitation and traffic loading (Askegaard and Mossing; 1988; Alampalli, 1998; Peeters and De Roeck 2001; Kim et al., 2003; Xia et al., 2006; Clinton et al., 2006; Catbas et al., 2008).

Considerable research efforts have been devoted to the inevitable environmental interference to the modal frequencies of civil engineering structures. Askegaard and Mossing (1988) reported that 10% annual periodic variation in the natural frequencies of a three-span reinforced concrete footbridge were observed during a three-year monitoring period. Alampalli (1998) recorded the measurements of a reinforced concrete bridge under freezing conditions and compared the variation in the natural frequencies of a three-span reinforced concrete footbridge with the measurements of a reinforced concrete bridge before introducing artificial saw cuts to the bridge girders. It was found that the variation due to freezing were ten times larger than that induced by the artificial damage. Peeters and De Roeck (2001) studied the environmental conditions induced variation of the Z24 Bridge in Switzerland. In the ten-month monitored period, it was found that the modal frequencies could fluctuate up to 18%. Kim et al. (2003) conducted experiments on a plate-girder bridge. Based on the tested data, a set of linear empirical frequency correction relationships were developed.
for the temperature influence. It was found that all the observed modes exhibited the same trend but with different regression coefficients in the natural frequency-temperature relationships. Xia et al. (2006) performed a series of tests on a reinforced concrete slab to investigate the temperature and humidity influence on the structural vibration properties. The linear regression results illustrated that the modal frequencies exhibit strong correlation with temperature and humidity. Clinton et al. (2006) analyzed long term structural monitoring records of two reinforced concrete buildings. Over the thirty-year observation period, it was concluded that the background weather conditions (including rainfall, wind gust and temperature) induced considerable variation of the modal frequencies. Catbas et al. (2008) monitored the longest truss bridge in America. It was found that the structural reliability was highly affected by the ambient temperature and they concluded that it was a difficult task to develop the structural property-ambient condition relationship. Deng et al. (2010) developed a statistical modeling technique using a six-order polynomial in formulating the correlations between the modal frequencies and temperature. These works give solid evidence that the environmental conditions induce notable effects to the modal frequencies. Such influence may even trigger a false alarm signal for structural damage or may mask the possible damage. Therefore, reliable and consistent structural health assessment can be accomplished only if the inevitable environmental interference can be quantified.

This study attempts to model and quantify the environmental influence on the modal frequencies of reinforced concrete buildings based on the Bayesian probabilistic framework (Beck and Katafygiotis, 1998; Box and Tiao, 1992). For this purpose, one-year daily monitoring of a twenty-two story reinforced concrete building was conducted to capture the variation of the modal parameters. The Bayesian spectral density approach (Katafygiotis and Yuen, 2001; Yuen and Beck, 2003; Yuen, 2010) is applied to identify the modal frequencies of this building. The method takes advantage of the convenient properties of discrete Fourier transform (Yuen et al., 2002). Then, the Timoshenko beam model (Timoshenko, 1922; Smith and Coull, 1991) is utilized to obtain the full model class and other reduced-order model class candidates are generated for the model frequency-environmental factors relationship. Finally, the Bayesian model selection approach (Beck and Yuen, 2004; Yuen, 2010) is employed to choose the most plausible one from the candidates. The environmental influence on the modal frequencies can be estimated and uncertainty can also be quantified.

2 Environmental conditions and modal frequency of reinforced concrete buildings

Reinforced concrete buildings can be modeled as vertical cantilever beams subjected to gravitational and lateral loads (Clark, 1972; Smith and Coull, 1991). The Timoshenko beam model incorporates both the shear deformation and rotational inertia effects of the structure and it provides good approximation of the global behavior of buildings with different aspect ratios and configurations. In this model, the deflection and rotation function of the beam are considered as the target variables to account for the flexural, shear and inertia effects (Timoshenko, 1922).

Although the algebraic equations for the modal frequencies of the Timoshenko beam are available, there is no closed-form solution due to the nonlinearity of these equations. However, the squared modal frequencies can be approximated by a linear combination of bending and shear components (Kapur, 1966; Wittrick and Williams, 1971; Weaver et al., 1990):

\[
\Omega_n^2 = \frac{EI}{\rho AL^4} \left( c_{h,m} + \frac{\kappa AGL^2}{EI} c_{s,m} \right) \quad (1)
\]

where the dimensionless coefficients \( c_{h,m} \) and \( c_{s,m} \) can approximately be found by assuming the mode shape. The geometric and material properties of the beam, \( L, A, I, \rho, E \) and \( G \) are the length, cross sectional area, second moment of inertia of the cross section, density, elastic and shear modulus, respectively; and \( \kappa \) is the shear coefficient which depends only on the shape of the cross section. Note that Eq. (1) provides a general approximation for buildings with different aspect ratios and configurations.

Environmental conditions affect both the geometrical and material properties of a structure. Under the normal ambient temperature range, thermal expansion and Young’s modulus vary linearly (Naus, 2006). The parameter \( \alpha_T \) is used to denote the thermal coefficients of expansion. Then, the beam length, the cross sectional area and the second moment of inertia satisfy the following relationships:

\[
L = \left( 1 + \alpha_T T \right) L_0
\]

\[
A = \left( 1 + \alpha_T T \right)^2 A_0 \quad (2)
\]

\[
I = \left( 1 + \alpha_T T \right)^4 I_0
\]

where \( T \) is the temperature and the subscript 0 is used for the quantity at an arbitrarily selected reference environmental condition. Due to conservation of mass, the density is inversely proportional to the volume and so

\[
\rho = \left( 1 + \alpha_T T \right)^{-3} \rho_0 \quad (3)
\]

On the other hand, the Young’s modulus follows a similar relationship:

\[
E = \left( 1 + \alpha_T T \right) E_0 \quad (4)
\]