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A stochastic analysis framework for a steel frame structure using wireless sensor system measurements

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ABSTRACT

This paper presents a stochastic analysis framework for estimating the system-level first-passage probability of the structural responses of multi-degree-of-freedom structural systems based on experimentally measured uncertainties. The uncertainties are quantified by comparing the measured structural responses using a wireless sensor system and the predicted responses from an analytical model. The wireless sensor network is designed based on a modular design method, and the experimental program details for the measurement of structural responses are provided using the developed wireless sensor network. This framework employs a Monte Carlo simulation (MCS)-based first-passage probability estimation technique in which a structural dynamic analysis is performed in each simulation realization. The framework is applied to a 16-story steel frame structure, and the first-passage probability of 16 locations and the series system passage probability of the entire system have been estimated. The effect of the dependency between the structural responses is considered, and the improvements that need to be made to the presented framework in the future works are discussed.

1. Introduction

Structural systems should be designed to withstand natural and manmade hazards within allowable structural responses. These structural responses are often estimated using dynamic analyses with given hazard inputs. For realistic estimation of the response, the uncertainties due to the imperfectness of structural models need to be considered carefully, and accordingly, the responses should be represented in a probabilistic way. These uncertainties include inherent uncertainties in the random hazard inputs, modeling uncertainties in approximated design equations and model parameters, and statistical errors in a finite number of model evaluations. These uncertainties are considered in the stochastic dynamic analyses of structural systems, and the outputs are estimated in terms of the structural reliability, which is often expressed as the probability of exceedance in terms of the structural responses. This estimated structural reliability is of use to support decision making in structural design and control. However, stochastic structural dynamic analyses considering these uncertainties are statistically and computationally complex because of the sufficiently large amount of observation data required for the measurement of uncertainties, time-variant nature of structural responses, nonlinearities in the geometry and material properties of structural members, correlation between structural components, and time-consuming repeated evaluation of structural simulations. Furthermore, theoretical difficulties are faced in stochastic dynamic analyses, such as the complex

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calculation of the joint density functions between stochastic processes, unrealistic assumptions regarding the distribution of the stochastic process, and nonlinearity of a stochastic process. To overcome these challenges and to improve the computational accuracy and efficiency of the reliability analyses, there has been considerable research on such stochastic dynamic analysis to estimate the probability of first excursion, using various methodological attempts including analytical methods under special assumptions, crossing rate evaluation methods, Kolmogorov equation based methods, and advanced simulation based methods [1–5]. However, despite these theoretical developments, there are still limited research works on the integration of these stochastic structural analysis framework and the quantification of the uncertainties using real sensor measurements.

In addition, there are further challenges in structural response monitoring of a large structure. One important element for inspection system is the transmission of the measurement data from the sensors to the processing terminal; conventionally and most popularly, wired networks are used for this task. However, with a great number of sensors for a large structure, a huge amount of wires is needed. As a result, installation time and costs can be very high, and this may also affect the reliability of the data transmission. Moreover, there may be cases in which wires cannot be placed in certain locations of a structure. Fortunately, with the development of technologies in sensing, wireless communication, and Micro electro mechanical systems (MEMS), wireless sensor network (WSN) technique has been developed rapidly, and is being used gradually in structural health monitoring for civil engineering structures in an attempt to install quickly, inspect conveniently and lower the high capital costs associated with wire-based structural monitoring systems [6–8].

In this context, in this paper, a simple Monte Carlo simulation (MCS) based stochastic analysis framework for calculating a first-passage probability based on the observed responses is presented. This framework proposes to quantify the uncertainties in dynamic analysis through the comparison with the measurements by using wireless sensor network. The design details of the wireless sensor network are also proposed in the framework. This simulation-based method provides a robust way to handle the nonlinearity and various types of distributions of a stochastic process. In this study, a 16-story frame structure example is considered to demonstrate the framework. The uncertainties of the computational model of the structure are measured as the differences between the computational analysis results and the sensor observations of the structural responses. A system-level reliability analysis with correlated joint passage failure modes is performed using a simulation-based method for simple implementation, and the effect of considering correlation is briefly discussed.

2. Theoretical analysis

2.1. First passage problem using simulation method

This study aims to estimate the reliability of a frame structure based on the evaluation of the first passage probability, defined as the probability of first passage into the failure domain where the failure domain is defined by the given threshold value of the structural responses. In this section, the process for evaluating the first-passage probability based on a crude MCS is reviewed.

Let $X(t)$ be a random process. The calculation of the first passage probability is started from the evaluation of the mean upcrossing rate. Let $M(T) = \max\{X(t);\ 0 \leqslant t \leqslant T\}$ denote an extreme value of the response process $X(t)$ over the time interval of length T. The distribution of $M(T)$ under the Poisson assumption is given in terms of the averaged mean upcrossing rate by the following relation [9,10]:

$$F_{M(T)}(\xi) = prob(M(T) \leqslant \xi) = 1 - \exp\{-\bar{\nu}^{+}(\xi)T\} \tag{1}$$

where ξ = threshold value for $X(t)$ and $\bar{\nu}^{+}(\xi)$ is the averaged mean upcrossing rate defined by

$$\bar{\nu}^{+}(\xi) = \frac{1}{T}\int_0^T \nu^{+}(\xi;t)dt \tag{2}$$

where $\nu^{+}(\xi;t)$ = mean upcrossing rate of $X(t)$ at time t. In most nonlinear systems, analytical or numerical solutions for calculating $\nu^{+}(\xi;t)$ are not available, and therefore, empirical time series need to be used. By generating k time histories of $X(t)$ within time length T, the empirical estimation of the averaged mean upcrossing rate is calculated to be

$$\hat{\bar{\nu}}^{+}(\xi) = \frac{1}{kT}\sum_{j=1}^{k} n_j^{+}(\xi;0,T) \tag{3}$$

where $n_j^{+}(\xi;0,T)$ = counted number of upcrossings of level ξ for time history number j. This empirical averaged mean upcrossing rate can replace the analytical or numerical solution of Eq. (2) when a sufficient number of simulations are conducted. By using this statistical estimator of the averaged mean crossing rate, we can avoid the derivation of analytical solutions for the mean upcrossing rate of the stochastic process for nonlinear systems.

2.2. A target steel frame structure and dynamic analysis results

As an application for the first-passage probability estimation procedure presented in the previous section, we consider a structural model; the 16-story steel frame structure shown in Fig. 1. This structural model represents a transverse section of atypical steel building at 1:8 geometrical scale ratio. The structure measures 2.25 m × 1.05 m in plane and 8 m in height as shown in Fig. 1. The cross-section types of the column, girder and brace of the structure are 50 mm × 50 mm × 4 mm, 160 mm × 4 mm × 30 mm × 5 mm and 2L25 mm × 3 mm (with/without braces located within the middle span on each story, including 122 beams and 68 nodes), respectively. Approximately 300 kg of mass is added to each story of the structure. Joint-bolt connections are assumed to be rigid connections. A 36 steel material is chosen as the structural member's main materials. Payload concrete slab's compressive strength is chosen to be 20.7 MPa; however, this will not affect the dynamic analysis results of the structure.