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Probabilistic simulation of tornado-like loading on a low-rise building based on laboratory testing

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SUMMARY
Tornadoes can cause severe damage to buildings, but it is difficult to measure tornado loading on structures due to limitation of equipment. To enable investigations of tornado effects on buildings, this paper presents a method that can be used to numerically simulate nonstationary, non-Gaussian tornado-like loading based on laboratory testing. An illustrative application shows that the proposed method can successfully simulate tornado-like loading that is statistically similar to the loading measured in experiments.

Keywords: Nonstationary non-Gaussian tornado-like loading, spectral representation, translation theory

1. INTRODUCTION

Previous investigations show that tornado loading on low-rise buildings can be much larger than the loading prescribed by design codes (e.g.,Haan Jr et al., 2010) for boundary-layer type winds. This is believed to be a major reason why low-rise buildings continue to fail or suffer extensive damages in tornado events. The quantification of structural response to tornado loading, however, remains a challenge because the loading is nonstationary and non-Gaussian. This paper presents a method that incorporates the spectral representation method and the translation theory for stochastic processes (Grigoriu, 1998) to numerically simulate tornado-like loading on a low-rise building. To illustrate the application of this method, the loading on a low-rise building is simulated based on a subset of the data from testing of a model of the building in a tornado simulator, and the simulated loading is compared with the loading estimated based on the full data set from the experiments.

2. METHODOLOGY

2.1. Experimental Testing of a Low-Rise Building Model

The subject of the study is a 1:100 model of a low-rise building that is 13.8 m, 9.3 m, 3.9 m, and 4 m, respectively, in length, width, eve height, and roof ridge height. The model is tested in a two-celled vortex with a swirl ratio of S=0.83, a core radius of r_c=0.46 m, and a maximum mean tangential velocity of $\bar{V}_{\theta,\max} = 11.46\ \text{m/s}$ that is generated by the tornado simulator at Texas Tech University. In the tests, the model was translated through the center of the vortex at a speed of 0.75 m/s, and the pressures at 204 taps on the model were measured by a Scanivalve system at a frequency of 625 Hz. In the following, the pressure at each tap is represented by a pressure coefficient C_P defined as $(P - P_{ref}) / (0.5\rho\overline{V}_{\theta,\max}^2)$, where P is the pressure, P_{ref} is the reference pressure, taken as the static pressure beneath the simulator floor, and ρ is the density of air.

Because the loading on the translating model is non-stationary, the test was repeated 1700 times. To provide targets for the numerical simulation, 100 of the 1700 records were used to extract the statistic characteristics of the loading. For these 100 records, the time varying mean pressure coefficients were estimated using ensemble averaging the 100 measurements at every time instant and adaptive Gaussian kernel regression (Shimazaki & Shinomoto, 2010) of the resultant ensemble averages. The fluctuating components were obtained by removing the mean components from the pressures and were used to estimate the evolutionary power spectral density functions (EPSD) and cross-evolutionary power spectral density functions (X-EPSD) of the pressure coefficients using a wavelet-based method (Spanos & Failla, 2004). In addition, ensemble averaging and adaptive Gaussian kernel regression were used to estimate the skewness and kurtosis of the coefficients. Figure 1 a) and b) show the skewness and kurtosis of the pressure coefficient at an example tap which located at middle edge of roof, and Figure 1 c) and d) show the EPSD of the pressure coefficient at this tap and the magnitude of the X-EPSD of the pressure at this tap and the pressure at another tap at center of roof. It is seen that the pressures can be highly non-Gaussian in addition to being non-stationary.

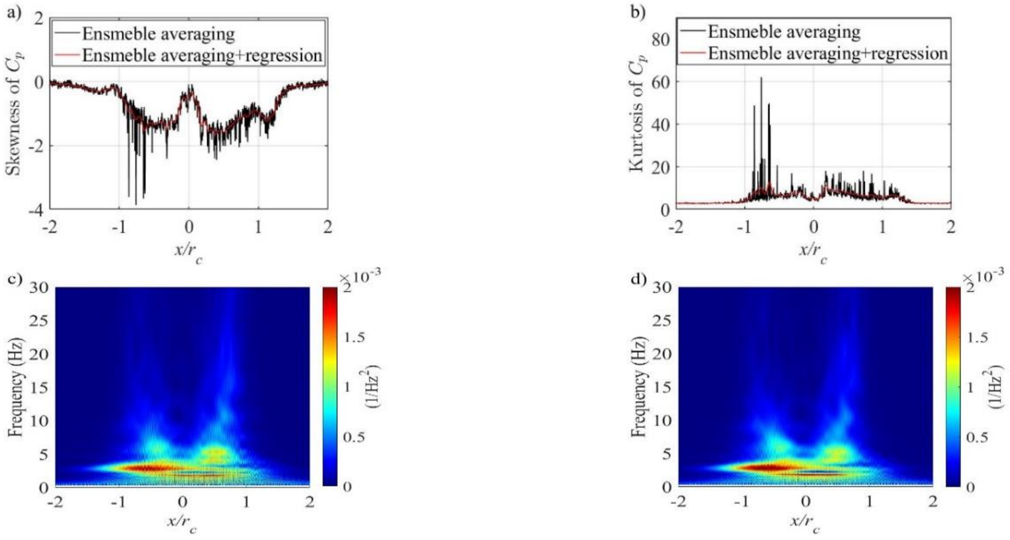

Figure 1. a) and b) skewness and kurtosis of the pressure at a tap, c) EPSD of the pressure at the tap, and d) magnitude of the X-EPSD of the pressure at two taps.

2.2. Numerical Simulation of Non-stationary, Non-Gaussian Loading

The proposed method for simulating nonstationary non-Gaussian tornado-like loading incorporates the spectral representation method and the translation theories for random processes. Based on the Wiener-Khintchine theorem, the Pseudo autocorrelation function of the j^{th} process, $R_{N,jj}^P(t,\tau)$, of a nonstationary non-Gaussian process can be estimated based on the EPSD of the process, $S_{N,jj}(\omega,t)$ (Shields & Deodatis, 2013):

$$R^P_{N,jj}(t,\tau) = \int_{-\infty}^{\infty} S_{N,jj}(\omega,t) e^{i\omega\tau} d\omega; \quad j,k = 1,\ldots,m \tag{1}$$

Here t is time; τ is time lag, and m is the number of processes. Similarly, the pseudo cross-correlation functions, $R^P_{N,jk}(t,\tau)$, of processes j and k can be estimated based on the X-EPSD $S_{N,jk}(\omega,t)$. The pseudo auto- and cross- correlation functions can be normalized to yield the pseudo auto- and cross- correlation coefficient functions:

$$\rho^P_{N,jk}(t,\tau) = R^P_{N,jk}(t,\tau) / [\sigma_j(t)\sigma_k(t)]; \quad j,k = 1,\ldots,m \tag{2}$$

where $\sigma_j(t)$ and $\sigma_k(t)$ are the standard deviations of processes j and k at time t.

Based on the translation theory, the pseudo auto- and cross- correlation coefficients of the underlying Gaussian processes for the non-Gaussian processes, $\rho^P_{G,ij}(t,\tau)$, can be determined based on the relationship expressed as

$$\rho^P_{N,jk}(t,\tau) = h_j(t)h_k(t)(\rho^P_{G,jk}(t,\tau) + 2c_j(t)c_k(t)[\rho^P_{G,jk}(t,\tau)]^2 + 6d_j(t)d_k(t)[\rho^P_{G,jk}(t,\tau)]^3; \quad j,k = 1,\ldots,m \tag{3}$$

where *h*, *c*, and *d* are Hermite coefficients, which are provided by (Zhang et al., 2019).

$\rho^P_{G,jk}(t,\tau)$ can be used to determine $R^P_{G,jk}(t,\tau)$, the auto- and cross- correlation functions of the underlying Gaussian processes, which can be used to determine the EPSD and X-EPSD of the underlying Gaussian processes according to the Wiener-Khintchine theorem:

$$S_{G,jk}(\omega,t) = \int_{-\infty}^{\infty} R^P_{G,jk}(t,\tau) e^{-i\omega\tau} d\omega / (2\pi); \quad j,k = 1,\ldots,m \tag{4}$$

Realizations of the underlying Gaussian processes can be simulated based on the EPSD and X-EPSD using the spectral representation method (Shinozuka & Jan, 1972). The results of the simulation can be transformed to realizations of the target non-Gaussian processes based on the first four statistical moments of the process through Hermite transform (Yang & Gurley, 2015).

3. ILLUSTRATIVE APPLICATION

The methodology presented above is used to simulate 2000 realizations of the non-stationary, non-Gaussian pressure coefficients at the taps on the building model based on the first four statistical moments and the EPSD and X-EPSD of the pressures estimated based on 100 experimental test runs. Figure 2 a) and b) show the cross-covariance function of the pressures at two taps estimated based on the numerically simulated samples and that estimated based on measurements from the 1700 repeat test runs. The estimates based on the numerical simulation and experimental measurements are close. Figure 2 (c) and (d) show the skewness and kurtosis of the pressure estimated based on the simulated and measured records. The results of the numerical simulation again closely match those from the measurements.

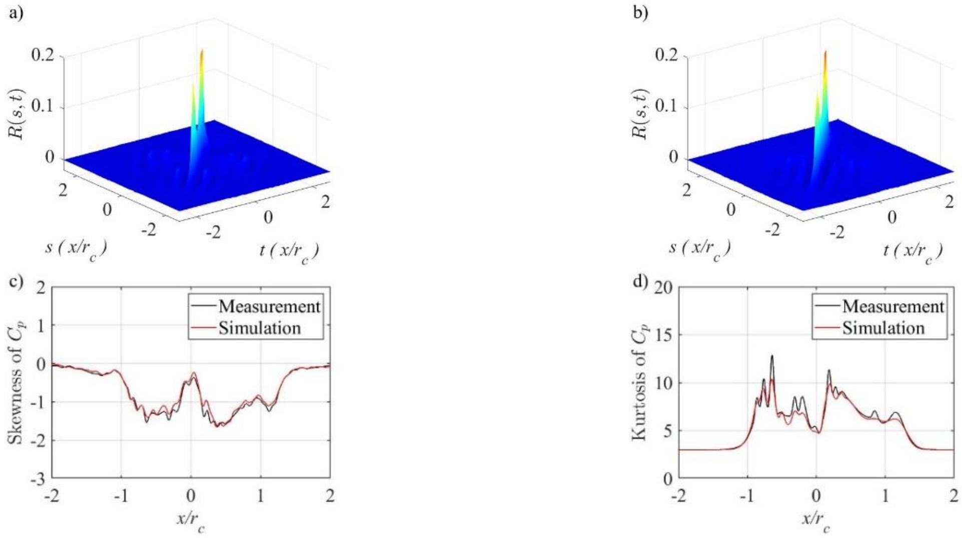

Figure 2. Cross-covariance function of pressures at two taps estimated based on a) numerically simulated records and b) experimental measurements and the c) skewness and d) kurtosis of the pressure at a tap based on numerically simulated records and experimental measurements.

4. CONCLUSION

This paper presents a method that incorporates the spectral representation method and the translation theory for simulating realizations of nonstationary, non-Gaussian tornado-like loading on low-rise buildings. The method is used to simulate the pressures on a building model based on the statistics of the pressures measured in testing of the building model in a tornado-like vortex. A comparison between results of the numerical simulation and the measurement in the experiments suggests that the method is effective in producing realizations of the pressures.

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