Description and Simulation of Gust Front Wind Field

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ABSTRACT: An efficient model for simulating gust front wind field is proposed based on the time-frequency description of the wind field. Traditionally, transient or non-stationary random processes are simulated to account for amplitude modulations invoking envelop processes to shape these modulations. In this study, a time-frequency based scheme is introduced to account for both modulations in amplitude and frequency. This scheme involves stationary wavelet and Hilbert transforms in tandem and relies on the property that the discrete wavelet decomposition of a non-stationary process can be treated as mono-component processes that permit their Hilbert transform in terms of instantaneous amplitude and frequency. The instantaneous frequency at each frequency band is modeled as a Gaussian process. Example simulations based on the measured array of data during a thunderstorm downdraft outflow experiment in Texas are presented. The results demonstrate that simulated time histories exhibit time-frequency characteristics that are consistent with the measured sample time histories. These time histories are critical for structural response analysis under these rare extreme events due to limited available data.

KEYWORDS: Downburst winds, non-stationary processes, simulation, instantaneous frequency

1 INTRODUCTION

The built environment experiences forces of nature generated by a host of damaging atmospheric events such as gust fronts induced by downdrafts associated with thunderstorms. An accurate prediction of load effects that result from the interaction of structures with these extreme events is a critical part of designing and constructing the built environment and protecting its occupants. Accordingly, in recognition of the impact of gust fronts on the built environment, recent research efforts are focusing on modeling and simulating these events based on measured sample time histories. However, the non-stationarity of the wind field associated with these extreme events poses serious challenges in their modeling and simulation. Most of the studies have addressed modeling of these features as non-stationary with time varying mean or in some cases time varying variance. In [1], initial developments of a time-frequency modeling and simulation framework have been presented which captures the essence of non-stationary features that cannot be characterized in either time or frequency domain individually. It neither relies on customary assumption of piecewise stationarity, nor assumes modulation functions that typically account for only amplitude modulations. Such a framework holds the promise of detecting non-stationary features that are randomly embedded in downburst winds and makes it possible to explore the involved localized pattern and help us understand the underlying phenomena. This paper presents description and modeling of gust front/downburst winds and offers effective simulation tool for generating time histories that are consistent with time-frequency characteristics of the measured records.

2 TIME-FREQUENCY REPRESENTATION

This study utilizes stationary wavelet transform (SWT) in the modeling and simulation of downburst/gust front wind field. SWT permits decomposition of an arbitrary signal via basis functions through dilation and translation of parent wavelets. This decomposition facilitates the use of Hilbert transform (HT) to extract instantaneous amplitude and frequency at each level of the decomposition. Fig. 1(a) shows the wind time histories measured during a thunderstorm downdraft outflow experiment by the Atmospheric Science Department of Texas Tech University. Fig. 1(d) shows a decomposition of the gust front at 6m height in which top to bottom are detail functions at levels 1-6 and the approximation function, respectively. Obviously, due to the filter bank characteristics of the wavelet transform, the frequency component related to each decomposition level decreases as level increases, and the approximation function represents the time-varying mean of the original signal. The Hilbert spectrum and wavelet scalogram are shown in Figs. 2(a) and (b). Both exhibit high concentration of energy at time interval during the fist 50 sec, 800-1000 sec and 1300-1650 sec at around frequency of 0.03 Hz and between 0.05 and 0.1 Hz. These plots help to characterize the time-frequency description of energy in the gust front winds which are quite different from steady wind conditions noted in extratropical storms. Further analysis of the instantaneous frequency or the phase differences has revealed that at each frequency band of the wavelet based decomposition it follows a normal distribution. This has laid the framework from the simulation of these extreme transient events relying on a single sample function.

3 SIMULATION MODEL

In the characterization and simulation of random processes, due to the difficulty of establishing a mathematical model for the physical phenomena because of its mathematically intractability, approximations and assumptions are introduced. Alternatively, reliance on limited or a single observation is made to simulate stochastically consistent realizations. In recognition of the time-frequency feature extraction of wavelet based decomposition and the Hilbert spectrum of non-stationary processes, in this study, it is assumed that the Hilbert spectrum of the available measurements may be used in lieu of the Hilbert spectrum of the underlying non-stationary process. This assumption facilitates the implementation of the proposed simulation scheme and requires no further assumptions or approximations.

3.1 *Univariate processes*

The analysis of statistical structure of phase angle differences at each frequency band suggested that the underlying non-stationary random process can be represented by introducing a Gaussian random variable in the following expression for simulating a process

$$\hat{X}(t) = \mathrm{Re}[\sum_{j=1}^{N} a_j(t) e^{i\int \hat{\omega}_j(t)dt}] + A_N(t) \tag{1}$$

in which $a_j(t)$ is the instantaneous amplitude, $\hat{\omega}_j(t)$ is independent random phase angle difference normally distributed at each decomposition level j and $A_N(t)$ is the time-dependent mean. A three-step procedure for characterizing and simulating a univariate processes can be summarized as follows: (1) Decompose the sample data into a set of sub-components (detail functions) and the approximation by means of SWT (Fig. 1(d)); (2) apply Hilbert transform at each level to obtain instantaneous amplitude $a_j(t)$ and frequency $\omega_j(t)$; (3) introduce Gaussian random variables to model instantaneous frequency, i.e., $\hat{\omega}_j(t)$ ~$N(\mu_j,\sigma_j^2)$, in Equation (1).

Correspondingly, the simulated non-stationary processes have the following mean, covariance and variance functions

$$\mu_{\hat{X}}(t_m) = \sum_{j=1}^{N} a_j(t_m)\cos(t_m\mu_j)e^{-\frac{m}{2}\Delta t^2\sigma_j^2} + A_N(t_m) \tag{2}$$

$$K_{\hat{X}\hat{X}}(t_m, t_n) = \sum_{j=1}^{N} a_j(t_m)a_j(t_n)\{E[\cos\tilde{\theta}_j(m)\cos\tilde{\theta}_j(n)] - \cos(t_m\mu_j)\cos(t_n\mu_j)e^{-\frac{m+n}{2}\Delta t^2\sigma_j^2}\} \tag{3}$$

$$\sigma_{\hat{X}}^2(t_m) = \sum_{j=1}^{N} a_j^2(t_m)[\frac{1}{2} + \frac{1}{2}\cos(2t_m\mu_j)e^{-2m\Delta t^2\sigma_j^2} - \cos^2(t_m\mu_j)e^{-m\Delta t^2\sigma_j^2}] \tag{4}$$

in which t_m denotes $m\Delta t$. The otherwise elusive statistical characteristics of the underlying non-stationary random process are analytically expressed based on the finding of the statistical property of phase angle differences. Although only one realization is available, the closeness of the histogram of phase angle differences to Gaussian distribution justifies the above expressions.

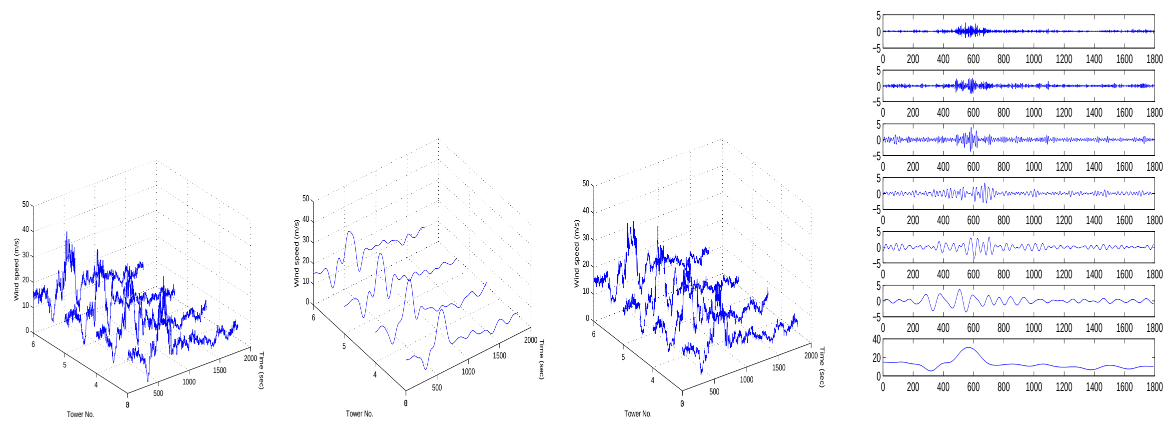
3.2 *Multivariate processes*

The aforementioned simulation procedure can be seamlessly extended to simulate multivariate processes by introducing the proper orthogonal decomposition (POD) of the covariance matrix of instantaneous frequency. For the sample record of the non-stationary vector processes, $\mathbf{X}(t)=[X_1(t), X_2(t), ..., X_M(t)]^T$, the instantaneous frequency vector is formulated in terms of an appropriately selected dominant mode number of eigenvectors of its covariance matrix. This scheme is similar to the concept of stochastic decomposition [2] that decomposes a set of random processes into either fully coherent or noncoherent subprocesses. Accordingly, by introducing random frequency variable, the simulation of the multi-variate random processes can be expressed as:

$$\hat{X}_k(t) = \mathrm{Re}[\sum_{j=1}^{N} a_{j,k}(t)e^{i\int\hat{\omega}_{j,k}(t)dt}] + A_{N,k}(t) \tag{5}$$

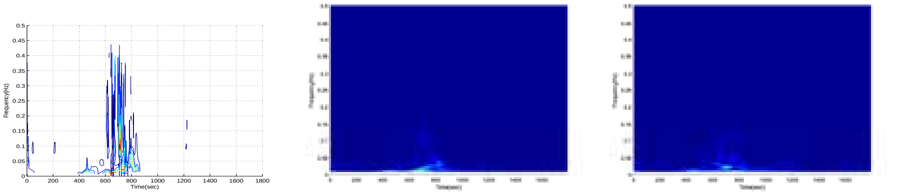
The mean and auto-covariance functions remain the same form as given in Equations. (2)-(4). The cross-covariance function between any two components is given by

$$K_{\hat{X}_p\hat{X}_q}(t_m, t_n) = \sum_{j=1}^{N}\sum_{k=1}^{N} a_{j,p}(t_m)a_{j,q}(t_n)\{E[\cos\tilde{\theta}_{j,p}(m) - \cos(t_m\mu_{j,p})e^{-\frac{m}{2}\Delta t^2\sigma_{j,p}^2}][\cos\tilde{\theta}_{k,q}(n)] - \cos(t_n\mu_{k,q})e^{-\frac{n}{2}\Delta t^2\sigma_{k,q}^2}\} \tag{6}$$



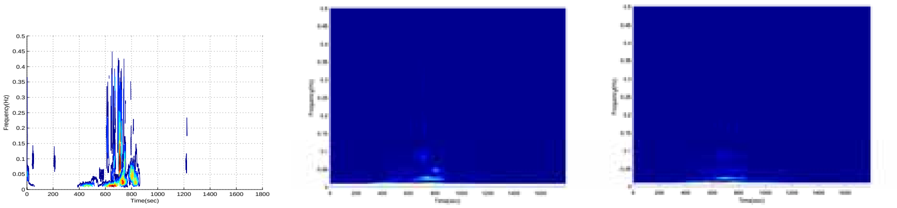
(a) (b) (c) (d)

Figure 1: Downburst wind 263 apart (a) measurement (b) time-dependent mean (c) simulation (d) decomposition



(a) (b) (c)

Figure 2: Time-frequency properties of measurement (a) Hilbert spectrum (b) scalogram (c) cross-scalogram



(a) (b) (c)

Figure 3: Time-frequency properties of simuation (a) Hilbert spectrum (b) scalogram (c) cross-scalogram

4 EXAMPLE

The simulation of a set of gust front data (Fig. 1(a)) is presented in Fig. 1(c). The time-varying mean in Fig. 1(b) presents the rapid velocity change during the passage of the downburst. A comparison between the simulated and measured record shows that the simulation captures the significant features of the measurements. A comparison of their evolutionary energy distribution, i.e., the Hilbert spectra and scalograms shown in Figs. 2(a), (b) and 3(a), (b), demonstrates that the evolutionary features of measurement are faithfully captured in the simulation. The cross-scalogram of the measurements and the simulation shown in Figs. 2(c) and 3(c) show a good agreement suggesting that the simulation satisfactorily preserves the correlation between components. Similar observations are made for other components of the data set.

5 CONCLUSIONS

A time-frequency domain framework to model the evolutionary characteristics of downburst wind field was presented. This scheme invoked SWT and HT in tandem to model the instantaneous frequency as a Gaussian random process. Based on this framework, a new scheme for the simulation of non-stationary gust front wind field was developed. By utilizing POD the uni-variate simulation was extended to multi-variate. Examples of a gust front wind field simulation demonstrated the efficacy of the simulation scheme, which captured the evolutionary characteristics of measured data and maintained the correlation between measured components. Unlike most reported simulation models, this scheme did not invoke an assumption of piecewise stationarity, predetermined modulation functions, or spectral expressions.

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