WIND-INDUCED PEAK BENDING MOMENTS IN LOW-RISE BUILDING FRAMES

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Wind-Induced Peak Bending Moments in Low-Rise Building Frames

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Abstract: We present a procedure for estimating peaks of non-Gaussian processes representing fluctuating internal forces induced by wind in low-rise building frames. The procedure is designed for inclusion in computer programs that use surface pressure databases to obtain peak internal forces in frames. In general, the processes of interest are non-Gaussian, and we apply translation models to estimate the distribution of their peaks. To illustrate the procedure we calibrate a translation model to the record of a 1 h time history of the bending moment at the upwind bent of a low-rise frame.

INTRODUCTION

The purpose of this note is to present a first phase of the development of a procedure for calculating peaks of non-Gaussian processes as applied to wind-induced internal forces in low-rise building frames. The procedure is designed for use in computer programs that calculate internal forces in frames from large aerodynamic databases, that is, from full records of pressures measured at hundreds of taps over the building envelope. (For details of the methodology on which such programs are based, see Whalen et al. 1998). The procedure is needed for the following reason: even though internal forces in frames are obtained by the addition of weighted pressures obtained at a large number of points, which has in the past led to the belief that they have normal marginal distributions, numerous calculations of the type reported in Whalen et al. (1998) show that, typically, the distributions are in fact non-Gaussian. An example is shown in Fig. 1. It represents, in arbitrary nondimensional units, a 1 h time history of the bending moment at the upwind bent of the two-hinge, center bay frame of a building in open terrain, 11 m high, 27.5 m wide, 45 m long, with a 5° pitched roof, and was obtained at the Ruhr-University Bochum wind tunnel (Kasperski et al. 1966).

A procedure suitable for the purpose just described should have the following attributes: (1) The procedure should use the entire time history of the process of interest. This improves the stability of the peak value estimates; (2) the procedure should be capable of yielding sampling-error estimates. This is essential because a large aerodynamic database covering hundreds of building types and geometries must consist of relatively short records (say, records corresponding to one hour in the prototype of perhaps even less). The ensuing sampling errors in the estimation of the peaks must be added to errors from other sources in a reliability-based specification of the wind loads. A study of sampling errors in such a reliability context would indicate to what extent the duration of the records may be reduced without affecting significantly the overall uncertainty in the estimation of the wind loads; (3) the procedure should be transparent, and its input should be easily modifiable by standards committees as additional information becomes available.

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In this paper we describe the theory underlying our procedure, apply it to the analysis of the record of Fig. 1, and discuss future research.

THEORY

Consider a stationary stochastic process $X(t)$ and let $\nu(x)$ be the average number of crossing with positive slope of level x of $X(t)$ during the unit time, or the mean x-upcrossing rate. If x is large, the x-upcrossing of $X(t)$ follows a homogeneous Poisson process with intensity $\nu(x)$. Hence, the probability that the maximum value of $X(t)$ within the time interval τ, X_τ, does not exceed x is

$$P(X_\tau \le x) \cong \exp[-\nu(x)\tau] \tag{1}$$

If $X(t)$ is a stationary Gaussian process with mean μ, standard deviation σ_x, and standard deviation of $\dot{X} = dX/dt$, $\dot{\sigma}_x$, then the mean x-upcrossing rate of $X(t)$ is

$$\nu(x) = \frac{1}{2\pi}\frac{\dot{\sigma}_x}{\sigma_x}\exp\left\{-\frac{1}{2}\left[\frac{x-\mu}{\sigma_x}\right]^2\right\} \tag{2}$$

If $X(t)$ is a non-Gaussian translation process (Grigoriu 1995) defined by

$$X = F^{-1}[\Phi(Y)] = g(Y) \tag{3}$$

where F = distribution of X and F = distribution of the normalized Gaussian process $Y(t)$, then the mean x-upcrossing of X is

$$\nu(x) = \frac{1}{2\pi}\dot{\sigma}_y\exp\left\{-\frac{1}{2}[g^{-1}(X)]^2\right\} \tag{4}$$

The probability of (1) can be used with $\nu(x)$ given by (2) and (4), respectively, to calculate the expectation of the peak dur-

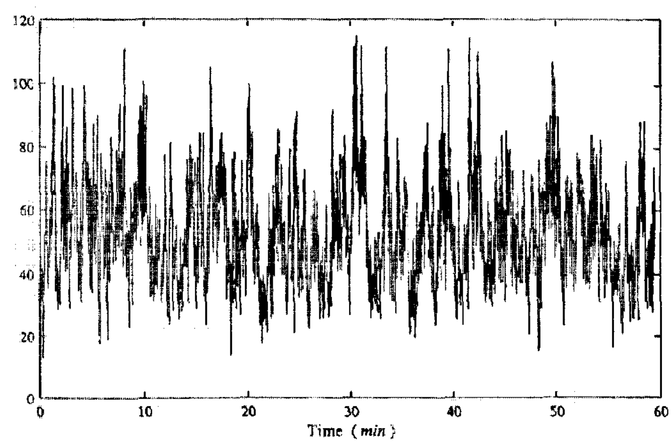

FIG. 1. Time History of Bending Moments (in Arbitrary Units) at Knee of Portal Frame

ing a time interval τ for both Gaussian and non-Gaussian models. If $X(t)$ is a translation model, the expectation and the variance of the peak X_τ are

$$E[X_\tau] = \int_0^\infty x\, dP(X_\tau \le x)$$

$$\cong \int_0^\infty x\tau g^{-1}(x) \frac{f(x)}{\phi\{g^{-1}(x)\}} \nu(x)\exp[-\nu(x)\tau]\, dx$$

$$\cong \int_0^\infty (x - E[X_\tau])^2 \tau g^{-1}(x) \frac{f(x)}{\phi\{g^{-1}(x)\}} \nu(x)\exp[-\nu(x)\tau]\, dx \quad (5a\text{–}c)$$

where $f(x)$ and $\phi\{g^{-1}(x)\}$ are the density functions of $X(t)$ and $Y(t)$, respectively.

ANALYSIS AND RESULTS

We proceed to fitting a non-Gaussian probability distribution to the time series of Fig. 1. First we estimate the first three moments of the time series. They are mean $\mu = 53.1158$, standard deviation $\sigma_x = 15.0458$, coefficient of skewness $\gamma_3 = 0.5663$, and coefficient of kurtosis $\gamma_4 = 3.317$. The histogram of the time series is shown in Fig. 2, which also shows the Gaussian probability density function (pdf) with this mean and standard deviation, as well as the gamma distribution

$$f(x) = \frac{x^{\alpha-1}\exp[-(x - \mu)/\beta]}{\beta^\alpha \Gamma(\alpha)}, \quad x - \mu > 0, \alpha > 0, \beta > 0 \quad (6)$$

with parameters $a = 12.4714$ and $b = 4.2605$ estimated by the method of moments. The fit of the gamma distribution to the data is judged by inspection to be satisfactory (Fig. 2). Fig. 3 shows, in addition to the Gaussian and gamma models of the time series, the corresponding probability density functions of the peak values for $\tau = 10$, 20, 30, 45, and 60 min. Table 1 shows, for $\tau = 20$ min and $\tau = 60$ min, the peaks corresponding to various probabilities of exceedance α. Depending upon the quantile, the values of Table 1 were found to be larger by about 30–50% than the values obtained by assuming the marginal distribution to be Gaussian. Note that in many studies it

TABLE 1. Quantiles $a(a)$ Yielded by Gamma Model

	$a(\alpha)$	
α (1)	$\tau = 20$ min (2)	$\tau = 60$ min (3)
0.500	4.2131	4.7564
0.250	4.6501	5.1736
0.100	5.1295	5.6347
0.050	5.4625	5.9567
0.020	5.8826	6.3645
0.010	6.1904	6.6644
0.001	7.1732	7.6260

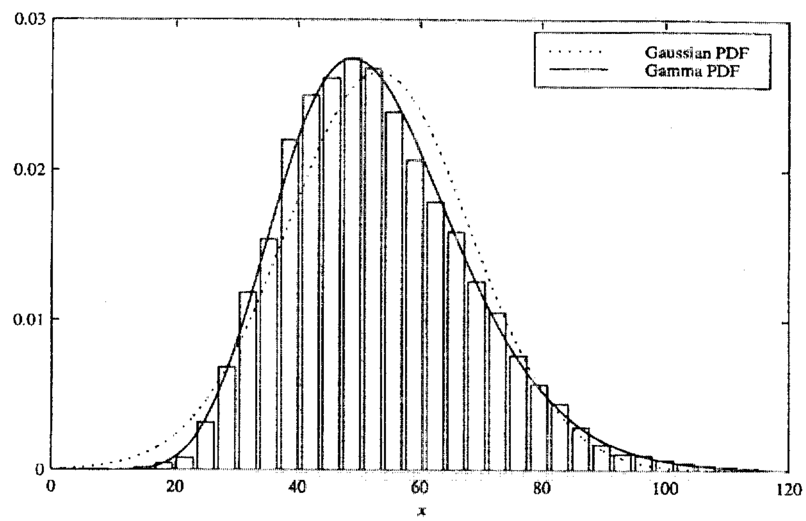

FIG. 2. Marginal Histogram of Bending Moment Data Compared with Gaussian and Gamma Probability Density Functions

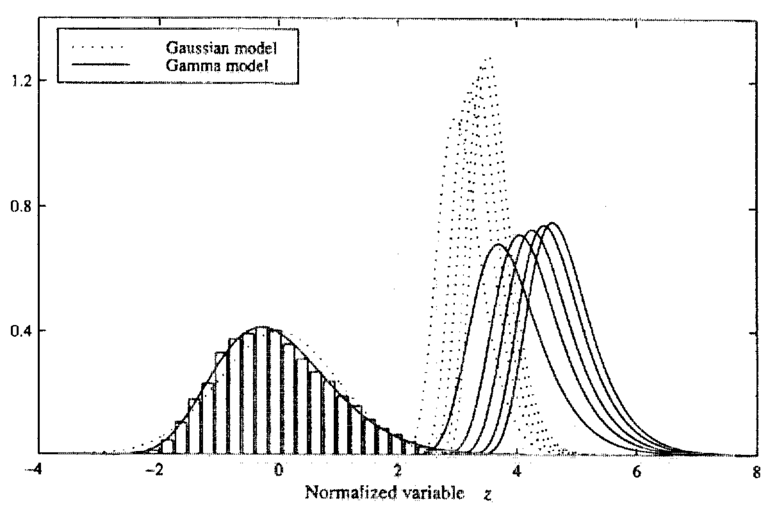

FIG. 3. Density Functions of Parent Distributions and Peak Bending Moment for $\tau = 10$, 20, 30, 45, and 60 min

is common practice to assume the validity of the Type I distribution of the largest values—which has two parameters—rather than that of the gamma distribution or of other three-parameter distributions. We plan to study in the future the extent to which this practice is satisfactory for engineering purposes.

CONCLUSIONS

We have presented the basic principle of a simple and transparent procedure for estimating internal forces in low-rise building frames that is suitable for use in computer programs utilizing large aerodynamic databases. The calculations showed not only that the estimates of peak wind-induced moments in frames based on the assumption of normality would be unsafe, but also that the peak value obtained in a single wind tunnel test can be unsafe. This is seen in Fig. 1, which shows that for $\tau = 60$ min the observed peak is (115-53)/15.05 = 4.12 standard deviations above the mean, whereas the estimated expected value of the peak is 4.76 standard deviations above the mean. We note that our application of the procedure is illustrative and that our choice of the gamma model for the marginal distribution of the bending moment is empirical, i.e., it does not rest on fundamental theoretical considerations. A future phase of our work will address (1) the issue of the optimal choice of marginal distribution, which will be dealt with by using large numbers of recorded realizations of internal forces in frames, and (2) the issue of sampling-errors estimation.

APPENDIX. REFERENCES

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