Dynamic response of structures to thunderstorm winds

John Holmes[1], George Forristall[2], Jason McConochie[3]
[1]Director, JDH Consulting, Mentone, Victoria, Australia, jdholmes@bigpond.net.au*
[2]Consultant, Forristall Ocean Engineering, Camden, Maine, USA
[3]Ocean Engineer, Woodside Energy Ltd., Perth, Western Australia, Australia
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ABSTRACT

This paper discusses a method to evaluate the dynamic response of structures represented by second-order single degree-of-freedom systems, to thunderstorm winds, using, as an example, data recorded from a downdraft recorded at Lubbock, Texas in 2002. The response is expressed in the form of a response factor; that is the ratio of the maximum value of the effective static force, in the time history, to the maximum value of the applied force in the same time history.

KEYWORDS: Downdraft; Dynamic response; Thunderstorm.

INTRODUCTION

Traditional approaches to the dynamic response of structures to strong winds have used frequency domain methods based on spectral analysis and stationary random process theory (e.g. [1], [2]). Such methods have been applied to offshore structures as well as land-based structures (e.g. [3]). These methods are appropriate to large-scale events such as Atlantic gales and hurricanes.

For small scale and transient events, such as downdrafts and squalls generated by thunderstorms, such methods require modification. Choi and Hidayat [4] proposed an approach that separates the loading and response into a non-stationary 'running mean', and a stationary fluctuating component. Conventional random vibration response theory is then applied to the latter component.

The present paper describes a relatively simple deterministic approach that makes use of recorded time histories of wind speeds in thunderstorms to generate 'dynamic response factors' for the design of structures. The approach is similar to that used to generate 'response spectra' in earthquake engineering [5].

An alternative, more complex approach to the dynamic response of tall buildings in thunderstorms was applied by Chen and Letchford [6], using the same data used in the present paper.

THUNDERSTORM WINDS

It is becoming increasingly clear that downdrafts and squalls generated within thunderstorms are the dominant design winds for many locations in the world [7]; such locations include those parts of the tropical and equatorial oceans where tropical cyclones (hurricanes and typhoons) do not occur, and many non-coastal land locations in the lower latitudes between 0 and 30 degrees. Actual recordings of wind speeds in these events have produced gusts exceeding 45 m/s, or 100 mph, on several occasions at a single site (e.g. unpublished recordings by Woodside Mauritania Ltd), and the largest recorded wind speed in a microburst is 65 m/s [8].

THE LUBBOCK DOWNBURST OF JUNE 4 2002

The meteorological aspects of the rear flank downdraft recorded at Reese AFB, near Lubbock, Texas, on June 4 2002, and a description of the instrumentation, are given in [9]. The data revealed a well-

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[*] Corresponding author: Tel.+61-3-9584-5885; fax: .+61-3-9585-3815
Mailing address: P.O. Box 269, Mentone, Victoria, 3194, Australia

correlated gust structure extending horizontally over a span of at least 1.5 kilometres. The maximum wind speed in this event exceeded 41 m/s at 10 metres height.

Figure 1 shows the individual time histories at 10 metres height from Towers 3, 4, 5 and 6; each tower was separated from its neighbour by a distance of 263m. The general similarity of the underlying slow period fluctuations in wind speed at the various towers, are shown in this figure.

DYNAMIC RESPONSE OF A SECOND-ORDER SYSTEM

The use of Duhamel's Integral is a standard technique for calculation of the dynamic response of structures, to transient loadings such as blast loadings, or earthquakes [5]. Since it represents the response to an arbitrary loading as the superposition of the response to many discrete impulses, this technique is limited to linear structures. However, structures with non-linear characteristics (e.g. stiffness and damping) can usually be linearized with sufficient accuracy to make use of this very convenient technique. The technique is ideally suited to calculating the dynamic response of structures to thunderstorms for which time histories of wind speed are available.

The displacement response of any linear system to an arbitrary force input F(t), can be written as :

$$x(t) = \int_0^t h(t-\tau).F(\tau)d\tau \tag{1}$$

h(t-τ) is the unit impulse response function. Equation (1) is a 'convolution integral'.

A second-order, single degree-of-freedom, system has a differential equation of motion that can be written :

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{2}$$

The unit impulse response function depends on the value of the damping ratio, ζ, and the natural circular frequency, ω_o, where ζ = c/2√(mk), and ω_o = √(k/m).

For ζ<1,

$$h(t) = \left(\frac{1}{m.\omega_0\sqrt{1-\varsigma^2}}\right)\exp\left[-\varsigma\omega_0(t)\right].\sin\left[\omega_0\sqrt{1-\varsigma^2}.(t)\right] \tag{3}$$

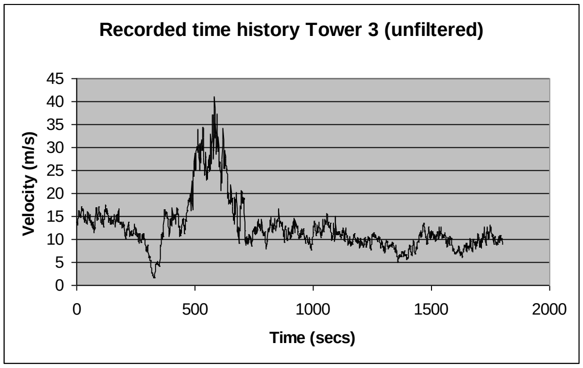
Hence, from Equation (1),

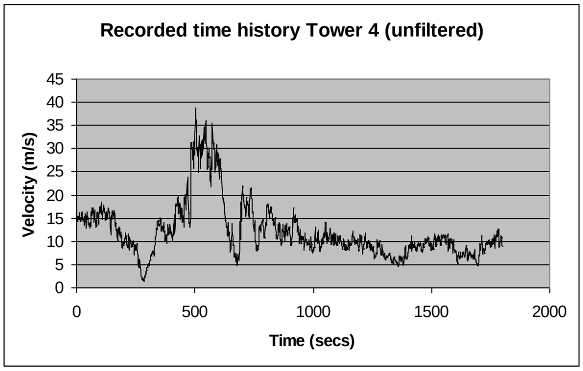
$$x(t) = \left(\frac{1}{m.\omega_0\sqrt{1-\varsigma^2}}\right)\int_0^t \exp\left[-\varsigma\omega_0(t-\tau)\right].\sin\left[\omega_0\sqrt{1-\varsigma^2}.(t-\tau)\right]F(\tau)d\tau \tag{4}$$

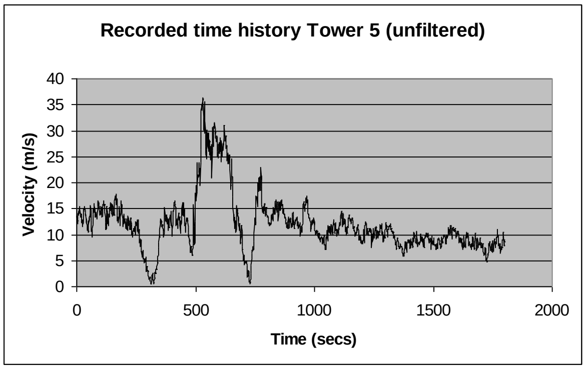
(the right-hand-side of Equation (4) is known as 'Duhamel's Integral' e.g. [5])

The effective static force, $F_{eff}(t)$, is then given by the product of the displacement response x(t), and the stiffness, k:

$$F_{eff}(t) = k.x(t) = \left(\frac{\omega_0}{\sqrt{1-\varsigma^2}}\right)\int_0^t \exp\left[-\varsigma\omega_0(t-\tau)\right].\sin\left[\omega_0\sqrt{1-\varsigma^2}.(t-\tau)\right]F(\tau)d\tau \tag{5}$$







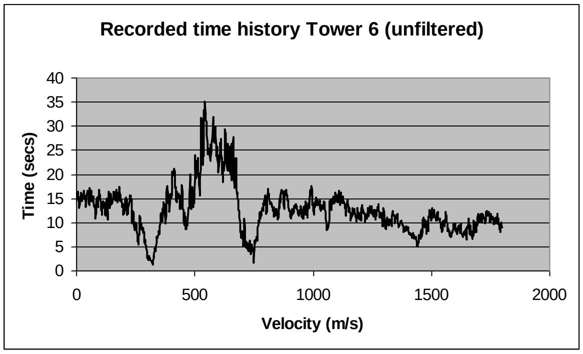


Figure 1. Time history records from Towers 3, 4, 5, and 6 at Reese AFB, Lubbock, TX, June 4 2002 (all at 10 m height; spaced 263 m)

It should be noted that different expressions to Equations (3) to (5) apply when ζ is equal to 1, and greater than 1.

A non-dimensional 'dynamic response factor' can then be obtained as the ratio of the maximum value of the effective static force, $F_{eff}(t)$, in the time history, to the maximum value of the applied force F(t) in the same time history. Note that these maxima will generally not occur at the same time, t.

DYNAMIC RESPONSE TO THE LUBBOCK DOWNBURST

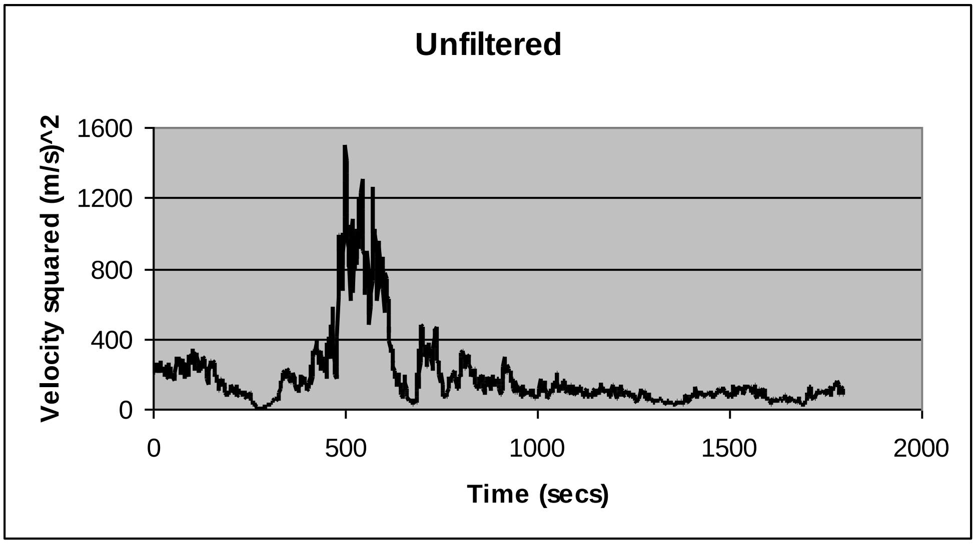
As an example of the application of this technique, numerical calculations of along-wind response were made for structures with various natural periods and damping ratios, using wind speed data obtained from the Lubbock downburst. Note that, because of the relatively large sampling time interval of 1 second for this data, reasonably accurate responses can only be obtained for structures with natural periods ($2\pi/\omega_o$) greater than about 5 seconds.

Figure 2(a) shows the time history of velocity squared from the Lubbock downburst obtained from Tower 4. This is proportional to the along-wind force, F(t), acting on the structure - it is actually equal to $2.F(t)/(\rho_{air}.A)$, where ρ_{air} is the density of air, and A is the projected area of the structure. Figure 2(b) shows the filtered time history $2.F_{eff}(t)/(\rho_{air}.A)$, obtained by applying Equation (5) for the case with the natural circular frequency, ω_o equal to 0.2 rad/sec, and for the damping ratio ζ equal to 0.1. The dynamic response factor can be obtained by taking the ratio of the maximum value from Figure 2(b), to the maximum value from Figure 2(a). For this case, the ratio is less than 1.0, but the dynamic response factor can exceed 1.0 for low damping cases.

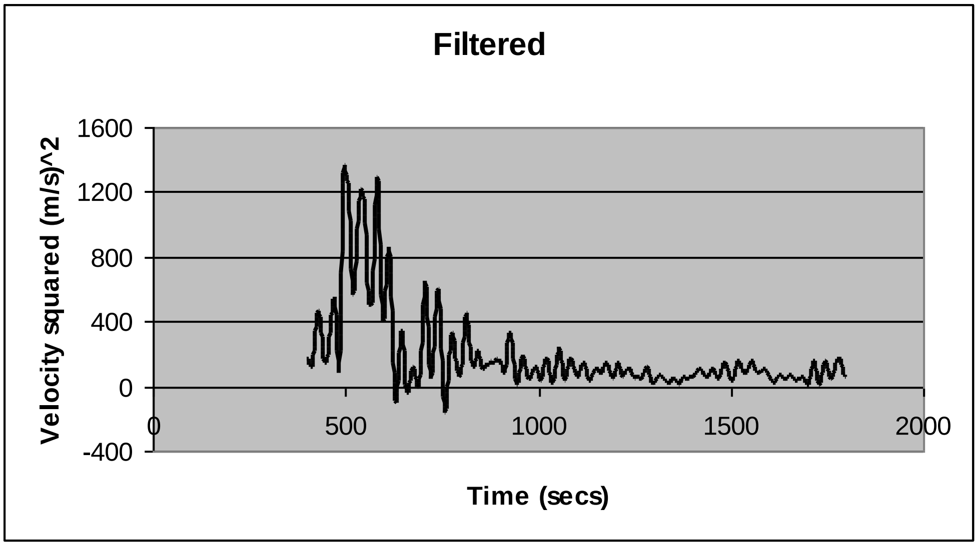
Figure 3 shows calculated dynamic response factors to the Lubbock event, for structures with periods of 6 to 100 seconds (circular frequencies of 0.06 to 1 rad/sec), and damping ratios from 0.1 to 3. These values are characteristic of compliant offshore structures, but not of stiffer structures with periods in the 1 to 5 second range. For the latter, more closely spaced time intervals are required. The information in Figure 3 resembles closely that provided in 'response spectra' for earthquake design. The dynamic response factors can be applied directly to the wind load calculated from a design value of maximum gust wind speed. These factors are also directly compatible with the dynamic response factors used in codes and standards based on peak gust wind speeds (e.g. ASCE-7 [10] and AS/NZS1170.2 [11]).

CONCLUSIONS

- It is clear that thunderstorms produce the dominant extreme winds for the design of structures in many locations, and that alternative techniques to conventional stationary random vibration analysis are required to calculate dynamic structural response to these events.
- Techniques for calculating the transient dynamic response to earthquakes can readily be adapted to calculate the response of structures to downbursts and squalls, and a deterministic method based on this approach has been described in the present paper.
- In future, wind speed data from thunderstorm events should be sampled at closer time intervals, to be useful for calculation of the response of structures with natural periods in the 1-5 second range.



(a)



(b)

Figure 2. Examples of effective time histories, with and without ‘filtering’ for a second-order system structural response (ω_0=0.2 rad/s, ζ=0.1)

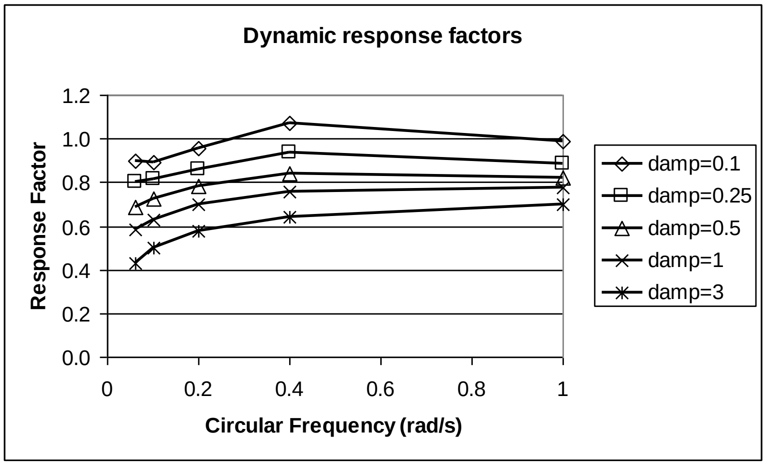


Figure 3. Dynamic response factors for structures of various frequencies and damping

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