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EXPERIMENTAL AND THEORETICAL ESTIMATION OF WIND LOADS

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Abstract

The paper describes & compares the experimental aproach known as "the base balance technique" and the gust factor approachs of estimating the static and dynamic wind loads. The agreement between the experimental data and the theoretical approach is fairly good in the range of wind speeds of practical significance(15 - 50 m/sec).

1. Introduction

The trends towards lighter, more flexible and less damped structures demanded an increasing degree of attention to their behaviour in the wind. The traditional design for static loads was more suitable for the structures built in the first half of this century.

Definition of the elastic response, both static & dynamic, to wind, has been considerably clarified in recent years [1]. The wind induced forces on structures depend upon the oncoming flow and the geometry and mechanical properties of the building. The building Code of some counteries [2,6] outlines a gust factor approach to pridict the along wind response. Analytical methods to solve the flow and induced pressures around bluff bodies are being developed by some investigators. At present only simple shapes and flow conditions have been solved with some success [3,4]. In the absence of analytical methods capable of describing the wind load phenomenon, or of previous experience with similar structure or enviroments the response of building has to be measured experimentally. Two basically different approachs are possible:

i. measuring of response using complete aeroelastic models simulating the stiffness mass and damping charateristics, and
ii. measure of the total dynamic forces with high frequency rigid but light weight models.

The latter method of experiment has been dubbed the "base balance technique", since it involves the use of an ultra-sensitive-multi-component balance on which the building model is mounted. This technique is less elaborate than the full aerollastic test but more specific to the particular geometry than the gust response factor. The construction of the multi-component balance is described by Tschanze in reference [5].

The force spectra measured from high frequency models for a selection of bulding shapes and expcsures are compared with the National building Code of Canada [2] and a other codes [6]. The agreement between the experimental data and the gust factor approach is good.

2. Linear Elastic Response to Dynamic Wind Forces

The linear response of an elastic system can be expressed in the general form:

$$R = \bar{R} + g\,\sigma_R \qquad (1a)$$

where $$\bar{R} = \frac{\bar{F}}{k} \qquad (1b)$$

$$\sigma_R = \frac{1}{k}\sqrt{\int_0^{\infty} S_{GF}(f)\,|H(f)|^2\,df} \qquad (1c)$$

$$|H(f)|^2 = \frac{1}{\left[1 - \left(\frac{f}{f_o}\right)^2\right]^2 - 4\varepsilon^2\left(\frac{f}{f_o}\right)^2} \qquad (1d)$$

where $\bar{R}$ is the mean response, k is the generalized stiffness, ε the modal damping, σ_R the rms respononse and g a dimensionless time varying factor. A particular response is the peak response, $\hat{R}$, in which case the corresponding value of g is roughly 3 to 4 [7].

Also, in equation (1), $\bar{F}$ is the mean generalized force, $S_{GF}(f)$ the power spectrum of the generalized force and $H(f)^2$, the mechanical admittance function which accounts for the dynamic resonant response arising from inertnial effects Figure 1).

The exact evaluation of the integral in equation (1C) presents some difficulties because of the rapidly varying mechanical admittance function, $|H(f)|^2$, in the resonance range for low damping values. Novak [8] presented a solution based on the residua theory. If a high speed computer is available, the integral can be evaluated efficiently to a high accuracy. A good approximation of the response is obtained by evaluating equation (1C) as two components: a quasi-static component σ_B and a resonant component σ_{R_r}. σ_B is evaluated for a value of 1.0 for the mechanical admittance function, $|H(f)|^2$, and σ_{Rr} is evaluated assuming the spectrum to be constant, with a Value of $S_{GF}(f_o)$ for all frequencies.

This results in the well known equations

$$\sigma_B = \frac{\sigma_{GF}}{k}, \qquad \sigma_{R_r} = \sqrt{\frac{\pi}{4}\,\frac{1}{\varepsilon}\,\frac{f_o S_{GF}(f_o)}{k^2}} \tag{2}$$

Using the mean square addition of the components results in :

$$\sigma_R = \frac{\sigma_{GF}}{k}\sqrt{1 + \frac{\pi}{4\varepsilon}\,\frac{f_o S_{GF}(f_o)}{\sigma_{Gf}^2}} \tag{3}$$

This representation has been given in various references ((9) for example) and is the basis of the gust factor approachs . To apply equation 1 to 3 to solve for the response, the aerodynamic in formation reeded concerns (a) the mean force , $\bar{F}$; (b) the rms generalized force, σ_{GF}; (c) the spectrum of the generalized force, $S_{GF}(f_o)$; and (d) the dampings

In the gust response factor approachs , this information is provided for standard shapes using steady aerodynamic coefficients and velocity profiles for the mean forces, as well as estimates of the rms geneeralized force and its spectrum. Damping has generally been estimated.

The generalized forces and its spectra are easily measured using the multi-component balance. This is discussed in the next section

3. Experimental Measurements

The generalized force, its instantanecus value F(t), its mean value $\bar{F}$, its variance σ^2_{GF} and its spectral density $S_{GF}(f)$ are defined from the measured pressures by:

$$F(t) = \int_A P(Z,t)\,\varphi(Z)\,dA \tag{4a}$$

$$\bar{F} = \int_A \overline{P(Z,t)\,\varphi(Z)}\,dZ \tag{4b}$$

$$\sigma^2_{GF} = \iint_{AA} P(z,t)P(z',t)\,\varphi(z)\,\varphi^*(z)\,dA\,dA' - \bar{F}^2 \tag{4c}$$

$$S_{GF}(f) = \iint_{AA} S_p(z,z',f)\,\varphi(z)\,\varphi^*(Z')\,dA\,dA' \tag{4d}$$

in these, $P(z,t)$ and $\varphi(z)$ are the instantaneous pressures and mode shapes at point z respectively. $S_p(z,z',f)$ is the cross-epectrum of pressures at points z and z' at frequency f, and dA and dA' are elementary areas at positions z and z' of the projected area A (figure 2).

For tall buildings the fundamental mode shape is usually close to being a straight line, so $\varphi(Z)$ is proportional to z. This simple fact enables the generalized force in the fundamental mode to be measured directly using a straight forward base moment balance. The additional measurement of the base shear forces permits the magnitude and line of action of the mean forces to be defined. These ideas were basic to the development of a balance measuring components of the force at the base [7].

In applying equation 3, it is more convenient to consider the force spectrum as a function of the reduced velocity $(\bar{V}_T/f\sqrt{BD})$ rather than the frequency f. The frequency, f, and the characteristic area, DB, have a fixed value for a projected building; variable are the design wind speeds at the top of the building $\bar{V}_T$. Then the rms response can be expressed as

$$\delta_R = \frac{\delta_{GF}}{k}\sqrt{1 + \frac{\pi}{4\varepsilon}\,\frac{\frac{\bar{V}_T}{f_o\sqrt{BD}}\,S_{Gf}\left(\frac{\bar{V}_T}{f_o\sqrt{BD}}\right)}{\delta_{GF}^2}} \qquad (5a)$$

This form of representation, the normalized spectral density as a function of the reduced velocity for the top of the building is used in the comparison with the gust response factor approachs .

It is important to estate that the force spectra as presented are only dependent on the turbulent flow and aerodynamic shape of the structure; and independent of the wind velocity or structural parameters such as mass, stiffness, or damping.

Ccmpining equations (1a) and (5) , the peak response is

$$\hat{R} = \bar{R}\left(1+g\frac{\sigma_R}{\bar{R}}\right) = \bar{R}\left\{1 + g\frac{\sigma_{GF}}{\bar{F}}\sqrt{1 + \frac{\pi}{4\varepsilon}\frac{F.S_{GF}(f)}{\sigma_F^2}}\right\} = G.\bar{R} \qquad (5b)$$

4. Ccmparison with the Gust Factor Approachs

The gust factor approachs are design procedures derived on the basis of the random vibration theory by means of a few simplfying assumptions (2,6,9,10). They consider only the response in the first vibration mode which is assumed to be linear. These assumptions are similar to those used to drive the generalized force spectra in the base-balance technique; and they are particularly suitable for buildings. The method yields all the data reeded for design; the maximum response, the equivalent static wind load that would produce the maximum response and the maximum acceleration needed for the evaluation of the phsiological effects of strong winds (human comfort).

The gust factor G is, as defined by Daverport [7] as the ratio of the expected peak displacement (load), $\hat{R}$, in a period T to the mean displacement (load), $\bar{R}$. Hence, maximum expected response

$$\hat{R} = G\,\bar{R} = \left(1 + g\,\frac{\delta_R}{\bar{R}}\right)\bar{R} \qquad (6)$$

Similar approaches have been proposed by others but these can all be reduced to the same form of equation (6).

Some codes (e.g Canadian Code [2]) have adopted this approach and given the gust factor G as

$$G = 1 + g\sqrt{\frac{K\,B'}{C_e}}\sqrt{1 + \frac{S\,F}{B'\varepsilon}} \qquad (7)$$

where g = the peak factor in equation (1a);

K = a factor related to surface roughness : .08 for open country; .10 for suburban; .14 for downtown

C_e = an exposure factor based on the mean wind speed profile;

B' = a background excitation factor ;

S = a size reduction factor ;

F = gust energy spectrum;

ε = the damping ratio;

All parameters appearing in equation (7) can be obtained from Figure (3).

Comparing the form of equations (5b) and (7), the assumed generalized force spectrum distribution of the Building Code of Canada [2] can be calculated as

$$\frac{\dfrac{\bar{V}_T}{f_o\sqrt{BD}}\, S_{GF}\left(\dfrac{\bar{V}_T}{f_o\sqrt{BD}}\right)}{\sigma^2_{GF}} = \frac{4}{\pi}\,\frac{S\,F}{B'} \qquad (8)$$

and

$$\frac{\sigma_{GF}}{\bar{F}} = \sqrt{\frac{K\, B'}{C_e}} \qquad (9)$$

Other codes [6] have also adopted the gust factor approach in which the gust factor is defined as

$$G = 1 + g(2IB'')\sqrt{1 + \frac{\pi}{4\epsilon} S' \left(\frac{\bar{V}_T}{f_o H}\right)^{\ell}} \qquad (10)$$

where g = the peak factor in equations (1a) and (7);

I = intensity of turbulence = 1./ln (H/z_o); z_o is roughness length:

= 3 cm for open country; 30 cm for suburban ; 500 cm for downtown

B" = a back ground response factor (figure 4a);

S' = aspectral energy factor (figure 4b);

ℓ = an exponant equal to 8/3 for B/H > 0.25 and equal to 5/3 or B/H < 0.25

Again comparing equations (5a) & 10, the assumed spectral distribution of the Danish standard [6] can be calculated as :

$$\frac{\dfrac{\bar{V}_T}{f_o\sqrt{BD}}\, S_{GF}\left(\dfrac{\bar{V}_T}{f_o\sqrt{BD}}\right)}{\sigma_{GF}^2} = S'\left(\frac{\bar{V}_T}{f_o H}\right)^{\ell} \qquad (11)$$

amd

$$\frac{\sigma_{GF}}{F} = 2IB'' \qquad (12)$$

Figures 5 to 15 show comparisons of measured values of spectra from high frequency models with both the Canadian Code and and the Danish Standard for a selection of building shapes and exposures. Several points are Note-Worthy: the good agreement in the range of practical wind speeds gives confidence in the gust factor approach and in the experimental method (knom as the base balance technique); the agreement with the more slender models may be less precise, partly due to the fall off in the turbulence intensity in the outer part of the wind tunnel boundary layer which is not accounted for in the gust factor approach. Also, while the mean drag force $C_{\bar{m}}$ decreases slightly with roughness, the rms drag force, $C_{\tilde{m}}$, increases substantially. In all cases the gust factor approachs overestimate the resonance effect $(F\ S(f)/\sigma^2)$

Table 1 shows comparisons between the experimental values of the intensity of terbulence $\sigma_{GF}/\bar{F}$ and the corresponding values from both codes (equation (9) and (12)) for different building shapes. In all cases the codes underestimate the intensity of turbulence and consequently the background turbulence effect.

Conclusions

This paper compares the direct measurements of total dynamic wind forces with the simulated ones from the gust factor approachs . The comparisons show good agreement for realistic wind speeds and hence give confidance in both the base balance tecknique and the gust factor approachs .

Table (1) Comparisons of the experimental value of $\sigma_{GF}/\bar{F}$ with the simulated values from gust factor approaches

H:B:D	experiment	$\tilde{C}_m/\bar{C}_m$ NBC	$\sqrt{KB'/C_e}$ Danish code	2IB"
6:4:1 open country	.153	.149	.146	
6:4:1 suburban	.261	.192	.202	
4:4:1 suburban	.432	.213	.254	
3.75:5.65:1 open sentry	.204	.156	.186	
3.75:5.65:1 suburban	.339	.207	.267	
7:1:1 suburbm, Tallbuilding	.218	.150	.171	
7:1:1 open sentry, Med, Tall	.214	.146	.198	
7:1:1 suburban, med. Tall	.398	.184	.273	
8.1:1.8:1 suburban	.233	.17	.205	
9.21:1.38:1 suburban	.213	.146	.161	
9.21:1.38:1 city exposure	.235	.187	.273	

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