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Probabilistic Criteria for Serviceability Limit of Wind Response

Critères probabilistes pour l'aptitude au service relative au vent

Probabilistische Gebrauchstauglichkeitskriterien für Windschwingungen

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SUMMARY

Probabilistic criteria are proposed for serviceability limit state design for annual maximum wind speed. The variability of human perception limit based on simulated experiments is taken into account. Numerical examples for number of days per year of perception of motions are shown by utilizing wind speed data in Tokyo. Comparisons with an existing guideline in Japan are also made.

RESUME

Des critères probabilistes sont proposés pour l'état limite de l'aptitude au service pour la vitesse maximale, annuelle, du vent. La limite de perception humaine basée sur les expériences simulées est prise en considération. Des exemples numériques pour le nombre de jours par an pour la perception des mouvements sont indiqués en utilisant les données de la vitesse du vent à Tokyo. Des comparaisons avec une directive japonaise sont également effectuées.

ZUSAMMENFASSUNG

Es werden Wahrscheinlichkeitskriterien zur Bemessung auf Gebrauchstauglichkeit für jährliche maximale Windgeschwindigkeiten vorgeschlagen. Dabei werden die Unterschiede der menschlichen Wahrnehmungsgrenzen in simulierten Experimenten berücksichtigt. Numerische Beispiele bezüglich der Anzahl der Tage pro Jahr für die Wahrnehmung von Bewegungen werden unter Verwendung der Windgeschwindigkeitsdaten von Tokio gezeigt. Weiterhin werden Vergleiche zu bestehenden Richtlinien in Japan vorgestellt.

1. INTRODUCTION

Until recently design loads for most of tall buildings in Japan were dominated by the earthquake load rather than by wind load. Although the design criteria for the wind and the earthquake have to be carefully discussed on their relevance and consistency, wind responses of some flexible and/or light tall buildings, now, tend to be predicted in the range of deflection criteria. In such cases human perception of the wind response in fairly frequent storms can easily be anticipated.

Some vibration control devices have been installed in these buildings in order to suppress the wind response. However the serviceability criteria for wind responses are not well established. Several guidelines are available to describe the performance of the wind response, but they have not taken into account the variability of neither individual perception limits nor wind response magnitudes. And it is difficult for engineers to judge what is the appropriate level for the wind response.

Probabilistic criteria for the serviceability limit of wind responses are proposed based on some statistical information for the human perception of horizontal vibration. The meaning of the criteria is examined in various manners including comparisons with conventional criteria given to return period winds. Effects of the variability of wind response on the perception probability are also discussed.

2. SERVICEABILITY LIMIT STATE DESIGN

The magnitude of wind response is a function of the wind speed, which is a random variable. The perceptible level of motion varies considerably from a person to a person. Then a probability-based limit state design becomes necessary to take those variabilities into account. Since the perception of motion is a clear definition in comparison with the discomfort or the annoyance, it can be regarded as a representative serviceability limit for the wind response. Then a typical schematic flow of serviceability limit state design for wind-induced vibration is shown in Fig. 1.[1)]

Once a construction site is given, the probability distributiion of annual maximum wind speed is estimated from statistical meterological data. The magnitude of wind response can be calculated in several ways for buildings with known dynamic characteristics. For human perception problems the acrosswind response has to be estimated as its peak acceleration usually dominates that of the alongwind response. The estimation is made either by empirical formlae or by wind tunnel experiments.

The perception limit for horizontal sinusoidal motions, P, may be modeled by a log-normal distribution with the mean μ_p and the coefficient of variation (c.o.v.) which is assumend as 0.4 based on simulation experimants [2)], where μ_p in terms of the acceleration amplitude (m/s^2) is approximately expressed as follows,

$$\mu_p = 0.0148\, f_0^{-0.6} \qquad (1)$$

where f_0 is the frequency (Hz) of motion. Eq.(1) was obtained in a frequency range between 0.3 Hz and 2Hz.

Then the probability of perception of motion, P_p, can be estimated. When the target reliability index β_T is given, the design format becomes,

$$P_p = \text{Prob}\,[\,A > P\,] \leq \Phi(-\beta_T) \qquad (2)$$

where A is the annual maximum response predicted in terms of the acceleration, and $\Phi(\cdot)$ is the standard normal cumulative distribution. Since the wind response is a random vibration, A must be a value equivalent to the amplitude of simusoidal motion to be compared with a ramdom variable P based on experiments. Tentatively $A=2\sigma_a$ is proposed[1), where σ_a is the standard deviation of random acceleration response.

When the probability distribution of A is also modeled by the log-normal, the reliability index β for non-perception, i.e., A<P, is obtained by a simple formula as,

$$\beta = \frac{\lambda_P - \lambda_A}{\sqrt{\varsigma^2_P + \varsigma^2_A}} \qquad (3)$$

where $\lambda = \ln \mu - 1/2\,\zeta^2$(mean of logarithm)

$\zeta^2 = \ln \{ 1 + (\sigma/\mu)^2 \}$ (variance of logarithm).

According to eq.(2) for design formula, β of eq.(3) is compared with β_T as showm in Fig.1, and $\beta \geq \beta_T$ concludes the procedure, while $\beta < \beta_T$ requires some changes in design parameters as indicated in the flow.

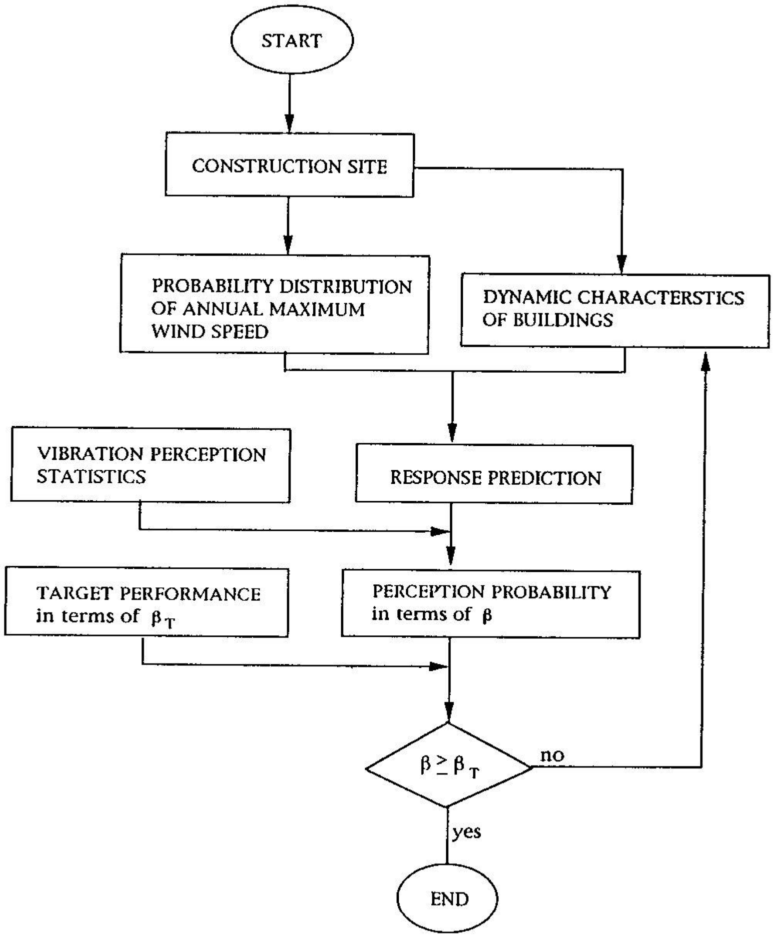

Fig.1. Schematic flow of serviceability limit state design for wind response

3. PROBABILISTIC CRITERIA FOR WIND RESPONSE

It is not so simple to judge which β is the most appropirate. Generally people do not expect that buildings vibrate in strong winds but they may accept if the perception of motion is not very frequent. Social and economical view points also have to be considered. Possible human reactions for β values may be described in Table 1.

Descriptions of human reactions are still only relative measures of performance. Nevertheless the β value provides objective wind response performance reflecting human perceptibility of motion. In order to discuss the appropriateness of β level, we need social experiments to examine feed-back opinions from occupants who are given information of design β. The annual probability of perception of motons is somehow general but rather abstract concept and can be explained more specifically in terms of number of days for peception of motions. Numerical examples are demonstrated for buildings in Tokyo area with different β values.

Wind data obtained at the Tokyo meteorological station during 10 years between 1979 and 1988 are utilized. The wind response in terms of equivalent acceleration amplitude , A, is assumed to be expressed as a function of U as,

$$A = \gamma\, U^{3.3} \tag{4}$$

When β is specified, γ is obtained for a frequency, f_0, in eq.(1) according to the serviceability limit state design described in the previous section with the coefficient of variation for both A and P as 0.4. According to the probability distribution model of P, wind reponse level A, at which 10%, 30% and 50% of occupants perceive the motions of frequency f_0, is calculated. From this A value for f_0, the corresponding wind speed U can be obtained by eq.(4) with γ representing β levels. Then the number of days when 10%, 30% and 50% of occupants perceive the motion can be counted for each year. This number is obtained as constant with the frequency f_0. Results are shown in Fig.2 for β=-1.0, 0.0 and 1.0.

Relatively frequent vibration perceptions are observed before 1982 in the figure. In 1984, vibration causing the perception to 30% occupants or more almost did not occur even for buildings designed with β=-1.0.

The average tendency is shown in Fig.3, where the average number of days of perception for 10 years are shown with β as the abscissa. In this example, the variability of the response calculation is neglected. In buildings with β=-0.5, 30% occupants or more perceive wind responses in 4 days per year and in buildings with β=0.5, they perceive

Table 1. β categories for wind response

β value	human reactions
less than 0	complaints will occur
0 - 1	complaints may occur
1 - 2	perceptible but no complaints
greater than 2	not perceptible in majority

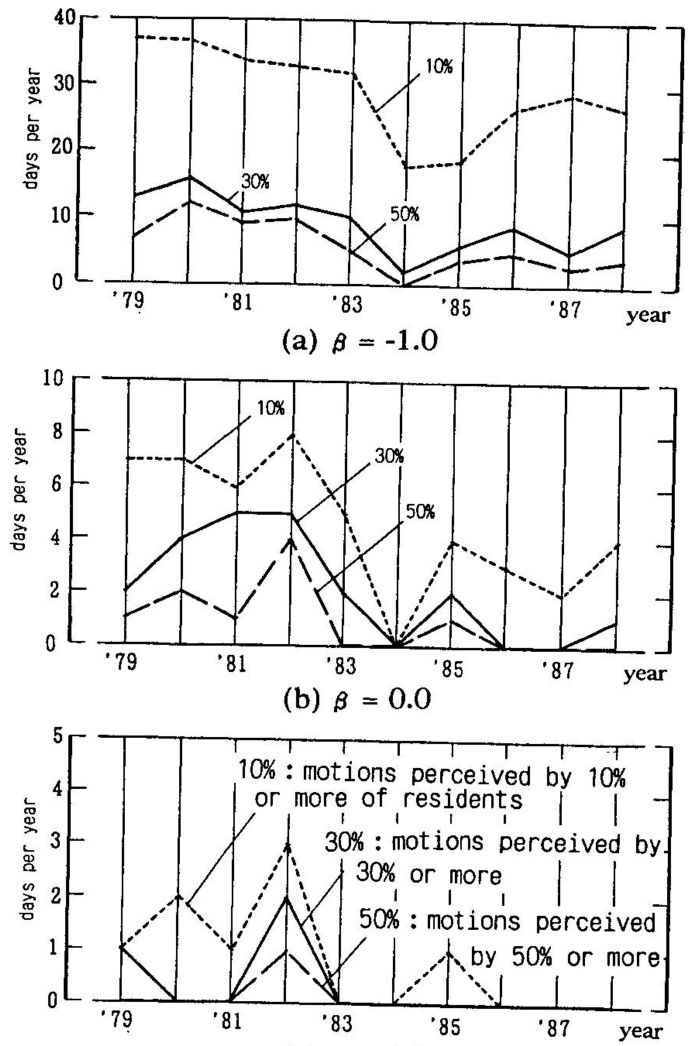

Fig.2. Annual change of number of days when occupants perceive motions due to wind

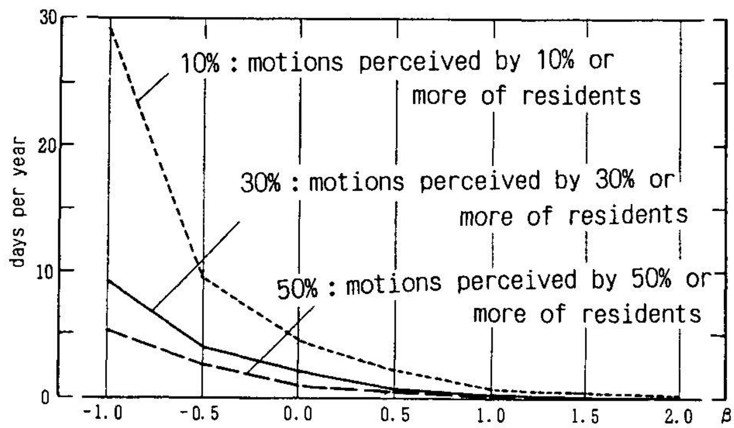

Fig.3. Average number of days for pereption of motions due to wind with β

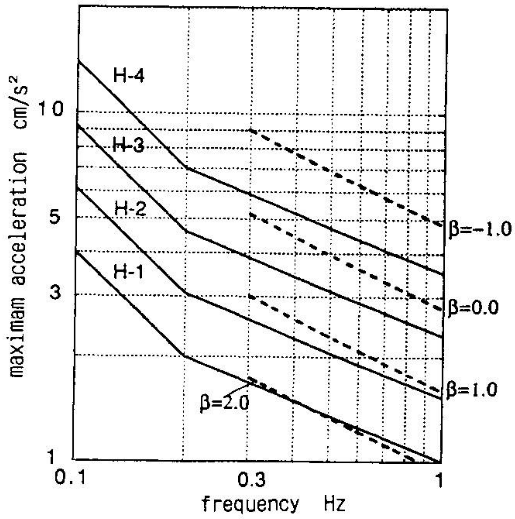

Fig.4. Comparison of perception criteria for wind response

motions in only one day per year as an average. Such numerical studies have to be followed in actural situations in order to reach a concensus on the target β_T among engineers, architects and occupants.

4. COMPARISONS WITH EXISTING GUIDELINE

Most exiting guidelines for the serviceability criteria of wind responses are deterministically specified to a wind speed corresponding to a return period. [3),4)] One of recent guidelines is shown in Fig. 4, when a design wind speed of one year retrun period obtained from daily maximum wind speed data is recommended to be used. The lowest level, i.e., H-1, is approximately consistent to ISO minimum perception limit .[5)]

For those criteria, the design format may be written as,

$$\hat{P} \geq \hat{A}_R \tag{5}$$

where $\hat{P}$ is the perception limit and $\hat{A}_R$ is the wind response amplitude due to the wind speed of R-year return period. When statistical data for the human perception of motion is utilized, $\hat{P}$ can be specified in a probabistic manner. For example, when P is modeled by the log-normal distribution with the mean of eq.(1) and the c.o.v. of 40%,

$$\hat{P} = \mu_p e^{-2\zeta_p} = 0.685\, f_o^{-0.6} \tag{6}$$

also gives a limit close to H-1 in Fig.4.

Probabilistic serviceability limit state design format can be rewritten, based on the log-normal distribution model, from eq.(3) as ,

$$\mu_P \geq e^{\beta\sqrt{\varsigma^2_P + \varsigma^2_A}}\, \mu_A \tag{7}$$

In order to examine the relationship between probabilistic criteria in terms of β in eq.(7) and the deterministic criteria due to eq.(5), a parametric study was conducted. The c.o.v. of annumal maximum wind speed, V_{va},the uncertainty in the response prediction in terms of c.o.v., V_G, the c.o.v. of individual perception limits, V_p, and the retrun period R are chosen as variables. When the variability of the annual maximum wind speed and the uncertainty of the wind response prediction are given, Prob[A>P] can be calculated for the deterministic criteria with the design wind speed of return period R.

The c.o.v. of annual maximum wind load is assumed to be approximated by 2 V_{va}. Then the wind load for R-year return period, W_R, is obtained based on the Gumbel distribution for the annual maximum wind load as,

$$\hat{W}_R = [\, 1 + \{-0.78 \cdot 2V_{V_a} \ln(-\ln(1-\frac{1}{R})) - 0.9\}V_{V_a}]\, \mu_{W_a} \tag{8}$$

where μ_{Wa} is the mean of annual maximum wind load.

The peak acceleration response for R-year return period, $\hat{A}_R$, may be obtained by multiplying a coefficient C as,

$$\hat{A}_R = C\, \hat{W}_R \tag{9}$$

Although C may not be a constant in a wide range of wind load, a linear relationship between $\hat{A}_R$ and $\hat{W}_R$ is assumed for the simplification. Eq.(6) is also assumed, i.e., the deterministic perception criteria is given as the probability point which is specified as (the mean) -two times (standard deviation) for the log-normal distribution, namely,

$$\lambda_p - 2\,\zeta_p = \ln(\hat{A}_R) \tag{10}$$

When the c.o.v. is on the order between 0.2 and 0.5, the Gumbel distirbution can be approximated by a log-normal distribution. In particular when coefficient C is a random variable, the product of C and W_a can be well represented by a log-normal distribution.[6]

Then the perception probability is obtained by eq.(3) with $V_A^2 = (2V_{va})^2 + V_G^2$, $\mu_A = C\mu_{wa}$. The annual perception probability $\Phi(-\beta)$ is calculated and listed for V_{va}=0.1, 0.2 and 0.3; V_p=0.3, 0.4 and 0.5; V_G=0.0, 0.2 and 0.4 in Table 2 (a) for R=2(years) and (b) for R=5(years).

For a typical case of V_{va}=0.20, V_p=0.40 and V_G=0.20, the perception probability, P_p, values for R=2(years) and R=5(years) are 9% and 3% respectitvely. P_p for R=5 is not sensitive to the change of V_{va}, V_p and V_G in comparison with that for R=2. By utilizing the wind data in Tokyo, proposed criteria with various β which are shown by dotted lines, are compared with A.I.J. criteria introduced in Fig. 4. The peak factor commonly used in the

Table 2. Perception probability for the criteria specified for a return period wind[1]

(a) 2-year retrurn period wind

(i) V_{va} = 0.10

V_p	V_G		
	0.0	0.20	0.40
0.3	0.053	0.072	0.108
0.4	0.040	0.052	0.076
0.5	0.034	0.042	0.059

(ii) V_{va} = 0.20

V_p	0.0	0.20	0.40
0.3	0.110	0.132	0.140
0.4	0.077	0.085	0.101
0.5	0.059	0.065	0.078

(iii) V_{va} = 0.30

V_p	0.0	0.20	0.40
0.3	0.157	0.159	0.167
0.4	0.112	0.117	0.155
0.5	0.086	0.090	0.098

(b) 5-year return period wind

(i) V_{va} = 0.10

V_p	V_G		
	0.0	0.20	0.40
0.3	0.018	0.030	0.059
0.4	0.016	0.024	0.043
0.5	0.016	0.021	0.034

(ii) V_{va} = 0.20

V_p	0.0	0.20	0.40
0.3	0.029	0.037	0.055
0.4	0.022	0.027	0.040
0.5	0.019	0.022	0.031

(iii) V_{va} = 0.30

V_p	0.0	0.20	0.40
0.3	0.040	0.044	0.055
0.4	0.029	0.032	0.040
0.5	0.023	0.025	0.032

random vabration theory, which is 3.74 for f_0=1, is used to calculate the maximum amplitude in A.I.J. criteria, while 2 is tentatively used in the proposed one as mentioned previously. β=2.0 corresponeds to the H-1 level and β=0.0 corresponds to a level between H-3 and H-4. Since V_{va} and V_G vary depending on site and design situation, perception probability consistent criteria seem to be preferable to a conventional criteria with a specified return period wind speed. The flexibility in the specification of building performance is described by the second moment reliability intex β. A more consistent β value should be achieved through many opportunities of use of the serviceability limit state design with proposed probabilistic criteria, although it may take time to make such an index as a common measure for wind response performance in the society.

5.CONCLUSION

Probabilistic design criteria with the second moment reliability index are proposed based on experimental data on the human perception limits to low-frequency horizontal motions. A comparison with one of recent guidelines with conventional criteria was made by demonstrating numerical examples. The flexibility in the specification and the rationality for allowing the variability of both wind loads and individual perceptions are stressed.

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