論

文

高周波数領域における矩形角柱の風力スペクトルの 周波数特性に関する考察

Spectral Characteristics of Wind-Induced Forces on a Rectangular Column Structure in a Higher Frequency Range

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SUMMARY

Spectral characteristics of wind-induced forces on rectangular column structures are analyzed for the frequency range higher than the spectral peak. The developed model is based on the assumptions that 1) ambient wind turbulence is fully developed and isotropic, and 2) dominant wind forces on the structure are caused by pressure fluctuations associated with the ambient turbulence. Using the Kolmogorov theory and length scales of effective pressure fluctuation, the power spectra of the transverse force on the column are found to be proportional to the frequency to the $-10/3$ power. The similar analysis leads to the result that the power spectra of the streamwise force are proportional to the frequency to the $-4/3$ power or $-2/3$ power, depending on the frequency range.

Key Words : *ambient wind turbulence, Kolmogorov theory, rectangular column structure, spectral characteristics, wind-induced force*

1. Introduction

Consider a typical high-rise building that is modeled as a rectangular column placed on a horizontal ground as shown in Fig.1 having its height H , breadth B , and length D , being exposed to the wind with the velocity u . When flow-induced forces exerted on the column are considered, we often focus on the Kármán vortex-shedding phenomenon which acts in the direction perpendicular to the mean flow direction, i.e. the transverse direction. However, a typical structure, such as a high-rise building, a tower,

a bridge column or the like, does not respond significantly to this vortex-shedding induced force because such a structure is often designed and constructed to be stiff enough so that the natural response frequency (e.g. eigen-frequency) is much higher than that at the Kármán vortex shedding. (Note that, as an exception, significant structural vibration could occur owing to the Kármán vortex shedding, if the structure is sufficiently soft, for example, a super-high rise building more than, say 400m tall, so that its eigen frequency is close to that of the vortex shedding.) Based on the

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Fig.1 A schematic view of a rectangular column, having its height H , breadth B , and length D , submerged in a turbulent wind boundary layer with the velocity u in the mean flow direction parallel to the length D .

laboratory experiments by Sockel¹⁾ and Wakahara²⁾, the Strouhal number of the Kármán-vortex shedding for a rectangular column is known to be approximately $0.05 \sim 0.15$ in the range of the column aspect ratio $B/D = 0.5 \sim 2$: here, the Strouhal number is defined as fD/U where f is the frequency of the Kármán vortex shedding in hertz (Hz), and U is the ambient mean flow velocity. Note that the frequency of the Kármán-vortex shedding usually corresponds with that of the maximum force on a structure in the across-wind direction. Incidentally, the Strouhal number for a circular cylinder of infinite length (with no free end) is known to be 0.2 in a wide range of Reynolds number, $2 \times 10^2 < R = Ud/\nu < 3 \times 10^5$, where d is the diameter of the cylinder and ν is the kinematic viscosity of the fluid³⁾. Suppose that the fundamental eigen-frequency of a typical high-rise structure with the height $150 \sim 250$ m and the vertical aspect ratio $H/D = 4 \sim 6$ is $0.2 \sim 0.5$ Hz, the structure's eigen frequency in terms of the Strouhal number is then in the range of $0.3 \sim 1.0$, under a design wind speed of $20 \sim 30$ m/sec which is typically used for its serviceability criterion. Hence, the response frequency of the structure is several times higher than the Kármán vortex-shedding frequency. In this paper, spectral characteristics of forces exerted on a rectangular-column structure are analyzed for the frequency range several times higher than that of the Kármán vortex shedding. It is empha-

sized that a super-high-rise structure, e.g. a 450 m tall building, might have its response frequency at a value very close to the Kármán vortex-shedding frequency. The present analysis excludes such a rare situation.

2. Analysis

Traditionally, forces exerted on a structure are conveniently analyzed based on the well-established drag force concept although it is only applicable to steady flows. Ambient wind under consideration is fully turbulent, and a column structure is totally submerged in the turbulent boundary layer. Ambient wind velocity u can be decomposed to the mean velocity U and the fluctuation $u'(t)$: $u(t) = U + u'(t)$.

Simiu and Scanlan⁴⁾ analyzed the drag-force spectra, i.e. in the streamwise direction. Assuming the total drag force F_D be expressed as

$$F_D(t) = \frac{1}{2} C_D \rho \ell^2 u(t)^2, \quad (1)$$

where ℓ is a typical body dimension (in this case, $\ell \approx \sqrt{A}$ where A is the projected area of the structure on a plane normal to the mean flow), ρ is the air density and C_D is the drag coefficient. Then, substituting $u(t) = U + u'(t)$, the fluctuating part of the drag force is found to be

$$F'_D(t) = C_D \rho \ell^2 U u'(t). \quad (2)$$

Based on equation (2), the drag-force spectral density,

Fig.2 Aerodynamic admittance $|\chi(f)|^2$ of plates and columns: after Vickery⁶⁾. The solid line represents the present result of equation (21), and A is the projected area of the structure on a plane normal to the mean flow, in this case, $\sqrt{A}$ corresponds to a typical body length ℓ in equation (6).

$S_x(f)$, can be derived as

$$\frac{S_x(f)}{\left(\frac{1}{2}\rho\ell^2U^2\right)^2} = 4C_D^2 \frac{S_u(f)}{U^2}, \quad (3)$$

where $S_u(f)$ is the spectral density of the velocity fluctuations $u(t)$ and f is the frequency. Simiu and Scanlan⁴⁾ used the spectral density of wind turbulence in the inertial range proposed by Lumley and Panofsky⁵⁾:

$$S_u(f) = 0.26 \frac{u_*^2}{f} \left(\frac{fz}{U}\right)^{-2/3}, \quad (4)$$

where u_* is the shear velocity and z is the elevation from the ground. It can be shown that the substitution of equation (4), into equation (3) leads to the nondimensionalized drag-force spectra of the form

$$\frac{fS_x(f)}{\left(\frac{1}{2}\rho\ell^2U^2\right)^2} \propto \left(\frac{f\ell}{U}\right)^{-2/3}. \quad (5)$$

It is emphasized that this relation is for the drag-force spectra based on the dynamic pressure forces: the wind kinetic energy is converted to the pressure work exerted on the structure as expressed in equation (1). None the less, it must be recognized that the form of equation (1) is originally derived for steady flows of inviscid fluids: the use of equation (1) cannot be justified for analyses for any (unsteady) flow

fluctuations. In other words, the use of equation (1) is inappropriate to extract unsteady characteristics of the flow. This is the reason why equation (5) is only applicable to the low frequency range where the flow behaves as quasi-steady. In practice, the discrepancy in equation (5) that appears in the higher frequency range is often adjusted by introducing the empirical multiplier to the right-hand-side of equation (3), termed the aerodynamic admittance $|\chi(f)|^2$, which makes the gradient of the spectra density function steeper. Figure 2 shows the aerodynamic admittance obtained from the laboratory experiments, and Vickery⁶⁾ suggested the following empirical relation to fit the data:

$$|\chi(f)|^2 = \frac{1}{\left\{1 + \left(\frac{2f\ell}{U}\right)^{4/3}\right\}^2}. \quad (6)$$

Based on Kolmogorov's hypothesis⁷⁾, Inoue and Maki⁸⁾ derived the drag-force spectra as:

$$S_x(f) \propto f^{-7/3}. \quad (7)$$

This result will be re-derived in Section 2.2, and we will take the similar approach to analyze the force spectra in the transverse (across-wind) direction in Section 2.1.

Fig.3 A conceptual flow pattern of the Kármán vortex shedding and ambient eddies of various sizes.

2.1 Transverse Force Fluctuation

Let us first consider the net force exerted on the column in the transverse (across-wind) direction, i.e. perpendicular to the mean flow direction. The pressure force in the transverse direction must be exerted on the column surface D (see Fig.1) which points perpendicular to the mean flow direction, and there is no stagnation point on the side-wall surface. In the transverse direction, the most significant force is often attributed to the Kármán-vortex shedding. The shedding phenomenon can be thought to be created by the oscillating flow separations from the column corners due to flow instability⁹). Since, as we discussed, such slow fluctuation induced by the Kármán-vortex shedding is not of our interest; pressure variations associated with the vortex shedding are not considered. In addition, small eddies that might be created at the flow separation are advected quickly away from the column, and there is not enough time to develop and to manifest themselves to cause pressure variations on the column structure. In fact in order to form a complete and effective eddy, it takes at least one turn-over time (or one eddy circulation time) $\tau = L/U$, where L is the length scale of the eddy. (Note that one turn-over time is equivalent to the corresponding normalized frequency fD/U of unity.) Hence only very small eddies with the length scale $L \ll D$ can cause pressure fluctuation on the column, i.e. $fD/U \gg 1$. None the less, such small eddies are ineffective to cause signif-

icant net pressure force on the column structure because they are not acting coherently over the structure length scale. Furthermore, stresses exerted tangential to the column surface are considered to be negligible because of the high Reynolds number flow and the finite (relatively short) column dimensions, hence the viscous effect is insignificant. We also assume that the column is immovable so that there is no force caused by the column's vibration. Possible turbulent eddies that surround the structure are depicted in Fig.3.

The above-mentioned assumptions and considerations lead to the hypothesis that the transverse (across-wind) forces exerted on the column at the frequency higher than that of the Kármán-vortex shedding are due mainly to the effects of pressure fluctuation existing in the ambient flow. Because of the velocity fluctuation, the ambient pressure field also fluctuates with the magnitude

$$p' \sim \rho u'^2, \quad (8)$$

(e.g. see Landau and Lifshitz¹⁰). This is often called the "static" pressure fluctuation and this fluctuation is the one which would be measured when the pressure probe is moving with the mean velocity U . In other words, "static" pressure is the one that would be measured by a piezometer, while the "dynamic" pressure is the one that would be measured by a pitot tube. The ambient pressure fluctuation (8) can be readily derived based on Kolmogorov's hypothesis⁷), as shown later in

equation (9). Just like the traditional boundary-layer analyses, we assume that the entire side-wall surfaces are submerged in the flow-separation zone all the time and the streamlines never re-attach on the surface. It is also re-emphasize that the present analysis is focusing on the flow and force characteristics in the frequency range several times higher than that of the Kármán vortex shedding; hence the fluctuations associated with the separation eddies are not examined. This means that the pressure variations which influence in the separation zone, hence on the column in the transverse direction, are dominated by the ambient pressure fluctuation induced by background turbulence, described in equation (8).

It is well known that fully developed isotropic turbulence can be described by Kolmogorov's energy cascade hypothesis⁷⁾. Isotropic turbulent flow motion must depend only on the energy flux supplied by the large scale eddies but not the specific details of its formation. By dimensional reasoning, the only relevant parameter is the energy flux per unit mass, $\varepsilon \sim u_0^3/L$, where u_0 and L are, respectively, the velocity variations and the length scale of large eddies (or the integral scale of the turbulence). The magnitude of u_0 is assumed to be proportional to and the same order of magnitude of the mean velocity U : $u_0/U \simeq 0.2$, according to Simiu and Scanlan⁴⁾. In the inertial range, there is no direct energy input nor dissipation, and the energy flux must be equal to the mean energy dissipation rate ε . Hence, smaller turbulent eddies of the length scale λ ($< L$) have the velocity variations of $u_\lambda \sim (\varepsilon\lambda)^{1/3}$.

Kolmogorov's hypothesis states that the local properties of turbulence are independent of the dimension L and the velocity u_0 of the flow as a whole, but determined by the combined parameter ε . Hence, the order of magnitude of the pressure variations over distance λ must be uniquely determined only by ε , λ , and the fluid density ρ . Consequently, by the dimensional reason,

$$p_\lambda \sim \rho \varepsilon^{2/3} \lambda^{2/3}, \quad (9)$$

and the substitution of $\varepsilon \sim u_\lambda^3/\lambda$ into equation (9) reduces to equation (8): this is the justification of equation (8) for the ambient pressure fluctuations. Hence,

$$F_y \sim \frac{1}{2} \rho \varepsilon^{2/3} \lambda^{2/3} D H, \quad (10)$$

where the coefficient 1/2 is added without loss of generality.

We assume that the length scale of ambient pressure fluctuation is the same as the length scale of the corresponding velocity fluctuation. In order to create a net force in the transverse direction, it is necessary that pressure-fluctuation length scale due to ambient turbulence be comparable to the column dimension, i.e. $\lambda \sim D$. As depicted in Fig. 3, the pressure variations associated with the larger length scale ($\lambda \gg D$) are ineffective in producing net pressure force on the column structure. It is because the pressure forces on the two side-wall surfaces that are oriented opposite each other are counterbalanced and the resulting pressure differentials are negligible. On the other hand, turbulent pressure variations of the scale much smaller than the column dimension ($\lambda \ll D$) are also ineffective in producing net pressure forces on the column, because the turbulent eddies are not acting coherently over the scale D . Hence equation (10) can be expressed as

$$F_y \simeq \frac{1}{2} \rho \varepsilon^{2/3} \lambda^{5/3} H \simeq \frac{1}{2} \rho \varepsilon^{2/3} U^{5/3} f^{-5/3} H, \quad (11)$$

where f is the frequency associated with the velocity-fluctuation length scale λ and the relation $f = U/\lambda$ was used. Equation (11) can be arranged to:

$$\frac{F_y}{\frac{1}{2} \rho U^2 D H} \simeq \varepsilon^{2/3} U^{-1/3} f^{-5/3} D^{-1}. \quad (12)$$

Since energy flux per unit mass is $\varepsilon \sim u_0^3/L \propto U^3/L$, and the integral scale of turbulence is proportional to the column dimension, i.e. $L \propto D$,

$$\frac{F_y}{\frac{1}{2} \rho U^2 D H} \propto U^{5/3} f^{-5/3} D^{-5/3}. \quad (13)$$

Based on equation (13), the power spectra of transverse force $S_y(f)$ can be found to be

$$\frac{f S_y(f)}{\left(\frac{1}{2} \rho U^2 D H\right)^2} = C_1 \left(\frac{f D}{U}\right)^{-10/3}, \quad (14)$$

where C_1 is the proportionality constant. This demonstrates that the power spectra of transverse force on the column is proportional to the normalized frequency fD/U to the $-10/3$ power. It is emphasized that this result is valid for the frequency range

of $fD/U \sim O(1)$, and is based on the assumption that the ambient turbulent pressure field is the sole cause for the transverse force on the column. As discussed, when the frequency is lower than approximately $fD/U \leq 0.1$, equation (14) becomes invalid since the dominant mechanism for transverse forcing becomes the Kármán vortex shedding due to the oscillatory movements of flow separation at the upstream corners of the column. Equation (14) is the main result of this paper.

2.2 Streamwise Force Fluctuations

Let us now consider the streamwise (along-wind) force fluctuation. The streamwise net force is caused by forces exerted on the front and rear faces of the column, and, unlike the transverse force, the flow conditions on the front and rear faces are grossly different.

We assume no force contribution from the side-wall surfaces because the tangential viscous shear forces are negligible for the high Reynolds-number flows. There is flow stagnation on the front surface and, if the flow variations are slow and considered to be quasi-steady, then the "dynamic" pressure-force fluctuation of equation (2) might be as important as the force due to ambient pressure fluctuation: it is emphasized that equation (1) is not really applicable for unsteady motions, consequently equation (2) should be considered to be an approximation only for a quasi-steady flow.

The rear face of the column is located in the wake and the pressure there is not significantly influenced by the ambient pressure fluctuation. In the frequency range of our interest (several times higher than that of the Kármán-vortex shedding), we assume that the total pressure force exerted on the rear face to be constant; note that a practically constant pressure on the rear side of the high-rise building was reported by the prototype measurements made by Dalglish¹¹). Hence all the fluctuation is caused by pressure variations on the front face. Unlike the case of the transverse pressure force, there is no upper limit in length scale of flow fluctuation to create the net pressure force in the streamwise direction: even flow fluctuation much larger than the column size is capable of causing the net pressure force on the column because the pressure

force on the front face is not canceled out by that on the rear face. Then, the similar analysis made for the case of transverse pressure-force variations, but not to restrict to a narrow range of the effective length scale, i.e. $\lambda \neq B$, yields

$$\begin{aligned} \frac{F_x}{\frac{1}{2}\rho U^2 BH} &\simeq \varepsilon^{2/3} U^{-4/3} f^{-2/3} \\ &\simeq U^{2/3} f^{-2/3} L^{-2/3}. \end{aligned} \quad (15)$$

Hence the power spectra of streamwise force can be found to be

$$\frac{f S_x(f)}{\left(\frac{1}{2}\rho U^2 BH\right)^2} = C_2 \left(\frac{fB}{U}\right)^{-4/3}, \quad (16)$$

where C_2 is the proportionality constant. Here we set the integral scale of the turbulence L in the ambient flow to be proportional to B without loss of generality. This result indicates that the power spectra of streamwise force on the column is proportional to the normalized frequency fB/U to the $-4/3$ power. Note that, for given column dimensions and mean wind velocity, equation (16) is equivalent to the result derived by Inoue and Maki⁸) in equation (7), i.e. $S_x(f) \propto f^{-7/3}$.

It must be noted that equation (16) is based on pressure variations in the ambient flow without any dynamic pressure contribution. Since the flow becomes stagnant on the front face, the dynamic pressure should become important for a slowly varying flow. The dynamic pressure for a steady flow can be expressed by $p_d = 1/2\rho u^2$. If the velocity is decomposed into the mean value U and the slow fluctuation u' , the dynamic pressure fluctuation on the front face is written by

$$p'_d \simeq \rho U u'. \quad (17)$$

It must be emphasized that equation (17) is only valid for a quasi-steady flow. A similar analysis to the previous cases can be made for the dynamic pressure fluctuation based on equation (17), which yields

$$\frac{F_x}{\frac{1}{2}\rho U^2 BH} \propto 2 U^{1/3} f^{-1/3} L^{-1/3}, \quad (18)$$

and

$$\frac{f S_x(f)}{\left(\frac{1}{2}\rho U^2 BH\right)^2} = C_3 \left(\frac{fB}{U}\right)^{-2/3}, \quad (19)$$

Fig.4 Experimental data of power spectra of wind forcing a) in the transverse direction and b) in the streamwise direction, after Wakahara²⁾. The slopes shown on the spectra plotted in the log-log scales are the predictions of equation (14), (16) and (19).

where C_3 is the proportionality constant. Incidentally, equation (19) is identical to equation (5), which was derived from the drag forces in equation (1) and the turbulent flows in the boundary layer in equation (4).

Note that only slow variations of the velocity associated with very large eddies would contribute to the dynamic pressure fluctuation; most of the smaller turbulence eddies cannot maintain their original forms and are smeared during the flow impact onto the front face of the column, hence cannot contribute to the stagnation pressure fluctuation. Hence equation (19) should be invalid for the frequency range of our interest, i.e. the range higher than that of the Kármán vortex shedding.

3. Discussion

Our analytical models presented in equation (14), (16) and (19) are compared with laboratory data of power spectra of wind-induced forces²⁾. The wind-tunnel experiments yield the power spectra of forces on rectangular-column structures in the transverse

and streamwise directions. Figures 4 (a) and (b) show the measured spectra in the transverse (across-wind) and the streamwise (along-wind) directions, respectively, for the column structure with $B = 100$ mm, $D = 100$ mm, and $H = 500$ mm (see Fig.1). The two different ambient turbulent boundary-layer conditions are imposed, $\alpha = 1/4$ and $1/6$, in which α is the power of velocity profiles by the power law⁴⁾; $U(z)/U_H = (z/H)^\alpha$, where z is the elevation from the ground, U_H is the mean wind speed at the top of the column structure, $z = H$. Note that the condition of $\alpha = 1/4$ contains more energetic turbulence than that of $\alpha = 1/6$. More detailed descriptions with regard to the wind-tunnel experiments are referred to Wakahara²⁾.

As shown in Fig.4 (a), the measured spectra in the transverse direction are in excellent agreement with our prediction of (14) in the frequency range $f D/U$ from 0.2 to 1.0; the agreement is better under the stronger ambient turbulence intensity $\alpha = 1/4$ than the case of $\alpha = 1/6$. Recall that one of the model

assumptions is that the transverse force is controlled completely by ambient pressure fluctuation, hence the more energetic the ambient turbulence ($\alpha = 1/4$), the better agreement results.

One of the applications of the results is the deduction of structural acceleration response under a wind loading: the acceleration response is often used for a serviceability criterion for a high-rise building. For a given structure with a fixed eigen frequency, the structural acceleration, that is proportional to the net force, can be derived from (13) and found to be proportional to the magnitude of $U^{11/3}$ in the transverse (across-wind) direction. This result can be compared with the empirical formula of the structural maximum accelerations provided by the Associate Committee on National Building Code and National Research Council of Canada¹²⁾, i.e.

$$\ddot{y}_{max} = g_{\ddot{y}} C_N \left(\frac{\rho_A}{\rho_B} \right) \frac{f_s^2}{\sqrt{\xi_s}} \sqrt{BD} \left(\frac{U_H}{f_s \sqrt{BD}} \right)^{3.3} \quad (20)$$

where ρ_B and ρ_A are the building and air density, respectively, ξ_s is the damping constant, f_s is the natural frequency of the building, $C_N (= 0.0006)$ is a constant, and $g_{\ddot{y}}$ is the peak factor for acceleration response. It is emphasized that the empirical formula (20) shows that the acceleration response is proportional to $U^{3.3}$, which is close to but not exactly the same as our theoretical result, $U^{11/3}$. The wind-tunnel tests for the acceleration response, $\ddot{y}_{max}$, were performed in a wide range of the B/D ratio by Marukawa et al.¹³⁾. They found that $\ddot{y}_{max} \propto U^{3.8}$, for $B/D = 1.0$, which is in better agreement with our theoretical value $U^{11/3}$, than the formula (20). Marukawa et al.¹³⁾ further pointed out that this value of the exponent ($= 3.8$) is maximum near $B/D \simeq 1.0$; the exponent value is smaller when $B/D < 1.0$ and $B/D > 2.0$.

Figures 4 (b) shows the measured force spectra in the streamwise direction. The gradual transition of the streamwise force spectra must have resulted from the influence of the dynamic pressure contribution: equation (19) indicates that the slope of the spectra in the range associated with large eddy sizes is $-2/3$. This slope is gradually decreased to $-4/3$ of equation (16) as the frequency range increases (for smaller eddies).

Such a transition is not present in the spectrum of the transverse force in Fig.4 (a), because no dynamic pressure contribution exists for the pressure forces exerted on the side-wall surfaces of the column. The predictions of equations (16)(19) are in good agreement with the measured spectra. It is also noted that equation (16) is equivalent to the aerodynamic admittance to be

$$|\chi(f)|^2 \propto \left(\frac{f\sqrt{A}}{U} \right)^{-2/3} \quad (\sqrt{A} \simeq B), \quad (21)$$

in which the rate of decrease appears to be underestimated in comparison with the empirical formula (6) for a higher frequency, i.e. $fB/U \gg O(1)$. On the other hand, the solid line in Fig.2 shows that in the frequency range $0.1 < fB/U < 1.0$, equation (21) is in good agreement with the laboratory data. Perhaps, for $fB/U \gg O(1)$, the size of driving eddies ($\lambda \simeq U/f$) becomes much smaller than the column surface, hence the small turbulent eddies are not acting coherently over the scale B (see Fig.1). The fluctuating forcing due to small-eddy turbulence diminishes quickly and, consequently, the aerodynamic admittance $|\chi(f)|^2$ decreases at the faster rate as the frequency increases. As we stated in Section 1, the frequency range $0.3 < fB/U < 1.0$ is the one that we focus on, since the eigen frequency of a typical structure often falls within this range.

4. Conclusions

Based on the Kolmogorov hypothesis⁷⁾ and the physical argument for the effective pressure fluctuation, the wind-force spectra in the frequency range higher than that of the Kármán-vortex shedding are modeled for rectangular shaped column structures. The models can be summarized as

$$\frac{f S(f)}{\left(\frac{1}{2} \rho U^2 \ell H \right)^2} = C \left(\frac{f \ell}{U} \right)^{-n}, \quad (22)$$

where ℓ is the structural length scale, and $\ell = D$ for the transverse direction and $\ell = B$ for the streamwise direction. Our analyses found $n = 10/3$ for the transverse direction, $n = 4/3$ for the streamwise direction due to ambient pressure fluctuation effects, and $n = 2/3$ for the streamwise direction due to "dy-

namic" and quasi-steady pressure fluctuation effects. The frequency dependence of our result, $n = 4/3$ for the streamwise direction, is equivalent to equation (7) and is a re-discovery of Inoue's work in 1950 that was reported in their paper⁸⁾.

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References

- 1) Sockel, H. ; Fundamentals of Wind Engineering. in Wind-Excited Vibrations of Structures (H. Sockel, Ed), Springer-Verlag, Wien, 1994.
- 2) Wakahara, T. ; Suppression of wind induced response of structure using tuned liquid damper. Ph.D. thesis, University of Tokyo, 1996 (in Japanese).
- 3) Schlichting, H. ; Boundary-Layer Theory, Seventh ed. McGraw-Hill, New York, 1979
- 4) Simiu, E. and Scanlan, R.H. 1996. Wind Effects on Structures, Third ed. Wiley, New York, 1979.
- 5) Lumley, J.L. and Panofsky, H.A. ; The Structure of Atmospheric Turbulence, Wiley, New York, 1964.
- 6) Vickery, B.J. ; Load fluctuations in turbulent flow, Proc. ASCE, EM 1, 31-45, 1968.
- 7) Kolmogorov, A.N. ; The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers. Dokl. Akad. Nauk SSSR, 30, 299-30. Also Proc. R. Soc. Lond. A, 434, 9-13, 1941.
- 8) Inoue, E. and Maki, T. ; Turbulent fluctuations in wind pressure. Proc. 3rd. Symposium on Wind Effects on Structures in Japan, 71-76, 1974 (in Japanese).
- 9) Lamb, H. ; Hydrodynamics. Sixth ed. Cambridge University Press, Cambridge, 1932.
- 10) Landau, L.D. and Lifshitz, E.M. ; Fluid Mechanics. Pergamon Press, Oxford, 1959.
- 11) Dalglish, W.A. ; Statistical treatment of peak gust on cladding. J. Struct. Div., ASCE, 97, 2173-2187, 1971.
- 12) Associate Committee on National Building Code and National Research Council of Canada ; National Building Code of Canada 1990, Part 4: Structural Design, 1990.
- 13) Marukawa, H., Ohkuma, T., and Momomura, Y. ; Across-wind and torsional acceleration of prismatic high rise buildings. J. Wind Eng. Ind. Aerodyn., 41/44, 1139-1150, 1992.
- 14) Ohkuma, T., Kanda, J., and Tamura, Y. ; Structural Design for Wind Effects. Kajima Publication, 1996 (in Japanese).