Structural Eng./Earthquake Eng., JSCE, Vol. 14, No. 1, 73s—82s, 1997 April

ESTIMATION OF THE VORTEX-INDUCED VIBRATION OF BRIDGE GIRDER UNDER NATURAL WIND

Katsuaki TAKEDA[1] and Nobumitsu FUJISAWA[2]
[1,2]Member of JSCE, Dr. of Eng., Chief Researcher, Applied Technology Research Center, NKK (1-1, Minami-watarida-cho, Kawasaki-ku, Kawasaki, 210 Japan)

This paper deals with a method to estimate the amplitude of vortex-induced vibration of long span bridge girder under natural wind based on the test results of conventional spring-mounted model test in smooth flow. A series of experiments were conducted to clarify the effects of vibrational mode, turbulence intensity and scale on bridge response, and the results indicate that turbulence effect is remarkable ; it was found that the effect of turbulence intensity which is the most important parameter depends on cross-sectional shape of girder, width to depth ratio (B/D) and so on. Observation of vortex-induced vibration of a real bridge is consistent with the test results obtained in the present study.

Key Words *: long span bridge, wind tunnel test, vortex-induced vibration, turbulence effect*

1. INTRODUCTION

It is desirable to conduct a full bridge model wind tunnel test using a 3-dimensional elastic model in a simulated turbulent flow to investigate the aerodynamic stability of the bridge girder of a long span bridge, but this is not always possible because it is a time-consuming and difficult work using a large wind tunnel. On the other hand, the test in a smooth flow that is the most fundamental one is considered to be always conducted. Therefore, it could be quite significant to estimate the response of an actual bridge based on the test results in a smooth flow.

In the study, a series of wind tunnel tests were conducted to consider (a)3-dimensional effect (vibrational mode, spanwise correlation of vortex force) and (b)turbulence effect (turbulence intensity, turbulence scale) which are important factors to estimate the amplitude of vortex-induced vibration of a long span bridge girder under natural wind based on the test results of conventional spring-mounted model tests in a smooth flow. Observation of the aerodynamic behaviour of an actual bridge was also conducted to examine the consistency of the new findings in the present study.

In order to consider the 3-dimensional effect such as vibrational mode, some methods are proposed[1)2)] to calculate the 3-dimensional response based on the strip theory where "the local wind force is assumed to depend only on the local displacement" after identifying the aerodynamic force coefficients by spring-mounted wind tunnel tests. And it is found that the strip theory can also be applied to the calculation of the amplitude of vortex-induced vibration whose wind forces are comparatively small. In these methods, the external wind forces are formulated according to the characteristics of the vibration, that is, forced vibration or self-excited one, and it is found that the calculated result agrees with each other when the external vortex force completely resonates to the vibration of bridge girder[2)]. In these studies, however, the characteristics of the wind forces acting on the models are not strictly taken into consideration, and the test results on a rigid circular cylinder are used to correct the spanwise correlation of vortex force[1)].

Concerning the turbulence effect on vortex-induced vibration of bridge girders, it is found that the parameter of turbulence intensity is quite important, and that the magnitude depends on cross sectional shape and its slenderness ratio (road width to girder height)[4)-9)]. In "*Wind Resistant Manual for Highway Bridges*", the correction coefficients on turbulence effect are given by a function of these parameters[10)]. However, more detailed study is desired, because these recommended values were determined based on some experimental data that do not seem to be sufficient to assure accuracy. In addition, it is necessary to make clear the effect of turbulence scale on which few studies[12)] have been conducted. To clarify the effect of respective turbulence parameter is quite important when wind tunnel tests in a turbulent flow are conducted

This paper is translated into English from the Japanese paper, which originally appeared on J. Struct. Mech. Earthquake Eng., JSCE,No.465/I-23,pp.57-66,1993.4.

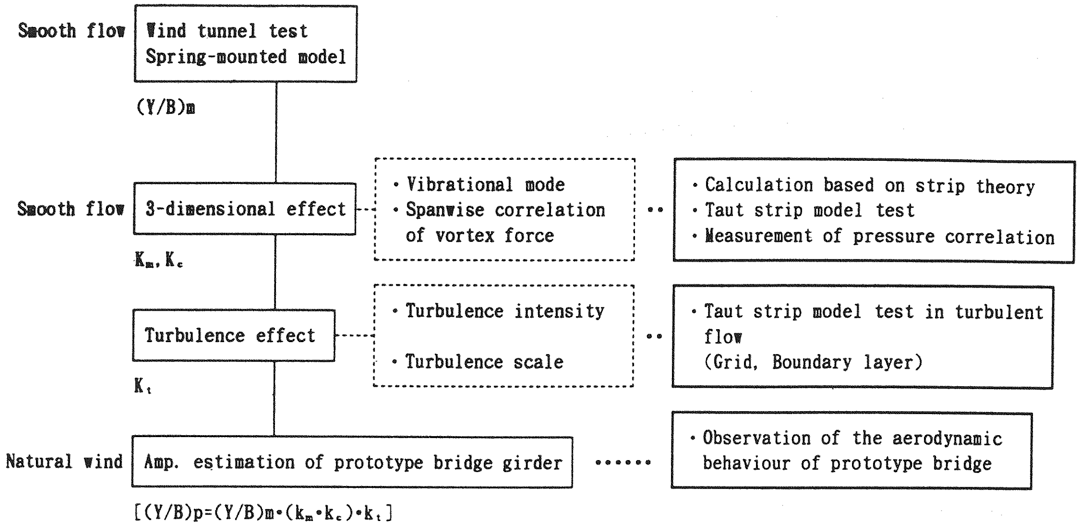


Fig.1 Estimation flow of the vortex-induced vibration of bridge girder under natural wind and the outline of the current study

where all the turbulence parameters cannot be simulated at the same time.

In the study, a method to consider the 3-dimensional effect is attempted, that is, the wind forces are properly formulated based on the observed data in the spring-mounted model test focusing on the fact that the type of wind forces acting on the model could be identified by the variation of observed model frequency, and so on. The effect of spanwise correlation of vortex force is also studied by measuring the surface pressure of taut strip models. Concerning the turbulence effect, a series of wind tunnel tests in both grid and boundary layer turbulent flows are carried out, and the effects of turbulence intensity and turbulence scale on the amplitude of vortex-induced vibration are discussed. Finally, the aerodynamic behaviour of a cable-stayed bridge is observed, and the amplitude is compared with the predicted values based on the results obtained in the present study. **Fig.1** shows the estimation flow of vortex-induced vibration of a bridge girder under natural wind, primary similitude parameters, and the wind tunnel tests, calculation, and observation conducted in the present study.

2.ESTIMATION OF VORTEX-INDUCED VIBRATION OF BRIDGE GIRDER IN SMOOTH FLOW

(1) Calculation method of 3-dimensional response amplitude

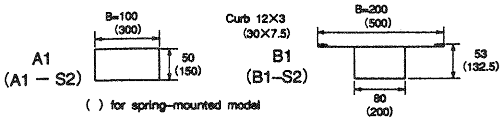
It is necessary to formulate the external wind forces properly in order to calculate the amplitude of vortex-induced vibration taking the 3-dimensional effect such as vibrational mode into consideration based on the results of conventional spring-mounted model tests. The wind forces consist of forced-type wind force which is caused by the alternating vortices in the wake of bridge girder, and self-excited-type one which is caused by the motion of bridge girder itself. It is impossible to identify each coefficient of dynamic wind forces from the results of spring-mounted model tests, because they only indicate the superimposed information of forced and self-excited wind forces. In the study, however, wind forces are formulated focusing on the fact that the type of wind force, forced one or self-excited one, could be judged by the variation of observed model frequency and so on.

When the wind force acting on the model can be regarded as forced-type one, the coefficients of dynamic wind force at any amplitude can be obtained by the variation of the peak amplitude of vortex-induced vibration with wind speed plotted for various values of structural damping. In the case of self-excited-type wind force, on the other hand, the observed aerodynamic damping for several levels of amplitude are used to identify the coefficients of dynamic wind force. It is possible to calculate the 3-dimensional response using the identified coefficients of dynamic wind force if the strip theory is assumed to be applicable. In the case of forced vibration, the amplitude, $Y_f^*(m)$, at $\phi_j(x)=1$ is given by the following expression.

$$Y_f^* = \frac{\rho U^2 B}{2\sqrt{(\omega_{0j}^2-\omega^2)^2+(2h_0\omega_{0j}\omega)^2}} \cdot \int_0^l C_L(Y_f^*)\left|\phi_j(x)\right|dx \Big/ \int_0^l m\phi_j^2(x)dx \qquad (1)$$

Table 1 Experimental cases and their conditions. (3-dimensional effect)

Case no.	Model	Test method	Scruton No. $m\delta_0/(\rho B^2)$	Flow
1-1	A1−S2	Spring-mounted	1.1∼3.3	Smooth
1-2	A1	Taut strip	2.2∼2.7	
1-3	B1−S2	Spring-mounted	0.4∼0.5	
1-4	B1	Taut strip	0.4∼0.5	



On the other hand, the stationary amplitude in case of self-excited vibration, $Y_s^*(m)$, can be calculated by the following condition which is derived from the balance of damping forces.

$$\int_0^l \left(C - \rho UBC_I(Y_s^*, x)/2\right)\phi_j^2(x)dx = 0 \qquad (2)$$

where ρ : air density, U : wind speed(m/s), B :deck width, ω_{0j} : jth natural circular frequency, ω : circular frequency of alternating vortices, h_0 : damping ratio, C_L : dynamic lift coefficient, m: mass per unit length, C: viscous damping coefficient, C_I : imaginary part of dynamic wind force, l : bridge length, $\phi_j(x)$: jth mode function, x : coordinate along bridge axis.

The correction factor on vibrational mode K_m is the ratio of 3-dimensional response to the observed one in 2-dimensional spring-mounted model test.

(2) Wind tunnel tests

a) Experimental method

Spring-mounted model test and taut strip one were conducted to examine the calculation method mentioned above. As shown in **Table 1**, two kinds of cross sections were tested, that are, rectangular cross section whose slenderness ratio B/D is equal to 2 (Model A1, A1-S2) which causes a self-excited-type vibration judged from the variation of frequency with wind speed and so on, and box girder one with cantilevered deck (Model B1, B1-S2) which shows the characteristics of forced-type vibration. Spring-mounted model test and taut strip one were conducted under almost the same experimental conditions for each cross section, so the difference in test results between the two kinds of tests is considered to come from the 3-dimensional effect.

b) Test results and discussion

The test results on Model A1 and A1-S2, and calculated

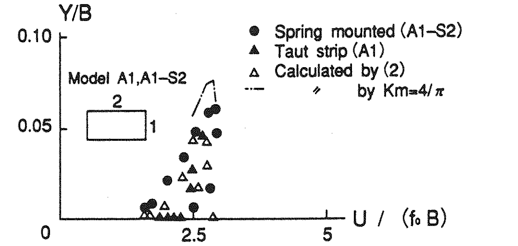


Fig.2 Response comparison between Model A1 and A1-S2

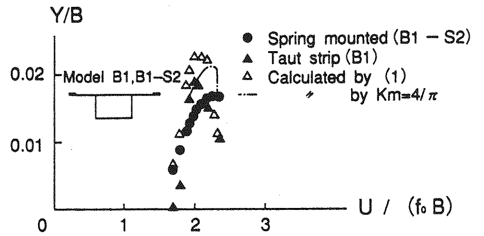


Fig.3 Response comparison between Model B1 and B1-S2

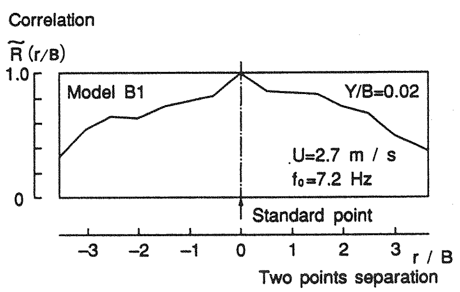


Fig.4 Spanwise pressure correlation on a vibrating taut strip model. (Model B1)

values from Eq.(2) are shown in **Fig.2** which indicates the variation of non-dimensional amplitude Y/B (Y: average of response amplitude at the center of the 1st symmetric mode in vertical vibration, B : deck width) with non-dimensional wind speed $U/(f_0 B)$ (U : wind speed, f_0 : natural frequency).

It is found from the figure that the peak amplitude of taut strip model test is smaller than that of spring-mounted one by 25% (K_m=0.75). The calculated values from Eq.(2) where self-excited-type external wind force is assumed to fall in an excellent agreement with the test results of taut strip model test. It is also found that the calculated values from the simple formula $K_m = 4/\pi$ [10] where wind forces are assumed to be constant at all levels of amplitude give fairly large (safety-side) estimation.

On the other hand, **Fig.3** shows the test results on Model B1 and B1-S2 which cause forced-type vibrations, and the calculated values from Eq.(1). In the cases, the peak amplitude of taut strip model test becomes larger than that of spring-mounted one by 10% (K_m=1.1) in contrast with the cases of Model A1 and A1-S2. This is considered to come from the difference in the dependence of wind forces on amplitude between the models.

The calculated peak value based on the assumption of forced-type wind force is larger than the experimental value by 20%. The result suggests that the spanwise correlation of vortex force is not negligible, in other words, the strip theory is not strictly applicable when forced-type wind force is dominant. In the study, the calculated amplitude from Eq.(1) with the assumption that the strip theory is applicable is tried to be corrected by the observed data on surface pressure of the vibrating model. Pressure taps were set on the upper surface of Model B1, and the spanwise correlation of surface pressure was measured when the taut strip model is vibrating in vertical symmetric 1st mode. **Fig.4** shows the test results on spatial correlation when the non-dimensional amplitude, Y / B, is 0.02. It is found from the figure that the larger two points separation is, the smaller the correlation becomes just like the test results on a rigid circular cylinder model[3].

When the surface wind pressures during vibration at two different points are assumed to be $P_1(t) = P_1^* \sin \omega t$, $P_2(t) = P_2^* \sin(\omega t - \alpha)$, respectively where α is phase lag, the correlation coefficient between the two dynamic pressures is expressed by

$$C_{12} = \cos \alpha \tag{3}$$

By using Eq.(3), the spatial correlation coefficient as shown in **Fig.4** can be replaced with the value of phase lag between two points, which enables to obtain the correction factor on spanwise correlation of vortex force, K_c, as follows;

$$K_c = \int_0^l |\phi(x)| \cos \alpha(x) dx \,/ \int_0^l |\phi(x)| dx \tag{4}$$

The correction factor, K_c, calculated by Eq.(4) using the test results in **Fig.4** becomes 0.8. When the calculated peak amplitude by Eq.(1) in **Fig.3** is corrected by $K_c = 0.8$, it falls in an agreement with the experimental result of taut strip model test. These results suggest that the wind forces are properly formulated, and that the correction method on correlation proposed in the study is effective in case of forced-type vibration. In the case of Model A1 which causes self-excited type vibration, on the other hand, it is found that the correlation coefficient does not decrease remarkably with two points separation, that is, $K_c \fallingdotseq 1.0$.

It is also found from **Fig.3** that the peak amplitude corrected by the formula, $K_m = 4 / \pi$, is larger than the experimental value by 10%, which suggests that this simple formula gives safety-side estimation in the cases of Model B1 and B1-S2, too.

3.TURBULENCE EFFECT ON VORTEX-INDUCED VIBRATION OF BRIDGE GIRDER

(1) Effect of turbulence intensity

a) Method of wind tunnel test

In the study, 16 types of cross sections including basic configuration are selected and modeled as representative ones of bridge girder as shown in **Table 2** and **Fig.5**, and the effect of turbulence intensity on the amplitude of vortex-induced vibration is investigated. The tests on Model B1-2～B1-6 are conducted to study the effect of the cantilevered length of box girder. Model HX-2～HX-5 are the cases to clarify the effect of the slenderness ratio of flat hexagonal cross sections for which it has been found that turbulence exceptionally amplifies vortex-induced vibration[11]. In the tests, curbs are modeled, but guard rails whose effect is considered to be comparatively small are neglected.

Turbulence effect is investigated by comparing the amplitude of taut strip model in grid turbulent flow with that in smooth flow. This method enables to change the parameter of turbulence intensity under the condition of comparatively large turbulence scale. **Table 2** shows the experimental cases and conditions where Reynolds number, $\mathrm{Re}(= UD / \nu)$, is 6×10^3～1.5×10^4, and wind tunnel blockage ratio is 1.8% at the largest. The magnitude of turbulence intensity is adjusted by changing the distance between the taut strip model and coarse grid (bar size b=50mm, mesh size M=200mm). The value of turbulence scale also changes with distance as shown in **Table 3**, but this effect is considered to be small enough to be neglected in comparison with that of turbulence intensity.

b)Test results and discussion

Fig.6 shows the relation between turbulent intensity, Iu, Iw (%), and the correction factor on turbulence effect, K_t (peak amplitude in turbulent flow / that in smooth flow), for Model A1～HX in **Table 2**. It is found from the figure that turbulence intensity remarkably affects the amplitude of vortex-induced vibration, that is, the increase in turbulence intensity induces the remarkable decrease in response amplitude for most cross sections such as Model B1 in contrast with the case of Model HX, and that the effect is comparatively small for Model A1, which have been already pointed out in the previous studies[4)～9)].

Fig.7 shows the test results of Model B1-2～B1-6 (**Table 2**) together with that of Model A1. It is found from the figure that the decrease in response amplitude due to turbulence intensity is not so remarkable for bluff bodies whose slenderness ratio B/D≦2, but that turbulence intensity sensitively decreases amplitude in the cases of B/D ＞2. It is supposed in the cases of bluff cross sections that the large separation bubble would not be reattached by

Table 2 Experimental cases and their conditions. (Effect of turbulence intensity)

Case no.	Mod-el	B/D	Attack angle	Test method	Scruton No. $m\delta_0/(\rho B^2)$	Flow
2-1	A1	2.0	0°		0.8～1.6	
2-2	A2	4.0	0°		0.8～1.5	
2-3	B1	3.8	0°		0.4～0.5	
2-4	B2	5.4	+4°		0.4～0.5	
2-5	B3	6.5	+7°		0.7～1.6	
2-6	DB	5.4	+4°		0.4～0.6	
2-7	HX	3.8	0°		0.4～0.9	
2-8	B1-2	1.4	0°		0.8～1.8	Grid Table 3
2-9	B1-3	1.9	0°	Taut strip	0.5～1.4	
2-10	B1-4	2.4	0°		0.4～1.1	
2-11	B1-5	2.8	0°		0.3～1.3	
2-12	B1-6	3.3	0°		0.3～1.3	
2-13	HX-2	2.8	0°		0.2～1.1	
2-14	HX-3	3.3	0°		0.3～0.8	
2-15	HX-4	4.2	0°		0.2～0.8	
2-16	HX-5	4.7	0°		0.2～0.7	

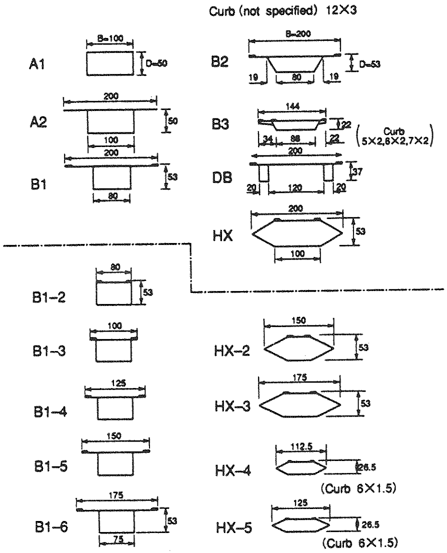


Fig.5 Cross section of models. (Effect of turbulence intensity)

Table 3 Flow characteristics. (Effect of turbulence intensity)

	Turbu. intensity, %		Turbu. scale (cm)		
	Iu	Iw	L_x^u	L_y^u	L_x^w
Smooth	0.2～0.3 (0.3)	0.2～0.5 (0.3)	—	—	—
Grid $X_G/M=20$	4.9～5.7 (5)	3.9～4.3 (4)	14～15 (15)	5～9 (7)	5 (5)
Grid $X_G/M=10$	8.7～9.6 (9)	6.4～7.0 (7)	4～14 (11)	3～4 (3)	4 (4)

1)Measured at z=0.7m where taut strip model was installed. 2)X_G: Distance between grid and model, M: Mesh size of grid. (200mm)

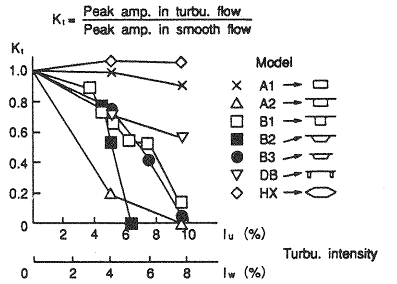


Fig.6 Variation of K_t with turbu. intensity for Models A1～HX

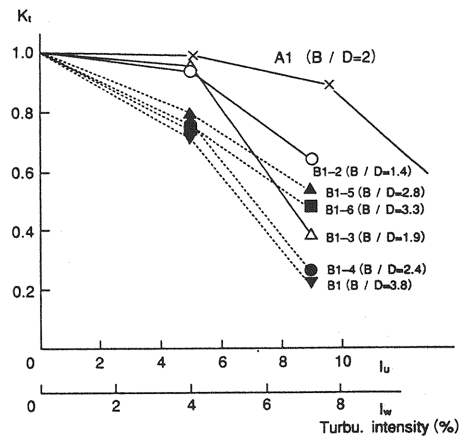
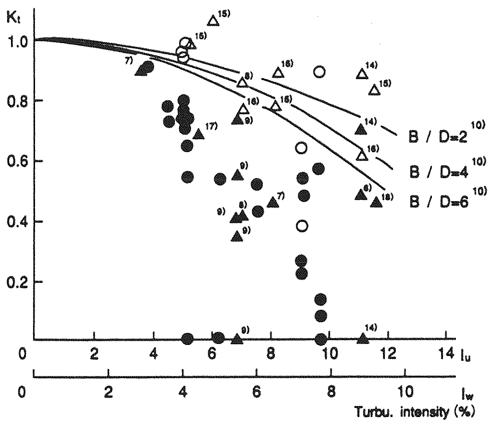


Fig.7 Variation of K_t with turbu. intensity for Model B1 series and Model A1

turbulence, which results in smaller effect on response amplitude. On the other hand, in flat cross sections with B/D>2 where reattachment type vortex-induced vibration is supposed to occur, the reattachment point may be sensitively moved to upstream position due to turbulence, which relaxes the effect of separation bubble and may result in the reduction of response amplitude. For further study, the values of correction factor, K_t, are classified for B/D ≦2 and B/D>2, and plotted vs. turbulence intensity including the data in the previous studies[6)~9),14)~18)], and recommended values in "*Wind Resistant Manual for Highway Bridges*"[10)] as shown in **Fig.8**. The figure shows that the tendency observed in the models of box girder with cantilevered deck (**Fig.7**) is also found in other cross sections, that is, it can be concluded that turbulence effect on response amplitude of vortex-induced vibration changes at the boundary of slenderness ratio B/D≒2. It is also found that the recommended value[10)] gives moderately safety-side estimation for the models of B/D>2, and averaged-value one for those of B/D≦2.

Fig.9 and **Fig.10** show the test results of Model HX-2～HX-5 (**Table 2**) varying the parameter of slenderness ratio B/D. The figures show the relation between the correction factor on turbulence effect, K_t, and turbulence intensity



$B/D \leqq 2$; ○ Present study, △ from other studies*)
$B/D > 2$; ● Present study, ▲ from other studies*)
*) The number corresponds to the reference number

Fig.8 Effect of B/D on K_t for various models. (Model HX series excluded)

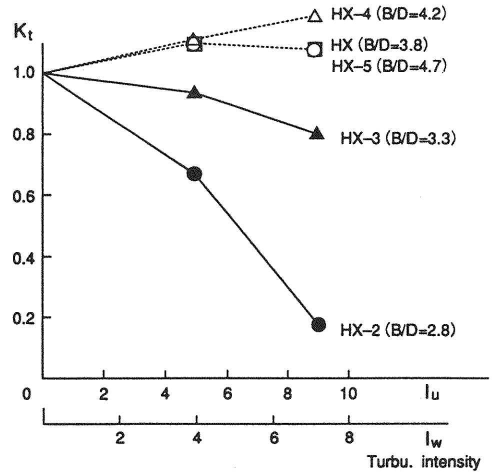
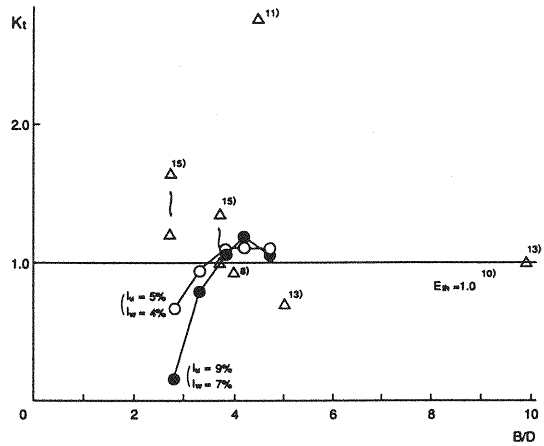


Fig.9 Variation of K_t with turbu. intensity for Model HX series



○● : Present study, △ : from other studies

Fig.10 Effect of width to depth ratio (B/D) on K_t for Model HX series

and slenderness ratio (B/D), respectively. The values presented in the previous studies[8),10),11),13),15)] are also plotted in **Fig.10**. It is found from the figures that turbulence effect changes characteristics at the boundary value of B/D ≒3.5, that is, turbulence amplifies the amplitude of vortex-induced vibration when B/D>3.5, and the increase in turbulence intensity induces the decrease in amplitude like most other cross sections when B/D<3.5. In case of flat hexagonal cross sections whose B/D>3.5, the effect of secondary vortices separated from the trailing edge is more dominant than those from the leading one[19)], so the reattachment effect of turbulence may not directly affect the wind forces. In case of B/D<3.5 where separation bubble from the leading edge is dominant, the movement of reattachment point to upstream position due to turbulence is considered to decrease the amplitude. However, the data in the references do not always agree with those in the present study as shown in **Fig.10**. In case of hexagonal cross section, it has been pointed out that turbulence effect largely depends on the shape and position of curb and guard rail[11)]. The turbulence effect on hexagonal cross section may be so complicated that it cannot be sufficiently identified by single parameter of B/D. Also, the value of K_t=1.0 is recommended in "*Wind Resistant Manual for Highway Bridges*"[10)] as shown in **Fig.10**, which requires further study, for it is found that turbulence sometimes amplifies vortex-induced vibration on this kind of cross section.

(2) Effect of turbulence scale

a) Method of wind tunnel test

Wind tunnel tests on Model A1 and Model B1 (**Fig.5**) were conducted in order to investigate the effect of turbulence scale on the amplitude of vortex-induced vibration. Experimental cases and their conditions are shown in **Table 4** and **Fig.11**, and the characteristics of the grid and boundary layer turbulent flows are shown in **Table 5**. The nondimensional parameter on turbulence scale, L_x^u/B, could be varied quite widely (0.3~6.8 for Model A1) because both the turbulence scale L_x^u and the width of the model B were changed. The peak frequency of the power spectrum of grid turbulent flow roughly falls in an agreement with the natural frequency of the model, but, the peak frequency is obliged to be smaller than the natural frequency of the model in case of boundary layer turbulent flow due to experimental difficulty.

The above-mentioned method must be carefully conducted to assure accuracy. First, not only turbulence scale but also the ratio of vertical turbulence intensity to

Table 4 Experimental cases and their conditions. (Effect of turbulence scale)

Case no.	Model	Test method	Scruton No. $m\delta_o/(\rho B^2)$	Flow Type	L_x^u/B Iu=5%	L_x^u/B 9%
3-1	A1-S2	Spring-mounted	2.6~5.2	Grid Table 5	0.3	0.3
3-2	A1-S3	Spring-mounted	2.6~5.2	Grid Table 5	0.7	0.5
3-3	A1	Taut strip	0.8~1.6	Grid Table 3	1.5	1.1
3-4	A1-S4	Taut strip	0.8~4.4	Grid Table 3	3.0	2.2
3-5	A1-S3	Taut strip	0.8~1.6	Boundary layer Table 5	2.3	
3-6	A1	Taut strip	0.8~1.6	Boundary layer Table 5	3.4	
3-7	A1-S4	Taut strip	0.8~1.6	Boundary layer Table 5	6.8	
3-8	B1-S2	Spring-Mounted	1.3~2.3	Grid Table 5	0.2	0.2
3-9	B1-S3	Spring-Mounted	1.3~2.3	Grid Table 5	0.4	0.3
3-10	B1	Taut strip	0.4~0.5	Grid Table 3	0.8	0.6
3-11	B1	Taut strip	0.4~0.5	Boundary layer Table 5	1.7	

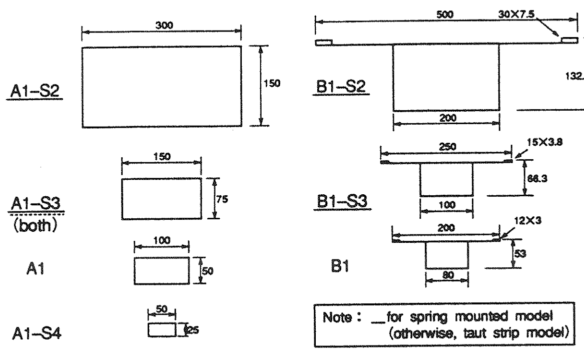


Fig.11 Cross section of models. (Effect of turbulence scale)

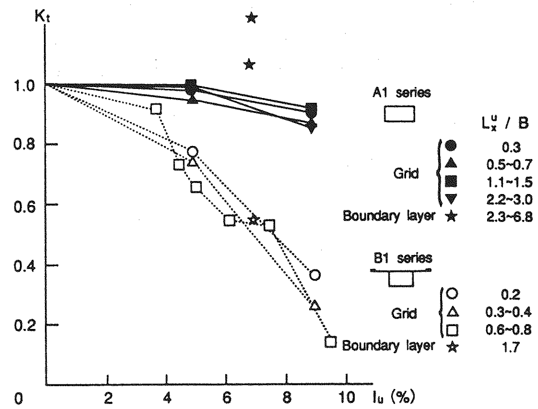


Fig.12 Variation of K_t with turbu. intensity for different values of turbu. scale

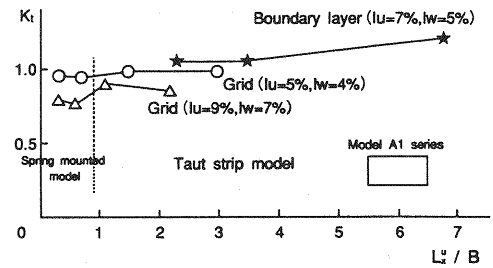


Fig.13 Effect of turbu. scale on K_t for Model A1 series

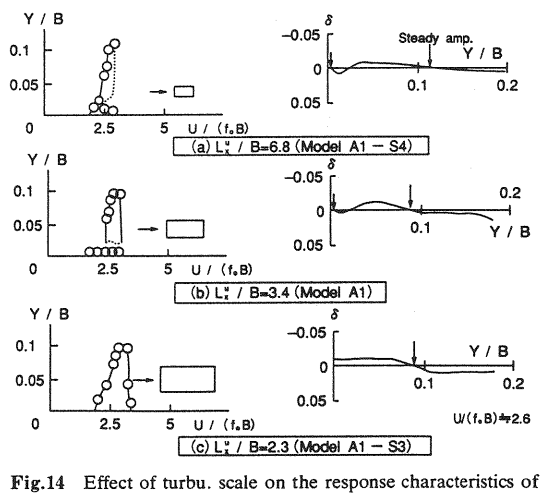


Fig.14 Effect of turbu. scale on the response characteristics of Model A1 series. (Boundary layer turbu. flow ; $Iu=7\%$, $Iw=5\%$)

Table 5 Flow characteristics. (Effect of turbulence scale)

	Turbu. intensity,% Iu	Turbu. intensity,% Iw	Turbu. scale (cm) L_x^u	Turbu. scale (cm) L_y^u	Turbu. scale (cm) L_x^w
Smooth[1)]	0.1~0.8 (0.2)	0.1~0.8 (0.3)	—	—	—
Grid[1)] $X_G/M=20$	4.5~5.9 (5)	3.2~4.6 (4)	9~12 (10)	3~5 (5)	6~8 (7)
Grid[1)] $X_G/M=10$	8.0~9.6 (9)	6.5~8.1 (7)	7~9 (8)	2~6 (3)	6 (6)
Boundary layer[2)]	6.2~8.5 (7)	4.7~5.7 (5)	21~49 (34)	7~15 (10)	11 (11)

1)Measured at z=1m where spring-mounted model was installed. 2)At z=0.7m, taut strip model.
3)( ):Mean value.

longitudinal (along-wind) one, Iw / Iu, differs between grid and boundary layer turbulent flows, which must be carefully taken into consideration to discuss the test results. Also, the effects of Reynolds number and wind tunnel blockage on the amplitude of vortex-induced vibration must be considered because the wind tunnel test is to be conducted varying the size of models. In fact, the Reynolds number of spring-mounted model test (9×10^3~

2.7×10^4) is roughly equal to that of taut strip model test ($6\times10^3\sim1.5\times10^4$), and the wind tunnel blockage ratio is as small as 5% at the largest (Model A1-S2). Accordingly, the effect of turbulence scale can be estimated with accuracy by a series of wind tunnel tests shown in **Table 4**.

b)Test results and discussion

Fig.12 shows the relation between longitudinal turbulence intensity, Iu, and the correction factor on turbulence effect, K_t, for both Model A1 series and Model B1 series varying the parameter of non-dimensional turbulence scale, L_x^u/B. **Fig.13** shows the variation of K_t with L_x^u/B for Model A1 series. It is found from these test results that turbulence scale does not affect the amplitude of vortex-induced vibration significantly though the amplitude slightly tends to increase with the increase in turbulence scale in case of Model A1. In the figures, the amplitude of Model A1 in a boundary layer turbulent flow whose Iu=7% is larger than that of grid turbulent flow whose Iu=5%, which seems singular considering the test results on the effect of turbulence intensity. One of the reasons may come from the difference in the ratio of Iw/Iu between the two kinds of turbulent flows.

Fig.14 shows the effect of turbulence scale on the response characteristics of Model A1 series found during the taut strip model tests in boundary layer turbulent flows. In the figure, not only the variation of response amplitude with wind speed but also aerodynamic damping δ at around the peak amplitude is shown. It is found that turbulence scale clearly changes the characteristics of unstable limit cycle which is peculiar to Model A1 (rectangular cross section whose B/D=2).

The test results mentioned above suggest that the effect of turbulence scale on the peak amplitude of vortex-induced vibration is smaller than that of turbulence intensity, but it is desired to simulate the parameter of turbulence scale as well if possible to estimate vortex-induced vibration more accurately.

4. OBSERVATION OF THE AERODYNAMIC BEHAVIOUR OF A CABLE-STAYED BRIDGE

(1) Aerodynamic stability of the bridge

Spring-mounted model test was carried out on the cable-stayed bridge shown in **Fig.15**, and it was found that vortex-induced vibration possibly occur at the wind speed of around 10m/s[20]. In the wind tunnel test, flap and fairing were found to be effective to suppress the vibration, but it was determined that the aerodynamic behaviour of the bridge be observed without installing these aerodynamic devices so as to find the necessity of them. Consequently, this bridge gave us most desirable chance to examine the reliability of wind tunnel test, and the estimation method on

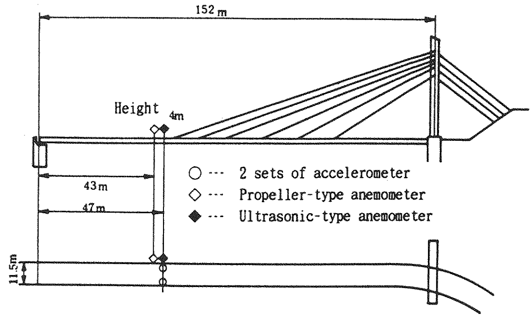


Fig.15 Measurement of wind velocity and girder vibration

Table 6 Experimental cases and their conditions. (Observation of prototype bridge)

Case no.	Model	Attack angle	Test method	Scruton No. $m\delta_o/(\rho B^2)$	Flow
4-1	B3-S2 (S=1/25)	-7°～+7°	Spring-mounted	0.8～1.1	Smooth
4-2	B3 (S=1/80) [Fig.5]	+7°	Taut strip	0.7～1.6	Grid Table 3
4-3					Boundary layer Table 5

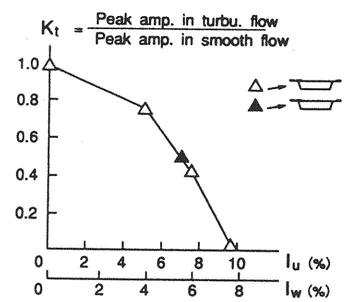


Fig.16 Variation of K_t with turbu. intensity

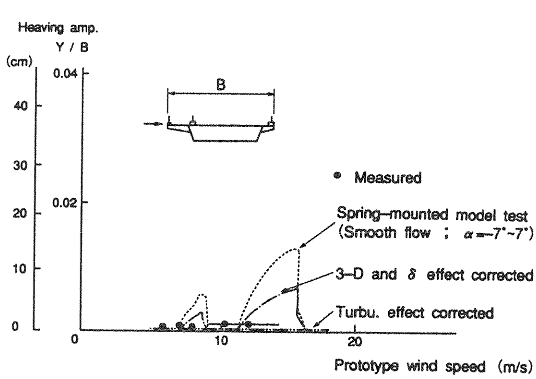


Fig.17 Comparison of measured response with predicted one from wind tunnel test

3-dimensional effect and turbulence effect proposed in the present study.

(2) Method of observation of aerodynamic behaviour and the results

Wind direction, wind speed and acceleration of girder were measured to make clear the relation between wind and girder vibration of vertical 1st mode as shown in **Fig.15**. Wind direction and wind speed were measured by propeller-type anemometer and ultrasonic-type one which were installed at 4m height above road surface to avoid the effect of girder, and girder vibration was measured by 2 sets of accelerometer installed inside of the box girder. In the observation, longitudinal (along-wind) and vertical turbulence intensity was Iu=30～45%, Iw=20～45% respectively, which are much larger than the assumed values in wind tunnel test (Iu≒10%, Iw≒5%). This may be because the bridge is constructed in inland areas, and observed wind speed range is low. Turbulence scale calculated from the measured power spectrum is L_x^u=20～30m.

Fig.17 shows the measured response comparing with the predicted one from wind tunnel test which is spring-mounted model test **(Table 6)**. The predicted response where the effects of structural damping and 3-dimensionality are considered is shown, and in addition, the one where turbulence effect is further taken into consideration is also plotted in the figure. The measured structural damping of the bridge is found to be δ_Y=0.04～0.065 which is 2～3 times larger than the assumed value δ_Y=0.02 in wind tunnel test, so the difference is corrected based on the Scruton number similarity. 3-dimensional effect is considered by the simple formula, K_m=4/π≒1.3, which is found to give safety-side prediction, considering that turbulence effect is much larger than 3-dimensional one. Because the measured turbulence intensity is quite large, the correction factor on turbulence, K_t, estimated from taut strip model test **(Table 6, Fig.16)** and recommended value in "*Wind Resistant Manual for Highway Bridges*"[10] turns out to be 0, which means that the bridge would not cause vortex-induced vibration under natural wind. It is observed that vortex-induced vibration tends to occur in the predicted wind speed range, but its amplitude is as small as the final prediction value. It is found from the above-mentioned results that the predicted vortex-induced vibration of the bridge from spring-mounted model test in smooth flow is suppressed by turbulence effect of natural wind. The results suggest the validity of the estimation method proposed in the present study, and the importance of taking turbulence effect into consideration when vortex-induced vibration under natural wind is estimated.

5. CONCLUDING REMARKS

a) 3-dimensional effect

In order to consider the effect of vibrational mode, it is effective to calculate the 3-dimensional amplitude based on the strip theory considering the dependence of wind forces on amplitude after identifying the type of wind forces (self-excited one or forced one) based on the observed data in conventional spring-mounted model test. When the forced-type wind force is dominant, it is found that the effect of spatial correlation causes about 20% reduction in amplitude. The recommended value in "*Wind Resistant Manual for Highway Bridges*" gives larger (safety-side) estimation regardless of the type of wind force.

b) Turbulence effect

The increase in turbulence intensity induces remarkable decrease in response amplitude in most cross sections whose slenderness ratio B/D>2 such as box girder with cantilevered deck. On the other hand, the effect is smaller in bluff bodies whose B/D≦2.

In hexagonal cross sections where exceptional tendency had been pointed out, it is found that the characteristics of turbulence effect change at the boundary value of B/D≒3.5. However, the turbulence effect on hexagonal cross section may be so complicated that it cannot be sufficiently identified by single parameter of B/D.

The test results suggest that the effect of turbulence scale is smaller than that of turbulence intensity. But, considering the fact that the characteristics of unstable limit cycle are clearly affected by turbulence scale, it is desired to simulate the parameter of turbulence scale as well if possible to estimate vortex-induced vibration more accurately.

c) Examination by field observation

The aerodynamic behaviour of a cable-stayed bridge whose main span length is about 150m was observed, and it is found that the predicted vortex-induced vibration of the bridge from spring-mounted model test in smooth flow is suppressed by turbulence effect of natural wind. The results suggest the validity of the estimation method proposed in the present study, and the importance of taking turbulence effect into consideration when vortex-induced vibration under natural wind is estimated.

REFERENCES

1) Yamada, H. and Tanaka, H. : Mass Simulation Requirement of Sectional Model Testings and Estimation of Responses of a Full Bridge Model, *J. Struct. Mech. Earthquake Eng.* No.380/I-7, pp.341～348, 1987.
2) Hikami, S. and Suzuki, T. : Applicability of Strip Theory to the Estimation of Vortex-induced Vibration, *38th Annual Conference of the Japan Society of Civil Engineers*, pp.599～600,1983.
3) Novak, M. and Tanaka, H. : Pressure Correlations on a Vibrating Cylinder, *Proc. 4th Int. Conf. on Wind Effects on Buildings and Structures*, pp.227～232, 1975.

4) Takeda, K., Sonobe, Y. and Hashimoto, M. : Experimental Study to Estimate the Amplitude of Vortex-induced Vibration, *9th National Symposium on Wind Engineering*, pp.265～270,1986.

5) Miyata, T. and Yamada, H. : Flutter of Bridge Girder and Turbulence of Wind, *Bridge and Foundation Engineering*, 82-11, pp.10～17, 1982.

6) Wardlaw, R.L., Tanaka, H. and Utsunomiya, H. : Wind Tunnel Experiments on the Effects of Turbulence on the Aerodynamic Behaviour of Bridge Road Decks, *Proc. 6th Int. Conf. on Wind Engineering*, pp.247～257,1983.

7) Miyazaki, M. and Kazama, K. : The Effect of Turbulence on the Aerostatic and Aerodynamic Characteristics of Box Girder Bridges, *9th National Symposium on Wind Engineering*, pp.133～138, 1986.

8) Matsumoto, M., Shiraishi, N., Shirato, H., Mashimo, Y., Yukawa, M. and Hirai, S. : Effect of Turbulence on Aerodynamic Oscillation, *10th National Symposium on Wind Engineering*, pp.115～120, 1988.

9) Yokoyama, K., Sato, H. and Higashikubo, M. : Effects of Turbulence on Wind-induced Vibrations of Long-span Bridges, *10th National Symposium on Wind Engineering*, pp.313～318, 1988.

10) Japan Road Association : *Wind Resistant Manual for Highway Bridges*, 1991.

11) Matsumoto, M., Shiraishi, N. and Shirato, H. : Turbulence Unstabilization on Bridge Aerodynamics, *Innovation in Cable-Stayed Bridge*, Fukuoka, Japan, pp.175～183, 1991.

12) Kobayashi, H., Kawatani, M., Kim, H., Ota, K. and Uejima, H. : Effects of Turbulence Characteristics on Vortex-induced Oscillation of Two-dimensional Rectangular Cylinders, *11th National Symposium on Wind Engineering*, pp.167～172.

13) Civil Engineering, Kyoto University : *Investigation on the Wind-resistant Engineering Characteristics of Natural Strong Wind*, Association for Disaster Prevention Research, 1976.

14) Yamada, H. : *Identification and Estimation of Vortex-induced Responses of Shallow Bluff Bodies*, Thesis for a Doctor's Degree of the University of Tokyo, 1983.

15) Suzuki, T. and Hikami, S. : On the Relation between Turbulence Characteristics and Responsive Amplitude of Vortex-induced Vibration, *40th Annual Conference of the Japan Society of Civil Engineers*, pp.445～446, 1985.

16) Nakagami, Y. and Yamamoto, K. : Response of Taut Models of Rectangular Cylinders in Uniform and Turbulent Flows, *38th Annual Conference of the Japan Society of Civil Engineers*, pp.569～570, 1983.

17) Public Works Research Institute, the Ministry of Construction : *Investigation on the Wind-resistant Characteristics of Sapporo Ohashi*, Report of the Public Works Research Institute 2293,1986.

18) Public Works Research Institute, the Ministry of Construction : *Study on the Design and Construction of Honshu Shikoku Bridges*, Report of the Public Works Research Institute 1973, 1983.

19) Shiraishi, N. and Matsumoto, M. : On Vortex-induced Oscillations of Bluff Cross Sections Used for Bridge Structures, *J. Struct. Mech. Earthquake Eng.* No.322, pp.37～50, 1982.

20) Shimada, K. and Takeda, K. : On the Aerodynamic Stability of Chichibu Bridge, *16th Japan Road Conference*, pp.621～622, 1985.

21) Takeda, K. and Shimada, K. : Vibration Test and Observation of Aerodynamic Behaviour on Chichibu Bridge, *41st Annual Conference of the Japan Society of Civil Engineers*, pp.619～620, 1986.