IEXPERIMENTAL STUDY ON TURBULENCE PARTIAL SIMULATION FOR BLUFF BODY

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Wind-induced response/vibration of a bridge deck is governed by the surrounding flow field including flow separation and reattachment. It was also pointed out that the flow field is strongly affected by a small-scale turbulence component in an approaching flow. In wind-tunnel testing, in order to simulate turbulence effects, turbulence intensity is usually simulated. However the simulation of the power spectral density (PSD) of a small-scale turbulence component (high-frequency sub-inertia range), the so-called "turbulence partial simulation" may be a more rational way. In fact, past studies suggested that the turbulence partial simulation could give a better explanation for bridge deck vortex-induced vibration response between full scale and wind-tunnel test. In this study, using "reduced turbulence intensity", the turbulence partial simulation was experimentally investigated for bluff-body structures. Results showed that reduced turbulence intensity could represent turbulence effects to the same degree as could turbulence intensity do. In addition, it was observed that a small-scale turbulence component governed the flow field around a bluff body.

Keyword: turbulence partial simulation, bluff body, small-scale turbulence, wind-tunnel test

1. INTRODUCTION

Wind-induced response/vibration of a bridge deck is governed by the surrounding flow field including flow separation and reattachment. It was also pointed out that the flow field is strongly affected by a small-scale turbulence component in an approaching flow[1)]. In wind-tunnel testing, in order to simulate turbulence effects, simulation of turbulence intensity is practically adopted. However the simulation of the power spectral density (PSD) of a small-scale turbulence component (high-frequency sub-inertia range), the so-called "turbulence partial simulation" may be a more rational way. In fact, Irwin et al. suggested that the turbulence partial simulation could give a better explanation for bridge deck vortex-induced vibration response between full scale and wind-tunnel test[2, 3, 4)].

In this study, using "reduced turbulence intensity", the turbulence partial simulation was experimentally investigated for bluff-body structures. For that purpose, more than 10 different turbulent flows with different intensity and integral scale were generated by grids. Then wind-tunnel tests were conducted for the following items. Measurement results were examined in terms of turbulence intensity, integral scale and reduced turbulence intensity.

1) Base pressure of rectangular cylinder (B/D = 0.26 – 0.98)
2) Surface pressure and static coefficient of bridge deck (B/D = 5 and 7.5)
3) Surface pressure and PIV test of rectangular cylinder (B/D = 2 and 3)

where B/D is slenderness ratio of bluff bodies.

2. TURBULENCE PARTIAL SIMULATION

Turbulence flow can be perfectly simulated in a wind tunnel if its PSD is simulated over all frequency range. However, due particularly to the wind-tunnel size, the turbulence scale generated in a wind tunnel is usually much smaller than that of full-scale turbulence. Therefore, it is very difficult to simulate the low-frequency part of that (large-scale turbulence) in a wind tunnel.

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Small-scale turbulence affects flow fields around a bluff body and therefore it governs characteristics of cross-sectional aerodynamics. On the other hand, large-scale turbulence will decrease span-wise correlation and change mean wind speed, which will decrease the amplitude and probability of wind-induced vibration. Disregard of large-scale turbulence effects will therefore be practically conservative. Considering these, one can suggest that the simulation of PSD in a high-frequency part might give a good explanation of the full-scale behavior in a wind-tunnel test.

Assuming the Karman-type PSD function (Eq. 1) and considering the simulation of a high-frequency part of it, Eq. 1 is transformed to Eq. 2.

$$\frac{fS_u}{\sigma_u^2} = \frac{4\left(fL_u{}^x/U\right)}{\left(1+70.8\left(fL_u{}^x/U\right)^2\right)^{5/6}} \tag{1}$$

$$\frac{fS_u}{U^2} \equiv I_u{}^2\left(\frac{f}{U}\right)^{-2/3}\left(L_u^x\right)^{-2/3} \tag{2}$$

where f is frequency, U is wind speed, I_u is turbulence intensity and L_u^x is turbulence scale.

Quantity f/U has an inverse dimension of length, then replacing f/U by $1/D$ (D: representative length) transforms Eq. 2 to Eq. 3. Therefore, simulating or equating a reduced PSD yields a similarity law as in Eq. 4.

$$\frac{fS_u}{U^2} = \left[\frac{I_u}{\left(L_u^x/D\right)^{1/3}}\right]^2 \tag{3}$$

$$\frac{\left(I_u\right)_m}{\left(I_u\right)_p} = \left(\frac{\left(L_u{}^x/D\right)_m}{\left(L_u{}^x/D\right)_p}\right)^{1/3} \tag{4}$$

where subscripts m and p represent model and prototype (full scale), respectively.

From Eq. 4, if a turbulence scale ratio to the structural dimension in a wind tunnel $(L_u^x/D)_m$ is by one order smaller than that in the full scale, the similarity requirement for the turbulence intensity in the wind tunnel will be about half of that in the full scale, as shown in Fig. 1. This turbulence similarity requirement (referred to turbulence partial simulation) was suggested by Irwin[2, 4] and pointed out that the full-scale measurement by Macdonald et al.[3] might prove this.

Based on Eq. 4, a new similarity parameter "reduced turbulence intensity" calculated by turbulence intensity divided by the cubic root of the turbulence scale ratio (L_u^x/D) is introduced as shown in Eq. 5. It is understood that the similitude of reduced turbulence intensity represents the turbulence partial simulation.

$$I_r = \frac{I_u}{\left(L_u{}^x/D\right)^{1/3}} \tag{5}$$

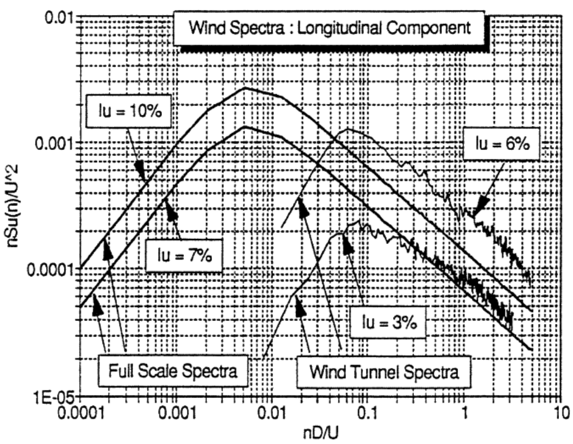


Figure 1: Turbulence partial simulation[2)]

3. BASE PRESSURE OF RECTANGULAR CYLINDER[5)]

(1) Base pressure coefficient

Wind-induced response of a bluff body is governed by the flow field around the body and it was thought that base pressure rather than the response would be sensitive to the change of the flow field and that base pressure coefficient would be a good indicator to judge whether the partial simulation is satisfied or not. Base pressure was compared under various combinations of turbulence properties (intensity and scale).

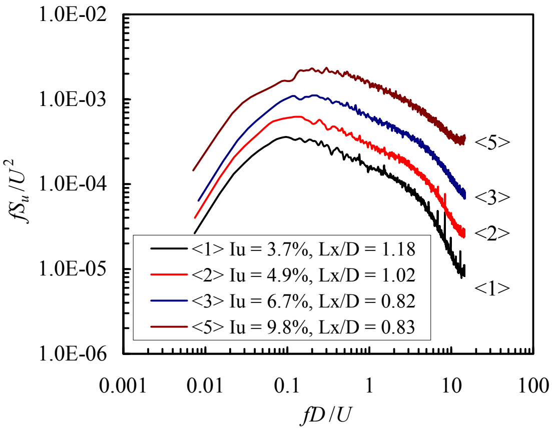
Table 1 shows the turbulence properties generated and Fig. 2 shows their PSD. Three different size of a rectangular cylinder (projection height D = 3, 6 and 9 cm) was used in order to cover the wide range of the turbulence scale ratio to the model size. Of those combinations with the different turbulences and model sizes in Table 1, two series of combinations were chosen to investigate the small-scale turbulence simulation. First series are different turbulence-intensity flows, PSDs of which do not coincide with each other as shown in Fig. 2(a). Second series are turbulence flows with the same PSD in a high-frequency part as shown in Fig. 2(b). After all, comparisons were made in model cases of D = 9cm as shown in Table 1.

The base pressure was measured at a 100Hz sampling frequency for 300 seconds. The Reynolds number at the measurement was approximately 3.7×10^4 with respect to the model height D. In order to correct the wind-tunnel blockage effect, correction factors were obtained from the base-pressure measurement results of the different model size at each B/D ratio based on Ref. 6). For the sake of brevity, the base-pressure coefficient represents the corrected one hereinafter.

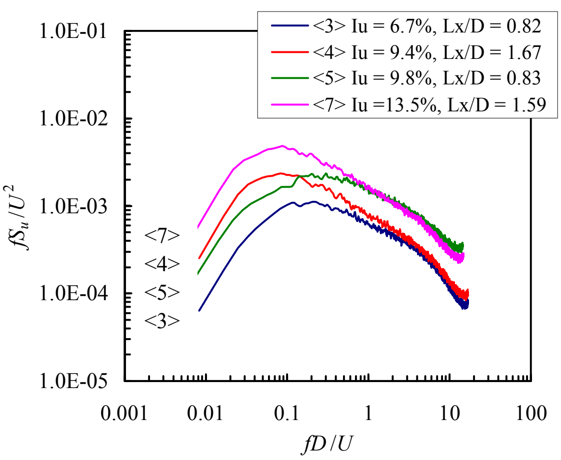
Table 1: Properties of turbulence generated

Turbulence intensity I_u (%)	Turbulence scale L_x (cm)	Ratio of turbulence scale and model scale (L_x / D)		
		D = 3cm	D = 6cm	D = 9cm
3.7	10.6	3.53	1.77	1.18 <1>
4.9	9.2	3.07	1.53	1.02 <2>
6.7	7.4	2.47	1.23	0.82 <3>
9.4	15.0	5.0	2.50	1.67 <4>
9.8	7.5	2.50	1.25	0.83 <5>
10.8	16.6	5.53	2.77	1.84 <6>
13.5	14.3	4.77	2.38	1.59 <7>
Smooth	—	—	—	—

* The number in < > is referred to in Fig. 1.



(a) Different turbulence intensity series



(b) Small-scale turbulence simulation series

Figure 2: Power spectral density of wind-tunnel turbulence

Fig. 3 shows the comparisons of C_{pb} in turbulent flows with different turbulence intensities but close turbulence scale together with that in a smooth flow. Negative peak of C_{pb} at around 5.5 of B/D can be seen as pointed out by past studies[7, 8]. It can be seen that C_{pb} for B/D less than the critical value is not so much different but that C_{pb} at and larger than the critical value becomes large (to positive value) as the turbulence intensity becomes large. This may result from the enhancement of interaction of shear layers with small eddies around the cylinder by the increase of turbulence intensity. In addition, the critical slenderness ratio of B/D moves to lower B/D as the turbulence intensity increases.

Fig. 4 shows the comparisons of C_{pb} for partially simulated turbulences. As shown in Fig.2 (b), turbulences <3> and <4>, and <5> and <7> are pairs of turbulences with PSD simulated in a high-frequency part. These two pairs hold the relationship of Eq. 4. It can be seen that C_{pb} at and larger than the critical slenderness ration of B/D is almost identical for the partially simulated turbulences. This fact proves that flow patterns around a rectangular cylinder can be simulated if turbulence is simulated in a high-frequency part, in other word, the turbulence partial simulation can be achieved. However C_{pb} in Figs. 3 and 4 covers B/D ranging from 0.26 to 0.98 which is much smaller than a typical value of a bridge deck ($B/D > 3$).

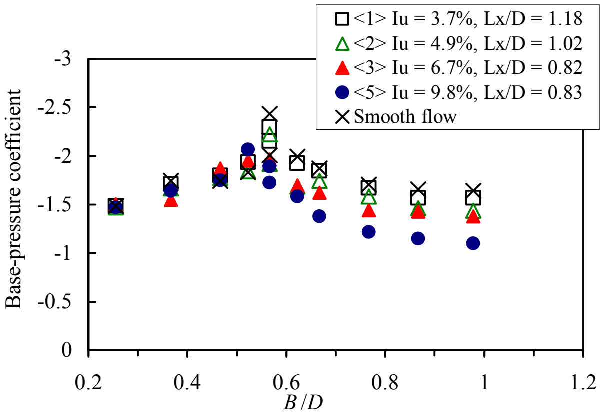


Figure 3: Comparison of C_{pb} in different turbulence intensity

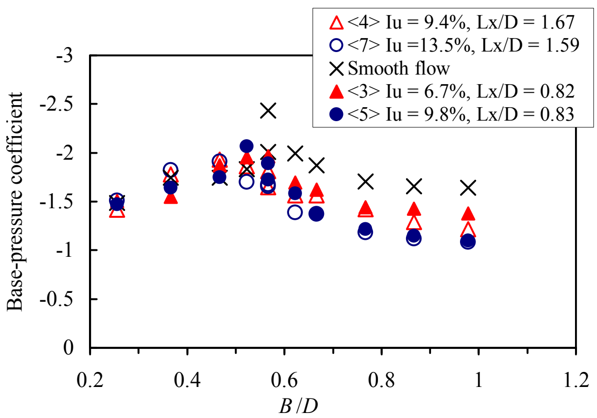


Figure 4: Comparison of C_{pb} in partially-simulated turbulence

(2) Reduced turbulence intensity

In order to investigate turbulence partial simulation quantitatively, base pressure of rectangular cylinders was measured similarly to the previous section (1) and examined by reduced turbulence intensity. PSDs of turbulences (1, 2 & 3), (4, 5 & 6) and (7 & 8) in a high-frequency part coincide as shown in Fig. 5 and they are partially simulated turbulence groups. Table 2 shows the reduced turbulence intensity for those turbulences. It can be recognized that reduced turbulence intensities for partially simulated turbulence groups have close values and therefore it can be an index of turbulence partial simulation.

Fig. 6 shows C_{pb} measured vs. slenderness ratios. It can be seen again that C_{pb} for partially simulated turbulence pairs fairly agree in a large slenderness ratio range. Fig. 7 shows C_{pb} vs. the reduced turbulence intensity where broken lines are linear regression lines. Results for the slenderness ratio greater than the critical value are only shown. It can be seen that C_{pb} changes linearly against the reduced turbulence intensity. It was also checked that C_{pb} has a linear relationship with turbulence intensity and turbulence scale as shown in Figs. 8 and 9, respectively. However, the degree of linear regression in cases of turbulence intensity and turbulence scale is less than the case of reduced turbulence intensity. Based on these observations, the effects of turbulence on the base pressure can be represented by reduced turbulence intensity and in turn the flow field around a rectangular cylinder can be simulated by the turbulence partial simulation method.

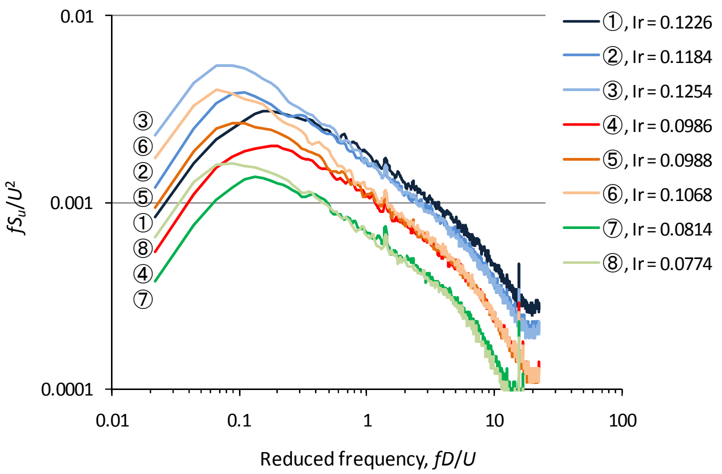


Figure 5: PSD of wind-tunnel turbulences

Table 2: Properties of turbulence flows

No.	I_u (%)	L_u^x (m)	I_r
①	11.11	0.067	0.1226
②	11.84	0.090	0.1184
③	13.76	0.119	0.1254
④	8.85	0.065	0.0986
⑤	9.99	0.093	0.0988
⑥	11.76	0.120	0.1068
⑦	7.23	0.063	0.0814
⑧	7.96	0.098	0.0774

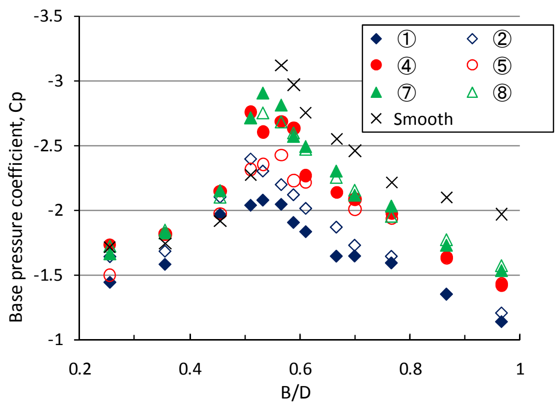


Figure 6: Base pressure coefficients vs. slederness ratio

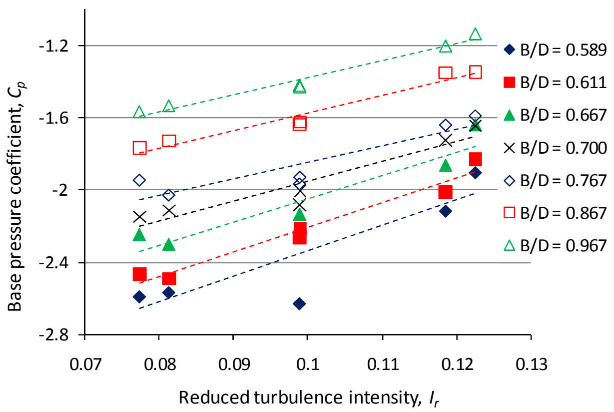


Figure 7: Base pressure coefficients vs. reduced turbulence intensity

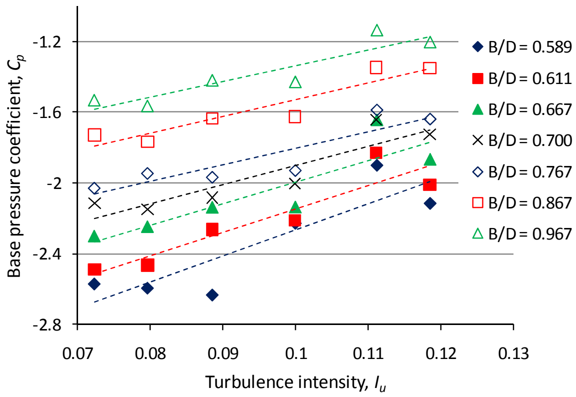


Figure 8: Base pressure coefficients vs. turbulence intensity

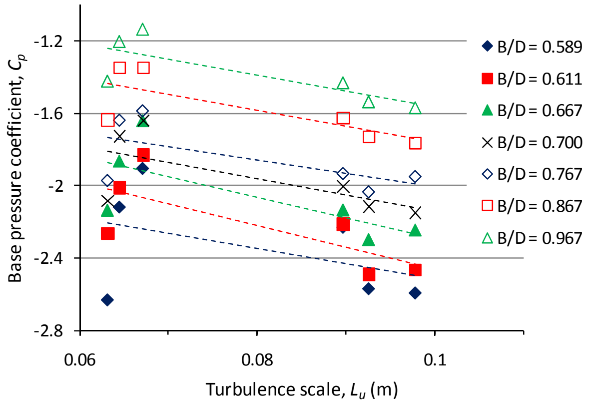


Figure 9: Base pressure coefficients vs. turbulence scale

4. SURFACE PRESSURE AND STATIC COEFFICIENT OF BRIDGE DECK[9)]

Turbulence partial simulation was also checked using a hexagonal bridge deck model as shown in Fig. 10. Two slenderness ratio models (B/D = 5 and 7.5, B = 0.3 m) were tested. Surface pressures at 38 points were measured at a wind speed of 10 m/s in partially simulated turbulences as shown in Table 2 and Fig. 5. Fig. 8 shows the distribution of mean surface pressure coefficients for B/D = 7.5 model at 0 degree angle of attack. Negative peak pressure was produced at just after the leading edge on the upper and lower surfaces. In addition, mean pressure coefficients are not so much different on leeward surfaces among different turbulence flows.

The negative peak pressure coefficients are plotted by reduced turbulence intensity, turbulence intensity and turbulence scale for B/D = 7.5 and 5 in Figs. 11 and 12, respectively. This is because the negative peak pressure represents a flow separation intensity, separation flow width and wind excitation force intensity. It can be seen that the negative peak pressure coefficients have the best linear relationship with reduced turbulence intensity. This implies that the flow field around the bridge deck can be simulated by the turbulence partial simulation, and that reduced turbulence intensity can be a simulation index.

Secondly, lift and pitching moment coefficients were calculated by integrating the surface pressures over the deck cross section in order to estimate the aerodynamic characteristics pseudo-dynamically. Figs. 13 and 14 show the slopes of lift and pitching moment coefficients at 0-degree angle of attack with reduced turbulence intensity, turbulence intensity and turbulence scale for B/D = 7.5 and 5, respectively. The slope was calculated as an average slope between -4 to +4 degrees. The slope of pitching moment coefficient is insensitive to turbulences while that of lift coefficient has a weaker linear relationship with each turbulence parameter. However, there is no significant difference among three turbulence parameters. This may be due to the fact that surface pressure distribution is not so different except for neighborhood of the separation point. Contrarily to the negative peak pressure, superiority of reduced turbulence intensity to turbulence intensity or turbulence scale was not observed. However it can be understood that the reduced turbulence intensity as well as turbulence intensity will be an index of turbulence simulation.

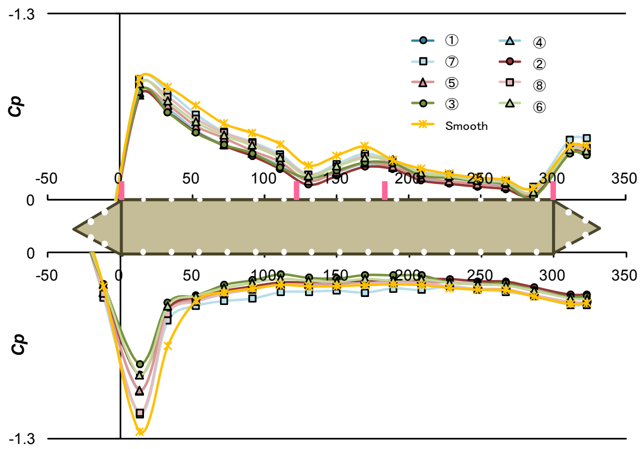
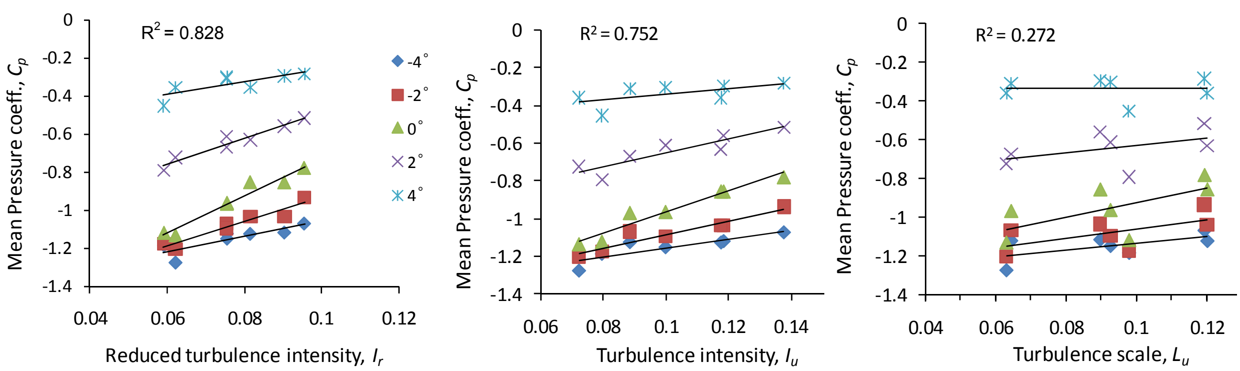
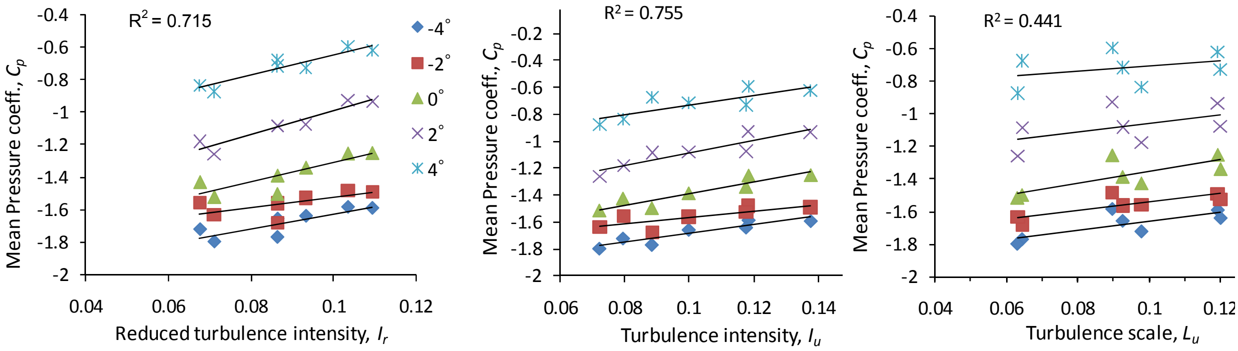


Figure 10: Bridge deck model and mean pressure distribution of B/D = 7.5



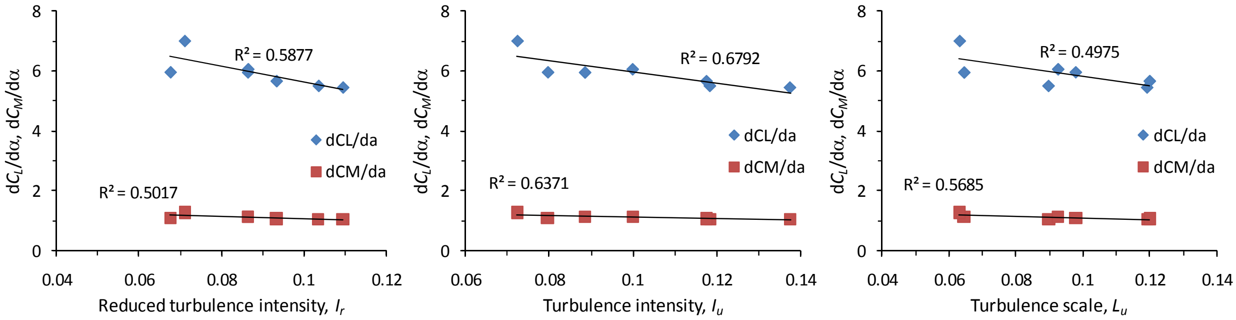
(a) Reduced turbulence intensity (b) Turbulence intensity (c) Turbulence scale

Figure 11: Negative peak pressure coefficient at separation point of lower surface for B/D = 7.5



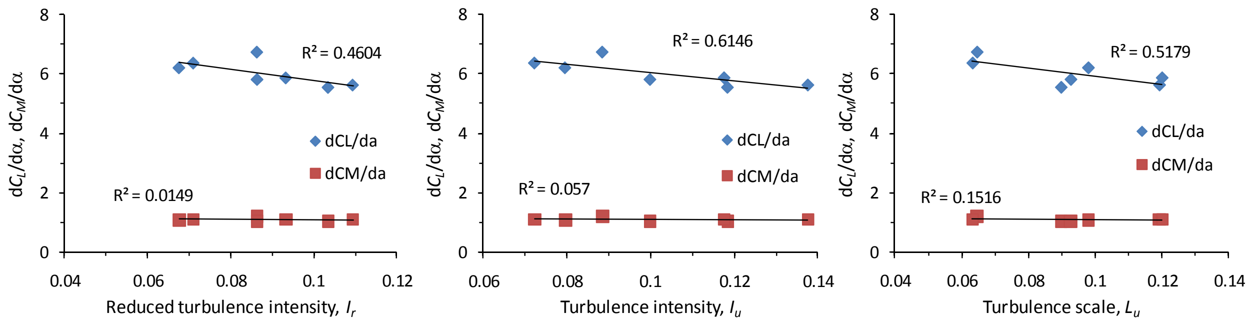
(a) Reduced turbulence intensity (b) Turbulence intensity (c) Turbulence scale

Figure 12: Negative peak pressure coefficient at separation point of lower surface for $B/D = 5$



(a) Reduced turbulence intensity (b) Turbulence intensity (c) Turbulence scale

Figure 13: Slope of lift and pitching moment coefficient for $B/D = 7.5$



(a) Reduced turbulence intensity (b) Turbulence intensity (c) Turbulence scale

Figure 14: Slope of lift and pitching moment coefficient for $B/D = 5$

5. SURFACE PRESSURE AND PIV TEST OF RECTANGULAR CYLINDER[10, 11)]

(1) Surface pressure

In order to understand more clearly the effects of the turbulence parameters on flow field around bluff bodies, surface pressures of rectangular cylinders of $B/D = 2$ and 3 were measured in various turbulent flows. Results were examined by focusing on the reduced turbulence intensity. Measurement was taken at wind speeds of 6 and 9 m/s, which is equivalent to Reynolds number of 40,000 and 60,000, respectively.

Figs. 15 and 16 show mean surface pressure coefficient around rectangular cylinder of $B/D = 2$ and 3, respectively. Surface pressures at the leading edge generally become smaller as the reduced turbulence intensity increases. On the other hand, surface pressures at the trailing edge become larger as the reduced turbulence intensity increases. This suggests that reattachment of the flow to the side surface is enhanced by turbulence. In addition, larger reduced turbulence intensity which is equivalent to larger small scale turbulence enhances the reattachment trend. Furthermore, peak location of the mean surface pressure coefficient was identified by fitting a sixth order polynomial equation. The peak locations on both top and bottom surfaces shift to the leading edge as the reduced turbulence intensity increases. Therefore, reduced turbulence intensity might be the better representative index of flow field around a rectangular cylinder.

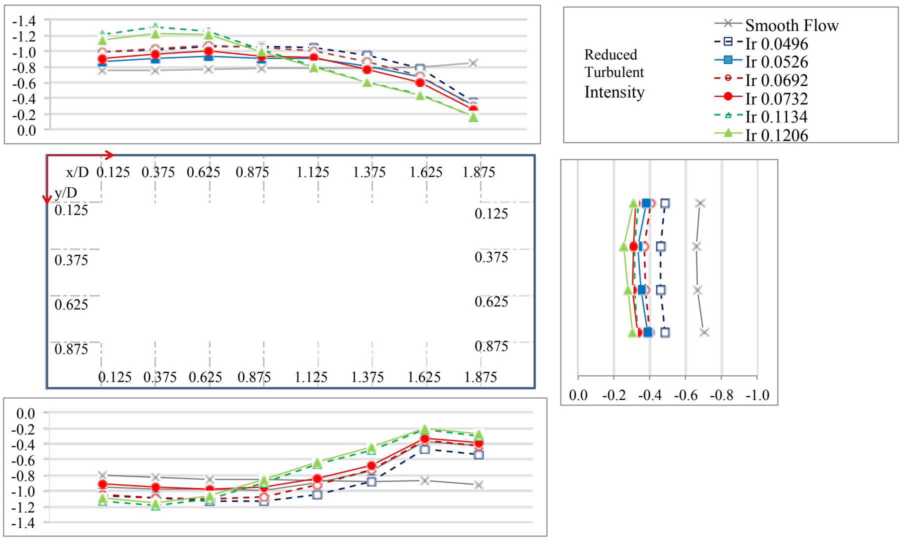


Figure 15: Mean surface pressure coefficients around a rectangular cylinder of *B*/*D* = 2

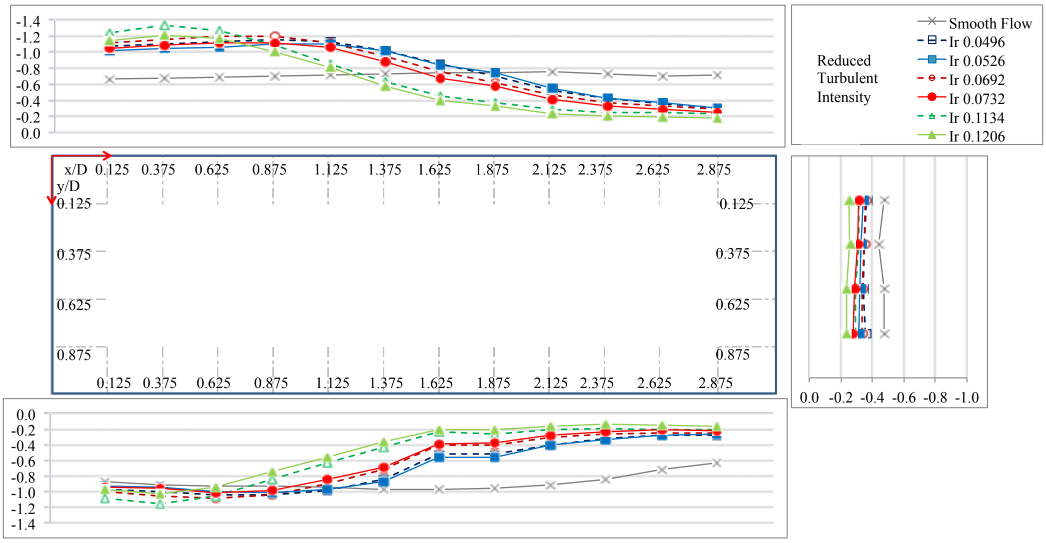
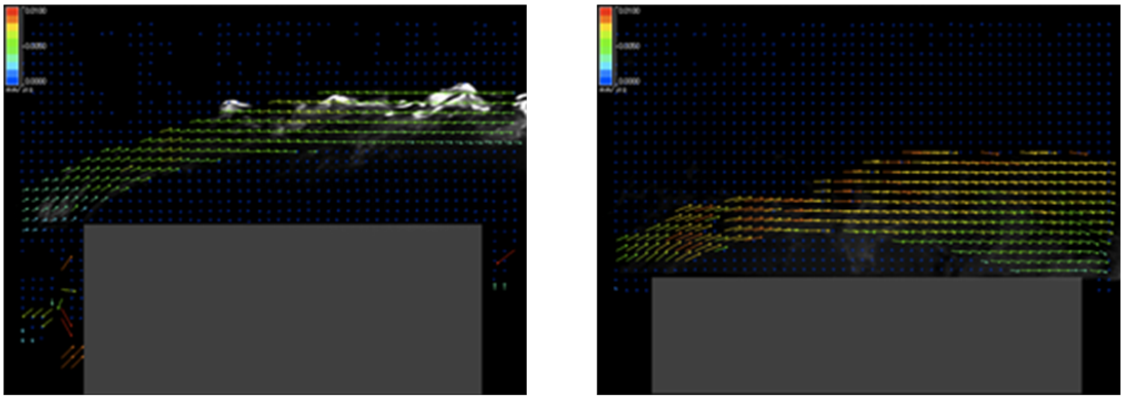


Figure 16: Mean surface pressure coefficients around a rectangular cylinder of *B*/*D* = 3

(2) PIV test

A PIV test was conducted to illustrate effects of small-scale turbulence on flow field around a rectangular cylinder. Measurement was done at wind speeds of 5 – 7 m/s, which is equivalent to Reynolds number of 52,500 – 73,500, respectively. Fig. 17 shows time-average velocity vector fields for a rectangular cylinder of B/D = 3. It can be seen that flow separates at the leading edge and does not reattach in a smooth flow case while flow reattaches at the trailing edge in a turbulent flow case.

Using this PIV test results, wind velocity data was taken and PSD was analyzed. Fig. 18 shows the peak frequency in PSD along the shear layer (shown by red circles) for different turbulent flows. Generally peak frequency increases near the leading edge while it decreases toward the trailing edge. Clear trend among different turbulent flows is not observed, larger reduced turbulence intensity shows lower peak frequency, however. It can also be understood that higher frequency component of turbulence (small-scale turbulence) enhances flow reattachment near the leading edge.



(a) Smooth flow at 5m/s (b) Reduced turbulence intensity of 0.1206 at 6m/s

Figure 17: Time-average velocity vector field for rectangular cylinder of B/D = 3

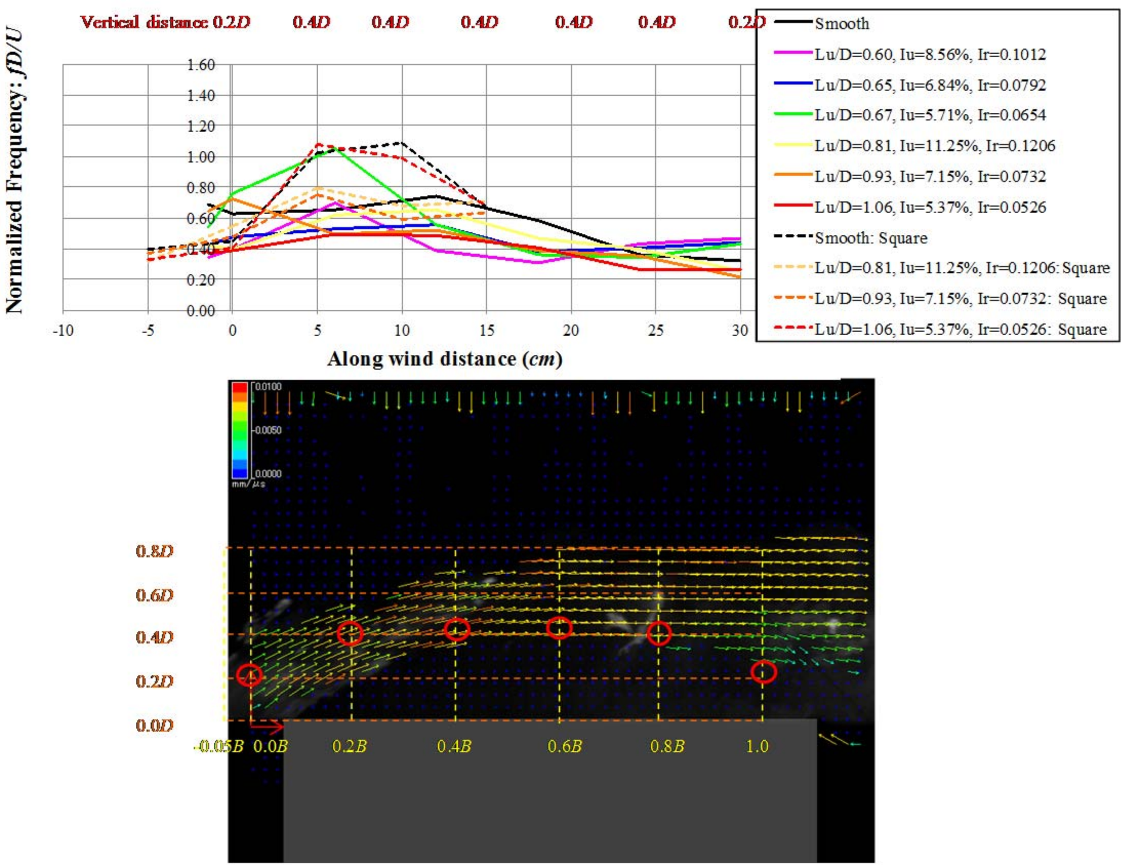


Figure 18: Variation of peak frequency in PSD of shear layer along-wind speed fluctuation

6. CONCLUSIONS

In this study, the turbulence partial simulation was experimentally investigated for three different bluff-body structures from the view point of "reduced turbulence intensity". Results obtained are as follows:

Base pressure measurement of rectangular cylinder (B/D = 0.26 – 0.98) showed that the base pressure coefficients of a rectangular cylinder with and larger than the critical slenderness ratio fairly agree in partially-simulated turbulences.

Measurement of surface pressure and static coefficients of bridge deck (B/D = 5 and 7.5) showed that reduced turbulence intensity as well as turbulence intensity can represent a negative peak pressure of a hexagonal bridge deck. On the other hand, turbulence scale cannot represent it as can the reduced turbulence intensity do. Reduced turbulence intensity can also represent the slopes of static force coefficients of the bridge deck model as can turbulence intensity and turbulence scale do.

Surface pressure measurement and PIV test of rectangular cylinder (B/D = 2 and 3) showed that reattachment of the flow to the side surface is enhanced by turbulence. In addition, larger reduced turbulence intensity which is equivalent to larger small scale turbulence enhances the reattachment trend. It can also be understood from PIV test that higher frequency component of turbulence (small-scale turbulence) enhances flow reattachment near the leading edge.

Based on these observations, further study on reduced turbulence intensity should be conducted.

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