

Study on turbulence effects on flow patterns around rectangular cylinders

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ABSTRACT: Wind tunnel experiments were performed to study the flow pattern around bluff bodies. Flows around square and rectangular cylinders with various slenderness ratios were studied. Flows with turbulence intensity ranging between 5.66% to 11.43% were generated by installing a grid in the wind tunnel. The study concentrated on the effect of turbulence properties on the flow structures around bluff bodies.

KEYWORDS: small-scale turbulence, turbulence partial simulation, reduced turbulence intensity, bluff-body, rectangular cylinder, wind tunnel.

1 INTRODUCTION

Flow patterns around bluff bodies have long been interesting topics among researchers but the relationships between flow patterns and flow parameters such as turbulence intensity are still vague.

Nakamura and Ohya [1] showed that flow structures strongly depend on small-scale turbulence in the incoming flow. It increases negative base pressures of a long rectangular cylinder (a rectangular cylinder which has slenderness ratio more than 0.6). Nakamura and Ozono [2] stated in their research that if the turbulence scale has more magnitude than twice the frontal dimension (or depth of a cylinder; D), the effect of the turbulence scale will approach to that of smooth flow. Then, large turbulence scale will have no significant effect on the mean pressures on the side surfaces.

However, Cherry et al.[3] and Kiya and Sasaki [4] argued that explaining by using only the magnitude of mean pressures is inadequate to describe the behavior of complicated natural flow fields. Haan et al. [5] defined that turbulence intensity or turbulence scale alone cannot fully explain changes of aerodynamic behavior of bridge decks.

Irwin et al. [6] stated that because past studies discovered that small-scale turbulence affects flow pattern and aerodynamic parameters, then it is reasonable to match the power spectrum of turbulence only at high frequencies which is the range that small-scale turbulence dominates the flow. This approach is called “turbulence partial simulation”.

Matching between the power spectrum of a wind tunnel model and that of the prototype (full-scale) can be formulated as shown in Equation 1.

$$\left(f \frac{S_u}{U^2} \right)_m = \left(f \frac{S_u}{U^2} \right)_p \quad (1)$$

where f = frequency; S_u = power spectrum of the longitudinal component of turbulence; and U = mean wind speed.

Irwin et al. also recommended that turbulence partial simulation would be more reasonable to compare wind-induced vibration of bridge decks between wind-tunnel test and full scale observation.

Katsuchi and Yamada [7] initiated to use new parameter “reduced turbulence intensity” combining turbulence intensity and turbulence scale together. Formulation of reduced turbulence intensity begins with assuming the Karman type PSD in Equation 2.

$$f \frac{S_u}{\sigma_u^2} = \frac{4(fL_u^x / U)}{(1 + 70.8(fL_u^x / U)^2)^{5/6}} \quad (2)$$

where σ_u = fluctuating part of wind speed; L_u^x = length scale of turbulence (or turbulence scale).

Equation 2 can be transformed to Equation 3 by determining the simulation of a high frequency part of the power spectrum.

$$f \frac{S_u}{\sigma_u^2} = \left(\frac{fL_u^x}{U} \right)^{-2/3} \quad (3)$$

Multiplying (U^2 / U^2) in the left hand side of Equation 3 leads to

$$f \frac{S_u}{U^2} = I_u^2 \left(\frac{fL_u^x}{U} \right)^{-2/3} \quad (4)$$

where I_u = turbulence intensity = σ_u / U

The dimension of f/U is inverse dimension of length, then f/U can be transformed to $1/D$ (where D = representative length). Equation 4 can be rewritten in the term of $1/D$.

$$f \frac{S_u}{U^2} = \left(\frac{I_u}{(L_u^x / D)^{1/3}} \right)^2 \quad (5)$$

After that, substituting Equation 5 into Equation 1 leads to Equation 6.

$$\left(\frac{I_u}{(L_u^x / D)^{1/3}} \right)_m = \left(\frac{I_u}{(L_u^x / D)^{1/3}} \right)_p \quad (6)$$

Katsuchi and Yamada named the new parameter obtained from Equation 6 as “reduced turbulence intensity” which is equal to turbulence intensity divided by cubic root of the ratio between turbulence scale and the representative length (L_u^x/D , this parameter will be called length scale ratio hereafter).

$$I_r = \frac{I_u}{(L_u^x / D)^{1/3}} \quad (7)$$

It can be seen from Equation 6 that reduced turbulence intensity of the prototype is equal to that of the wind-tunnel model. Moreover, this parameter also represents the effect of small scale turbulence as explained above. Then, it is expected that using reduced turbulence intensity as a new representative will be more reasonable and give us better understanding than using only turbulence intensity or length scale ratio alone.

The aim of this study is to understand more clearly the effects of the turbulence parameters of flow fields on the flow structures around bluff bodies by focusing on the reduced turbulence intensity.

2 EXPERIMENTAL SETUP

Experiments were carried out in a closed-circuit wind tunnel located at Yokohama National University. Its working section is 1.3 m. (width) x 1.8 m. (height). Three square cylinders with breadth (B) and depth (D) of 100 mm. were used in this experiment. Each cylinder had four pressure probes installed in each side, giving a total of 16 pressure probes per section in a cylinder. In order to study the effect of slenderness ratio (B/D), we adjoined 2 or 3 square cylinders to be a rectangular cylinder with a slenderness ratio of 2.0 or 3.0 respectively. The cylinder was mounted between two acrylic end plates in the center of the working section. It could also be rotated in order to study the effect of angle of attack.

Representative wind speeds in this experiment were 6 m/s and 9 m/s, giving the corresponding Reynolds number of 40,000 and 60,000 respectively.

Turbulent flow fields were generated by using a wooden grid with bar size of 60 mm. and bar spacing of 240 mm. The grid was installed at 3 different locations upstream of the cylinder. Turbulent flow properties such as turbulence intensity and turbulence scale were measured by using a hot-wire anemometer. There were four types of flow fields studied in this experiment. They were smooth flow and turbulent flow with turbulence intensity of 5.66%, 7.40%, and 11.43%.

Pressure data measured from the pressure probes were sent to an A/D converter to transform from analog signal to digital signal. After that the data were sent to a personal computer for recording.

Turbulence scales were calculated by using the peak frequency method which was suggested by Fichtl and McVehil [8]. The frequency that the power spectrum reaches to the maximum value will be brought to calculate the turbulence scale as shown in Equation 8.

$$L_u^x = \frac{1}{2\pi} \left(\frac{U}{f_{peak}} \right) \quad (8)$$

Reliability of the turbulence scale obtained from this method has been proved by comparing an experimental power spectrum with that obtained by substituting the turbulence scale into Equation 1. An example of the comparing results can be seen in Figure 1.

It can be seen from Figure 1 that calculated power spectrum matches the experimental power spectrum very well. Thus, the turbulence scales calculated from the peak frequency method are reasonable.

Turbulence parameters in this study such as turbulence intensity, turbulence scale and reduced turbulence intensity are shown in Table 1. Figure 2 shows the power spectrums of all cases corresponding to the data in Table 1.

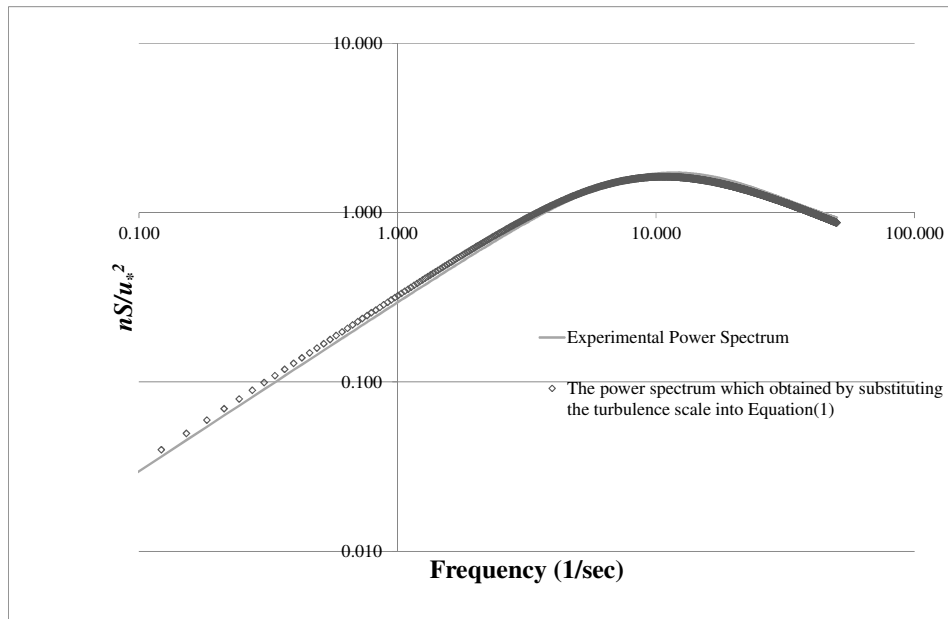


Figure 1. An example of the comparing results of power spectrum.

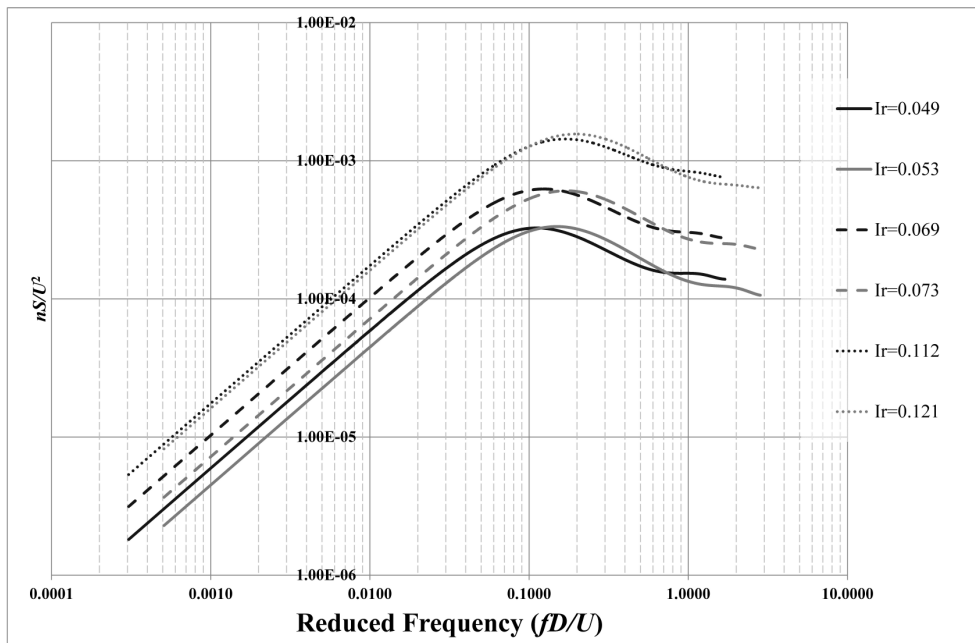


Figure 2. Power spectra obtained from the experiment.

Table 1. Turbulence parameters.

Wind speed : U (m/s)	Reynold No.	I_u	L_u (cm)	L_u/d	$I_r = I_u / (L_u/d)^{1/3}$
6.0	40,000	0.0537	0.11	1.06	0.0526
		0.0715	0.09	0.93	0.0732
		0.1125	0.08	0.81	0.1206
9.0	60,000	0.0552	0.14	1.38	0.0496
		0.0728	0.12	1.17	0.0692
		0.1102	0.09	0.92	0.1134

3 EXPERIMENTAL RESULTS

Some results obtained from the experiment can be seen in Figure 3 which illustrates mean surface pressure coefficients (C_p) for every cases of reduced turbulence intensity around a square cylinder and a rectangular cylinder with a slenderness ratio of 2.0 and 3.0. The figure shows that increasing reduced turbulence intensity clearly makes the side surface pressures on the after-body decrease especially in a long rectangular cylinder. The peaks of the mean pressures can be also seen more obviously and shift closer to the leading edge. This means that re-attachment of the flow around bluff bodies is induced by increasing reduced turbulence intensity. Negative pressures on leeward surface were also reduced due to growth of turbulence level.

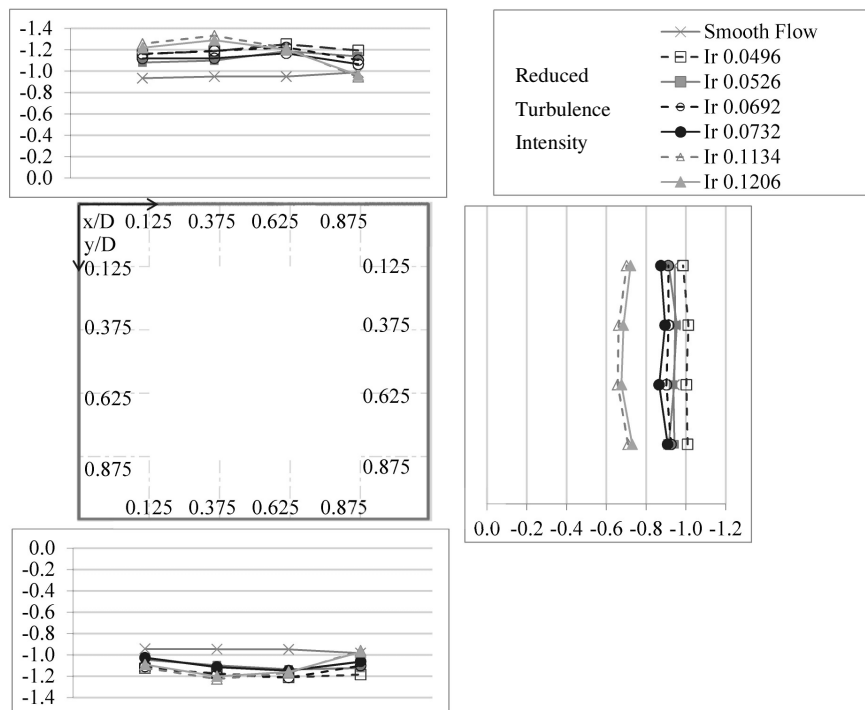


Figure 3a. Mean surface pressure coefficients (C_p) around a square cylinder

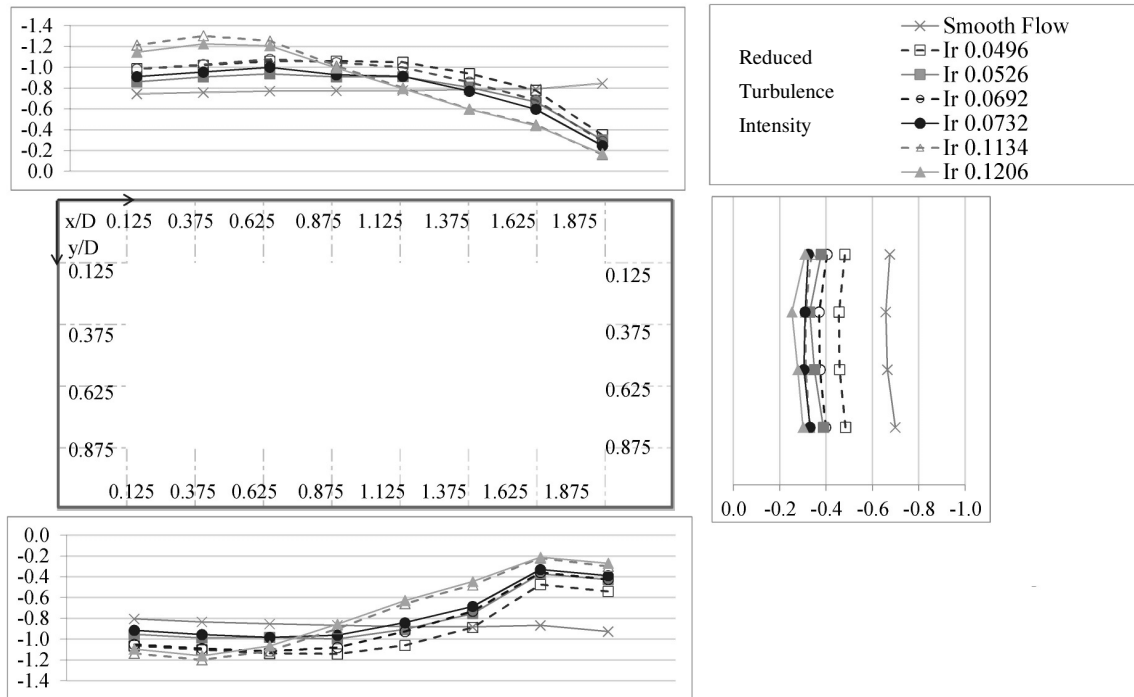


Figure 3b. Mean surface pressure coefficients (C_p) around a rectangular cylinder with a slenderness ratio (B/D) of 2.0

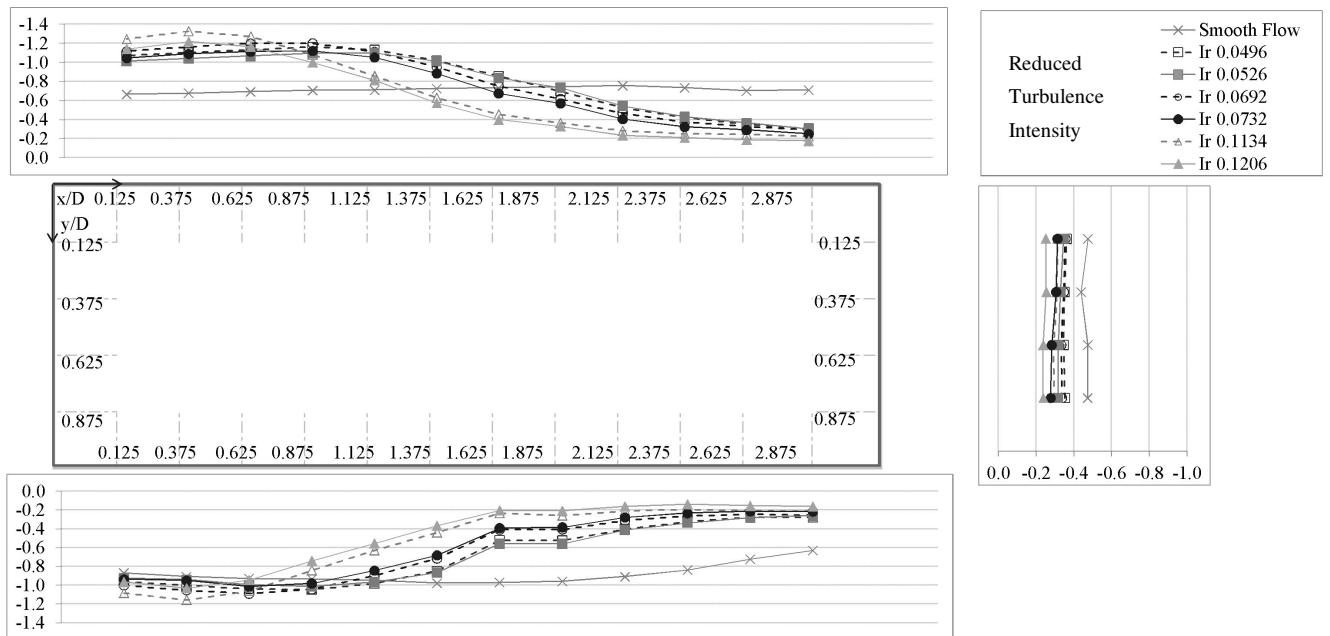


Figure 3c. Mean surface pressure coefficients (C_p) around a rectangular cylinder with a slenderness ratio (B/D) of 3.0

The capability to be a representative for turbulence level of reduced turbulence intensity will be pointed out in this section. In the case of 0.0496 and 0.0526 reduced turbulence intensity, the surface pressures of the rectangular cylinder with a slenderness ratio of 2.0 decrease obviously against increasing reduced turbulence intensity. On the contrary, the surface pressures decrease with reduction of turbulence intensity from 0.0552 (corresponding to 0.0496 of I_r) to 0.0537 (corresponding to 0.0526 of I_r). It might be because turbulence intensity in this case almost does not change (from 0.0552 to 0.0537) but turbulence scale ratio decreases from 1.38 to 1.06, then corresponding reduced turbulence intensity calculated from the first two parameters also decreases. This means that reduced turbulence intensity might be the better representative than turbulence intensity because it can capture change of the flow while turbulence intensity cannot in this case.

Locations of the peak of mean surface pressures were identified by fitting mean surface pressure curves with sixth order parabola equations. The locations of the peak pressures of the rectangular cylinder with a slenderness ratio of 2.0 and 3.0 are shown in Table 2. It can be seen that the locations of the peak pressures on both top and bottom surface shift to the leading edge when reduced turbulence intensity increases. The locations of the peak pressures on the top surface are not identical to that of the bottom surface. It can be noticed from the locations of the peak pressures or from the pressure graphs in Figure 3 that the flows are not symmetric as they should be. The reason of this behavior is still obscure but it might be because two-dimensional flow behaviors were not fully developed due to the grid or other reasons.

Table 2. Locations of the peaks of mean surface pressures.

Locations of the peak of mean surface pressures (x/D)				
I_r	Cylinder with a slenderness ratio of 2.0		Cylinder with a slenderness ratio of 3.0	
	Top	Bottom	Top	Bottom
0.0496	0.87	0.63	0.85	0.75
0.0526	0.75	0.55	0.92	0.80
0.0692	0.71	0.58	0.72	0.66
0.0732	0.60	0.58	0.73	0.69
0.1134	0.42	0.42	0.38	0.33
0.1206	0.47	0.40	0.40	0.34

Therefore, this phenomenon leads a net mean lift force not to be zero. Table 3 summarizes the net mean lift coefficients (C_L). It can be noticed that in the case of the rectangular cylinder with a slenderness ratio of 2.0, the net mean lift coefficient decreases to be negative value (or downward direction) against increasing reduced turbulence intensity. On the other hands, the net mean lift coefficient of the rectangular cylinder with a slenderness ratio of 3.0 does not change significantly and the magnitude of the coefficient is negative in every cases. The cause of this inconsistency is still unclear but it might be because of some effects of complicated three-dimensional flow fields as stated before.

Table 3. Net mean lift coefficient (C_L).

I_r	Net mean lift coefficient (C_L)	
	Cylinder with B/D of 2.0	Cylinder with B/D of 3.0
0.0496	0.019	-0.134
0.0526	0.008	-0.121
0.0692	-0.026	-0.158
0.0732	-0.035	-0.144
0.1134	-0.101	-0.146
0.1206	-0.107	-0.153

4 CONCLUSION

The results from this experiment emphasized that increasing turbulence level will enhance the re-attachment of the flow on sharp-edged bluff bodies. Therefore, there will be pressure recovery occurring on the after-body. The size of recirculation bubbles become smaller and shift closer to the leading edge due to the effect of turbulence. Reduced turbulence intensity can be efficiently used as a representative for turbulence level of the flow. The results also showed that the flow was not symmetric as it should be. Therefore, a net lift force was not zero due to asymmetric flow. The reason of asymmetric flow is still unclear but it was predicted that might be because three-dimensional flow effects.

Flow visualization around bluff bodies will be studied in the future for observation of the mechanisms of the flow fields around these bodies. The authors believe that studying flow visualization could make effects and mechanisms of turbulence on flow structures more understandable.

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