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Effect of Turbulence Intensity and Length Scale on Vortex-Induced Vibration of Parallel Cable-Stayed Bridges

난류길이와 난류강도가 병렬교량 와류진동에 미치는 영향

2018년 2월

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Abstract

In this study, the target turbulence length and turbulence intensity were generated by using active turbulence generator device and turbulence grid. The study carried out about the effect of the generated turbulent wind on vortex-induced vibration of parallel cable-stayed bridges. The developed active turbulence generator consists of aerofoil and flat gust. Two wing plates can control vertical and along-wind turbulent winds respectively. The relationship between the turbulent wind velocity and the wing motion was experimentally derived and the turbulence was simultaneously achieved by independently controlling each wing. Turbulent wind satisfied vertical and along-wind von karman spectrum at the same time. In order to verify the effects of turbulence length scale and intensity on the response to parallel bridges, three of the four variables (along-wind turbulence intensity, along-wind turbulence length scale, vertical turbulence intensity, vertical turbulence length scale) were used as control variables and the other one was used as a dependent variable. To verify whether the experimental results are characteristic of parallel bridge or not, compared response between single bridge test and parallel bridge test.

Among the variables, turbulence intensity was main factor in the amplitude response about parallel bridge section model. However, turbulence length scale was not main factor to response of bridge model.

Keyword : Parallel bridge, turbulence intensity, turbulence length scale, Vortex-induced vibration(VIV), Active turbulence generator, Grid

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CHAPTER 1
INTRODUCTION

The 1st Jindo Bridge was completed in 1984. This bridge had no vortex-induced vibration when it existed as a single bridge. But after 2nd Jindo Bridge was built adjacent to the 1st Jindo Bridge in 2005. Vortex-induced vibration was occurred on the deck of the 2nd Jindo Bridge on May 13, 2009. Even though the wind velocity was not high, the bridge response had a vibration exceeding the allowable acceleration value suggested by KSCE. For this reason, there has been a need to identify the cause of this abnormal VIV and many studies have been carried out. The previous researches have been carried out about damping and gap distance, not about wind flow conditions like turbulence intensity and length scale. However, wind flow conditions can be factors affecting the vortex-induced vibration to parallel bridge. Consideration points was three. First, Bridges almost operate in the turbulent wind. Second, the turbulence component can not be ignored because there has been research that turbulence can enhance or diminish the structure response (Wu and Kareem, 2012). Last, there was no case of turbulence test about parallel bridge. This study focuses on determining the main factors for parallel bridge vibration in turbulence components through wind tunnel test.

Chapter 2.
THEORETICAL BACKGROUND

2.1. Vortex-Induced Vibration

In fluid dynamics, vortex-induced vibrations(VIV) are motions induced on bodies with an external fluid flow, produced by periodical irregularities on this flow. The generated vortex is periodically generated and extinguished, affecting the structure. If the period in which the vortex is generated and dissipated is similar to the natural frequency of the structure, vibration will occur. The properties of the shedding frequency are characteristic to the cross section of the bridge.

$$St = \frac{f \cdot B}{U} \tag{1}$$

where f =number of vortex generated per unit time, U =the mean wind velocity, B =section width

There will be some differences depending on the stiffness of the structure when a regular pressure change occurs on the surface of the bridge, but displacement occurs. The displacement of the bridge changes the surface pressure distribution and affects to vortex-shedding. But if the displacement is very large, the vibration of the bridge is reduced and the vibration is made to have a constant amplitude. The faster the wind velocity, the higher vortex is generated as shown in Fig 1. The vortex generation frequency does not change even if the wind velocity changes slightly in the wind velocity zone where the vortex generation frequency is

similar to the natural frequency of the structure. Vibration occurs only in the vicinity of the wind velocity where the vortex generation frequency and the structure frequency are similar, and when the wind velocity is different, the vibration is eliminated. We call this phenomenon as lock-in phenomenon.

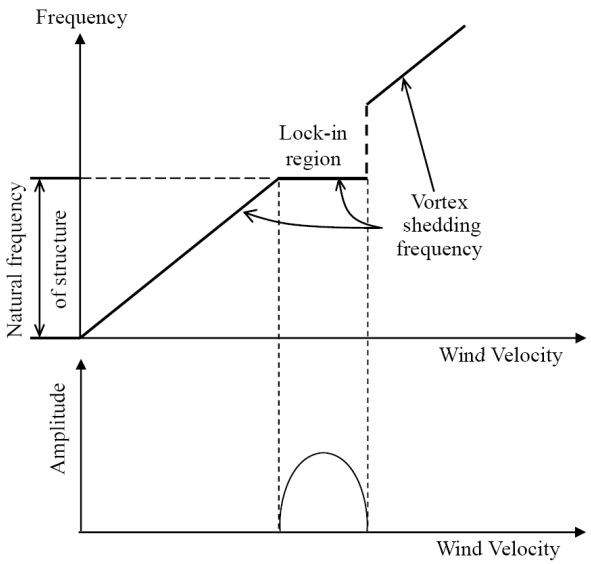

Fig 1. Lock-in phenomenon in vortex-induced vibration

2.2. Turbulent Wind

The wind in the natural state generates an irregular fluctuation component due to the friction with the surface. The wind velocity component at any time is expressed by the sum of the mean wind velocity and the fluctuating wind speed. Turbulence intensity, turbulent integral length scale, and turbulent spectrum are characteristic of turbulent flow of natural wind. Turbulence is important for turbulence intensity, turbulence length scale, and turbulence spectrum.

2.3. Turbulence Intensity

The turbulence intensity can be expressed in the along-wind, horizontal, and vertical directions as the mean square of the fluctuating wind velocity divided by the mean wind velocity. The mean wind velocity uses a 10-minute mean wind velocity.

$$I_u = \frac{\sigma_u}{U}, \quad I_w = \frac{\sigma_w}{U} \tag{2}$$

,where $\overline{U}$ =mean wind velocity, σ_u =standard deviation of along-wind velocity fluctuation, σ_w =standard deviation of vertical wind velocity fluctuation.

2.4. Turbulence Integral Length Scale

The velocity fluctuation in a flow passing to a certain point may be considered to be caused by a superposition of conceptual eddies transported by the mean wind. Integral length scale is a physical quantity describing the size of the large energy-containing eddies.

The auto covariance functions and corresponding auto covariance coefficients are defined by



(3)



(4)

$$\rho_u(\tau)=\frac{Cov_u(\tau)}{\sigma_u^2} \tag{5}$$

$$\rho_w(\tau)=\frac{Cov_w(\tau)}{\sigma_w^2} \tag{6}$$

where τ =arbitrary time lag

The time scale may be interpreted as the average duration of a u , v or w wind gust

$$T_u=\int_0^\infty \rho_u(\tau)d\tau \tag{7}$$

$$T_w=\int_0^\infty \rho_w(\tau)d\tau \tag{8}$$

The corresponding length scale

$$L_u=\bar{U}\times\int_0^\infty \rho_u(\tau)d\tau \tag{9}$$

$$L_w=\bar{V}\times\int_0^\infty \rho_w(\tau)d\tau \tag{10}$$

2.5. Turbulence Spectrum Density

The spectrum shows how the variance of some variables is distributed according to wavelength or period. The wind velocity spectrum shows the distribution of turbulent energy. Von-Karman(1948) proposed a natural wind property in the shape of the auto spectrum density.

$$\frac{f \cdot S_u(f)}{\sigma_u^2} = \frac{4 f_u}{(1+70.8 f_u^2)^{5/6}} \qquad f_u = f \times L_u / \bar{U} \tag{11}$$

$$\frac{f \cdot S_w(f)}{\sigma_w^2} = \frac{4 f_w (1+755.2 f_w^2)}{(1+283.2 f_w^2)^{11/6}} \qquad f_w = f \times L_w / \bar{U} \tag{12}$$

where σ_n^2 =wind variance, L_n =turbulence length scale, $\bar{U}$ =mean wind velocity

Chapter 3.
EXPERIMENT PROCEDURE

3.1. Bridge Section Model

The Bridge section model was installed in the wind tunnel laboratory of the Department of Civil and Environmental Engineering, Seoul National University. The wind tunnel laboratory can test upto 23m/s wind velocity. The 2nd Jindo bridge model is located on the windward side in the northwest direction and the 1st Jindo bridge model is located on the downwind side in the southeast direction. Length scale of bridge section model is 1/36. Width is respectively 0.353m, 0.329m, length is 0.9m. Fig 2. and Fig 3. shows the shaped of model section of the parallel bridge. Damping ratio is 0.17% and 0.21% respectively.

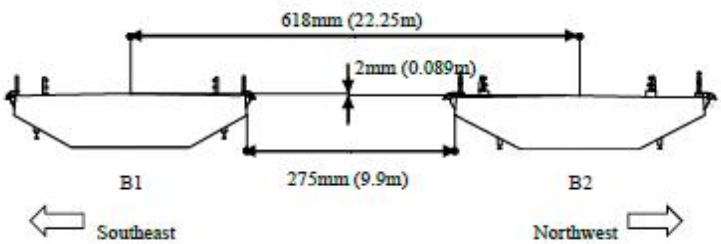

Fig 2. Setup of bridge section model in wind tunnel tests

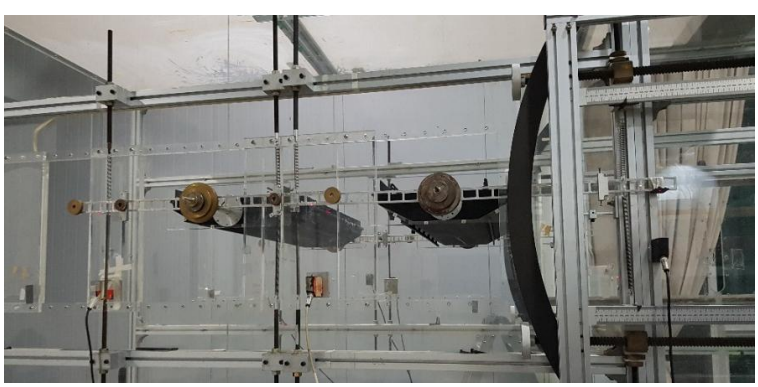

Fig 3. Actual setup of bridge section model in wind tunnel tests

Table 1. Bridge model parameters

Parameter	Similarity Scale	1st Jindo Bridge		2nd Jindo Bridge	
		Prototype	Model	Prototype	Model
Length (m)	λ_L=1/36	32.400	0.900	32.400	0.900
Width (m)	λ_L	11.860	0.329	12.690	0.353
Height (m)	λ_L	2.800	0.078	2.750	0.076
Mass (kg / m)	λ_L^2	6950	5.363	8978	6.874
Mass Moment of Inertia (kgm^2 / m)	λ_L^4	84030	0.048	152836	0.092
Natural Freq. Vertical (Hz)	λ_f=11.7	0.513	5.7	0.436	4.8
Natural Freq. Torsional (Hz)	λ_f	1.490	15.917	1.834	18.857
Vertical Damping Ratio (%)	1	0.5~0.7	0.17	0.2~0.3	0.21

3.2. Generation Wind Velocity Fluctuations

3.2.1 Active Turbulence Generator (ATG)

Active Turbulence Generator consists of flat gust, aerofoil wing, AC motor and control devices. Flat gust which controls the along-wind direction turbulence component and aerofoil which controls vertical direction turbulence component. Flat gust is located on the windward side of aerofoil. After the determination of the frequency range and the random phase, the amplitude of each sinusoidal wave is determined by target Von-Karman spectrum.

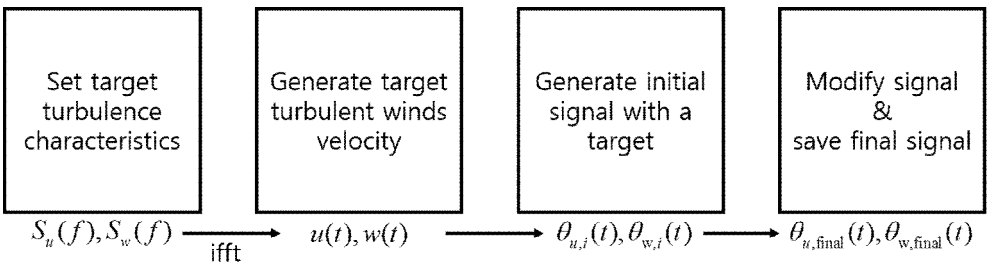

Fig 4. Algorithm of active turbulence generator



Fig 5. Active turbulence generator front view (a)aerofoil (b)flat gust



Fig 6. Active turbulence generator (a)side view, (b)control device

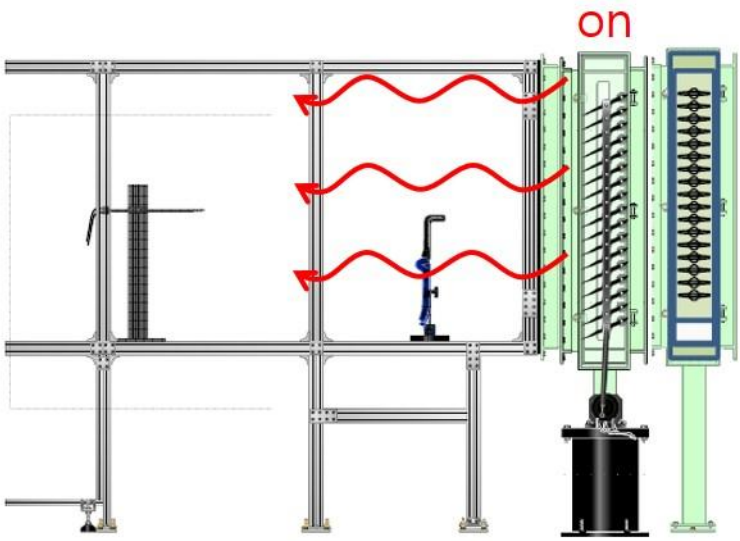

Fig 7. Vertical Active Turbulence Generator

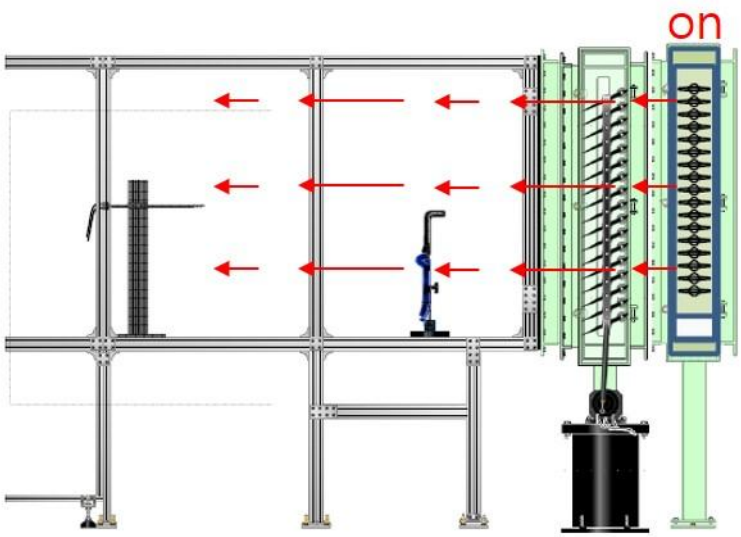

Fig 8. Along-wind Active Turbulence Generator

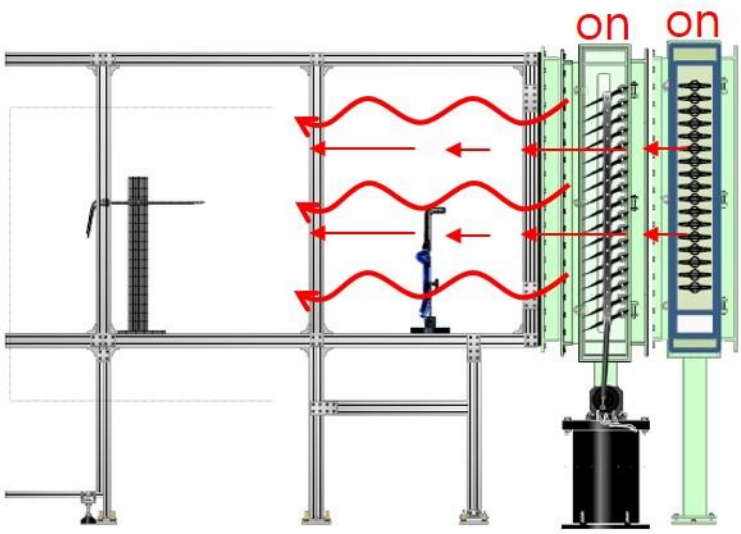

Fig 9. Both Active Turbulence Generator

3.2.2 Simulation Along-Wind Turbulence by ATG

Along-wind velocity fluctuation is a sum of harmonic component.

$$u(t)=\lim_{N\to\infty}\sum_{k=1}^{N} c_k\cos(\omega_k t+\varphi_k) \tag{13}$$

$$S_u(\omega_k)=\frac{E[(c_k\cdot\cos(\omega_k t+\varphi_k))^2]}{\Delta\omega}$$

$$=\lim_{N\to\infty}\frac{1}{\Delta\omega}\cdot\frac{1}{T}\int_0^T[c_k\cdot\cos(\omega_k t+\varphi_k)]^2 dt=\frac{c_k^2}{2\Delta\omega} \tag{14}$$

$$\therefore c_k=\sqrt{2\cdot\Delta\omega S_u(\omega_k)}=\sqrt{2\cdot\Delta f\cdot S_u(f_k)}$$

$$\frac{|u|}{U}=0.182|\theta| \tag{15}$$

,where $|u|$=amplitude of along-wind velocity fluctuation, $|\theta|$=angle of the moving flat gust plate. The constant value 0.182 is determined by an experiment.(S.Y. Baek, 2016). If the same value is used at the different location,

the experiment needs more modify numbers. To control the turbulence component in the along-wind direction, an initial excitation signal is generated using a linear relationship between the turbulent wind velocity and the angle of the flat gust.

3.2.3 Simulation Vertical Turbulence by ATG

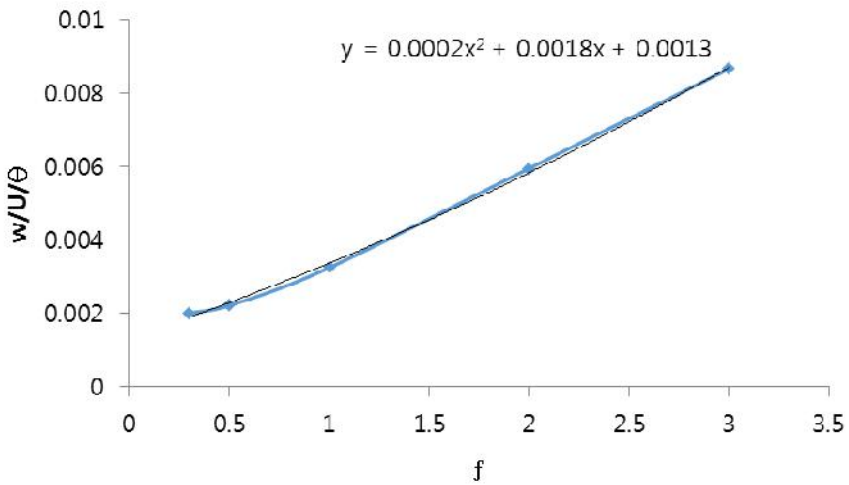

Fig 10. The relationship among amplitude of vertical velocity fluctuation, angle of wing plate and frequency

$$\frac{|w|}{U} = a_w f^2 + b_w f + c_w \quad (16)$$

,where $|w|$ =amplitude of vertical velocity fluctuation, $|\theta|$ =angle of the moving wing plate. a_w =0.002, b_w =0.0018, c_w =0.0013. The constant values are determined by an experiment.

3.2.4 Simulation Turbulence by Grid

Depending on the size of the grid or the location of the grid, turbulent wind can be created with various turbulence characteristics in the two-dimensional wind tunnel. The turbulence generated by the turbulence grid is affected by various factors such as the size of the wind tunnel test area, the surface roughness of turbulent grid, and the location of the turbulence grid. The grid bars were aluminum. Depending on the size of the grid bars, turbulence was generated by arranging the width(mm) and depth(mm) of 30X15 and 15X10. Considering the size of the wind tunnel test section, the horizontal grid bars were 990mm and the vertical grid bars were 1490mm. Each grid bars are fastened to the grid bar fixed frame installed on 4 part with the bolts. Fig 11. shows grid bars and setting.

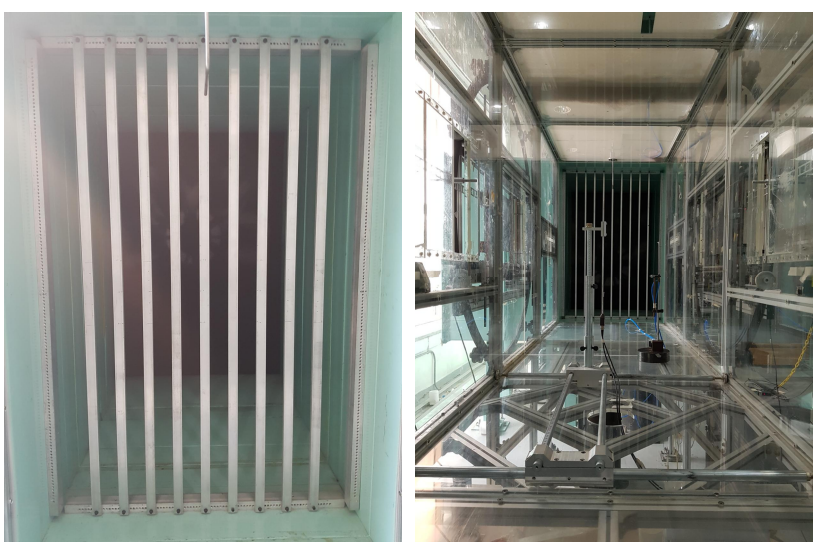

Fig 11. Grid (a)bars, (b)set-up

3.3. Site Wind Parameters Analysis

Wind direction and wind velocity were recorded by ultrasonic anemometers that were installed on Bridge 2 and Bridge 1 at a height of 3m from the top of decks, respectively. 10-minute average wind velocity and wind direction during the Oct. 15, 2012 to Oct. 17, 2012. (S.J. Kim, 2017)

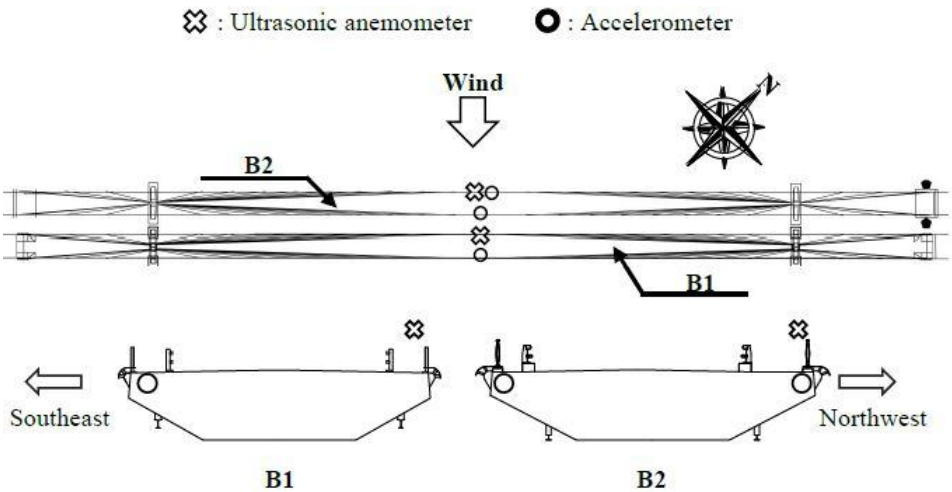

Fig 12. Deployment of the two bridges and built-in sensor (J. Park, 2016)

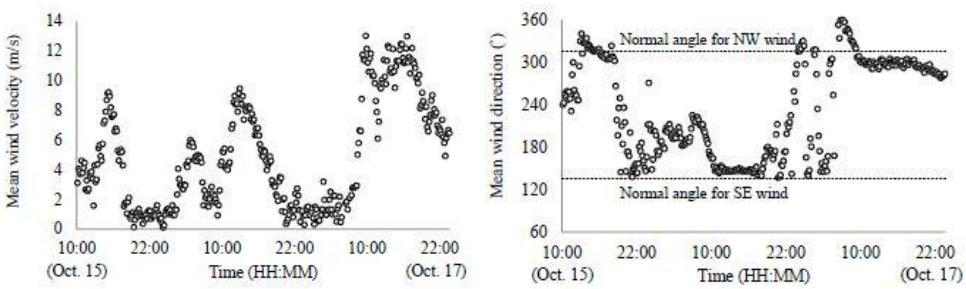

Fig 13. Wind properties for a three-day monitoring period : (a) 10-minute average wind velocity and (b) 10-minute average wind direction (S.J. Kim, 2017)

The turbulence intensity and turbulence length were measured on the site. The turbulence intensity and the turbulence length were calculated from the data

measured at the actual bridges using only the data satisfying the wind speed of 9 ~ 13m/s and the wind direction northwest wind conditions. Turbulence intensity and length scale were calculated as mean value. The values of the mean turbulence intensity were 14.11% and 6.99% respectively. The values of the mean turbulence length scale were 241.m and 45.05m respectively.

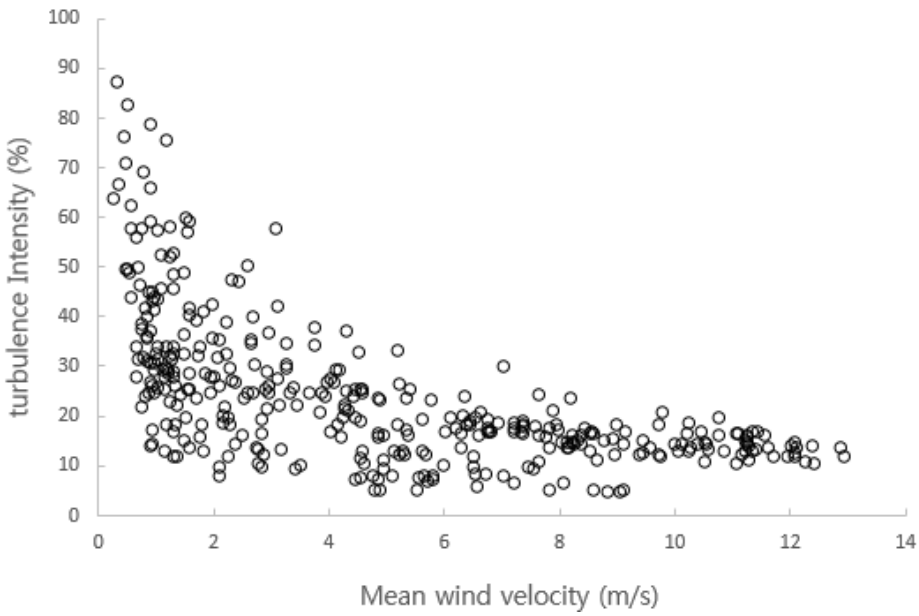

Fig 14. Along-wind turbulence intensity on the site

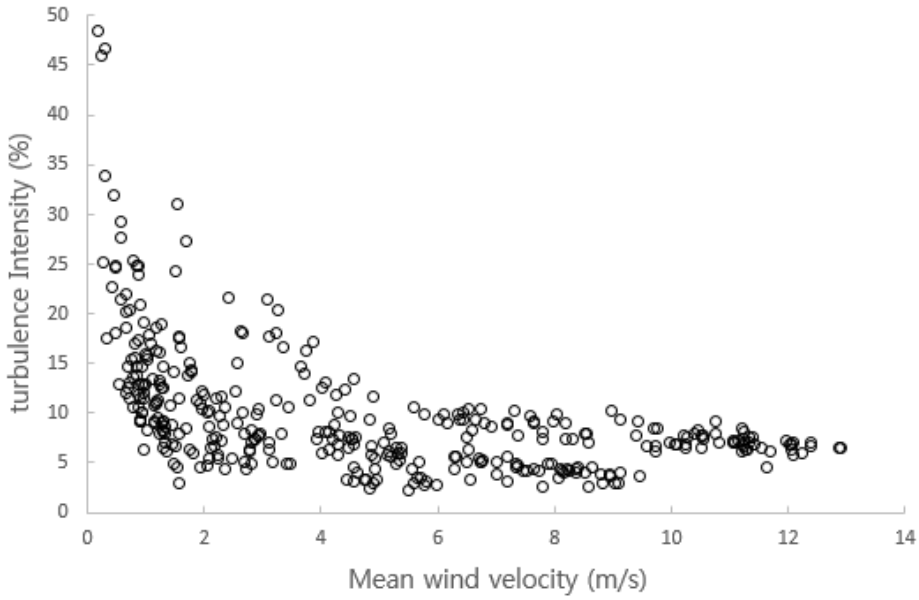

Fig 15. Vertical turbulence intensity on the site

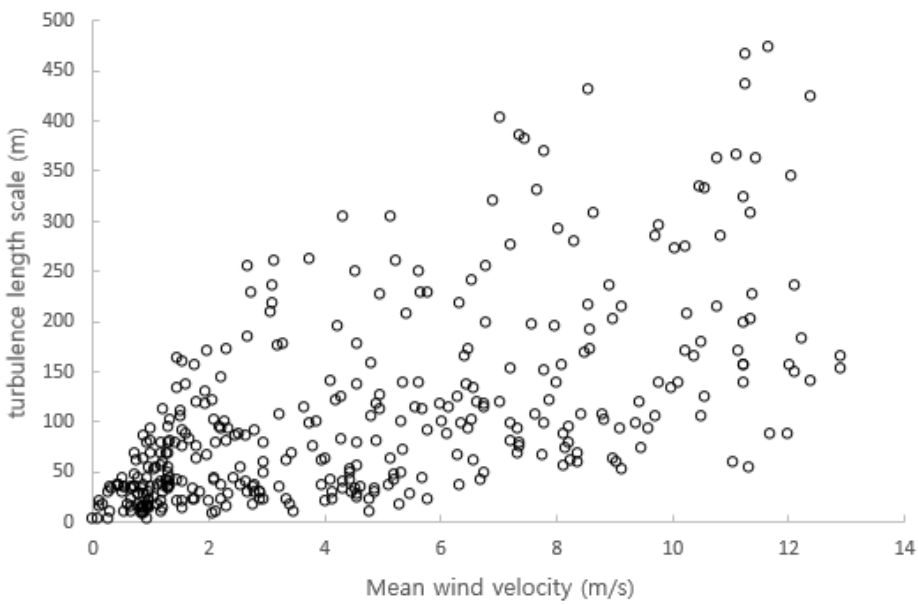

Fig 16. Along-wind turbulence length scale on the site

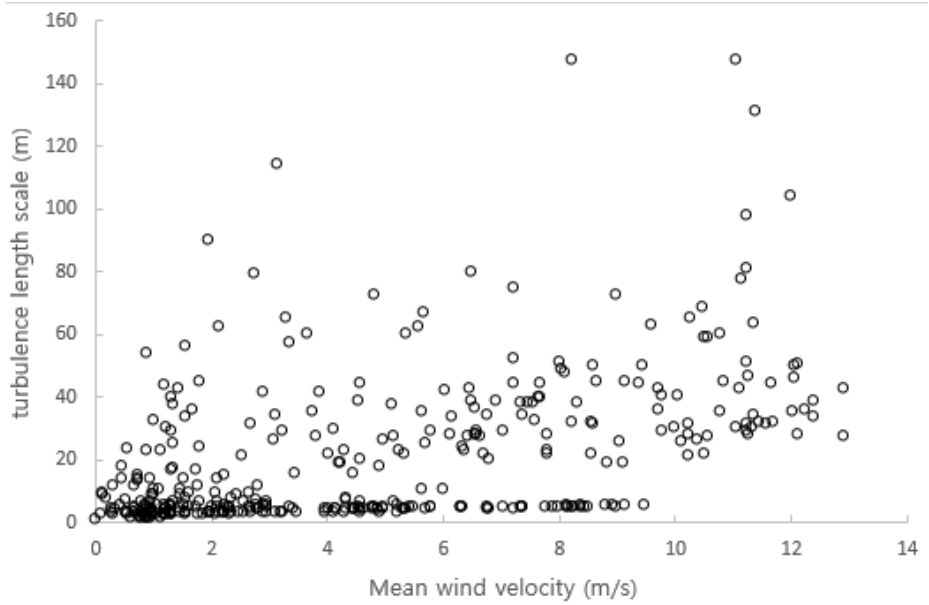

Fig 17. Vertical turbulence length scale on the site

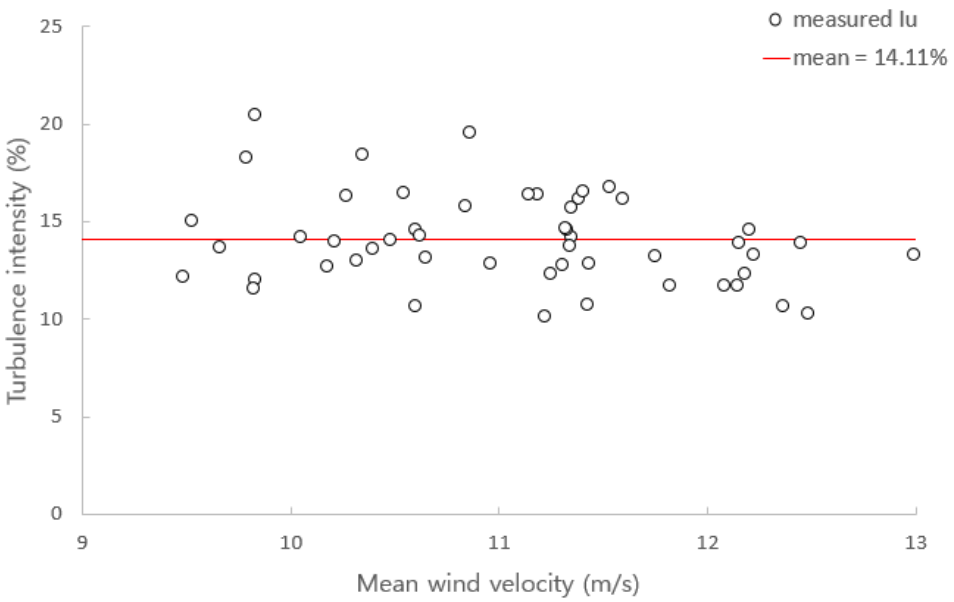

Fig 18. Along-wind turbulence intensity on the site, U=9~13m/s

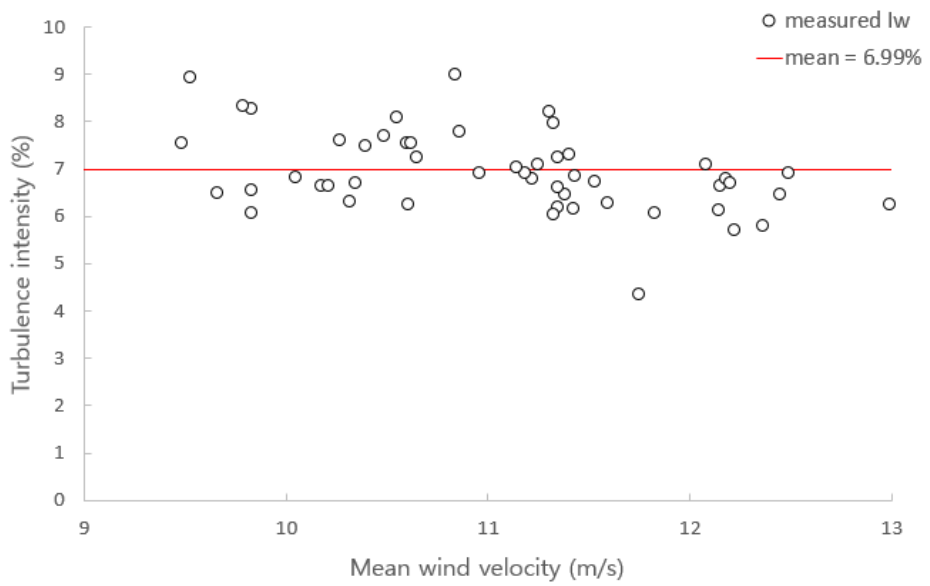

Fig 19. Vertical turbulence intensity on the site, U=9~13m/s

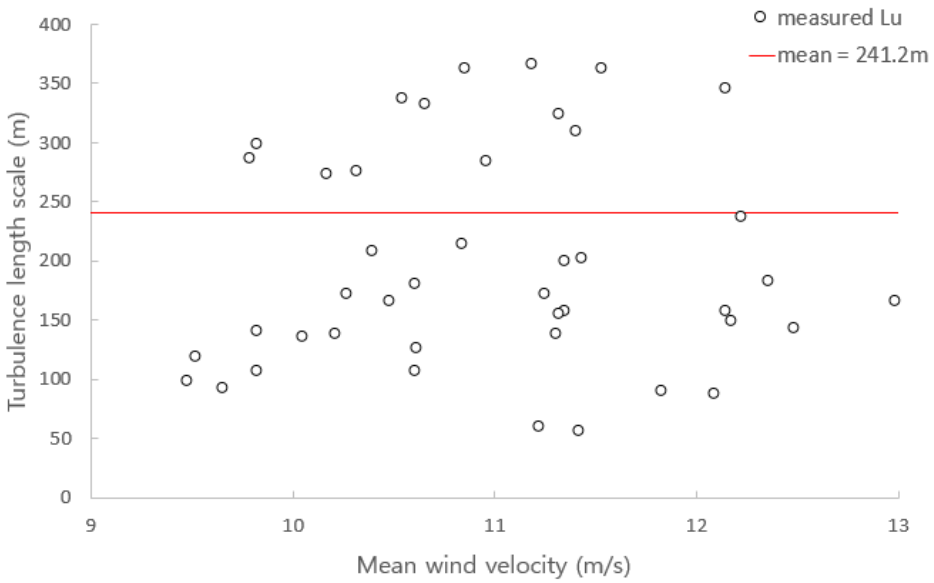

Fig 20. Along-wind turbulence length scale on the site, U=9~13m/s

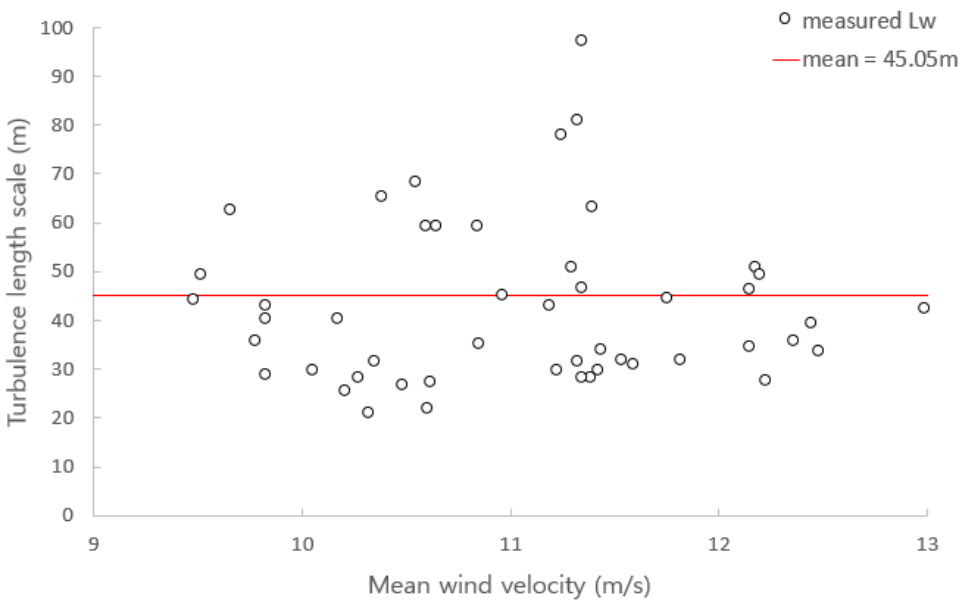

Fig 21. Vertical turbulence length scale on the site, U=9~13m/s

The turbulence intensity was derived from the "Design Guideline for Steel Cable-Supported Bridges" book by KSCE. However, due to the limitation of the active turbulence generator, it is difficult to similitude the turbulence length on the site bridge in the wind tunnel. The turbulence length scale is not written in the design guideline. For the calculation of the turbulence length scale, another reference is used. Length scale calculation was based on the "Theory of Bridge Aerodynamics"book by N.Strommen. The turbulence intensity and the turbulence length were determined within the range of the active turbulence generator device of the wind tunnel laboratory of Seoul National University.

$$I_u = \frac{1}{\ln(30/z_0)} \cdot (\frac{30}{z})^{\alpha}, \quad z_b < z < 100m \tag{17}$$

$$I_w = 0.5 \cdot I_u \tag{18}$$

,where z_b =minimum heigth, z =height of point, z_0 =roughness length,

α =power law exponent,

$$L_u = L_0 \cdot (\frac{z}{z_{b1}})^{\alpha}, \quad z \geq z_{b1} \tag{19}$$

$$L_w = L_u / 12 \tag{20}$$

,where L_0=100m, Z=23m, z_{b1}=10m, α=0.3

Table 2. Target wind parameters

	Wind velocity (m/s)	Turbulence Intensity (%)			Turbulence Length Scale (m)		
		Iu	Iw	Ratio	Lu	Lw	ratio
Site Measured	9.0~13.0	14.11	6.99	1:2	241.2	45.05	1:5.4
Design Guideline	9.0~13.0	13.1	6.55	1:2	123.1	10.25	1:12
Proposed Target in Wind Tunnel	3.0~5.0	10.0	5.0	1:2	2.0	0.3	1:6.7

3.4. Parameter Study

3.4.1. Test cases for Parallel Vortex-Induced Vibration Response Experiment

3.4.1.1 Case1 : Varying Along-Wind Turbulence Intensity by Active Turbulence Generator (ATG)

Turbulent winds were generated to satisfy the proposed target in wind tunnel test. The turbulence intensity in the along-wind direction is varied and the other factors are kept constant. The wind speed is set to 3m/s ~ 5m/s at the wind tunnel. Vertical turbulence intensity (Iw) is 5%, Along-wind turbulence length scale (Lu) is 2m, Vertical turbulence length scale (Lw) is 0.3m. The values for along-wind turbulence intensity were are follow : 4.0%, 6.0%, 7.5%, 10.0%, 12.8%.

Table 3. Wind case with varying along-wind turbulence intensity (ATG)

Mark	Turbulence Intensity		Turbulence Length Scale	
	Iu (%)	Iw (%)	Lu (m)	Lw (m)
□	4.0	5.0	2.0	0.3
◆	6.0	5.0	2.0	0.3
○	7.5	5.0	2.0	0.3
X	10.0	5.0	2.0	0.3
△	12.8	5.0	2.0	0.3

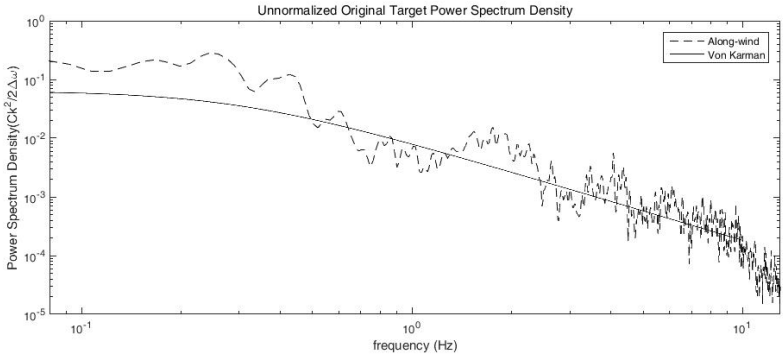

Fig 22. Wind power spectral density, Along-wind Direction Iu=4.0%

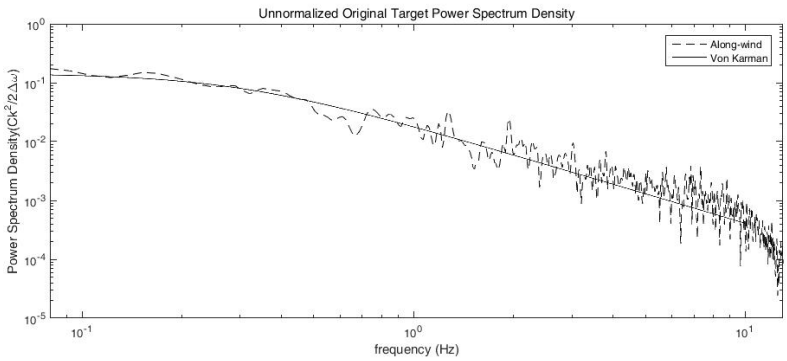

Fig 23. Wind power spectral density, Along-wind Direction Iu=6.0%

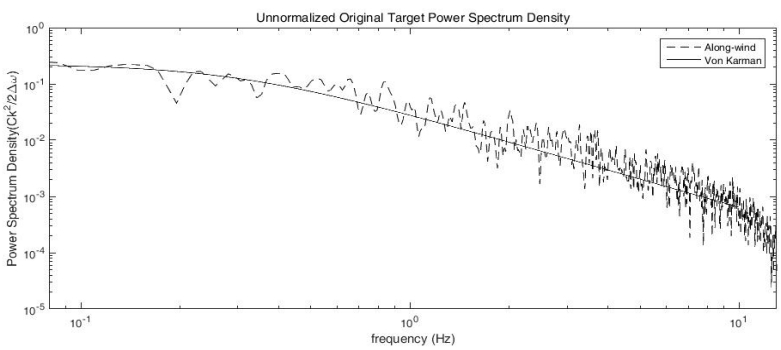

Fig 24. Wind power spectral density, Along-wind Direction Iu=7.5%

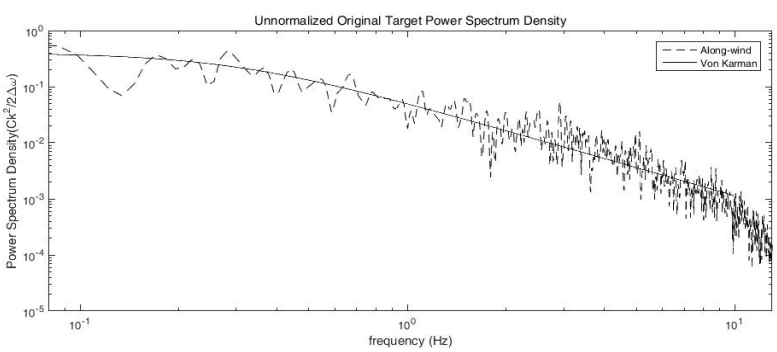

Fig 25. Wind power spectral density, Along-wind Direction Iu=10.0%

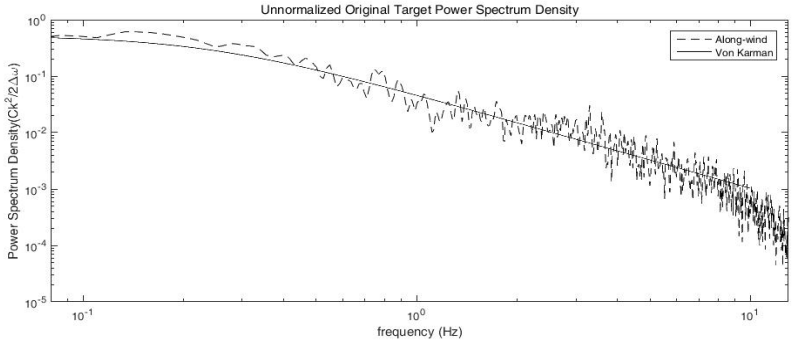

Fig 26. Wind power spectral density, Along-wind Direction Iu=12.8%

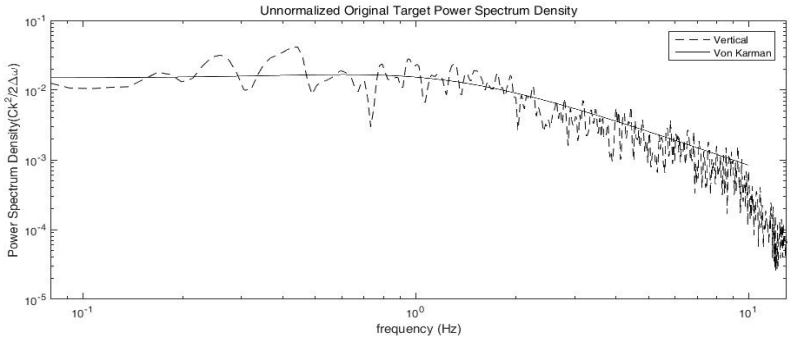

Fig 27. Wind power spectral density, Vertical Direction, Iu=4.0%

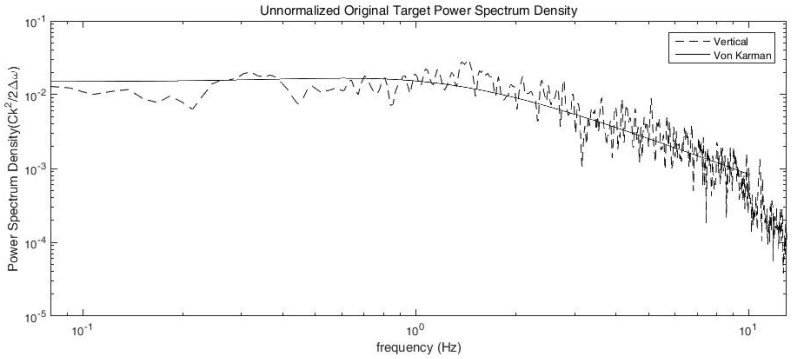

Fig 28. Wind power spectral density, Vertical Direction, Iu=6.0%

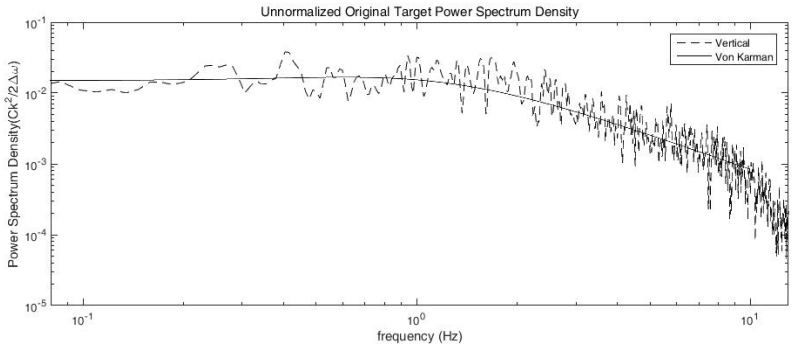

Fig 29. Wind power spectral density, Vertical Direction, Iu=7.5%

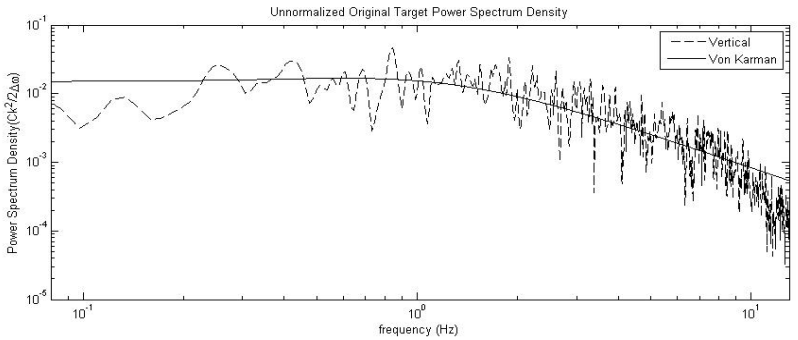

Fig 30. Wind power spectral density, Vertical Direction, Iu=10.0%

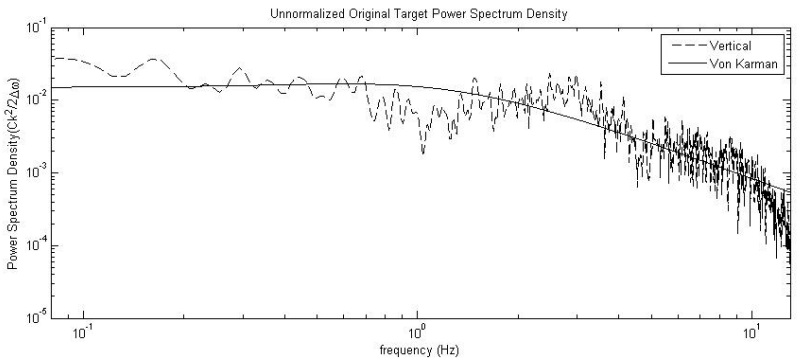

Fig 31. Wind power spectral density, Vertical Direction, Iu=12.8%

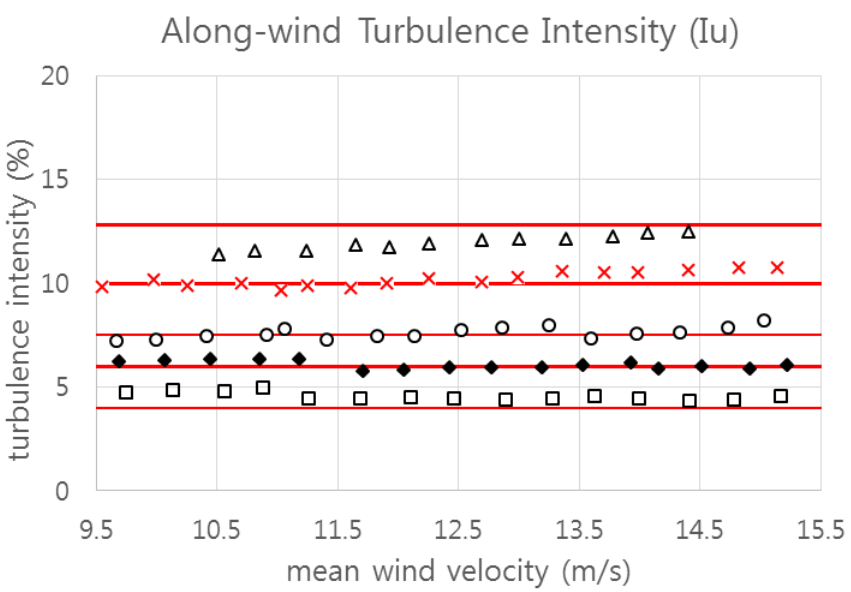

Fig 32. Dependent variable of case 1 : Iu

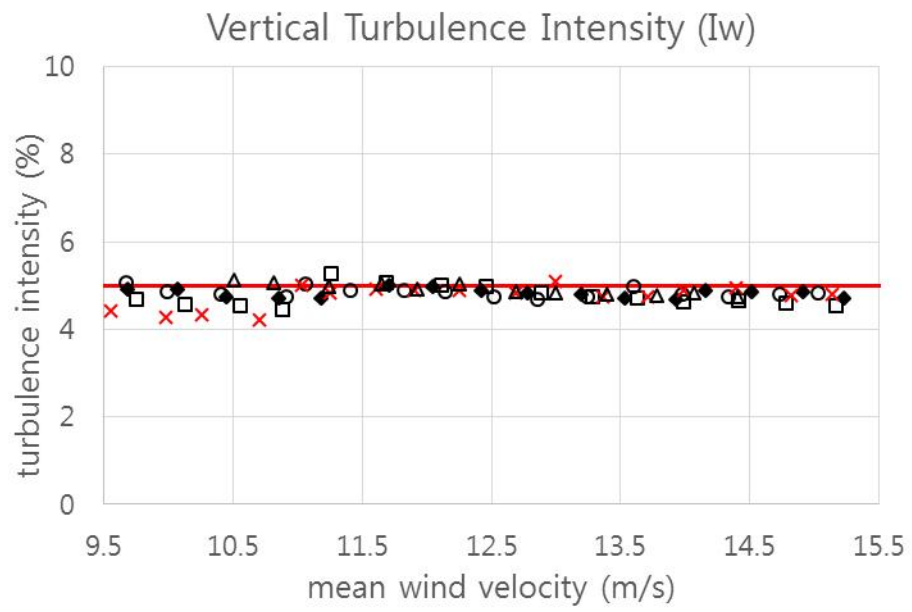

Fig 33. Control variable of case 1 : Iw

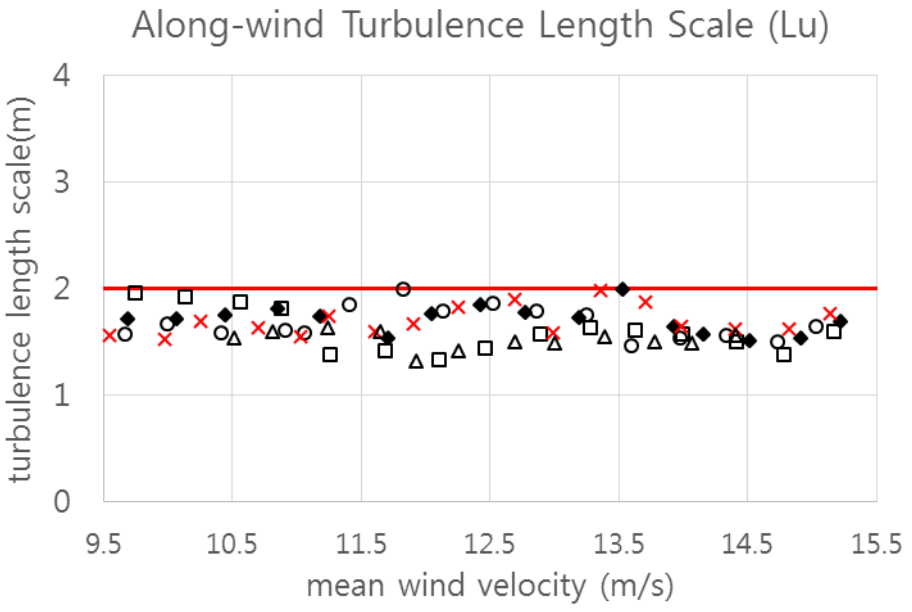

Fig 34. Control variable of case 1 : Lu

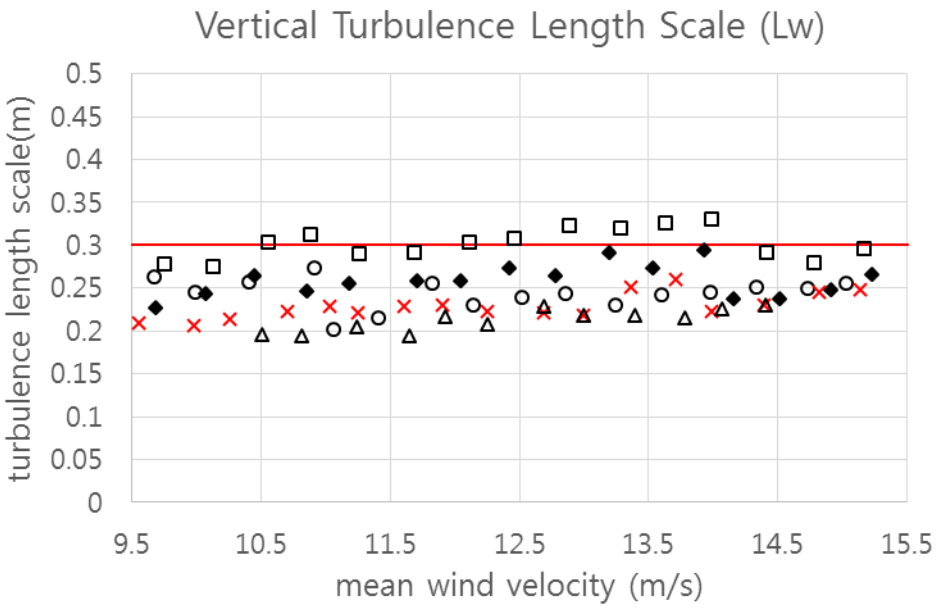

Fig 35. Control variable of case 1 : Lw

3.4.1.2 Case 2 : Varying Along-Wind Turbulence Length Scale by ATG

The turbulence length in the along-wind direction is varied and the other factors are kept constant. Along-wind turbulence intensity (Iu) is 10.0%, Vertical turbulence intensity (Iw) is 5.0%. Vertical turbulence length scale (Lw) is 0.3m. The values for along-wind turbulence length scale were are follow : 2.0m, 3.0m

Table 4. Wind case with varying along-wind turbulence length scale (ATG)

Mark	Turbulence Intensity		Turbulence Length Scale	
	Iu (%)	Iw (%)	Lu (m)	Lw (m)
○	10.0	5.0	2.0	0.3
X	10.0	5.0	3.0	0.3

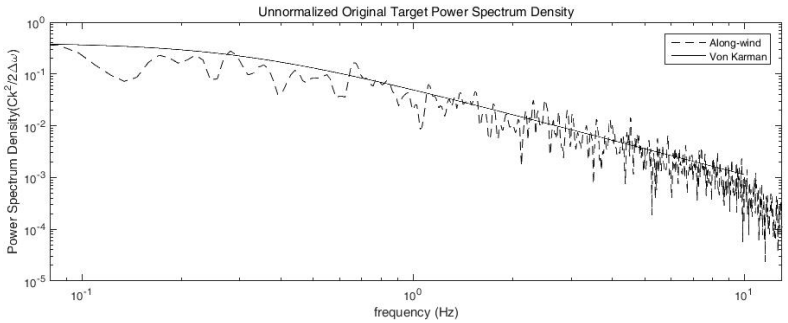

Fig 36. Wind power spectral density, Along-wind Direction Lu=2m

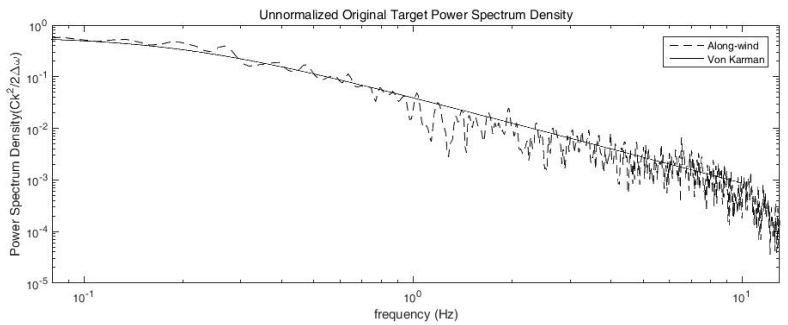

Fig 37. Wind power spectral density, Along-wind Direction Lu=3m

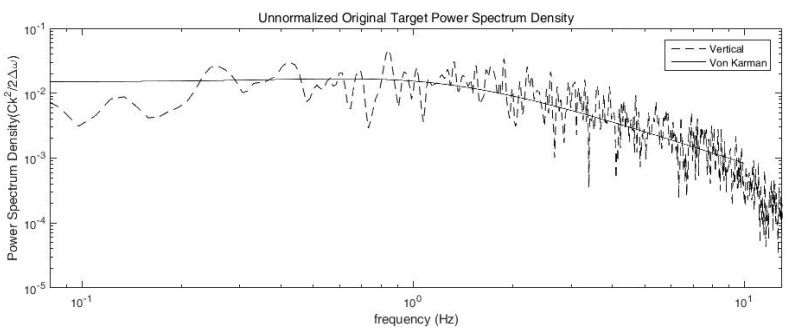

Fig 38. Wind power spectral density, Vertical Direction Lu=2m

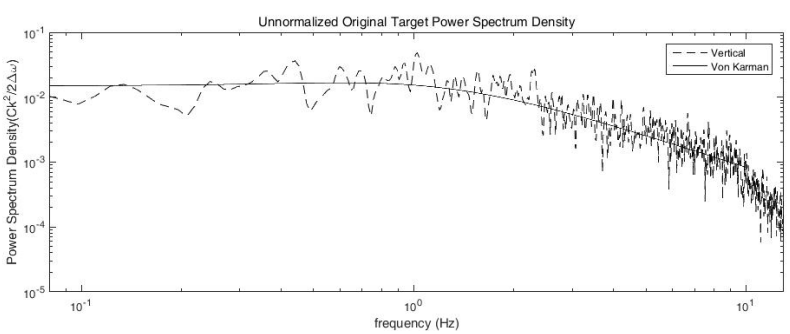

Fig 39. Wind power spectral density, Vertical Direction Lu=3m

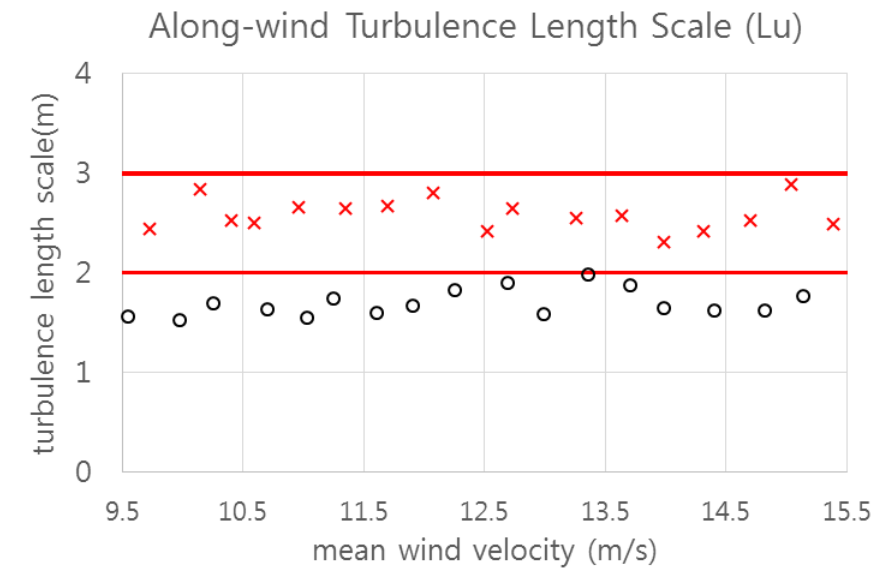

Fig 40. Dependent variable of case 2: Lu

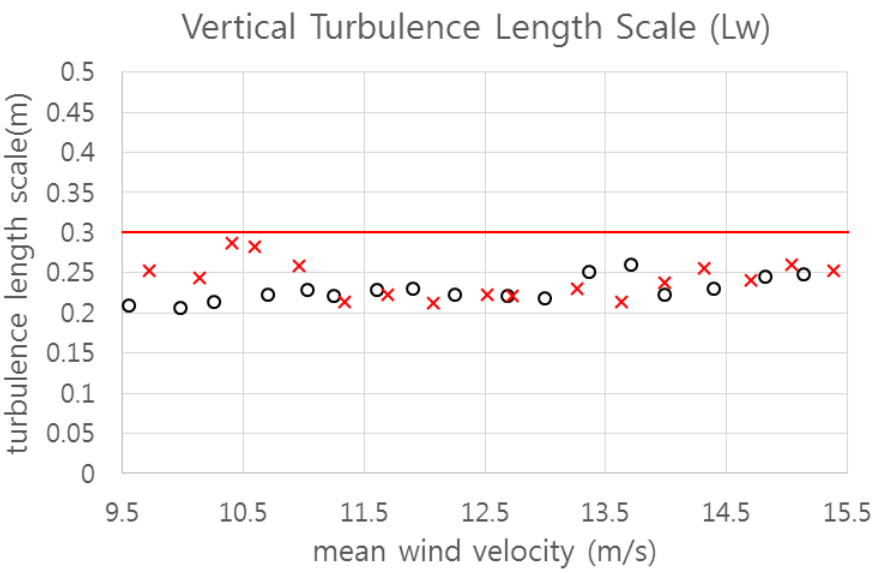

Fig 41. Control variable of case2: Lw

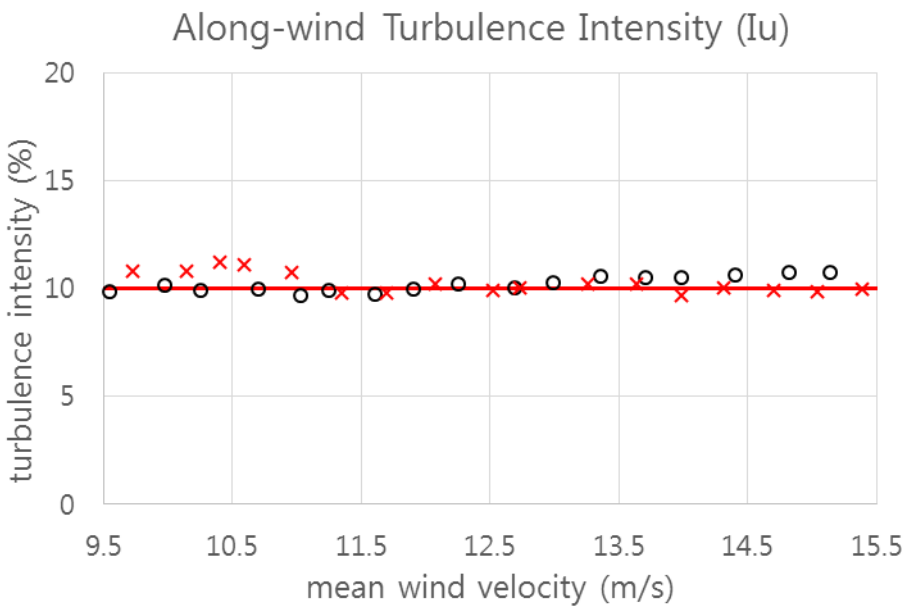

Fig 42. Control variable of case2 : Iu

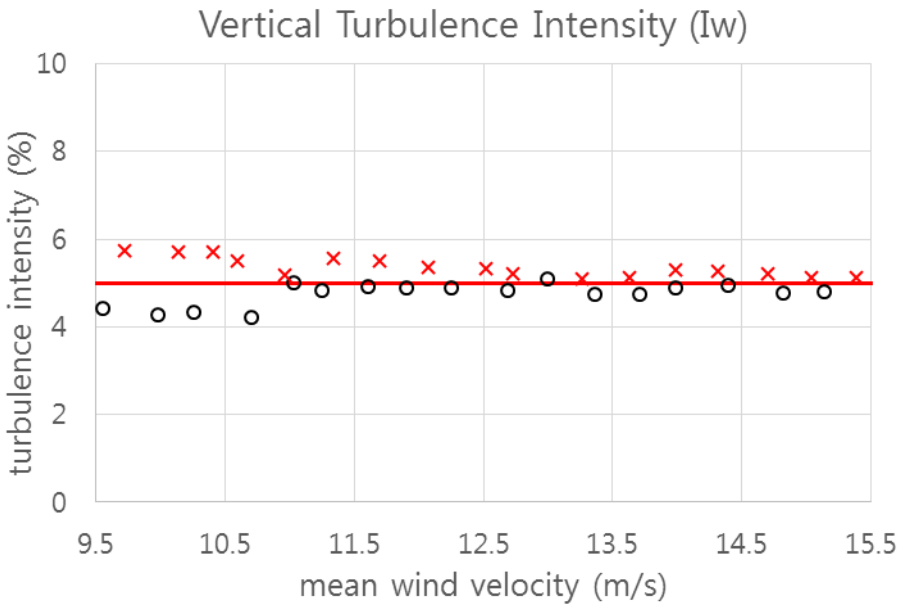

Fig 43. Control variable of case2 : Iw

3.4.1.3 Case 3 : Varying Vertical Turbulence Intensity by ATG

The turbulence intensity in the vertical direction is varied and the other factors are kept constant. Along-wind turbulence intensity (Iu) is 10.0%, Along-wind turbulence length scale (Lu) is 2m, Vertical turbulence length scale (Lw) is 0.15m. The values for vertical turbulence intensity were are follow : 4.0%, 5.0%, 6.5%

Table 5. Wind case with varying vertical turbulence intensity (ATG)

Mark	Turbulence Intensity		Turbulence Length Scale	
	Iu (%)	Iw (%)	Lu (m)	Lw (m)
○	10.0	4.0	2.0	0.15
X	10.0	5.0	2.0	0.15
Δ	10.0	6.5	2.0	0.15

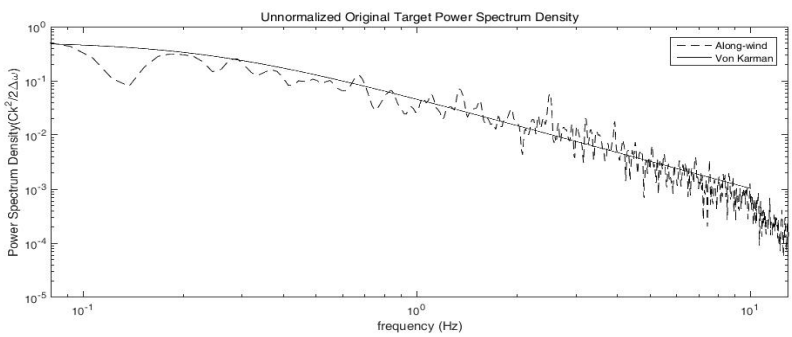

Fig 44. Wind power spectral density, Along-Wind Direction Iw=4.0%

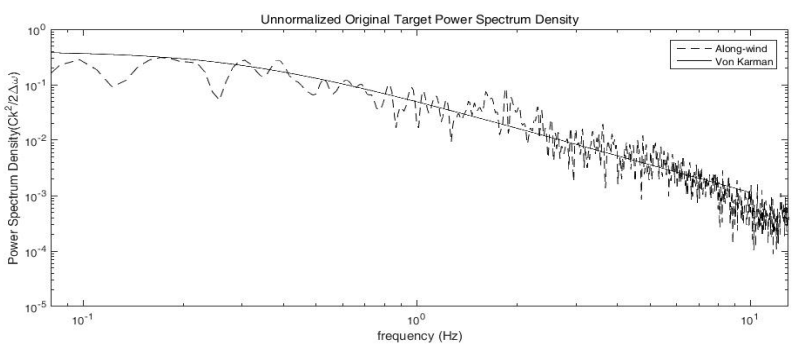

Fig 45. Wind power spectral density, Along-Wind Direction Iw=5.0%

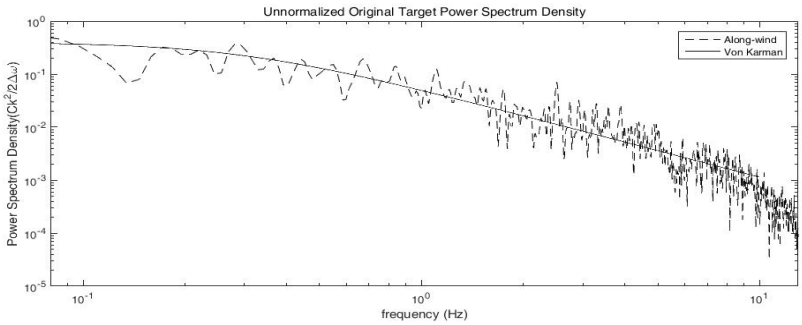

Fig 46. Wind power spectral density, Along-Wind Direction Iw=6.5%

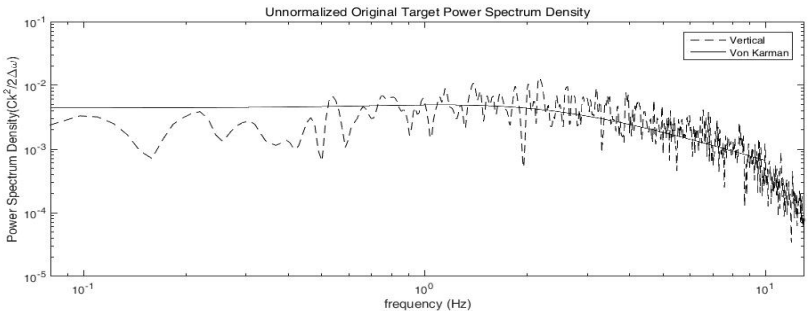

Fig 47. Wind power spectral density, Vertical Direction Iw=4.0%

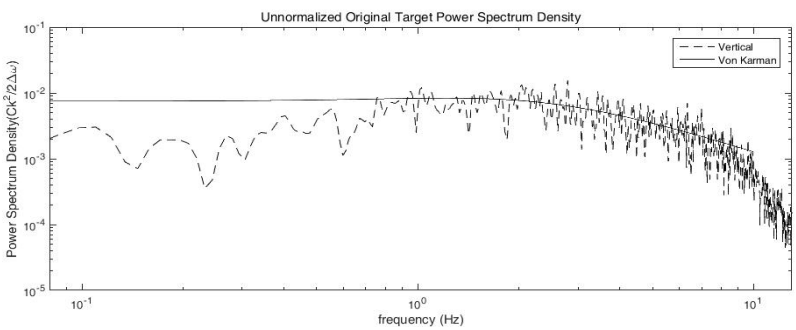

Fig 48. Wind power spectral density, Vertical Direction Iw=5.0%

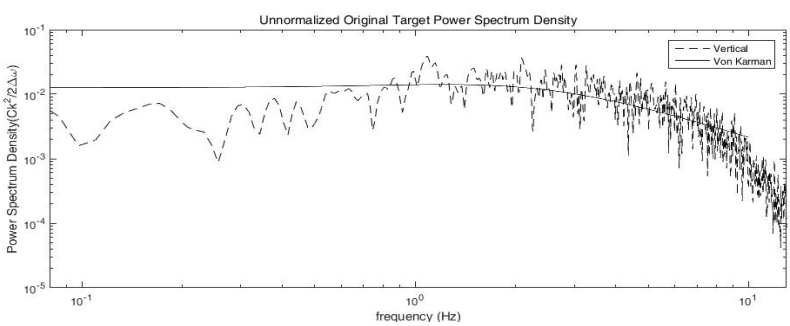

Fig 49. Wind power spectral density, Vertical Direction Iw=6.5%

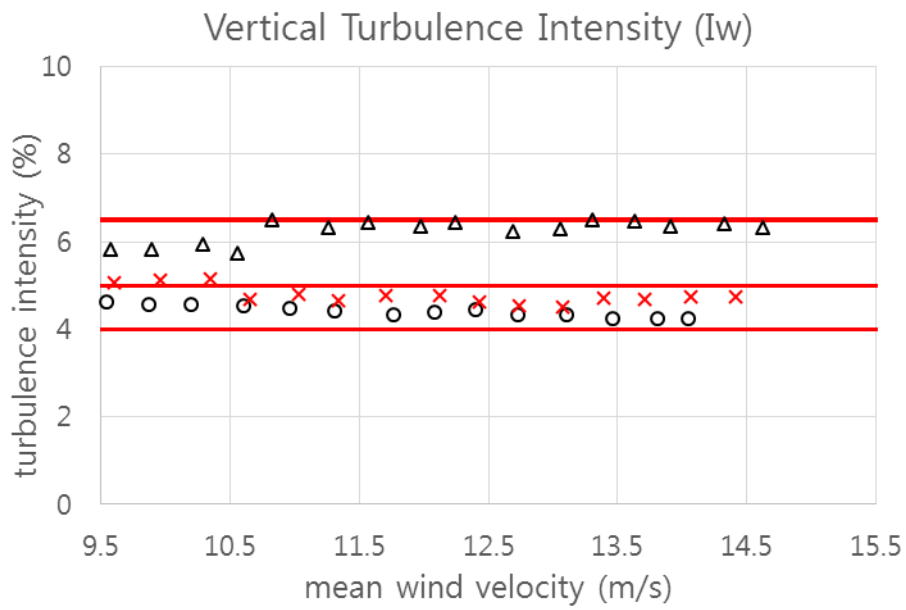

Fig 50. Dependent variable of case 3: Iw

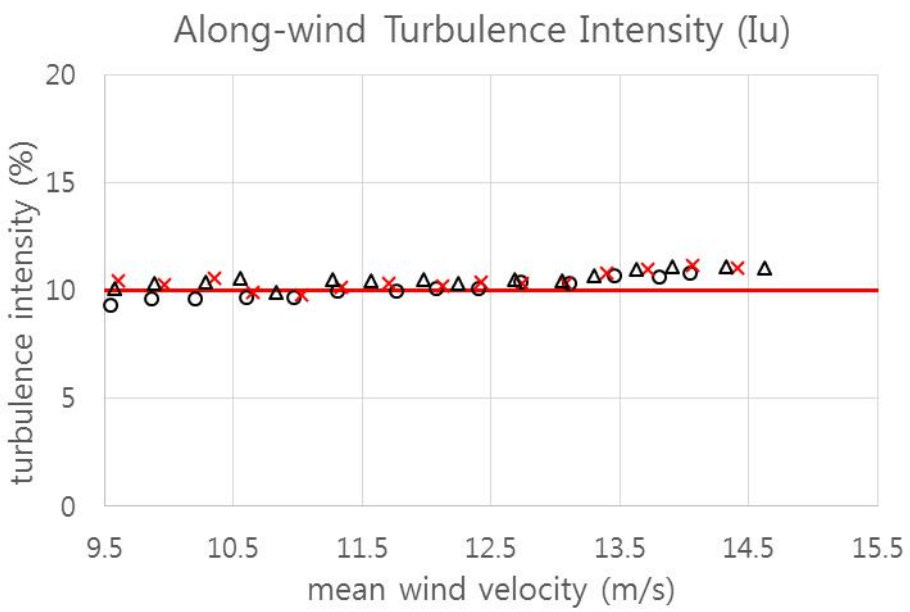

Fig 51. Control variable of case 3: Iu

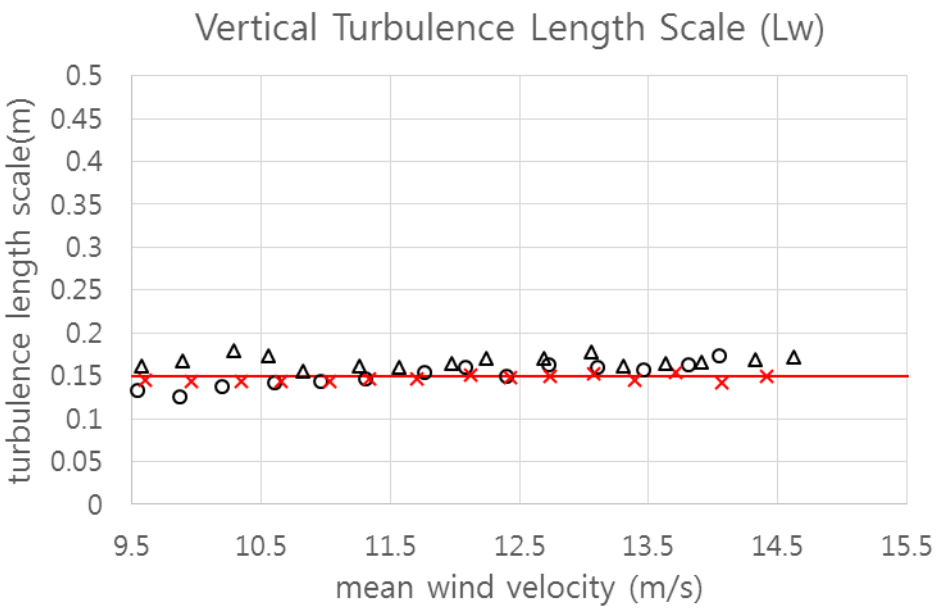

Fig 52. Control variable of case 3 : Lw

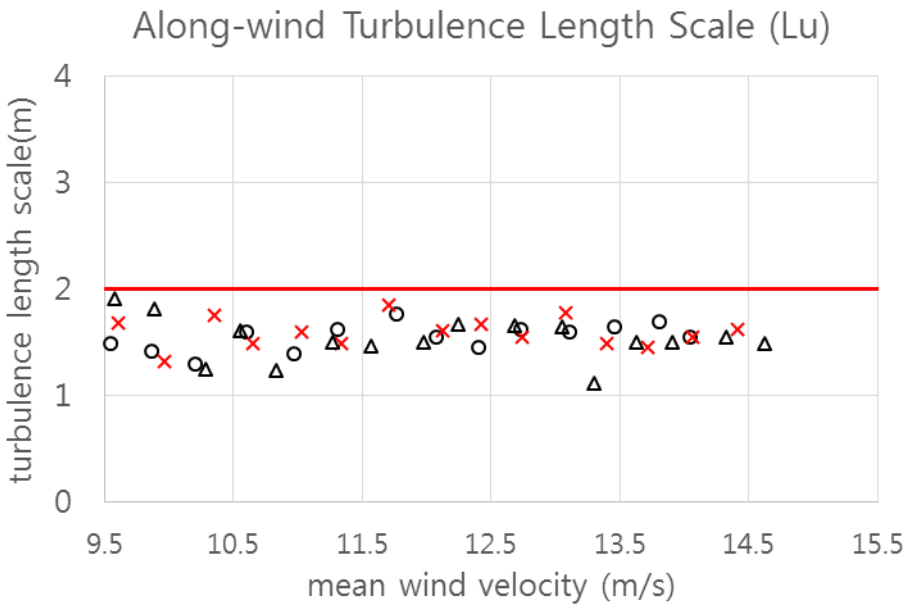

Fig 53. Control variable of case 3 : Lu

3.4.1.4 Case 4 : Varying Vertical Turbulence Length Scale by ATG

The turbulence length in the vertical direction is varied and the other factors are kept constant. Along-wind turbulence intensity (Iu) is 10.0%, Vertical turbulence intensity (Iw) is 5.0%. Along-wind turbulence length scale (Lu) is 2.0m. The values for vertical turbulence length scale were are follow : 0.15m, 0.3m

Table 6. Wind case with varying vertical turbulence length scale (ATG)

Mark	Turbulence Intensity		Turbulence Length Scale	
	Iu (%)	Iw (%)	Lu (m)	Lw (m)
○	10.0	5.0	2.0	0.15
X	10.0	5.0	2.0	0.3

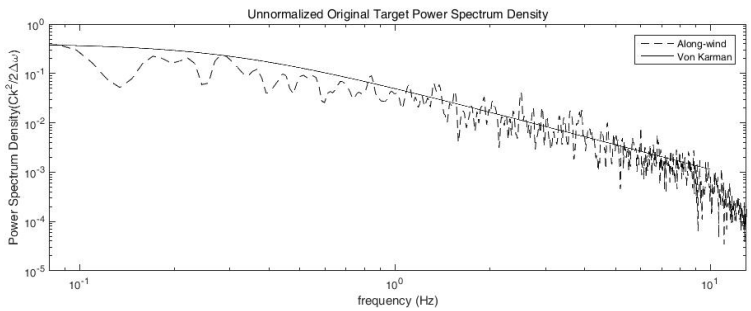

Fig 54. Wind power spectral density, Along-Wind Direction Lw=0.15m

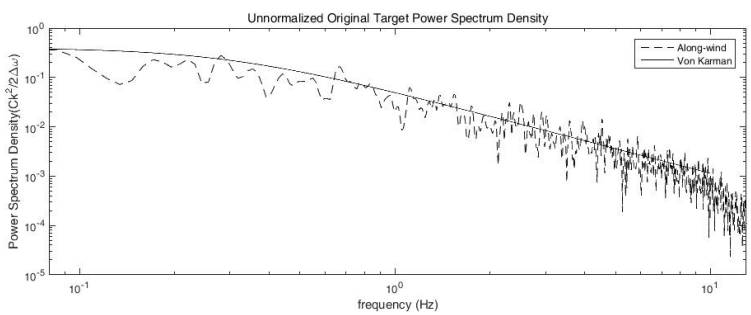

Fig 55. Wind power spectral density, Along-Wind Direction Lw=0.3m

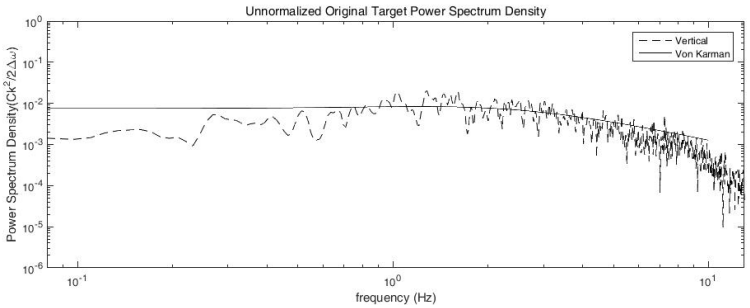

Fig 56. Wind power spectral density, Vertical Direction Lw=0.15m

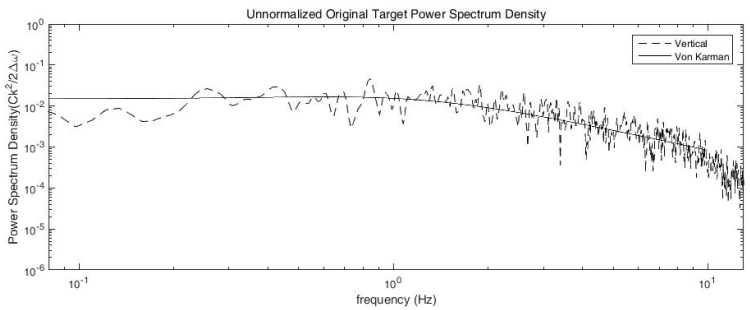

Fig 57. Wind power spectral density, Vertical Direction Lw=0.3m

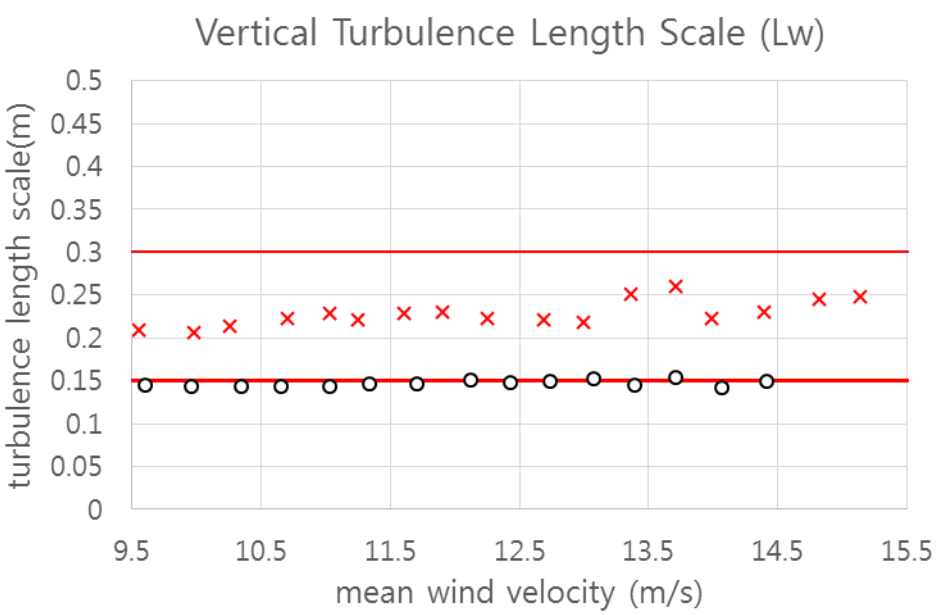

Fig 58. Dependent variable of case 4 : Lw

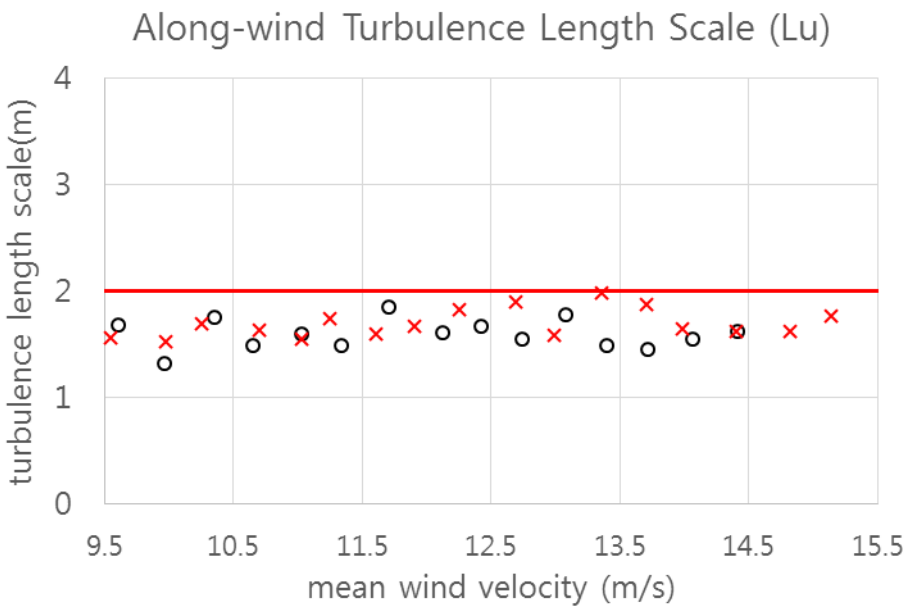

Fig 59. Control variable of case 4 : Lu

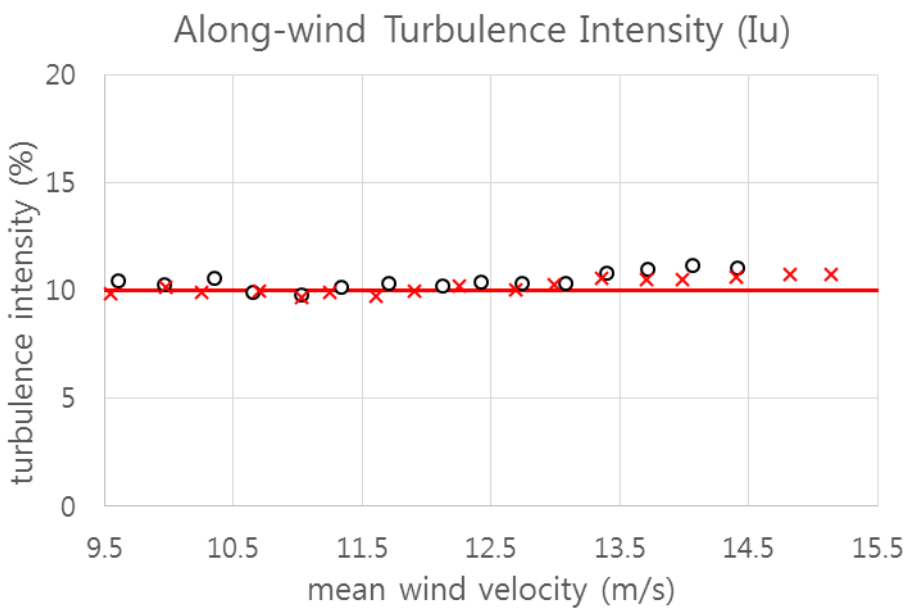

Fig 60. Control variable of case 4 : Iu

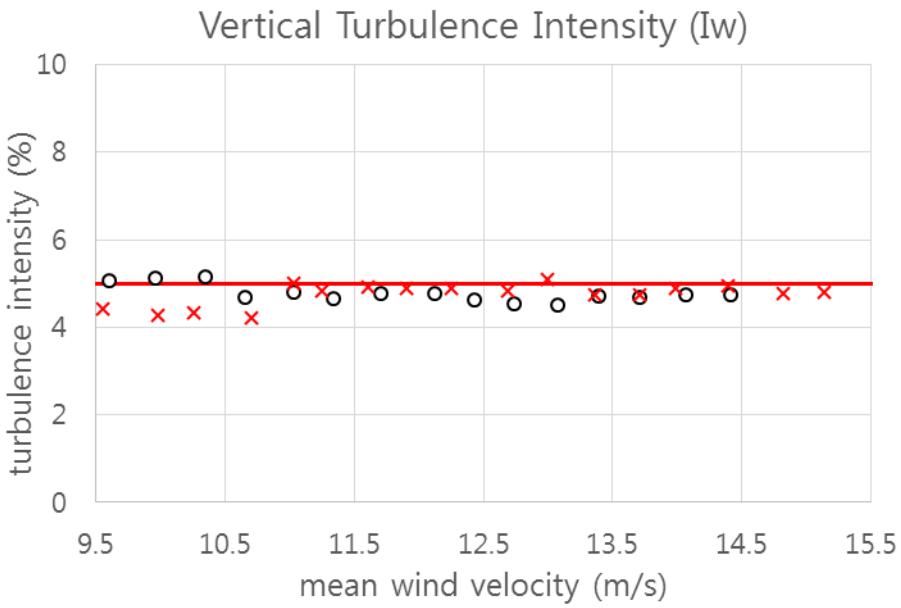

Fig 61. Control variable of case 4 : Iw

3.4.1.5 Case 5 : Varying Turbulence Intensity by Grid

The Active Turbulence Generator is advantageous for generating long target turbulence length scale. Grid was used to compare with the long target turbulence length scale created using the ATG. The Grid is advantageous in generating the target turbulence intensity, but there is difficulty in making the target turbulence length scale. Turbulence length scales are very small when using grid. The effect of the turbulence length on the vortex-induced vibration response can be confirmed by comparing the grid with the active turbulence generator device.

Table 7. Wind case with varying turbulence intensity (Grid)

Mark	Turbulence Intensity	
	Iu (%)	Iw (%)
○	2.0	2.0
X	4.0	4.0

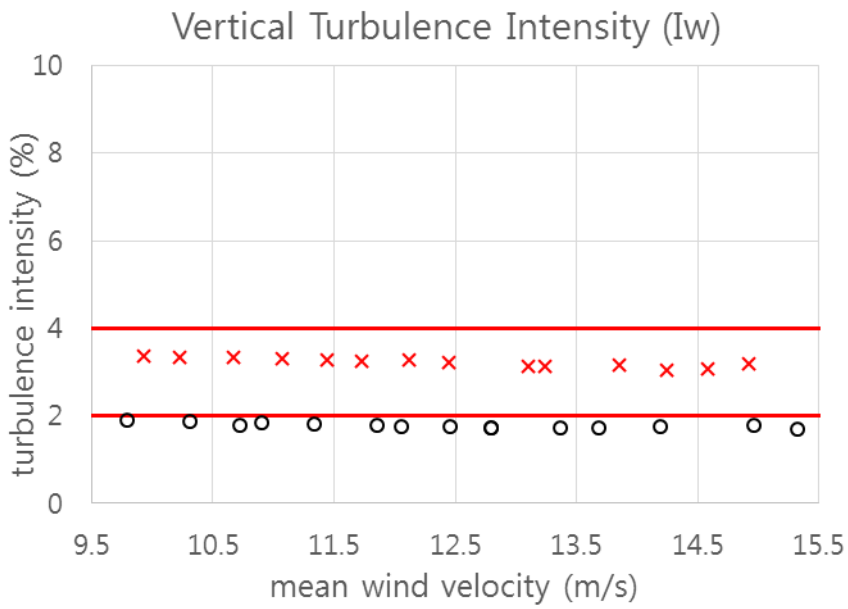

Fig 62. Control variable of case 6 : Iw

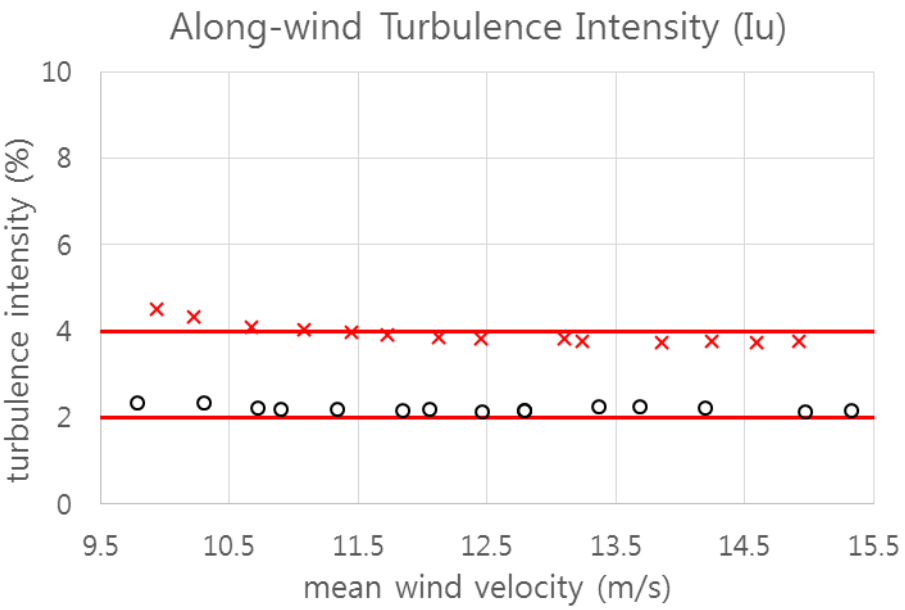

Fig 63. Control variable of case 6 : Iw

Chapter 4.
EXPERIMENT RESULTS

4.1 Wind Velocity of Vortex-Induced Vibration

The Fig 63. shows sharply decreasing part between 2s and 3s. This part is found in entire time domain. Due to this effect, the mean wind velocity was underestimated and was varied at the maximum bridge response. This was caused from ATG wing plate and its motion. This problem also appeared at the previous paper. This problem needs to be improved.

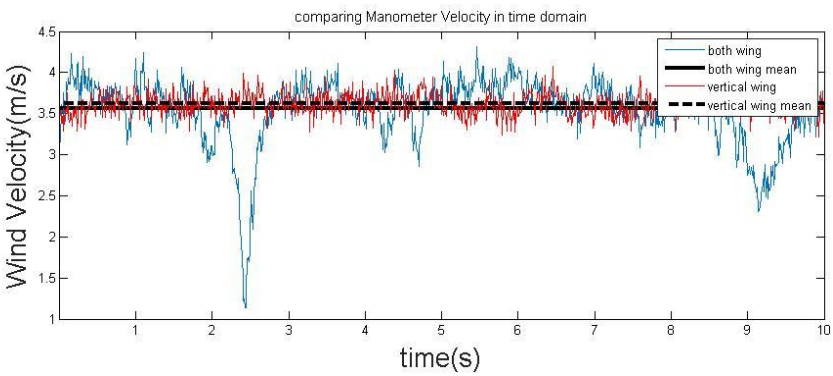

Fig 64. Comparing wind velocity in time domain between vertical and both wing

4.2 Checking Characteristic of Cross Section

Before concluding the response of parallel bridges, the parallel bridge test is compared with the single bridge test to verify if the responses are characteristics of the parallel bridges. The responses of the parallel bridges are based on the results of using grid. Maximum root mean square(rms) amplitude shows different reduction

rate between single bridge test and parallel bridge test.

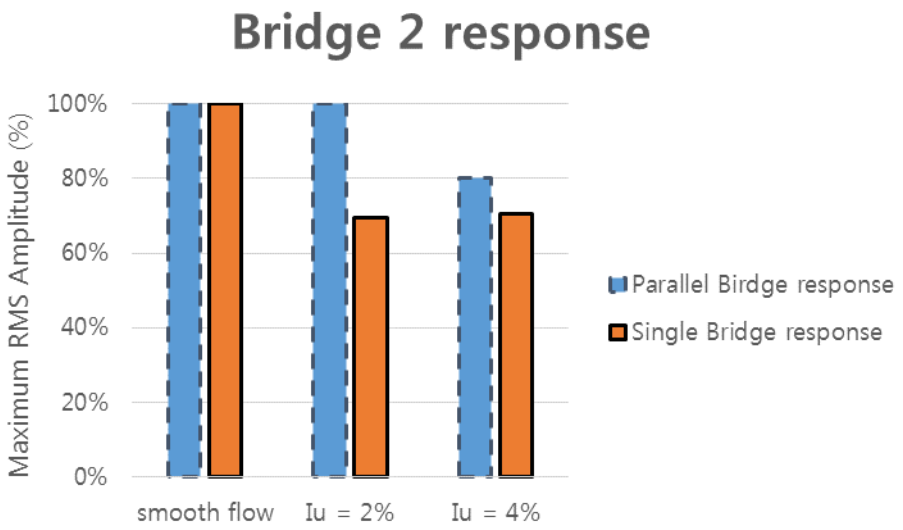

Fig 65. Comparing Bridge 2 response between parallel test and single test by Grid

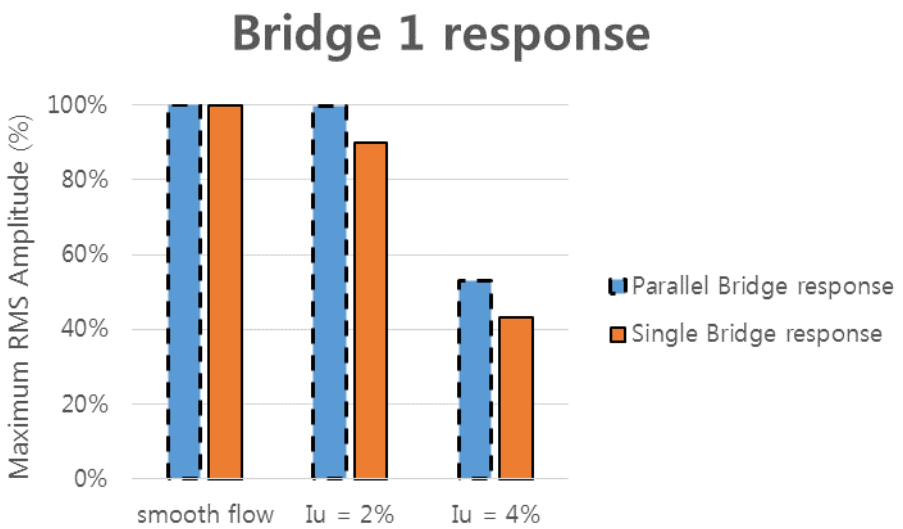

Fig 66. Comparing Bridge 1 response between parallel test and single test by Grid

4.3 Bridge Response by Vortex-Induced Vibration

4.3.1 Effect of turbulence type

The parallel bridge section model was tested for vortex-induced vibration under smooth flow and turbulent flow. The responses under the conditions by different types of ATG were compared : smooth flow, only vertical ATG, only along-wind ATG, and both ATG. In case of only vertical ATG, B2 response was not reduced. The response was reduced to 86.3% when only along-wind wing was used, and the largest reduction effect was obtained when both ATG was used.

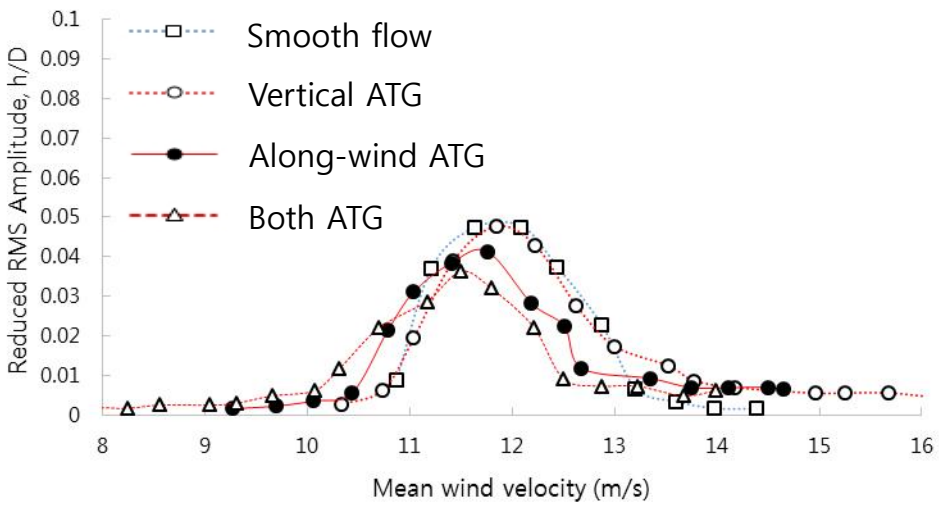

Fig 67. Reduced rms amplitude of B2 under different using ATG

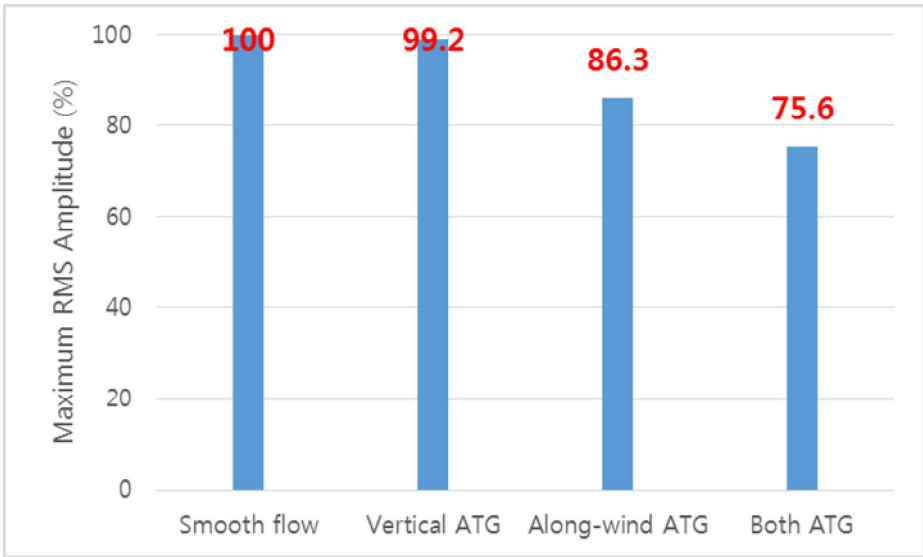

Fig 68. Comparing B2 response under different using ATG

B1 response decreased to 77.7%, 62.4%, and 50.7%, respectively, according to the use of ATG

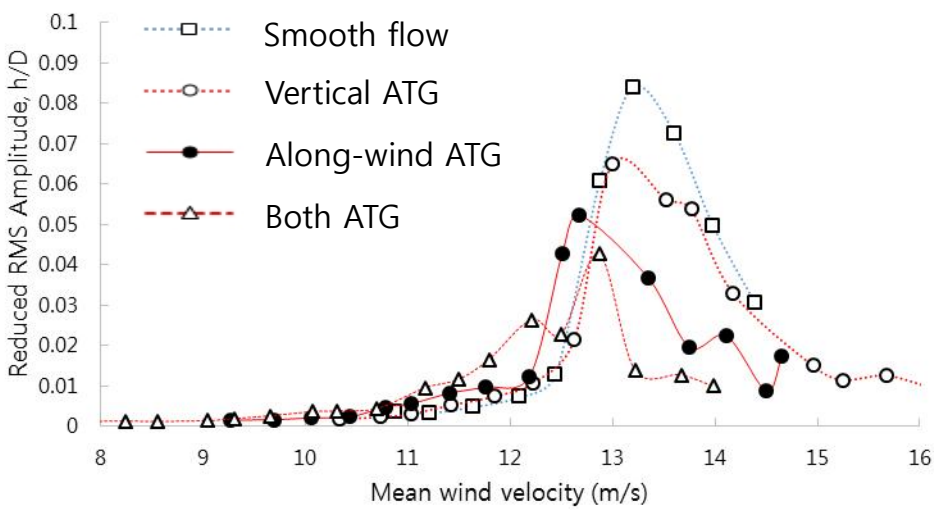

Fig 69. Reduced rms amplitude of B1 under different using ATG

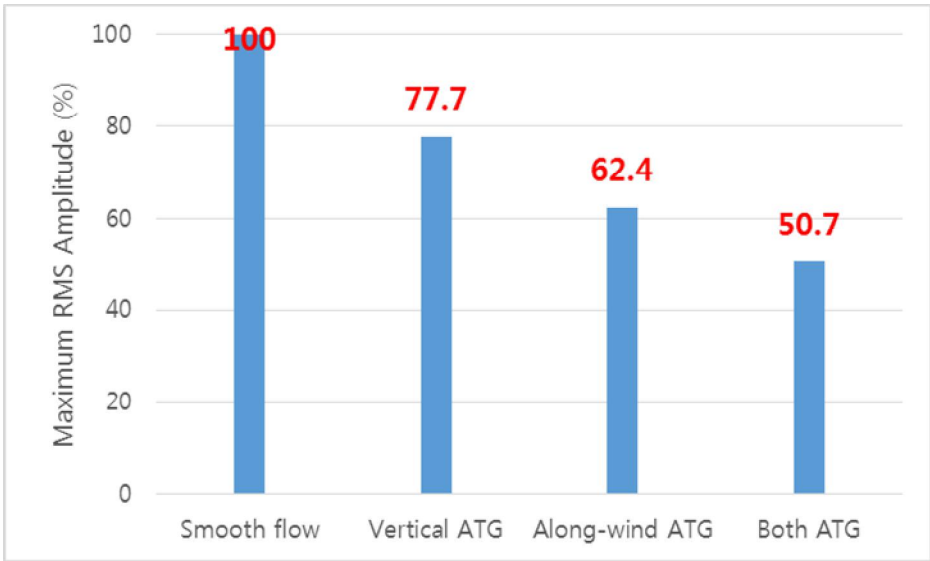

Fig 70. Comparing B1 response under different using ATG

4.3.2 Effect of along-wind turbulence intensity

The parallel bridges were tested at the five different types of the along-wind turbulence intensity generated by active turbulence generator. Fig 70. shows the response of B2(upstream) and Fig 71. shows the relationship between B2 response and along-wind turbulence intensity. When turbulence exists, B2 shows about 80% response compared to the smooth flow. More than 10% turbulence intensity makes B2 response lower.

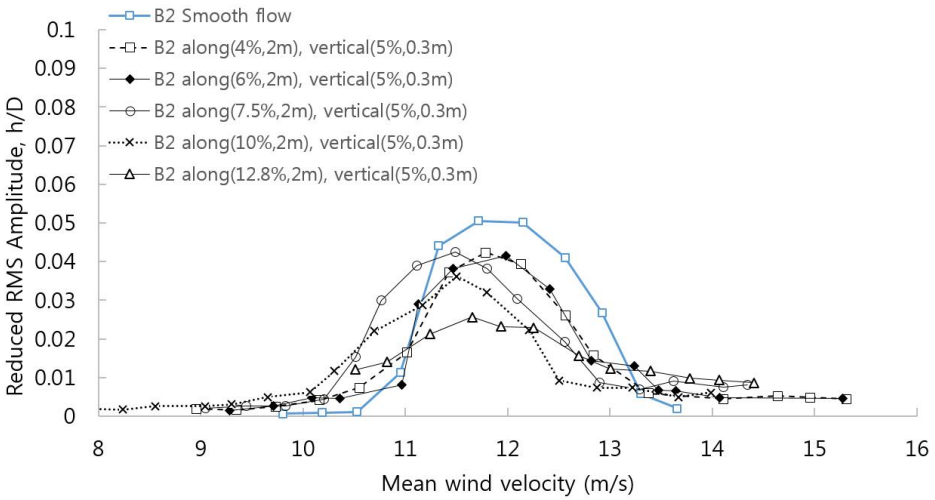

Fig 71. Reduced rms amplitude of B2 under different along-wind turbulence intensity

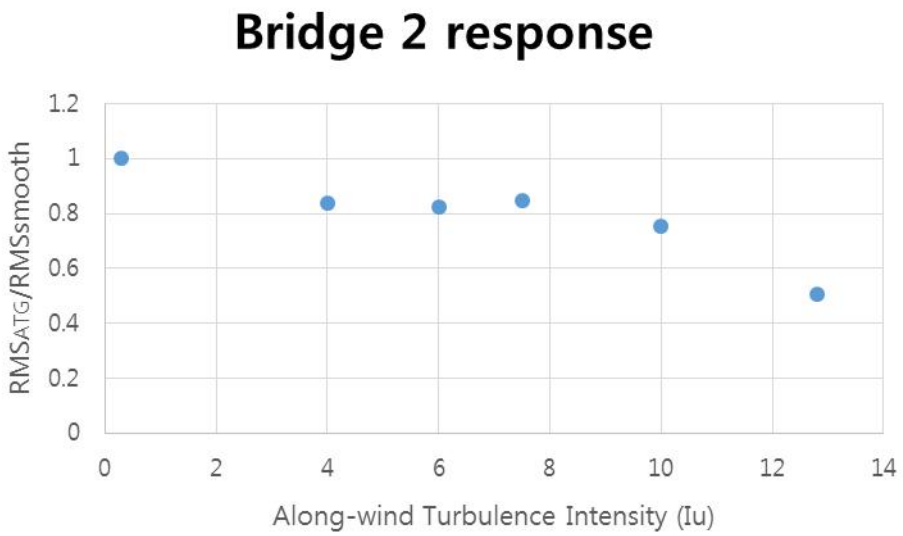

Fig 72. Bridge 2 response under different along-wind turbulence intensity

When turbulence exists, B1 shows about 40% response compared to the smooth flow. B1 response shows a similar response even though the along-wind turbulence intensity increases.

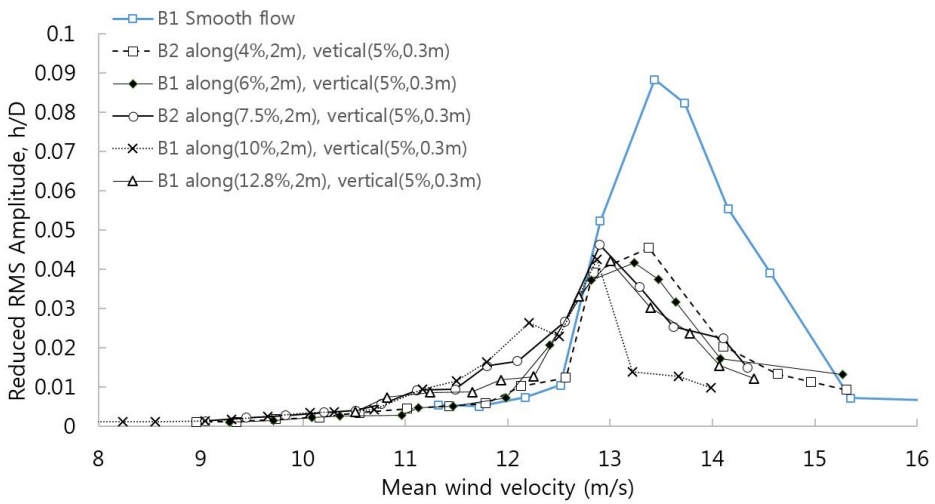

Fig 73. Reduced rms amplitude of B1 under different along-wind turbulence intensity

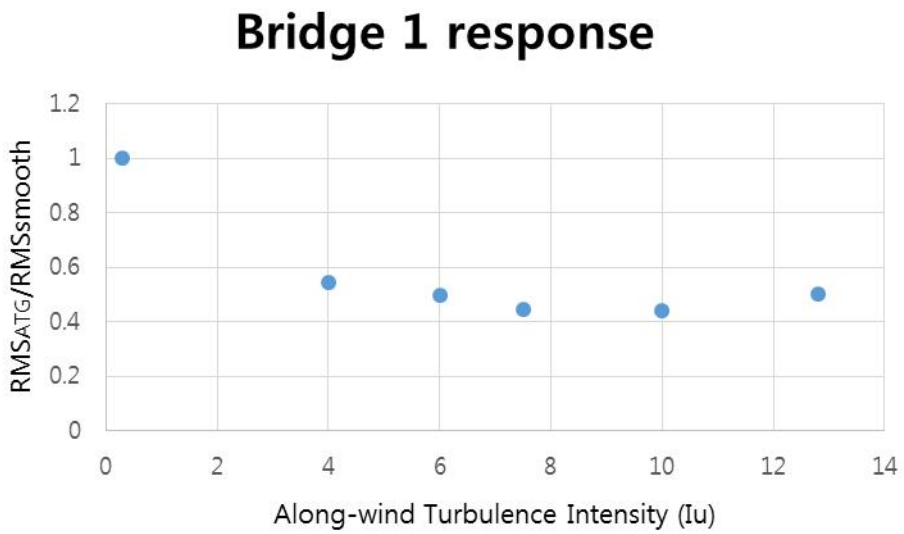

Fig 74. Bridge 1 response under different along-wind turbulence intensity

4.3.3 Effect of Vertical Turbulence Intensity

The parallel bridges were tested at the three different types of vertical turbulence intensity generated by active turbulence generator. Fig 74. shows the response of B2(upstream) and Fig 75. shows the relationship between B2 response

and vertical turbulence intensity. When turbulence exists, B2 shows about 80% response compared to the smooth flow. B1 shows about 40% response compared to the smooth flow.

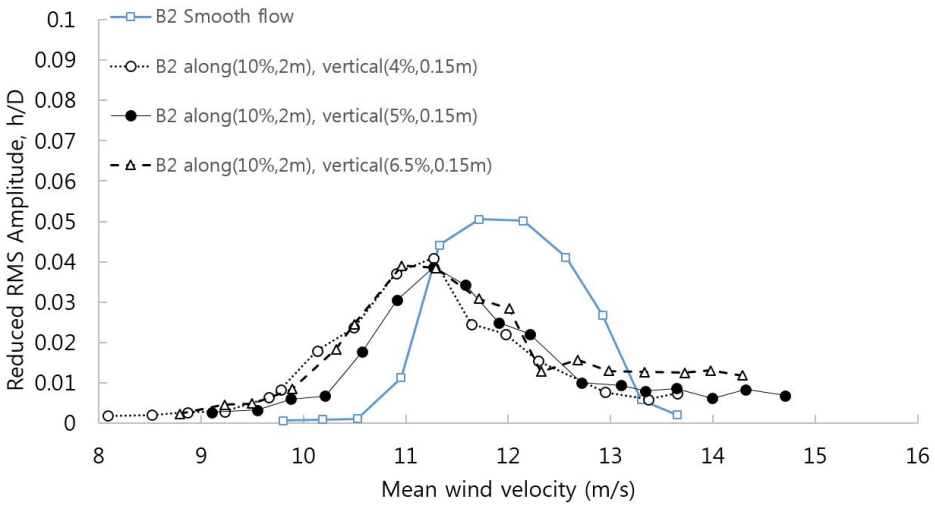

Fig 75. Reduced rms amplitude of B2 under different vertical turbulence intensity

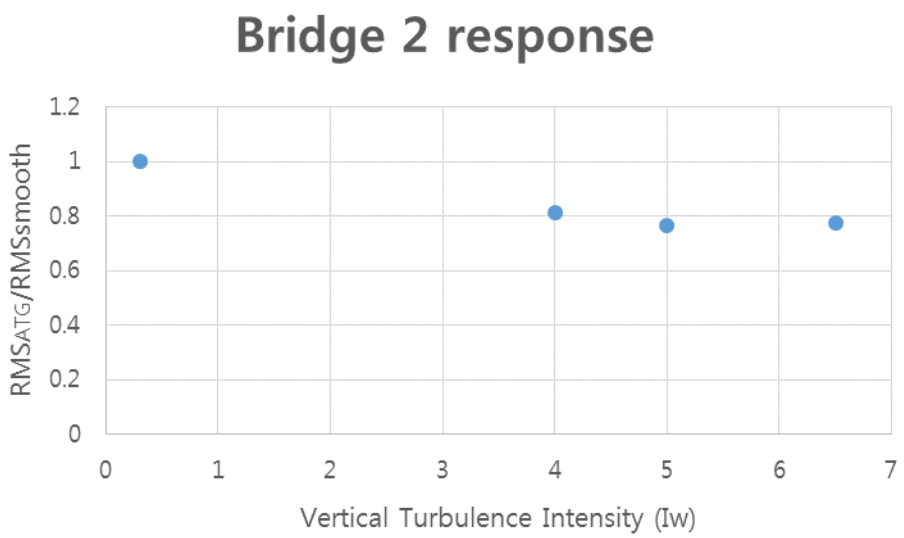

Fig 76. Bridge 2 response under different vertical turbulence intensity

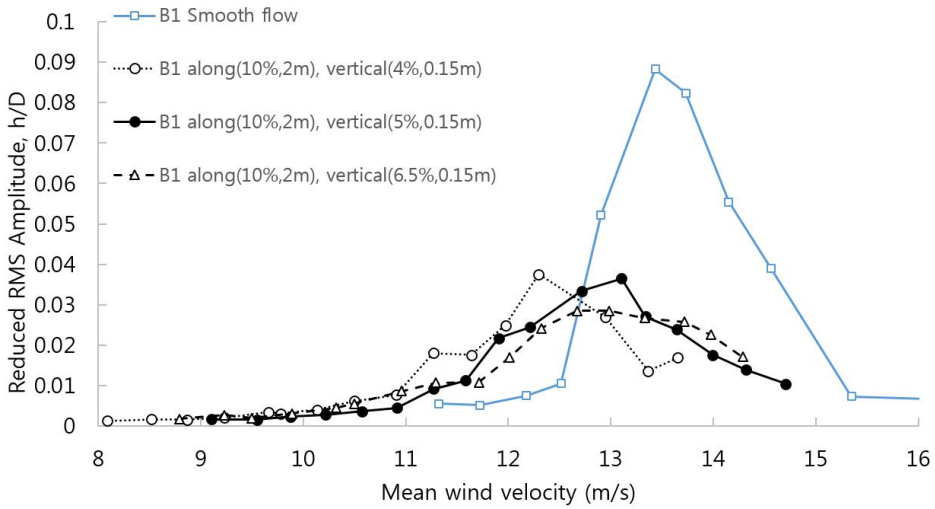

Fig 77. Reduced rms amplitude of B1 under different vertical turbulence intensity

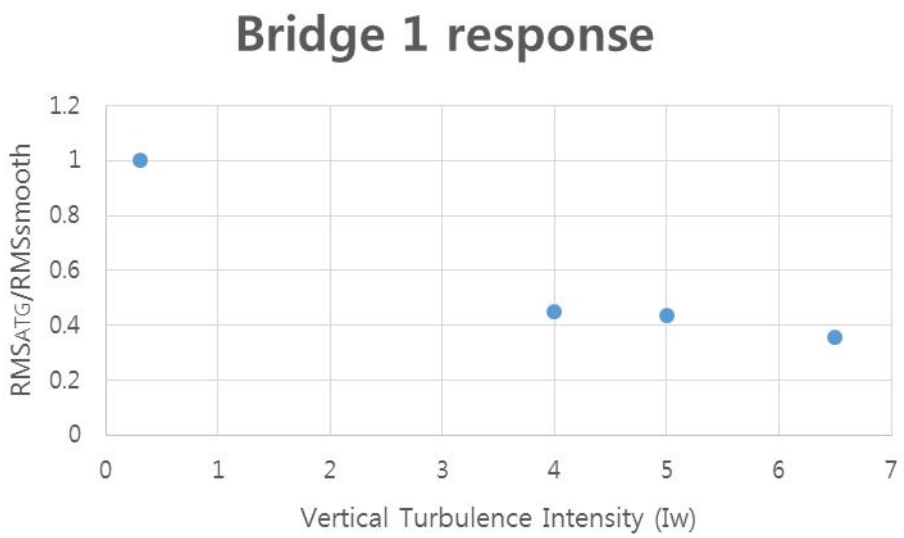

Fig 78. Bridge 1 response under different vertical turbulence intensity

4.3.4 Effect of Turbulence Length Scale

4.3.4.1 Comparing turbulence length scale between ATG and grid.

The effects of turbulence length scale on the parallel bridge responses by ATG and grid were compared. Long turbulence length was generated by ATG and short turbulence length was generated by grid. Turbulence intensity was used 4%. Fig 78. and Fig 79. Show that turbulence length scale did not affect the bridge model response.

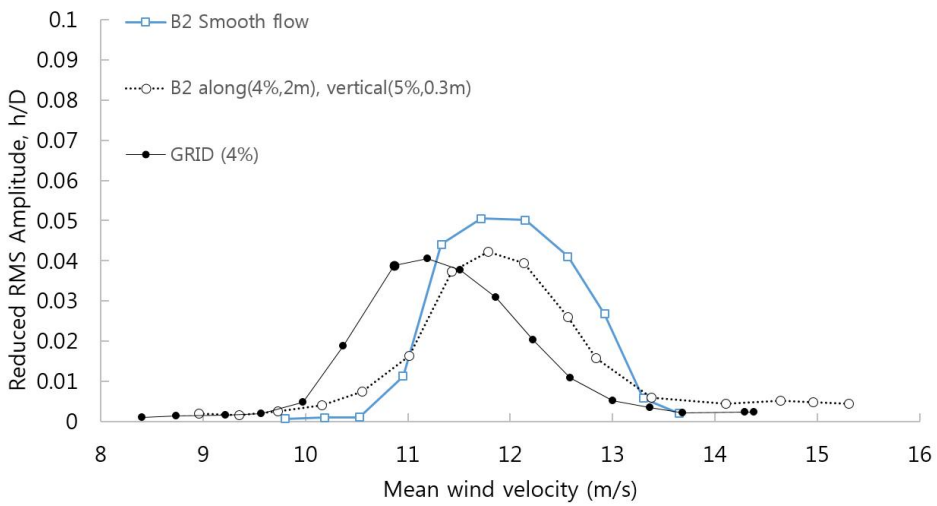

Fig 79. Reduced rms amplitude of B2 under 4% along-wind turbulene intensity, compared ATG and grid

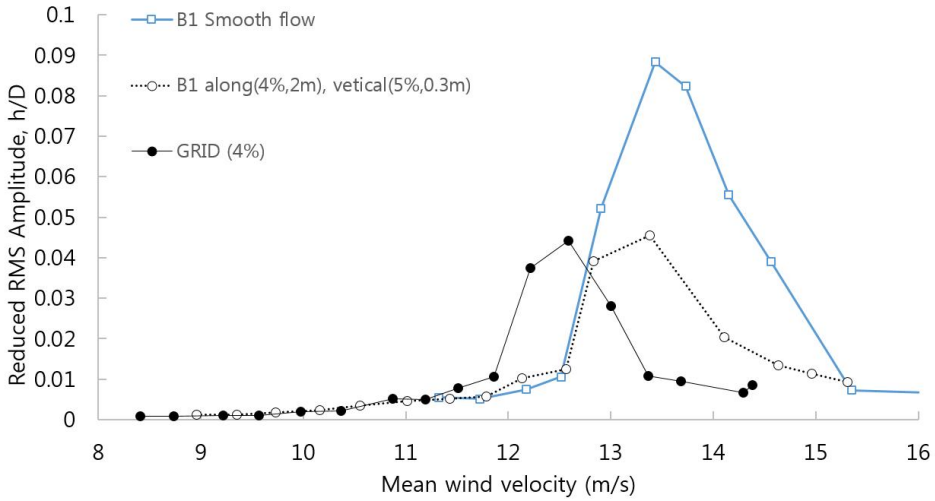

Fig 80. Reduced rms amplitude of B1 under 4% along-wind turbulene intensity, compared ATG and grid

4.3.4.2 Effect of Along-wind turbulence length scale by ATG

The response of parallel bridges was verified by changing the turbulence length in the along-wind direction through ATG. With this result, along-wind turbulence length scale did not affect the bridge model response.

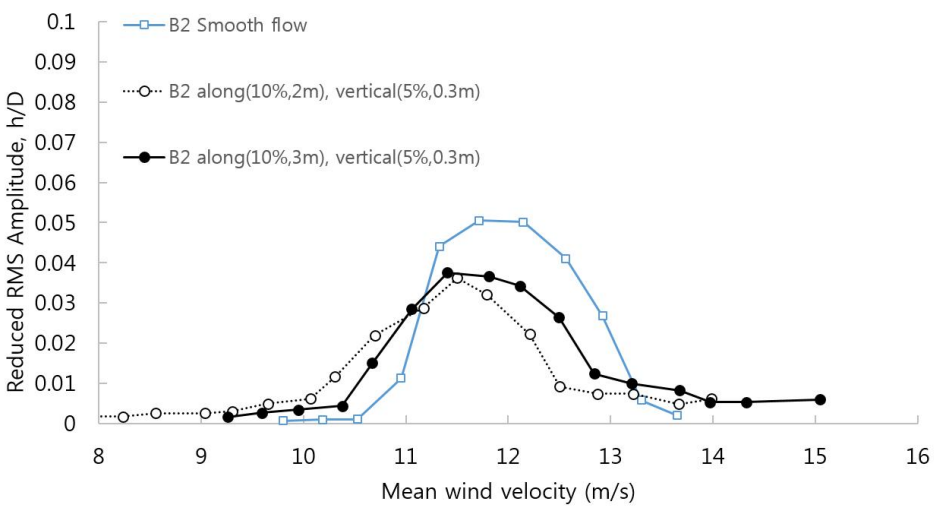

Fig 81. Reduced rms amplitude of B2 under different along-wind turbulence length

scale

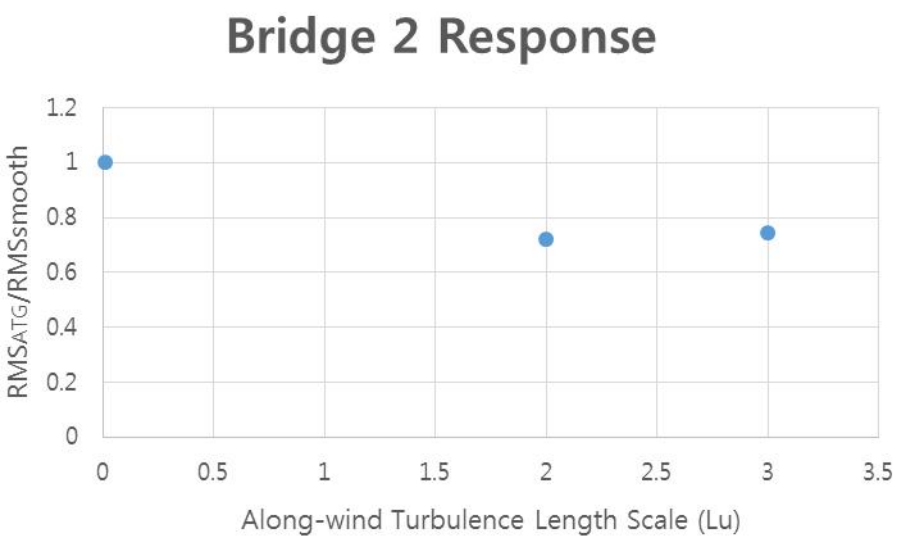

Fig 82. Bridge 1 response under different along-wind turbulence length scale

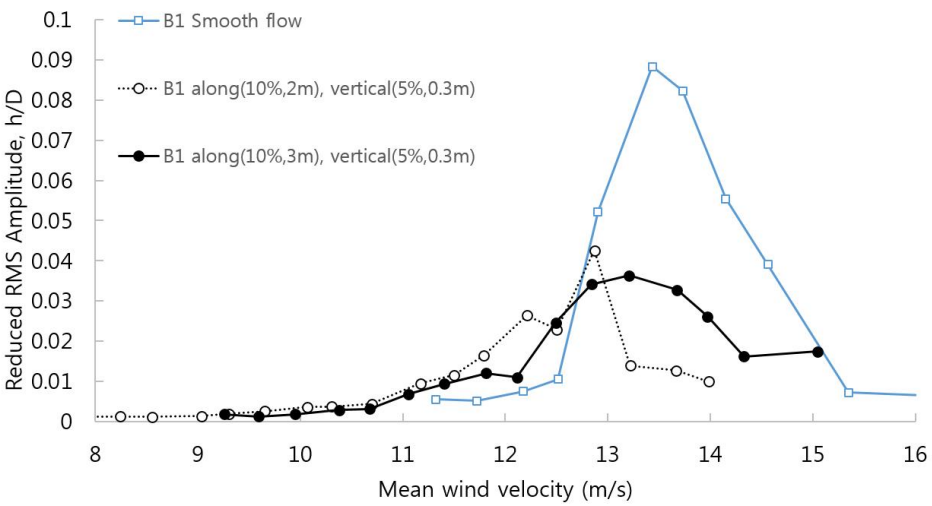

Fig 83. Reduced rms amplitude of B1 under different along-wind turbulence length scale

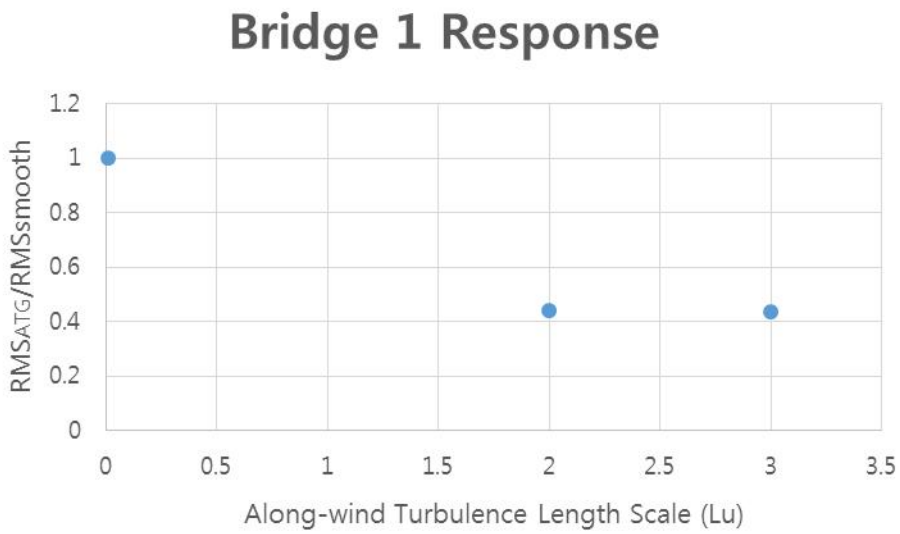

Fig 84. Bridge 1 response under different along-wind turbulence length scale

4.3.4.3 Effect of Vertical turbulence length scale by ATG

The response of parallel bridges was verified by changing the turbulence length in the vertical direction through ATG. With this result, vertical turbulence length scale also did not affect the bridge model response.

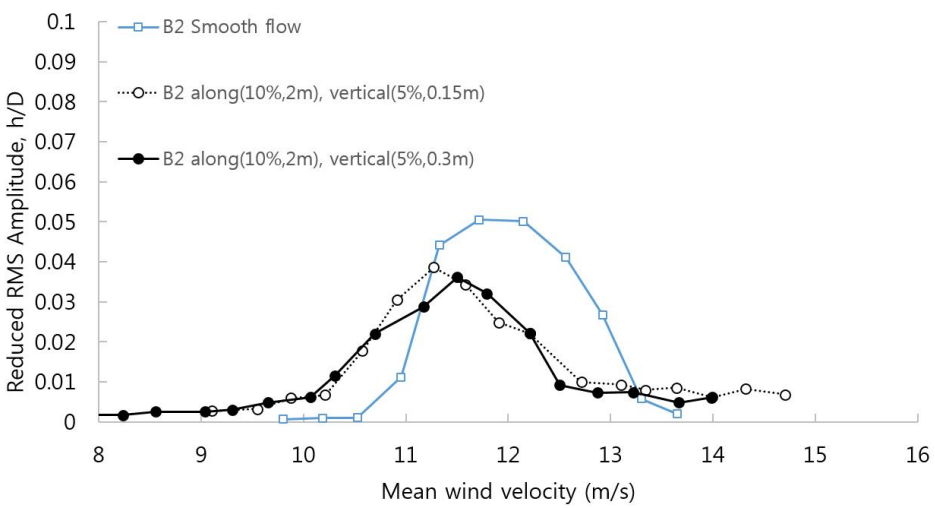

Fig 85. Reduced rms amplitude of B2 under different vertical turbulence length scale

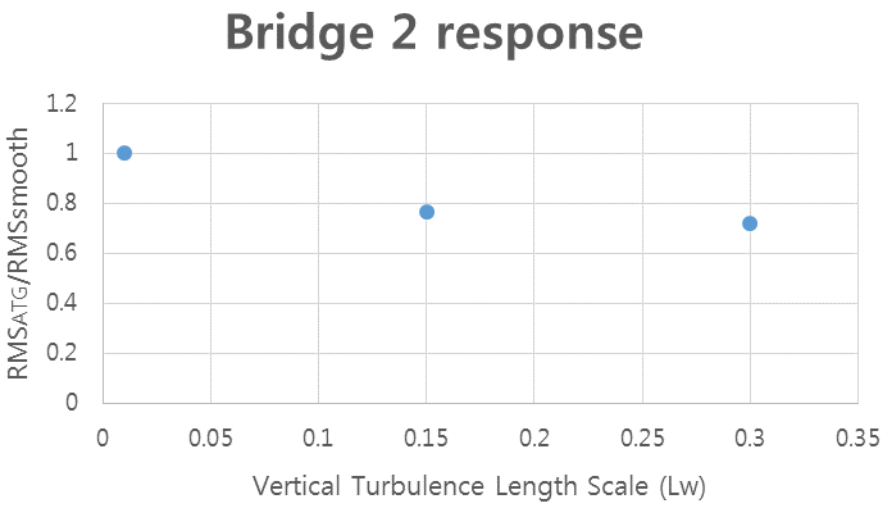

Fig 86. Bridge 1 response under different vertical turbulence length scale

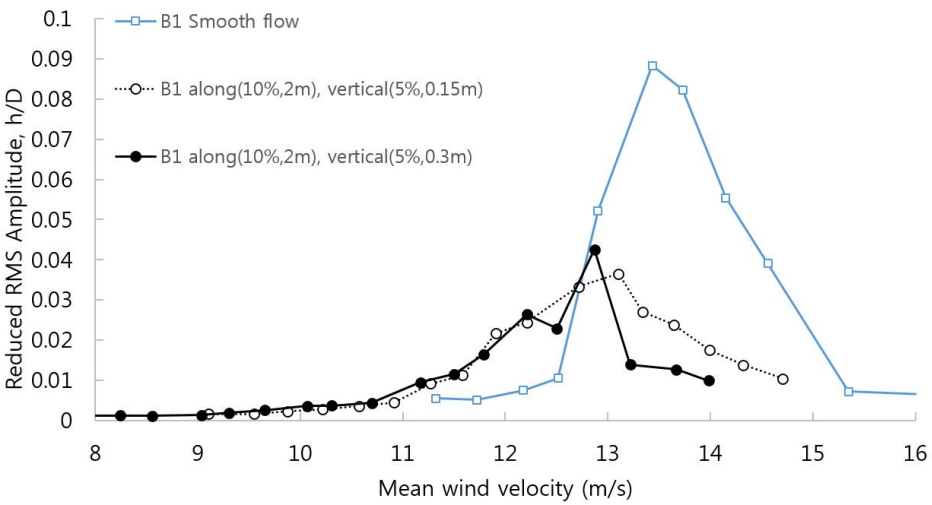

Fig 87. Reduced rms amplitude of B1 under different vertical turbulence length scale

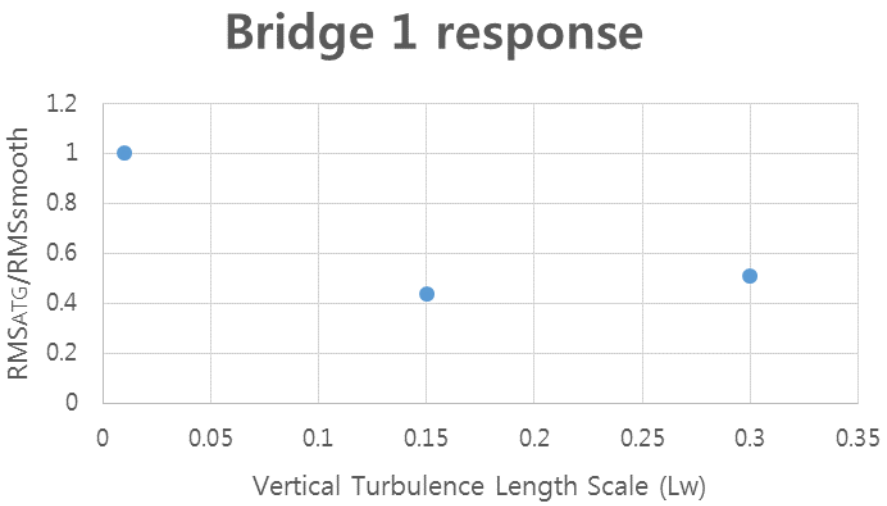

Fig 88. Bridge 1 response under different vertical turbulence length scale

Chapter 5.
CONCLUSION

1. Turbulent winds were generated by the use of grid and active turbulence generator. Turbulent winds were generated by aerofoil and flat gust at the same time. Turbulence intensity and turbulence length scale were well generated to proposed target turbulent components.
2. In parallel bridge section model, the responses of wing usage of ATG affect to parallel bridge model responses. The effect of reducing the parallel bridge section model response was the largest when using both ATG.
3. Along-wind turbulence intensity is main factor in the amplitude response about upstream bridge. As the along-wind turbulence intensity increases, the amplitude B2 response decreases. The response of parallel bridge model was affected by along-wind turbulence intensity. This leads to a conclusion that the along-wind turbulence intensity needs to be considered at the wind turbulence tests like the vertical turbulence intensity.
4. Vertical turbulence intensity is not main factor to both bridge model responses. The response of the parallel bridge was observed by changing the turbulence intensity in the vertical direction. However, the response corresponding to about 80% of the smooth flow in the upstream deck B2 and about 40% of the smooth flow in the downstream deck B1 was maintained.

5. Vortex-induced vibration of the parallel bridge section model was not affected by the turbulence length scale. The turbulence length scale was changed by ATG. The long scale wind turbulence generated by ATG and the short scale wind turbulence generated by grid. But the three results of the length scale experiments show that a length scale does not make a significant change to the bridge response.

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국 문 초 록

이 연구에서는, 목표하는 난류길이와 난류강도를 능동난류장치와 격자난류를 사용하여 생성하였고, 생성한 난류바람이 병렬교량 와류진동에 미치는 영향을 알아보았다. 능동난류장치는 두 개의 날개로 구성되어 있고, 기류방향과 연직방향 성분을 조절한다. 난류 풍속과 날개의 움직임 사이의 관계식을 실험으로부터 구하고 기류방향의 날개, 연직방향이 날개 순서로 독립적으로 제어하여 연직 및 기류 방향의 Von Karman 스펙트럼을 동시에 만족시키는 난류를 모사하였다. 난류길이와 난류강도가 병렬교량에 응답에 미치는 영향을 알아보기 위하여 기류방향의 난류강도, 난류길이와 연직방향의 난류강도, 난류길이 중 3개를 통제변인으로 사용하고, 나머지 1개를 조작변인으로 조합하여 사용하였다. 실험결과가 병렬교량의 특징인지 실험한 교량의 단면 특징인지 확인하기 위하여 단독교량과 병렬교량 실험을 비교하였다. 변인들 중 병렬교량의 응답에 영향을 주는 주요한 요인은 난류강도임을 확인하였고, 난류길이는 교량의 응답에 영향을 주지 않는 것을 확인하였다.

Keywords : 병렬교량, 와류진동, 난류강도, 난류길이, 능동난류장치, 난류
격자

Student Number : 2015 - 22923

감사의 글

2년 6개월이란 시간이 생각해보면 그렇게 긴 시간은 아니지만, 저에게 있어서 많은 도움이 되는 시간이었습니다. 그동안 힘들었고, 어려웠던 일들을 도와준 분들이 있었기에 이 글을 통해 감사의 마음을 전하려 합니다.

저에게 학문과 인생의 길을 가르쳐 주시고 수많은 조언과 꾸지람 속에 이만큼 가르쳐 주신 김호경 교수님께 진심으로 감사드립니다. 그리고 자신감 없을 때마다 선생님께선 잘 할 수 있고 잘하고 있다고 항상 저에게 자신감을 주셨습니다. 선생님의 이런 말씀 덕분에 제가 이렇게 논문을 잘 마무리 할 수 있었던 것 같습니다. 선생님 정말 감사드립니다.
또한 송준호 교수님, 이해성 교수님, 조재열 교수님, 박연철 박사님 그 밖에 건설환경공학부 교수님 저에게 많은 가르침을 주셔서 감사합니다. 그리고 멀리서도 많은 가르침을 주신 박진 형에게 감사합니다.

연구실 생활을 같이한 연구실 사람들에게 모두 고생이 많았고 정말 고맙다는 말을 전합니다.