FLUCTUATING WIND VELOCITY CHARACTERISTICS OF THE WAKE OF A CONICAL HILL THAT CAUSE LARGE HORIZONTAL RESPONSE OF A CANTILEVER MODEL

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Abstract. As a first step to clarify the bridge response characteristics in complex terrain, the flow structure in the wake of a conical hill that causes large horizontal response of a horizontally supported cantilever model was studied. Fluctuating wind velocities of u-, v-, w-components were measured with split film probes, and they were conditionally sampled based on the large horizontal response of the cantilever model. A clear flow structure with velocity toward downward and inward that acted around the tip location of the cantilever model was observed and it was thought to cause the large response. The flow structure seemed to develop as a downward flow and change its direction horizontally near the ground, and then intensify its magnitude in horizontal velocity components. The front line of the structure was skewed about 40 degrees from normal to the mean flow direction.
1 INTRODUCTION

Effects of complex terrain have to be carefully considered for the wind resistant design of long span bridges. In some cases, large along-wind responses were observed when the bridge is located in the wake of a hill, which cannot be explained by the conventional buffeting theory [1]. As a step to clarify the cause of such large responses, fluctuating wind velocity characteristics acting on a simplified bridge model in the wake of a conical hill were studied. Similar study has been presented by the authors [2] before, but the data presented in this paper were taken after the study for Ref. [2], and somewhat different characteristics were found and they are mainly discussed here.

2 EXPERIMENTAL SETUP

The size of the models was determined so that they corresponds to 1/1333 of the Tatara Bridge case [1]. A simplified conical hill model with height \( H \) of 30cm and diameter \( 2R \) of 135cm was used. The bridge model was a rigid square cylinder made of wood with width and height of 2.0cm and length \( L \) of 30cm. It was cantilever-supported horizontally at the height of 3.7cm with a steel plate to be allowed 1 DOF along-wind response. The natural frequency and damping ratio of the model were 7.3Hz and 7.5%. The structural damping was relatively large, because the cantilever model was equipped with pressure taps and tubes so that the fluctuating pressure on the model could be measured simultaneously with the response and fluctuating velocity measurements. Although the response, fluctuating velocities, and fluctuating pressures were measured simultaneously, only the results from the response and fluctuating velocities are mainly discussed in this paper.

An Eiffel type boundary layer wind tunnel at Kyushu Institute of Technology with the test section of width, height and length of 2.4m, 1.8m and 20m was used. No turbulence generating device was used but the boundary layer that can be approximated with power law coefficient of 0.16 and thickness of 60cm was generated at the hill model location.

The bridge model free end was set at the location of \( x/R=1.48 \) and \( y/R=-0.15 \), where the origin of the coordinate was taken at the center of the hill model and the height of the bridge model axis with \( x \)-coordinate defined toward leeward, \( z \) upward and \( y \) with the right-handed coordinate system. The wind yaw angle \( \beta \) of the model was set as 40° from normal to the model axis, so that the bridge model free ended pointed toward windward and center of the hill model direction (Fig. (1)). Those conditions were set based on the previous measurements with which large bridge model responses were observed.

The simultaneously measured bridge model response amplitude and fluctuating wind velocities were stored with sampling frequency and time of 1000Hz and 5 minutes, respectively. The measurement was repeated twice, so that the total sampling time was 10 minutes. The approaching gradient wind speed \( U \) was chosen to be 4.0, 6.0 and 8.0 m/s. The fluctuating wind velocities were measured by split film probes and hot wire anemometry. By using different types of split film probes, \( u \), \( v \), and \( w \)-components of the fluctuating velocity were measured. The measurements were taken at 4cm windward of the model windward surface at the locations as shown in Fig. (2). The axis \( y' \) was defined at the location of the velocity measurement from the free end location toward the support direction. The measurement was taken at 6 locations between \( y'/L=0 \) and 0.67. The measurement height was at 11 locations between \( z/H=0 \) and 0.67 for \( U=6.0 \) m/s. For the cases with \( U=4.0 \) and 8.0 m/s, measurements were taken at 8 location heights between \( z/H=0 \) and 0.47. The total numbers of the measurement locations were 66 for \( U=6.0 \) m/s case and 48 for \( U=4.0 \) and 8.0 m/s cases. Note that the wind velocity measurement location is also skewed by 40° as the cantilever model.
With $U=4.0$, 6.0 and 8.0 m/s, the mean wind speed at the cantilever model height and span-wise location of $y'/L=0.00$ (and 0.13) were 1.61 (1.84), 2.4 (2.5), and 3.3 (3.5) m/s, respectively. Assuming that the 1st natural frequency of the along-wind mode of the prototype bridge under construction as 0.05 Hz, the full scale mean wind speeds at the deck height corresponding to $U=4.0$, 6.0 and 8.0 m/s are 14.7 (16.8), 22 (23), 30 (32) m/s, respectively.

In order to clarify the fluctuating wind velocity characteristics that cause large horizontal responses, the fluctuating wind velocity components were conditionally sampled based on the occurrence of the large response peak. The large response peak was defined in this study as that with the leeward amplitude of more than 2.5 times of the standard deviation. The numbers of the conditionally sampled data were 130-189 ($U=4.0$ m/s), 76-173 ($U=6.0$ m/s), and 25-39 ($U=8.0$ m/s) in total 10 minutes data. The number of the sampled data considerably differs among the same wind speed cases. The number is particularly small with $U=8.0$ m/s, but it was confirmed that the kurtosis and non-dimensionalized power spectrum of the response with $U=8.0$ m/s were not so much different from other wind speed cases. The scatter of the numbers of the conditionally sampled data was probably due to its sensitiveness of slight difference of the response time history characteristics.
3 EXPERIMENTAL RESULTS

The characteristics of fluctuating wind velocities after conditional sampling are shown in the following. In all the figures, the origin of the horizontal coordinate corresponds to the instant when the large leeward response peak occurred.

3.1 Time history of the fluctuating wind velocities

In most of the cases, large wind velocity fluctuations were observed at a short time (0.05-0.15sec) before the response peak occurrence (t=0). These fluctuations are thought to cause the large response of the bridge model. In the cases with $U=6.0$ and 8.0 m/s, the velocity fluctuation peaks occurred almost simultaneously at different $y'/L$ locations along the bridge model axis at the bridge model height ($z=0$), as shown in Figs. (3a), (4a) and (5a) as examples. Because the model was located with wind yaw angle $\beta=40^\circ$, this means that the front line of the flow structure that caused the large response had the same skew angle at the model height. The similar observations were obtained in previous studies by the authors [2].

At higher locations (Fig. (3b), (4b) and (5b) as examples), on the other hand, the velocity fluctuation peaks occurred from the model tip location ($y'/L=0.00$) to the support ($y'/L=0.67$).

![Figure 3](image-url)

Figure 3: Time history of fluctuating wind velocity ($u$-component, $U=6.0$ m/s).

![Figure 4](image-url)

Figure 4: Time history of fluctuating wind velocity ($v$-component, $U=6.0$ m/s).
This means that the flow structure was less skewed at higher locations, and it can be understood because the flow is less affected by the hill at higher locations.

In Figs. (3)-(5), periodic fluctuations are observed in negative $t$ region, i.e., before large horizontal response of the cantilever model occurred. The period corresponds to the natural period of the cantilever model, and the fluctuation is thought to be caused by the conditional sampling based on the large response [4].

### 3.2 Possible flow structure causing large horizontal response

A trial was made to visualize the flow structure that causes the large horizontal responses by drawing the fluctuating velocity vectors (Figs. (6)-(8)), where the horizontal coordinate is “reduced $x$-coordinate”. Reduced $x$-coordinate is defined as the length that can be calculated by multiplying the time, average of $u$ at the measurement location, and $-1$. This procedure is similar to the Taylor’s frozen turbulence approximation. However, because the flow in the wake of the hill model is not stationary, the approximation cannot be applied. Instead, it has to be understood that Figs. (6)-(8) expresses the flow structure when it passed the velocity measurement location and it is placed side by side so that the overall characteristics can be caught more clearly. In order to clearly show the fluctuating wind velocity structure, the fluctuating component $u'$ was used to draw the velocity vectors for the stream-wise component of the wind velocity.

At $z/H=0$ and $y'/L=0$ location near the cantilever model free end, a clear flow structure can be seen with much larger magnitude that acted on the model just before the occurrence of large response (Figs. (6a), (7a) and (8a)). The structure had the downward (minus $z$-direction) and inward (plus $y$-direction in Fig. (1)) components. At higher locations, weaker but similar structure that acted a little earlier can be observed, and it probably shows that this flow structure developed from upward to downward. This downward flow structure probably intensified its velocity in horizontal, $u$- and $v$-components when the flow hit the ground and changed its direction to horizontal.

At other $y'/L$ locations far from the cantilever model free end, similar structure was seen, but its magnitude became smaller. Therefore, this flow structure which mainly acted around the free end of the model seems to effectively generate large response of the cantilever model.

In a previous study by the authors [2], the flow structure that caused the large horizontal response of the cantilever model was identified as somewhat upward flow, but there were
mistakes in the data processing procedure. The flow structure discussed in this study was also confirmed with other set of experimental data where the wind velocity was measured with x-probes.

In another previous study by the authors [3], it was pointed out that the large horizontal responses of the cantilever model were caused by the fluctuating pressure pattern of POD 1st mode. Therefore it would be more reasonable to catch the flow structure using a conditional sampling based on the occurrence of large POD 1st modal coordinate. Such discussion is also given elsewhere [4].

4 CONCLUDING REMARKS

As a step to understand the effects of complex terrain to the wind-induced response of long-span structures, wind tunnel studies were conducted. Fluctuating wind velocities in the wake of a conical hill were measured and conditionally sampled based on the large response of a cantilever model. Conditionally sampled wind velocity components were analyzed and a possible flow structure that caused large horizontal response of the cantilever model was discussed.
REFERENCES

Figure 8: Fluctuating wind velocity vectors after conditional sampling, \( v-w \)-component, \( U=6.0 \text{m/s} \).

