Wind energy harvesting at elevated bridges

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ABSTRACT: This paper presents overall procedure for wind energy harvesting at elevated bridge in order to enable the self powered bridge. The test bed bridge was carefully selected from short term wind data measured at 86 sites considering wind energy potential and safety issues for traffic. The position of wind turbine around bridge girder was chosen from the CFD analysis and wind tunnel tests, where wind speed boosted 17\textendash;27\% by oncoming wind. Two small wind turbines and associate monitoring system for wind data and electric power have been installed at the concrete girder of an elevated bridge over 57m above ground. Monitoring results for recent two months reveals a high correlation between the wind speed probability distribution and actual generated electric power. Long term monitoring of wind data and electric power is ongoing for further investigation.

KEYWORDS: Wind Energy, Bridge, Wind Turbine, Wind Tunnel Test.

1 INTRODUCTION

In modern bridges, electricity is needed for service and maintenance such as traffic control, lighting, and structural health monitoring. However, it is not easy to supply electricity to bridges in remote area. The cost for electric grid connection is $50/m in Korea, and is not acceptable for many bridges in rural or mountain area. One feasible way is to provide the harvested electricity from ambient energy sources to rechargeable battery equipped at bridges. Wind has an advantage of a continuous source of energy. The traditional wind turbines convert the ambient wind flows into useful electrical energy.

Elevated bridges are good places for wind energy harvesting because of escalated wind speed from the ground. Wind speed is also increased at elevated bridges which cross a valley or canyon, producing a convergence of streamlines. When wind turbines are installed at bridge girder, the major concerns for bridge are probable wind forces increase, mechanical vibration and wind-induced vibrations. In case of short and mid span bridges, wind induced vibrations and mechanical vibrations may be not significant because of its stiffness. The additional wind forces at the bridges introduced by wind turbines seem to be negligible compared with self load and other live loads.

In the first step for realizing the self powered bridges, an elevated concrete bridge with sufficient stiffness has been selected and equipped two different types of small wind turbines. This paper presents overall numerical and experimental results of site selection, position of wind turbine, monitoring system and short term measurement at field.
2 WIND RESOURCE ASSESSMENTS

2.1 Long term estimation of wind resource

While field observation of wind data at a specific site is the best solution for accurately assessing the wind energy potential, it is generally not feasible to acquire sufficient long-term wind data for the site. To overcome this problem, the Measure–Correlate–Predict (MCP) method has generally been used to estimate the long-term wind data at the target site from the wind data at the reference site. The fundamental principle behind MCP is that the wind at a new “test site” can be predicted on the basis of comparisons with data from a long-term “reference” site, which is located somewhere in the general vicinity [Manwell, et al., 2001].

When we obtained sufficient number of wind data at target site from the MCP method, we need to model the wind speed using probability distributions. The Weibull distribution is widely used in practical application. However, it is not acceptable at some case that the sources of wind are two or more. If probability density function of wind speed reveals two peaks, it is suitable to use the conventional Weibull distribution, and the mixed probability distribution seems to be solution. These two probability distributions are explained at next section.

Once the probability distribution is determined, next step for wind energy assessment is combining and integrating the probability distribution and power performance curve of the selected wind turbines. The output electrical power can be expressed as

\[ E = T \int_0^\infty P(v)f_v(v)dv \]  

(1)

where, \( v \) is wind speed, \( P(v) \) is power performance curve of wind turbine, \( f_v \) is probability density function, and \( T \) is time period. \( T = 8760(=365 \times 24) \) hours for calculating annual energy production (AEP).

2.2 Probability distributions of wind speed

The two parameter Weibull is a flexible distribution that is useful frequency distributions of wind speeds. The probability density function (PDF) of the Weibull distribution is expressed as

\[ f_v(V) = \frac{k}{c} \left( \frac{V}{c} \right)^{k-1} \exp \left\{ -\left( \frac{V}{c} \right)^k \right\}, \text{ for } V>0 \]  

(2)

where, \( c>0 \) is the scale parameter, and \( k>0 \) is the shape parameter of the distribution. The following shape and scale parameters can be calculated from the maximum likelihood method.

\[ k = \frac{\sum_{i=1}^n v_i^k \ln(v_i)}{\sum_{i=1}^n v_i^k} \]  

(3a)

\[ c = \left( \frac{1}{n} \sum_{i=1}^n v_i \right)^{\frac{1}{k}} \]  

(3b)

where, \( v_i \) is the wind speed in \( i^{th} \) time step, and \( n \) is the number of data points.

A mixture density is a probability density function that is linear combination of other probability density functions. Suppose that \( v_i (i = 1, 2) \) are independently distributed as two-parameter Weibull \( f(v, c, k, \omega) \), a random variable \( v \) that is distributed as \( v_i \) with mixing parameters \( \omega_i \), is said to have a two-component mixture Weibull distribution. The PDF of \( v \), which depends on five parameters \( (c_1, k_1, c_2, k_2, \omega) \), is given by [Carta, et al., 2007]

\[ f_v(c_1, k_1, c_2, k_2, \omega) = \omega f_{v_1}(c_1, k_1) + (1 - \omega) f_{v_2}(c_2, k_2) \]  

(4)
where, \( v > 0 \), \( c_1, k_1, c_2, k_2 > 0 \), and \( 0 \leq \omega \leq 1 \). Parameter estimation method consists of finding the values of the parameters \((c_1, k_1, c_2, k_2, \omega)\), which maximize the function of log-likelihood is given by

\[
\text{Maximise } \ln L_v(c_1, k_1, c_2, k_2, \omega) = \sum_{i=1}^{n} \ln \left\{ \omega \left[ \frac{k_1}{c_1} \left( \frac{v_i}{c_1} \right)^{k_1-1} \exp \left\{ - \left( \frac{v_i}{c_1} \right)^{k_1} \right\} \right] + (1 - \omega) \left[ \frac{k_2}{c_2} \left( \frac{v_i}{c_2} \right)^{k_2-1} \exp \left\{ - \left( \frac{v_i}{c_2} \right)^{k_2} \right\} \right] \right\} \tag{5}
\]

3 SELF POWERED BRIDGE

3.1 Site survey

Short term wind speeds measured at 86 bridges were used to find a test bed bridge site for wind energy harvesting. The wind data on bridge were measured for one year in order to investigate the effect of side wind on vehicle runnability [KEC, 2009]. These were the only reliable wind data for bridges in mountainous region where local topographical effect dominated. The strong seasonal variations of the measured short term wind speeds were interpolated comparing the wind data at nearby local weather station.

Bridges near residential area and overpass were eliminated from test bed site to avoid any civil complaint and traffic danger. Figure 1 shows the average wind speeds measured at several highway bridges. All bridges except the first one were located at mountainous area. Though the Seohae Bridge revealed the highest average wind speed, it was discarded from the candidate bridge because of high traffic volume.

The KJC Bridge shown in Figure 2 was finally selected as test bed for wind energy harvesting because of its relatively high wind speed, stiff girder and low traffic volume. The KJC Bridge, located in Yangyang, Kangwon, Korea which was north eastern part of South Korea. Annual average wind speed of the bridge was 4.38m/s. Single span length and width of the prestressed concrete box girder were respectively 57m and 11.3m. Height of the superstructure was 57m from ground. Wind barrier of 3m high has been installed at southwest side of the bridge for traffic safety.

![Figure 1. Average wind speed measured at highway bridges in Korea.](image1)

![Figure 2. Aerial view of the KJC Bridge.](image2)
3.2 Wind data at test bed bridge

10 minutes averaged wind speed and direction of the KJC Bridge were measured from June 2007 to May 2008 to obtain the basic data for assessment of traffic safety. KJC Bridge was tilted 45 degrees from the north. As shown in Figure 3, the main wind direction represented frequency of more than 50% from the southeast that was perpendicular to the bridge. These wind direction was good to install wind turbines near the side surface of bridge girder.

The MCP interpolation was not carried out because of poor correlation among wind speed at the bridge and those at nearby weather stations. The wind speed and directions at the bridge seemed to be strongly influenced by local topography. Table 1 shows annual mean wind speed, power density, and Weibull scale and shape parameters above the girder of KJC Bridge, which were respectively 4.38m/s, 173W/m², 4.95 and 1.9. The graphical representation of the same data in the table is given in Figure 3. Figure 4 shows probability distribution function for the observed wind speed above the girder from June 2007 to May 2008.

Figure 3. Wind characteristics of KJC Bridge. Marks represent the values evaluated from the measured wind data, and the shaded area represents bridge axis.

Table 1. Wind characteristics above the girder from June 2007 to May 2008.

<table>
<thead>
<tr>
<th>No.</th>
<th>Angle</th>
<th>Frequency (%)</th>
<th>Weibull-c (m/s)</th>
<th>Weibull-k</th>
<th>Mean wind speed (m/s)</th>
<th>Power Density (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 (North)</td>
<td>3.5</td>
<td>2.9</td>
<td>2.13</td>
<td>2.60</td>
<td>19</td>
</tr>
</tbody>
</table>
2  22.5  1.8  2.7  1.46  2.41  24
3  45   2.0  2.3  1.44  2.08  16
4  67.5 4.7  2.9  1.14  2.77  58
5  90   6.4  3.6  2.29  3.21  34
6  112.5 5.2  3.6  1.97  3.16  38
7  135  1.4  1.5  0.96  1.50  14
8  157.5 1.1  1.0  1.07  1.00  3
9  180 (South) 1.2  1.0  1.06  1.02  3
10 202.5  5.3  2.6  2.01  2.27  14
11 225  24.9  3.8  1.77  3.36  51
12 247.5 25.9  8.9  2.27  7.84  503
13 270  9.4  6.3  1.89  5.58  216
14 292.5 3.3  2.7  1.54  2.42  23
15 315  1.9  1.9  1.44  1.74  9
16 337.5 2.2  2.3  1.65  2.03  12

Mean - - 4.95 1.9 4.38 173

Figure 1. Probability density function for the observed wind speed above the girder from June 2007 to May 2008.

3.3 Estimation of annual energy prediction at test bed bridge

By applying the measured wind data and associate Weibull distribution into the Equation (1), annual energy production of a turbine equipped at bridge girder was roughly estimated. In the study, a wind turbine with rated power of 2.4kW was assumed to be installed at bridge. The power performance curve of the target wind turbine, Skystream3.7, is shown in Fig. 5. Fig. 6 shows estimation of energy production for the observed wind speed above the girder from June 2007 to May 2008. In this case, the annual energy production estimated from histogram was 3.26 MWh, and that from Weibull distribution was 3.21 MWh. The Weibull distribution could be effectively used for estimating energy production at present wind data.
4 PLACING WIND TURBINES AT BRIDGE GIRDER

It was very important to decide where the wind turbines were installed at bridge girder. The electric output power might be varied depending on position of the wind turbine because wind speeds around the girder are different at point by point. However wind flow field near the girder was complicated and was dependent on girder shape. Accordingly, numerical simulation based on computational fluid dynamics (CFD) analysis was first performed, and then wind tunnel test were carried out in order to investigate wind speed, wind direction and turbulent intensity around the bridge girder.

4.1 Numerical simulation

For the selection of the optimal installation location for wind turbines, CFD analysis was performed to examine the flow field around the bridge girder prior to wind tunnel test. A commercial CFD software, FLUENT, on supercomputer in Korea Institute of Science and Technology Information was used in the analysis. Conditions and results of analysis are as follows.

In the two dimensional CFD analysis, a typical the bridge girder section at center span was adopted and pier was not modeled. Uniform wind speed of 30m/s was applied to the input domain regardless of height variation. Wind barrier installed at west side of the girder was included in the modeling. Transmittance of the wind barrier (wind speed passing wind barrier per basic wind speed) was set at the rate of 50%. Analysis was performed for two different wind directions; the southwest direction and the northeast direction. In former case, wind flow passed through the wind barrier at windward edge.

Figure 7 shows analysis results for two different wind directions. From the figures, wind speed just near the bridge girder decreased significantly, yet wind speed increased at beneath or above the girder height. Both safety of traffics and power efficiency of wind turbine were considered in determination of wind turbine position. Positions above the girder slab were excluded from the installation place for wind turbine to prevent any effects on high speed traffics passing the bridge. In the beneath of the girder, the wind speed at 13m beneath the bridge slab was respectively 17% and 2% higher than oncoming wind speed. In the figure, “x” mark denotes possible position of wind turbine to get more electric energy and less effect on traffics. Figure 8 shows variation of wind speed along height from leeward and windward edges of slab. It is apparent from the figure that wind speed boosts up at a few meters depart from the girder.
Figure 2. Contour of x-direction wind speed. left: wind barrier at windward edge, right: wind barrier at leeward edge.

Figure 3. Variation of wind speed along height (a) from windward edge of slab, (b) from leeward edge of slab.

4.2 Wind Tunnel test

Wind tunnel test of single span bridge was performed at KOCED Wind Tunnel Center in Chonbuk National University. Model scale was 1:15. Wind speeds were measured at total 113 points near the bridge girder to investigate the flow field. Figure 9 shows the bridge model in the wind tunnel.

This closed return type vertical returning wind tunnel has two test sections. The tests were carried out at the high speed test section of 5m(W) × 2.5m(H) × 20m(L). The wind tunnel has five fans and motors with 275 KW each. The free stream velocity of this low speed test section ranges from 0.5 m/s to 31m/s. The mean velocity of the free stream flow was made by using two pitot tubes and pressure transducers (Setra 239). A temperature and humidity sensors (Vinotech GHP-20R) was used to evaluate air density. DANTEC CTA-90C10 constant temperature anemometer incorporated with DANTEC 55P11 hotwire sensors was used to measure the turbulent wind velocity near the bridge girder. At each measurement, velocity data for 100 seconds were acquired at a 6 kHZ sampling rate.

Figure 10 shows wind speed contour around bridge girder measured from wind tunnel test. Undisturbed input wind speed was 10m/s. The wind speed at 10m beneath from bridge slab was 27% higher than oncoming wind speed. Turbulent intensity at the position was 4.1%. Finally it

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was decide to install the wind turbine at 10m beneath the bridge slab to get more electric energy and not to disturb the passing traffics.

![Figure 4. 1/15 scale model of single span bridge in wind tunnel.](image)

Figure 4. 1/15 scale model of single span bridge in wind tunnel.

![Figure 5. Wind speed measured at wind tunnel test.](image)

Figure 5. Wind speed measured at wind tunnel test.

5 FIELD MEASUREMENTS AND RESULTS

5.1 Wind turbines

As shown in Figure 11, two wind turbines have been installed at 10m beneath the bridge slab of the KJC Bridge. The first wind turbine has three blades in horizontal axis. Diameter and rated power are respectively 3.7m and 2.4kW. The second one is Savonius type vertical axis turbine with 2kW rated power. Diameter and height of the second one are 0.8m and 1.4m respectively. Self weights of the two wind turbines excluding tower were 93kg and 140kg respectively.

![Figure 6. Tow wind turbines installed at the KJC Bridge.](image)

Figure 6. Tow wind turbines installed at the KJC Bridge.

![Figure 7. Monitoring system at bridge site.](image)

Figure 7. Monitoring system at bridge site.

5.2 Monitoring system

Monitoring system shown in Figure 12 was designed and installed at the bridge to measure wind data as well as generated electric power. Total three cup anemometers provided by NRG System were equipped at the bridge; two at near each wind turbines, and one at 10m above bridge slab to measure undisturbed wind speed. Two digital power meters provided by LSIS were used to measure the electric voltage, current and power from wind turbines. All data from
electric power meters, anemometers, wind direction sensors, temperature sensor, relative humidity sensor and barometric pressure sensor have been recorded at the data logger, and periodically transmitted to remote computer at KOCED Wind Tunnel Center in Chonbuk National University through cellular network.

5.3 Short term monitoring results
The wind data and electric power at the KJC Bridge for every 10 minutes from 2/1/2012 to 3/31/2012 were measured by using the monitoring system. Figure 13 shows the frequency of occurrence and mean wind speed as function of wind direction. Wind shows strong directionality in southwest as was expected from the wind data at 2007~2008.

Table 3 summarizes the energy production during two months monitoring. It is clear from table that the mixture Weibull distribution reveals more accurate estimation of energy production compared with the conventional Weibull distribution. Power estimation error for the Weibull distribution was 6.4% but the mixture Weibull distribution showed 1.4% error in the estimation. The superiority of mixture Weibull distribution compared with conventional Weibull distribution can be clearly seen at Figure 14.

When we compare the recently observed two months data and those at the same period in 2008, there is some difference between two results. The generated electric power was less than expected one because of mainly poor average wind speed compared with that at 2008. Average wind speed at 10m above slab was 5.48 m/s at 2008 but decreased to 4.75 m/s at 2012. Moreover the wind speed at 10m beneath the slab was about 3% less than that at 10m above the slab.

Table 3. Wind energy production for two months from February to March.

<table>
<thead>
<tr>
<th>Period</th>
<th>Location</th>
<th>Average speed (m/s)</th>
<th>Power density (W/m²)</th>
<th>Energy production (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/1/2008~3/31/2008</td>
<td>above slab</td>
<td>5.48</td>
<td>227</td>
<td>701</td>
</tr>
<tr>
<td>2/1/2012~3/31/2012</td>
<td>above slab</td>
<td>4.75</td>
<td>165</td>
<td>642</td>
</tr>
<tr>
<td></td>
<td>beneath slab</td>
<td>4.61</td>
<td>95</td>
<td>414</td>
</tr>
</tbody>
</table>

440 (measured)

Figure 8. Wind characteristics observed at 2/1/2012~3/31/2012. B: above slab, C: near wind turbine.
6 CONCLUDING REMARKS

This paper presents design, analysis, test, installation and monitoring of wind turbine equipped at elevated bridge in order to enable the self powered bridge. Two small wind turbines have been installed beneath the bridge girder that was selected from 86 sites considering wind energy potential and safety of passing traffics. The installation position of wind turbine near the bridge girder was chosen from the CFD analysis and wind tunnel tests, where wind speed boosted 17~27% by oncoming wind. Monitoring results for recent two months reveals a high correlation between the wind speed probability distribution and actual generated electric power.

7 REFERENCES