International Journal of Bridge Engineering (IJBE), Vol. 10, No. 2, (2022), pp. 71-81

PREDICTION OF DECK VIBRATIONS OF A SUSPENSION BRIDGE UNDER WIND LOAD

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ABSTRACT: The aim of this study is the prediction of deck vibration of a suspension bridge. Abaqus finite element program is being adopted to simulate the response of a suspension bridge under a strong wind. Twenty-five models based on the study of five variables are being generated to determine the vertical and torsional vibrations of the deck. A design sampling method is considered to prepare the models for numerical simulations. The regression model for the vertical and torsional vibrations of the deck would be generated supporting on three terms for their equations. The linear terms, quadratic terms, and interaction terms are utilized to represent the response of the structural system under the wind. The results of the regression models show that the prediction of the deck vibrations is an excellent representation of the numerical simulations for the same responses to a ratio of 93.47% and 92.71% for both vibrations. The regression model technique can be used further to undergo optimization for the design of the suspension bridge due to the efficiency of the regression model tool.

KEYWORDS: Coefficient of Determination; Design Sampling Method; Hanger Cable; Main Cable; Regression Model.

1 INTRODUCTION

Wind load is one of the important design loads on civil engineering structures, especially for long-span bridges with low damping and high flexibility. Deck sections of long-span bridges are one type of bluff bodies that are usually elongated with sharp corners which make the flow around them cause aerodynamic instabilities. Such instabilities may cause serious catastrophic structural failures such as the Old Tacoma Narrows Bridge collapse in 1940 [1]. Cable-supported bridges are flexible structures that dynamically respond to the wind. Therefore structural dynamics plays a vital role in bridge aerodynamics. It is important to correctly estimate the vertical and torsional vibrations of the deck [2,3]. Suspension bridges are long, slender, and flexible structures that are very sensitive to dynamic actions induced by wind, which potentially cause a variety of instability phenomena. The importance of wind-resistant design for these structures has been highly recognized and has led to many research works and investigations on bridge aerodynamics. Some historical views of long-span bridge aerodynamics are presented in [4,5].

Recently, many research studies have been conducted to analyze and predict the behavior of suspension bridges under wind loading. Wang et al. [6] studied the effects of handrails solid ratio, the position of the rail, and the guide vanes of the wind fairing on the aerodynamic behavior of the bridge by adopting tests on many sectional models. Larsen et al. [5] recognized that the lower end angle of the bridge deck less than 15 degrees would significantly remove the vortex-induced vibration of the deck.

Diana et al. [7] verified the aerodynamic stability and the buffeting behavior of the Izmit Bay Bridge under different flow fields. They used four models of three various construction stages and a service stage of the bridge. Meng et al. [8] analyzed the Xiangshangang Bridge and Jiaojiang Bridge by performing tests on the sectional models of the two bridges. They recognized that changes in the wind fairing angles of the bridge deck will change the generation of the vortex-induced vibration of the fully enclosed steel box girder and semi-enclosed separated double box girder deck of the cable-stayed bridges. They determined that the prototype of the bridge can simulate multi-modalities of the structure which can better describe the aerodynamic stability of the bridge and the response against the wind. Tang et al. [9] recognized that improvement of the torsional stability of the bridge could be accessed by considering the reasonable type of wind fairings which weakens the vortex generation.

Sham et al. [10] performed sectional and full-bridge aero-elastic model tests of the Stonecutters Bridge. They approved that the aero-elastic damping can control the vertical and the torsional vibrations of the bridge. Also, they detected that the wind fairing is a sensitive and important index to enhance the torsional stability and the vortex-induced vibration of the cable-stayed bridges having girders with steel box shapes.

It is very necessary to investigate the deck vibrations of the suspension bridge using easier and smooth tools instead of lab instruments and other ways for measurements. In this research study, we are going to use the regression model tool to predict the deck vibrations of the suspension bridge with the support of a design sampling method to numerically simulate the response of the suspension bridge under the wind. Five certain material variables are deployed to construct the regression models. The determined equations of the responses would be a reliable tool to predict the deck vibrations due to wind load.

2 REGRESSION MODEL

The regression model is being constructed by dedicating five variables of the main cables, hanger cables, concrete, and steel reinforcement as mentioned in Table 1 in the following sections. The main representation of the regression model for both vertical and torsional vibrations of the deck is shown by the following Eq. (1):

$$y = f(x)\beta + \epsilon \tag{1}$$

where $x = (x_1, x_2, \ldots, x_k)$, $f(x)$ is a function for the vector x of k elements. β is a vector of regression coefficients, and ϵ is called random error which is assumed by a zero mean value. The regression model needs to determine the regression coefficients which are represented byβ which can be determined utilizing the equation of the least square method as follows:

$$\beta = (X'X)^{-1}\, X'Y \tag{2}$$

The matrix X' represents the transpose of matrix X. Matrix $(X'X)^{-1}$ is the inverse of the matrix $X'X$ [11].

The terms of the regression model which is the function *f(x)* for both vertical and torsional vibrations consist of linear terms, quadratic terms, and interaction terms for the five involved variables.

3 FINITE ELEMENT MODEL

The finite element model of the suspension bridge is 2694 m in length, 237 m in height, and 39.5 m in width. It consists of two reinforced concrete pylons positioned symmetrically. The distance between the pylons is 1624 m see Figure 1. The deck is made of reinforced concrete beams which is positioned on the pylons and hung by the hanger cables which are made from steel. The hangers are connected above to the suspension cables which are also made of high steel material. The loads from the deck are transferred to the hanger cables and then to the suspension cables which are connected to the pylons from four points. The loads are being exerted on the pylons and finally from the pylons to the foundation soil.

The suspension cables are pre-stressed initially to reach the final shape of the bridge. The force is 192.5 MN. The bridge is supported in both directions in such a way to permit energy dissipation due to vibrations. A dynamic implicit step consisting of a critical wind action is applied on the suspension bridge for 30 seconds.

The suspension bridge has been meshed with 1714 beam elements as (B31: A 2- node linear beam in space) elements. The mesh size is obtained utilizing mesh convergence analysis.

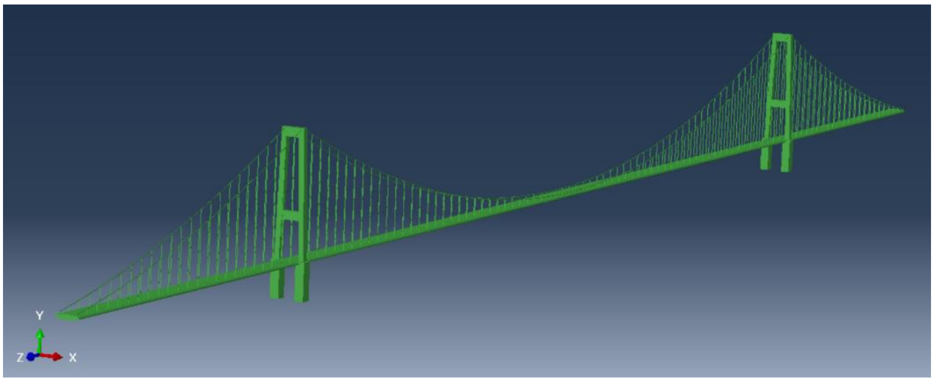

Figure 1. The suspension bridge model

4 MATERIAL DATA RANGES

The regression models are constructed for the considered five variables supporting on the Lp-Tau design sampling method by deploying 25 models of the suspension bridge in the ABAQUS program. The following Table 1 shows the adopted variables and the range of their values. Table 2 authorizes the 25 models with five variable values arranged by considering the Lp-Tau method.

Table 1. Material data ranges

Variable	**Material**	**Range**
X_1	Diameter of the Main Cables (m)	0.7 - 1.1
X_2	Diameter of the Hanger Cables (m)	0.10 - 0.14
X_3	Density of Concrete (kg/m^3)	2200 - 2600
X_4	Density of Steel (kg/m^3)	7800 - 8000
X_5	Modulus of Elasticity of Concrete (GPa)	24 - 35

Table 2. Numerical models

	X_1	**X_2**	**X_3**	**X_4**	**X_5**
Model 1	0.7000	0.10000	2200.00	7800.00	24.00000
Model 2	0.9000	0.12000	2400.00	7900.00	29.50000
Model 3	0.8000	0.13000	2300.00	7950.00	26.75000
Model 4	1.0000	0.11000	2500.00	7850.00	32.25000
Model 5	0.7500	0.12500	2550.00	7975.00	30.87500
Model 6	0.9500	0.10500	2350.00	7875.00	25.37500
Model 7	0.8500	0.11500	2450.00	7825.00	33.62500
Model 8	1.0500	0.13500	2250.00	7925.00	28.12500
Model 9	0.7250	0.13750	2475.00	7862.50	26.06250
Model 10	0.9250	0.11750	2275.00	7962.50	31.56250
Model 11	0.8250	0.10750	2575.00	7912.50	28.81250
Model 12	1.0250	0.12750	2375.00	7812.50	34.31250

	X_1	X_2	X_3	X_4	X_5
Model 13	0.7750	0.11250	2325.00	7937.50	30.18750
Model 14	0.9750	0.13250	2525.00	7837.50	24.68750
Model 15	0.8750	0.12250	2225.00	7887.50	32.93750
Model 16	1.0750	0.10250	2425.00	7987.50	27.43750
Model 17	0.7125	0.12125	2362.50	7843.75	29.15625
Model 18	0.9125	0.10125	2562.50	7943.75	34.65625
Model 19	0.8125	0.11125	2262.50	7993.75	26.40625
Model 20	1.0125	0.13125	2462.50	7893.75	31.90625
Model 21	0.7625	0.10625	2412.50	7968.75	33.28125
Model 22	0.9625	0.12625	2212.50	7868.75	27.78125
Model 23	0.8625	0.13625	2512.50	7818.75	30.53125
Model 24	1.0625	0.11625	2312.50	7918.75	25.03125
Model 25	0.7375	0.11875	2537.50	7881.25	27.09375

5 WIND TIME HISTORY

The wind data was considered supporting on the reference [12]. The wind is not steady both in strength and inclination. For the wind analysis in ABAQUS, two components X and Y are used to apply the wind forces on the suspension bridge for 30 seconds. The wind forces are applied in many elevations starting from the ground until the top of the pylons.

6 RESULTS AND DISCUSSION

The results compromise both vertical and torsional vibrations in the center part of the deck, the construction of the regression models for both vibrations in addition to the coefficients of regression. The coefficient of regression displays the efficiency of the regression models.

6.1 Vertical vibration

After running the 25 models in ABAQUS, maximum values of the vertical vibration of the deck are collected for each model. The maximum vertical vibrations for the 25 models show that model 6 has the greatest vertical vibration of the deck which is 0.67968 m. The minimum vertical vibration is seen in model 21 with a value of 0.311917 m (see Figure 2).

The vertical vibration responses of the deck are up to the LP-TAU design sampling method and there are no regular criteria to get the optimized responses. Consequently, the results would be used to construct the regression model so that to utilize it in the optimization process. Randomly, two selected figures (model 1 and model 8) for the suspension bridge are shown which are manifesting the responses of the structural system under the critical wind (see Figure 3 and Figure 4). The color of the deck is a scale of vertical vibration.

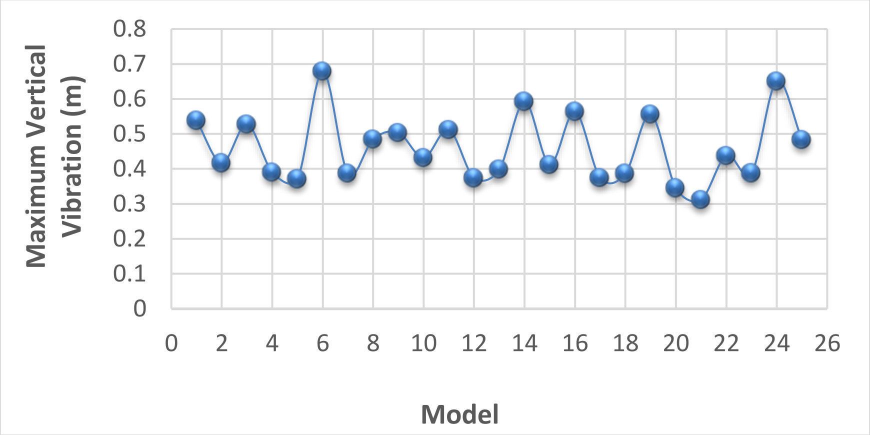

Figure 2. Maximum vertical vibration for 25 models

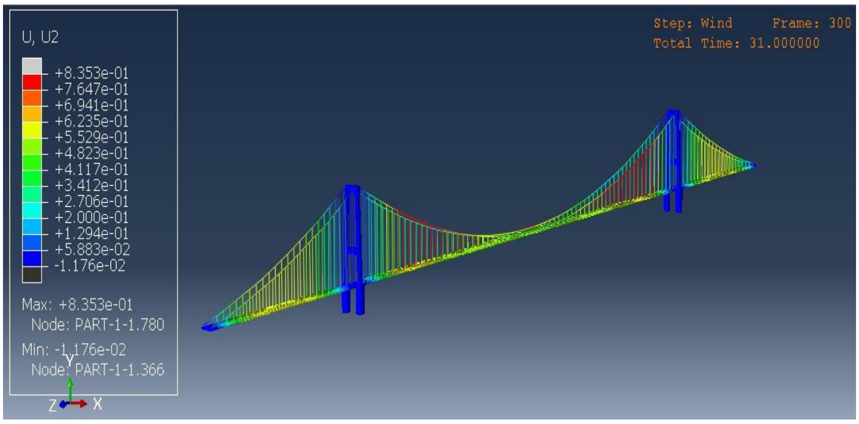

Figure 3. Maximum vertical vibration (u2) - model 1

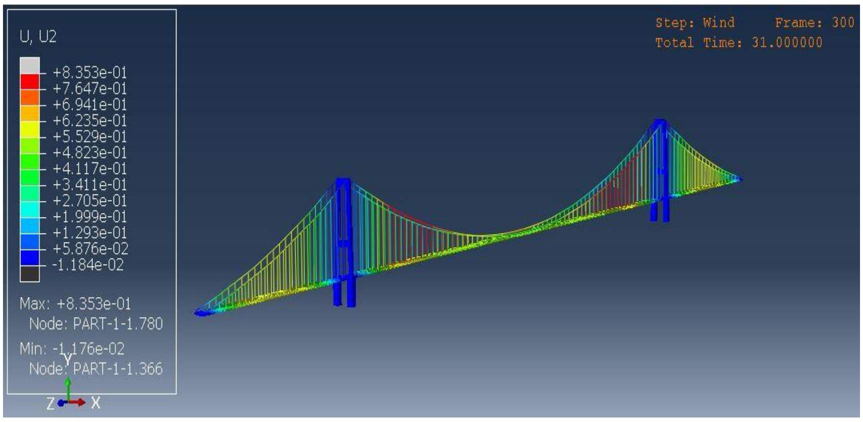

Figure 4. Maximum vertical vibration (u2) - model 8

6.2 Torsional vibration

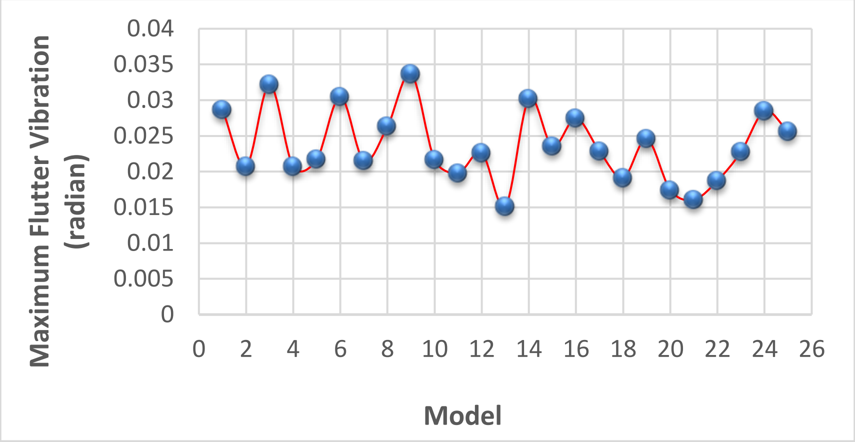

Figure 5. Maximum torsional vibration for 25 models

The maximum torsional vibrations for the 25 models display that model 9 has the greatest torsional vibration of the deck which is 0.0336896 radian. The minimum vertical vibration is seen in model 13 with a value of 0.0151441 radian (see Figure 5). The results would be adopted to create the regression model of the torsional vibration so that to utilize it for the optimization stage. Also, both (model 1 and model 8) for the suspension bridge are shown which are showing the responses of the structural system under the critical wind (see Figure 6 and Figure 7). The color is an indication of the torsional vibration of the deck.

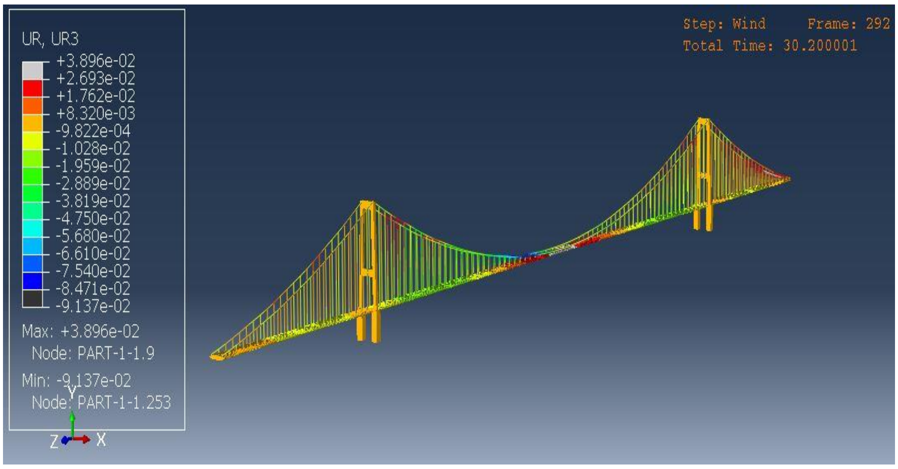

Figure 6. Maximum torsional (UR3) - Model 1

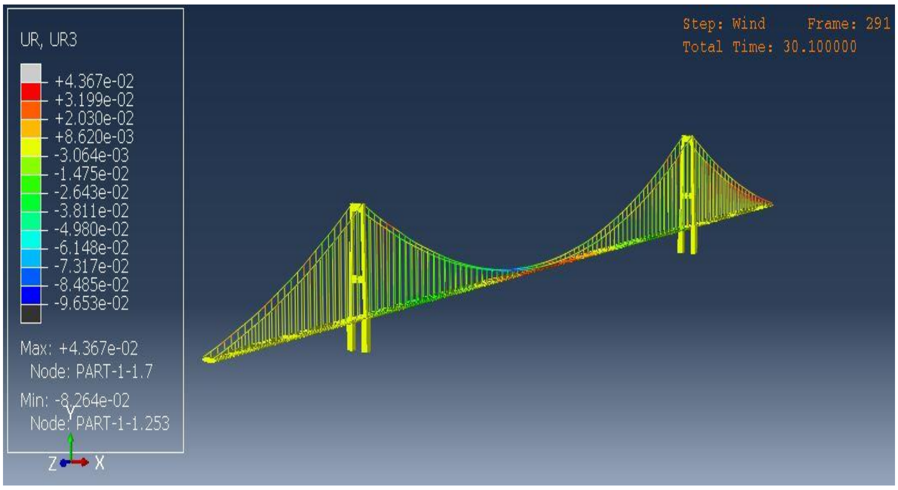

Figure 7. Maximum torsional (UR3) - Model 8

6.3 Regression models

The results of both regression models for the vertical vibration and the torsional vibration of the deck under the wind load have been determined by using the LP-TAU design sampling method and MATLAB codes. The least-square method has been adopted to determine the regression coefficients for the regression models. The vertical vibration of the deck has been denoted by **VV** and the torsional vibration of the deck has been denoted by **TV** (see the following equations 3 and 4 below):

$$\begin{aligned}\mathbf{VV} &= 25.9611432102077 + 10.3661581632189 * \mathbf{X1} \\ &- 348.1814022549670 * \mathbf{X2} + 0.0049210106643 * \mathbf{X3} \\ &- 0.0066481231107 * \mathbf{X4} + 0.7469768658000 * \mathbf{X5} \\ &- 1.7547362649908 * \mathbf{X1}^2 + 193.7395263127580 * \mathbf{X2}^2 \\ &+ 0.0000000913183 * \mathbf{X3}^2 + 0.0000004263164 * \mathbf{X4}^2 \\ &+ 0.0036154190199 * \mathbf{X5}^2 - 9.0603340501688 * \mathbf{X1} * \mathbf{X2} \\ &- 0.0009097697044 * \mathbf{X1} * \mathbf{X3} - 0.0001698280757 * \mathbf{X1} * \mathbf{X4} \\ &- 0.0874548079846 * \mathbf{X1} * \mathbf{X5} - 0.0033958468350 * \mathbf{X2} * \mathbf{X3} \\ &+ 0.0387166557864 * \mathbf{X2} * \mathbf{X4} + 0.3820382088630 * \mathbf{X2} * \mathbf{X5} \\ &- 0.0000004484003 * \mathbf{X3} * \mathbf{X4} - 0.0000206402831 * \mathbf{X3} * \mathbf{X5} \\ &- 0.0001145562263 * \mathbf{X4} \\ &* \mathbf{X5}\end{aligned} \tag{3}$$

$$
\begin{aligned}
&\mathbf{TV} \\
&= 1.188027204608650 - 0.502444273165496 * \mathbf{X1} \\
&- 26.795414239743200 * \mathbf{X2} - 0.000161715452841 * \mathbf{X3} \\
&- 0.000056151808806 * \mathbf{X4} + 0.068629550402353 * \mathbf{X5} \\
&- 0.029812669278981 * \mathbf{X1}\text{^}2 + 16.237656766678700 * \mathbf{X2}\text{^}2 \\
&- 0.000000009400110 * \mathbf{X3}\text{^}2 - 0.000000013711169 * \mathbf{X4}\text{^}2 \\
&+ 0.000310737821834 * \mathbf{X5}\text{^}2 - 1.167279734018320 * \mathbf{X1} * \mathbf{X2} \\
&- 0.000007566140580 * \mathbf{X1} * \mathbf{X3} + 0.000090561148122 * \mathbf{X1} * \mathbf{X4} \\
&- 0.000229185659481 * \mathbf{X1} * \mathbf{X5} - 0.000061877521210 * \mathbf{X2} * \mathbf{X3} \\
&+ 0.003066889701517 * \mathbf{X2} * \mathbf{X4} + 0.000248134163750 * \mathbf{X2} * \mathbf{X5} \\
&+ 0.000000049556694 * \mathbf{X3} * \mathbf{X4} - 0.000005839202833 * \mathbf{X3} * \mathbf{X5} \\
&- 0.000009333034443 * \mathbf{X4} \\
&* \mathbf{X5} \qquad (4)
\end{aligned}
$$

Both regression models are used to predict the deck vibrations for involved variables by using the ranges of values as mentioned in the previous sections. The regression models should undergo reliability before being used for prediction. The reliability is to calculate the coefficient of determination for both regression models which is denoted by R^2 where in the following section further details are provided.

6.4 Coefficient of determination

To construct reliable regression models of the deck vibrations of the suspension bridge, we must determine the coefficient of determination R^2 for the deck vibrations by comparing the results data between the numerical analysis and the regression model.

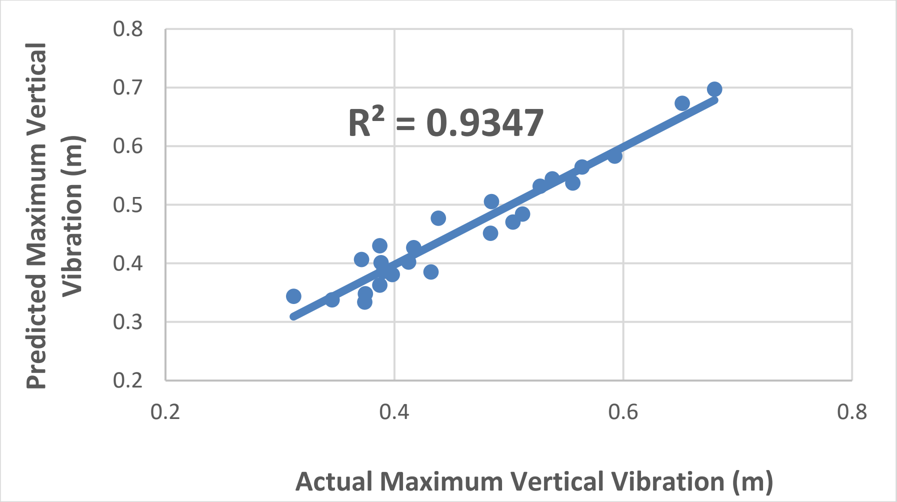

Figure 8. Coefficient of determination-maximum vertical vibration

We determine the coefficient of determination for the vertical vibration and torsional vibration of the deck which is collected from 25 models of the suspension bridge. The coefficient of determination for the vertical vibration of the deck is $R^2 = 0.9347$ (see Figure 8). It is obvious that there is 6.53% of the suspension bridge response is not recognized which is a very small portion when compared to 93.47%. This is an indication that the regression model is a very good tool for predicting the structural system behavior with excellent efficiency.

This time, the coefficient of determination for the torsional vibration of the deck is $R^2 = 0.9271$ (see Figure 9). It is clear that there is only 7.29% of the suspension bridge response is not recognized which is a very small fraction compared to 92.71%. This is evidence for the regression model to be so good in predicting the behavior of the suspension bridge regarding the torsional vibration of the deck.

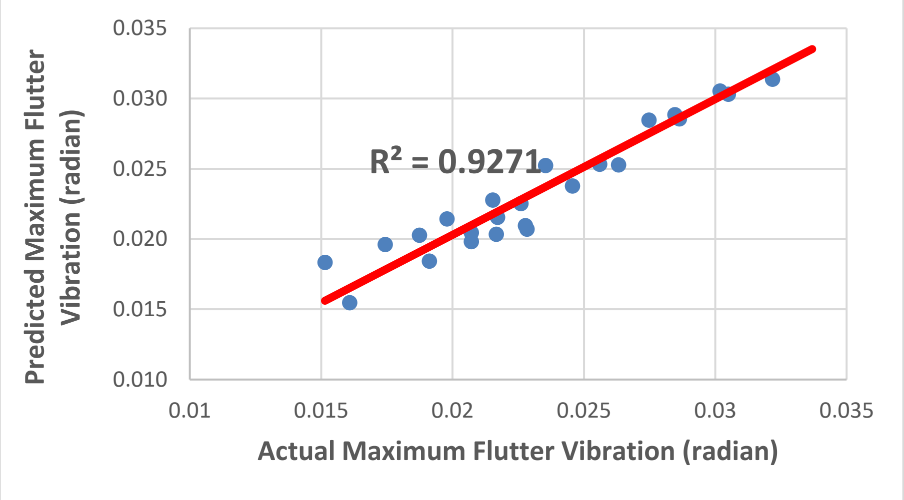

Figure 9. Coefficient of determination-maximum torsional vibration

7 CONCLUSIONS

We can write the following conclusions depending on the results:

1. The LP-TAU sampling method has presented an excellent tool for predicting the vertical and torsional vibrations of the deck of the suspension bridge due to critical wind loading. Consequently, efficient regression models and optimized design variables can be determined.
2. The roles of the five variables in the sensitivity of the system responses were recognized through many generated numerical simulations representing the vertical and torsional vibrations of the deck in conjunction with the ABAQUS program.

3. The regression modeling process is an efficient tool that can be utilized to predict and test the structural stability of the suspension bridge through the design stage and at the service stage of the structure by constructing many efficient designs in a very short duration and low-cost process.

ACKNOWLEDGMENTS

We would like to thank Gajendra Kumar Nhaichaniya for his assistance in FEA with ABAQUS.

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