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Improved Prediction Method of Lateral Girder Response of Footbridges Induced by Pedestrians

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Abstract

Besides having structural rationality and elegant feature, cable-supported bridges are flexible and often suffer from dynamic problems. On the T-bridge, a pedestrian cable-supported footbridge, the girder vibrated laterally with a frequency of 0.93 Hz, the natural frequency of first lateral mode, when a large number of pedestrians crossed the bridge. The zigzag movement of pedestrians caused the bridge girder to vibrate laterally. When the frequency of this dynamic force is close to the bridge's natural frequency, it makes a resonance which results in a big response. The same vibration occurred on the London Millennium Bridge. The response of the London Millennium Bridge was much larger than that of the T-bridge and the bridge was closed for 20 months until the vibration was suppressed by viscous and tuned mass dampers. Nakamura proposed a simplified model to predict girder responses by introducing non-linear pedestrian behaviors. When the vibration amplitude becomes large, some of the pedestrians feel unsafe and stop walking or change their walking pace. Therefore, the pedestrian-induced forces do not increase proportionally with deck vibration at the large girder amplitude. Nakamura's method includes this non-linear behavior but it assumes that this lateral vibration only occurs when the bridge's natural frequency is around 0.9-1.0Hz. In this paper, the improved method is proposed for the bridge's natural frequencies. However, the authors have found that lateral vibration could occur on the bridge with a frequency far less than 0.9Hz. The authors have proposed the new
The prediction method covers the resonant frequencies outside 0.9-1.0Hz and the new method is verified by comparing with the field-measured data.

Keywords: Lateral vibration, Cable-stayed bridge, Dynamic model, Resonance, Pedestrians

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1. Introduction

Although cable-supported bridges have structural rationality and elegant feature, they are flexible and often suffer from dynamic problems. The T-bridge (Figure.1), a pedestrian cable-stayed bridge located in Japan, suffered strong lateral vibration induced by pedestrians. The bridge connects the motor boat race stadium and the bus terminal. The girder vibrated laterally with a frequency of 0.93Hz, the natural frequency of the first lateral mode when a large number of people crossed the bridge after the final race was over (Figure.2). This type of lateral vibration had not been reported before and research was conducted to clarify the mechanism [1-7].



Figure 1: T-Bridge



Figure 2: Pedestrians after the final race

The mechanism of this vibration was studied by Fujino et al. [1] and Nakamura et al. [2,3,6] and clarified. The gravity center of the human body moves laterally while they walk to their left and right foot in turn, which makes the girder vibrate laterally with a frequency of about 1.0Hz, this is called lateral dynamic force which is induced by pedestrians. When the frequency of this dynamic force is close to the bridge's natural frequency, it makes a resonance which results in a further response. Even though many people walk at the same frequency, their phases would be different and the induced forces could cancel out. This phase problem was solved by assuming that people synchronize their walking pace to the vibrating deck. However, the girder response reached about 10 mm and some pedestrians felt uncomfortable and unsafe. But, this was not considered to be too large and the bridge was not closed.

The same vibration problem occurred on the London Millennium Bridge in 2000. The lateral response of the London Millennium Bridge was much larger than that of the T-bridge, and the bridge was closed for 20 months until the vibration was suppressed by viscous and tuned mass dampers [4]. To clarify the mechanism of the vibration, field tests on the bridge and experiments at Imperial College were carried out. Then, a dynamic model based on the single degree of the dynamic equation was proposed by Dallard et al. [4,5], assuming that the external force induced by pedestrians is proportional to the girder lateral velocity.

Nakamura proposed a simplified model to predict girder responses by introducing non-linear pedestrian behaviors [7]. When the vibration amplitude becomes large, some

of the pedestrians feel unsafe and stop walking or change their walking pace. Therefore, the pedestrian-induced forces do not increase proportionally with deck vibration at the large girder amplitude. Nakamura's method includes this non-linear behavior but it assumes that this lateral vibration only occurs when the bridge's natural frequency is around 0.9-1.0Hz. In this paper, the improved method is proposed for the bridge's natural frequencies. However, the authors have found that lateral vibration could occur on the bridge with a frequency far less than 0.9Hz. The authors have proposed a new prediction method to cover the resonant frequencies outside 0.9-1.0Hz and the new method is verified by comparing it with the field-measured data.

2. Dynamic Model for The Lateral Vibration

2.1.The layout of the T-Bridge

The layout of the T-bridge is shown in Fig.3. The T-bridge is a cable-stayed footbridge with a main span length of 134 m, a side span length of 45m, two cable planes, and 11 stays per plane (Fig.3) Semi-parallel type cables with epoxy resin surface layer are used. The girder is a steel box girder with an orthotropic deck. The web height is 1.8m and the walkway width is 5.26m (Fig.4).

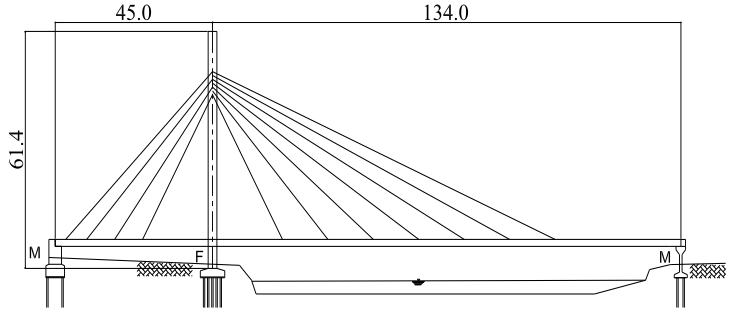


Fig.3 Layout of the bridge (m)

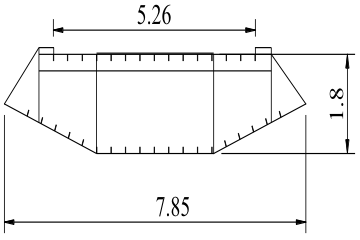


Fig.4 Girder cross-section (m)

$$M_B X''(t) + C_B X'(t) + K_B X(t) = Fp \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$Fp = k_1 k_2 H(X'_B) G(f_B) Mpg \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$H(X'_B) = \frac{X'_B(t)}{k_3 + |X'_B(t)|} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$G(f_B) = \begin{cases} G_0 = 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4) \\ G_1 = 1 - 20(f_B - 0.9)^4 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5) \\ G_2 = 1 - 5(f_B - 0.9)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6) \end{cases}$$

The T-bridge connects the motor boat race stadium and the bus terminal. On a race day too many spectators entered the stadium through the bridge at a random time. When the final race was over, the spectators left the stadium and walked through the bridge to get to the bus terminal on the opposite side of the stadium. As the entrance areas to the

bridge were fairly large, the pedestrians could proceed on the bridge and were not forced to stop in this congested situation. At that time the bridge deck was overcrowded with pedestrians. In several minutes of this overcrowded situation, the girder and the cables started to vibrate. [2,3,6]

The field measurements were carried out on the T-bridge to find the mechanism of this vibration by Fujino et al. [1] and Nakamura et al. [2,3,6]. Accelerometers were attached to the girder and cables in vertical and lateral directions. By analyzing the obtained data, it was found that the girder vibrated laterally. It was also found that the zigzag movement of pedestrians was the exiting force and the synchronization of the pedestrian to the girder vibration was the phase problem.

Nakamura proposed the following method to predict the girder response induced by pedestrians [7]. The dynamic model for the lateral vibration can be modeled by a single-degree-of-freedom system. Eq. (1) shows the dynamic equation of motion; X_B is the modal displacement of the girder, X'_B the modal velocity of the girder, X''_B the modal acceleration of the girder, M_B is the modal mass, C_B is the modal damping coefficient and K_B the modal stiffness of the bridge.

The external force induced by pedestrians is key in this dynamic equation. Dallard et al. proposed that the dynamic force induced by a pedestrian is proportional to the girder velocity [4,5]. Based on the field test conducted on the Millennium Bridge, the coefficient is proposed to be 300 N.s/m. According to the Dallard method, if the lateral force FP is larger than the damping force CBX', there is no upper limit for the girder response and it increases linearly. This does not seem correct because some pedestrians feel unsafe and hold handrails or stop walking when the vibration amplitude becomes large. Therefore, the exciting force must saturate at a certain level. The right side of Eq. (1) is the external force induced by pedestrians. Nakamura assumed that the pedestrian force is proportional to the modal self-weight of pedestrians, Mpg, multiplied by two coefficients, k1 and k2, and two functions, H (X'B) and G (fB), as shown in Eq.(2). The coefficient k1 is the ratio of the lateral force to the pedestrian`s weight and is assumed to be 0.0987 in this study. The coefficient k2 is the percentage of pedestrians who synchronized to the girder vibration and is assumed to be 0.2.

H (X'B) is a function to describe the pedestrian' synchronization nature. It is assumed that the pedestrians synchronize proportionally with the girder velocity X'_B at low velocities. When the girder velocity becomes large, the pedestrians feel uncomfortable or unsafe and they decrease their walking paces. Therefore, the girder response does not increase infinitely but is limited at a certain level. The denominator of Eq.(3) expresses this saturation phenomenon. The saturation rate depends on coefficient k3[8]. The pedestrian forces proposed by Dallard and Nakamura are shown in Fig.5. The one by the Dallard method is linear and no upper limit exists. Whereas, the one by the Nakamura method is linear only in the small girder velocity range and saturates at a certain level. This seems more appropriate to explain the pedestrian's walking attitude on the vibrating deck.

G (fB) is the function to describe how pedestrians synchronized with the girder response. It was originally thought that the lateral vibration only occurred at the bridge frequency of 0.8-1.0 Hz and, therefore, the value of G (fB) was assumed to be 1.0, as

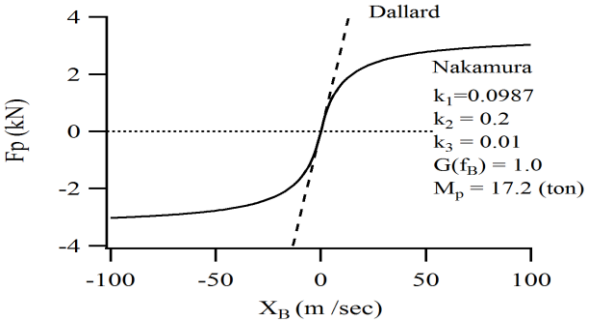


Fig.5 Lateral force induced by pedestrians

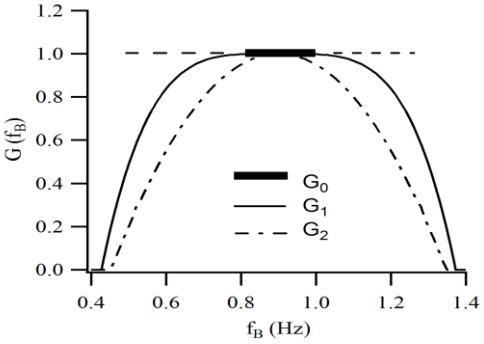


Fig.6 G-function

shown in Eq.(4). This is shown as G_0 in Fig.6. However, the authors have recently found on another bridge that the lateral vibration could occur with the bridge natural frequency outside this range.

The authors have proposed the two improved G (fB) functions, as shown as G1 and G2 in Eq. (5) and Eq. (6). Both functions have peaks at 0.9 Hz and Eq. (6) have a sharper shape. These three G-functions are shown in Fig.5. In this study the effect of these new G-functions is compared and studied.

Field measurements were conducted in 1989 and two data were used in this study: Data T1 with a pedestrian density of 0.8 person/m2 and data T2 with a pedestrian density of 0.6 person/m2. Fig.7 and Fig.8 show the girder lateral displacements of these two cases. Both show clear sinusoidal waves with a natural frequency of 0.93 Hz. This indicates that resonance occurred between the pedestrians and the girder in both cases. The maximum amplitude of T1 is 13.1mm and that of T2 is 8.4mm. These differences are caused by the number of pedestrians, in other words, the pedestrian density. In the T1 data, the bridge was more overcrowded than in the T2.

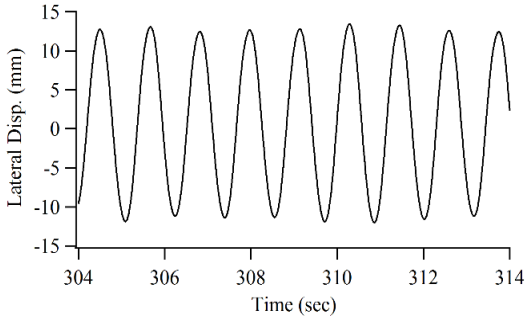


Fig.7 Measured girder displacement (T_1)

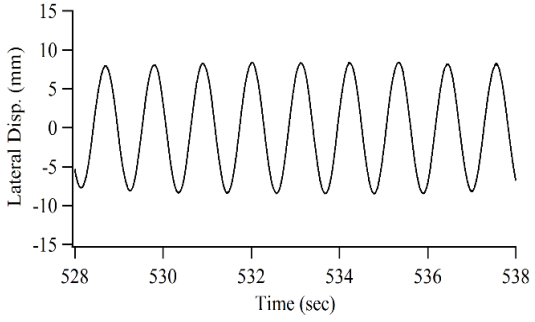


Fig.8 Measured girder displacement (T_2)

The eigenvalue analysis was conducted by FEM. The natural frequency of the first lateral mode of the T-bridge fB is 0.93Hz, which is the same as the measured natural

frequency of T1 and T2. It is therefore clear that resonance occurred in the first lateral mode. The mode shape is shown in Fig.9. The modal mass MB is 185.2 tons.

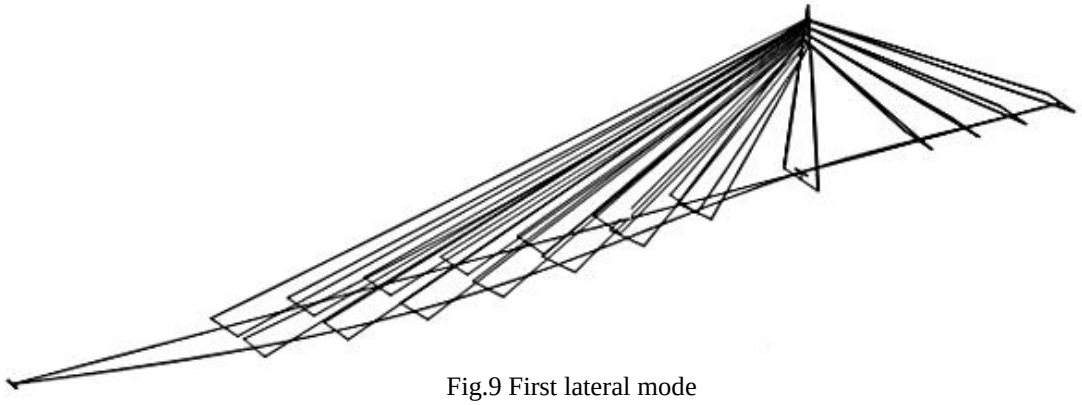


Fig.9 First lateral mode

3. Parametric Studies

The dynamic responses of the girder were obtained for T1 and T2 data by the proposed dynamic model. Eqs. (1)-(6) were solved numerically by Runga-Kutta method [2,3,6,7]. Parametric studies were conducted to clarify the effects of pedestrian density, girder mass, and bridge natural frequencies on the girder responses.

Fig.10 shows the girder response with different pedestrian densities. In this calculation girder, modal mass is kept at 185.2 tons, and the girder's natural frequency of 0.93Hz. The girder response increases with pedestrian density. This tendency is easily understood: the vibration amplitude of the girder becomes larger as more people walk on the bridge. The measured data, T1 and T2, are also shown in this figure and agree with the calculated values, which validate the proposed method.

Fig.11 shows the girder response with different girder masses. In this calculation, pedestrian density is kept at 0.8 person/m2 and the girder natural frequency of 0.93Hz. The girder response decreases with girder mass, showing that the lighter girder has more likely to have a vibration problem. The measured data T1 is also shown in this figure.11, corresponding to the calculated value.

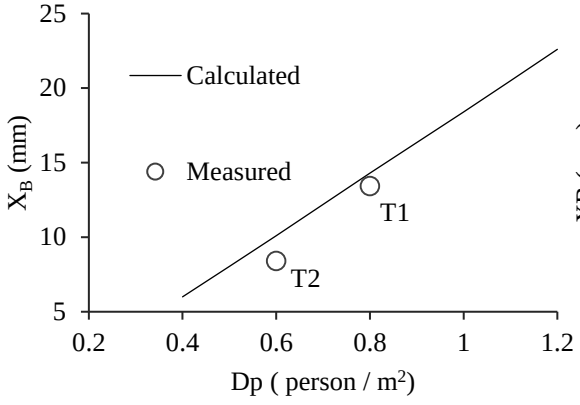


Fig.10 Effect of density of pedestrian

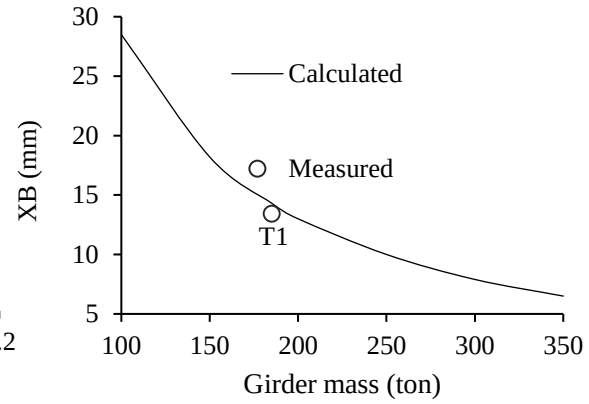


Fig.11 Effect of girder mass

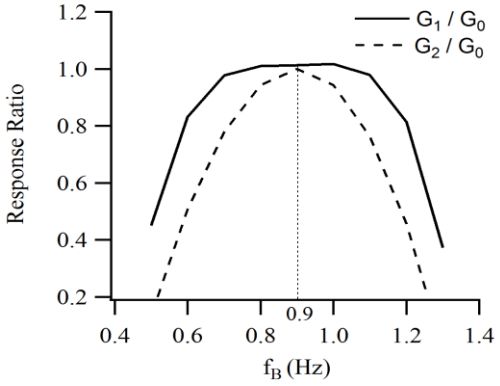


Fig.12 Response ratio due to G_1 and

Fig.12 shows the girder response ratio; the response is calculated by G_1-function over that by G_0-function. The response ratio calculated by G_2-function over that by G_0-function is also shown in this figure. Both response ratios have a peak at 0.9Hz and they decrease as the bridge's natural frequency becomes further away from 0.9Hz. This decreasing ratio with G_2-function is sharper than that with G_2-function.

The improved method with G_1-function and G_2-function is useful to Fig.11 shows the girder response ratio; the response calculated by G_1-function over that by G_0-function. The response ratio calculated by G_2-function over that by G_0-function is also shown in this figure. Both response ratios have a peak at 0.9Hz and they decrease as the bridge's natural frequency becomes further away from 0.9Hz. This decreasing ratio with the G_2 function is sharper than that with predicted responses when the bridge's natural frequency is away from the usual resonant frequency of about 0.9Hz. However, further study is necessary to decide which is more suitable for practical bridges.

4. Conclusions

The lateral vibration problem induced by the pedestrian was first observed on the T-bridge and it has then been widely known in the world. This is mainly because many footbridges suffer from this type of vibration. After all, footbridges have become lighter and more flexible. The mechanism of this vibration has almost been clarified but the prediction method and the design criteria have not been established yet.

Nakamura proposed a simple method to predict the response induced by pedestrians which seems useful for practical bridge designers and engineers. One of his assumptions is that this problem only occurs for bridges with a natural frequency of about 0.9Hz (0.8-1.0Hz). However, this vibration has been observed with a natural frequency outside of this range.

This paper has proposed an improved method to cover a wide range of bridge natural frequencies by introducing the distribution function, G_1-function, and G_2 function. The predicted girder responses generally agree with the measured values obtained on the T-bridge. Parametric studies were conducted with the proposed method. The girder response increases with pedestrian density. The girder response decreases with girder mass, showing that the lighter girder has more likely to have a vibration problem.

The girder response ratio has a peak at 0.9Hz, and it decreases as the bridge's natural frequency becomes further away from this peak frequency. This decreasing ratio with G_2-function is sharper than that with G_1-function. The improved method with G_1 and G_2 functions is useful to predict responses when the bridge's natural frequency is away from the usual resonant frequency of about 0.9Hz. However, further study is necessary to decide which is more suitable for actual bridges.

5. Acknowledgements

The first author would like to thank JICA for providing him the opportunity to study at Tokai University through the PECE program.

6. Abbreviations

X_B:	**modal displacement**
X'_B:	modal velocity
X''_B:	modal acceleration:
M_B:	modal mass
C_B:	modal damping coefficient
K_B:	modal stiffness
$M_p g$:	modal self-weight of pedestrians
F_P:	the lateral force of pedestrians
F_b:	natural frequency of the first lateral mode of the bridge
K_1:	ratio of the lateral force to the pedestrian`s weight
K_2:	percentage of synchronized pedestrians
K_3:	Saturation rate

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