

Long-term Bridge Deflection Monitoring Using a Connected Pipe System Considering Structural Vibration

Pan Zeng* and Ronghui Wang

School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, Guangdong, 510641, China.

*Corresponding author: 2715424820@qq.com

Abstract. Structural health monitoring is an important technical solution to track the evolution of bridge performance and prevent sudden damage, which receives rapid development in the past decades. While, long-term deflection is a critical index to evaluate bridge state and provide references for bridge maintenance and management. Hence, health monitoring of bridge long-term deflection is studied in the paper using a connected pipe system. First, bridge deflection monitoring system using a connected pipe is designed. Then, theoretical formulation of bridge deflection considering bridge vibration is deduced. Finally, the deflection monitoring system is verified through a model test. Results indicate the proposed bridge deflection monitoring using a connected pipe system could precisely measure the long-term static deflection induced by structural degradation as well as transient dynamic deflection caused by environment loads, and the relative error between theoretical formulation and realistic measurements is no more than 2.3%. The long-term bridge deflection monitoring using a connected pipe system studied in the paper could find wide application in bridge health monitoring.

1. Introduction

Structural health monitoring (SHM) is a rapidly developing technical solution in the field of civil engineering in the past two decades. In SHM, modern technical measures of electronic, information, and sensing are incorporated such that environmental loads and structural responses are measured, which provides basis for structural performance analysis, abnormal load identification, and security warning over structure life-cycle [1-2]. Bridges is the lifeline node of civil transportation and is often designed with long life up to 100 years. Considering complex factors such as environment load variation, natural disaster, material degradation, bridges inevitably suffer damage even collapses [3-4]. Therefore, health monitoring of bridge structure can not only detect hidden damage in time, but also prevent sudden collapse. Bridge performance could be reflected by different indexes such as deflection, strain, and natural frequency. While, deflection is the most intuitive and important evaluation index to characterize the overall health condition of bridges, and is focused in the paper. Real-time monitoring of bridge deflection could be used to evaluate the safety and health of the structure, avoiding major accidents and providing references for daily management and normal maintenance of bridges.

Currently, main methods for bridge deflection monitoring at home and abroad include measuring robot, inclination instrument, laser image, photoelectric imaging, GPS, and connected pipe [5-6]. These methods provide alternative solutions to acquire bridge deflections, and both show their advantages and disadvantages. Wherein, deflection measurement system based on connected pipe method uses a fully closed structure, and thus the physical concept of the method is clear, direct and reliable, which is not affected by the environmental conditions of high dust, high humidity and dense



fog in the bridge site. Moreover, the measurement precision of connected pipe could well meet the requirements of long-span bridges. Recently, deflection monitoring using connected pipe method is widely employed [7-8].

Most of the researches and applications of connected pipe are for static measurement. While, bridges are always in working conditions that environmental loads are applied, and thus the monitored deflections contain static and dynamic parts. However, the work on dynamic deflection measurement of structures is limited [9-11]. Zhang et al. [9] noted liquid oscillation in the connected pipe would affect the measurement accuracy of deflection, and therefore deduced the differential equation, which is then verified by numerical simulation. Chen et al. [11] discussed the correlation between pipeline pressure and structural deflection, and proposed the performance of a new pressure field deflection monitoring system. Note that the pressure variation of connected pipes is highly related with the movement of pipes, i.e. structural deformation, however, are also affected by structural vibration. Therefore, the realistic dynamic deflection of the structure is not simply converted from the pressure change of the connected pipe according to measurement, wherein the effect of structural vibration on the measurement should be considered.

In the paper, effect of structural vibration on bridge deflection monitoring is investigated to improve the measurement precision of long-term bridge deformation. A structure deflection monitoring system based on the pressure field using connected pipe is first designed, and the overall structure and hardware of the monitoring system are defined. Then, the influence of bridge vibration on the dynamic deflection measurement of bridges is theoretically deduced, wherein the influence of acceleration on the theoretical formula of dynamic pressure of connected pipe is analyzed, and the error correction formula of bridge vibration is formed. Finally, comparison between theoretical and practical values is conducted based on a model test, to verify the proposed measurement correction equation. The precision improved method of dynamic deflection using connected pipe can be further developed and applied to the real-time and long-term monitoring of dynamic deflection of bridges.

2. Bridge deflection monitoring system

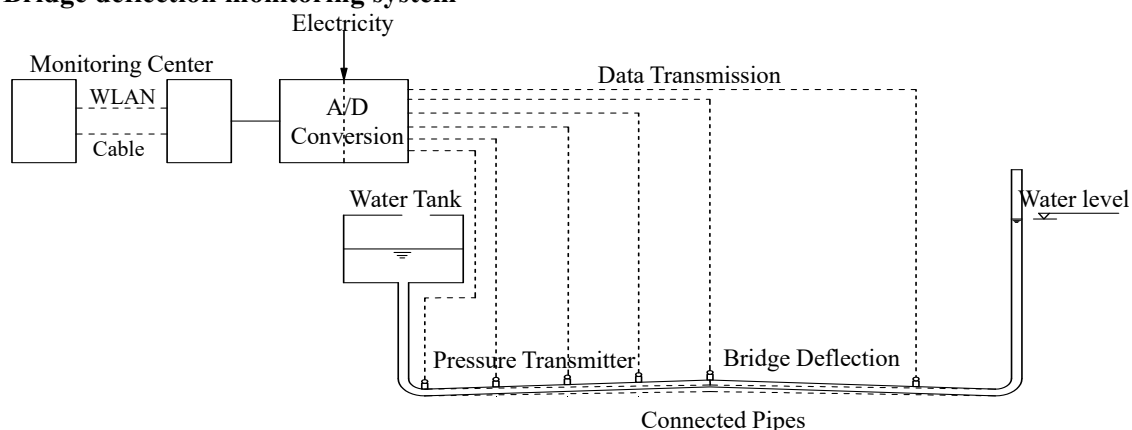


Figure 1. Bridge deflection monitoring based on a connected pipe system.

In the paper, bridge deflection monitoring is studied based on a connected pipe system. The fundamental principles of connected pipe system for bridge deflection monitoring could be illustrated from figure 1. Water tank, water level, and connected pipes are incorporated together to establish the pressure field where bridge structure needs to be monitored. Water tank is fixed at same height according to the design height requirement. Water pipe is laid along the bridge beam longitudinal and fixed to the side wall of the beam body, and pressure transmitters are arranged at the points to be monitored. When the bridge deforms under environmental loads, the pipe fixed on it will deform along with the structure, but the level of liquid level in the water tank in the fixed position will not change, and so the pressure of the pipe do change. In this circumstance, bridge deflection could be revealed based on pressure transmitters.

According to hydrostatics principle, when the connected pipe in a measuring point deformed statically with the bridge structure, the change of liquid pressure in the pipe along that measurement point could be formulated as

$$\Delta F_s = u_s \rho g \quad (1)$$

where, u_s is structural deflection; ρ is the liquid density; g is gravity acceleration.

For static deflection monitoring, the measured liquid pressure change ΔF could be captured using pressure transmitter, and thus the change could be transferred to analog single, which is then converted to the value of deflection change. However, as for dynamical deflection monitoring, the conversion becomes complex since bridge vibration affects the liquid pressure change but this component should not be the realistic bridge deflection.

3. Theoretical formulation

When the pressure field based connected pipe system is applied to dynamic deflection monitoring of bridges, fluid in the pipe will produce additional pressure due to the non-uniform forced motion of the liquid following bridge vibration. Clearly, the relationship between bridge deflection and liquid pressure of the connected pipe could not be simply formulated by Equation 1. In the following, we deduce the calculation formula of the dynamic liquid pressure of the connected pipe caused by structural vibration. Figure 2 gives a simplified dynamic mechanical analysis model of the connected pipe, in which the pipe is arranged at a dip angle, φ , to the horizontal line, the liquid in the pipe is water, and the coordinate system is established as shown in the diagram. The origin of the coordinate is located at the lowest point of the pipe.

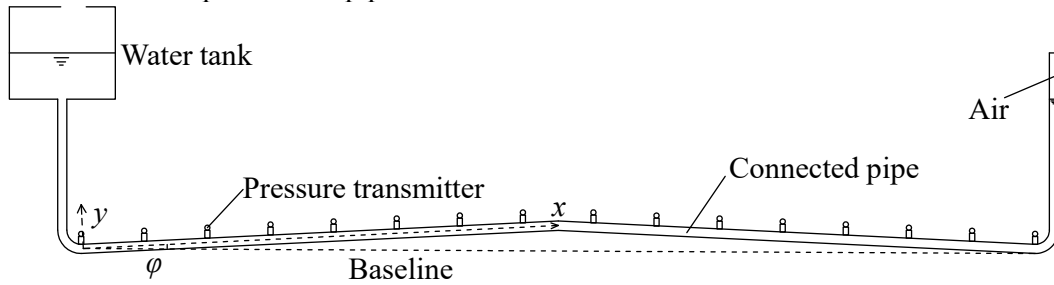


Figure 2. Mechanical model of dynamical deflection monitoring using a connected pipe system.

Segmental water in the pipe is taken as an isolator for analysis as shown in figure 2. When the connected pipe fixed on the bridge girder deforms up and down with the structure, the acceleration of the section of the pipe is $u''(x)$ where x is the distance of the isolator to the origin point.

$$p(x) = m \cdot u''(x) \quad (2)$$

The acting force on the water isolator, $p(x)$, has the same direction of girder deflection. It is noted structural vibration could cause liquid vibration, and liquid vibration will generate very small deflection on the pipe compared with deformation caused by environment loads. Therefore, we can ignore the small deformation caused by liquid vibration and get the component of acting force along the pipe direction as

$$p(x) = m \cdot u''(x) \cdot \sin \varphi \quad (3)$$

Moreover, the liquid pressure change of the isolated water body along x axis of the pipeline caused by bridge deflection could be formulated as

$$\Delta F_d(x) = \frac{1}{A} \int_{x_1}^{x_2} u''(x) \cdot \sin \varphi \cdot dm \quad (4)$$

where, x_1 and x_2 are the distances from left and right of the isolated water body to the origin point. A is the area of the section of the pipe. dm is the mass of the isolated water body with dx , i.e. $dm = A \rho dx$.

Then, the above equation 4 could be simplified to the following

$$\Delta F_d(x) = \rho \cdot \sin \varphi \cdot \int_{x_1}^{x_2} u''(x) \cdot dx \quad (5)$$

Equation 5 is the additional liquid pressure in the pipe of the bridge structure caused by vibration. Therefore, the dynamic liquid pressure of the connected pipe caused by structural vibration should be the sum of static pressure and additional pressure, namely

$$\Delta F(x) = \Delta F_s(x) + \Delta F_d(x) = \mu_s \rho g + \rho \cdot \sin \varphi \cdot \int_{x_1}^{x_2} u''(x) \cdot dx \quad (6)$$

For bridge deflection monitoring, it is very important to know the static structural deflection since it is highly related to bridge condition. When bridges degraded, the cumulative static deflection (also called long-term deflection) will be very significant, which is of particular importance for engineers. Moreover, the dynamical structural deflection can also be measured such that abnormal loading conditions could be detected for bridge management.

4. Model test verification

4.1. Model test design

The structural deflection monitoring system consists of reference barrel, steel gate frame, steel tube, stainless steel plate and connected pipe as shown in figure 3. The stainless steel plate is 2.0m in length, 0.1m in width and 1.7mm in height. The two ends of the stainless steel plate are suspended under the steel gate frame, which forms a simply supported plate. Under the excitation of initial displacement in the mid-span, the steel tube could be vibrated together with the simply supported plate. The steel tube is 0.985m in length and 0.02m in inner diameter. The upper end of the steel tube is closed after filling with water. While, the lower end of the tube is supported on the hinge support and the upper end is suspended from the span of the simply supported plate. In order to prevent the change of liquid reference level during vibration, a rigid plastic drum with a diameter of 0.35 m and a height of 0.2m is used, and two connecting holes with diameter of 0.6cm and one connecting hole with diameter of 2cm are left in the middle and lower end of the datum barrel, respectively. The connected pipe is connected to the upper end of the pipe and the low end of the pressure transmitter. While, the higher end of the pressure transmitter is connected to the lower end of the pipe. Since the ratio of moment of inertia of steel frame to stainless steel plate is 25: 1, the influence of deformation of steel frame can be omitted. Moreover, the ratio of reference barrel to plastic hard pipe area is 306: 1, so the vibration of steel tube has no effect on the liquid level of reference barrel. In order to measure the acceleration of the upper end of the steel tube for the convenience of placing the accelerometer in the middle of the span of the simply supported plate, the upper end of the steel tube is welded with a steel plate with 300×200×3mm.



Figure 3. Photo of the model test.

From a primary study on the model, the natural frequency of the beam is 0.8Hz. According to Shannon's sampling theorem, the sampling frequency should be two times or more than the natural frequency of the structure. Therefore, the sampling frequency of the pressure transmitter is set to be 4Hz. In the process of the model test, the pressure transmitter is used to measure the hydraulic

pressure change caused by the vibration of the simply supported steel plate in each test condition. At the same time, the acceleration sensor is used to measure the vertical acceleration of the model span of the simply supported plate as reference. In order to eliminate the effect of the initial displacement and the vertical inclination of the steel tube on the pressure difference (essentially the acceleration of the upper end of the steel pipe), nine test conditions were designed and shown in table 1.

Table 1. Description of test conditions.

Test condition	1	2	3	4	5	6	7	8	9
vertical inclination of connected pipe, $\phi(^{\circ})$		16.24			21.24			26.24	
Initial displacement of middle span(mm)	60	80	100	60	80	100	60	80	100

4.2. Theoretical formulation verification

In the model test, the static deflection of the girder is zero, i.e. $\mu_s = 0$. According to equation 6, the measured change of liquid pressure is the additional pressure caused by the vibration of the structure. The theoretical value of additional pressure could be calculated using the measured structural acceleration and equation 6. While, the measured value of additional pressure is from the transmitter of the connected pipe. Therefore, the comparison of theoretical and measured time-history additional pressures is shown in figure 5, and maximal values of the additional pressures are listed in table 2.

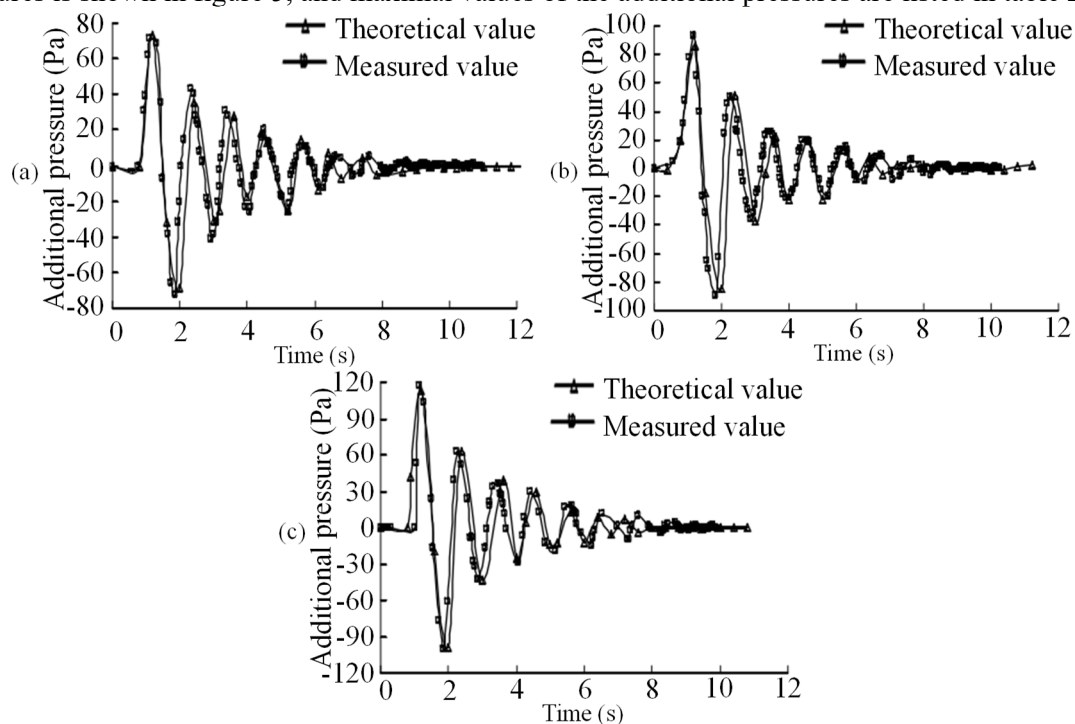


Figure 4. Comparison of time-history additional pressures between theoretical and measurement with (a) test condition 1, (b) test condition 2, and (c) test condition 3.

Table 2. Comparison of maximal additional pressures between theoretical and measurement.

Test condition	1	2	3
Maximal theoretical value (Pa)	72.7	90.9	136.7
Maximal measured value (Pa)	71.0	91.9	139.0
Relative error (%)	2.3	1.1	1.7

It is found from figure 4 and table 2 that the measured values are in good agreement with the theoretical values, which verifies the correctness of the derived formulation of bridge dynamical deflection considering bridge vibration. The maximal error between theoretical and measurement is

2.3%, showing good precisions. Therefore, the designed bridge deflection monitoring using a connected pipe system could well measure the long-term structural deformation as well as transient bridge vibration.

5. Conclusion

Long-term bridge deflection monitoring is very important to know structural condition, such that maintenance and management could be implemented accordingly. In this paper, bridge long-term deflection monitoring using a connected pipe system is designed and verified. Theoretical formulation of bridge deflection related with structural vibration is deduced. The relationship between the dynamic hydraulic pressure of a connected pipe (i.e. structural deflection) and the vibration acceleration of the structure and the dip angle of the pipe are revealed. The theoretical formulation is then verified by a model test, and the results of data analysis prove that the monitoring system could consider the effect of bridge vibration, and the long-term static deflection as well as transient dynamic deflection could all be measured precisely with relative error no more than 2.3%. Hence, the proposed long-term bridge deflection monitoring using a connected pipe system could find wide application in practice.

References

- [1] Sohn, H., Farrar, C.R., Hemez, F.M. (2003). A review of structural health monitoring literature: 1996–2001. Los Alamos National Laboratory, USA.
- [2] Brownjohn, J.M.W. (2007). Structural health monitoring of civil infrastructure. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 365(1851): 589–622.
- [3] Ko, J.M., Ni, Y.Q. (2005). Technology developments in structural health monitoring of large-scale bridges. *Engineering Structures*, 27(12): 1715–1725.
- [4] Ou, J., Li, H. (2010). Structural health monitoring in mainland China: review and future trends. *Structural Health Monitoring*, 9(3): 219–231.
- [5] Nassif, H.H., Gindy, M., Davis, J. (2005). Comparison of laser Doppler vibrometer with contact sensors for monitoring bridge deflection and vibration. *Ndt & E International*, 38(3): 213–218.
- [6] Meng, X., Roberts, G.W., Cosser, E., et al. (2003). Real-time bridge deflection and vibration monitoring using an integrated GPS/accelerometer/pseudolite system. *Proceeding of 11th International Symposium on Deformation Measurements, International Federation Surveyors (FIG), Commission 6-Engineering Surveys, Working Group. 6: 25–28.*
- [7] Yang, J., Chen, W. (2006). Application of connected pipe optoelectronic liquid level sensor in bridge deflection monitoring. *Transducer and Microsystem Technologies*, 8: 027.
- [8] Liu, Y., Deng, Y., Cai, C.S. (2015). Deflection monitoring and assessment for a suspension bridge using a connected pipe system: a case study in China. *Structural Control and Health Monitoring*, 22(12): 1408–1425.
- [9] Zhang, L., Chen, W., Zhang, P., et al. (2010). Liquid fluctuation analysis of displacement measurement system using connected pipe. *Journal of Vibration, Measurement & Diagnosis*, 30(5): 552–598.
- [10] Liu, G., Lei, X., Chen, W., et al. (2007). Dynamic characteristics of displacement measurement system based on connected pipe with U pipe model. *Transducer and Microsystem Technologies*, 26(11): 41–44.
- [11] Chen, D., Ban, X., Li, X., et al. (2008). Reliability analysis of a new bridge deflection monitoring system based on fluid dynamics pressure computation. *Chinese Journal of Hydrodynamics*, 23(4): 385–392.