Study on the Effect of Temperature on Weigh-in-Motion Accuracy of Piezoelectric Thin

TANG Hao[1, a] and DUAN Min[1, b]

[1]State Key Laboratory of Bridge Engineering Structural Dynamics, China Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd., Chongqing 400067, China

[a]tanghao9@163.com, [b]duanmin@cmhk.com

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Abstract. Temperature is an important factor affecting the weighing accuracy of the piezoelectric thin film Weigh-in-Motion (WIM) system. Because the temperature compensation coefficient formula given in the existing technical data is not effective in practical application, and because the time and cost factors can not be used to calibrate the compensation coefficient of each temperature one by one, this paper studies the law between temperature and weigh-in-motion accuracy. The calibration coefficients were calculated by using the least-squares linear fitting method at two temperatures, and the compensation coefficients were calculated for all the temperature gradients. This not only reduced the test time and cost, but also to obtained a high weighing accuracy. The reliability and validity of the proposed method were proved by the experimental results and the actual test results.

Introduction

Vehicle load is a key fact affecting the safety and endurance of the bridges. And overload transportation is the major reason for bridge structure destruction and collapse. Research shows, vehicles are generally over load in practical. In order to suppress the damage of overload transportation on the infrastructures, European Union, American, Japan, Canada and other organizations have conducted a lot of researches on the Weigh-in-Motion(WIM) technology and obtained valuable achievements since 1950s. In 1974, American firstly utilized the WIM system in the research of vehicle loads. In the same year, France acquired a patent on piezoelectric WIM –the Vibracoax sensors [1,2]. In 1988, Britain developed a new and more advanced piezoelectric WIM sensor- Vibetek5, which is remodeled as Vibetek20 in 1991[3,4]. In 1992, FEHRI launched a plan called as COST323[5-7] according to the procedure framework of ECTD, the most important activities of which is the WIM system application test over a period of 30 mouths in Switzerland. In 1994, European Union started the Weighing in motion of Axle and Vehicles for Europe [8] plan. The systematical test for the product was conducted under the cold weather of Sweden from June, 1997 to June, 1998, which is known as the Cold Environment Test (CET). In 2000, the MSI company exhibited a copolymer piezoelectric sensor on the ITS annual meeting, which can measure the vehicle speed, number of axles and axle distance at the same time, as well as distinguish the vehicle's class and weigh them in motion. As so far, the piezoelectric WIM technology has been widely used over 60 countries, such as American, Brazil, Germany, Korea and so on in the past 10 years.

With the development of the safety monitoring technology of bridges, the bridge management and maintenance administrations pay more attention to the effect of traffic load on the bridge structure. It is expected that the service status of the bridges could be reflected scientifically through data as traffic flow and vehicle load, in conjunction with the traditional bridge structure safety monitoring information. Thus, proper measures can be made accordingly. The accuracy of the piezoelectric technology is mainly affected by the road surface roughness, vibrations and bounces of the vehicles and temperature. After installation The WIM system should be calibrated though the practical vehicle running experiments and temperature coefficient compensation. This is the key point to guarantee the accuracy of the system. Strictly speaking, different temperatures correspond to different temperature compensation coefficients. But in practical, it is hard to realize for the limitations of the

implementation cost and time. This paper mainly investigates the relationship between the accuracy of the WIM system and the temperature as well as proposes a temperature coefficient calibration and verification method which is suitable for practical engineering use.

Effect of temperature on WIM

When the vehicle passing the piezoelectric sensors, the relationship between the static weight and dynamic weight of the vehicle is

$$C = \frac{W_0}{W} \tag{1}$$

Where, W_0 is the static weight. W is the dynamic weight. C is the calibration coefficient. For the WIM system, the key point is to inspect the consistency of the calibration coefficient C, namely, to test whether C has good consistency when the same vehicle passing though the piezoelectric sensors with different speeds. Better consistency means higher accuracy. Wherein, the temperature has significant effect on C. The relationship between them is

$$C = C_0 \cdot C_T(T_a) \tag{2}$$

Where, C_0 is the basic calibration coefficient. $C_T(T_a)$ is the temperature compensation coefficient at temperature T_a. The calibration coefficient is concluded from massive experiment data of different speeds and temperatures so as to obtain higher accuracy of WIM. However, it is impractical for the technicians to obtain the compensation coefficients of different temperatures one by one due to the limitation of cost and time.

Pater [9] points out that, the temperature will change the physicochemical properties of the glue used for encapsulation when embedding the piezoelectric sensors. Under different circumstances, the glue presents different properties of viscous, viscous-elastic or elastic, which affects the measurement signals reaching the piezoelectric sensors. Further, the accuracy of WIM will be affected. The formula for calculating the temperature compensation coefficient by paper [9] is

$$C_T(T_a) = k_1 \cdot 10^{w_l(T_0 - T_a)} \tag{3}$$

Where, T_a is the road surface temperature in real measurement. T_0 is the initial temperature. k_1 and w_l are calculation coefficients. Wherein, ① $T_0 = 10$, $k_1 = 1.01286$ and $w_l = -0.005277$. Paper [10] uses the same formula as formula (3) for calculating the temperature compensation coefficient but with different parameters where ② $T_0 = 45$, $k_1 = 3.8702$, $w_l = -0.0053$. Figure 1 shows the comparison of two curves under different temperature compensation coefficients, $30\,^{\circ}\mathrm{C}$ versus $100\,^{\circ}\mathrm{C}$. It can be seen that, the calculation results by formula (3) are inconsistent under the given two sets of parameters.
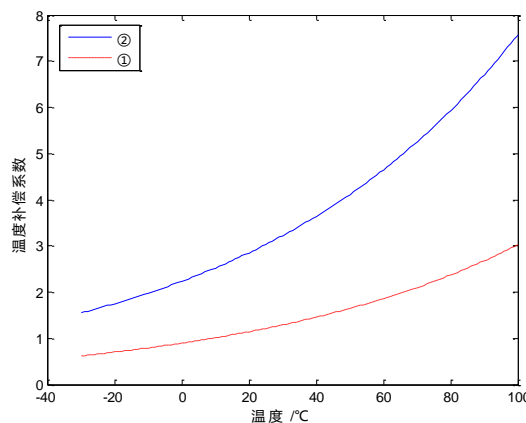

Fig.1 Temperature compensation coefficient at different temperature

Application of temperature compensation coefficient in engineering

In 2016, a piezoelectric WIM system was installed on some expressway in China, shown as figure 2. Then vehicle running experiment was conducted to calibrate the parameters. A two-axle van was used in the experiment. The overall weight of the wan is 21.8t and the road surface temperature is 45 $^{\circ}$C. At last, the mean weight obtained by WIM was 21.11t when $C_0 = 380$, $C_T = 218$. The mean test error calculated by formula (4) is 3.165%.

$$e = \left| \frac{y_0 - y}{y_0} \right| \qquad (4)$$

Where e is the test error. y_0 is the real weight. y is the test weight.

Fig.2 WIM system

According to the two temperature compensation curves calculated by the two sets of parameters ①, ②, the vehicle running experiment was conducted again under other temperatures. The test result is shown in table 1. As it can be seen, the WIM error is two big at 36 $^{\circ}$C，30 $^{\circ}$C and 26 $^{\circ}$C no matter which set of parameter is used to calculate C_T. Referring to the WIM criterion, the overall weight error should be less than 10%. Therefore, the method for calculating the temperature compensation coefficient given by formula (3) is not applicable in this situation. However, it is impossible to calibrate all temperatures in practical engineering for the limitations of cost and time. For example, the elapsed time for one vehicle-run of the mentioned experimental WIM system is 1.5 hours and cost of the car rental, road toll and labors is very high. Hence, it's necessary to develop a temperature compensation coefficient calculating method which suits for practical engineering applications and satisfies the requirements of WIM systems.

Table 1 Test results of different temperature

Group	Real weight(t)	Temperature($^{\circ}$C)	C_0	C_T	Average test weight(t)	Average test error(%)
①	21.8	45	380	218	21.11	3.165
		36		195.3561	14.64	32.844
		30		181.5729	12.61	42.156
		26		172.9935	10.03	53.991
②		45		218	21.11	3.165
		36		195.3550	14.64	32.844
		30		182.1173	12.65	41.973
		26		172.8791	10.03	53.991

Temperature compensation checking method

Shown as figure 3, a WIM experimental platform was built. And vehicle running experiments were conducted at the temperatures of 20 $^{\circ}$C and 13 $^{\circ}$C. The temperature compensation coefficient is calibrated by the rule of minimum mean test error and it yields $C_T(20) = 12.69$, $C_T(13) = 12.51$. The

experiment results are show as table 2. The mean test errors are 2.26% and 5.85% using the calibrated temperature, less than 10%, satisfying the requirement of WIM system.

Fig.3 WIM system experimental platform

Table 2 Test results for two kinds of temperature

	Test weight(t)	Error(%)		Test weight(t)	Error(%)
	10.66869	1.851954		10.15243	7.537097
	10.85365	0.150419		10.04117	8.550369
	10.60936	2.397751		10.42829	5.024667
	10.96787	0.900389		10.57553	3.683699
	11.09617	2.080643		11.8338	7.775918
	11.25202	3.514444		11.92051	8.565704
	10.81665	0.490796		10.22972	6.83313
	10.4573	3.796723		12.22199	11.31138
Real weight 10.87t 20 °C $C_T = 12.69$	10.56935	2.765848	Real weight 10.98t 13 °C $C_T = 12.51$	10.91467	0.594991
	10.62297	2.272622		10.78659	1.761463
	11.16454	2.709666		11.94789	8.814986
	11.15322	2.605539		11.18443	1.861856
	10.55535	2.89466		9.976122	9.142782
	11.22184	3.236812		10.19745	7.127016
	10.61676	2.329703		10.66567	2.862757
	10.56522	2.803831		12.3535	12.50912
	10.61973	2.302406		11.05805	0.710812
	11.06161	1.762714		10.77826	1.83737
	10.98762	1.082038		10.45982	4.737567
	11.37517	4.647393			
	10.96729	0.89501			

Then the vehicle running data are applied to curve fitting using the least squares formula and it yields $C_T(30) = 12.947$. Similarly, vehicle running experiment was conducted again under this temperature. The calculated mean test error is 3.902% by substituting the temperature compensation coefficient at 30 °C, shown as table 3.

Table 3 Test results in 30 °C

Real weight(t)	Temperature(°C)	C_T	Average test weight(t)	Average test error(%)
11.02	30	12.947	10.59	3.902%

In conclusion, for the piezoelectric WIM system, vehicle running should be conducted at least under two different temperatures. The temperature compensation coefficients under different temperatures are calculated using the least squares fitting formula. This method guarantees the accuracy of WIM on condition of saving cost and time. Using this method for the calibration of the expressway WIM system mentioned in chapter 2, the temperature compensation coefficients at 45 °C and 36 °C are obtained .The results are $C_T(45) = 218$ and $C_T(36) = 280$ with the mean test errors of 3.165% and 3.762%, respectively. It can be calculated that $C_T(30) = 321$ and $C_T(26) = 349$. Then

vehicle running experiment was conducted at the temperatures of 30 $^{\circ}$C and 26 $^{\circ}$C to verify the accuracy of the method. The test results are shown in table 4. Compared to table 1, it can be found the proposed temperature compensation coefficient calculation method is more accurate with an error less than 10%, proved to be reliable.

Table 4 Least squares calibration test results

Real weight(t)	Temperature($^{\circ}$C)	C_0	C_T	Average test weight(t)	Average test error(%)
21. 8	45	380	218	21. 11	3. 165
	36		280	20. 98	3. 762
	30		321	22. 30	2. 294
	26		349	20. 24	7. 156

Conclusions

After the installation of the piezoelectric WIM system, calibration is needed to guarantee its accuracy. In practical engineering, it is impossible to calibrate all temperatures due to the limitations of cost and time. This paper proposes a method for calculating the temperature compensation coefficient using the least squares linear fitting algorithm. The method grantees the accuracy of WIM on condition of saving cost and time. At last, test results of the experimental platform and the practical engineering both prove the proposed method is reliable.

Acknowledgements

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