XXI IMEKO World Congress "Measurement in Research and Industry"
August 30 - September 4, 2015, Prague, Czech Republic

DEVELOPMENT AND EXPERIMENTS OF MINIATURE MODELS FOR THE STUDY OF ESTIMATION METHOD OF AXLE WEIGHTS FOR IN-MOTION VEHICLES

Koji Yoshida [1], *Kengo Fukuda* [2], *Kento Ogawa* [3], *Tetsuya Kinugasa* [1], *Shinsaku Fujimoto* [4]

[1] Department of Mechanical Systems Engineering, Okayama University of Science, Okayama, Japan,
k_yoshida@mech.ous.ac.jp
[2] Sohatsu Systems Laboratory Inc., Kobe, Japan
[3] Graduate School of Engineering, Okayama University of Science, Okayama, Japan
[4] Department of Intelligent Mechanical Engineering, Okayama University of Science, Okayama, Japan

Abstract - Axle weighing system measures axle weights of in-motion vehicles. Methods have been studied for estimating axle weights by processing the weight signal to improve the accuracy of measured axle weights. The examination of the accuracy of estimated axle weights of in-motion vehicles with higher velocity has not yet completed. To examine and improve the accuracy of the estimated axle weight, miniature models have been developed. The method have been applied to the obtained weight signals. This paper presents the developed miniature models and application results of the method.

Keywords: Axle weight, In-motion vehicle, Axle weighing system, Instrumented vehicle

1. INTRODUCTION

Overloading a vehicle makes the vehicle less stable, difficult to steer and take longer to stop. Also, it causes excessive wear and damage to roads, bridges, and pavements. Moreover, it causes noise and vibration pollution to the environment along roads and increases fuel consumption and air pollution. Then, in Japan, axle weighing system is often used to check the axle weights of heavy vehicles that are entering an expressway and give warnings to overloaded vehicles. The axle weighing system measures axle weights of in-motion vehicles. The weighbridge of the axle weighing system is detector part of the system and consists of weighing platform and loadcells. The platform has the length of 76 cm in vehicle traveling direction which is nearly equal to the diameter of a tire, to avoid measuring two axle weights at the same time. (See Fig. 1.) The weighbridge is usually installed in front of a toll gate and used to detect axle weights of vehicles in low speed. We have studied estimation methods for axle weighing by processing the weight signal from the weighbridge in order to improve the weighing accuracy of the system[1-3].One of the difficulties in estimating the axle weights of in-motion vehicles with using the axle weighing system would be that when vehicles are in-motion, vehicle bodies have vibrations which affect the weight signals when the vehicles go through on the weighbridge, i.e., the weight signal consists of a dynamic component and a static one, which would be considered as the true value of axle weight. Moreover the signal segments which are effective for weight estimation are extremely short, because the length of the platform is almost the same as that of the diameter of tire. When a vehicle passes on the weighbridge with low velocity under about 15 km/h, the frequency of the most dominant vibration component in the weight signal is around 3Hz; the dynamic component is caused by vibration of vehicle body. Suppose that the length of the contacting area with ground of a tire is 250 mm, when a vehicle passes on the weighbridge with 15 km/h, the time period for measuring would be about 0.12 s; extremely short. Hence it was impossible to obtain the weight of in-motion vehicles in high accuracy if conventional signal processing method is used. If the dynamic component is due to the natural vibration of vehicle body, the dynamic components in each segment of the weight signal have a common frequency. Then, by the best use of this fact, we have proposed a method to estimate the axle weights which takes vibrations of vehicle body into account. Applying our method to in-motion

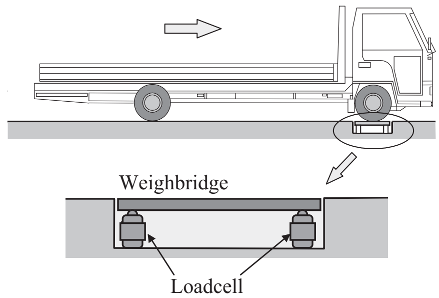

Fig. 1. Weighbridge of the axle weighing system.

vehicles at the velocity of less than 15 km/h, we can obtain axle weights in high accuracy that has not been attained[2]. However the requirement for measuring axle weights of in-motion vehicles at higher velocity is increasing as ETC (Electronic Toll Collection) systems are widely used these days in Japan. We have also conducted experiments using an experiment site for axle weighing system to examine the accuracy of estimated axle weights of in-motion vehicles with higher velocity. In the experiments, upper limit of velocity was 40 km/h, because the lane of the experiment site is not long enough for a vehicle to accelerate to have high constant velocity before reaching the weighbridge. Hence the examination of the accuracy has not yet completed. To examine the accuracy of the estimated axle weights of in-motion vehicles with higher velocity, we need to use an experimental site which has both an axle weighing system and a long lane enough for vehicles to accelerate to have higher velocity. It is difficult to execute the high speed experiments for some reasons such as cost, time, safety and traffic congestion. Moreover, to improve the accuracy of the estimated axle weights, we would need also an instrumented vehicle which is equipped with accelerometers on adequate positions of the vehicle. Using the instrumented vehicle, we could obtain data of the vertical motion of the vehicle body which would affect the axle weights. Then, we could obtain the motion data of the instrumented vehicle and weight signals from the weighbridge of axle weighing system simultaneously when the vehicle passes on the weighbridge in various situations. By analyzing and comparing them, we could improve the estimation methods for axle weighing which we have studies. However, developing the instrumented vehicle and executing experiments with it are very expensive. Though the experiments with the instrumented vehicle would be finally indispensable for the examination and improvement of the accuracy of the estimated axle weights for in-motion vehicles, as the previous step for the final experiments, we have developed a miniature instrumented vehicle and a miniature weighbridge. Through the experiments using these miniature models, we have obtained motion data of vehicle body and weight signals when the miniature instrumented vehicle passes on the weighbridge in various situations. Also, we have applied the estimation method to the obtained weight signals. Then, in this paper, we describe the basic idea of the method we have proposed, the miniature models and the results of applying the estimation method.

2. CONVENTIONAL METHOD FOR DETERMINING AXLE WEIGHTS

Each loadcell that supports the weighing platform detects the force $D_i(t)$ when the i-th axle is on the platform and converts it to the voltage signal. The calibrated output signals of all loadcells are summed up to be one signal. We call it "weight signal" from the weighbridge. Fig. 2 shows a schematic picture of time behavior of the weight signal $f(t)$ and the force $D_i(t)$. $f(kT)$ and $D_i(kT)$ for $k \in Z$ denote the discrete signals sampled from $f(t)$ and $D_i(t)$, respectively with sampling time T . The part of $f(kT)$ indicated with $S_i(kT)$ in Fig. 2 is the segment when the whole contacting areas of tires are on the platform. By processing $S_i(kT)$, we obtain measured weight for the

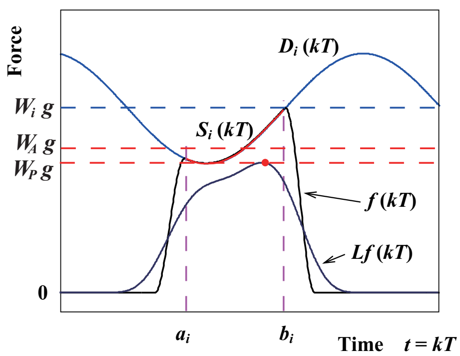

Fig. 2. Graphical representation of the signals and estimated values of an axle weight.

i -th axle. We refer to $S_i(kT)$ as "effective part" and the time interval corresponding to effective part as "effective interval". The force $D_i(kT)$ contains the vibration components caused by the vibration of vehicle body. We refer to the most dominant component of the vibration as "dynamic component". Supposing that it can be represented by sine wave, we can express $D_i(kT)$ as

$$D_i(kT) = A_i \sin(\omega_i kT + \phi_i) + W_i g, \tag{1}$$

where, A_i, ω_i, ϕ_i are the amplitude, angular frequency, initial phase of the dynamic component, respectively. W_i is static value for i -th axle weight which should be obtained accurately. g is the gravity acceleration constant. Hence, as shown in Fig. 2, the effective part would not be flat but a curved line affected by the dynamic component. The typical conventional processing methods are as follows[1]:

i) $W_A g$: average of a part of the effective part

ii) $W_P g$: maximum value of $Lf(kT)$ which is the signal obtained by processing $f(kT)$ with a low pass filter

The methods could give us an accurate value if the effective part is flat. As is clear from Fig. 2, if the period of the dynamic component is longer than the effective time, we cannot obtain accurate axle weight by using the conventional methods.

3. ADVANCED METHOD FOR DETERMINING AXLE WEIGHTS

If the period of the vibration component is longer than the effective time, it would be generally very difficult to estimate the amplitude and frequency of it. We have proposed a method to get over the difficulty. First, we have assumed following:

Assumption 1: We can represent the dynamic components is sine wave

Assumption 2: We can represent the noise on the effective part as sine wave

Then, we apply a regression equation to the effective part $S_i(kT)$ as follows:

$$\begin{aligned} &S_i((k_i+N)T) \\ &= -\frac{\alpha_1}{\alpha_0} S_i((k_i+N-1)T) - \cdots \\ &-\frac{\alpha_{N-1}}{\alpha_0} S_i((k_i+1)T) - \frac{\alpha_N}{\alpha_0} S_i(k_i T) \\ &+\frac{C_i}{\alpha_0}\epsilon(k_i), \end{aligned} \tag{2}$$

for $k_i T = a_i, \cdots, b_i - NT$, where C_i denotes a constant and $\epsilon(k_i)$ denotes random variable normally distributed with mean 0. Here, we set N an even number and arrange the coefficients symmetrically with respect to $\alpha_{n/2}$, i.e.,

$$\begin{aligned} &\alpha_0 = \alpha_N = 1, \alpha_n = \alpha_{N-n}, \\ &n = 1, \ldots, (N-1)/2. \end{aligned} \tag{3}$$

Estimating the coefficients in (2) by using the least square method, we obtain the following different equation:

$$\begin{aligned} &\hat{C}_i + e(k_i) \\ &= S_i((k_i+N)T) + \hat{\alpha}_1 S_i((k_i+N)T) + \cdots \\ &+\hat{\alpha}_{N/2} S_i((k_i+N/2)T) + \cdots \\ &+\hat{\alpha}_1 S_i((k_i+1)T) + S_i(k_i T), \end{aligned} \tag{4}$$

where, $\hat{C}_i$ and $\hat{\alpha}_i$ denote estimated values, $e(k_i)$ denotes the residue. When $S_i(k_iT)$ and $\hat{C}_i + e(k_i)$ are considered to be an input and an output, respectively, (4) can be regarded as the input and output expression of a linear-phase FIR filter. If the order N of (4) is selected adequately, then the zeros of the filter are allocated on the unit circle of z plane. Then, if $e(k_i) \cong 0$, each zero corresponding to a sine wave that is a vibration component attenuate the input $S_i(k_iT)$. Hence we can obtain the i-th static axle weight as

$$\hat{F}_i(k_i) \cong (\hat{C}_i + e(k_i))/\{2(1 + \sum_{j=1}^{N/2-1} \hat{\alpha}_j) + \hat{\alpha}_{N/2}\}, \quad (5)$$

Here, $e(k_i)$ has a property:

$$\sum_{k_i=a_i/T}^{b_i/T-N} e(k_i) = 0 \quad (6)$$

Hence, $\hat{F}_i$ which is the average of $\hat{F}_i(k_i)$ would be

$$\hat{F}_i = \hat{C}_i/\{2(1 + \sum_{j=1}^{N/2-1} \hat{\alpha}_j) + \hat{\alpha}_{N/2}\}. \quad (7)$$

Consequently, we can obtain

$$\hat{W}_i = \hat{F}_i/g, \quad (8)$$

as the estimated equivalent mass of the i-th axle. The dynamic component contained in the effective part of actual weight signal is usually influenced by disturbances such as a pitching motion due to acceleration or deceleration of a vehicle when it passes on the weighbridge, electrical noises, and so on. Hence, the dynamic component would not be perfect sine wave: it would be "distorted sine wave". In case that the distortion is large, we might not estimate the dynamic component accurately even if we use the method above. Also, when vehicle passes on the weighbridge with high speed, the effective interval becomes shorter. To overcome the serious difficulty of estimation, we add the following assumption to the assumptions above.

Assumption 3: The dynamic component of the weight signal is caused by the natural vibration of vehicle body.

Then, all weight signals obtained when one vehicle passes on the weighbridge would have the dynamic components that have a common frequency. Let $D_1(t)$ and $D_2(t)$ denote the forces exerted by front axle and by rear axle on the road, respectively, when a two-axle vehicle is traveling. They can be represented as

$$D_1(kT) = A_1 \sin(\omega kT + \varphi_1) + W_1 g, \quad (9)$$

$$D_2(kT) = A_2 \sin(\omega kT + \varphi_2) + W_2 g, \quad (10)$$

To obtain the similar FIR filter as (4) from (9) and (10), we set different values independently for each axle, and common values to the coefficients in each regression equation for (9) and (10), then, we have a linear regression model. By estimating with the least square method and sampled data, we can obtain axle weight. The details are in [3, 6].

4. DEVELOPMENT OF MINIATURE MODELS

We have developed the miniature models: a miniature instrumented vehicle and a miniature weighbridge of axle weighing system.

4.1. A miniature instrumented vehicle

We have developed the miniature instrumented vehicle provided with the functions enumerated below.

1. Accelerometers for measuring the body motion.
2. A tacho generator for detecting the velocity.
3. An accelerator and brake for velocity control.
4. A shaker for giving an arbitrary vibratory component to the body.
5. A load-carrying platform for weights used to change the mass.

A radio controlled 1:6 scale vehicle model powered by a gasoline engine has been modified to be the miniature instrumented vehicle (Fig. 3). Since we cannot operate a gasoline engine in a laboratory room, it has been replaced with a DC motor. Also, solid tires are replaced with pneumatic tires.The outer dimensions and weight of finished miniature instrumented vehicle are width: 480 mm × length: 750 mm and 18.5 kg. The outer diameters of its tires are 240 mm. Small size accelerometers are attached at the four points of the load-carrying platform where are located at the upper positions of the suspensions in order to measure the vibratory motion of the body. Each acceleration signal is stored in the four SD-memory-card data loggers. A shaker

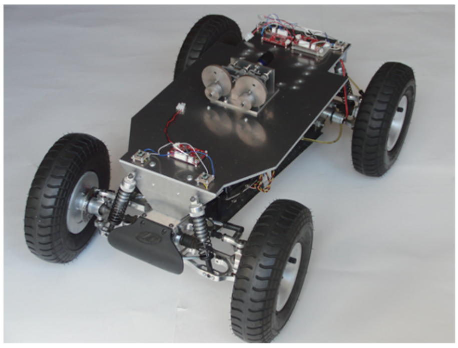

Fig. 3. Miniature instrumented vehicle.

for giving an arbitrary vibratory component to the body is fixed on the centre of the load-carrying platform as shown in Fig. 3. This shaker has been designed to generate around 7 Hz force wave whose maximum amplitude is equal to about 20 % of the force corresponding to the axle weight.

We have conducted the driving experiments for the developed miniature instrumented vehicle in order to examine its functions[7].

4.2. A miniature weighbridge of axle weighing system

In the present study, we have decided that the miniature weighbridge should be composed of an metal platform, loadcells and a base frame as well as the actual one. Then we have developed a miniature weighbridge which were designed according to the size of the miniature instrumented vehicle. Fig. 4 shows the developed weighbridge whose demensions are width:848 mm × length:88 mm. Fig. 5 shows the base of weighbridge and four loadcells. The loadcells support the metal platform. In the experiments, upper surface of the weighbridge must be in the same level of that of road, hence we have made metal lanes and set them both approach and departure sides of the weighbridge. Fig. 6 shows the weighbridge and lanes. We also have made wooden lanes and set them before the metal lane; the instrumented vehicle could pass through on the weighbridge smoothly. The

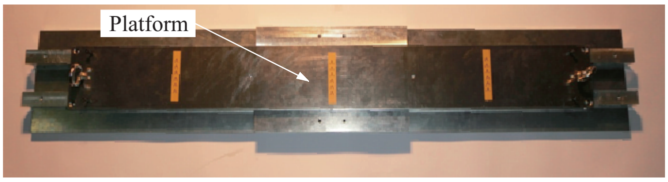

Fig. 4. Miniature weighbridge of the axle weighing system.

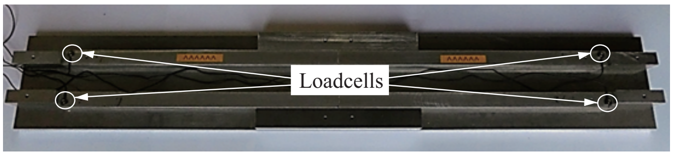

Fig. 5. The base of the miniature weighbridge and loadcells.

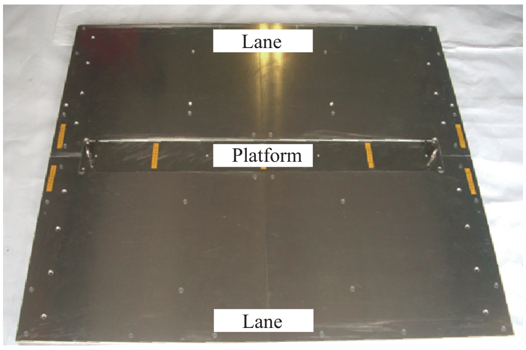

Fig. 6. Miniature weighbridge and lanes.

loadcells support the platform on their load points: the platform is just set on four points, hence there arose ploblems as follows.

1. Problem of the contact points between the platform and the loadcells
   Since the load points of the loadcells have not been in the same plane, the each of them has not supported the platform equally.

2. Problem of the lateral dislocation of the platform
   The platform laterally dislocated during the vehicle passing over it.

In order to solve these problems, the devices mentioned below are employed.

- Headless socket screw
  We employed the stainless headless socket screw whose tips were flattened by filing so that the each loadcell could equally support the platform. This screw is referred as to the adjust screw. The adjust screws are installed in the tapped holes whose horizontal positions are located so that the flat tips of them may contact with the load points of the loadcells. We can adjust the contact points between the platform and the load points.

- Linear bush
  We use the device called the linear bush in order to prevent the lateral dislocation of the platform. The linear bush is a bush that contains many metal balls inside in order to reduce friction. The two linear bushes are installed in the platform. As shown in Fig. 7, the hex socket head cap bolt through the linear bush installed in the platform is fixed to the base of the weighbridge where the loadcells are installed.

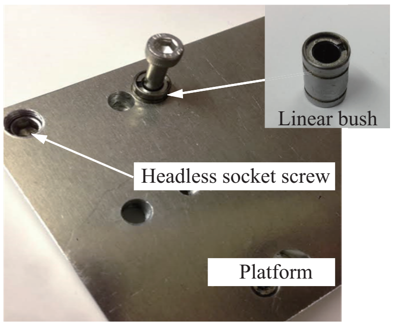

Fig. 7. Device for preventing the lateral dislocation of the platform.

The main specifications of the loadcell equipped with the weighing bridge are as follows:

- Rated capacity: 100 N
- Safe Overload Rating: 150 %
- Natural Frequency: approx.47 kHz

We have obtained weight signals with the developed weighbridge. We have judged that the developed axle weighing system works as a scale by that the effective parts were almost flat when the miniature instrumented vehicle was pushed to pass on the weighbridge quasi-statically. See [7] in detail.

5. APPLICATION OF THE ADVANCED METHOD TO THE OBTAINED DATA

In this section, we examine the advanced method described in Section 3 by applying the method to the weight signals which were obtained through experiments by using the developed miniature models.

5.1. Weight signal without vibration excited by the shaker

Fig. 8 shows a sample of weight signals when the miniature instrumented vehicle passes on the weighbridge without vibration excited by the shaker to the body of the miniature instrumented vehicle. The velocity of the vehicle was about 1.1 m/s.

The length of the effective part of the weight signal is almost the same as those of the actual weight signals which would be otained when an actual vehicles pass on the actual weighbridge with the velocity of about 18 km/h. We can find the vibration components in it which are natural vibration of the weighbridge.

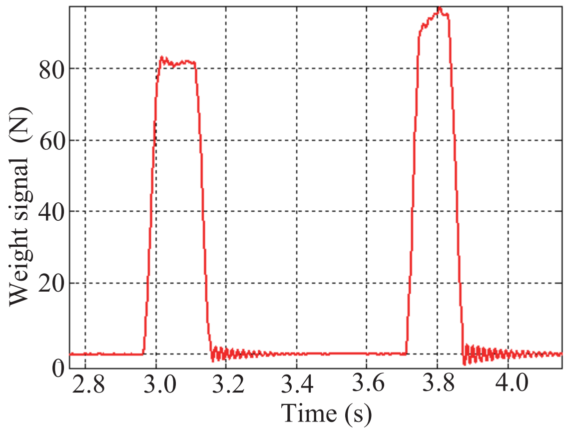

Fig. 8. A weight signal without excitation by the shaker.

Fig. 9 shows the result of applying the advanced method to the weight signal of Fig.8. In the figure, the intervals of the weight signal segmented by a pair of vertical red lines are the effective part. The blue solid lines denote the sine waves whose frequencies and phases are estimated by the advanced method. The red level line segments denote the estimated axle weights by the advanced method. The blue dotted lines denote static axle weights. The black solid line segments denote mean values of the weight signal within the effective parts; determing the axle weight by taking mean value is one of the conventional methods. The estimated weights, the mean values, and the static axle weights for both axles are tablated in Table 1. The relative errors of the estimated axle weights and mean values are also shown in the table.

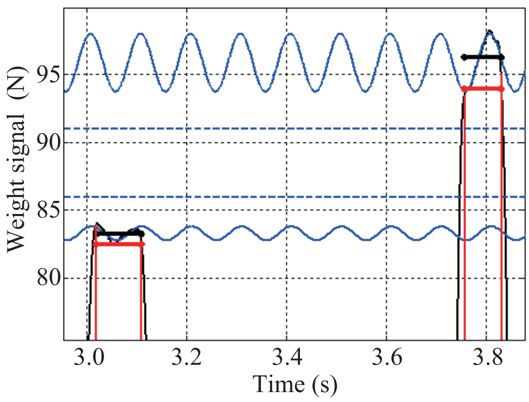

Fig. 9. The result of application of the advanced method to the weight signal.

Table 1. Estimation result for the weight signal of Fig. 8

	Front axle	Rear axle
Estimated value	82.91 [N]	94.19 [N]
Mean value	83.25 [N]	96.16 [N]
Static axle weight	85.67 [N]	90.82 [N]
Error of estimated value	-3.2 %	3.7 %
Error of mean value	-2.8 %	5.9 %

The errors are calcurated by the following equation

$$\text{Error} = \frac{(\text{Estmated or Mean value}) - (\text{Static axle weight})}{(\text{Static axle weight})} \times 100\% \qquad (11)$$

The frequency of the sine wave included in the effective part was estimated as 10.0 Hz by the advanced method.

The errors of the estimation values by the advanced method are -3.2 % for front axle, 3.7 % for rear axle while those of the mean values are -2.8 % for front axle, 5.9 % for rear axle. The weight signal in this case includes weak vibration component, hence the relative errors result to be not so different between the methods.

5.2. Weight signal WITH vibration excited by the shaker

Fig. 10 shows a sample of weight signals when the miniature instrumented vehicle passes on the weighbridge with excitation by the shaker to the body of the miniature instrumented vehicle. The velocity of the vehicle was about 1.1 m/s. We can find that the vibration component was added on the both effective parts of the weight signal by the shaker. The frequency of the vibration exited by the shaker was about 7.3 Hz, however the advanced method estimated it as 10.9 Hz. Fig. 11 shows the re-

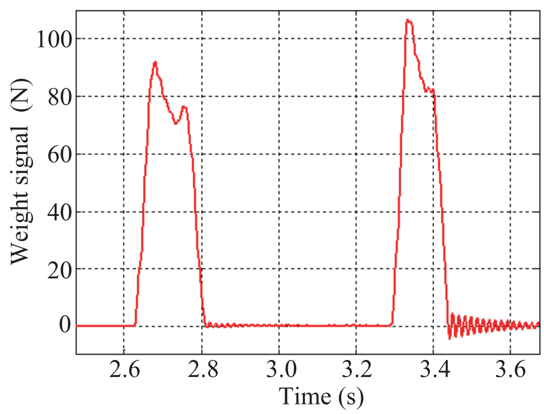

Fig. 10.A weight signal with excitation by the shake.

sult of applying the advanced method to the weight signal. The estimated weights, the mean values, and the static axle weights for both axles are tablated in Table 2. The relative errors of the estimated axle weights and mean values are also shown in the table.

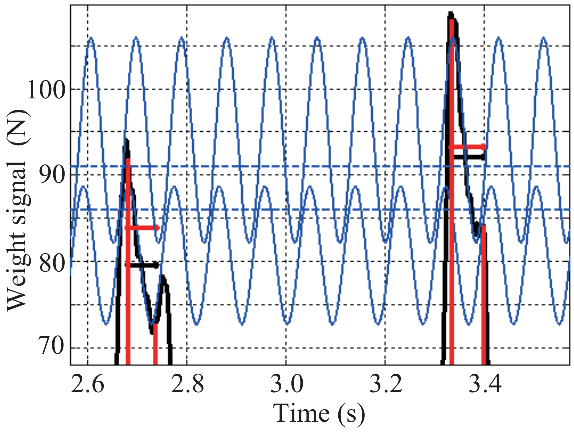

Fig. 11. The result of application of the advanced method to the weight signal.

Table 2. Estimation result for the weight signal of Fig. 10

	Front axle	Rear axle
Estimated value	84.03 [N]	92.20 [N]
Mean value	79.63 [N]	92.11 [N]
Static axle weight	85.67 [N]	90.82 [N]
Error of estimated value	-1.9 %	2.6 %
Error of mean value	-7.1 %	1.4 %

While the error of the estimated value for rear axle is more than that of the mean value, the error of the estimated value for front axle is less than that of the mean value. The result seems to show that the accuracy of the mean value, which is obtained just by taking average of the weight signal within effective part, depends on the part of sine wave that is cut off by the effective part.

We can see from the Figs. 9,10 that the advanced method can estimate the vibration component adequately. We have estimated axle weights from other weight signals and obtained errors relative to the static axle weight. Then, all the errors turned to be within ± 4.0 % . The examination of the accuracy of the estimated axle weights is next research topic which must be completed with nemerous experimental data.

6. CONCLUSIONS

We have developed a miniature instrumented vehicle and a miniature axle weighing system to examine and improve the accuracy of the obtained axle weights by the advanced method. Through the experiments using these miniature models, we have obtained motion data of vehicle body and weight signals when the miniature instrumented vehicle passes on the weighbridge in various situations. We have applied the estimation method to the obtained weight signals. Then, we can see that the advanced method can estimate the vibration component adequately and the obtained errors relative to the static axle weight are all within ± 4.0 % . The examination of the accuracy of the estimated axle weights is next research topic which must be completed with nemerous experimental data.

The another research topic is the improvement of the estimation method by analyzing the relationship between the motion data of the miniature instrumented vehicle and the weight signals obtained simultaneously when the instrumented vehicle passes on the weighbridge in various situations.

ACKNOWLEDGMENTS

The authors would like to thank the late Professor Emeritus Toshiro Ono of Osaka Prefecture University for his suggestions.

REFERENCES

[1] Hanshin Expressway Management Technology Center, "Report on Investigation and Research on Improving the Measurement Accuracy of Axle Weighing System", *Hanshin Expressway Public Corporation*, 1985.

[2] T. Ono, K. Fukuda, K. Yoshida, H. Uozumi, and H. Tottori, "Mass-estimation methods for in-motion vehicles using axle weighing system", *Proc. IMEKO-XV*, pp.51–58, 1999.

[3] K. Fukuda, H. Tottori, K. Kameoka, T. Ono, and K. Yoshida, "Axle Weighing of In-motion Vehicles", *Transactions of the Society of Instrument and Control Engineers* , Vol. 38, pp.653–659, 2002. (In Japanese)

[4] Oyo Measurement Co., Ltd. , "Report on Experiments for Improving Axle Weighing System for Application to In-motion Vehicles with High Velocity", *Hanshin Expressway Public Corporation*, 2005.

[5] Hanshin Expressway Management Technology Center, "Report by a Committee for Investigation and Research on Improving the Measurement Accuracy of Dynamic Loads", *Hanshin Expressway Public Corporation*,1997.

[6] K. Fukuda, K. Yoshida, T. Kinugasa, S. Fujimoto, K. Kanazawa, T. Ono, "Axle Weighing of In-motion Vehicles with High Velocity Using Higher Order FIR Filters", *CD Proc. Asia-Pacific Symposium on Mass, Force and Torque*, pp. 200-209, 2009.

[7] T. Sato, K. Fukuda, T. Kinugasa, S. Fujimoto, K. Yoshida, "Experimental Study for the Improvement of Accuracy of the Estimated Axle Weights of In-Motion Vehicles - Development and Experiments of Miniature Models", *CD Proc. SICE Annual Conference 2013*, MoBT14.12, 2013.