Proceedings of the 17th International Conference on Force, Mass, Torque and Pressure Measurements,
IMEKO TC3, 17-21 Sept. 2001, Istanbul, Turkey

Evaluations of a New Mass-estimation Method for Axle Weights of In-motion Vehicles Using Vehicle Models

Kengo Fukuda*, Koichi Kameoka**, Toshiro Ono***, Koji Yoshida****

** Oyo Measurement Co., Ltd.*

10-14, Hiroshiba-cho, Suita, Osaka 564-0052, Japan

*** Department of Mechanical & Intelligent Engineering, Himeji Institute of Technology*

2167 Shosha, Himeji 671-2201, Japan

**** Department of Assistive and Rehabilitation Engineering, Okayama University of Science*

1-1, Ridai-cho, Okayama, Okayama 700-0005, Japan

*****Department of System Engineering, Okayama Prefectural University*

111, Kuboki, Soja, Okayama 719-1197, Japan

Abstract

An axle weighing system is a system that measures each axle weight of in-motion vehicles while they pass though on the weighbridge. In the weighing, signal processing technique is the key to achieve the precise measurement since the output signal from the weighbridge is contaminated with the noise due to the vibration of the vehicle in motion. In our previous paper, we proposed a new signal processing method using normal equations to estimate the vibration parameters. In the present paper, we examined the relation between the velocities of in-motion vehicles and the estimated values obtained with the new method, through a consideration on the computer simulation with the output signal generated by using the linear models of vehicles. As a result, it was clarified that precise estimation is possible when the velocity of a vehicle is approximately less than 15 km/h.

1. Introduction

The number of over-loaded vehicles has been increasing recently, causing serious problems such as damage to roadways, public nuisance due to the noise and vibration, and so on. Axle weighing systems, installed in front of tollgates, have been used to pick up vehicles suspected of committing the over-load regulations and give them warnings. The axle weighing system meeting the demand of more strict regulation of the over-load vehicles will be inevitable.

Figure 1 shows the weighbridge of the axle weighing system, load-receiving element with force sensors, installed in a road, the upper surface level of which is adjusted to that of the road. The passing distance of a vehicle on the weighbridge is nearly equal to the diameter of the tire in general.

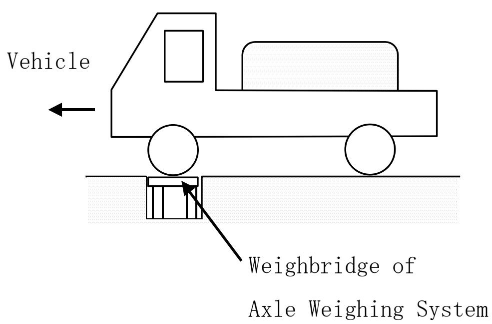

Figure 1. Weighbridge of an axle weighing system

A conventional signal processing method to

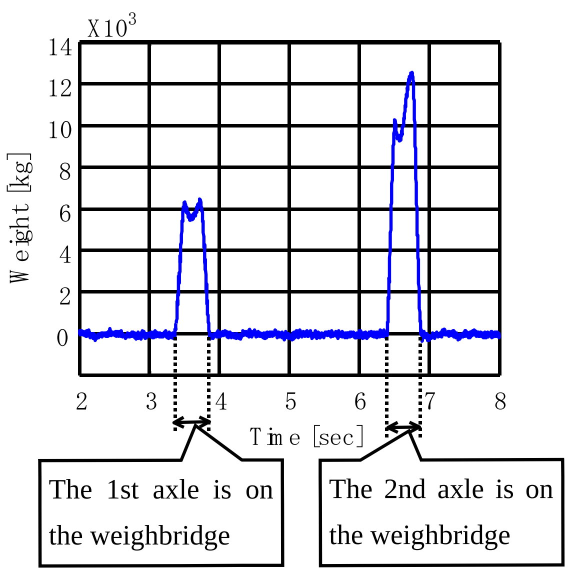

Figure 2. Time behavior of the actual signal from a weighbridge

determine each axle weight is to take the mean value of the output signal from the weighbridge when the whole contacting surface of each tire is on the weighbridge. This method, referred to as the mean method, is appropriate for the steady-state signal. However, the steady-state signal cannot be obtained at the vehicle velocity of greater than 10 km/h, as shown in Fig. 2, resulting in low precision of the measured axle weight. If the axle weights of in-motion vehicles can be estimated from the segments of a steady-state signal and the estimated weights are sufficiently accurate, the axle weighing systems will be used to check all the vehicles in real time.

In our previous paper, we proposed a signal processing algorithm, referred to as the novel method, to improve the precision affected by the length of available signals and showed the effect of improving the precision, applying the method to the actual signals that were recorded in the field. However, it was impossible to confirm the basic characteristics of the method clearly because the signals used from actual systems contained many unknown factors.

Since the traffic restriction around the tollgate is not desirable on a heavy traffic expressway, we had no time to inspect the weighing system in detail and were obliged to be hurried to collect data in small area. In this situation, we have to emphasize that the accuracy depending on the mechanical mechanism is unknown. Though static accuracy is described in the specifications of an axle weighing system, dynamic accuracy is not clearly shown. The inaccuracy in the mechanism affects the estimated value. Furthermore, we cannot avoid an anxiety that uncertainty in signals might cause a bad influence on the estimation results. What we concern here is not the accuracy of the hardware, but the characteristics of the new signal processing algorithm itself.

To examine the characteristics of the new method, simulations have been done with the simulated signals cut out from the responses of the linear model of vehicle. The signal provides us with the information such as their axle weights, their natural frequencies, and so on, which enable us to do the simulation without inaccuracy due to the mechanism.

In this paper, we first give a brief explanation of three types of vehicle model used for the simulation and then review the new method, which is a new version of the novel method. The new method is so modified as to estimate accurately the lower frequency in a short-time signal. The simulation results are shown in Section 4, with a discussion on the limit of the velocity of a vehicle.

2. Vehicle Model

2.1. 2-Axle model

As shown in Fig. 3, the 2-axle model has the simplest structure, which is indispensable to investigate the characteristics of the new method in detail.

2.2. 3-Axle Model

The 3-axle model, derived automatically from the 2-axle model, is shown in Fig. 4. It is reported that this type of vehicles frequently commits the over-load regulations, probably because of their robust structure. An example of

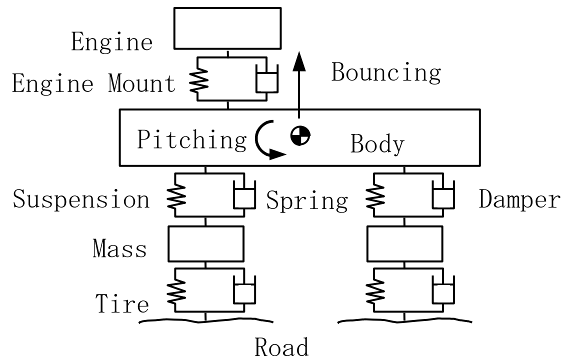

Figure 3. 2-axle model of a vehicle

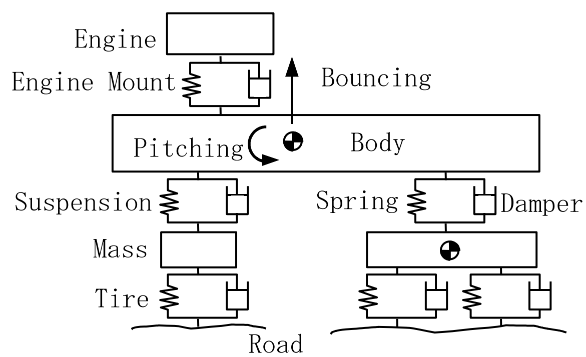

Figure 4. 3-axle model of a vehicle

an actual signal is shown in Fig. 5 and a simulated one in Fig. 6 of the next page.

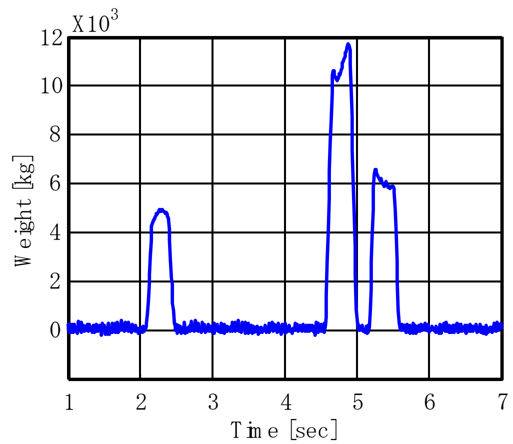

Figure 5. Example of an actual signal in 3-axle cases

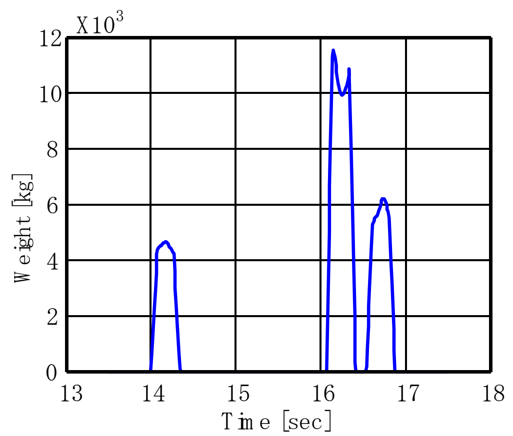

Figure 6. Example of the simulated signal generated by using the 3-axle model

2.3. 5-Axle Model

It is not appropriate to treat the load-carrying platform of a trailer body as a complete rigid body, for the effect of the flexibility of the body can be seen in the actual signal.

To consider the flexibility in a model of a tractor-trailer, we divide the trailer body into two parts that are connected by the spring and damper elements, which are supported by springs and dampers with torsional springs and dampers, as shown in Fig. 7.

The model can be regarded as a tractor-trailer. The structure of a tractor-trailer is so complex that a FEM model is not adequate to treat the tractor-trailer.

2.4. Equations

The vehicle models introduced in this study consist of rigid bodies, springs, and viscous dampers. Then the equations of motion and observation become finite dimensional, linear, and time-invariant ones as follows:

$$\frac{dx}{dt} = Ax + Bu\,, \qquad (1)$$

$$y = Cx + Du\,, \qquad (2)$$

where

$$u^T = \begin{bmatrix} r(t) & r'(t) & \cdots & r(t-\tau_m) & r'(t-\tau_m) & g \end{bmatrix}, \qquad (3)$$

$$y^T = \begin{bmatrix} f_1(t) & \cdots & f_m(t) \end{bmatrix}, \qquad (4)$$

in which

t : time,

$r'(t)$: differential coefficient of $r(t)$,

g : acceleration of gravity,

$f_m(t)$: force generated in the m-th tire,

$m = 1,2$ for 2-axle model,

$m = 1,2,3$ for 3-axle model,

$m = 1,2,3,4,5$ for 5-axle model.

The values of the model parameters are chosen so that the simulated signal is fitted to the signal from the actual weighbridge.

τ_m : time rag due to the distance between the 1st and m-th axles,

$m = 2$ for 2-axle model,

$m = 2,3$ for 3-axle model,

$m = 2,3,4,5$ for 5-axle model,

$r(t)$: vertical displacement of the surface of road,

3. New Method

3.1. Mathematical Estimation Model

Figure 8 shows the typical response signals in an axle weighing system and tire forces, in which $w_1(t)$ and $w_2(t)$ are the parts of the signal from the weighbridge, corresponding to the tire forces while the vehicle is on the weighbridge. The problem is how to estimate the axle static forces W_1 and W_2 using $w_1(t)$ and $w_2(t)$.

Mathematical Estimation Model [1]

Time behaviour of the i-th tire force $f_i(t)$ of an in-motion vehicle with K axles can be approximately described as

$$f_i(t) = W_i + \sum_{r=1}^{p} A_{ir} \sin(\omega_r + \phi_r), \qquad (5)$$

$$i = 1,2,3,\cdots,K,$$

where

W_i : static force on the i-th axle,

A_{ir} : amplitude of the r-th sinusoidal wave on the i-th axle,

ω_r : angular frequency of the r-th sinusoidal wave, ϕ_r : phase of the r-th sinusoidal wave.

Note that viscous damping is neglected in Eq. (5).

The purpose of the new method is to obtain the equivalent mass M_i on the i-th axle, which is defined as

$$M_i = W_i / g. \qquad (6)$$

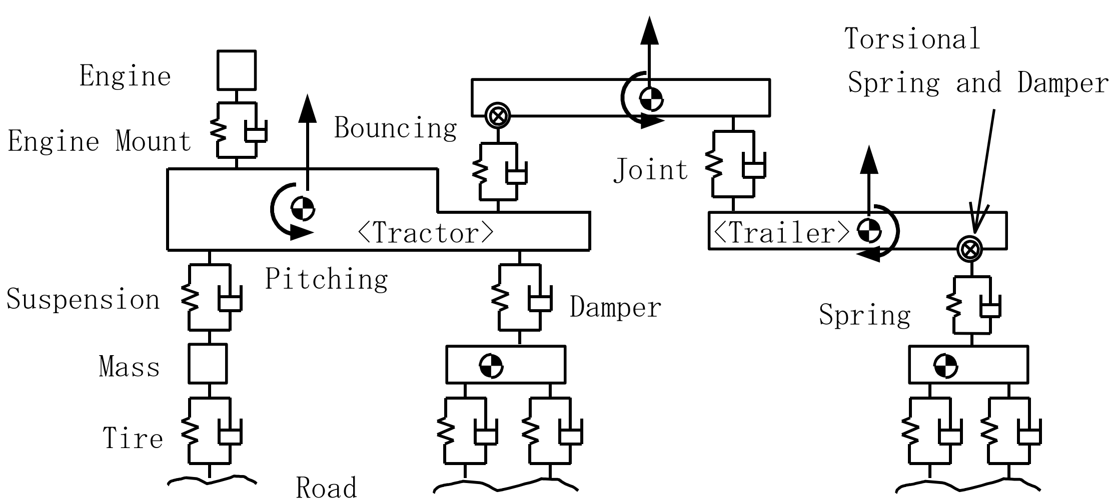

Figure 7. 5-axle model of a tractor-trailer

A signal for one axle is shown in Fig. 9. The signal available for axle weight estimation is the signal for the interval $[t_i^s, t_i^e]$ when the whole contacting surface of a tire is on the weighbridge.

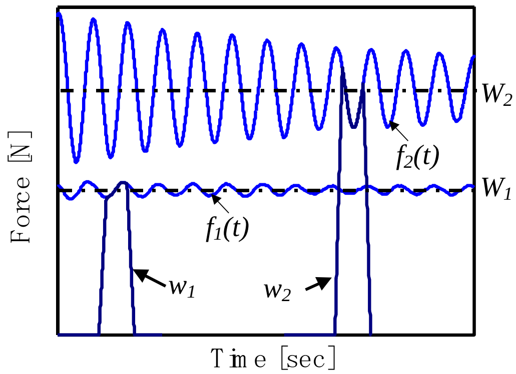

Figure 8. Typical response signals in an axle weighing system and tire forces

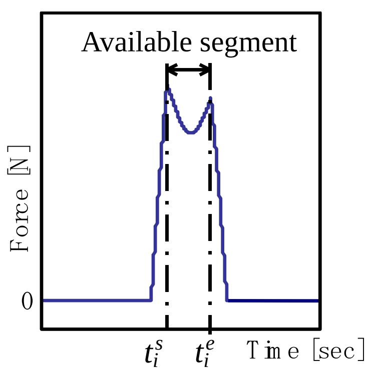

Figure 9. Signal from the weighbridge for one axle

We refer to this part as the available segment or the segment. Since the interval of the segment decreases in inverse proportion to the velocity of a vehicle, it is very difficult to estimate the axle weight when the vehicle passes through on the weighbridge at a comparatively high velocity.

3.2. Frequency Estimation

Let $f_i(n)$ be the sequence of the discrete data of the available segment for the i-th axle, $f_i(0)$ the value of the signal at time t_i^s and $f_i(N_i)$ the value at time t_i^e, where $n = 0,1,2,\cdots,N_i$. The difference of $f_i(n)$ can be written in the form:

$$f_i^d(n) = f_i(n+1) - f_i(n) . \tag{7}$$

Applying an AR (Auto-Regressive) model to the sequence $f_i^d(n)$, we obtain following expression.

$$f_i^d(n) + a_1 f_i^d(n-1) + a_2 f_i^d(n-2) + \cdots + a_q f_i^d(n-2) = \varepsilon_n , \tag{8}$$

where a_j ($j = 1,2,\cdots,q$) are constants, q the order of the AR model, and ε_n uncertainty. Assuming ε_n to be "White Noise", we estimate a_j by the least squares method using $f_i^d(n)$ for all i, i.e., all the segments for a vehicle. Thereby we obtain the q-th order linear difference equations with constant coefficients as follows:

$$f_i^d(n) + \bar{a}_1 f_i^d(n-1) + \bar{a}_2 f_i^d(n-2) + \cdots + \bar{a}_q f_i^d(n-2) = 0, \tag{9}$$

where $\bar{a}_j$ ($j = 1,2,\cdots,q$) are the estimated constants of a_j.

The solutions of Eq. (9) depend on the roots of the characteristic equation

$$z^q + \bar{a}_1 z^{q-1} + \bar{a}_2 z^{q-2} + \cdots + \bar{a}_q = 0 . \tag{10}$$

Let $\angle z_r$ ($\in [0, \pi]$) denote the angle in z-plane of root z_r. Then,

$$\omega_r = \angle z_r / T_s \ , r = 1,2,\cdots, p(\le q) \qquad (11)$$

are the angular frequencies included in the available segment. Here T_s denotes the sampling period.

Choosing the coefficients of the AR model symmetrically such as

$$a_i = a_{q-i} \ (a_0 = 1 \ , i = 0,1,2,\cdots, q/2 \ ; \ q : \text{even}), \qquad (12)$$

the frequency estimation for the lower frequencies can be improved.

$$\bar{f}_i(n) = \sum_{r=1}^{p} \{ \alpha_{ir} \sin(\omega_r n T_s) + \beta_{ir} \cos(\omega_r n T_s) \} + C_i, \qquad (13)$$

$$\alpha_{ir}, \beta_{ir}, C_i \ \text{for} \ \mathit{Minimize}\{ \bar{f}_i(n) - f_i(n) \}^2 . \qquad (14)$$

3.3. Axle Weight Estimation

The waveform of $\bar{f}_i(n)$, superimpose of sinusoidal waves with frequency ω_r, is fitted to the segment for the i -th axle:

Generally, the lower natural frequency in the neighbourhood of 3 Hz exists in the segment.

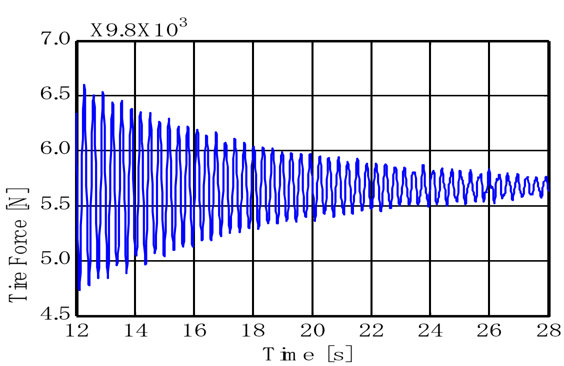

Figure 10. Third tire force of a 3-axle model

The higher natural frequencies beyond 10 Hz, mainly depending on the suspension mechanism, does not almost appear in the signal. In Eq. (13), ω_r are restricted within the domain between 2 Hz and 15 Hz. Therefore $\bar{f}_i(n)$ consisting of sinusoidal waves with low frequencies is a sort of smoothed data of $f_i(n)$. In Eq. (13) C_i can be regarded of the estimated axle weight.

4. Axle Weight Estimation Results

4.1. Simulated Signal

Following is the estimation results obtained by processing the simulated signal of the tire force. The vehicle model is excited by the weight and the forced displacement due to the unevenness of road. The resulting frequencies involved in the signal are sinusoidal waves between 1 Hz to 30 Hz. In the model, the coefficients of damping factor are assumed to be negligible values.

This vibratory signal is considered the approximation of the mathematical estimation model defined as Eq. (5) in Section 3. The available segments are the signals cut out from the vibratory signal.

The vibratory components of the signal can be corresponded to the effect due to natural frequencies of the vehicle. As time passes, the effect of the unevenness of road becomes evident as shown in Fig. 10.

4.2. Estimation Results

The conditions for the simulation are tabulated in Table 1. The simulated signal is a discrete signal sampled with a sampling period of 1 ms.

Table 1. Conditions for the simulation

Model Type	Weight (kg)	Dominant Natural Frequencies* (Hz)	Velocity (km/h)
2-axle	16,680	2.93, 8.30, 9.28	10,15,20
3-axle	20,960	2.93, 8.30, 9.77, 11.72	
5-axle	42,210	2.44, 5.86, 11.72, 15.63	

* Frequencies are calculated from the tire forces by using 4098 point FFT.

The dimensions of the tire and platform are shown in Fig.11. It is assumed that the transfer function of the weighing system from the tire force (input) to the signal (output) is unity.

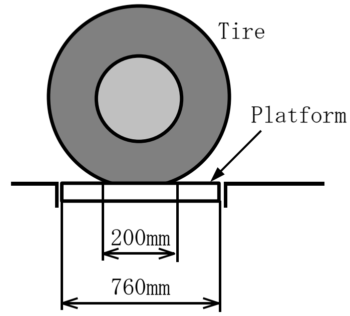

Figure 11. Dimensions of the tire and platform

The order q of the AR model (8) is the round number of $0.5N$, where N is the number of sampled data in the segment for the first axle.

The errors of the estimated gross weights of a vehicle, the sum of axle weights, are shown in Table 2 (a). The error is defined as follows:

error =estimated weight –true weight, (15)

in which the true weight is known.

Table 2. Errors of the estimated gross weight of the vehicle

(a) New method

Error (kg)	2-axle model (16,680kg)			3-axle model (20,960kg)			5-axle model (42,210kg)		
	10 km/h	15 km/h	20 km/h	10 km/h	15 km/h	20 km/h	10 km/h	15 km/h	20 km/h
Average	3.9	6.3	-0.7	0.7	2.9	0.5	2.5	-0.8	-5.5
Range	239.5	275.9	657.0	93.0	750.3	711.3	201.1	491.4	640.2
Maximum	163.2	170.6	444.7	37.6	326.3	339.3	102.2	243.1	239.4
Minimum	-76.3	-105.3	-212.3	-55.4	-424.0	-372.0	-98.9	-248.3	-400.8
S.D.	29.3	45.6	77.1	14.4	106.9	121.7	43.3	91.5	99.3
N.D.	140	140	140	140	140	140	110	110	110

(b) Mean method

Error (kg)	2-axle model (16,680kg)			3-axle model (20,960kg)			5-axle model (42,210kg)		
	10 km/h	15 km/h	20 km/h	10 km/h	15 km/h	20 km/h	10 km/h	15 km/h	20 km/h
Average	-4.5	8.5	-5.1	0.0	5.0	-4.3	-13.3	-13.4	-9.8
Range	2716.8	4472.5	6120.6	520.5	3111.9	3306.0	6023.5	8268.2	4168.6
Maximum	1302.9	2332.5	2922.0	252.3	1657.5	1542.2	3021.5	4148.9	2050.0
Minimum	-1413.9	-2140.0	-3198.6	-268.2	-1454.5	-1763.9	-3002.0	-4119.3	-2118.6
S.D.	502.1	820.2	1116.5	97.5	611.5	632.2	1375.1	1895.0	935.9
N.D.	140	140	140	140	140	140	110	110	110

- Average:average of the estimation errors [kg]
- Range:range of the estimation errors [kg]
- Maximum:maximum value of the range [kg]
- Minimum:minimum value of the range [kg]
- S.D.:standard deviation of the estimation errors [kg]
- N.D.:number of the data used

For comparison with the new method, the results obtained by the mean method, method of taking the average of the available segment, are shown in Table 2 (b).

4.3. Discussions

Although the error increases in proportion to the velocity of vehicle, it is clear that the results by the new method is more accurate than those by the mean method.

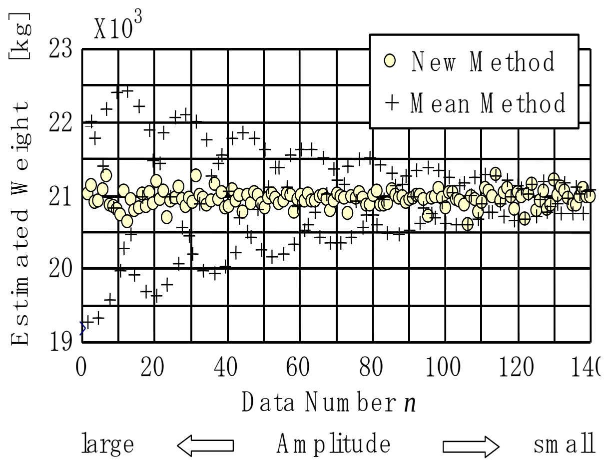

Figure 13. Relation between the estimated vehicle weight and data number in case of the 3-axle model at 20 km/h

We should examine the effect of the amplitude of the signal to the estimated vehicle weight. The amplitude of the signal decreases as time passes because cutting out makes the signal from the damped free vibration in Fig. 10. Since the data number n is one assigned to the signal used for each execution of estimation, as shown in Fig. 12, the order of the data number is chosen according to the decreasing amplitude. We show the relation between the estimated vehicle weights and the data number in Fig 13. It is confirmed that the accurate weight can be obtained with the new method regardless of the amplitude of the response.

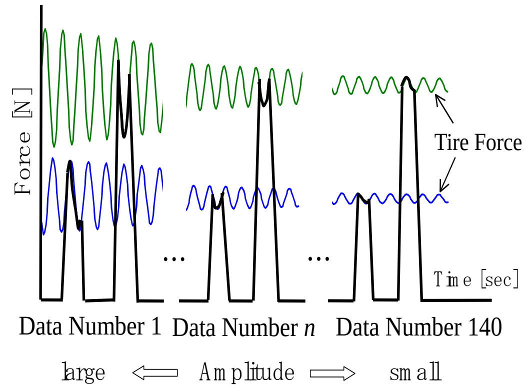

Figure 12. Tire force and the data number

The estimated frequencies are shown in Fig. 14 in case of the 3-axle model for three different velocities: 15 km/h, 20 km/h, and 25 km/h. The frequency to be noticed here is 2.93 Hz, which is the dominant component of the tire force. The data greater than 6 Hz are plotted together on the upper line.

Since it is obvious that the result of frequency estimation directly affects the precision of an estimated axle weight, a glance at Fig. 14 will reveal that the upper limit of vehicle models' velocity is approximately 15 km/h.

As to a velocity of 20 km/h, the frequency estimation fails to estimate the lower frequency of the true value 2.93 Hz for n > 100, in which the amplitude is comparatively small. This is because of the unevenness of road. Even for the condition of v = 20 km/h and $n > 100$, the precision of the estimated gross weight by the new method is almost equal to that by the mean method, both of which are in high precision as is evident from Fig. 13. Thus, the limit of the velocity is extended to 20 km/h in practical application.

5. Conclusions

To sum up the major points of our work are as follows:

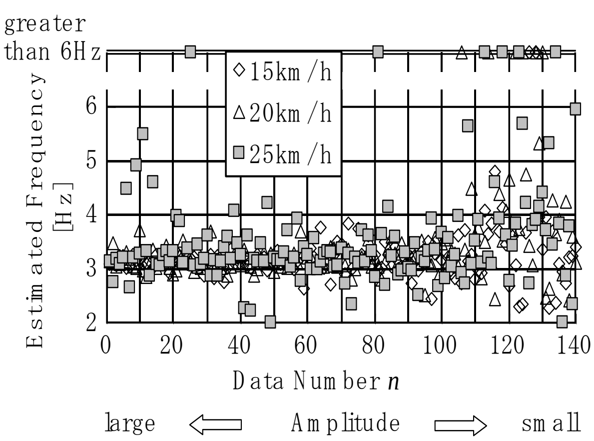

Figure 14. Estimated frequencies in segments for 2.93 Hz, which is the dominant component

I. The evaluation method is established for the new mass estimation method, introducing the linear models of in- motion vehicles.

II. The lower frequency in the neighbourhood of 3 Hz can be detected for the signal component with large amplitude, even though the length of the segment for an axle is about 0.1 s.

III. If the lower frequency wave is not evident in the segment, it cannot be detected correctly. In this case, the new method could substitute for the conventional method taking the average of the segment.

6. References

[1]. Ono T., Fukuda K., Yoshida K., and Tottori H., *A Mass-Estimation Method with Linear Regression Models for In-motion Vehicles Using Axle Weighing System*, Proc. of IMEKO TC3/APMF '98, Sep.14-18, 1998, pp.321-328.

[2]. Ono T., Fukuda K., Yoshida K., Uozumi H., and Tottori H., *Mass-Estimation Methods for In-motion Vehicles Using Axle Weighing System*, Proc. of IMEKO-XV, Jun.13-18, 1999, Vol. III pp.51-58.

Acknowledgements

The authors would like to express their appreciation to Mr. H. Tottori of Hansin Expressway Public Corporation for his constructive advice and support. They shall thank Mr. H. Uozumi and Mr. H. Miyamoto for their great contribution to making vehicle models. Mr. S. Sakamoto of Oyo measurement Co., Ltd. should be appreciated for his support and permitting one of the authors, K. Fukuda, to engage in this study.

Contact Person for Paper:

Kengo Fukuda

Address: Oyo Measurement Co., Ltd., 10-14, Hiroshiba-cho, Suita, Osaka 564-0052, Japan

Tel: +81 6 6380 0121

Fax: +81 6 6330 6562

E-mail: fukuda.k@oyomm.co.jp