AN ADVANCED ALGORITHM FOR ESTIMATING AXLE WEIGHTS OF IN-MOTION VEHICLES

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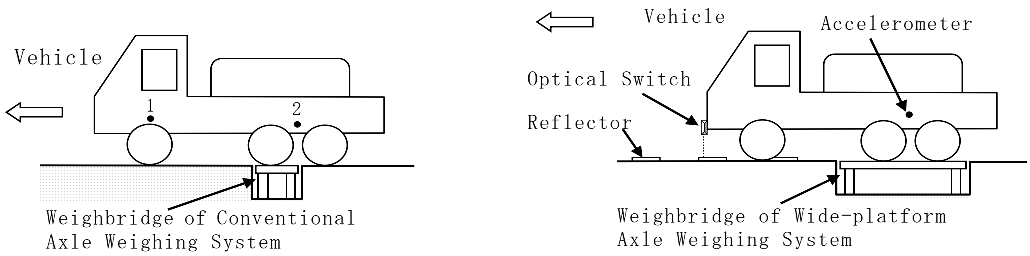
ABSTRACT

A signal processing method to improve the accuracy of measured axle weights of an in-motion vehicle is proposed and is evaluated by applying it to the actual weight signals from a new axle weighing system with a platform having a length of about 2.2m, approximately three times longer than that of a conventional one. In spite of several undesirable experimental conditions, the accuracy improvement was confirmed within the range of vehicle velocity, 5 ~ 40km/h.

1. INTRODUCTION



(I) Conventional axle weighing system (II) New axle weighing system

Figure 1: Conventional and new axle weighing systems

An axle weighing system, installed in front of a tollgate, has been used to pick up vehicles suspected of committing the over-load regulations and to give them warnings. The platform of an axle weighing system has a length of about 75cm, nearly equal to the diameter of a tire, to avoid measuring two axle weights at the same time (Fig. 1 (I)). Since the weight signal from its weight sensor is affected by a low frequency component of the natural frequencies of a vehicle and the data length effective used for the measurement is extremely short, we cannot obtain a precise axle weight with the conventional algorithm of averaging the data. We have studied a signal-processing algorithm based on the assumption that the vehicle vibration is described by the superposition of sine waves [1-4]. In the present paper, we first give a brief explanation of the improved algorithm and then confirm the feasibility of the algorithm against the actual weight signals from a new axle weighing system with a platform of about 2.2m in length, approximately three times longer than that of a conventional one (Fig. 1 (II)).

2. WEIGHT SIGNAL FROM A CONVENTIONAL WEIGHBRIDGE

The solid line in Fig. 2 illustrates a sketch of time behavior of a weight signal $F(t)$ when a 3-axle vehicle passed on its platform [1,2,4]. The tire force $F_i(t)$ acting on the i-th axle tires partly appears in $F(t)$ is the force. The portion of $F(t)$ over the time interval $[t_i^s,\ t_i^e]$, when the whole contacting surface of the i-th axle tires is on the weighbridge, is referred to as the effective segment $f_i(t)$ and the time interval is referred to as the effective interval. Hence, the relation between $f_i(t)$ and $F_i(t)$ is written by $f_i(t) = F_i(t)$, $t_i^s \le t \le t_i^e$.

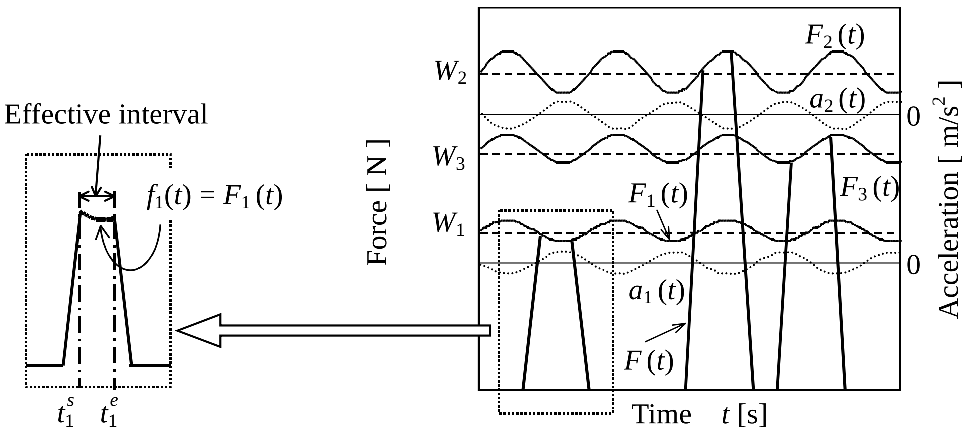


Figure 2: Typical weight signal $F(t)$ and the forces $F_i(t)$

It can be observed that the phases of force $F_i(t)$ and the acceleration $a_i(t)$ at the location of an upper suspension 1 or 2 in Fig. 1 are of inverse each other in the effective intervals [1]. The phenomenon appears in the case of a weighbridge embedded in a road having smooth surface, which means that the acceleration of the vehicle body directly affects the effective segment and the dynamics of the weighbridge can be ignored.

If $F_1(t) - W_1 \propto -a_1(t)$ and $F_2(t) - W_2, F_3(t) - W_3 \propto -a_2(t)$ being composed of sine waves, then each effective segment $f_i(t)$ can be easily formulated to be the superposition of common sine waves and a constant. The mathematical expression in the discrete-time domain of the effective segment $f_i(kT)$ for a vehicle with K axles can be approximately described by

$$f_i(kT) = W_i + A_{i0} \sin(\omega_0 kT + \phi_{i0}) + \sum_{j=1} A_{ij} \sin(\omega_j kT + \phi_j),$$
$$i = 1, 2, \cdots, K, \quad k = k_i, k_i + 1, \cdots, k_i + P_i - 1, \tag{1}$$

where T denotes a sampling time and ω_0 the fundamental frequency of the common dynamic component due to the vibration of a vehicle body. Note that $f_i(k_i T)$ is the value at the beginning time of the effective interval and $f_i((k_i + P_i - 1)T)$ is the value at the end. The method to estimate the static component W_i in Eq. (1) is explained in the next section.

3. ADVANCED METHOD

We derive an estimation algorithm for axle weighing through considering an identification problem in the following difference equation:

$$f_i(k+N) + b_1 f_i(k+N-1) + \cdots + b_{N/2} f_i(k+N/2) + \cdots + b_1 f_i(k+1) + f_i(k) = C_i, \tag{2}$$

where N is even number and the coefficients b_n is arranged symmetrically with respect to $b_{N/2}$, which represents a common dynamic component among all effective segments. Note that the sampling period T is taken here to be unity without loss of generality. The symmetrical arrangement of coefficients is one of the main points of this method [4]. Estimating the coefficients in Eq. (2) using the least square method, the residue $e_i(k)$ can be written by

$$e_i(k)+\hat{C}_i = f_i(k+N)+\hat{b}_1 f_i(k+N-1)+\cdots+\hat{b}_{N/2} f_i(k+N/2)+\cdots+\hat{b}_1 f_i(k+1)+f_i(k), \qquad (3)$$

where $\hat{C}_i$ and $\hat{b}_n$ denote estimated values.

When $f_i(k)$ and $e_i(k)+\hat{C}_i$ are considered to be an input and an output, respectively, Eq. (3) may be regarded as the input and output expression of a linear-phase FIR filter. If order N of Eq. (3) is approximately selected, then the zeros of the filter are allocated on the unit circle of the z plane. This means that the general solution $f_i(k_i)$ satisfying Eq. (3) can be expressed by the superposition of sine waves and a constant. Hence, Eq. (3) is considered as another expression of the mathematical expression of the effective segment (1). For the above reason, if $e(k_i)\cong 0$, then the zeros corresponding to sine waves attenuate the input $f_i(k_i)$. Accordingly, the estimated value of the static force W_i is obtained as follows:

$$\hat{W}_i=\hat{M}_i g=\frac{1}{P_i-N}\sum_{k_i=0}^{P_i-N-1}\hat{W}_i(k_i)=\hat{C}_i/\{2(1+\sum_{j=1}^{N/2-1}\hat{b}_j)+\hat{b}_{N/2}\}, \qquad (4)$$

where g is the acceleration of gravity and $\hat{M}_i$ the equivalent mass corresponding to $\hat{W}_i$ [4].

The order N is determined based on the number of dominant spectrum peaks in each effective segment. Although the determination of N depends on experiences, it may be a practical method without any iterative calculations. To estimate axle weights with the application software using the above algorithm is referred to as the advanced method.

4. FIELD TEST WITH THE NEW WEIGHBRIDGE AND A 3-AXLE VEHICLE

The platform of a conventional axle weighing system has a length of about 750mm in the vehicle traveling direction. On the other hand, the longer-platform axle weighing system has a platform whose length is 2250mm, approximately three times longer than that of the conventional weighing system. It means that the measurement time of the longer-platform is three times longer than that in the conventional one. This system permits 2-axle lording at the same time, but the effective segment for each axle can be extracted by a sophisticated idea.

A cab-over-engine truck with 3 axes was selected as the test vehicle. The loaded weight is 8t (80% of carrying capacity) to ensure the acceleration ability of the test vehicle. An optical switch is attached at the front of the test vehicle and reflectors (white plastic plates) are installed on the approach surface as shown in Fig. 1 (II). The velocity of the vehicle is calculated using the interval of output pulse from the switch and the distance of the reflectors

5. ACTUAL WEIGHT SIGNAL FROM THE LONGER-PLATFORM EIGHBRIDGE

The longer-platform axle weighing system permits two axles on the platform at the same time. In this case, $f_{23}(kT)$, $kT\in[t_2^e,\ t_3^s]$ denotes the effective segment when the whole contacting surfaces of the second and the third axle tires.

Figure 3 shows an example of the actual signal at the velocity of about 30km/h. The dynamic component of $f_{23}(kT)$ is obviously deferent from that of $f_2(kT)$ which is affected by the vibration due to the suspension mechanism. Moreover, the vibratory component of forced vibration is also observed in $f_3(kT)$. The reason for this response may be sought in bumpy surface around the weighbridge. The affection due to the unevenness of the surface cannot be ignored at the velocity over 30km/h. Hence, we determined to exclude $f_2(kT)$, $f_3(kT)$ and to apply the advanced method to $f_1(kT)$ and $f_{23}(kT)$. In this case, $f_{23}(kT)$ mainly affects the measurement values, because the dynamic component of $f_1(kT)$ is very small. We have eventually been obliged to discard the advantage of much longer effective intervals brought by the longer-platform.

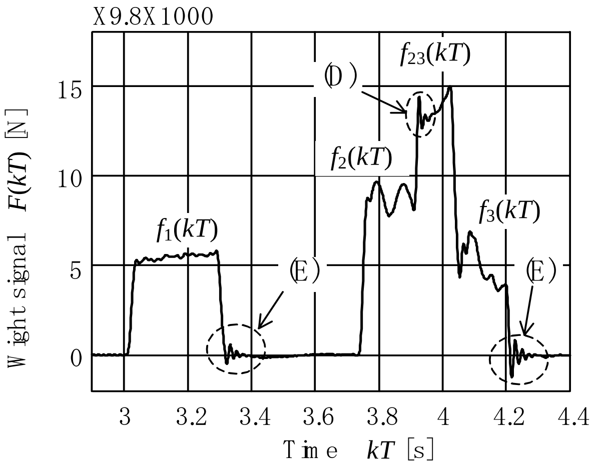


Figure 3: Weight signal generated by the test vehicle at the velocity of 30km/h

Another estimation problem rises in damped vibration observed in $f_{23}(kT)$ and the part of the signal at the moments when the axle weights are unloaded, as indicated by (D), and (E) in Fig. 3. Since the magnitude of impulsive force generated, when the tires pass on the platform, increases with the velocity of the vehicle, these vibratory components, which are not observed at low speed, are exited at the velocity of about 30km/h. Their frequencies in (D) and (E) are about 45Hz and 60Hz, respectively. The reason for the difference of these frequencies is considered that these dumped vibrations observed in effective segments are supposed to be the coupling vibrations due to the dynamics combined the mechanism of the vehicle and that of the weighbridge. This fact implies the lack of the stiffness of the longer-platform. It seems that the longer-platform is lack of stiffness for measuring the weight of in-motion vehicles at high velocity.

We must remove these vibrations using the filter whose time delay is required to be minimized, because the length of the effective segment is extremely short. Hence, we have adopted the FIR notch filter $F_7(z)$ whose zeros are located on the unit circle and their arguments correspond to 45Hz, 60Hz, and 500Hz (corresponding to Nyquist frequency) as shown in Fig.4:

$$F_7(z) = \prod_{j=1}^{3} \frac{1 - 2\cos(2\pi f_j T) z^{-1} + z^{-2}}{2(1 - \cos(2\pi f_j T))}, \quad f_1 = 45 \text{ Hz}, \; f_2 = 60 \text{ Hz}, \; f_3 = 500 \text{ Hz}. \tag{5}$$

Although influence in higher frequency domain is expanded, it is confirmed that the dumped vibratory components in Fig. 5 (I) are sufficiently removed by $F_7(z)$ as shown in Fig. 5 (II).

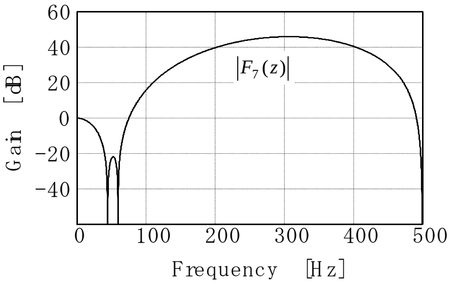
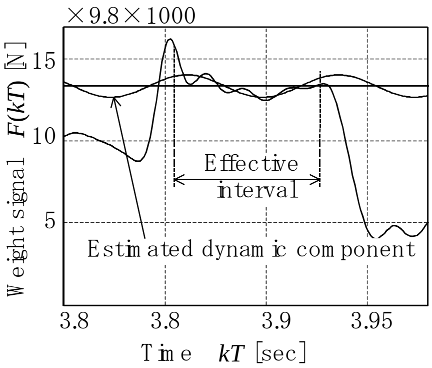
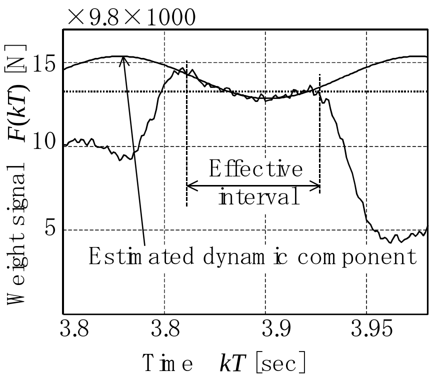


Figure 4: Gain characteristic of $F_7(z)$



(I) $F(kT)$ around $f_{23}(kT)$



(II) Filtered $F(kT)$ around $f_{23}(kT)$

Figure 5: Effect of the 7-tap notch filter $F_7(z)$

6. RESULTS OF MEASUREMENT

The experiments have been done for the nominal velocities of 5, 10, 15, 20, 30, 40, and 50km/h. The true total value M is defined by the sum of the first axle weight M_1 measured and the second and the third axle weight M_{23} simultaneously measured at rest:

$$M = M_1 + M_{23}. \tag{6}$$

Let $\hat{W}_{23}$ $(= \hat{M}_{23} g)$ be the static component obtained from $f_{23}(k)$ by the advanced method. Then, the measured total weight $\hat{M}$ and the error E are defined by $\hat{M} = \hat{M}_1 + \hat{M}_{23}$, $E = 100 \times (\hat{M} - M)/M\,(\%)$, respectively. For comparison, the error E_c in the sum of the mean values of the effective segments $\overline{M}$ was also calculated as the measured value by a typical conventional method.

The statistics in the measurement error E in $\hat{M}$ by the advanced method and E_c in $\overline{M}$ by the conventional one are tabulated in Table 1. Their plots versus v are also shown in Fig. 6. We can confirm that the accuracy is improved up to the velocity of 50km/h, especially in the range of 15km/h and 40km/h with comparison of E and E_c.

Table 1: Statistics in the measurement error E and E_c

(%)	Average	Range	Maximum	Minimum	Standard Deviation	Data No.
E	-1.4	12.5	5.4	-7.1	2.5	67
E_c	-1.1	14.1	6.3	-7.8	3.3	67

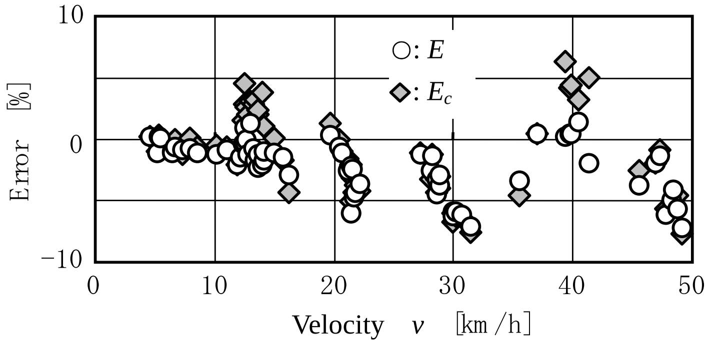


Figure 6: Plots of E and E_c versus the velocity v of the test vehicle

7. CONCLUSIONS

Owing to the affection of unevenness of the approach to the weighbridge and the lack of the stiffness of the longer-platform of the new weighbridge, the actual weight signals were not suitable for measurement by the advanced method. However, we could attain the accurate weighing of an in-motion vehicle with the weighbridge. The conclusions are as follows:

1) An advanced algorithm without using any iterative calculations is introduced to estimate axle weights for in-motion vehicles under the assumption that the dynamic comportment of the weight signal is a simple harmonic vibration;
2) The dumped vibrations in higher velocities over 30km/h due to the lack of the stiffness of the weighbridge with a long-platform were effectively removed by the 7-tap FIR filter;
3) High accuracy measurement was attained by the advanced method especially in the velocity range of 15km/h and 40km/h.

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