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AXLE WEIGHING FOR IN-MOTION VEHICLES USING SIMPLE FIR FILTERS

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Abstract: Real time design methods of FIR filters for weigh-in-motion have been proposed in order to improve the accuracy of measured axle weights. However, if the order of the filter is inappropriately set, the method fails to estimate the frequency of the vibratory component. The application of a reduced-tap sparse FIR filter, which has only one non-zero coefficient to be determined, has recently been studied for preventing miscalculation of axle weights. The latest results show that the adoption of the filter is very effective for estimating virtual vibration and static axle weights of weighing in-motion vehicles.

Keywords: Vehicle, Axle Weighing, LS-WIM.

1. INTRODUCTION

An axle weighing system measures axle weights of in-motion vehicles. The weighbridge is a detector of the system and consists of a weighing platform and load cells. It has the length of 76 cm in travelling direction which is nearly equal to the diameter of a tire, to avoid measuring two axle weights at the same time (see Fig. 1) [1]. The weighbridge is usually installed in front of a toll gate and used to detect axle weights of vehicles in low velocity range. This type of the weighbridge, however, has become to be used as the principal detector in the axle weighing system for ETC (Electronic Toll Collection) gate, which is requested to measure the axle weights of an in-motion vehicle with higher velocity in Japan [2].

The detecting unit of the axle weighing system for ETC , which is installed at the road surface, consists of the weighbridge and two of the bar shaped sensors for weighing whose length of detecting surfaces are narrower than the length of the contact faces of tires of an in-motion vehicle in the travelling direction. Axle weight values are obtained by integrating the pressure of the tires using digital processing or an integration circuit. Since an axle weight is measured in three times, the variance of a weight value is slightly improved. However, we cannot expect an accurate axle weight value, because the axle weighing system for ETC does not sufficiently consider the vibration of an in-motion vehicle. Meanwhile, the bar sensor is a sort of load cells, because it converts a strain into an electric signal using strain gages. It differs from the strip sensor using piezoelectric elements which has been put into practice in Europe. That leads a suspicion that the responsibility of the bar sensor is not sufficiently high for weighing in-motion vehicles.

For axle weighing in-motion vehicles with low velocity using only the weighbridge alone, estimation and removal of lower frequency vibration has been the major challenge. When a vehicle passes on the weighbridge with low velocity under about 15 km/h, the frequency of the most dominant vibratory component in the weight signal is around 3Hz; the dynamic component is caused by vibrations 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 difficult to remove the dynamic components from the weight signal to measure the axle weight with high accuracy. A new method proposed by the authors has overcome the difficulty [3],[4],[5].

If the dynamic response of the weighbridge is not a problem, we may realize high velocity weigh in-motion using the weighbridge alone by introducing the weighing algorithm considering the vibratory components generated by the vertical vibration of a vehicle. Though the experimental data is not enough, the data suggests that the frequency of the dominant component of vibrations which the weight signal contains becomes higher and the amplitude of it becomes smaller in the case that a vehicle travels at a high velocity over 40 km/h. This phenomenon would be preferable for measuring the axle weight, but we could not still neglect the vibration component. The time period for measuring becomes shorter as the vehicle velocity becomes higher, even though the frequency of the component is high. Hence, accurate estimation of vibratory components contained in the weight signal stays an important problem.

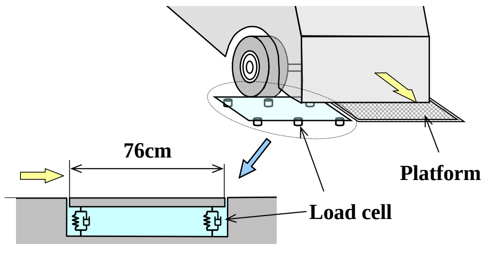

Fig. 1 Weighbridge of an axle weighing system

In the present paper, we first give a brief explanation of conventional methods to estimate the axle weight and make clear the problem of them. Then, we propose the newest method that estimates the frequency of the vibratory component by identifying a high-order sparse notch FIR filter, only three coefficients of which are non-zero. It is showed that this filter keeps the merit to detect lower frequency. Lastly the availability of the newest method are discussed and confirmed on the basis of the results obtained by applying it to actual weight signals.

2. CONVENTIONAL METHOD FOR AXLE WEIGHING

Each load cell which supports the weighing platform detects the force $D_i(t)$ which apply to the i -th axle tires, while it is converted to the voltage signal. The calibrated output signals of all load cells are summed up to be one output signal from the weighbridge. We call it the weight signal $F(t)$.

Figure 2 shows a schematic of time behaviour of the weight signal $F(kT)$ and the tire force $D_i(kT)$. $F(kT)$ 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 i -th axle. We refer to $S_i(kT)$ as the effective part and the time interval corresponding to the effective part as the effective time interval.

The tire force $D_i(kT)$ contains the vibration components caused by the vibration of a vehicle body. We refer to the most dominant component of the vibration as the dynamic component. Supposing that it can be represented by sine wave, we can express $D_i(kT)$ as

$$D_i(kT) = A_i \sin(2\pi f_i kT + \phi_i) + N_i(kT) + W_i g\ ,\ \ i = 1, 2, \cdots , \qquad (1)$$

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, denoting $[a_i, b_i]$ the i-th effective time interval, the effective part would not be flat but a curved line affected by the dynamic component:

$$S_i(kT) = F(kT) = D_i(kT), \quad kT \in [a_i, b_i] \qquad (2)$$

Values obtained using the typical conventional processing methods are as follows:

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

They could give us an accurate value if the effective part is flat. As shown in Fig. 2 where $N_i(kT)$ in eq. (1) is neglected, it is clear that $W_i \neq W_A \neq W_P$. If the period of the dynamic component $1/f_i$ is longer than the effective time $b_i - a_i$, we cannot obtain accurate axle weight by using the conventional methods.

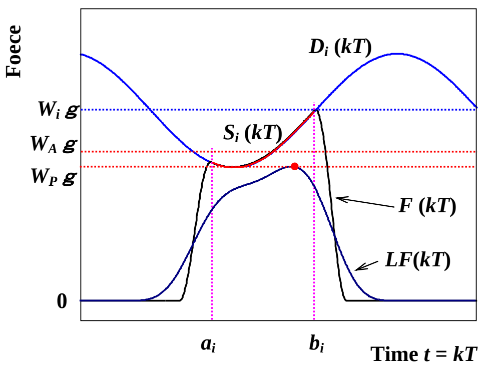

Fig. 2 Graphical representation of the signals without noise component and estimated values of an axle weight

3. PROPOSED METHOD

The dynamic component contained in the effective part of actual weight signal is usually influenced by disturbances such as transitional motions due to acceleration or deceleration of a vehicle, electrical noises, and so on. Hence, in most cases, the dynamic component would not be a perfect sine wave: it would be a distorted sine wave. In case that the distortion is large, we cannot accurately estimate the dynamic component. Also the effective time decreases linearly with the velocity of a vehicle. The difficulty of estimating the dynamic component becomes more serious in high velocity weigh in-motion. To overcome the difficulty, we introduce the following assumptions.

Assumption 1: As is described in Eq. (1) , the dynamic component is a sine wave $A_i \sin(2\pi f_i kT + \phi_i)$.

Assumption 2: The lowest frequency of the noise $N_i(kT)$ in Eq. (1) is sufficiently higher than f_i and the root mean squared value of it is sufficiently small.

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

Assumption 3 is added in order to overcome the serious lack of the data points of the effective parts. It is mostly satisfied for the vibration of vehicle travelling at low velocity. If the dynamic component is due to the natural vibration of a vehicle body, then all effective parts contains the dynamic components which have a common frequency. Namely, $f_1 = f_2 = f_0$ in the case of a two-axle vehicle. As shown in Fig. 3, the tire forces $D_1(kT)$ and $D_2(kT)$ can be represented from Eq. (1) as

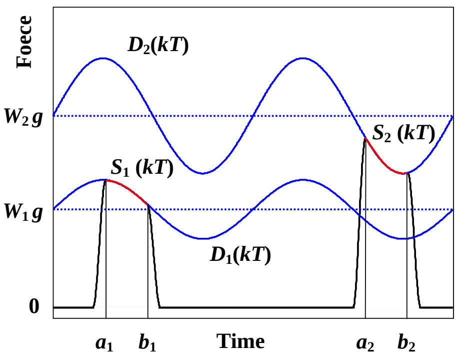

Fig. 3 Graphical representation of the signals affected by dynamic component due to a natural vibration of a 2-axle vehicle

$$D_1(kT) = A_1 \sin(2\pi f_0 kT + \phi_1) + N_1(kT) + W_1 g \quad (3)$$
$$D_2(kT) = A_2 \sin(2\pi f_0 kT + \phi_2) + N_2(kT) + W_2 g \,. \quad (4)$$

To obtain f_0 in above equations, we adopt the common coefficients $\alpha_{N/2}$ corresponding to the dynamic components and different constants C_1 and C_2, which correspond to static ones, independently for each axle:

$$S_1((k_1+N)T) = -\alpha_{N/2} S_1((k_1+N/2)T) - S_1(k_1 T) + C_1 \quad (5)$$
$$S_2((k_2+N)T) = -\alpha_{N/2} S_2((k_2+N/2)T) - S_2(k_2 T) + C_2 \,. \quad (6)$$

The linear regression model for identifying $\{\alpha_{N/2}, C_1, C_2\}$ is as follows:

$$\begin{bmatrix} S_1(a_1+NT)+S_1(a_1) \\ \vdots \\ S_1(b_1)+S_1(b_1-NT) \\ S_2(a_2+NT)+S_2(a_2) \\ \vdots \\ S_2(b_2)+S_2(b_2-NT) \end{bmatrix} = \begin{bmatrix} -S_1(a_1+(N/2)T) & 1 & 0 \\ \vdots & \vdots & \\ -S_1(b_1-(N/2)T) & 1 & 0 \\ -S_2(a_2+(N/2)T) & 0 & 1 \\ \vdots & \vdots & \\ -S_2(b_2-(N/2)T) & 0 & 1 \end{bmatrix} \begin{bmatrix} \alpha_{N/2} \\ C_1 \\ C_2 \end{bmatrix} + \begin{bmatrix} \varepsilon(a_1) \\ \vdots \\ \varepsilon(b_1-NT) \\ \varepsilon(a_2) \\ \vdots \\ \varepsilon(b_2-NT) \end{bmatrix}, \quad (7)$$

for $k_i T = a_i, \cdots, b_i - NT$, $i = 1, 2$, where C_i denotes a constant and $\varepsilon(\bullet)$ denotes random variable normally distributed with mean zero. By estimating $\{\alpha_{N/2}, C_1, C_2\}$ using the least square method, we can obtain axle weight. Even in case that a vehicle has more than three axles, we can derive the similar equation as Eq. (7). If the number of the axle increases, it is more effective to estimate the dynamic component frequency. This is because the data points available for estimation increase with the number of axles.

By solving the normal equation for Eq. (7), we obtain the deferential equations:

$$S_i((k_i+N)T) = -\hat{\alpha}_{N/2} S_i((k_i+N/2)T) - S_i(k_i T) + \hat{C}_i + e(k_i)\,, \quad (8)$$

where $\hat{C}_i$, $\hat{\alpha}_{N/2}$ denote the estimators of C_i, $\alpha_{N/2}$, respectively and $e(k_i)$ denotes the residue. When $S_i(k_i T)$ and $\hat{C}_i + e(k_i)$ are considered to be an input and an output, respectively. Equation (8) can be regarded as the input and output expression of a linear-phase FIR filter:

$$H_{Nz}(z) = 1 + \overbrace{0 + \cdots + 0}^{Nz} + \hat{\alpha}_{N/2} z^{-N/2} + \underbrace{0 + \cdots + 0}_{Nz} + z^{-N} \,. \quad (9)$$

If the order N of Eq. (9) is selected adequately, then the zeros of the filter are allocated on the unit circle of z plane and they attenuate sine wave $A_i \sin(2\pi f_0 kT + \phi_i)$, which are the dynamic components in the effective parts $S_i(k_i T)$. Hence, by means of normalizing the static gain of $H_{Nz}(z)$, we obtains the static force of the *i*-th axle as

$$\hat{W}_i(k_i) g \cong (\hat{C}_i + e(k_i)) / (2 + \hat{\alpha}_{N/2}) \,. \quad (10)$$

By the virtue of the property of residue:

$$\sum_{k_i = a_i/T}^{b_i/T - N} e(k_i) = 0 \,, \quad (11)$$

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

$$\hat{W}_i g \cong (\hat{C}_i + e(k_i)) / (2 + \hat{\alpha}_{N/2}) \,. \quad (12)$$

Consequently, we can obtain $\hat{W}_i$ as the estimated equivalent mass of the *i*-th axle.

Let Z, $\bar{Z}$ denote the zeros of FIR filter (9), then $H_{Nz}(z)$ whose static gain is set to unity is represented as

$$H_{Nz}(z) = \frac{1}{2 + \hat{\alpha}_{N/2}} z^{-N} (z^{N/2} - Z)(z^{N/2} - \bar{Z}) \,. \quad (13)$$

Since the number of zero coefficients between non-zero ones is

$$Nz = (N-2)/2 \,, \quad (14)$$

the frequency of the dynamic components is

$$f_0 = (\angle Z / (N/2)) / (2\pi T) = (\angle Z / (Nz+1)) / (2\pi T) \,, \quad (15)$$

which is calculated from the $N/2$-th root of Z ($\angle Z > 0$).

The series of estimation and calculation of the coefficients and parameters in above equations are referred to as the newest method in the present paper. Since each vehicle has different f_0, $H_{Nz}(z)$ is identified every weighing. It is a non-recursive adaptive filter in this sense.

4. SPARSE FIR FILTERS

4. 1. SPARSE NOTCH FIR FILTER

Since FIR filter (13) gives the notches at

$$f_n = (\angle Z + 2n\pi) / \{(2\pi T)(Nz+1)\}\,, \; n = 0, 1, \cdots, Nz \quad (16)$$

including the frequency of the dynamic component f_0, we refer it to as the sparse notch filter. The zeros $\exp(\pm j 2\pi f_n T)$ ($n \geq 1$) restrain the gain at higher frequency domain. Gain characteristics of $H_0(z)$ ($Nz = 0$) and $H_{25}(z)$ ($Nz = 25$), both of which have the zeros at 3 Hz, are shown in Fig. 4, when *T*=1 msec. $H_0(z)$ means the 3-tap filter without zero coefficients:

$$H_0(z) = \frac{1}{2 + \hat{\alpha}_1} (1 + \hat{\alpha}_1 z^{-1} + z^{-2}) \,. \quad (17)$$

Both of them are a high-pass filter, because the zeros $\exp(\pm j 2\pi 3T)$ raise the gain of higher frequency domain.

For obtaining the dynamic component frequency about 3 Hz,

$$|N_i(e^{j2\pi fT})| \cong 0 \; (f \cong 3\,\text{Hz}),\; |N_i(e^{j2\pi fT})| << 1 \; (f >> 3\,\text{Hz}) \quad (18)$$

shoud hold. If we use $H_0(z)$, the high frequency gain of it is too large to estimate 3 Hz. This is the reason why we use the high order filter (13) which is obtained by adding the zeros

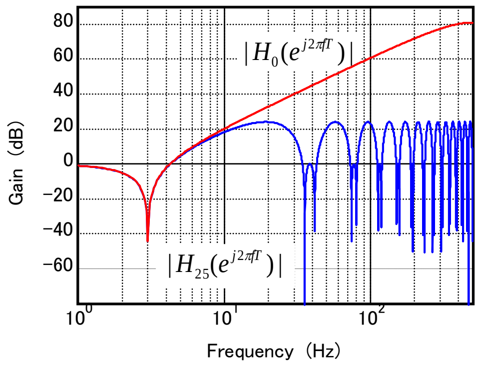

Fig. 4 Plots of $|H_{25}(e^{j2\pi fT})|$ and $|H_0(e^{j2\pi fT})|$, *T*=1 msec

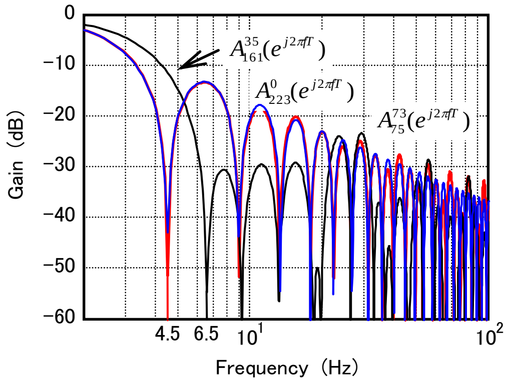

Fig. 5 Gain characteristics of the averaging filter and the sparse average filter ($n = 223$, $Nz = 35, 73$)

$\exp(\pm j2\pi f_n T)$ ($n \geq 1$) to $H_0(z)$. The sparse notch filter whose the lowest notch frequency is f_0 Hz has the maximum gain:

$$\max |H_{Nz}(e^{j2\pi fT})| = \frac{2-\hat{\alpha}_1}{2+\hat{\alpha}_1} = \frac{1+\cos\{2\pi(Nz+1)f_0 T\}}{1-\cos\{2\pi(Nz+1)f_0 T\}} \quad (19)$$

We can quantitatively know the height of ripples in the high frequency domain by Eq. (19).

4. 2. SPARSE AVERAGE FILTER

If **Assumption 1** is not satisfied, we are obliged to adopt the average of the effective part W_A as the axle weight value. Actually, when the dynamic component is not distinguished, there are no merits of using the newest method. The pulse transfer function which gives W_A is

$$A_n^0(z) = \frac{1}{n}\sum_{i=0}^{n-1} z^{-i}\ , \quad (20)$$

where n denotes the length of the effective part. Applying $A_n^0(z)$ to the effective part is equivalent to the signal processing i) in Section 2. $A_n^0(z)$ is referred as to the average filter.

$A_n^0(z)$ is a type of the FIR filters. Let us introduce the spare filter like $H_{Nz}(z)$. We set $\hat{\alpha}_{N/2} = \hat{\alpha}_{Nz+1} = 1$ in Eq. (13). Namely,

$$A_3^{Nz}(z) = \frac{1}{3}(1 + z^{Nz+1} + z^{2(Nz+1)})\ . \quad (21)$$

$A_{\rm III}^{Nz}(z)$ is referred as to the sparse moving average filter. We obtain the output signal the length of which is n-2(Nz+1) by inputting the effective part to $A_{\rm III}^{Nz}(z)$. The pulse transfer function from the effective part to the average of that output signal is

$$A_{Ne}^{Nz}(z) = A_{n-2(Nz+1)}^{Nz}(z) = A_{n-2(Nz+1)}^{0}(z)\cdot A_{\rm III}^{Nz}(z)\ . \quad (22)$$

$A_{Ne}^{Nz}(z)$ is referred as to the sparse average filter.

The gain characteristics of $A_{223}^0(z)$ ($n = 223$), $A_{161}^{35}(z)$ and $A_{75}^{73}(z)$ ($n = 223, Nz = 35, 73$) are shown as examples in Fig. 5. $|A_{75}^{73}(e^{j2\pi fT})|$ is almost equal to $|A_{223}^{0}(e^{j2\pi fT})|$, while $|A_{161}^{35}(e^{j2\pi fT})| < |A_{223}^{0}(e^{j2\pi fT})|$ ($5.2\ \text{Hz} < f < 17.8\ \text{Hz}$) and the lowest notch frequency 6.5 Hz of $A_{161}^{35}(z)$ is higher than that of $A_{223}^0(z)$, which is about 4.5 Hz.

4. 3. DETERMINATION OF ODRER OF SPARSE NOTCH FIR FILTER

In the first place, let us show estimated values of the 2-nd axle obtained by applying the newest method to the weight signal of an actual in-motion 3-axle vehicle with low velocity. Fig. 6 shows the relationship between $Nz = (N-2)/2$ and the values: the estimated value $\hat{W}_2 = H_{Nz}(z)S_2(k_2T)$ ($\hat{\alpha}_{N/2}$ is common to all the effective parts), the sparse average value $A_{Ne}^{Nz} = A_{Ne}^{Nz}(z)S_2(k_2T)$, the average value $A_{223}^0 = A_{223}^0(z)S_2(k_2T)$, the true value W_2 .

It is seen from both Fig. 5 and Fig. 6 that $|N_2(e^{j2\pi fT})| << 1$ and the dynamic component frequency f_0 is lower than 4.5 Hz because of $|A_{233-2(Nz+1)}^{Nz} - W_2|$ < $|A_{223}^0 - W_2|$ ($Nz \geq 73$). Furthermore, we can observe $A_{23}^{104} \cong W_2$ in Fig.6, which means that A_{23}^{104} may be regarded as an accurate axle weight value. But we cannot practically evaluate the sparse average value A_{Ne}^{Nz} , because W_2 is unknown in actual real-time weighing.

Meanwhile, $\hat{W}_2$ is accurate in the range of $40 < Nz < 75$ which is a comparatively wide range. It means that we do not have to be sensitive to the choice of the number of inserted zeros Nz . Nevertheless, the error of $\hat{W}_2$ increases in the range of $Nz \geq 75$, which means that the number over 74 is excessive for Nz . Since we cannot ignore this fact, we uncritically adopt Nz (=73) which minimize $|A_{223}^0 - A_{Ne}^{Nz}|$. Namely, Nz that should satisfy

$$\min_{Nz} |A_n^0 - A_{Ne}^{Nz}| \quad (23)$$

is adopted as the number of inserted zero coefficients Nz of Eq. (13). In the case where $|N_2(e^{j2\pi fT})| << 1$ as shown in Fig. 6, if the lowest zero frequency of $A_{\rm III}^{Nz}(z)$ is equal to that of $A_n^0(z)$, then $|A_n^0 - A_{Ne}^{Nz}| = 0$ should hold from Eq. (22). Thus, we can simply determine the number of zeros coefficients between non-zero ones by

$$Nz = \lfloor n/3 - 1 \rfloor, \quad (24)$$

where $\lfloor x \rfloor = \max\{x_0 \in \mathrm{Z} \mid x_0 \leq x\}$. The reason why we adopt the floor function $\lfloor x \rfloor$ is that we had better guarantee Ne as much as possible.

$A_{\rm III}^{Nz}(z)$ is the sparse notch filter $H_{Nz}(z)$, $\hat{\alpha}_{N/2}$ of which is unity. When the lowest zero frequency of $H_{Nz}(z)$ which is estimated by the newest method using the least square method is greater than that of $A_{\rm III}^{Nz}(z)$, there is no merit to use $H_{Nz}(z)$. In this case, we must adopt not the estimated value but the average one as the axle weight.

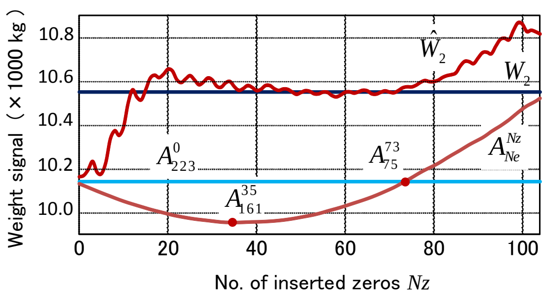

Fig. 6 A_{223}^0, A_{Ne}^{Nz} , W_2 and $\hat{W}_2$ obtained by processing the effective parts of an actual vehicle with low velocity versus Nz

5. ESTIMATION RESULTS OF WEIGH IN-MOTION BY PROPOSED MEYTHOD

The results of the experimental weighing using an actual in-motion 2-axle vehicle are tabulated in Table 1. The vehicle used and the venue for the experiment in this section and those in Sub section 4. 3 are different. The nominal velocity in the table is not the measured value but the indicated one to the driver. Even here, the sampling period is 1 msec. the effective time per an axle is in the range from 0.226 s (n=227) to 0.04 s (n=41). Errors E_W, E_A are defined by

$$E_W\ (E_A) = \frac{\hat{W}_i\ (A_n^0) - W_i}{20000} \times 100\quad (\%) \tag{25}$$

The denominator 20000 kg is the full scale of the weighbridge. Nz is the smaller number of the two axles.

From Table 1, the accuracy of $\hat{W}_i$ is superior to that of A_n^0 except for the front axle estimated value $\hat{W}_1$ in the case of the 25 km/h travelling. We cannot exactly know the cause of this inaccuracy in actual practical weighing. However, high accuracy could still be realized by introducing the rule that "we adopt A_n^0 instead of $\hat{W}_i$ as the measured value in the case that the dynamic component frequency f_0 is lower than 3 Hz."

In this way, the dynamic component frequency is very effective for evaluation of the estimated weight value. Also, the newest method succeeds in estimating the axle weight even in the case of the 30 km/h travelling. It is confirmed that we can obtain the sufficient data length for estimation by introducing the common frequency f_0 to each the dynamic component.

6. CONSIDERATION

If the dynamic component frequency f_0 is known, then we can easily estimate the dynamic component. For this purpose, we fit the equation of the structure:

$$D_i(kT) = A_i \sin(2\pi f_0 kT + \phi_i) + W_i g \tag{26}$$

to the effective parts. Equation (26) is obtain by substituting $N_i(kT) = 0$ and the estimated value of f_0 into Eq. (1). Instantly, we obtain the estimated tire force:

$$\hat{D}_i(kT) = \hat{A}_i \sin(2\pi f_0\, kT + \hat{\phi}_i) + \hat{W}_i g \tag{27}$$

Note that the estimated value $\hat{W}_i$ has been obtained from Eq. (12). The fitting of Eq. (26) is, therefore, unnecessary in the practical weighing.

A build-in vehicle weighing system for self-checking the carrying load is supplied in the market. It successively displays the load weight by converting the stains detected by the strain gages bonded to both axles to the weight. The test vehicle was equipped with the system and we could record the weight signal from its indicator. By considering that the forces which act on the axles directly communicated to the tires, the signal from the system $\Lambda_i(kT)$ can be regard as the approximate signal of the tire force $D_i(kT)$:

$$\Lambda_i(kT) \cong D_i(kT), \quad i = 1, 2. \tag{28}$$

Namely, the vibratory component of $\Lambda_i(kT)$ is considered to be the actual dynamic component of the i-th axle.

Figures 7, 8 and 9 show the weight signal $F(kT)$, estimated value $\hat{W}_i$, estimated tire force $\hat{D}_i(kT)$ and actual tire force $\Lambda_i(kT)$ which is given the proper offset in order to observe the correlation $\hat{D}_i(kT)$ and $\Lambda_i(kT)$. The part bordered by two vertical lines is the effective part and horizontal lines are $\hat{W}_i$ estimated by using Eq. (12). As can be seen in Fig. 7 which illustrates the data in the case of the travelling at the nominal velocity 20 km/h, the vibratory characteristics of $\Lambda_i(kT)$ and those of $\hat{A}_i \sin(2\pi f_0 kT + \hat{\phi}_i)$ are similar on the whole range of time.

Consider Fig. 8 in the case of the nominal velocity 25 km/h. Although we can recognize the correlation between $\hat{D}_i(kT)$ and $\Lambda_i(kT)$, $\Lambda_1(kT)$ is distorted and its amplitude becomes small at the effective interval of the 1st axle. This distortion, which looks unlike the part of a sin wave, directly appears in the effective part. A notch filter cannot eliminate such a distorted wave form as this. Also, if we pay attention to $\Lambda_2(kT)$, we notice that its wave form is distorted before and after passing over the weighbridge platform (kT<2.5 s, kT>3.6 s). It is conjectured that the test vehicle was accelerated or decelerated in order to keep the indicated velocity at that time. Although Non-harmonic dynamic component due to the acceleration or deceleration deteriorates the accuracy of the estimated value, we can know the existence of non-harmonic characteristics by unexpected far lower frequency estimated using the newest method. As is mentioned in Section 5, it would be appropriate that we adopt A_n^0 instead of $\hat{W}_i$ as the measured value in the case of the dynamic component frequency f_0 is lower than 3 Hz.

As can be seen in Fig. 9 in the case of the nominal velocity 30 km/h, it is difficult to say that $\Lambda_i(kT)$ contains only one harmonic vibration. Since the amplitude of vibratory component in $\Lambda_1(kT)$ is small, there is no need for considering the dynamic component. In the contrary, $\Lambda_2(kT)$ still contains the large amplitude vibration. Also the vibratory component of $\hat{D}_2(kT)$ and that of $\Lambda_2(kT)$ are almost the same shape during the very short time of

Table 1 Measurement results of an actual in-motion vehicle with nominal velocities from 10 km/h to 30 km/h

Nominal velocity	Common		1st axle					2nd axle				
	Nz	f_0 (Hz)	n	$\hat{W}_1$ (kg)	A_n^0 (kg)	E_W (%)	E_A (%)	n	$\hat{W}_2$ (kg)	A_n^0 (kg)	E_W (%)	E_A (%)
10 km/h	65	2.80	199	5126.45	5250.28	0.057	0.676	227	10023.01	9856.58	0.132	-0.700
20 km/h	33	3.26	111	4852.97	4649.36	-1.310	-2.328	103	10154.56	10463.18	0.790	2.333
25 km/h	20	2.68	65	5596.10	5060.69	2.406	-0.271	77	10081.18	9397.73	0.423	-2.994
30 km/h	12	5.32	41	5113.49	5042.17	-0.008	-0.364	43	10015.43	9513.95	0.094	-2.413

Static weights of the first and second axle are 5114.99 kg and 9996.62 kg, respectively.

the 2nd axle effective time interval. This is the reason why we could obtain the highly accurate axle weight value $\hat{W}_i$ even in the case of the travelling at comparatively high velocity of 30 km/h. As

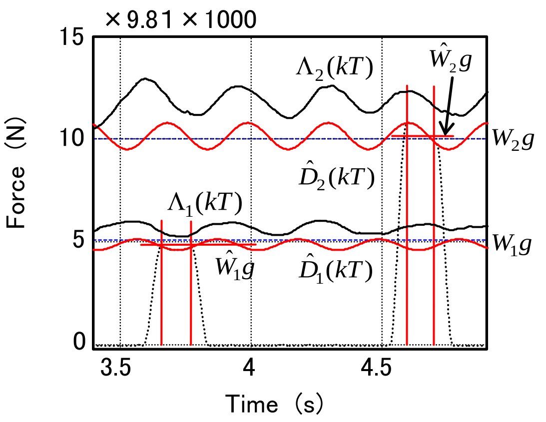

Fig. 7 Estimated weight $\hat{W}_i$, tire force $\hat{D}_i(kT)$ and vertically shifted actual tire force $\Lambda_i(kT)$ in the case of travelling at 20 km/h, *i*=1,2

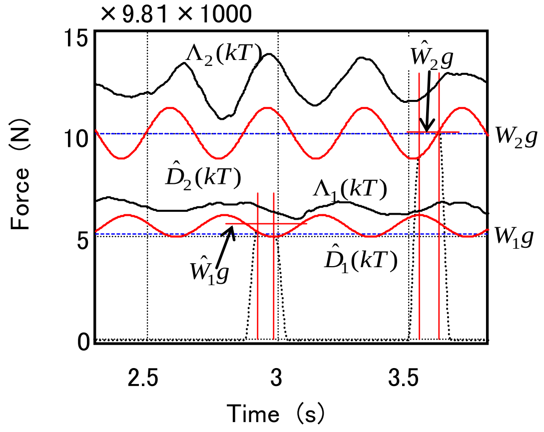

Fig. 8 Estimated weight $\hat{W}_i$, tire force $\hat{D}_i(kT)$ and vertically shifted actual tire force $\Lambda_i(kT)$ in the case of travelling at 25 km/h, *i*=1,2

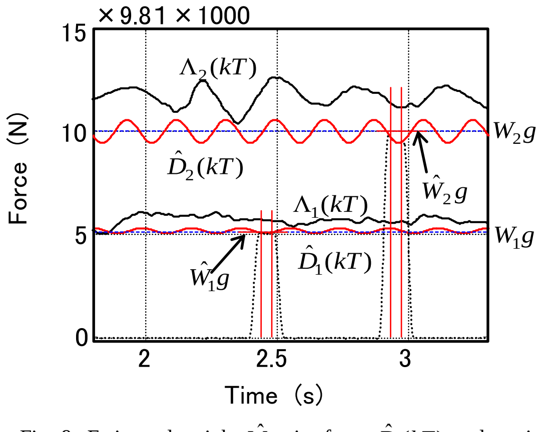

Fig. 9 Estimated weight $\hat{W}_i$, tire force $\hat{D}_i(kT)$ and vertically shifted actual tire force $\Lambda_i(kT)$ in the case of travelling at 30 km/h, *i*=1,2

is understood from the figure, if the weighing timing (the effective time interval) was shifted a little, we would not obtain such an accurate value as $\hat{W}_i$ in the row of 30 km/h of Table 1. Also, the figures in this section show that it is difficult to assume that the dynamic component is a harmonic vibration and it of the front axle becomes smaller in inverse proportion to the velocity.

7. CONCLUSION

The essential points of the present paper are as follows:

1) We explained the new weighing method which removes the lowest frequency vibration from the effective part (the part of the weight signal available for weighing) by adaptively designing the simplest FIR filter whose coefficients are symmetric using the least square methods.
2) The filter mentioned above is the sparse *N*-th order FIR filter:

$$H_{Nz}(z) = (1 + \hat{\alpha}_{N/2} z^{-N/2} + z^{-N})/(2 + \hat{\alpha}_{N/2}),$$

where $Nz = (N-2)/2$. We only have to estimate a coefficient $\hat{\alpha}_{N/2}$ and an estimated axle weight is not sensitive to Nz.
3) We introduced the sparse average filter $A_{\rm III}^{Nz}(z)$ obtained by substituting $\hat{\alpha}_{N/2} = 1$ into $H_{Nz}(z)$. The order *N* of $H_{Nz}(z)$ is determined so that the lowest zero frequency of $A_{\rm III}^{Nz}(z)$ is equal to that of a moving average filter order of which is *n*-1, where *n* is the data length of the effective part. This determination method is based on the results of actual weighing test.
4) In the case of travelling at from 10 km/h to 30 km/h (the shortest weighing time par an axle is about 42 msec), accurate axle weight values are estimated from the actual weighing signals of an in-motion vehicle through the adoption of the newest method.

8. REFERENCES

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