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Gravity center height estimation for the rollover compensation system of commercial vehicles

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Abstract

This paper concerns a technology to estimate the vehicle dynamics transfer function and to correct the control parameter of roll-over compensation system. ARX-model is applied to estimate the transfer function of an actual vehicle. The gravity center height, one of the control parameters of the control model, is corrected so that the transfer function could be in congruence with that of the actual vehicle. The control model forecasts the critical roll-over condition and the control system compensates the critical condition by controlling the braking force distribution.

1. Introduction

Based on an investigation into accidents on Japanese highways, course-out and roll-over account for 50% of the serious heavy duty vehicle accidents. If a system which could control the yaw and roll dynamics by observating the vehicle condition were developed, heavy duty vehicles equipped with this system might be able to avoid these accidents. For such a system the following advanced technologies are needed:

- Vehicle weight estimation.
- Longitudinal position and height of vehicle gravity center estimation.
- Side slip angle estimation.
- Friction force estimation at combined slip condition [1] and so on.

This paper introduces a gravity center height estimation method and roll-over compensation control.

2. Phenomenal confirmation

Fig. 1 shows, as an example, the difference of vehicle height and width between trucks and passenger cars. The gravity center position and height of trucks and buses differ with the number of passengers and the unloaded or loaded status. Therefore it is very important to understand the kinetic characteristics such as gravity position, height, and so forth. Rolling feature during lane change varies with the variance of gravity center height as shown in Fig. 2. If the gravity center is higher, the vehicle roll rate is larger and phase delay increases. Generally, the truck driver can feel the roll motion according to loading status and can take measures to guarantee safe driving.

3. Gravity position estimation

3.1. Estimation consideration

In consideration of the gravity center position, the estimation method is investigated with respect to gravity center height. In this paper, based on a kinetics model with roll motion freedom, the transfer function from steering input to roll output can be estimated. Through a coefficient comparison with experimental transfer function data by ARX model [2,3], we can get the gravity center height.

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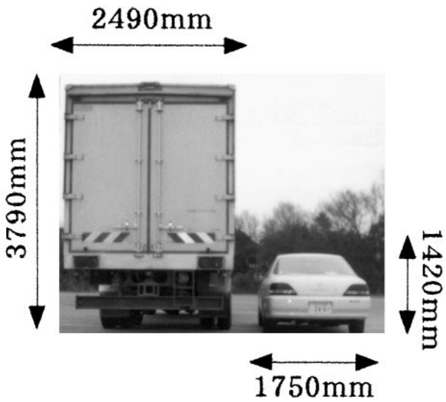

Fig. 1. Aspect ratio of large size truck and car.

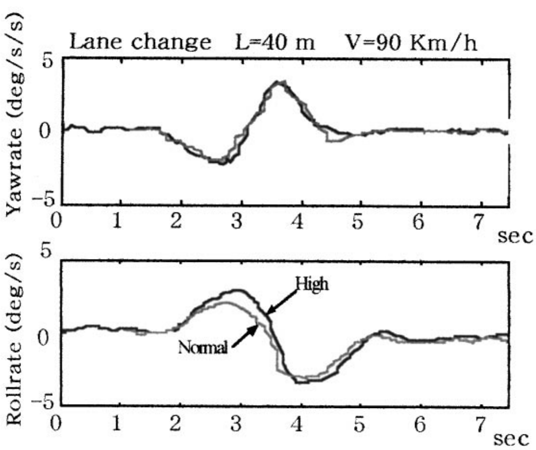

Fig. 2. Roll rate difference influenced by gravity center height.

3.2. Transfer function equation of steering angle–roll angle

In order to obtain the transfer function from steering input to roll out-put, the kinetics model with the rolling axis is described by a coordinate system fixed on the vehicle (Fig. 3). A model of 3DOF with rolling, yawing and lateral velocity is used. All equations are written as follows:

$$A' = M^{-1}A'', \quad sx = A'x + Bu,$$

$$M = \begin{pmatrix} MV & 0 & -Mhs & 0 \\ 0 & I & 0 & 0 \\ -MhsV & 0 & I_\phi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$A'' = \begin{pmatrix} 2(K_f + K_r) & \dfrac{2(K_f L_f - K_r L_r)}{V} - MV & 0 & -2(K_f \alpha_f + K_r \alpha_r) \\ 2(K_f L_f - K_r L_r) & \dfrac{2(K_f L_f^2 + K_r L_r^2)}{V} & 0 & -2(K_f L_f \alpha_f - K_r L_r \alpha_r) \\ 0 & MhsV & -C_\phi & -K_\phi \\ 0 & 0 & 1 & 0 \end{pmatrix},$$

$$B = M^{-1}B',$$

$$B' = (-2K_f \quad -2K_f L_f \quad 0 \quad 0)^{\mathrm{T}},$$

$$x = (\beta \quad \gamma \quad \dot{\phi} \quad \phi)^{\mathrm{T}},$$

$$\phi(s) = Cx \cdot \delta(s).$$

Concerning roll motion expanding the transfer function of steering angle-roll:

$$\frac{\phi(s)}{\delta(s)} = Cx = CA^{-1}B, \quad A = sE - A', \tag{1}$$

E: Identity,
det(A): determinant of A,

$$C = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

The transfer function from steering angle to roll angle is written in the following form:

$$\frac{\phi(s)}{\delta(s)} = \frac{e_2 s^2 + e_1 s + e_0}{\det(A)}. \tag{2}$$

3.3. Transfer function and gravity center height of actual vehicle

By fitting the ARX model with the steering angle as input and roll angle as output, the pulse transfer function can be determined. The pulse transfer function is transformed from discrete-time system to continuous-time system by the transformation between z-domain and s-domain. ARX model is expressed as follows,

$$A(z)y(t) = B(z)u(t) + e(t), \tag{3}$$

where z is transfer operator and $e(t)$ is white noise with zero mean value and $\sigma 2$ covariance. Fig. 4 shows the

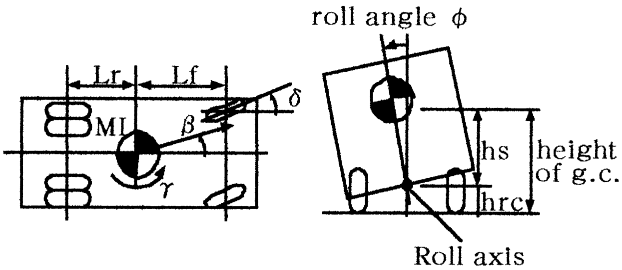

Fig. 3. 3DOF model with roll-axis.

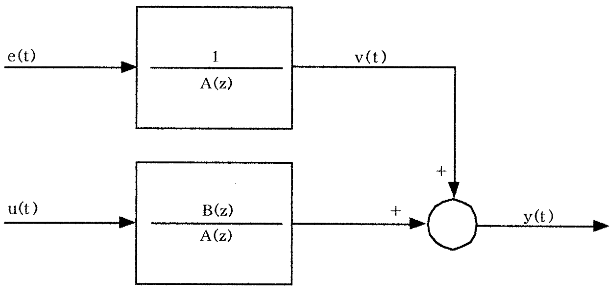

Fig. 4. ARX model.

ARX model. The transfer function $B(z)/A(z)$ is expressed as follows:

$$\frac{B(z)}{A(z)} = \frac{b_1 z^{-1} + b_2 z^{-2} + \cdots + b_m z^{-m}}{1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_n z^{-n}}. \tag{4}$$

This is the pulse transfer function expressed as discrete-time system. Described next is the ARX model fitting. If the parameters (parameter vector) and signal (signal vector) are expressed as follows:

$$\theta \equiv (a_1 \cdots a_n b_1 \cdots b_m)^{\mathrm{T}},$$
$$\varphi(t)^{\mathrm{T}} \equiv [-y(t-1) \cdots -y(t-n) u(t-1) \cdots u(t-m)]^{\mathrm{T}}. \tag{5}$$

Then Eq. (3) is rewritten in the following form:

$$y(t) = \varphi^{\mathrm{T}}(t)\theta + e(t). \tag{6}$$

To fit the ARX model means to determine the parameter vector θ. The θ determination is done by minimizing the square of noise, $e_2(t)$, as written in the following form:

$$\theta(N) = \left(\frac{1}{N}\sum_{i=1}^{N} \varphi(t)\varphi^{\mathrm{T}}(t)\right)^{-1} \frac{1}{N}\sum_{i=1}^{N} \varphi(t)y(t), \tag{7}$$

where N is the number of data, and θ depends on the N.

Here, Eq. (4) is the model expression for an actual vehicle in discrete-time domain. Then this model can be written as a form of continuous-time domain through the transformation from z- to s-domain. Therefore through the comparison of this model with kinetic model (Eq. (2)), the height of gravity center is estimated in the form below:

$$hs = F(e_2) = \frac{K}{MsV} \frac{(2/V) K_f K_r l^2 - VM(K_f l_f - K_r l_r)}{K_f/e_2 - 2K_r\{2K_r l_r \alpha_r - K_f l_f (\alpha_f + \alpha_r)\}}. \tag{8}$$

3.4. Measurement of static gravity center height

Firstly, the height of gravity center is measured statically by inclining the vehicle as shown in Fig. 5, which is the method based on Japanese Security Guarantee standard. Here a middle-sized truck is loaded under two conditions. One is lower flat concrete load and the other is higher load status, and both the gravity center height measurement and the gravity center height measurement in unloaded condition are taken as true values. According to these conditions, the steering angle, roll rate and vehicle velocity during actual running are measured.

3.5. Data processing

The roll rate is easily affected by the cant or undulation of the road surface. The correlation between steered angle and roll angle is not so high as seen in Fig. 6. Therefore, all accumulated mean values are started from zero in order to prevent zero-drifting measurement signals. Moreover, taking a certain value of steering input as the trigger signal and then recording the sample signals provides a reliable roll response.

Roll rate is sensitive to lateral motion caused by uneven road surface in high frequency range, and includes the rolling motion caused by the road cant and track groove in the measured roll angle caused by steering input. In order to protect roll angle calculation from these influences, a band-pass filter is applied for ordinary frequency range. This is helpful in enhancing measurement sensitivity. After these processes, single-input and single-output transfer function is determined according to ARX model then gravity center height can be calculated as described in Section 3.3.

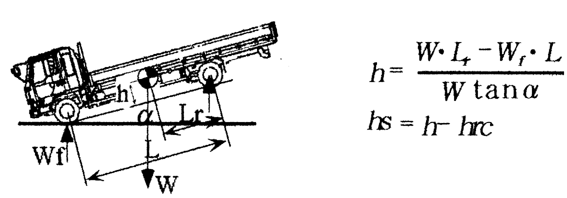

Fig. 5. Statical measurement of gravity center height.

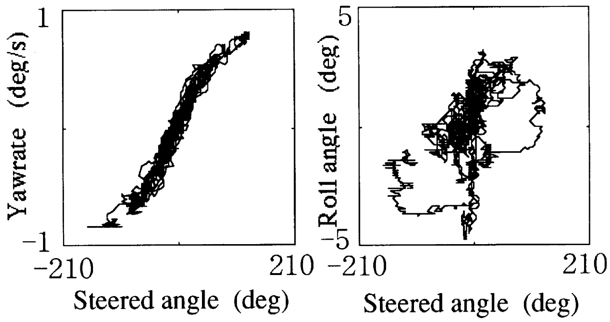

Fig. 6. Yaw and roll/steered angle correlation at winding road.

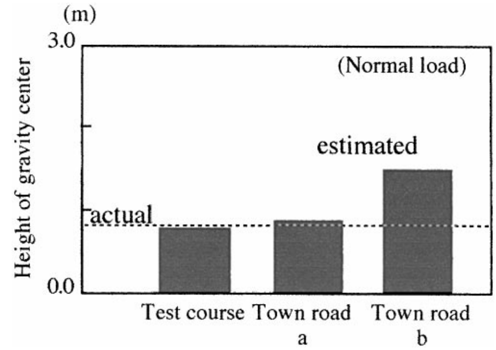

Fig. 8. Estimated gravity center height.

4. Estimation results

4.1. Premise condition for gravity center height estimation

The following are the analysis results. The data are collected from the test-course (Fig. 2) and from town road (Fig. 7 sections a and b). The estimation results when using these data are shown in Fig. 8. The areas indicated by sections a and b in Fig. 7 are used to construct the transfer function. It is very possible to perform the estimation when the coherence between steering input and roll rate is sufficient and located in a higher S/N ratio area (section a). On the other hand, when the input–output is not sufficient or the speed change rate is large, the estimation is different from the true value (section b). Therefore, higher S/N ratio and lower speed change rate is the necessary premise for the estimation.

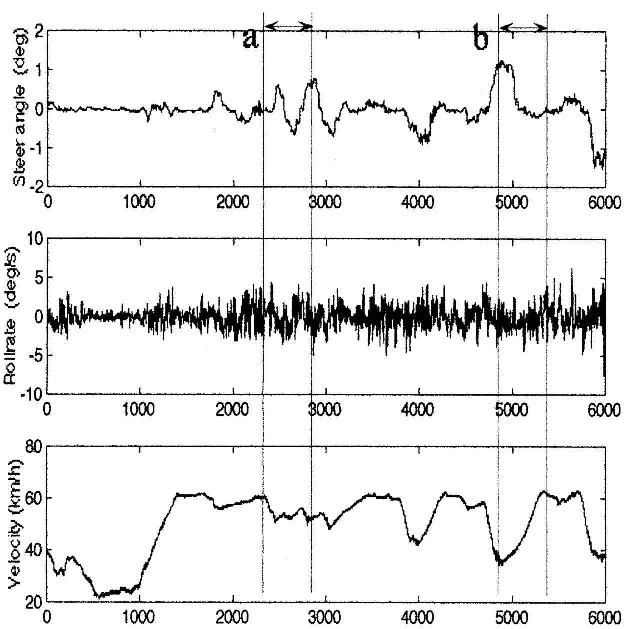

Fig. 7. Steered angle, roll rate and vehicle speed at actual road.

4.2. Loading condition and gravity center height estimation

With the premise condition of 4.1, the loading condition is changed and the gravity center height is calculated (Fig. 9). The gravity center height is in accord with the trend of the loading status.

5. Application to rollover compensation

The estimated gravity center height is applied to the vehicle model of Fig. 10. The model forecasts the rolling behavior as shown on the quadrant plane of Fig. 11 according to roll angle and roll rate. The rolling behaviors located in the first and third quadrant tend to be divergent. This result of stability estimation shows the wheel brake acts appropriately and prevents rollover.

An experimental result for rollover prevention is shown in Fig. 12. This is a measurement when the test vehicle is passing a J-turn. When the rollover behavior is over a certain threshold upon inspecting the gravity center height, the system makes each wheel brake work then reduce the rolling motion quickly.

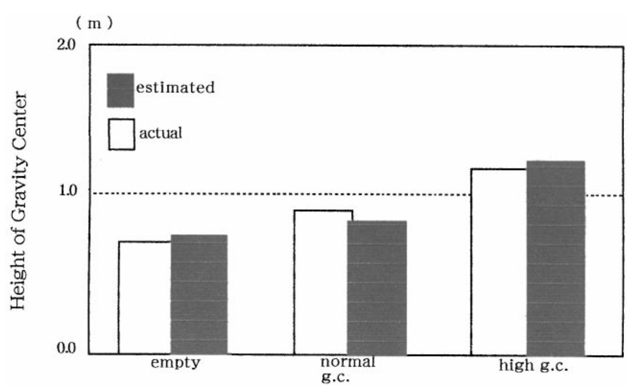

Fig. 9. Estimated value difference influenced by loading condition.

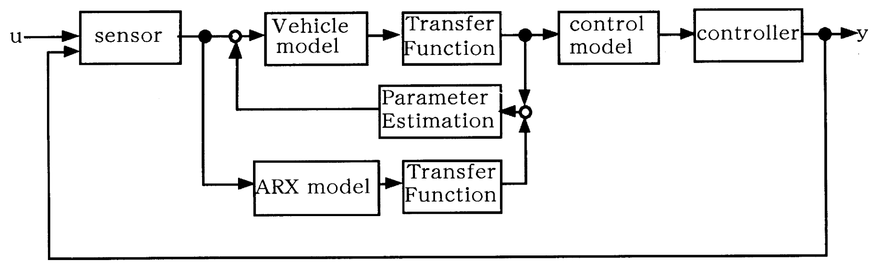

Fig. 10. ARX model and parameter estimation.

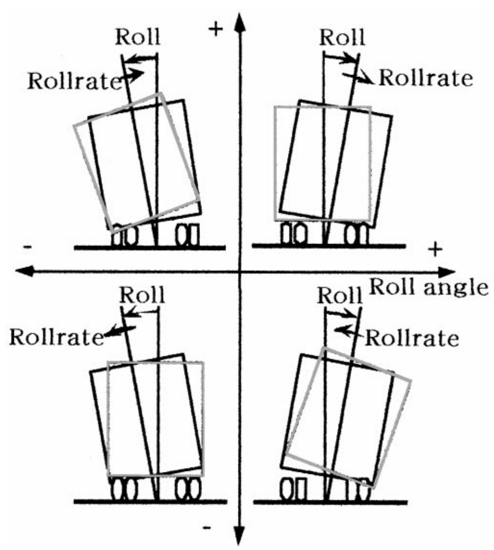

Fig. 11. Considerable roll angle/roll rate combination.

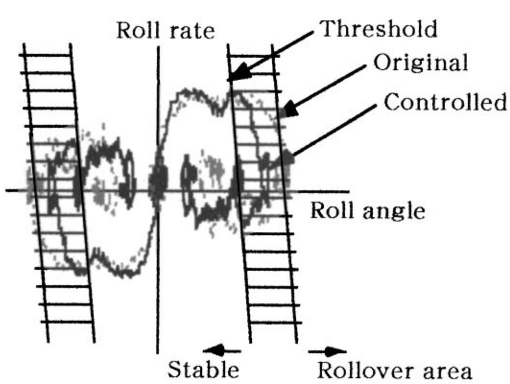

Fig. 12. Effect of roll compensation.

6. Conclusions and future work

Through the comparison of transfer function coefficients between the kinetic model and ARX estimation model coming from experimental data the gravity center height estimation is performed. As a result of our study, (1) vehicle gravity center height can be precisely estimated; and (2) the gravity center height can be decided according to the loading status e.g., flat loading or higher loading status. As an application, the lateral spin prevention control in using the information on vehicle roll and roll rate is testified and a good result is achieved.

As future work, we need to guarantee the system reliability for practical application.

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