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Look-ahead preview control application to the high-mobility tracked vehicle model with trailing arms [†]

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Abstract

Preview control involves using forward road information acquired from preview sensors in designing a controller. Preview control, which is composed of feedback and feed-forward input parts can lead to better performance than feedback control alone. In this paper, application of the preview control based on the active suspension to tracked vehicles will be introduced. The suspension unit of the tracked vehicle is in the form of a trailing arm type to increase the wheel travel. Because the preview control has been developed for the linear time-invariant system, a linearized model of the system is required. A linear model of the tracked vehicle, which the preview controller is designed based upon, is generated without considering the dynamics of the track elements for simplification. On the other hand, the nonlinear model, which the performance of the controlled system is investigated based upon, is generated by using Recurdyn^{TM}, commercial software. The nonlinear model includes nonlinear damping and stiffness characteristics of hydraulic suspension units(HSUs). From the simulation results for RRC 9, performance enhancement of the preview control will be shown in terms of ride comfort by using ISO 2631 under the assumption that actuators are ideal and the velocity of the vehicle is constant.

Keywords: Active suspension; Preview control; Ride comfort; Tracked vehicle model

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1. Introduction

It seems that research on preview control based on the active suspension unit for the high-mobility tracked vehicles has been developed in several developed countries, but related literatures are rarely open to the public. Thus, it is necessary to make a study of the preview control application to the tracked vehicles. Contrary to the commercial vehicles, tracked vehicles operate primarily on irregular road surfaces. Thus, feedback control has a limitation on improving control performance. To increase the control performance, preview control that uses additional information of forward road profile is needed.

In previous researches, application of the preview control to 1/2 tracked vehicles with trailing arms was performed [1-2]. In those, it is assumed that a frequency bandwidth of actuators is infinite and the tracked vehicles travel at constant speed. The performance variation according to the limited actuator bandwidth has been investigated for profile IV and hemi-sphere bump with radius 10 inch [3-4]. In addition, they employed a linear interpolation technique to construct road information for tracked vehicles of which the speed is varying. The technique was also handled in the work of [5].

In this paper, we would like to expand the application of preview control to the full tracked vehicle and evaluate the control performance in terms of driver's ride comfort by using ISO 2631.

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2. Full tracked vehicle model

2.1 Linear tracked vehicle model

The linear tracked vehicle model has totally 12 road wheels, 6 wheels on each side. There are 15 degrees of freedom such as roll, pitch and heave motions of sprung mass and 12 rotating motions of road arms in the full tracked vehicle model. This linear model is required to design a preview controller because the preview control has been developed against the linear model alone. The tracked vehicle model is complex and it is difficult to derive the dynamic equation. Thus, to reduce the complexity, the effect of track elements is neglected in the linear model.

Derivation of the dynamic equation is not handled in this paper. Readers interested in the derivation procedure should see the work of Kim [1]. The dynamic equation is derived by solving Lagrangian equation like Eq. (1).

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_j}\right) - \frac{\partial T}{\partial q_j} + \frac{\partial V}{\partial q_j} = Q_j^{(n)},\ j = 1,2,...,n \tag{1}$$

where T is kinetic energy and V is potential energy. q and Q are generalized coordinate and force.

By solving Eq. (1), a state space model can be represented like Eq. (2).

$$\dot{x}(t) = Ax(t) + Bu(t) + Dw(t) \tag{2}$$

where $x \in \mathbf{R}^{30\times30}$ denotes the state variables, $u \in \mathbf{R}^{30\times12}$ is the input vector, $w \in \mathbf{R}^{30\times24}$ is the road disturbance, and A, B and D are system matrices with appropriate dimensions.

2.2 Nonlinear tracked vehicle model

An experiment with a real tracked vehicle system is impossible due to limitations in terms of cost and space. Thus, commercial software, RecurdynTM, is used instead of the real system. The nonlinear model is depicted in Fig. 1.

Nonlinearities of springs and dampers of a hydraulic suspension unit (HSU) are considered in the nonlinear model. HSUs are located on 1st, 2nd and 6th road arms at each side and only torsion bars are equipped with others.

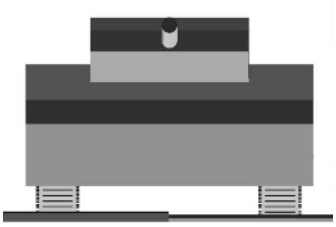


Fig. 1. Nonlinear tracked vehicle model.

3. Reference model tracking preview control

3.1 Preview control based on LQR

Preview control is designed by using LQR. The cost function is given in Eq. (3).

$$J = \int_0^T (\rho_1\ddot{y}^2 + \rho_2\ddot{\theta}_s^{\,2} + \rho_3\ddot{\theta}_R^{\,2} + \rho_3\sum_{k=1}^{6}\theta_{rk}^{\,2} + \rho_4\sum_{k=1}^{6}\theta_{lk}^{\,2} + \rho_5\sum_{k=1}^{6}(y_{rk} - w_{rk})^2 + \rho_6\sum_{k=1}^{6}(y_{lk} - w_{lk})^2 + \rho_7\sum_{k=1}^{6}(u_{rk}^2 + u_{lk}^2)dt \tag{3}$$

Where, $\ddot{y}, \ddot{\theta}_s$ and $\ddot{\theta}_R$ are accelerations of heave, pitch, and roll motions, respectively. $\theta_{rk}(\theta_{lk})$ is an angle of kth right(left) road arm, $u_{rk}(u_{lk})$ means a kth right(left) control input, $y_{rk}(y_{lk})$ is a vertical displacement of kth right(left) road wheel, and $w_{rk}(w_{lk})$ is the road disturbance entering to a kth right(left) road arm.

The cost function includes the terms related to ride comfort, road holding, suspension stroke, and input constraint. Because we are interested in increasing ride comfort of drivers, more weightings are allowed to the terms of heave, pitch and roll accelerations. The cost function can be represented in terms of state vector, input vector and weighting matrices in discrete time domain through some matrix manipulations.

$$J = \sum_{k=1}^{N}\frac{1}{2}x^T(k)Qx(k) + x^T(k)Nu(k) + \frac{1}{2}u^T(k)Ru(k) \tag{4}$$

And then, the preview control based on LQR is derived by using the Hamiltonian. Readers can see more details in the references of [1][6]. The final form of the preview controller is represented in Eq. (5).

$$\begin{aligned} u(k) = -R^{-1}\{(N^T + B^T\phi^{-1}(k)P(k+1)A_n)x(k) + \\ B^T\phi^{-1}(k)P(k+1)Dw(k) + B^T\phi^{-1}(k)r(k+1)\} \end{aligned} \tag{5}$$

where $A_n = A - BR^{-1}N^T$, $\phi(k) = I + P(k+1)BR^{-1}B^T$

As shown in Eq. (5), the final control structure is composed of feedback and feed-forward terms. The feedback term is calculated from the current state values, and the feed-forward term is calculated from the acquired preview information, i.e., road information.

3.2 Reference model tracking preview control

As mentioned in previous sections, preview control is designed based on the linear model. Thus, the error between a linear and a nonlinear model needs to be compensated. TDC is added to do such an action. We refer to the combination of preview control and TDC as reference model tracking preview control (RMTPC), and the control scheme is depicted in Fig. 2.

RMTPC is composed of main three parts such as reference model, tracked vehicle(nonlinear model) and TDC controller. First, the reference model is composed of a linear model and a preview controller. The control input from preview control is merged with the input of TDC. The combined control input goes to a nonlinear model. And then, TDC input is generated to compensate the error between state variables of linear and nonlinear models.

4. Simulation results

Before the evaluation of the controller performance, ISO 2631 will be introduced. It is used to evaluate the ride comfort of the driver. To employ ISO 2631, the weighted RMS value of heave acceleration on the driver's seat should be calculated. Generally, human bodies are sensitive to the special frequency band, so a weighting function is multiplied to the heave acceleration in frequency domain [7]. Comfort reactions of the drivers can be categorized based on the level of weighted RMS values. In addition, it is known that reducing the weighted RMS value to be less than 0.315 m/s^2 is desirable for drivers to feel comfortable [8].

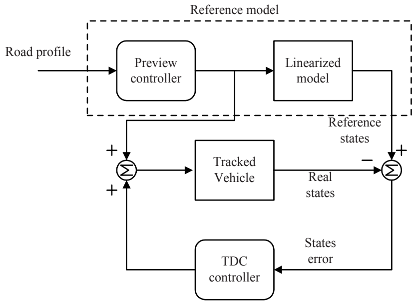


Fig. 2. Reference model tracking preview control.

To evaluate the performance of RMTPC, simulations for a road profile, RRC 9, which is asymmetric, are performed. Fig. 3 shows the road profile of RRC 9.

The simulation is performed for two cases of velocities, 30 kph and 60 kph, which are average speed and maximum speed, respectively. In passive cases, the weighted RMS values are 1.0581 m/s^2 for 30 kph and 1.3522 m/s^2 for 60 kph. From ISO 2631, it is known that drivers feel uncomfortable or very uncomfortable. When RMTPC is applied, however, the values are reduced to 0.0671 m/s^2 and 0.1354 m/s^2, respectively, attaining performance enhancement of 90~95%. Absolutely drivers feel comfortable.

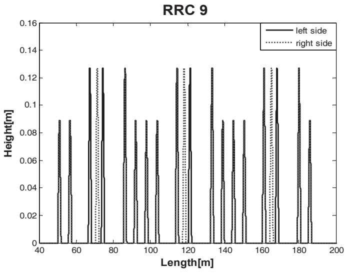
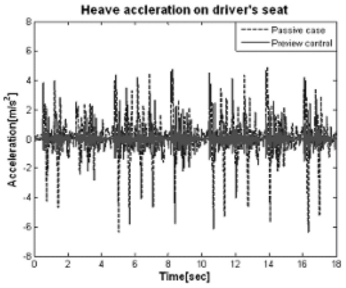
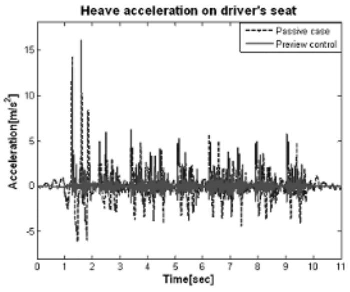


Fig. 3. Road profile of RRC 9.



(a) Velocity : 30 kph



(b) Velocity : 60 kph

Fig. 4. Heave acceleration on driver's seat.

Definitely, these results could be possible under assumption of ideal actuators. The heave accelerations on the driver's seat with respect to time for 30 kph and 60 kph are shown in Fig. 4. It is also shown from the Fig. 4 that the values of the maximum peak are reduced remarkably.

5. Conclusions

In this note, we design a preview control for the full tracked vehicle model. Because preview control is designed based on the linear model, TDC is added to compensate the nonlinearities of a nonlinear tracked vehicle model. The combined control structure is called reference model tracking preview control (RMTPC).

It is shown that the satisfactory level of control performance is achieved for RRC 9 by using RMTPC. The control performance is evaluated in terms of ride comfort of drivers by using ISO 2631 under the assumption that the frequency bandwidth of the actuators is infinite and the velocity is constant.

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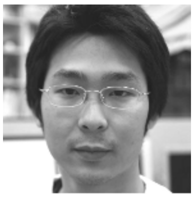

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