Realtime Generation of Smart Speed Pattern for EVs taking Driver's Command Change into Account

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***Abstract*—This paper attempts to draw up a general framework for consideration of motion control of EVs using speed patterns. Design of the speed pattern is related to improvement in ride comfort. The pattern is given as a polynomial with time as the variable. An interesting feature of the proposed method is that three parameters are able to be determined arbitrarily and separately. Some experimental results show that application of speed pattern and determination of parameters can affect the ride comfort.**

I. Introduction

In modern society, vehicles such as trains, automobiles, buses, elevators, planes are indispensable. For pleasant human life, these vehicles are necessary for transportation. Besides, they also should be fast, safe, and comfortable. It is certainly required to take ride comfort into account in evaluation of the vehicles.

Electric motors have remarkable advantages such as quick response of torque and accuracy of torque output, and then preciseness of control with a much shorter control period than that of internal-combustion engine. EVs are suitable for speed control because they use electric motors. For an example, motion control method to improve ride comfort by applying speed pattern was proposed [1]. This research attempts to improve ride comfort in ordinary travelling and emergency by applying speed pattern in wide range of velocity.

In this paper, both the speed and acceleration patterns are implemented in the motion control system of EV, with the acceleration pattern being used as a feedforward input while the speed pattern is used for error correction in a feedback loop. The effectiveness of the proposed method is confirmed by using our experimental EV "UOT (University of Tokyo) March II" shown in Fig.1.

Fig. 1. Photo of UOT March II

II. Ride Comfort and Speed Pattern

There are a lot of factors which affect ride comfort of automobiles: noise, temperature, humidity, and so on. In addition, it cannot avoid objective evaluation [2]. A lot of methods have been tried to improve ride comfort.

Ride comfort is classified to three categories: vertical, horizontal, and longitudinal vibration [3]. The variation in longitudinal acceleration has great influence on ride comfort [4][5]. In usual travelling, a car accelerates or decelerates constantly. Therefore, suppression of the vibration is supposed to improve ride comfort in whole travelling of vehicle. We attempt to achieve suppression of the vibration in a wide range of vehicle velocity by applying speed pattern to motion control of EVs.

Generation of speed pattern for EVs is consisted of three steps [1]:

1) Estimation of driver's intention and calculation of torque input
2) Generation of speed pattern using torque input, vehicle velocity and acceleration
3) Motion control of vehicle utilizing generated speed pattern

Ride comfort is supposed to be improved by achieving two things as follows:

- Smooth and speedy acceleration/deceleration
- Generation and application of speed pattern according to driver's intention of travelling

At the moment of switching between acceleration and deceleration, it is important to suppress variation in acceleration/deceleration. Smooth travelling can be realized by generating speed pattern which has continuity in both acceleration and jerk. Using a large value of acceleration within the bounds of good ride comfort makes speedy acceleration/deceleration possible.

The driver's evaluation of ride comfort is improved by generating speed pattern which is in accordance with driver's intention of travelling and motion of car based on the pattern. Driver's intention of travelling which is estimated from driver's operation of accelerator pedal and brake pedal is utilized for generation of speed pattern.

Driver's driving skill have wide variation, therefore the operation of accelerator/brake pedal does not necessarily correspond to driver's intention of travelling. A driver with proficient skill operates the pedals delicately and constantly in order to realize comfortable travelling. Taking driving support system for the inexperienced drivers and even automated driving system into account, application of speed pattern can improve not only ride comfort but also operationality and safety. Because realization of driver's travelling intention allows drivers to concentrate more on steering and surrounding vehicles.

III. Design of Speed Pattern

A. Optimal Control Theory to Generate Speed Pattern

Jerk, or the time derivative of acceleration, is often related to ride comfort. The level of jerk is said to be inversely proportional to the average value of jerk experienced over a period of time [4]. Therefore, it is logical to make use of jerk in the design of the speed pattern. First the cost function is defined as

$$J = \int_0^{t_f} \left(\frac{da}{dt}\right)^2 dt \tag{1}$$

where a is acceleration, and $\frac{da}{dt}$ is jerk which is to be minimized. Using state space equation $\dot{x} = Ax + Bu$, the solution can be expressed as a polynomial equation. Therefore,

$$v(t) = C_0 t^3 + C_1 t^2 + C_2 t + C_3 \tag{2}$$

$$a(t) = 3C_0 t^2 + 2C_1 t + C_2 \tag{3}$$

are obtained as the solutions. Further, by differentiating equation (3) with respect to time, we get

$$\alpha(t) = 6C_0 t + 2C_1 \tag{4}$$

where $\alpha \equiv \frac{da}{dt}$ is jerk, $C_i (i = 0, 1, 2, 3)$ are arbitrary constant coefficients. They are decided by defining boundary conditions. For an example, by letting the velocities and accelerations at time $t = 0$ and $t = t_f$ be $v(0) = v_0, v(t_f) = v_f, a(0) = a_0, a(t_f) = a_f$, the following equations are obtained.

$$C_0 = \frac{1}{t_f^2}(a_0 + a_f) - \frac{2}{t_f^3}(v_f - v_0) \tag{5}$$

$$C_1 = \frac{3}{t_f^2}(v_f - v_0) - \frac{1}{t_f}(2a_0 + a_f) \tag{6}$$

$$C_2 = a_0 \tag{7}$$

$$C_3 = v_0 \tag{8}$$

As the optimal control theory was applied during the design of the pattern, it is assured that jerk over the period of motion will be kept to the minimum for the given conditions if the pattern is strictly followed.

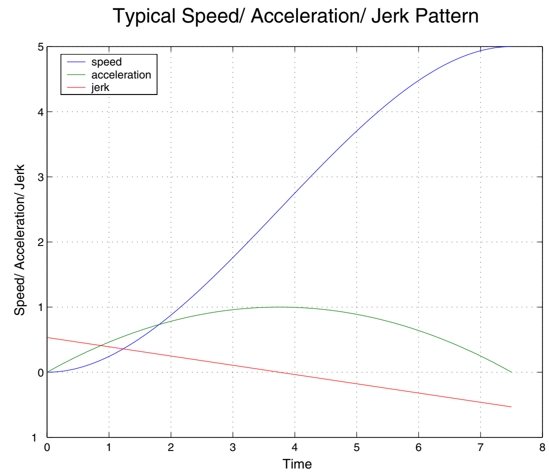

Fig. 2. Speed pattern generated by optimal control theory

B. Realtime Changes in Pattern

When driving a car, a driver operates accelerator pedal and brake pedal very frequently, that is to say, driver's control input constantly changes as surrounding conditions change. There is the very important factor to consider in the application of speed pattern to EVs: if the change of driver's control input occurs during mid-pattern, a new speed pattern must be recalculated in realtime. At that time, non-continuous jerk is undesirable for ride comfort. Therefore, it is necessary to generate new speed patterns which avoid jerk discontinuity in realtime.

C. Problem of the Speed Pattern Generation using Optimal Control Theory

When realtime change of pattern occurs, both continuity of jerk and reduction in acceleration to 0 at the last of pattern are desired. Therefore, by substituting this conditions to equation (4) and (6), the solution for the finish time of pattern after change t_f is obtained as

$$t_f = \frac{-2a_0 \pm \sqrt{4a_0^2 + 6\alpha_0 v_\Delta}}{\alpha_0} \tag{9}$$

where $v_\Delta = v_f - v_0$. Existence of the solution of t_f depends on the initial conditions, or the combination of signs of α_0, a_0, v_Δ. If the solution of t_f does not exist, any new speed pattern cannot be recalculated and speed pattern cannot change in realtime. Therefore, whether new pattern can be generated in realtime entirely depends on the initial conditions. That is to say, there is a possibility that both to keep continuity of jerk and to make acceleration 0 at the finish time cannot be compatible under specific conditions by applying optimal control theory for generation of speed pattern.

To solve this problem, classification of conditions when change of pattern occurs and generation of pattern in each of classes are necessary. However, because changes of pattern occur frequently in travelling actually, this method is inefficient. It is desirable to control vehicles using simpler generation of pattern.

IV. Realtime Generation of Speed Pattern

A. Driver's Command

The driver's operation of accelerator pedal is torque input for an engine or an electric motor. Taking account of the relationship of vehicle velocity and running resistance, accelerator pedal is related to acceleration input. In travelling, drivers operate accelerator/brake pedal delicately. When they want hard acceleration, they step on pedal more strongly and more quickly, and when they want to accelerate gradually, they step on more weakly and more slowly. Therefore, it can be said that length of step relates to acceleration input and velocity of step relates to jerk input. These inputs are used for generation of pattern. The maximum value of acceleration a_{max} and the maximum value of jerk α_{max} are supposed to be determined by driver's intention of travelling. Therefore, in generating speed pattern, a_{max} and α_{max} can be decided from length and velocity of step.

B. Novel Method of Speed Pattern Generation Independent from Finish Time of Pattern

Generation of speed pattern using optimal control theory has a problem that patterns cannot change under specific conditions because the finish time of pattern t_f is determined beforehand. Therefore, in this paper, we propose a novel method of speed pattern generation as follows.

For example, in the process of accelerating with an initial condition ($t = 0 : v = v_0, a = a_0, and \alpha = \alpha_0$), a car accelerates up to a velocity v_f as speedy and smooth as possible. Smooth acceleration can be realized by increasing/decreasing jerk and acceleration continuously. Speedy acceleration can be realized by keeping acceleration a_{max} as long as possible. In this process,

- Keep continuity of acceleration and jerk
- At the moment of reaching to v_f, acceleration a_f and jerk α_f should be 0

are the absolute conditions.

Then, speed pattern is generated from following algorithms.

1) raise a quickly by increasing α to α_{max}
2) if a get near to a_{max}, let α down, and when a reaches a_{max}, make α 0
3) raise v quickly by keeping acceleration a_{max}
4) if v get near to v_f, reduce a quickly by letting α down to $-\alpha_{max}$
5) if a get near to 0, raise α and when v reaches v_f, $a_f = 0, \alpha_f = 0$

Therefore, speed/acceleration/jerk pattern can be expressed as already mentioned,

$$v(t) = C_0 t^3 + C_1 t^2 + C_2 t + C_3 \quad (10)$$

$$a(t) = 3C_0 t^2 + 2C_1 t + C_2 \quad (11)$$

$$\alpha(t) = 6C_0 t + 2C_1 \quad (12)$$

Coefficients $C_i(i = 1, 2, 3)$ are decided by the initial conditions as

$$C_1 = \frac{\alpha_0}{2} \quad (13)$$

$$C_2 = a_0 \quad (14)$$

$$C_3 = v_0 \quad (15)$$

To increase and decrease jerk α continuously, it is necessary to make C_0 as the function of time. C_0 takes the values of $+C, -C, 0$, where C is constant, and is determined by the state of α shown in Fig.3. An example of typical accelerating pattern is shown in Fig.4.

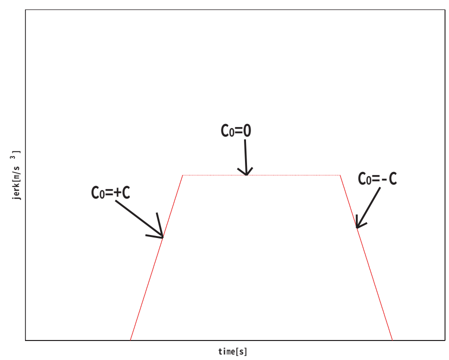

Fig. 3. Determination of C_0

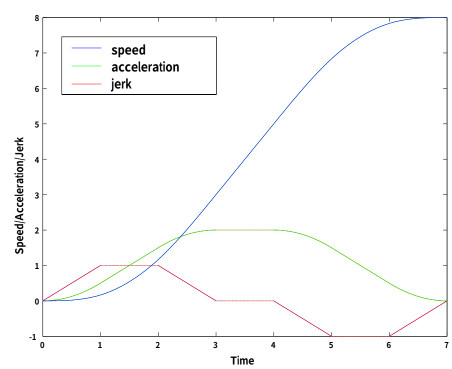

Fig. 4. Typical patterns of acceleration

C. Determination of Pattern Parameters

The advantage of this proposed method is that following three pattern parameters can be determined arbitrarily and separately: C_0, a_{max}, and α_{max}. Change of these parameters achieves variations of change rate in velocity, acceleration and jerk shown in Figs.4, 5, and 6. These figures show that in despite of using the same value of

a_{max}, increasing of C_0, α_{max} makes a profound difference in generated pattern. Therefore, determination of these parameters makes it possible for various speed, acceleration and jerk patterns to be generated.

This advantage enables flexible generation of pattern as follows.

- adjust to favorite travellings of drivers and passengers
- correspond to changes of road conditions rapidly
- deal with emergency braking, sudden changes of surrounding conditions, and so on

In addition, the finish time of pattern t_f is determined by these parameters and initial conditions. Therefore, arbitrary parameters make realtime generation and change of pattern possible without dependence on initial conditions. What change of pattern means is that driver's command for travelling changes. Therefore, the proposed method of speed pattern generation can deal with everything about driver's command change. An example of realtime speed pattern change is shown in Fig.7.

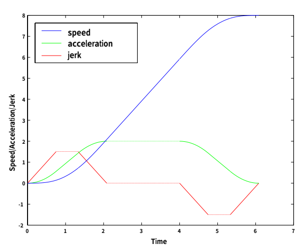

Fig. 5. Acceleration patterns increasing C, α_{max}

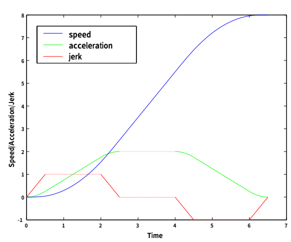

Fig. 6. Acceleration patterns increasing C

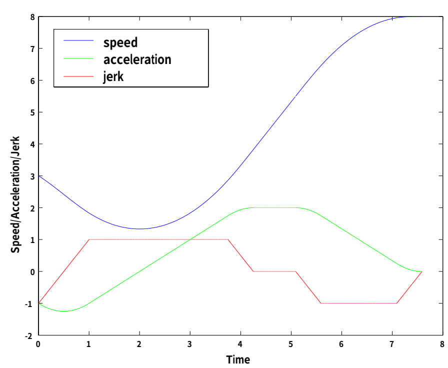

Fig. 7. Typical change of speed pattern in realtime

V. Speed Pattern Control System for EVs

The control block diagram shown in Fig.8 is applied to implementation of the proposed speed pattern. To improve a tracking performance and disturbance robustness, this system contains feedforward of acceleration and feedback of motor speed. The plant is $\frac{1}{Ms}$ in this case where M is the mass of the vehicle. Letting M_n be the nominal mass of the vehicle used in the inverse model, the transfer function of the system from speed reference v^* to output speed v is given by

$$\frac{v}{v^*} = \frac{M_n s + K_p}{Ms + K_p} \quad (16)$$

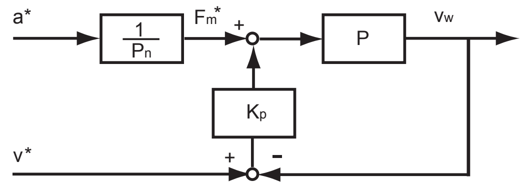

Fig. 8. Block diagram of control system

VI. Experimental Results

Experiments were carried out on a linear flat street paved with large iron plates using our experimental EV ”UOT march II” [6]. In the experiments of acceleration, EV was controlled by the system mentioned in Chapter V using ramp input and speed pattern generated beforehand. We attempted to uniform the conditions between ramp input and speed pattern by keeping speed reference 2m/s for 2 seconds before acceleration. Experimental results are shown in Figs.9 $\sim$ 16.

In the case of both ramp input and speed pattern, tracking errors occurred in whole travelling shown in Figs.9 and 10. EV could not accelerate into speed reference. Especially, at the process of running with constant speed, large value of errors occurred and EV decelerated. The running resistance consisted of friction resistance and air resistance was supposed as a great factor in these errors. In order to improve tracking performance, adjustment of the nominal mass of the vehicle M_n and incrementation of feedback loop gain K_p were attempted. As a result, tracking performance was improved, however the patterns could not be followed strictly.

According to Figs.11 and 12, in the process of accelerating, vehicle is accelerated nearly to the reference value. Meanwhile, in the process of running with constant speed, acceleration was substantially below the reference. On the speed pattern for running at a constant speed, acceleration reference was 0. Therefore, torque reference by the feedforward loop also became 0. As the result of adjustment of the nominal mass, excess motor torque was supposed to counter running resistance in acceleration. In running with constant speed, inversely, the running resistance was not supposed to be countered completely because the torque reference was output only by the feedback loop.

However the tracking did not work out strictly, smooth variations in velocity and acceleration were achieved by application of speed pattern compared with ramp input shown in Figs.9 $\sim$ 12. As a result, Figs.13 and 14 show that suppression of variation in jerk is accomplished. Application of speed pattern improved ride comfort.

Figs.15 and 16 show the effectiveness of the determination of pattern parameters for improvement of ride comfort. In this case, C, which indicates the rate of change in jerk, is different. However these make use of the same values of a_{max}, α_{max}, definite differences occur in rising edges of velocity and acceleration.

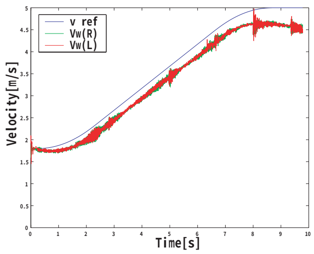

Fig. 9. Vehicle velocity by speed pattern

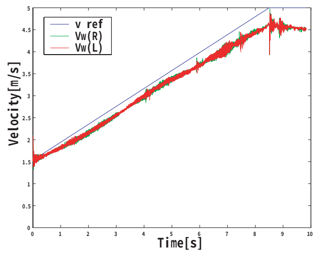

Fig. 10. Vehicle velocity by ramp input

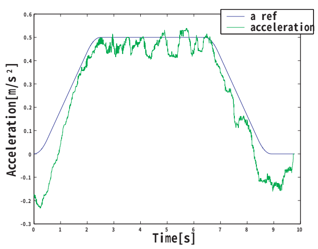

Fig. 11. Acceleration by speed pattern

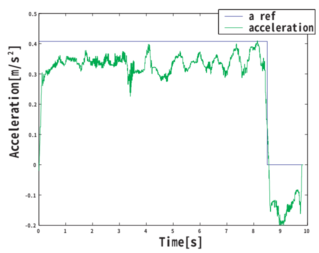

Fig. 12. Acceleration by ramp input

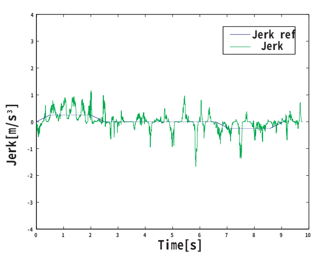

Fig. 13. Jerk by speed pattern

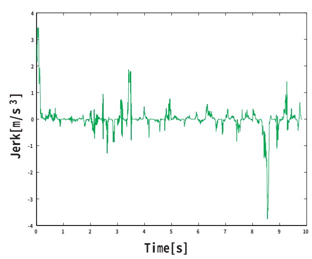

Fig. 14. Jerk by ramp input

VII. Conclusion

A novel method of motion control for EVs to improve ride comfort using speed pattern was presented. The method is applied to an EV through a control system with acceleration feedforward and velocity feedback loop. The most remarkable point of our research is in generation of speed pattern which has arbitrary parameters. This advantage enables us to generate speed pattern in realtime when driver's command and surrounding conditions change. Ride comfort can be improved by application of speed pattern and determination of the parameters.

This method has wide-range potential applications. For example, it can be used for the design of speed patterns

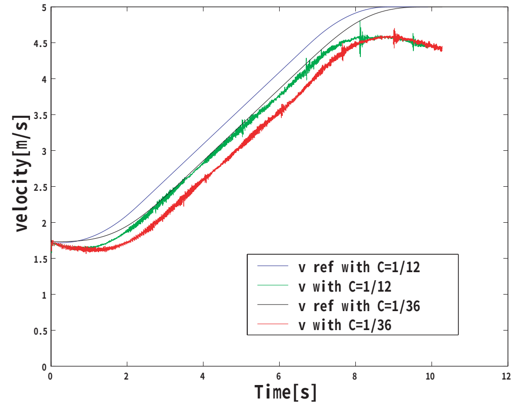

Fig. 15. Velocity with deferent C

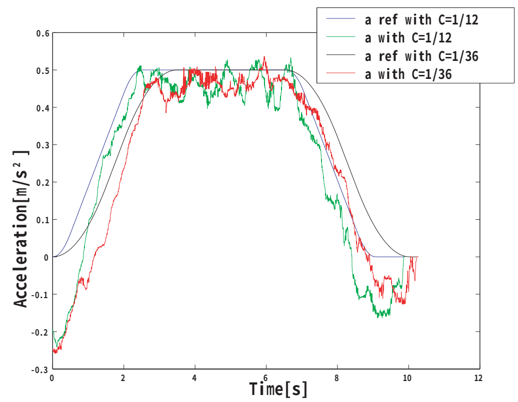

Fig. 16. Acceleration with deferent C

for autonomous vehicles travelling under ITS scheme, or that for a drive-by-wire system. High controllability of EVs realizes the proposed motion control. We think fundamental merits of EVs are not only benefits to the environment and energy efficiency, but also its possibility of high performance motion control. It can make EVs much safer and more comfortable than internal combustion engine vehicles, therefore dissemination of EV is supposed to be accelerated.

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