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Development of Vehicle Pitch Motion Control based on Human Perception System

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Executive Summary

Vehicle pitch motion which occurs during acceleration can affect ride comfort of passengers. To improve this, suspension system hardware should be modified. But in this paper, we propose a control method for improving ride quality using powertrain control without the hardware modification. For this, a control strategy based on human perception system is developed to reduce the pitch motion during acceleration without side effect on drivability. Also a simple estimating pitch model of a vehicle which uses demand torque as input is developed to control torque of powertrain. It is confirmed that pitch motion was reduced and also ride quality was improved in the vehicles by this proposed method.

Keywords: Powertrain, Propulsion, Torque, Controller, Perception

1 Introduction

When a vehicle accelerates, a front of the vehicle is lifted due to action between the vehicle inertia and the suspension system. We call this "pitch motion" or "nose up" (Figure 1). This pitch motion can shake passengers up and down in the vehicle with each acceleration, that can worsen ride comfort and even cause motion sickness. To reduce this motion, suspension system should be redesigned as stiffer but this kind modification can be negatively affect ride comfort. And this phenomenon is more common in SUVs which have higher center of mass. To solve this problem, we propose a control method for improving ride quality using powertrain control without the hardware modification. Since there is a high correlation between pitch motion and acceleration torque, we assume that this pitch motion can be reduced by controlling acceleration torque. Because a rootcause of the pitch moditon is longitudinal acceleration which is generated by a powertrain.

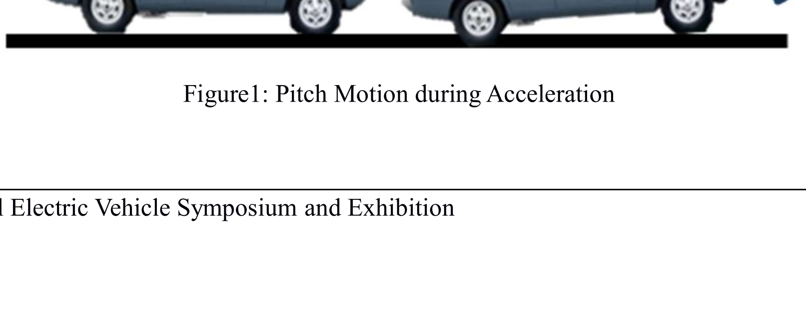

Figure1: Pitch Motion during Acceleration

To control pitch motion suitable, we reviewed a human perception system to understand that how human feel pitch motion. Previous study about human perception is about a vestibular system, that is very objective and suitable for designing control logic. And based on this, we designed control strategy that minimizes pitch rate by controlling powertrain torque. We developed a simple vehicle model which used demand torque as input to estimate pitch angle during acceleration without a pitch sensor. Using this model, we can estimate an additional pitch rate during acceleration. Designed simple vehicle model has good performance to estimate a pitch angle during acceleration in the real vehicle.

And we re-designed a demand torque controller that modifies demand torque to reduce the pitch rate. The re-designed demand torque controller can reduce the pitch rate suitably by modifying demand torque profile without side effect on drivability. Also We found that reduced the pitch rate by powertrain control can reduce unintentional feeling of passenger during acceleration and improving a ride quality.

2 Relation between Perception and Pitch Motion

Vestibular System is located in the inner ear and consists of an otolith that senses linear motion and a semicircular canal that detects rotation (Figure 2). The semicircular canal is composed of copula and lymph. When human head rotates, the cupula is deformed as the lymph fluid moves due to inertia and deformed cupula sent electrical signal to cerebellum, then rotation is recognized. But amount of perception is difficult to quantify because the sense of acceleration varies from person to person. Because when the signal from the vestibular system is processed in cerebellum, which can be influenced by person's experience or tendency. So we focused on the cupula behaviour to make this more objective problem. We assumed that cupula characteristic has less deviation compared to the person's experience or tendency.

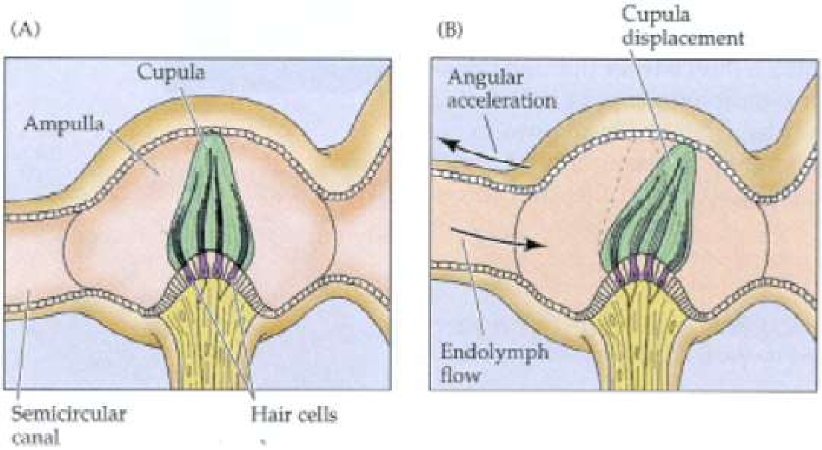

Figure 2: Structure of Semicircular[1]

To understand human perception related the pitch motion more objectly, we reviewed a mathmetical model of the vestibular system. This vestibular system model was developed by Van Egmond[2] and Mayne[3] as equation (1). This transfer function which is based on torsion-pendulum represent relation between anguluar velocity and deformation of cupular.

$$\frac{\theta_e(s)}{\alpha(s)} = \frac{\tau_1\tau_2}{(1+\tau_1 s)(1+\tau_2 s)} \tag{1}$$

But this model does not completely represent rotational sensation. So Young and Oman[4] proposed adding adaptation operator and Zrcharias[5] report several experiment adding lead component like as equation (2)

$$\frac{\phi_c}{\alpha} = K\left[\frac{\tau_a s}{(1+\tau_a s)}\right]\left[\frac{(1+\tau_L s)}{(1+\tau_1 s)(1+\tau_2 s)}\right] \tag{2}$$

Zacharias[5] assumed that the anular velocity from semicircular canals that is sensed by human subjects is proportional to the cupular deflection. So Zacharias described a relation between input and output of the cupula as equation (3).

$$\frac{\hat{\omega}}{\omega} = \frac{\tau_1 s}{(1+\tau_1 s)(1+\tau_2 s)} \quad (3)$$

This transfer function represents amount of a cupula deflection and a signal which sent to cerebellum when head rotates at what angular speed. This transfer function means that human feels rotating motion based on an angular velocity of theirs heads. So we can understand that we have to reduce the angular velocity of passanger's heads to improve ride quality during acceleration.

Based on equation (3), we found that the angular velocity is important value related humansto reduce the feeling of accelerationthe angular velocity of passanger's head during acceleartion, modifying suspension system and controlling acceleration torque can be considered. More stiff dampers can reduce a vehicle motion during acceleration. But these modified damper can have another side effect on ride quality. If we can control a rate torque of powertrain which is another rootcause of pitch motion without side effects on driverablity like torque ald or lack of power, we can also control the angular velocity of passanger's head using torque. For this we designed a control strategy to reduce rate of pitch motion.

3 Vehicle Pitch Estimation and Control Design

3.1 Vehicle Pitch Estimation

There is no pitch rate sensor in a mass production vehicle, a vehicle pitch model is needed to estimate pitch rate for this control strategy. To design the pitch estimation model, we assuming that the vehicle is a rigid body, and it is simplified to a secondary system that uses acceleration as input. We can describe the proposed pitch estmation model like equation (4). The natural frequency(ω_n) and damping coefficient(ζ)of the vehicle can be get with a simple acceleration test on the vehicle and a system identification process.

$$\frac{\theta_{pitch}}{a_{veh}} = \frac{G_{po}}{(\frac{s}{\omega_n})^2+2\zeta\frac{s}{\omega_n}+1} \quad (4)$$

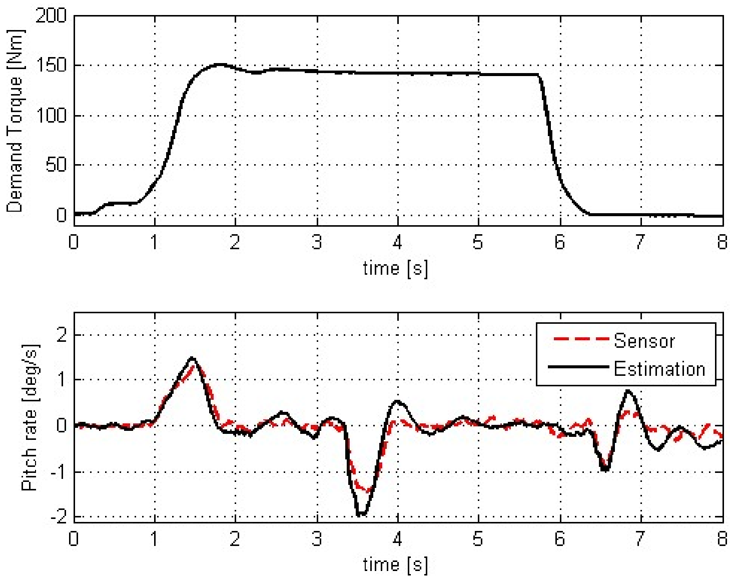

Figure 3: Comparison of Estimated and Measured Pitch

To check performance of the pitch estimation model, we put the model on a vehicle controller and tested with a pitch measuring device. We found that estimated pitch has sufficient accuracy to control pitch rate described as Figure 3. During acceleration, proposed pitch model estimated pitch rate of the vehicle. But we can find that estimating pitch rate is not correct after acceleration(around 3.5s). Because this model and parameters are used only for acceleration because parameters of suspension system can be changed during deceleration due to a expantion/deflation characteristic of dampers.

3.2 Design Pitch Motion Controller

As previous described, the proposed control strategy is that demand torque should be controlled to minimize the pitch rate. For that we designed a pitch rate controller like as Figure 4. The pitch rate estimation model has demand torque as input, calculates estimated pitch rate like equation (5). Compare to equation (4), input was changed to demand torque from vehicle acceleration. Because using acceleration to pitch estimation, it is good for getting exact pitch rate, but that is not good for modifying drive demand torque due to lag between target torque and real acceration. We can get estimating pitch rate without lag and sensor noise by design like this.

$$\ddot{\theta} = \omega_n^2 T_m - 2\zeta\omega_n\dot{\theta} - \omega_n^2\theta \tag{5}$$

This demand torque based estimated pitch rate and desired pitch rate (zero) make a compensation torque with control gains. That means this controller modify a driver demand torque to maintain zero pitch rate. Of course zero pitch rate means there is no additional torque, so pitch rate should be allowed appropriate level. Therefore proposed controller make compensation torque which reduces driver demand torque to control pitch rate like figure(4). And to implemt this control strategy, precise toqrue control is required. Threfore, accurate torque control of the engine and motor must implemented first.

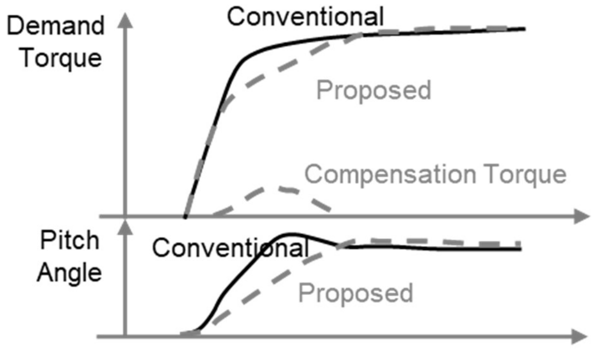

Figure 4: Control Concept for Pitch rate Control

There are calibratable gains that can be used according to various situation. For example, low gear step can make more torque and pitch motion, the compensation torque should be increased when low gear engaged. But high gear can not make big torque to shake vehicle, the modified torque don't need to reduce drive demand torque. Also some drivers want pitch motion to feel acceleration in a sports mode, for that propoased controller can adjust amount of torque based on the drive mode of vehicle. Overview of the proposed controller design can be described as figure 5.

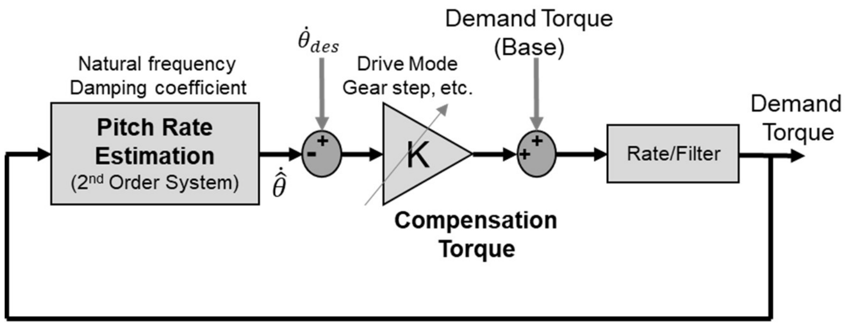

Figure 5: Pitch Rate Controller Design

4 Vehicle Test and Result

We tested the proposed pitch controller on a vehicle with a pitch motion measuring device. We found that the pitch rate reduced and passangers could feel improved ride quality during acceleration (Figure 6). The modified demand torque was reduced maximum 30% of base demand torque to reduce the pitch rate. But because of the proposed controller reduced demand torque slowly, driver could feel smoother accelearion during the launch instead of lack of power. Meanwhile the pitch rate was reduced by up to 40%, passengers felt a more linear and smoother acceleration feeling due to reduced pitch rate. And this result is consistent with our previous analysis of human perception and pitch motion.

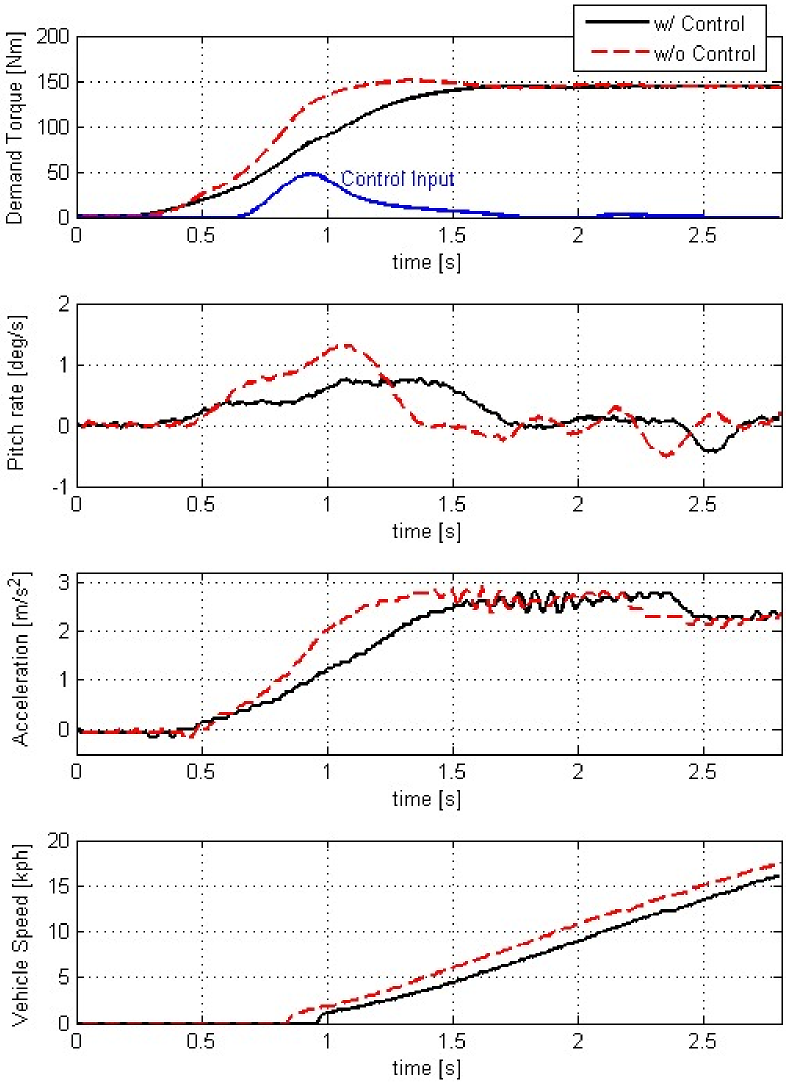

Figure 5: Test Results

By this vehicle test, we proved our assumption which is the small pitch rate can give small pitch feeling during acceleration. Especially related pitch feeling, most of passengers said that ride quality was improved. Also we found a method to find a balance between acceleration feeling and pitch motion feeling. Based on this research, we modified our proposed controller to use for a smart cruise control. When the smart cruise control activated, driver do not manuplate accelerator pedal. So we developed the balance strategy between acceleration and pitch motion for the smart cruise control. When smart cruise control activated, proposed controller get a higher gain to reduce pitch rate during acceleration. In that case, acceleration feeling can be neglectable becase driver doesn't control acceleration of vehicle. So we get a achievement on the ride quality improvement during the smart cruise control activated.

5 Conclusion

In this paper, we proposed a control method to improve ride quality by controlling powertrain. For this, we reviewed a perception mechanism of a human. And base on this, we assumed that if a pitch rate can be controlled by a drive motor, then the unintentional pitch feeling of passenger can be reduced. To confirm the assumption, simple pitch estimation model and a pitch rate controller were designed. And we found that the vehicle pitch motion was controlled properly by the proposed pitch rate controller and ride quality was improved. Additionaly, precised torque control is required to control pitch motion without side effect on driverablity, so this kind control strategy can only be implemented on HEVs or EVs. Proposed control strategy has been implemented in various production model those are midsize sedan, large luxury sedan and midsize SUVs with HEV system. And the pitch motion control strategy is developing for a electronic vehicle.

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Presenter Biography

Cho, Lee Hyoung received the MS degree in mechanical engineering from KAIST, Daejeon, Korea in 2008.In 2008 he joined the Powertrain Control Team of Renault Korea as a research engineer and worked for developing SW of CVT and Auto Transmission. In 2013 he joined the Advanced Technology Institute of Doosan Infracore and worked for developing controller for diesel engine and hydraulic integrated system for an excavator. In 2015 he joined the Electrification Control System Development Team of Hyundai Motor Company and has been working for developing a vehicle control for internal combustion engines, hybrid electric vehicles. His current research interests include electrified powertrain control and vehicle motion control.