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Development of a Washout Algorithm for a Vehicle Driving Simulator Using New Tilt Coordination and Return Mode

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A vehicle driving simulator is a virtual reality device which makes a man feel as if he drove an actual vehicle Unlike actual vehicles, the simulator has limited kinematical workspace and bounded dynamic characteristics So it is difficult to simulate dynamic motions of a multi-body vehicle model In order to overcome these problems, a washout algorithm which controls the workspace of the simulator within the kinematical limitation is needed However, a classical washout algorithm contains several problems such as generation of wrong sensation of motions by filters in tilt coordination, requirement of trial and error method in selecting the proper cut-off frequencies and difficulty in returning the simulator to its origin using only high pass filters This paper proposes a washout algorithm with new tilt coordination method which gives more accurate sensations to drivers To reduce the time in returning the simulator to its origin, an algorithm that applies selectively onset mode from high pass filters and return mode from error functions is proposed As a result of this study, the results of the proposed algorithm are compared with the results of classical washout algorithm through the human perception models Also, the performance of the suggested algorithm is evaluated by using human perception and sensibility of some drivers through experiments

Key Words : Vehicle Driving Simulator, Washout Algorithm, New Tilt Coordination, Return Mode

1. Introduction

Vehicle driving simulator is a virtual reality device which drivers feel as if they drive a real car In order to reappear reality of driving situation, we analyze vehicle motion generated by operating a steering wheel and accelerate pedal, and provide the motion situation such as the sense of motion, sight and hearing to driver according to the analysis

How can motion situation such as the characteristic of vehicle dynamics, the sense of motion according to change of driving condition, and

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the sense of sight and hearing reappear reality makes the efficiency of a vehicle driving simulator (Drosdol and Panik, 1985). However, a real vehicle has no limitation of motion range, a motion system which copies the real motion has a limitation to reappear the sense of motion because it has a limitation in kinematic motion range and dynamic characteristic of the system. Therefore we need a washout algorithm which limits motion range of a vehicle within a physical limitation of the simulator (Freeman et. al., 1995; Suetomi et al., 1991).

A representative washout algorithm is a classical one. However a classical washout algorithm has advantages such as short analysis time and verified stability, there are several problems such that it is difficult to select cut-off frequency of used filters, the original signal is falsified on tilt coordination; there is a limitation to reappear a continuous motion only restoration by filter and etc (Greenberg and Park, 1994; Samji and Reid, 1992). In order to overcome problem and a limitation of classical washout algorithm, we develop new tilt coordination algorithm and washout algorithm considering a return component. And we compare the proposed algorithm with classical washout algorithm quantitatively using human perception model.

2. Classical Washout Algorithm

2.1 Human perception model

Human feels translation motion by detecting specific force in otolith and rotational motion by detecting rotational angular acceleration in vestibular. The specific force detected in otolith is obtained by subtracting acceleration of gravity from translational acceleration such as

$$\overrightarrow{sF} = \vec{a} - \vec{g} \qquad (1)$$

where $\vec{a}$ is translational acceleration, $\vec{g}$ is acceleration of gravity.

Human sensory organ is modeled in spring, mass and damper system by Young and Oman. And transfer function of otolith system shows in Eq. (2) (Peter and Burnell, 1981). The characteristic of frequency response of otolith system has good perception in the band of 0.01~0.5 Hz.

$$G(s)_{otolith} = \frac{k(\tau_A s + 1)}{(\tau_L s + 1)(\tau_S s + 1)} \qquad (2)$$

The transfer function of the modeled vestibular system shows in Eq. (3), and the characteristic of frequency response has good perception in the band of 0.01~0.5 Hz.

$$G(s)_{vestibular} = \frac{T_L T_A s^2}{(T_L s + 1)(T_S s + 1)(T_A s + 1)} \qquad (3)$$

2.2 Classical washout algorithm

Classical washout algorithm is divided by three parts largely. One is translational washout, another is rotational washout and the other is tilt coordination. And the layout of the algorithm is shown in Fig. 1. The translational and rotational acceleration of a car derived from analysis result of car dynamics are inputted to washout algorithm, and then inputted signal is outputted to translational and rotational acceleration which can be reappeared in simulator through washout algorithm.

Translational motion washout algorithm consists of high pass filter separated two steps and coordinates transformation. The algorithm removes low frequency element using the first step high pass filter and generates high frequency acceleration on center of upper plate of motion generator. The acceleration on center of upper plate of motion generator is converted to the acceleration of center coordinate system of under plate through coordinate transformation. We can't reappear the motion within kinematical limitation of motion generator only using the first step high

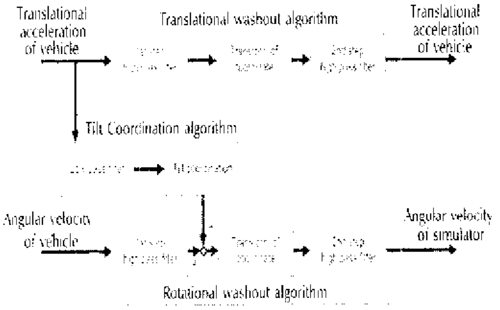

Fig. 1 Schematic diagram of classical washout algorithm

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pass filter because there is incidental specific force according to Bryant angle of motion generator in coordinate transformation process. In order to solve the problem, we generate high frequency translational acceleration on center of under plate of the motion generator using the second step high pass filter.

The rotational motion washout algorithm consists of high pass filter of 2 steps and coordinates transformation. The algorithm removes continuous low frequency rotational angular acceleration inputted to coordinate system of a car seat using the first step high pass filter and is converted to rotational angular acceleration which is represented to Bryant angle by coordinate's transformation. And it generates high frequency rotational angular acceleration which can return to the origin on restricting a gimbals angle of motion generator using the 2^{nd} high pass filter (Reid and Nahon, 1998).

We can't generate a low frequency specific force only using translational motion washout because the translational motion washout generates only high frequency specific force using the high pass filter. However, if we use tilt coordination algorithm, specific force which is removed in translational motion washout algorithm can be generated by tilt angle tracking rotational motion. As driver feels a specific force in the opposite direction to the amount of gravity, we can generate a specific force by tilting a motion generator in the opposite direction to the gravity vector.

The classical washout algorithm has advantages of fast computation, stable performance and etc. but has two problems.

First, the phase and characteristic of magnitude are falsified when the sum of high frequency and low frequency specific force is compared with specific force which is reappeared because high pass and low pass filter which are used in tilt coordination are not an ideal filter.

Second, the classical washout algorithm generates high frequency motion which can reappear within limitation of kinematic motion using high pass filter. However, a signal passed through these high pass filters caused to generate larger motion in the opposite direction to the movement of original signal according to larger cut off frequencies. Since then the motion inputted from high pass filter returns to the origin, the motion passing through high pass filter returns to the motional origin after a regular time. Therefore continuously generated motion can't be reappeared satisfyingly because there is a limit to reduce the time which it takes to return to the motional origin completely as using only force of restitution by high pass filter.

3. New Tilt Coordination Algorithm and Washout Algorithm Considering Return Mode

3.1 New tilt coordination algorithm

For translational and rotational angular acceleration which is analyzed from car dynamics, the motional perception which is recognized from a human perception model is the car motional one generated without signal processing such as washout algorithm. Fig. 2 is a schematic diagram for sensations of motion in actual vehicle.

The specific force which is recognized through driver's otolith in Eq. (1) is translated to coordinate system of the center of seat and then we can get Eq. (4) as

$$\overrightarrow{sF_P}=\overrightarrow{a_P}-{}^{P}_{G}R(\alpha,\ \beta,\ \gamma)\overrightarrow{g}=\begin{bmatrix} a_{px}+g\sin\beta \\ a_{py}-g\sin\alpha\sin\beta \\ a_{pz}+g\cos\alpha\cos\beta \end{bmatrix} \quad (4)$$

where $\overrightarrow{a_P}$ is translational acceleration of the coordinate system of the seat, $-{}^{P}_{G}R(\alpha,\ \beta,\ \gamma)\overrightarrow{g}$ is acceleration of gravity of the coordinate system of the seat.

We substitute $\overrightarrow{a_P}$ for specific force by translational motion, $\overrightarrow{sF_{Pt}}$, and $-{}^{P}_{G}R(\alpha,\ \beta,\ \gamma)\vec{g}$

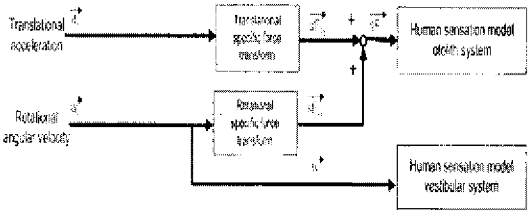

Fig. 2 Schematic diagram for sensations of motions in actual vehicle

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for specific force according to rotational motion, $\overrightarrow{sF_{\mathrm{Pr}}}$. Then specific force in coordinate system of seat is represented as

$$\overrightarrow{sF_P}=\overrightarrow{sF_{Pt}}+\overrightarrow{sF_{\mathrm{Pr}}} \tag{5}$$

Fig. 3 is a schematic diagram for sensations of motions by classical tilt coordination. In order to remove continuous translational acceleration using high pass filter and reappear a specific force which can not be reappeared by translational motion in classical washout algorithm, we generate low frequency translational acceleration by passing through low pass filter and then generate specific force through tilt coordination. The generated specific force using classical tilt coordination is written as

$$\overrightarrow{sF_{P,Classical}}=\overrightarrow{sF_{Pt,High}}+\overrightarrow{sF_{\mathrm{Pr},Low}}+\overrightarrow{sF_{\mathrm{Pr}}} \tag{6}$$

where $\overrightarrow{sF_{Pt,High}}$ is a specific force which is generated by high frequency translational acceleration passing through high pass filter, $\overrightarrow{sF_{\mathrm{Pr},Low}}$ is a specific force is generated after doing tilt coordination of low frequency translational acceleration passing through low pass filter.

However, real high pass and low pass filter are not ideal filers which can filter a signal completely ; the sum of the specific force which is applied to low and high pass filter is falsified with the original specific force.

Fig. 4 represents a schematic diagram for sensations of motions by new tilt coordination. In this paper, we propose new tilt coordination algorithm which uses the difference between translational acceleration and translational one passing through high pass filter in order to solve the problem using low pass filter on tilt coordination.

In order to generate additional specific force, acceleration component ($\overrightarrow{a_{P,Diff}}$) which is inputted to tilt coordination is defined as

$$\overrightarrow{a_{P,Diff}}=\overrightarrow{a_P}-\overrightarrow{a_{P,High}} \tag{7}$$

where $\overrightarrow{a_P}$ is a translational acceleration of the seat which is acquired from analysis result of car and $\overrightarrow{a_{P,High}}$ is translational acceleration passing through high pass filter.

The generated specific force by translational acceleration is defined as

$$\overrightarrow{sF_{Pt}}=\overrightarrow{sF_{Pt,High}}+\overrightarrow{sF_{\mathrm{Pr},Diff}} \tag{8}$$

where $\overrightarrow{sF_{Pt}}$ is the generated specific force by translational acceleration, $\overrightarrow{sF_{Pt,High}}$ is the generated specific force by translational acceleration passing through high pass filter, and $\overrightarrow{sF_{\mathrm{Pr},Diff}}$ is the generated specific force by the proposed tilt coordination algorithm.

The specific force which a driver recognizes on seat is represented as sum of the specific force by high pass filter, tilt coordination, and rotational angular acceleration. And the specific force which is generated by the proposed algorithm is defined as

$$\begin{aligned}\overrightarrow{sF_{P,New}}&=\overrightarrow{sF_{Pt,High}}+\overrightarrow{sF_{\mathrm{Pr},Diff}}+\overrightarrow{sF_{\mathrm{Pr}}}\\&=\overrightarrow{sF_{Pt}}+\overrightarrow{sF_{\mathrm{Pr}}}=\overrightarrow{sF_P}\end{aligned} \tag{9}$$

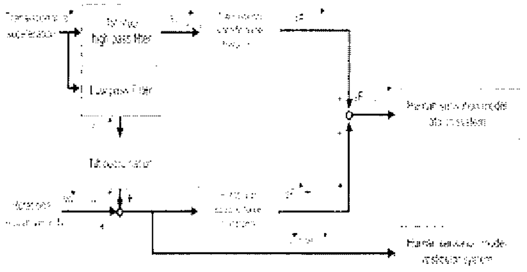

Fig. 3 Schematic diagram for sensations of motions by classical tilt coordination

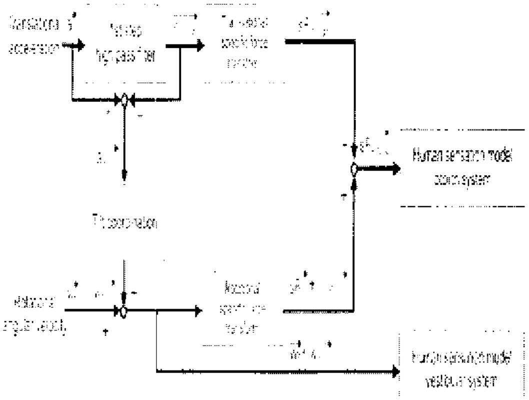

Fig. 4 Schematic diagram for sensations of motions by new tilt coordination

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3.2 Washout algorithm considering return mode

3.2.1 Return of the motional origin in classical washout algorithm

In classical washout algorithm, we generate a high frequency motion which can reappear in limitation of kinematic motion using high pass filter. After the motion which is inputted to high pass filter have been returned, to the origin of motion the motion which passes through high pass filter is returned to the one after a time.

Figs. 5 and 6 show a yaw directional angular velocity and angle through high pass filter. Cut off frequency of the high pass filter is 0.01 Hz. A solid line is a rotational angular velocity and rotational angle of the car when a driver turns left. A dotted line is a rotational angular velocity and a rotational angle which are transformed by high pass filter. An angular velocity which is opposite to motional direction is generated as shown in Fig. 5 as a low frequency component is removed by high pass filter. A rotational angle of car without washout preserves 90 degrees after left turn. However a rotational angle with classical washout increases to 60 degrees and returns to 0 degree of motional origin. That is, a rotational motion is onset mode till reaching peak angle. Then return mode starts. The motion rotates in the opposite direction to motional one and then returns to the origin slowly. Under conditions before returning to the origin completely and on being in move on opposite direction of the motion, if a continuous motion generates, motion generator will deviate from position limitation. Because various motions generate continuously in real car driving situation, the return of the motional origin is done as fast as possible and the opposite motion has to be removed.

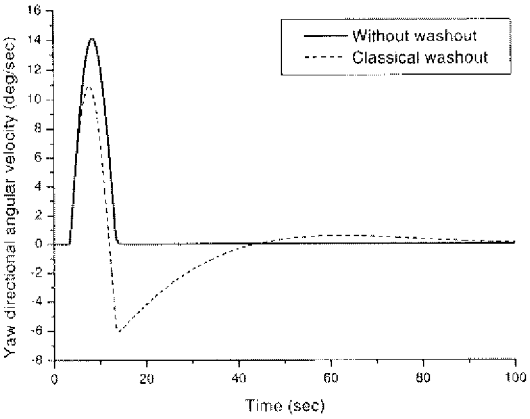

Fig. 5 Yaw directional angular velocity through high pass filter

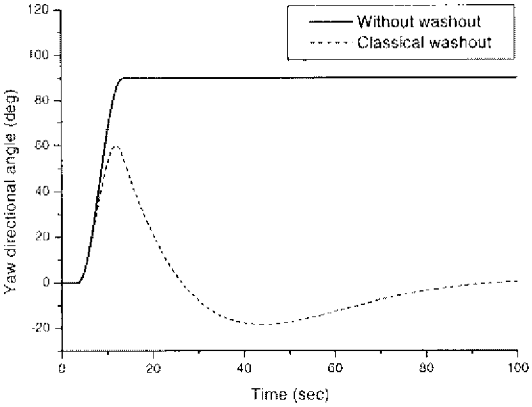

Fig. 6 Yaw directional angle through high pass filter

3.2.2 Washout algorithm considering return mode

In this study, we propose the algorithm which compensates for return mode using an error from the motional origin because there is limitation in reducing time which takes to completely return to the motional origin, in case of using only a force of restitution by high pass filter.

Fig. 7 shows a schematic diagram of washout algorithm using return mode. Washout algorithm using return mode consists of high pass filter, error function, switching function, integrator, and mode selector. An analytical result of vehicle

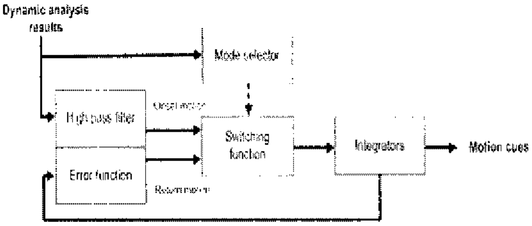

Fig. 7 Schematic diagram of washout algorithm using return mode

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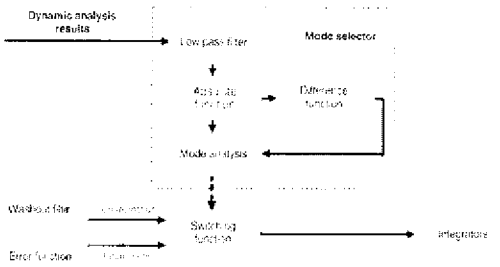

Fig. 8 Schematic diagram of mode selector

dynamics such as translational acceleration and rotational angular velocity is inputted to the proposed algorithm and motion cues which can generate within motional origin is outputted.

The algorithm removes a low frequency element which makes motion get out of motional limitation using high pass filter and select high frequency element passing through filter as a beginning motion which is from motional origin to peak displacement and rotational angle. The algorithm generates a return motion using integrator and error function and motional cue which can be implemented in simulator and always return to the origin.

Figure 8 shows a schematic diagram of mode selector which analyzes motion mode and controls a switching function. Mode selector consists of low pass filter to remove a noise, absolute function to consider return element in bidirectional motion, difference function to find time variable rate, and mode analyzer which analyzes a preprocessed signal and determines motion mode. We select a motion from motional origin to peak angle as a beginning mode and a motion mode shown in Fig. 6. However the result of vehicle dynamic analysis in analyzing motion mode is used because there is a problem such as a phase lead when we use a signal passing through high pass filter in analyzing mode.

4. Quantitative Evaluation Through Simulation

4.1 Virtual driving circumstance

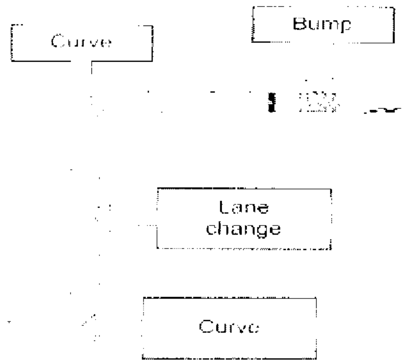

Fig. 9 Road map for simulator

Virtual driving circumstance is composed of a scenario which drives an asphalt road in the city. In order to estimate reappearance of sensations of motions variously, a road map includes general road conditions such as a straight road, curve, a change of lane, a bumper passage, a variable speed range, and an uneven road as shown in Fig. 9.

4.2 Quantitative evaluation for sensations of motion by new tilt coordination

Figs. from Fig. 10 to Fig. 15 show sensations of motions in virtual driving circumstance. We select sensation of translational motion of surge and sway direction and sensation of rotational motion of roll and pitch direction, because heave and yaw directional elements don't have effect on tilt coordination. Cut off frequency of high pass filter and low pass filter is all 0.01 Hz. In the figure which represents all directional sensation of motion, the solid line is sensation of motion which is response of human sensation model about vehicle analysis result not passing through wash out algorithm, a long dotted line is sensation of motion in simulator by classical tilt coordination and a short dotted line is a sensation of motion by new tilt coordination. Error of sensation of motion is defined as a difference between directional sensation in vehicle and directional sensation in simulator.

Figures 10 and 11 show surge directional sensation and surge directional sensation error. Directional sensation by classical tilt coordination as shown in Fig. 10 is falsified in characteristics

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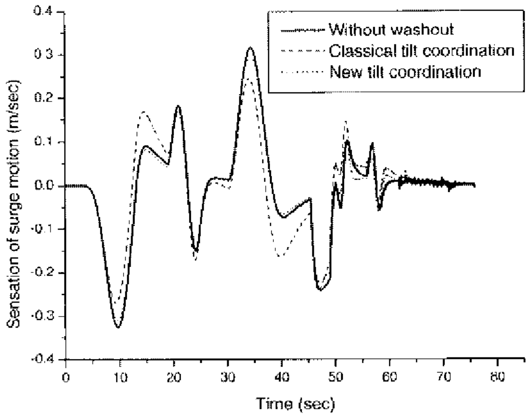

Fig. 10 Surge motion sensation

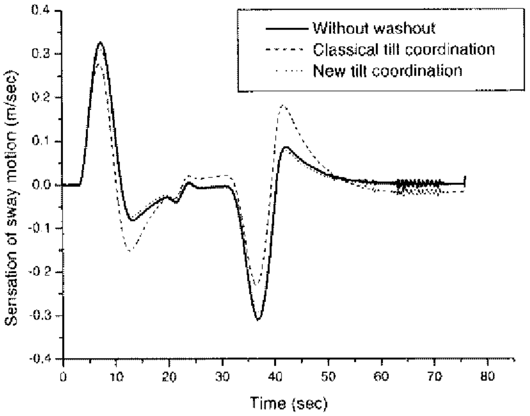

Fig. 12 Sway directional sensation

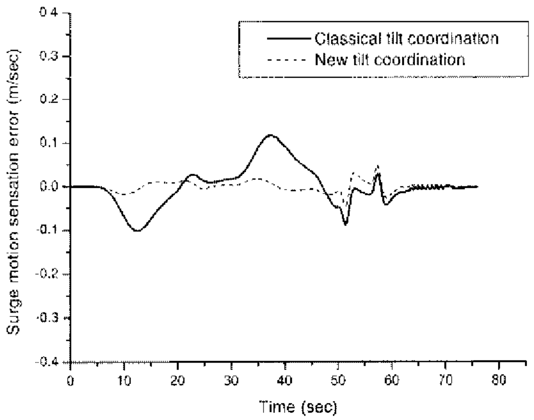

Fig. 11 Surge directional sensation error

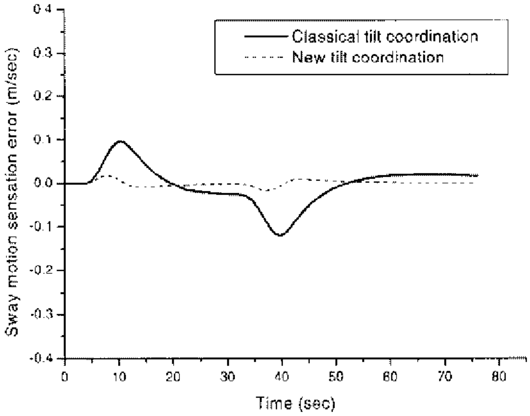

Fig. 13 Sway directional sensation error

of magnitude and phase compared with directional sensation by new tilt coordination. In Fig. 13, directional sensation error by classical tilt coordination represents within about ±0.1 m/sec of 30% of total surge directional sensation while directional sensation error by new tilt coordination represents within about ±0.02 m/sec.

Figures 12 and 13 represent sway directional sensation in translation and sensation error. Same as result of surge direction, characteristics of magnitude and phase by new tilt coordination is less falsified. And directional sensation error is decreased within ±0.02 m/sec range.

Figures 14 and 15 represent roll and pitch rotational sensation. Additional roll directional sensation in new tilt coordination is maximum ±0.4 degrees. However coordination However, considering a maximum magnitude of ±10 degrees in pitch directional sensation, we can assume that the additional rotational sensation does not affect total rotational sensation.

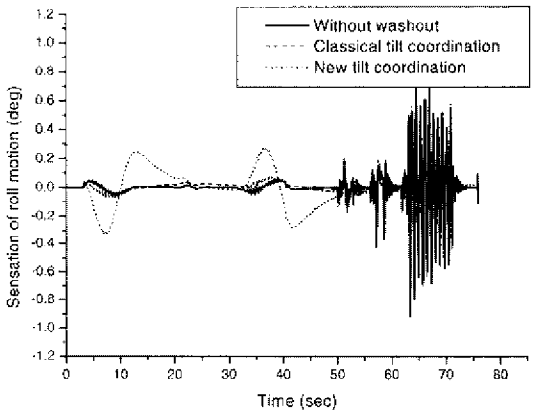

Fig. 14 Roll directional sensation

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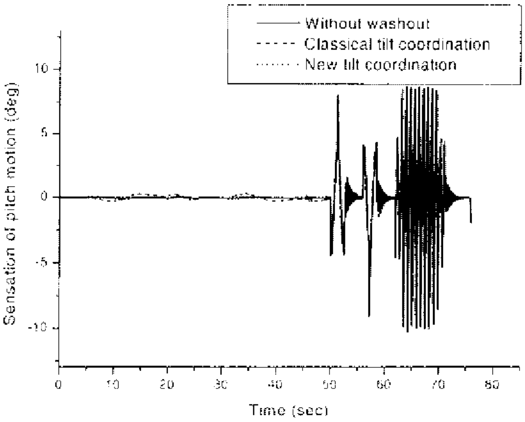

Fig. 15 Pitch directinal sensation

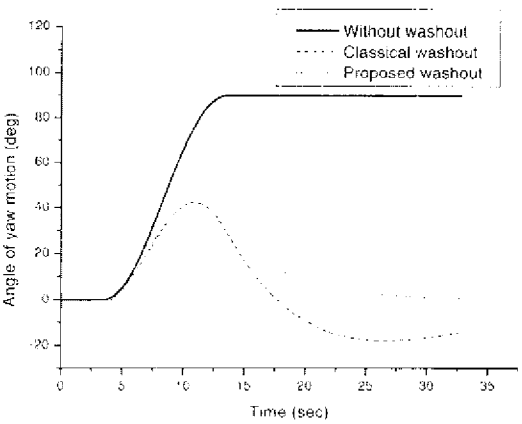

Fig. 16 Yaw motion angle

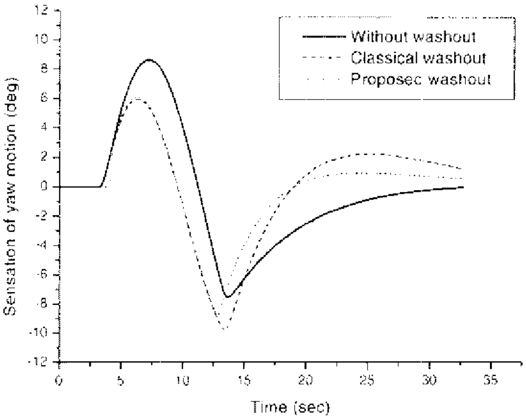

Fig. 17 Yaw motin sensation

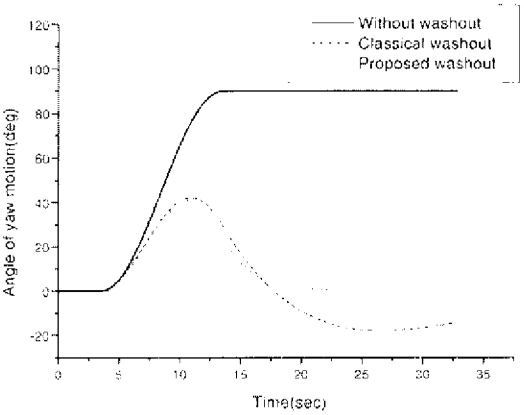

Fig. 18 Yaw directional angle

4.3 Quantitative evaluation for algorithm considering return mode

From Fig. 16 to Fig. 19 represent directional sensation from human sensation model about rotational angular velocity of yaw direction when a vehicle turns left and rotational angle in driving seat's center which is a value of the first integral of rotational angular acceleration. A solid line is a result of without washout, a long dotted line is an result by the classical washout and a short dotted line is a analysis result by proposed algorithm. And cut off frequency of high pass filter is 0.02 Hz.

Figures 16 and 17 show results which remove opposite directional motion generated by high pass filter using proposed algorithm and reduce a final return time to the motional origin. A rotational angle by classical washout as shown in Fig. 16 increases to about 40 degrees after starting motion then the first return occurs. After that, opposite rotation is generated. Compared with that, rotational angle by the proposed algorithm returns to the motional origin without opposite direction. Rotational sensation which a driver recognizes shown in Fig. 17 represents similarly in general though a little phase lead is generated in return motion.

Figures 18 and 19 show that the proposed algorithm more reduce a return tin to the motional origin. As shown in Fig. 18, the rotational angle by the algorithm removes opposite directional rotations and returns to the motional origin completely at about 18 seconds. However, a driver may feel wrong sensation of motion due to a generated big bouncing part.

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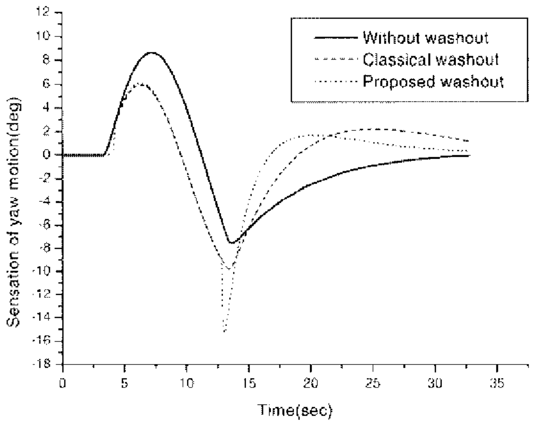

Fig. 19 Yaw directional sensation

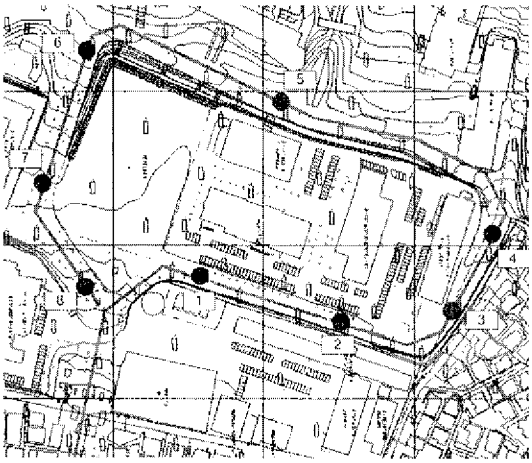

Fig. 20 Road map for experiments

5. Real Time Driving and Qualitative Evaluation

5.1 Survey plan

In order to evaluate validity of washout algorithm and performance of vehicle driving simulator developed by Pusan National University (Park et. al., 2001), it is important not only quantitative evaluation using human sensation model but also qualitative evaluation of driving sensational reappearance of driver. In order to evaluate validity of the proposed washout algorithm and investigate the influence of sensation of motion by washout and each module, we prepare a standard detail question qualitative evaluation.

Evaluation items consist of questions related to driving course and motional component. Evaluation related to driving course consists of questins comparing feeling of real car driving with sensation of motion which is embodied in Pusan National University's driving situation such as a straight section, a left turn section, a bended road, a slope section, and an uneven road. In order to evaluate according to motional direction, it consists of sensation of motion and feeling about each 6 degrees of freedom.

5.2 Driving experiment

In order to evaluate qualitatively vehicle simulator, we drive virtual road in Pusan National University. Fig. 20 shows driving path of car according to a scenario. A driving scenario is organized to experience a left turn, a straight section, a bended road and a climbing section from bumper 1 to bumper 8. It starts from 2 m back of bumper 1 and a driver drives subjectively with 0~35 km/h. Then it stops in front of bumper 8.

5.3 Evaluation result of survey

5.3.1 Motion sensation and feeling for each driving course

The result of survey which compares motion sensation and feeling for 6 DOF motion of simulator with those of a real car measures such as 'very difference (0), a little difference (1), normal (2), similarity (3), equality (4), and very equality (5)' and evaluates the numerical mean. Then we arrange them listed in Table 2. Evaluation for each item almost shows a value of 'similarity (3)'. There is evaluated that motion sensation of surge and heave direction is similar to a real car.

Table 2 shows that average value of evaluation for motion sensation according to motion direction is lager than the average one for driving course and handling. If we consider that washout algorithm is the most influential element for evaluating motion sensation according to motion direction, the proposed washout algorithm provides drivers with translational and rotational motion sensation which is similar to a real car. When distribution of drivers is represented to

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Table 1 Average values of motions and feelings as driving courses

Evaluation Items	Motion Sensation	Feeling
Straight Section	2.72	2.72
Left Turn Section	2.44	2.56
Bended Road	2.56	2.56
Slope Section	2.40	2.56
Uneven Road	3.36	3.28

Table 2 Average values of motions and feelings as each direction

Evaluation Items	Motion Sensation	Feeling
Surge Direction	2.92	2.96
Sway Direction	2.74	2.82
Heave Direction	3.37	3.46
Roll Direction	2.71	2.78
Pitch Direction	2.88	2.76
Yaw Direction	2.88	2.6

percentage of total persons, there is evaluation of 'very difference' (4%) in the sensation of sway direction. However, over 50% persons responsed positive evaluation for each item.

6. Conclusion

In this paper we proposed a new washout algorithm which can operate vehicle motion within limitation of motional range. We analyzed a problem which specific force is falsified in tilt coordination of classical washout algorithm and proposed new tilt coordination algorithm which can reappear specific force more completely. And we pointed out problem which is generated on producing return component as using only high pass filter in classical washout algorithm. In order to improve that, we proposed algorithm of considering return component, and evaluated validity of the proposed algorithm through qualitative evaluation and quantitative evaluation by simulation, experiment, and survey.

The proposed tilt coordination algorithm by quantitative evaluation generated somewhat additional rotational sensation in motion of roll and pitch direction comparing with classical tilt coordination, however almost results reappear well sensation of motion which feels in a real car. Besides the proposed algorithm with return component returned the simulator faster than classical washout algorithm, it removed opposite direction of motion to original signal's motional direction. It is verified that it can embody motion which always returns to the origin and is continuous. In qualitative evaluation, sensation of driving which a driver recognizes in simulator was over 'normality' compared with a real car, and sensation of motion and feeling showed a value of almost 'similarity' according to direction which largely affect washout algorithm. The proposed algorithm did not reappear wrong sensation of motion to driver in simulator and provided similar driving situation such as a real car.

The algorithm should be more improved as an algorithm which consider not only return component based on human sensation model but also sensation of motion recognized by driver.

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