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Washout Algorithm with Fuzzy-Based Tuning for a Motion Simulator

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In the virtual environment, reality can be enhanced by offering the motion based on a motion simulator in harmony with visual and auditory modalities. In this research the Stewart-Gough-platform-based motion simulator has been developed. Implementation of vehicle dynamics is necessary in the motion simulator for realistic sense of motion, so bicycle dynamics is adopted in this research. In order to compensate for the limited range of the motion simulator compared with the real vehicle motion, washout algorithm composed of high-pass filter, low-pass filter and tilt coordination is usually employed. Generally, the washout algorithm is used with fixed parameters. In this research a new approach is proposed to tune the filter parameters based on fuzzy logic in real-time. The cutoff frequencies of the filters are adjusted according to the workspace margins and driving conditions. It is shown that the washout filter with the fuzzy-based parameters presents better performance than that with the fixed ones.

Key Words : Motion Simulator, Washout Algorithm, Fuzzy Logic, Tilt Coordination

1. Introduction

A motion simulator presents a rider with motion cues as well as the visual and audio cues in the virtual environment. In the virtual environment, reality can be enhanced by offering the motion based on a motion base in harmony with visual and auditory modalities. Such motion simulators take the form of vehicle simulators, flight simulators, and simulators for entertainment. They are used in vehicle development, entertainment, and human factor studies such as motion sickness, etc.

Since the first flight simulator was developed in NASA, many automotive makers, research institutes and universities have developed various types of their own motion simulators. Recently, the state-of-the-art National Advanced Driving Simulator (NADS) has been developed. This simulator has a very wide motion range and a viewing angle of 360 degrees. Among many applications, Lee (1994) developed 6 degree-of-freedom (DOF) simulator for testing various automobile parts.

Workspace of a motion simulator is much smaller than that of a real vehicle. To overcome this problem, a so-called washout algorithm is used. Analog linear filters were used as washout filters until mid 70's, but this scheme posed difficulty in applying 6 DOF simulators. In 1970, linear coordinated washout was developed for 6 DOF simulators in NASA Ames Research Center. (Schmidt and Conrad, 1970) For better motion display, Parrish (1975) proposed coordinated adaptive washout, and Sivan et al. (1982) suggested optimal washout algorithms. Grant studied tuning of the washout filter to improve its performance. (Grant and Reid, 1997) Some washout algorithms have been developed in connection with particular vehicle simulators such as a mo-

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torcycle simulator (Barbagli, 2001) and a bicycle simulator (Lee, 2000). And Kim et al. used a fuzzy algorithm to tune the washout filter to improve its performance (Kim et al., 1995).

In this research a motion simulator based on the 6 DOF Stewart-Gough platform is developed. The platform motion is generated by leg movements through a combination of AC servo motors and ball screws. For a driving simulator, bicycle dynamics and washout algorithm are adopted. Since the workspace of a motion base is severely limited in comparison with that of a real vehicle, the real motion from computation of vehicle dynamics cannot be fully implemented in the simulated motion. The classical washout algorithm used to overcome this difficulty had the fixed filter parameters, so adaptation to various signals was not easy to achieve. As a means of facilitating adaptation of filter parameters, use of fuzzy logic to tune the filter parameters in the washout algorithm is proposed in this research.

The remainder of the paper is organized as follows. Chapter 2 introduces the motion simulator developed in this research and Chapter 3 deals with the bicycle dynamics that is an integral part of the driving simulator. The classical washout filters are presented in Chapter 4. Chapter 5 deals with fuzzy-based tuning of the washout filter parameters.

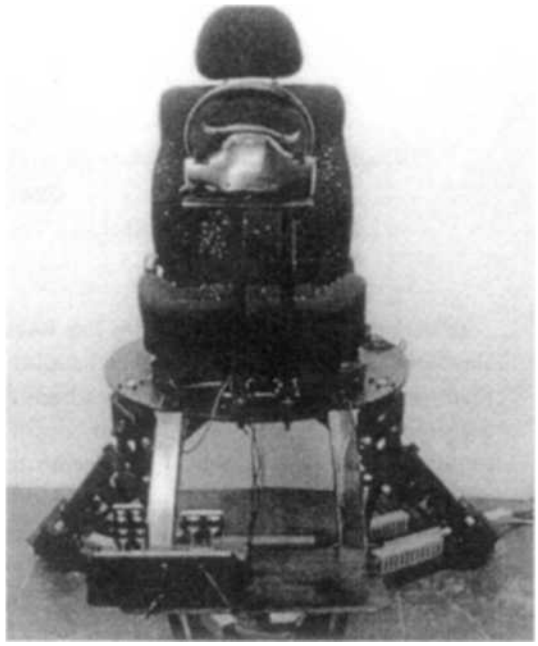

Fig. 1 Photo of motion simulator KU-MS

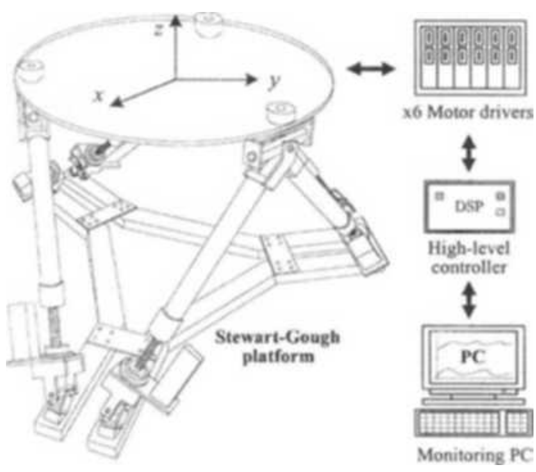

Fig. 2 Configuration of KU-MS

2. Motion Simulator

The motion simulator, KU-MS (Korea University-Motion Simulator), developed in this research consists of a motion base, visual and audio systems, and a motion-drive algorithm. The motion base shown in Fig. 1 comprises the 6 degree-of-freedom Stewart-Gough platform, a monitoring PC, a DSP controller (as a high-level controller), and motor drivers (as a low-level controller) as shown in Fig. 2.

The motion signals commanded by the user riding on the motion base using the input devices such as a joystick or a steering wheel and/or pedals are sent to the monitoring PC where pose (i.e., position and orientation) trajectories of the Stewart-Gough platform are generated through a motion-drive algorithm (i.e., vehicle dynamics and washout algorithm). The pose information is then sent to the high-level controller based on the TMS320C31 DSP controller at the sampling period of 20msec, which generates the trajectories of six leg lengths required to place the platform in a desired pose via inverse kinematics computation. The length signals are then commanded to the six low-level controllers embedded in the

Fig. 3 Integrated vehicle simulator system

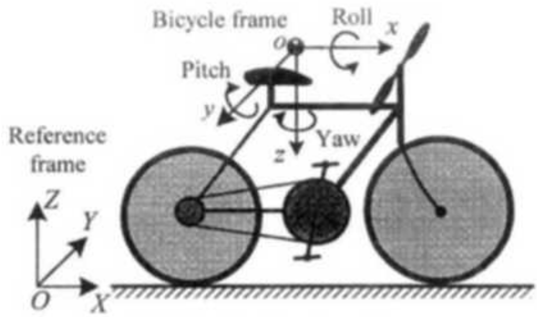

Fig. 4 Bicycle axis system

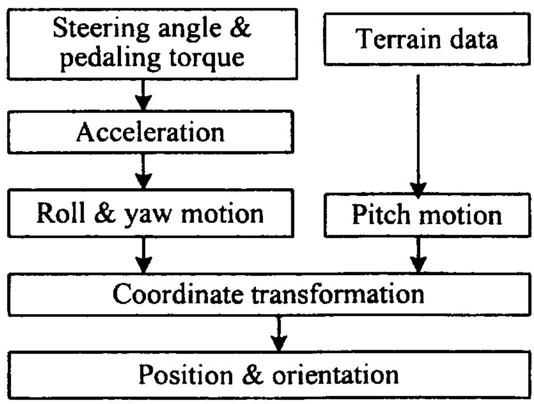

Fig. 5 Flow chart for bicycle dynamics

motor drivers. Each motor controller regulates the current supplied to the AC servo motor to achieve the target leg trajectory. Rotary motion of the motor in each leg is converted into linear motion by ball screws.

The motion base is often used together with the visual system which generates realistic graphic image shown in Fig. 3. A visual system is considered to be one of the most important subsystems for motion perception. The graphics workstation communicates with the monitoring PC of the motion base via UDP (User Datagram Protocol), which has faster transmission speed than TCP (Transmission Control Protocol). The graphic information generated in the graphic server is displayed on a screen by 3-channel projectors at a rate of 30 frames per second. The size of the screen is 9.555 m $\times$ 3.145 m, and the viewing angle is $150^\circ \times 40^\circ$.

The third element in a motion simulator system is the motion-drive algorithm. It is possible to control the platform directly through a joystick, but in most cases vehicle dynamics is considered to present more realistic ride feel. Furthermore, in order to represent vehicle motion in the severely restricted motion base, a washout algorithm is also required in the motion-drive algorithm. A motion-drive algorithm will be discussed below in details.

3. Bicycle Dynamics

A motion simulator can exhibit various types of vehicles, but in this research a bicycle is selected as a basic vehicle for its simplicity. A steering angle and a pedaling torque inputs required to determine the driving state of a bicycle are given in the form of a joystick signal which is given by the subject riding on the motion simulator. Figure 4 illustrates the coordinate frames used to describe bicycle motions. The reference frame O-XYZ is fixed in the ground, and the bicycle frame o-xyz attached to the bicycle is moving together with the bicycle. The primary bicycle motions are longitudinal, lateral, and yaw motions (i.e., x-axis translation, y-axis translation, and z-axis rotation). During a turning maneuver, roll motion (i.e., x-axis rotation) should be considered, while bounce and pitch motions (i.e., z-axis translation and y-axis rotation) are also important depending on the terrain data.

Based on these data, the linear accelerations (thus position), and the roll, pitch and yaw rates of a bicycle are computed as shown in Fig. 5. From this information, the position and orientation of a bicycle are determined through coordinate transformation. Bicycle dynamics is solved using the fourth-order Runge-Kutta method. The details of vehicle dynamics can be referred to Wong (1993).

Suppose that an arbitrary trajectory is generated as shown in Fig. 6 by means of proper input devices (e.g., a joystick). The linear and angular position and velocity of a bicycle are determined by solving the dynamics with the inputs of a steering angle and a pedaling torque. Figure 7 shows the position and orientation of a bicycle as a function of time from the solution of bicycle dynamics. It is noted that the motion is executed on the level ground and thus the z-displacement and the pitch angle are zero in this example.

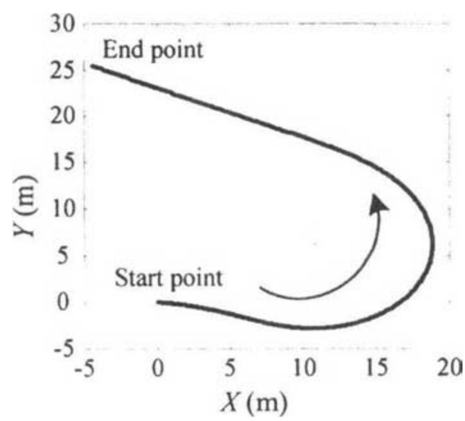

Fig. 6 Bicycle trajectory by joystick input

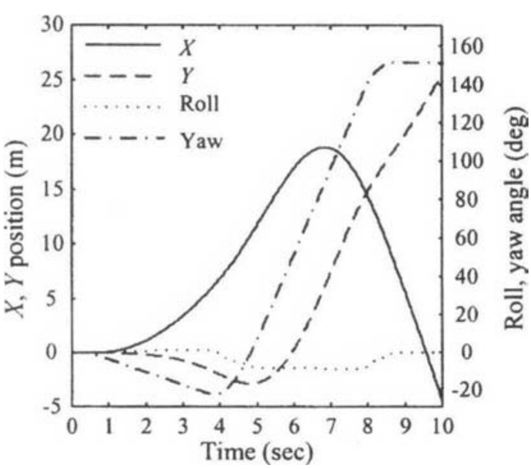

Fig. 7 Bicycle position and orientation by joystick input

4. Washout Filters

Due to the structural limit of the Stewart-Gough platform, a motion base has relatively small workspace compared with the operating range of a real vehicle. Because of this limited motion envelope of typical motion bases, filtering is required between the vehicle motion computed from vehicle dynamics and the simulated motion commanded to the motion base. The filter used for this purpose is called a "washout filter."

A vestibular system, consisting of semicircular canals and otoliths, has a great role in sensing physical motion cues in a motion simulator. It is known that the otoliths are able to detect the high-frequency components of the linearly accelerated motion via a specific force, while the semicircular canals can sense the high-frequency components of the angular motion. The specific force is defined as

$$\mathbf{f} = \mathbf{a} - \mathbf{g} \tag{1}$$

where $\mathbf{a}$ is the linear acceleration and $\mathbf{g}$ is the gravitational acceleration. It is noted that human sense of motion is more sensitive to high-frequency components of the motion than low-frequency ones.

Figure 8 shows the classical washout algorithm which consists of a high-pass filter (HPF) and a low-pass filter (LPF). (Grant and Reid, 1997) The linear acceleration (i.e., specific force) $\mathbf{a}$ and

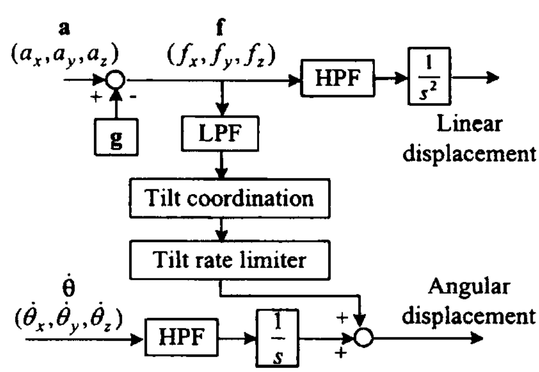

Fig. 8 Block diagram of classical washout algorithm

the angular velocity $\dot{\theta}$ from the vehicle dynamics are sent to the washout algorithm. The details on how the linear and angular displacements are computed in the washout filter are discussed below.

The specific force f_x, f_y, and f_z are computed by subtracting **g** from the given linear acceleration **a**. The high-frequency components of the specific force f_x are then obtained by the following 2nd-order HPF :

$$\frac{f_{Hx}}{f_x}=\frac{s^2}{s^2+2\zeta_{Hx}\omega_{Hx}s+\omega_{Hx}^2} \tag{2}$$

where ζ and ω represent the damping ratio and the cutoff frequency of the HPF, and the subscript H denotes the high-frequency. Note that f_{Hy} and f_{Hz} in the y and z axes are similarly obtained. This HPF filters out low-frequency motion signals which tend to lead to large linear displacements that cause the motion base to reach its motion limits. The high-frequency motion signals are realized by linear motion of the platform of the motion base by double integration of the filtered signals.

Low-frequency components of the specific force in the x axis can be obtained by the following 2nd-order LPF :

$$\frac{f_{Lx}}{f_x}=\frac{\omega_{Lx}^2}{s^2+2\zeta_{Lx}\omega_{LFx}s+\omega_{Lx}^2} \tag{3}$$

where the subscript L denotes the low-frequency. Note that f_{Ly} is similarly obtained. This low-frequency portion is realized by tilting the platform (i.e., angular motion about the x and y axes), since a human perceives as if he experienced a specific force when his body tilts. This is referred to as tilt coordination. Usually, a pitch angle is set to $\theta_{ytilt}=-f_{Lx}/g$ and a roll angle to $\theta_{xtilt}=f_{Ly}/g$ for relatively small angles. The rate of tilting is limited to 1-5deg/s to prevent the semicircular canal from perceiving this signal for tilt coordination as the angular motion cue (Nahon and Reid, 1989).

In the meantime, the high-frequency components of angular velocity about the x-axis are obtained by the following first-order HPF :

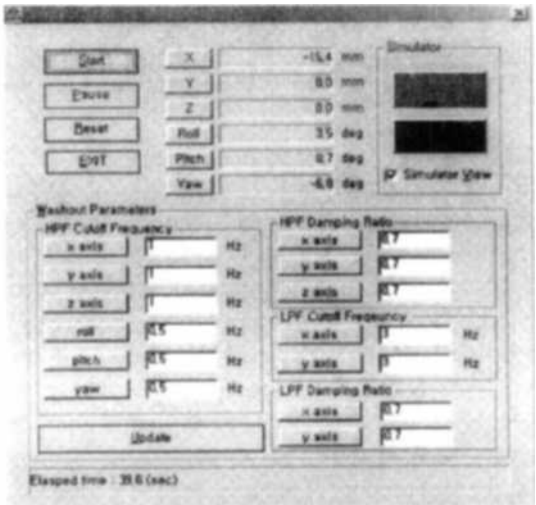

Fig. 9 Control panel of motion base

$$\frac{\dot{\theta}_{Hx}}{\dot{\theta}_x}=\frac{s}{s+\omega_{H\theta x}} \tag{4}$$

Note that $\dot{\theta}_{Hy}$ and $\dot{\theta}_{Hz}$ about the y and z axes are similarly obtained. The high-frequency components are integrated to give the angular displacement (θ_{Hx}, θ_{Hy}, θ_{Hz}) of the platform. The orientation angle (θ_x, θ_y) about the x and y axes are then obtained by adding the tilt angles (θ_{xtilt}, θ_{ytilt}) to the angles (θ_{Hx}, θ_{Hy}) due to angular motion, while θ_z is given as θ_{Hz} since not tilt coordination is performed about this axis.

The washout filter parameters can be adjusted depending on the driving conditions in the control panel shown in Fig. 9. This control panel can manage operation of the simulator as well.

5. Fuzzy-Based Washout Filters

Washout filters have parameters that can be adjusted to alter the motion responses of a simulator. Since the parameters of most classical washout filters remain fixed during their operation, they cannot cope with various driving conditions efficiently. On-line tuning of the washout filters can enable the simulator to offer better simulator motions within the limited motion range. In this research, fuzzy logic is suggested to tune the filter parameters, since it is known that the fuzzy logic is effectively applicable to a system in which the input-output relations are not clearly identified.

To this end, the fuzzy logic is used which takes the displacement limit (DL), the angle limit (AL) and the low-frequency specific force (LFSF) as inputs and then provides a proper filter parameters as outputs. Figure 10 illustrates the flowchart showing this fuzzy logic system. The first step to the fuzzy logic system is the fuzzifier process determining the membership function of the input-output variables. Five linguistic variables VF (Very Far from limit), F (Far from limit), M (Middle), N (Near to limit), and VN (Very Near to limit) are used for both DL and AL. Five variables VS (Very Small), S (Small), M (Middle), B (Big), and VB (Very Big) are used for LFSF. Since the DL represents how close the moving platform approaches its limit of translational motion, if the platform is placed far away from the limit, the DL is taken as either F or VF.

The second step is to determine the fuzzy rules with 5 linguistics variables for DL, 5 for AL, and 5 for LFSF. The underlying fuzzy rule bases shown in Table 1 will be explained in detail in the next section. For each combination of DL, AL and LFSF, the proper filter parameters are selected by one of the fuzzy rules. The last step is the defuzzifier process which converts the fuzzy variable (in this case the filter parameter) to the numerical value. The simplified center of gravity method is used in this research.

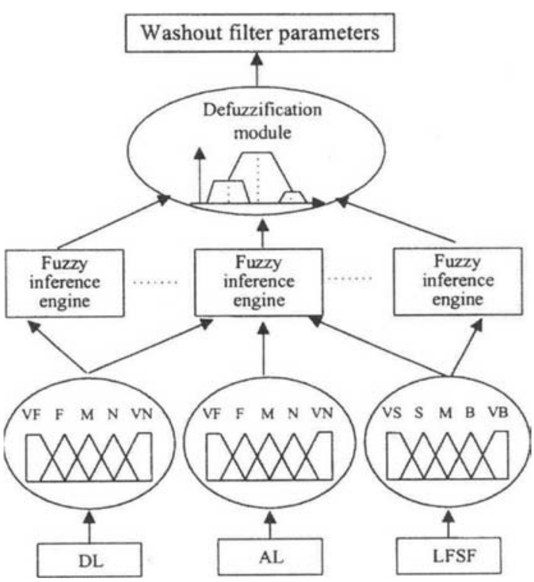

Fig. 10 Fuzzy logic used to determine washout filter parameters

5.1 Fuzzy rules for workspace limit

The severely restricted motion range of a motion simulator leads to considerable differences between motion states in the simulator and in the vehicle. One way to improve the simulator performance is to adjust the filter parameters in such a way that the motion cue error in the simulator is minimized through feedback of subject drivers. Another way, which is suggested in this research, is to make the simulated motion as close to the actual vehicle motion as possible, as long as the motion of a motion simulator is still within the motion envelope.

Since the filter parameters are fixed in classical washout filters, they are not capable of generating proper motions in response to input signals from dynamics. It is desirable in most cases that the filter parameters be adjusted depending on the workspace situation or driving conditions as shown in Table 1. Let us consider the role of the cutoff frequency of the high-pass filter (HPF). The HPF generates substantial phase error (i.e., phase lead in this case) at frequencies near and below its cutoff frequency. The phase error is not significant well below the cutoff frequency because the amplitude is substantially attenuated in this frequency range. In order to faithfully reproduce the input motion signal, therefore, the cutoff frequency is desired to be set to a value as low as possible. However, this lower cutoff frequency may lead to the motion base reaching its motion limit since the low frequency motion tends to quickly saturate the motion base. From this observation, one useful strategy is that the cutoff frequency of HPF is set to a lower value as the platform is placed farther from the motion limit. It is noted that the role of cutoff frequency of the low-pass filter (LPF) is reversed to that of HPF.

Consequently, if the platform is placed far away from its motion limit at the instant under consideration, lowering the cutoff frequency

Table 1 Fuzzy rule bases
Membership functions for filters

		ω_{HPFD}	ω_{LPFD}	$\omega_{HPF\theta}$	$\dot{\theta}_{lim}$	K
DL	VF	VS				
	F	S				
	M	M				
	N	B				
	VN	VB				
AL	VF		VB	VS		
	F		B	S		
	M		M	M		
	N		S	B		
	VN		VS	VB		
LFSF	VS				VS	B
	S				S	B
	M				M	M
	B				B	S
	VB				VB	S

DL : Displacement Limit
AL : Angle Limit
LFSF : Low Frequency Specific Force
VF : Very Far from limit
F : Far from limit
N : Near to limit
VN : Very Near to limit
Z : Zero
VB : Very Big
B : Big
M : Middle
S : Small
VS : Very Small

(ω_{HPFD}) of HPF and increasing the cutoff frequency (ω_{LPFD}) of LPF can lead to a more faithful motion without saturation of the motion base by allowing more frequency components of the original motion signal to be included in the filtered signals. On the contrary, if the platform is near the limit, increasing ω_{HPFD} of HPF and lowering ω_{LPFD} of LPF contributes to not reaching the limit by making less frequency components be included in the filtered signals. This strategy is applicable to both displacement limit and angle limit.

Figure 11 illustrates comparison of the washout filters with fuzzy-based parameters (i.e., cutoff frequencies in this example) with those with fi xed parameters. It is shown that the fuzzy-based filters reflect the input signal in terms of amplitudes better than those with fixed parameters for the input signal frequency of 0.5 Hz. Figure 12 illustrates a change in cutoff frequency, where it varies depending on the workspace situation. Figure 13 shows comparison of amplitude and phase difference as a function of input frequency.

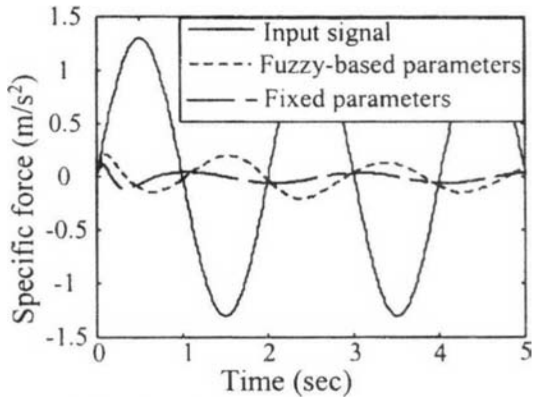

Fig. 11 Results of washout filters with fuzzy-based and fixed parameters

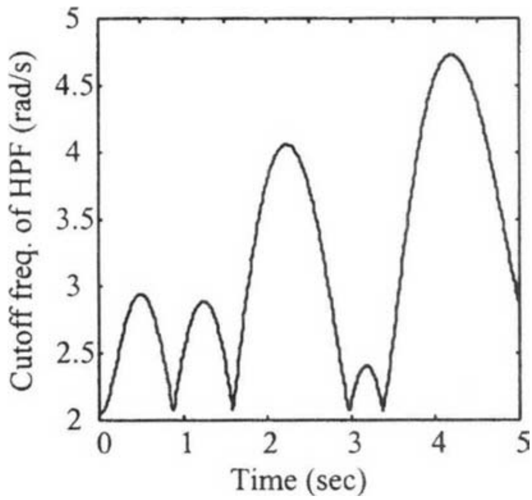

Fig. 12 Cutoff frequencies of HPF when fuzzy-based parameters are used

It is observed that the fuzzy-based filters create larger amplitudes and smaller phase differences as the frequency gets lower.

Another point to mention is that the maximum strokes in the linear and angular motions are reduced to some extent when the motions are coupled to other degrees of freedom. For example, the motion in the z direction with some angular displacements is smaller than that with all Euler angles set to zero. Such reductions in strokes should be taken into account when the motion limits for the current states of a simulator are computed.

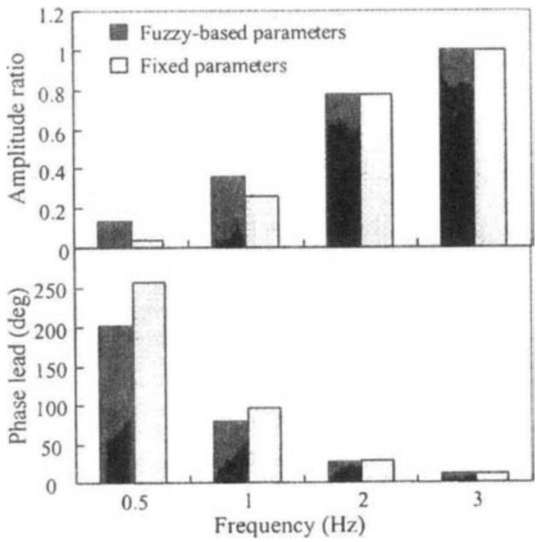

Fig. 13 Amplitude ratios and phase leads of fuzzy-based and fixed parameters

5.2 Fuzzy rules for tilt coordination

Representation of low-frequency motion signals by tilt coordination can be restricted according to the magnitude of input acceleration. Since the range of pitch and roll angles is less than $\pm 30°$ for typical motion bases, the maximum linear acceleration presented by tilt coordination is ± 0.5 g ($=4.9\ \mathrm{m/sec^2}$). Furthermore, the tilt rate is limited to $\dot{\theta}_{\mathrm{lim}}=1-5$ deg/sec to prevent tilting for low-frequency linear acceleration from being perceived as angular motion. Therefore, the low-frequency linear acceleration with large amplitude cannot be fully presented by tilt coordination. Figure 14 shows the situation in which large linear acceleration and deceleration are involved. In this case, considerable time delay exists in reaching the target in response to the step input signal or returning to the neural point.

Since the incorrect motion signal created by the washout filter may have an adverse effect on perception of a sense of motion, this type of delayed signal should be eliminated or at least reduced. In this research the following strategy is used to overcome this difficulty. If the low-frequency specific force (LFSF) is small, the tilt rate is set to a small value and the scaling factor K to a large value (i.e., close to 1). Note that the scaling factor K is multiplied to the specific force

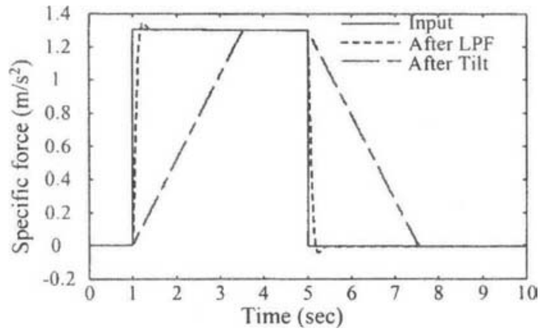

Fig. 14 Specific force by tilt coordination with no fuzzy logic

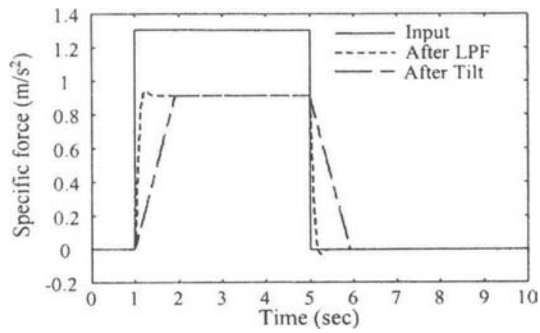

Fig. 15 Specific force by tilt coordination with fuzzy logic (tilt rate limit $\dot{\theta}_{\mathrm{lim}}$ and scale factor K)

to properly adjust the target-specific force. On the contrary, if the LFSF is large, then K is chosen as a smaller value to lower the target-specific force and the tilt rate is set to a large value as shown in Fig. 15. Although the correct specific force cannot be implemented with this small value of K, reduced time delay can contribute to providing more faithful sense of motion to a subject driver.

6. Conclusions

In this research a 6 DOF motion simulator is developed, which consists of the Stewart-Gough-platform-based motion base, visual and audio systems, and a motion-drive algorithm. Bicycle dynamics is adopted to offer realistic sense of motion to the motion simulator in real time. In order to compensate for the limited motion range of the motion simulator, the washout filter is used. In this paper a new approach is proposed to tune the filter parameters based on fuzzy logic in real-time.

(1) Fuzzy-based tuning of the cutoff frequencies of the washout filters in real time can make the motion base follow the real motion from vehicle dynamics without reaching its motion limits. If the platform is far from its motion limit, lowering the cutoff frequency of HPF and increasing the cutoff frequency of LPF can lead to a more faithful motion without saturation of the motion base.

(2) Tilt coordination with fuzzy-based adjustment of the tilt rate and scale factor provides better sense of motion than that without fixed parameters. If the low-frequency specific force is of large amplitude, increasing the tilt rate and decreasing the scale factor can provide better sense of motion.

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