Journal of Chongqing University English Edition [ISSN 1671-8224]
Vol. 17 No. 1
March 2018

doi:10.11835/j.issn.1671-8224.2018.01.03

To cite this article: WANG Hui, ZHU Dao-yang, CHENG Yuan-jie. Design of fuzzy adaptive washout algorithm based on the novel tilt coordinate [J]. J Chongqing Univ Eng Ed [ISSN 1671-8224], 2018, 17(1): 27-38.

Design of fuzzy adaptive washout algorithm based on the novel tilt coordinate *

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Received 29 March 2017; received in revised form 21 May 2017

Abstract: Motion simulator usually appears the phenomenon of false cues and the workspace is limited in the process of washout. The proposed washout algorithm combines fuzzy logic control with the vestibular system to design the tilt coordination fuzzy adaptive filter, in order to minimize the vestibular sensory error below the human perception threshold. Owing to tilt coordination angular velocity limiter, the loss of low-pass acceleration must be compensated by the acceleration transform model. The translational channel decreases the possibility of the workspace beyond limitation and expands the scope of motion platform simulating input acceleration by using third-order filter. The simulation results show that the proposed algorithm can effectively overcome the phase retardation of classical washout algorithm, and then prevent the produce of false cues, decrease the displacement of motion platform simultaneously; in addition, white Gaussian noise simulates large variations in acceleration. The proposed washout algorithm can have maximal extreme value of acceleration and accurate simulating performance in general. It also proves that the proposed washout algorithm has a strong adaptability and reliability, which can effectively improve the dynamic fidelity for motion simulator.

Keywords: classical washout algorithm; fuzzy control; false cues; tilt coordinate; washout filter; vestibular system

CLC number: TP391 Document code: A

NOMENCLATURE

ω	natural frequency response of filter
ξ	damping ratio
a_{A}	acceleration
ω_{A}	angular velocity
$\boldsymbol{L}_{\mathrm{IS}}$	translation transformation matrix
$\boldsymbol{L}_{\mathrm{IS}}^{\mathrm{T}}$	transpose matrix of $\boldsymbol{L}_{\mathrm{IS}}$
$\boldsymbol{T}_{\mathrm{IS}}$	rotational transformation matrix
g_{A}	acceleration of gravity in the upper platform coordinate system
g_{I}	acceleration of gravity in the reference coordinate system
f_{AA}	the specific force

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[*] Funded by the National Natural Science Foundation of China (U1233107) and Civil Aviation Science and Technology Innovation Project of China (MHRD20140210).

f_{L}	low-pass filtered of specific force
f_{TL}	compensated specific force of translational motion
f_{RL}	rotational motion specific force
$f_{\beta\mathrm{L}}$	specific force after passing tilt coordination
f_{SL}	specific force after passing rate limiter
β_{SL}	angle of tilt coordination channel
β_{SH}	angle of rotational motion channel
β_{S}	the sum of washout angle
e	sensed error of tilt coordination
r_{ce}	change rate of sensed error
AC	amplitude controller
HC	homeostatic controller
TCFAF	tilt coordination fuzzy adaptive filter

1 Introduction

Owing to its significant advantages in economy, security and so on, motion simulator has been widely applied for vehicle, ship, train, aircraft, etc. The workspace of motion simulator is limited, and the movement of motion simulator cannot be reproduced directly. Therefore, the general approach is to design the cues algorithm using the characteristics of human vestibular system. The core of the cues algorithm is to achieve motion washout below the human perception threshold. Motion washout is a progress that analogue systems receive the motion parameters (three axis linear accelerations, three angular velocities and attitude angles) from the simulator, then these parameters will go through a series of coordinate conversion, filter and compensation, and get a result of driving signals for motion platform.

To get more realistic washout results for motion simulator, researchers tried different kinds of washout algorithms to improve the fidelity of motion simulator. The first washout method is known as the classical algorithm and has been provided by Conrad et al. [1-2]. It is widely praised for its simplicity, easy to be adjusted and short processing time [3]. Although classical washout algorithm has many advantages, there are some significant drawbacks. For example, phase retardation leading to false cues cannot provide enough fidelity for the motion simulator; the filter parameters are fixed and need real-time adjustment; and large variations in acceleration cannot be very good for the washout effect. For overcoming the shortages of classical washout algorithm, Parrish et al. [4] proposed an adaptive washout algorithm to overcome the drawback of the constant classical filter parameters and the “worst case scenario” tuning method; then Sivan et al. [5] proposed the optimal algorithm at MIT that was based on human motion sensation and took into account the vestibular system model to cut back false cues and improve the dynamic fidelity. Houck et al. [6] tried to optimize and improve the algorithm; You et al. [7] put forward a washout algorithm that used a new tilt coordination and return mode to decrease the degree of false cues and sensation error for a vehicle driving simulator. Ye et al. [8] combined the optimal control and vestibular model to minimize pilots’ sensory errors between simulators and real aircraft from Harbin Institute of Technology.

The theory of fuzzy control in this paper has been obtained significant achievements in other fields, but it was firstly applied to motion simulator by Song et al. [9] to solve problems of constant parameters in classical washout filters and problems with adaption to variable acceleration. Since then researchers have made further progress in the theory of fuzzy logic control in washout algorithm. Hwang et al. [10-11] combined the optimal genetic with an adaptive fuzzy control in washout algorithm, especially, to solve the real-time auto-tuning washout parameters and adequately considered a limited workspace and the dynamic input signal. The results demonstrated that the sensing error values was suppressed below one threshold and translational displacement was controlled within the workspace. Wang et al. [12-14] had considered the washout algorithm by combining the characters of motion perception and actual movement of train with fuzzy control, to real-time adjust the motion perception of simulator driver. Secondly, to overcome the deficiencies of classical washout algorithm in the vertical vibration of high speed locomotive driving simulator, a fuzzy self-tuning algorithm was proposed to adjust the parameters of the filter in real time and the washout performance was improved by 14.21%. Finally, a new fuzzy adaptive washout algorithm was proposed in combination with the fuzzy characters of human motion sensations to overcome the difficulty of real-time solution of the adaptive parameters in the algorithm. Hsu et al. [15] developed a functional neural fuzzy controller for the electrical 6-DOF Stewart platform within the limited workspace, in order to have maximal instant acceleration and locate the position of the hydraulic platform accurately. Luo et al. [16] scaled high amplitude signal and transformed low amplitude signal by fuzzy adaptive washout algorithm to improve the accuracy of the Stewart platform. Guiatni et al. [17] proposed a fuzzy and PSO washout algorithm, considering both the physical limits of restitution platforms and realistic sensations. In recent years, Asadi et al. [18-20] used a fuzzy control theory to minimize the sensation error and exploited the platform more efficiently for the motion washout.

In this paper, a novel tilt coordination washout algorithm is proposed based on the fuzzy control theory and human vestibular system. The proposed approach integrates the tilt coordination low-pass acceleration channel and the translational motion acceleration channel which compensates the loss acceleration owing to tilt coordination angular velocity limiter. Ultimately, the proposed washout algorithm is expected to solve the problem of phase retardation, to minimize the sensation errors, and to overcome false cues within the process of washout.

2 Classical washout algorithm

Typically, the motion simulator is divided into three parts in classical washout algorithm: simulating instant acceleration channel (the translational motion channel), simulating low-pass continuous acceleration channel (the tilt coordination channel) and the attitude change of high-pass angular velocity channel (the rotational motion channel). The limited acceleration goes through LIS coordinate transformation matrix, then the acceleration and gravity are integrated, to get translational acceleration by second-order high-pass filter. Finally, the translational acceleration passes the second-order integral to acquire motion simulator washout displacement. The limited acceleration passes through low-pass filter to obtain low frequency acceleration. Then by using the principle of tilt coordinate, the motion simulator achieves continuous acceleration status, simultaneously reducing the washout displacement. The input angular velocity is also limited. TIS coordinates transformation matrix, high-pass filter and integral, to obtain the part of angular displacement, then controls the attitude of motion simulator. Fig. 1 shows the schematic block diagram.

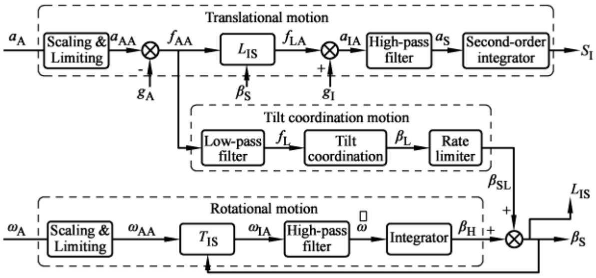

Fig. 1 Classical washout filter algorithm

The translation motion channel filter, which has a second-order high-pass filter, is

$$H_{\mathrm{ah}} = \frac{s^2}{s^2 + 2\omega_{\mathrm{ah}}\xi_{\mathrm{ah}}s + \omega_{\mathrm{ah}}^2} . \tag{1}$$

The tilt coordination channel filter is

$$H_{\mathrm{al}} = \frac{\omega_{\mathrm{al}}^2}{s^2 + 2\omega_{\mathrm{al}}\xi_{\mathrm{al}} s + \omega_{\mathrm{al}}^2} \,. \tag{2}$$

The rotational motion channel filter is

$$H_{\mathrm{\omega h}} = \frac{s^2}{s^2 + 2\omega_{\mathrm{\omega h}}\xi_{\mathrm{\omega h}} s + \omega_{\mathrm{\omega h}}^2} \,. \tag{3}$$

The filter between translational acceleration and displacement is

$$\frac{s_{\mathrm{I}}}{a_s} = \frac{1}{s^2 + v_{\mathrm{f}} s + p_{\mathrm{f}}} \,, \tag{4}$$

where $v_{\mathrm{f}} = 2\xi\omega$ and $p_{\mathrm{f}} = \omega^2$.

Angular displacement is composed of tilt angle $\beta_{\mathrm{SL}} = [\varphi_{\mathrm{SL}}, \theta_{\mathrm{SL}}, \phi_{\mathrm{SL}}]$ and rotational angle $\beta_{\mathrm{SH}} = [\varphi_{\mathrm{SH}}, \theta_{\mathrm{SH}}, \phi_{\mathrm{SH}}]$ as

$$\beta_{\mathrm{S}} = \beta_{\mathrm{SL}} + \beta_{\mathrm{SH}} \,. \tag{5}$$

The coordinate transformation matrix of classical washout algorithm is presented, to achieve the goal that the moving coordinate system is converted to a reference coordinate system in motion simulator.

$$\boldsymbol{L}_{\mathrm{IS}} = \begin{bmatrix} \cos\theta\cos\phi & \sin\varphi\sin\theta\cos\phi - \cos\varphi\sin\phi & \cos\varphi\sin\theta\cos\phi + \sin\varphi\sin\phi \\ \cos\theta\sin\phi & \sin\varphi\sin\theta\sin\phi + \cos\varphi\cos\phi & \cos\varphi\sin\theta\sin\phi - \sin\varphi\cos\phi \\ -\sin\theta & \sin\varphi\cos\theta & \cos\varphi\cos\theta \end{bmatrix}, \tag{6}$$

$$\boldsymbol{T}_{\mathrm{IS}} = \begin{bmatrix} 1 & \sin\varphi\tan\theta & \cos\varphi\tan\theta \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi\cos\theta & \cos\varphi\sin\theta \end{bmatrix}, \tag{7}$$

where φ, θ and ϕ represent three Euler attitude angles (roll, pitch and yaw angles), respectively.

The limited module of acceleration and angular velocity: The main role of the limiting module prevents the acceleration or the angular velocity to exceed the magnitude of the simulator. At a small input acceleration, it is expected that human can apperceive the acceleration variation, the phase retardation can be reduced and the phenomenon of false cues can be eliminated. At a relatively large input acceleration, the amplitude of input acceleration is limited, so as not to out of workspace. The empirical formula [21] is

$$y = -0.001x^3 - 0.03x^2 + x \,. \tag{8}$$

3 Human perception system

By studying and analyzing human perception system, it is found that the human perception system is composed of semicircular canals and otolith [22]. They are the main sensors mammals use to perceive external linear acceleration and angular velocity respectively. Otolith is the main organ of the vestibular system in the sense of linear motion, the specific force perceived [23] in otolith is attained by subtracting the acceleration of gravity g_{A} from translational acceleration a_{AA} as

$$f_{\mathrm{AA}} = a_{\mathrm{AA}} - g_{\mathrm{A}} \,. \tag{9}$$

Otolith cannot distinguish translational acceleration from gravity or motion. In 1981, Young et al. [24] used the spring, mass, damping model approximately to simulate human vestibular perception system, to make sensory system linearization in Fig. 2, and the transfer function is

$$H_{\mathrm{OTO}}(\mathrm{s}) = \frac{L[f]}{L[f]} = \frac{k(\tau_{\mathrm{A}} s + 1)}{(\tau_{\mathrm{L}} s + 1)(\tau_{\mathrm{S}} s + 1)} \,, \tag{10}$$

where f is a linear acceleration at brain vestibular central direction for the driver, f links specific force in sensation model, k is a gain factor, and τ_A, τ_S, and τ_L are physical parameters of otolith model. The body will not feel the movement below the human perception threshold. Table 1 shows otolith model parameters [25].

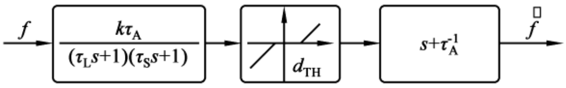

Fig. 2 Otolith model where f is a linear acceleration at brain vestibular central direction for the driver, f links specific force in sensation model, k is a gain factor, τ_A, τ_S, and τ_L are physical parameters of otolith model, and d_{TH} stands for the otolith model threshold

Table 1 Specific force sensation model parameter values

	k	τ_L	τ_S	τ_A	d_{TH}
Surge (y-axis)	0.4	13.2	0.66	5.33	0.17
Sway (x-axis)	0.4	13.2	0.66	5.33	0.17
Heave (z-axis)	0.4	13.2	0.66	5.33	0.28

$$H_{ROT}(s) = \frac{L[\omega]}{L[\omega]} = \frac{T_L T_A s^2}{(T_L s+1)(T_S s+1)(T_A s+1)} . \tag{11}$$

Semicircular canals of the vestibular system mainly sense angular velocity, and allow for the roll, pitch, and yaw motion to be detected by human. Table 2 shows the semicircular canals mode parameters [25].

4 Proposed washout algorithm

Classical washout algorithm commonly uses low-pass filter with fixed parameters. Although its structure is simple, the parameters should be adjusted according to the large variation in acceleration. In addition, the low-pass filter in classical washout algorithm will lose a part of acceleration signals, which will cause the phase retardation within tilt coordination, and bring about false cues. It is the principal reason that motion simulator declines the dynamic fidelity. The shortcomings of classical washout algorithm are acknowledged, and a kind of low-pass filter is designed by combining human vestibular system model with fuzzy adaptive control, to reduce the phase retardation within classical washout algorithm and overcome the problem of fixed parameters, and ultimately to prevent false cues in the produce of washout.

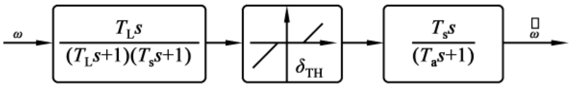

Fig. 3 Semicircular canal model where ω is an angular velocity of brain vestibular central direction for the driver, ω stands for the specific sensed angular velocity in Eq. (11), T_A, T_S and T_L are physical parameters of the semicircular canals mode, and δ_{TH} is the semicircular canals threshold

Table 2 Rotational motion sensation model parameter values

	T_A	T_S	T_L	δ_{TH}
Pith (y-axis)	30	0.1	5.3	3.6
Roll (x-axis)	30	0.1	6.1	3.0
Yaw (z-axis)	30	0.1	10.2	2.6

The schematic diagram of proposed tilt coordination algorithm is shown in Fig. 4. The specific force in Eq. (9) is translated to the center of platform coordinate system so that we can obtain Eq. (14).

$$g_A = \boldsymbol{L}_{IS}^{T} g_I , \tag{12}$$

$$g_I = [0, 0, g] , \tag{13}$$

$$f_{AA} = \begin{bmatrix} a_x + g\sin\theta \\ a_y - g\cos\theta\sin\varphi \\ a_z - g\cos\theta\cos\varphi \end{bmatrix} . \tag{14}$$

f_{AA} passes through the novel low-pass filter, then the tilt coordination principle will obtain angular β_{L} to simulate a continuous acceleration, finally getting the tilt coordinate angular β_{SL} below the semicircular canals threshold. However, because the human perception angular velocity threshold is below 3.6 °/s, it will loss a part of continuous acceleration, which is the second main reason that affects the dynamic fidelity of motion simulator. In the light of the tilt coordination angular velocity limiter, the loss acceleration will be compensated by the translational motion channel. The proposed method will have maximal extreme value of acceleration and accurate simulating performance in general, and the motion simulator will washout effectively.

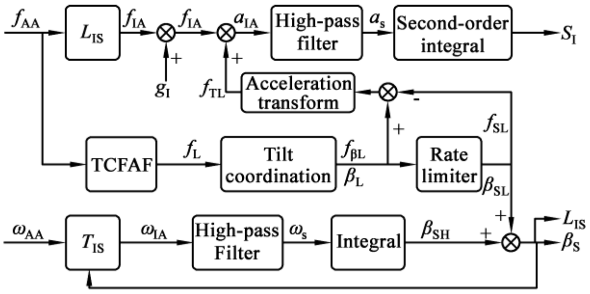

Fig. 4 Proposed washout algorithm

Compensated translational acceleration f_{TL} is

$$f_{\mathrm{TL}} = f_{\beta\mathrm{L}} - f_{\mathrm{SL}}\,, \tag{15}$$

where $f_{\beta\mathrm{L}}$ is a specific force which is generated after doing tilt coordination of low frequency translational acceleration passing through the TCFAF, and f_{SL} is a specific force which is generated after passing rate limiter.

Due to the limited workspace and a non-linear characteristics of novel low-pass fuzzy adaptive filter, the translational third-order high-pass filter is designed to overcome the shortcomings and its formula is

$$H_{\mathrm{ah}} = \frac{s^2}{s^2 + 2\omega_{\mathrm{ah}}\xi_{\mathrm{ah}}s + \omega_{\mathrm{ah}}^2} \times \frac{s}{s+\omega_0}\,. \tag{16}$$

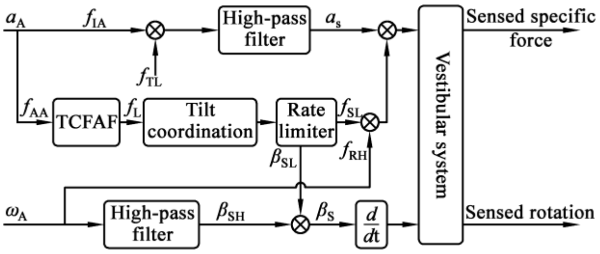

Fig. 5 Sensed motion of proposed washout algorithm

A schematic diagram for sensations of motions by proposed washout algorithm is as shown in Fig. 5. To eliminate the phase retardation and achieve maximal extreme value of acceleration and accurate simulating performance in general, we used the novel low frequency filter and compensated the loss acceleration for the rate limiter by f_{TL}. Translational acceleration is given in Eq. (17) before high-pass filter, the specific force is composed of a_{S}, f_{SL} and f_{RL}, which is generated after high-pass filter, tilt coordination channel can generate the acceleration f_{SL}, and f_{RL} is generated by rotational motion. The sum of specific force is expressed in Eq. (18).

$$a_{\mathrm{IA}} = f_{\mathrm{IA}} + f_{\mathrm{TL}}\,, \tag{17}$$

$$f_{\mathrm{specific}} = a_{\mathrm{S}} + f_{\mathrm{SL}} + f_{\mathrm{RL}}\,. \tag{18}$$

Fig. 6 shows the novel tilt coordination low-pass filter by combining human vestibular system and fuzzy adaptive control, or TCFAF. In the novel low-pass filter, amplitude controller (AC) and homeostatic controller (HC) are designed. AC adjusts the whole amplitude to approach the reference acceleration, and HC is used to adjust the stability of the low-pass filter. The sensation error of low frequency acceleration *e* is obtained by subtracting f_{L} from f_{AA} passing through the vehicle driver vestibular system and the simulator vestibular system, and then the fuzzy controller respectively adjusts AC and HC. It can adjust the controlled system automatically.

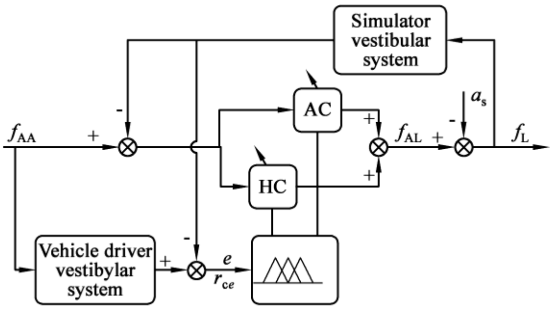

Fig. 6 Tilt coordination fuzzy adaptive filter

The transfer functions of AC and HC are shown in the following equations.

$$G_1(s) = k_2 k_{\text{fuzzy}} L[f(e,r_{ce})](1\text{-}H_{\text{ah}}(s)) \text{ ,} \tag{19}$$

$$G_2(s)=k_{\text{fuzzy}} L[f(e,r_{ce})]H_{\text{ah}}(s) \text{ ,} \tag{20}$$

$$P(s) = L[f_{\text{AA}}] - H_{\text{OTO}}(s)L[f_{\text{L}}] - G_{\text{HC}}(s) \text{ ,} \tag{21}$$

$$H_{\text{AC}}(s) = k_{\text{AC}}(P(s) - G_2(s)) \text{ ,} \tag{22}$$

$$H_{\text{HC}}(s) = 0.01(P(s) - G_2(s))^2 + 0.1(P(s) - G_2(s)) \text{ ,} \tag{23}$$

where k_{fuzzy} is a fuzzy control coefficient, and $L[f(e,r_{ce})]$ is a fuzzy transfer function. The transfer function of the vestibular system is given in Eq. (10). The transfer functions in Eqs. (22) and (23) demonstrate that the AC is a nonlinear feedback control system and the coefficient k_{AC} adjusts the amplitude range; the HC is a high-power non-linear feedback control system and prevents the system oscillation. The control coefficient can be easily selected by experience.

5 Fuzzy controller

Fuzzy controller automatically adjusts the system to achieve a dynamic balance by adjusting AC and HC. Fig. 7 shows the structure of fuzzy adaptive controller. Sensation error goes through normalization and fuzzification, processing the signals under the Rule Base and Inference Engine, and finally the defuzzification signal forms the truth value in fuzzy controller. The truth value signal passes through high-pass filter H_{ah} to obtain the desired signals and join homeostatic controller. The remaining signal gains k_2 and passes amplitude controller.

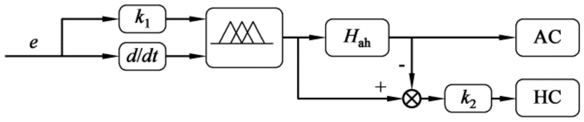

Fig. 7 Fuzzy controller

Fuzzy logic controller uses a structure of two dimensional Mamdani, *e* and *ce* are in the range of [–5, 5], the output values is in the range of [−1, 1], and the fuzzy degree of inputs and outputs is {NB, NM, N, Z, P, PM, PB}. Fuzzy inference and defuzzification respectively apply to maximum and minimum synthesis and area bisection method. Figs. 8 and 9 show their membership functions.

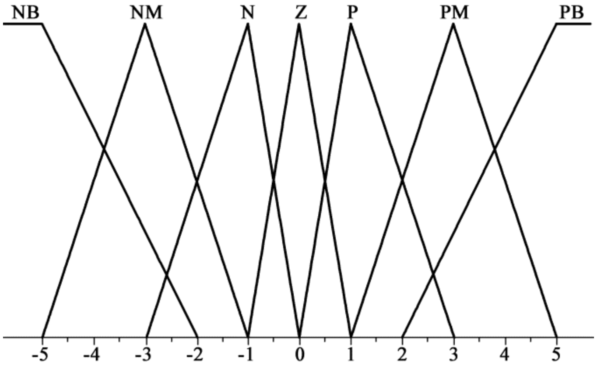

Fig. 8 Membership function of inputs

6 Simulation results

Input a step signal with the acceleration 2 m/s^2 in the *y*-axis and the angular velocity is zero. The input acceleration is shown in Fig. 10.

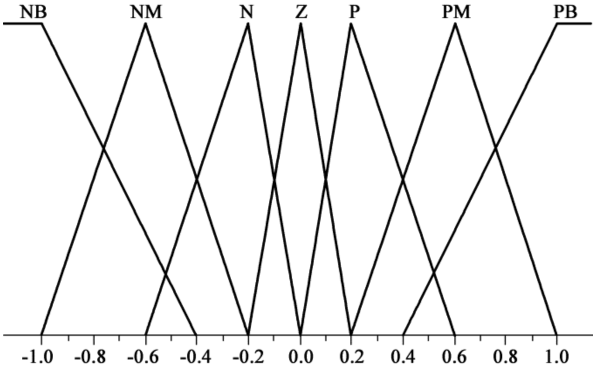

Fig. 9 Membership function of output

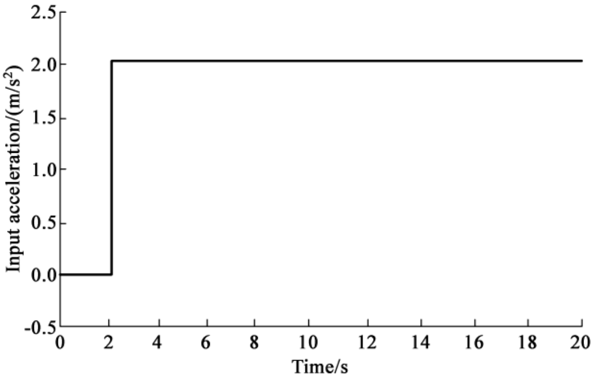

Fig. 10 Step reference input acceleration

The simulation model is established in MATLAB/Simulink, and the washout acceleration is shown in Fig. 11, where the three curves represent the reference sensed specific force, the proposed method sensed specific force and the classical sensed specific force, respectively. The reference curve shows that the sensed acceleration reaches the maximum value of 1.624 m/s^2 at 3.9 s. The classical washout algorithm gets a maximum acceleration of 1.543 m/s^2 at 5.2 s. The proposed method has a maximum acceleration of 1.607 m/s^2 at 3.4 s, and the sensed specific force is smooth. Thus, translational third-order filter can eliminate nonlinear defects of fuzzy control, and the proposed washout algorithm gets the time and the maximal extreme value of acceleration is close to the reference curve. In Fig. 12, the sensed force error has been decreased by the novel tilt coordinate fuzzy adaptive washout algorithm, and the maximum specific sensation force error reduces from 0.832 m/s^2 to 0.128 m/s^2 at the same time. In Fig. 13, the absolute of maximum tilt coordination sensed force error declines from 0.886 m/s^2 to 0.04 m/s^2 and the setting time declines from 2.7 s to 2.1 s. In addition, the proposed washout algorithm makes sensation errors below the otolith threshold, and the false cues cannot be apperceived.

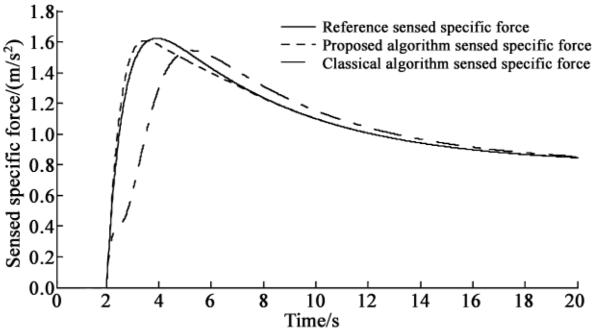

Fig. 11 Sensed specific force

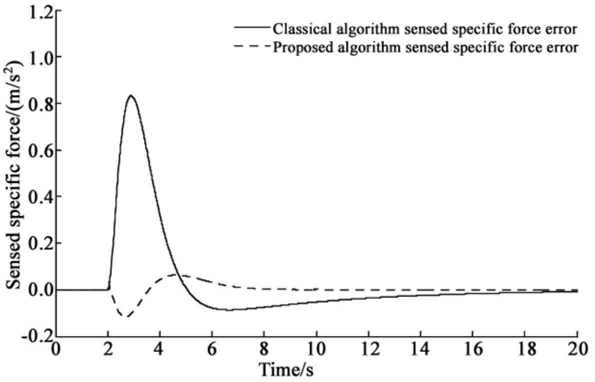

Fig. 12 Sensed specific force error

In Fig. 14, both classical washout algorithm and the proposed algorithm wash out the sensed angular velocity below the semicircular canal threshold, less than 3.6 °/s, thus human will not perceive the washout angular velocity because of tilt coordination. It proved that the novel low-pass filter meets the design requirements. In Fig. 15, the simulation results show that the proposed method only uses 0.02 m of platform, in comparison to classical washout algorithm that uses 0.042 m. Therefore, the proposed washout algorithm can reduce the displacement of motion platform, and reduce the possibility of motion platform necrosis doing extreme sports.

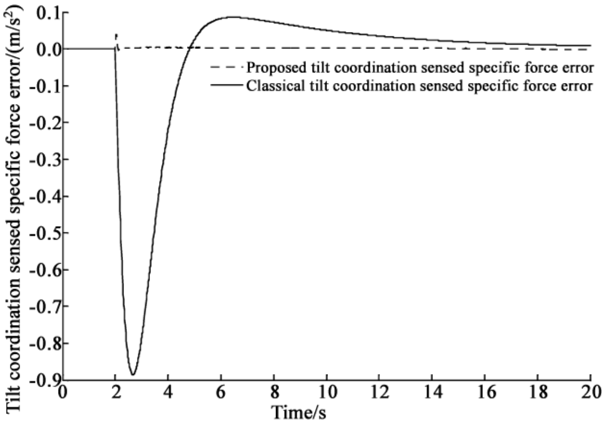

Fig. 13 Tilt coordination sensed specific force error

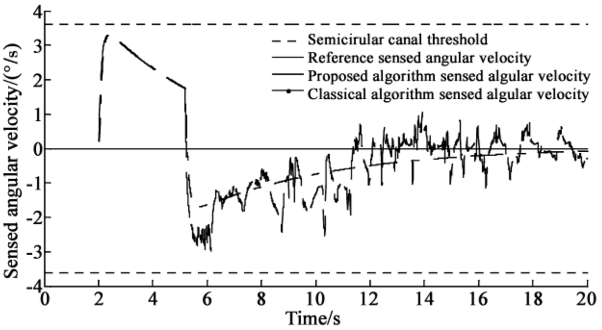

Fig. 14 Sensed angular velocity

A driving scenario has been used in the sway direction, including sudden acceleration, deceleration and braking, as an input to both classical and proposed methods. We will use white Gaussian noise with a strength of 1 dbw to verify the reliability of washout algorithm. Fig. 16 shows the input white Gaussian noise signal. Fig. 17 shows the comparison of sensed specific force for classical and proposed methods. The results of proposed method is closer to the reference sensed specific force, and extreme points are similar to the peak value of reference sensed specific force. Sensed force error between classical and proposed method is shown in Figs. 18 and 19. It has been shown that the proposed algorithm sensation error are below the otolith threshold, and false cues which caused by sensation error cannot be sensed by human vestibular system, while classical method sensation error is far beyond the semicircular canal threshold, and the human can sense it obviously.

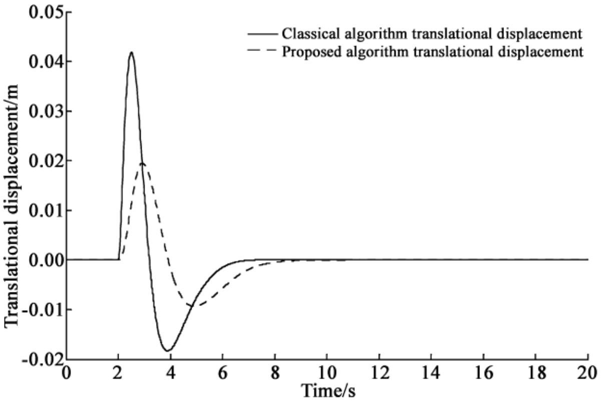

Fig. 15 Translational displacement

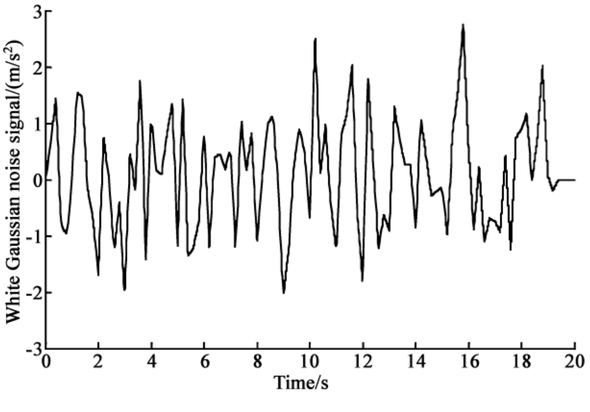

Fig. 16 White Gaussian noise signal

Fig. 20 shows the sensed angular velocity. The sensed angular velocity of classical and proposed methods are below the semicircular canal threshold, thus the tilt coordinate washout angular velocity is not to be perceived by the human body, and the reliability of the proposed washout algorithm will be ensured. In Fig. 21, the results indicate that the proposed method shrink translational displacement of motion platform from 0.05 m to 0.02 m. Therefore, the proposed method will expand the scope of simulation acceleration and decrease the possibility of motion platform necrosis doing extreme sports.

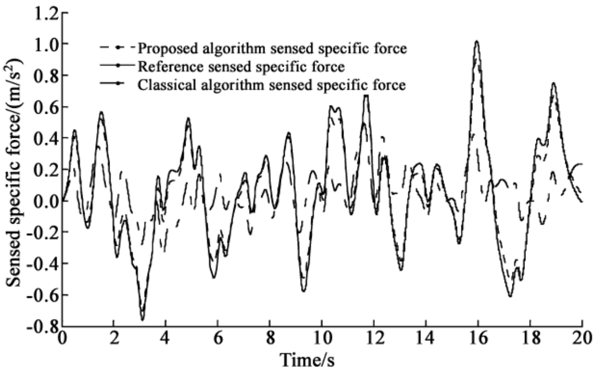

Fig. 17 Sensed specific force

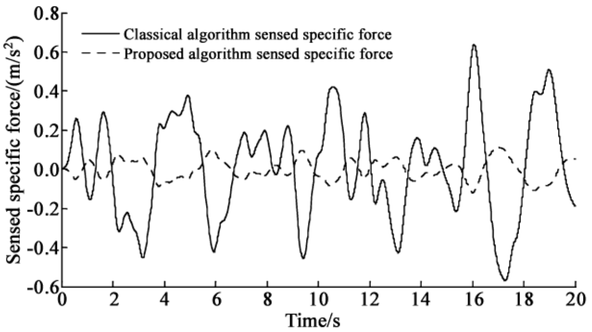

Fig. 18 Sensed specific force error

7 Conclusion

By verifying the proposed washout algorithm in MATLAB/Simulink, the results demonstrate that the proposed algorithm can overcome the phase retardation effectively, minimize the human sensation error, and eliminate the false cues significantly. In case white Gaussian noise simulates a driving scenario, the proposed method is closer to the reference signal. The sensed specific force and angular velocity do not exceed the vestibular system threshold, and it fully verifies the reliability of the proposed washout algorithm. By comparing two types of input accelerations, the proposed method can be made to reduce the displacement of motion platform. Meanwhile it can reduce the possibility of motion platform necrosis doing extreme sports. The results suggest that the proposed washout algorithm can effectively improve the dynamic fidelity of motion simulator in constant and variable accelerations.

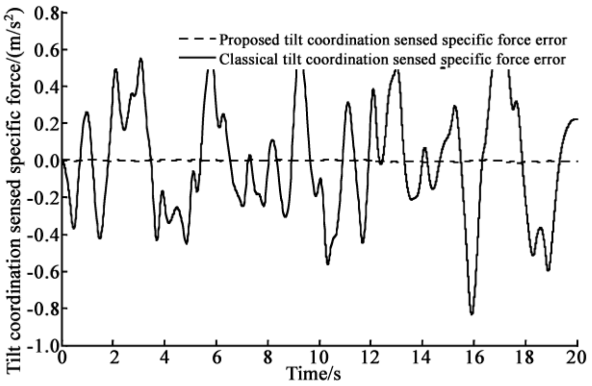

Fig. 19 Tilt coordination sensed specific force error

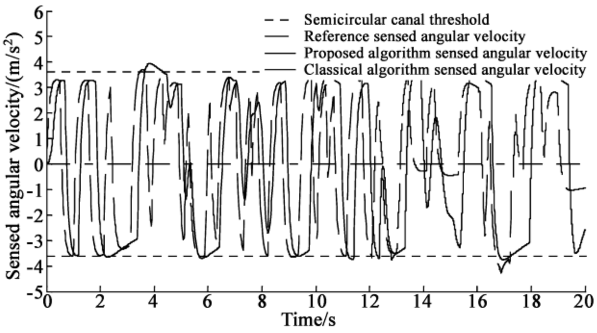

Fig. 20 Sensed angular velocity

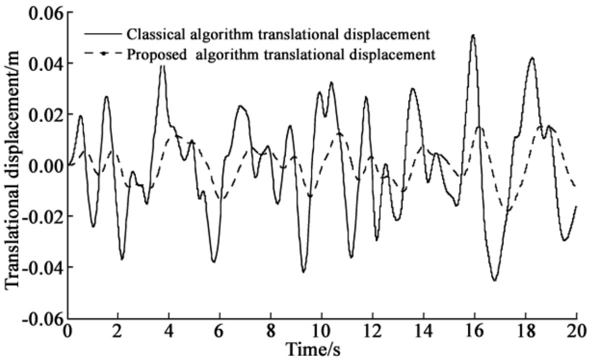

Fig. 21 Translational displacement

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