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Development of Cueing Algorithm Based on "Closed-Loop" Control for Flight Simulator Motion System

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Abstract: The classical washout algorithm had fixed gains and manually constructed filters, so that it led to poor adaptability. Furthermore, it lost the sustained acceleration cues of high- and mid-frequency in cross-over (tilt-coordination) channel, and the acceleration of cross-over frequency was also limited by angular velocity limiter, so the false cues in flight simulation process were clearly perceived by pilots. The paper studied the characteristics of the classical washout algorithm and flight simulator motion platform, tried to redesign the source of cross-over acceleration channel and translation acceleration channel, and transferred the part of cross-over acceleration that was unsimulated sustained acceleration to translation acceleration channel. Comparisons were mainly made between classical washout algorithm and revised algorithm in a longitudinal/pitch direction. The evaluation was based on the implementation of human vestibular perception system. The results demonstrated that the revised algorithm could significantly reduce the phase lag, and improved the spikes tracking performance. Furthermore, sensory angular velocity and the error of sensory acceleration were strictly controlled within the threshold of human perception system, and the displacement was a little broader than the classical washout algorithm. Therefore, it was proved that the new algorithm could diminish the filters parameters and heighten the self-adaptability for the washout algorithm. In addition, the magnitude of false cues was remarkably reduced during flight simulator, and the workspace utilization of the motion platform was developed by "closed-loop" control system.

Key words: classical washout algorithm; human vestibular system; "closed-loop" control; false cues

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0 Introduction

The motion system of flight simulator usually selected the synergistic six degrees of freedom hydraulic motion platform, which had a bit better performance[1]. However, its limited capacities severely constrained the flight simulator to effectively duplicate the motions of an actual aircraft. In response to the problems, researchers had developed a motion base drive algorithm which utilized the simulator's limited capabilities to provide the most necessary and beneficial motion cues. The drive algorithm is also called a cueing or washout algorithm. There are three mature types of cueing algorithms: classical washout algorithm[2,3], adaptive washout algorithm[4], and optimal washout algorithm[5,6]. In addition, the popular fuzzy adaptive washout algorithm was proposed in Refs. [7-10] in recent years. The algorithm theoretically combined the feature of human perception system and fuzzy control to minimize the sensation error. The classical washout algorithm (CWA) proposed by Conrad *et al*[2,3] was widely used because of its simple structure, fast execution speed and high feedback speed, but the CWA also had shortcomings. For example, the adjustment of the parameters in the filters had great subjectivity, which resulted in low satisfaction and poor flight quality for different pilots. In order to solve the problem, many scholars proposed adaptive classical washout algorithms that combined pilot behavior evaluation by which the filters and gain parameters could be adjusted adaptively[11-14]. The use of the tilt-coordination (cross-over) channel low-pass filter could effectively simulate sustained cues for the classical washout algorithm, but it was also the root cause of false cues[15], which further affected the dynamic fidelity of the flight simulator, and then it increased the number of the filter parameters, so that the computational complexity of the washout process was deepened. The principle of tilt-coordination that tilts the platform allows the use of gravity vector to provide the sustained cues. Washout entailed "sneaking" the cab back towards a neutral or steady-state position following the display of the "on-set" portion of a motion cue[16]. Therefore, the limited angular velocity in the tilt-coordination channel could seriously weaken the simulated sustained cues, which further decreased the dynamic fidelity of the flight simulator. Due to the fixed filter parameters of the classical washout algorithm, the classical washout algorithm was more conservative with the platform workspace utilization.

The adaptive algorithm was developed by Bowles *et al*[4] at the NASA Langley Research Center, each channel was added to adaptive gain parameters, which were designed to minimize a cost function, and adapted constantly throughout the simulation. The NASA adaptive washout algorithm went through modifications conducted in Refs. [4] and [17]. The adaptive gain in cross-over path was given and a null translation channel was used when dealing with pure rotational input. The linear optimal algorithm was developed by Sivan *et al* [18] and Ariel *et al* [19], and later implemented by Reid and Nahon[5,6]. The higher (6th or 7th) order filters were used and the sensation error was constrained between the simulated aircraft and motion platform dynamics. The nonlinear optimal algorithm was proposed and developed by Telban *et al*[20], which incorporated models of the human vestibular perception system. The algorithm obviously applied two separate Riccati equations in the translation and rotational channel. However, adaptive, optimal or fuzzy algorithms achieved a better washout effect at the price of the complicated control structure, sluggish execution speed and feedback speed of the washout algorithm.

In this study, a sample and fruitful washout algorithm combined with the human vestibular perception system is proposed to improve the high-pass channel and the tilt-coordination channel of the CWA, reduce the filter parameters, and overcome the influence of limited angular velocity. The surge and pitch degree of freedom are usually grouped as the surge/pitch channel, and verified the revised algorithm.

1 Classical Washout Algorithm

The pilot gives the operating signal (acceleration $\boldsymbol{a}_{\mathrm{A}}$ and angular velocity $\boldsymbol{\omega}_{\mathrm{A}}$) into the flight simulator to form specific force acceleration $\boldsymbol{f}_{\mathrm{AA}}$ and angular velocity $\boldsymbol{\omega}_{\mathrm{AA}}$ after scaling and limiting. The CWA splits into three channels in Fig. 1: high-pass (translation) acceleration channel, tilt-coordination (cross-over) channel, and rotational angular velocity channel. The washout group has four modes: longitudinal or surge/pitch, lateral or sway/roll, yaw, and heave, which are designed separately in the classical algorithm. The instantaneous acceleration cues of the flight simulator are simulated to get the displacement in the high-pass acceleration channel. The mid- and low-frequency part of motion signals $\boldsymbol{f}_{\mathrm{AA}}$ are

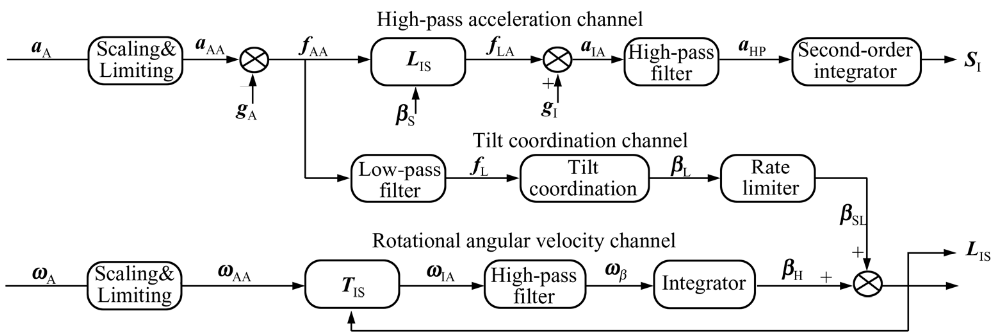

Fig. 1 Classical washout algorithm (CWA)

$\boldsymbol{a}_{\mathrm{A}}$: acceleration; $\boldsymbol{a}_{\mathrm{AA}}$: acceleration after scaling & limiting; $\boldsymbol{\omega}_{\mathrm{A}}$: angular velocity; $\boldsymbol{f}_{\mathrm{AA}}$: the specific force; $\boldsymbol{a}_{\mathrm{HP}}$: washout acceleration of high-pass filter; $\boldsymbol{\omega}_{\beta}$: washout angular velocity; $\boldsymbol{\omega}_{\mathrm{AA}}$: angular velocity after scaling & limiting; $\boldsymbol{L}_{\mathrm{IS}}$: translation transformation matrix; $\boldsymbol{T}_{\mathrm{IS}}$: rotational transformation matrix; $\boldsymbol{S}_{\mathrm{I}}$: washout displacement; $\boldsymbol{f}_{\mathrm{L}}$: specific force of low-pass filter; $\boldsymbol{\beta}_{\mathrm{S}}$: the sum of washout angle; $\boldsymbol{\beta}_{\mathrm{H}}$: angle displacement of rotational channel; $\boldsymbol{\beta}_{\mathrm{L}}$: specific force after tilt-coordination; $\boldsymbol{g}_{\mathrm{A}}$: acceleration of gravity in the upper platform coordinate system; $\boldsymbol{g}_{\mathrm{I}}$: acceleration of gravity in the reference coordinate system; $\boldsymbol{f}_{\mathrm{IA}}$:relative high-pass acceleration after the $\boldsymbol{L}_{\mathrm{IS}}$; $\boldsymbol{a}_{\mathrm{IA}}$: absolute high-pass acceleration after the $\boldsymbol{L}_{\mathrm{IS}}$; $\boldsymbol{\beta}_{\mathrm{SL}}$: angle displacement of cross-over channel; $\boldsymbol{\omega}_{\mathrm{IA}}$: angular velocity after the $\boldsymbol{T}_{\mathrm{IS}}$

removed to avoid generating the result that the motion platform goes beyond the workspace, which damages mechanical structure, then it goes through coordinate transformation and high-pass filter to obtain displacement in the desired direction after second integral. For the tilt-coordination channel, it is well known that the gravity-alignment technique exploits the inability of the otolith to distinguish between pitch (or roll) and longitudinal (or lateral) specific force. The trick is to present these sustained acceleration cues when maintaining any false platform angular rate levels (i.e, angular rates not associated with angular onset cues) below the threshold of the semicircular canals. Acceleration $\boldsymbol{f}_{\mathrm{AA}}$ goes through low-pass filter to get specific force of low-pass filter $\boldsymbol{f}_{\mathrm{L}}$ and produces the Euler angles of tilt coordination channel $\boldsymbol{\beta}_{\mathrm{SL}}$. In addition, another part Euler angles $\boldsymbol{\beta}_{\mathrm{H}}$ of the motion platform are washed out by the rotational angular velocity channel in the pitch or roll direction. Two part Euler angles make up the angular displacement of motion platform. According to the CWA, displacement and angular displacement are obtained to adjust the attitude of motion platform.

2 Human Vestibular Perception System

Through the research and analysis of the human perception system, it is found that the otolith and semicircular canals are the main organs of the human vestibular perception system that receive the outside motion signals[21,22]. Because of the nonlinear characteristics of the human vestibular perception system, Young *et al*[23] used a spring, mass, and damping model to approximately linearize the otolith system. The sensory specific force is the relative acceleration, that is, the translation acceleration minus the gravity acceleration. It can be known from Eq. (1).

$$\boldsymbol{f}_{\mathrm{AA}} = \boldsymbol{a}_{\mathrm{AA}} - \boldsymbol{g}_{\mathrm{A}} \tag{1}$$

It can be seen that the specific force $\boldsymbol{f}_{\mathrm{AA}}$ is mixed by the input acceleration and gravity vector in a direction, and the otolith cannot distinguish the acceleration caused by the motion or gravity, individually. This is the principle that tilt-coordination channel of the CWA can use the gravity vector to simulate the sustained acceleration cues of the aircraft.

The semicircular canal is the main sensory organ of the angular velocity in the vestibular system, and it can sense the angular velocity in roll, pitch and yaw directions. The mode of human vestibular perception system is shown in Fig. 2. The semicircular canals usually have a threshold. If the rotation rate is below the specified value, humans cannot feel the occurrence of rotational motion, so the parameter settings of angular velocity limiters in the tilt- coordination channel are based on the thresholds. The cockpit can be back towards a neutral or steady-state position following the display of the “onset” portion of a motion cue, and human vestibular perception system will not feel the change.

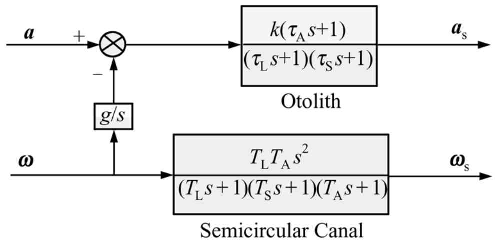

Fig. 2 Model of human vestibular perception system

k: gain factor; τ_{A}, τ_{S}, τ_{L}, physical parameters of otolith mode; T_{A}, T_{S} and T_{L}: physical parameters of the semicircular canals mode; $\boldsymbol{a}_{\mathrm{s}}$: the sensory acceleration; $\boldsymbol{\omega}_{\mathrm{s}}$: the sensory angular velocity

3 The Proposed Washout Algorithm

The specific force acceleration goes through the low-pass filter to simulate the sustained acceleration cues of the aircraft. No matter how the low-pass filter parameters are adjusted, it is impossible to completely eliminate the phase lag during the washout process, which is determined by the filter structure. The filter parameter settings have a great influence on the washout effect[12], and it is usually adjusted according to the flight requirements and behavior of different pilots. Moreover, the angular velocity limiters must have weakened the sustained acceleration cues that the part needs to be simulated, which in turn affects the overall flight simulation performance, but the thresholds of angular velocity limiters that are determined by the semicircular canals cannot be changed. In addition, another effect sometimes brought about by the constant filter parameters is the lower workspace utilization of the motion platform.

In this paper, the “closed loop” washout algorithm (CLWA) is proposed to directly eliminate the phase lag in Fig. 3, which redesigns the acceleration source of the tilt-coordination channel, then compensates the lost sustained acceleration into the translation motion channel because of the influence of angular velocity limiters.

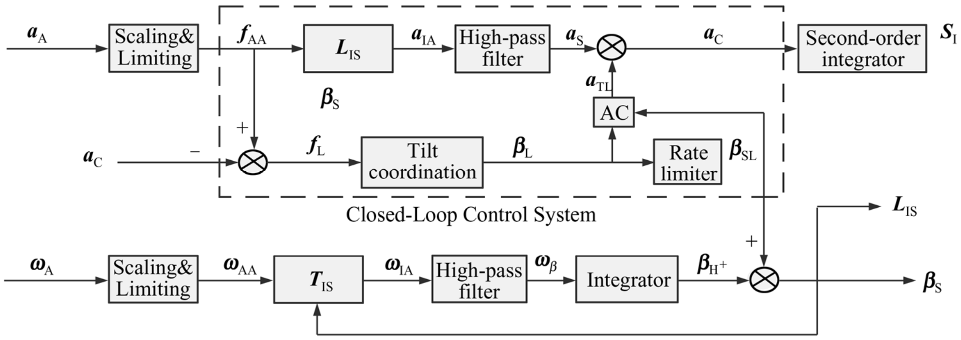

Fig. 3　"Closed-loop" washout algorithm (CLWA)

Specific measures are taken as follows:

1) Improvement of the tilt-coordination low-pass filter: The use of a low-pass filter inevitably causes some loss of sustained acceleration cues that high and mid-frequency part are filtered, which is the root cause of false cues in flight simulators. This paper combines high-pass acceleration channel and tilt-coordination principle with human vestibular perception system, redesigns the source of cross-over channel to reduce the filter parameters in the washout algorithm, and eliminates the phase lag in the tilt-coordination channel to further overcome the false cues during the washout process. The high-pass acceleration $\boldsymbol{a}_C$ is the absolute acceleration of the upper platform, so it needs to be converted to the relative acceleration. The formula is as shown in Eq. (2).

$$\boldsymbol{f}_L = \boldsymbol{f}_{AA} - (\boldsymbol{a}_C - \boldsymbol{g}_I) \tag{2}$$

2) Improvement of tilt-coordination angular velocity limiters: The effect of angular velocity limiters in tilt-coordination channel is shown in Fig. 4 (input acceleration is shown in Fig. 5). The most part of the angular velocity is beyond the specified threshold of semicircular canals. Therefore, the passed tilt angle is inevitably reduced, which will result in the partial acceleration that cannot be simulated. The acceleration $\boldsymbol{a}_{TL}$ is obtained by acceleration conversion (AC) module and then compensated to the high-pass acceleration channel, as shown in Eqs. (3) and (4).

$$\boldsymbol{a}_{TL} = (\boldsymbol{\beta}_L - \boldsymbol{\beta}_{SL}) \cdot \boldsymbol{g} + \boldsymbol{g}_I \tag{3}$$

$$\boldsymbol{a}_C = \boldsymbol{a}_{TL} + \boldsymbol{a}_S \tag{4}$$

4 Simulation Results

When simulating the flight of aircraft, it usually needs to complete different acceleration actions. The random white noise with a strength of 1 dBW is selected as longitude direction acceleration of the flight simulator in Fig. 5. In order to avoid the disturbance of the angular velocity, the input of high-pass angular velocity is zero. In Fig. 6, CLWA, CWA and reference model (the flight signal of the aircraft directly goes through the human vestibular perception system) are compared in tilt-coordination channel. It can be seen that the overall phase lag of the CWA through the low-pass filter is relatively serious. It can only blur the trend of sustained acceleration cues, and the spike tracking performance of the CWA is extremely poor. The CLWA adopts a new source of low-pass acceleration, greatly reduces the phase delay

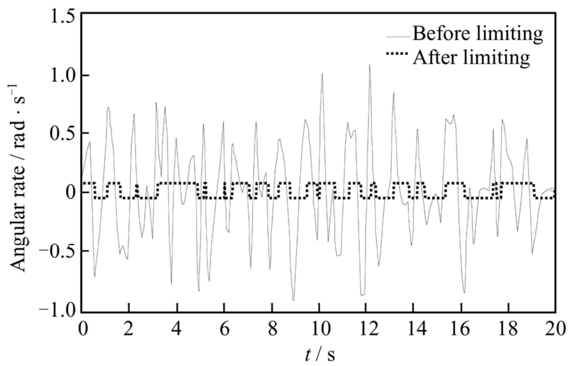

Fig. 4　Angular rate before and after limiting

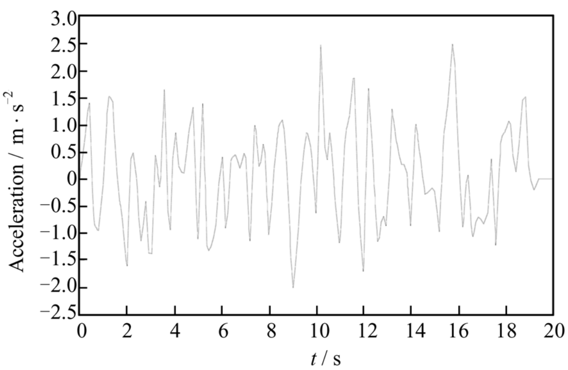

Fig. 5　Input acceleration

of the tilt-coordination acceleration, and can well approach the extreme points of the reference curve, thereby effectively overcoming the false cue phenomenon to improve the dynamic fidelity of the flight simulator. Figure 7 is a displacement curve of the CWA and CLWA. The CWA workspace is conservative and the motion range is within ±0.05 m, and the motion platform is not fully utilized. The CLWA washes out the displacement range within ±0.12 m under the same high-pass filter parameters, which can effectively increase the space utilization of the motion platform.

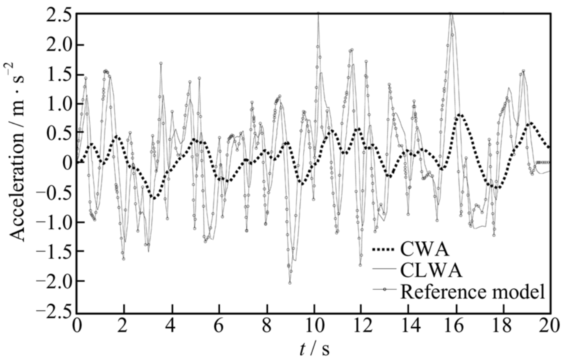

Fig. 6 Tilt-coordination acceleration

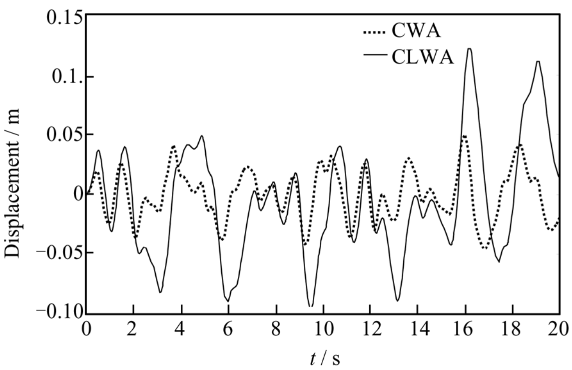

Fig. 7 Washout displacement

It is common knowledge that the angular velocity threshold of the semicircular canal is 3.6 °/s or 0.062 8 rad/s in the pitch direction. If the threshold is exceeded, people will feel the tilt-coordination motion, resulting in a sensory angular velocity during the washout process. It can be seen from Fig. 8 that washout angular velocity going through tilt-coordination channel is limited below 0.062 8 rad/s, and people cannot feel the angular velocity in the pitch direction, which proves that it has effect to follow human vestibular perception model, besides the continuous acceleration of the tilt-coordination is simulated in a maximum degree. It is more reasonable than the CWA. Figure 9 shows that the attitude angle of the motion platform is washed out by the CWA and CLWA. It can be seen that washout angular displacement is basically the same as the CWA. Compared with CWA, the washout angular displacement of CLWA does not significantly increase ensuring the occurrence of tilt-coordination process within the human perception threshold, so that people do not feel the continuous acceleration that is caused by the tilt component of gravity. It is proved that the structural design of the proposed algorithm is basically in line with the motion washout performance requirements of the flight simulator.

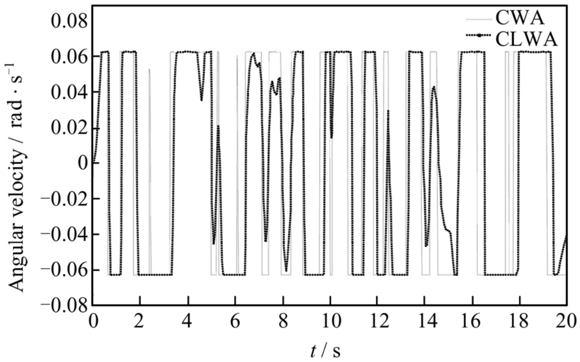

Fig. 8 Washout angular velocity

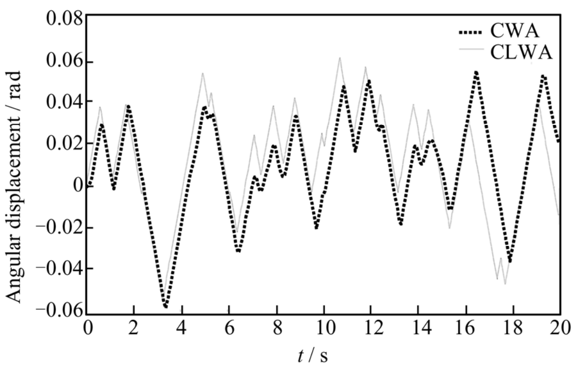

Fig. 9 Washout angular displacement

The washout acceleration consists of the translation acceleration of the high-pass acceleration channel and the continuous acceleration of the tilt-coordination channel. In Fig. 10 and Fig. 11, the CWA brings about relatively large phase delay and the sensory error due to the influence of the low-pass filter and the angular velocity limiter, which in turn causes false cue phenomenon in the X acceleration direction. The CLWA effectively overcomes the shortcomings of the CWA, so that the sensory acceleration during washout process produces a very small phase delay, and the sensory acceleration error below 5×10^{-3} m/s^2 is much smaller than the otolith threshold, so people cannot feel the false cue. It proves that the design of CLWA has a high degree of reliability.

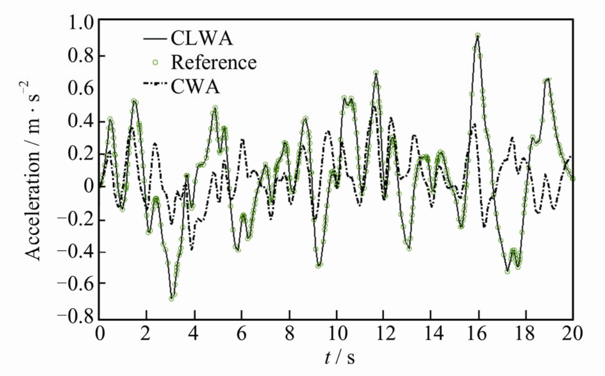

Fig. 10 Sensory acceleration

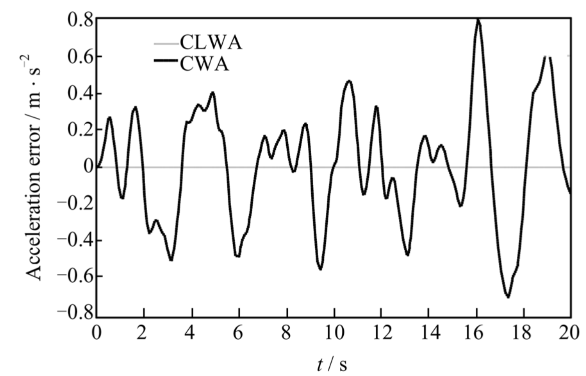

Fig. 11 Sensory acceleration error

5 Conclusion

The paper combines the motion characteristics of human vestibular perception system with the novel "closed loop" control system structure, and designs the CLWA. Simulation result shows that the CLWA can reduce the phase lag and increase the fitting degree of the sensory acceleration spikes during the washout process to effectively overcome the false cue phenomenon and significantly improve the washout effect and dynamic fidelity of the flight simulator. In addition, the design of "closed-loop" control system can reduce the number of filter parameters for washout algorithm, which helps to reduce the computational complexity, and remarkably heighten the self-adaptability for washout algorithm and the part of tilt-coordination acceleration that converts to the high-pass acceleration channel contributes to improve the space utilization of the motion platform, but the limited capabilities need to be considered for the spikes of displacement in future work.

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