附录 3：

華中科技大学

本科生毕业设计（论文）参考文献译文本

译文出处：ZHU Daoyang，DUAN Shaoli，FANG Da.Development of Cueing Algorithm Based on “Closed-Loop” Control for Flight Simulator Motion System[J].Wuhan University Journal of Natural Sciences，2019，24(05):376-382.

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基于“闭环”控制的飞行模拟器运动系统体感模拟算法的改进

摘要：

经典的洗出算法存在固定输入和手动构造滤波器的问题，导致其适应性较差。此外，在交叉(倾斜坐标系)通道中丢失了对高频和中频的持续加速度的模拟，而交叉频率的加速度也受到角速度限制器的限制，因此飞行员可以清楚地感知飞行仿真过程中的错误模拟。本文研究了经典洗出算法和飞行模拟器运动平台形式的特点，尝试对交叉加速通道和平动加速通道的来源进行重新设计，将未被模拟的持续交叉加速部分转移到平动加速通道中。主要对经典洗出算法和修正后算法在纵向/俯仰方向进行了比较。评价以人体前庭感知系统的实现为基础。实验结果表明，改进后的算法能显著减小相位滞后，提高峰值跟踪性能。此外，感知角速度和感知加速度误差被严格控制在人类感知系统的阈值之内，且位移比经典的洗脱算法略宽。另外，在飞行模拟器中，错误模拟的程度显著降低，并通过“闭环”控制系了运动平台的工作空间利用率

关键词：经典洗出算法人；体前庭感知系统；“闭环”控制；错误体感模拟；

0. 引入

飞行模拟器的运动系统通常选择具有较好性能的协同六自由度液压运动平台[1]，然而，其有限的能力严重限制了飞行模拟器有效地复制实际飞机的运动。针对这些问题，研究人员开发了一种运动平台驱动算法，利用模拟器有限的能力尽可能地提供最必要和合适的运动模拟。驱动算法也称为模拟算法或洗出算法。成熟的体感模拟算法有三种:经典洗出算法[2][3]、自适应洗出算法[4]、最优洗出算法[5][6]。此外，在参考文献中提出了目前流行的模糊自适应洗脱算法。[7][8][9][10]近年来。该算法从理论上结合了人体感知系统的特点和模糊控制，使感知误差最小化。Conrad 等[2][3]提出的经典的冲刷算法(CWA)以其结构简单、执行速度快、反馈速度快等优点得到了广泛的应用，但 CWA 算法也存在不足之处。例如，过滤器的参数调整有很大的子客观性，导致不同的飞行员满意度低，飞行质量差。为了解决这一问题，许多学者提出了结合了飞行员评估的自适应经典冲洗算法，通过该算法可以自适应调整滤波器和增益参数[11][12][13][14]。倾斜坐标系(cross-over)通道低通滤波器的使用可以有效为经典洗出算法持续的模拟体感，但它也是错误体感模拟[15]的根源，这进一步影响了飞行模拟器的动态逼真度，进而增加了滤波参数的数量，从而加深了冲刷过程的计算复杂度。倾斜坐标系的原则就是倾斜平台，它允许使用重力矢量提供持续的体感模拟。洗出算法在模拟完“设置”运动之后需要将运动平台“偷偷”地置于中立的或稳态的位置[16]。因此，倾斜坐标系通道的有限角速度会严重削弱持续的体感模拟，进一步降低飞行模拟器的动态逼真度。由于

经典洗出算法的滤波参数固定，经典洗出算法对平台工作空间的利用更加保守。该自适应算法是由 NASA 兰利研究中心的 Bowles 等人[4]开发的，每个通道都被添加到自适应增益参数中，这些参数被设计成最小化一个成本函数，并在整个仿真过程中始终保持自适应。

NASA 的自适应冲洗算法在参考文献[4][17]里进行了修改。给出了交叉路径的自适应增益，并在处理纯转动输入时采用了零平移通道。化算法是由 Sivan 等人[18]和 Arielet 等人[19]开发的，后来由 Reid 和 Nahon 实现[5][6]。采用高阶(6 阶或 7 阶)滤波器，感知误差被控制在模拟飞机与运动平台动力学之间。非线性优化算法是由 Telban 等人[20]提出并开发的，该算法融合了人类前庭感知系统的模型。该算法显然在平移和旋转通道中应用了两个独立的黎卡提方程。然而，自适应、最优或模糊算法以复杂的控制结构、缓慢的执行速度和反馈速度为代价，才取得了较好的洗出效果。

本研究结合人类前庭感知系统，提出了一种简单有效的洗出算法，以改善 CWA 的高通通道和倾斜坐标系通道，减少滤波参数，克服有限角速度的影响。将纵振和俯仰自由度归为纵振/俯仰通道，并对改进算法进行了验证。

1. 经典洗出算法

飞行员给操作信号(加速度 a_A 和角速度 ω_A)进入飞行模拟器，通过缩放和限制形成比力 f_{AA} 和角速度 ω_{AA}；

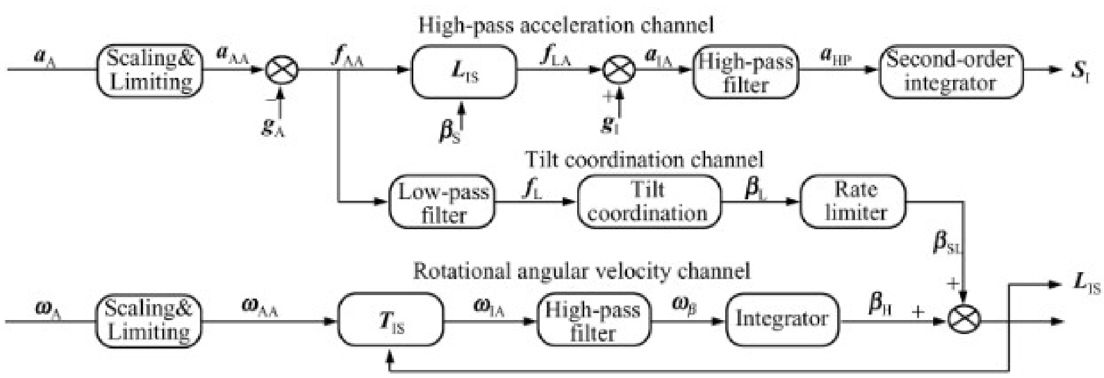

图 1 Classic Washout Algorithm 经典洗出算法

a_A: 加速度; a_{AA}: 经过缩放和限制的加速度; ω_A: 角速度; f_{AA}: 比力; a_{HP}: 高通滤波器洗出加速度; ω_β: 洗出角速度; ω_{AA}: 经过缩放和限制的角速度; L_{IS}: 平动转化矩阵; T_{IS}: 转动转换举证; S_I: 洗出位移; f_L: 低通比力; β_S: 洗出角总和; β_H: 旋转通道角位移; β_L: 倾斜坐标系后的比例; g_A: 上平台坐标系重力加速度; g_I: 参考坐标系中立加速度; f_{IA}: 经过 L_{IS} 后的相对高通加速度; a_{IA}: 经过 L_{IS} 后的绝对高通加速度;β_{SL}: 倾斜坐标系通道的角位移;ω_{IA}: 经过 T_{IS} 后的角速度;

在图 1 中，CWA 分为三个通道:高通(平移)加速通道、倾斜坐标系(交叉)通道和旋转角速度通道。洗出组有四种模式:纵向或纵荡/纵摇、横向或横荡/横摇、艏摇和垂荡，这四种模式在经典算法中分别设计。通过高通加速度通道中的位移来模拟飞行模拟器的瞬时加速度。去除运动信号 f_{AA} 的中频和低频部分，避免产生运动平台超出工作空间而破坏机械结构的结果，然后经过坐标变换和高通滤波，经过二次积分后得到所需方向的位移。对于倾斜坐标系通道，众所周知，重力校准技术利用了耳石无法区分纵摇(或横摇)和纵向(或横向)的比力。该技巧是通过维护任何错误的平台角速度水平(也就是说，角速率与初始设置的角度模拟无关)低于半规管的阈值展现这些持续的加速模拟。加速度 f_{AA} 通过低通滤波器来获得低通滤波器的比力 f_L，以此产生倾斜坐标系通道的欧拉角 β_{SL}。此外，平台的另一部分欧拉角 β_{SL} 则由在纵摇或者横摇方向的旋转角速度通道洗出。两部分的角位移组成了运动平台的角位移。根据经典洗出算法，得到的位移和角位移用于调整运动平台的姿态。

2. 人体前庭感知系统

通过对人类感知系统的研究和分析，发现耳石和半规管是人类前庭感知系统接收外界运动信号的主要器官[21][22]。由于人类前庭感知系统的非线性特性，Young 等[23]人使用弹簧、质量和阻尼模型来近似线性化耳石系统。感知比力就是相对加速度，也就是平移加速度减去重力加速度。由式(1)可知：

$$f_{AA} = a_{AA} - g_A \qquad (1)$$

可以看出，具体的力 f_{AA} 是由输入的加速度和重力矢量在一个方向上混合而成，耳石无法单独区分运动或重力引起的加速度。这是 CWA 倾斜坐标系通道利用重力矢量模拟飞机持续加速度线索的原理。半规管是前庭系统角速度的主要感觉器官，它能感觉横摇、纵摇和艏摇方向的角速度。人体前庭感知系统模式如图 2 所示。

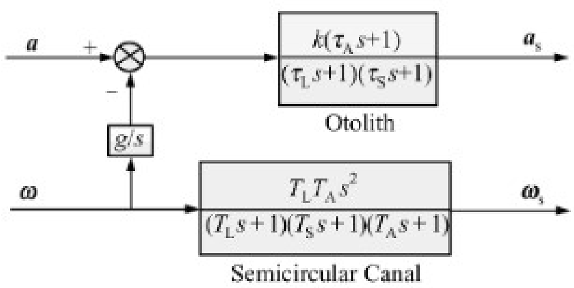

图 2 人体前庭感知系统

k: 增益因子；τ_A， τ_S， τ_L， 耳石模型的物理参数; T_A， T_S and T_L: 半规管模型的物理参数; a_s: 感受的加速度; ω_s:感受的角速度;

半规管通常有一个阈值。当转速低于规定值时，人感觉不到旋转运动的发生，因此倾斜坐标系通道角速度限制器的参数设置是基于阈值的。在显示运动提示的“开始”部分后，驾驶员座舱可以恢复到中性或稳定状态，而人类前庭感知系统不会感受到这种变化。

3. 改进的洗出算法

比力加速度通过低通滤波器来模拟飞机的持续加速度。无论如何调整低通滤波器参数，都不可能完全消除冲洗过程中的相位滞后，这是由滤波器结构决定的。滤波器参数设置对洗出效果[12]影响较大，通常根据不同飞行员的飞行要求和行为进行调整。此外，角速度限制器一定会削弱部件需要模拟的持续加速度，从而影响了整体的飞行模拟性能，但是由半规管决定的角速度限制器的阈值是不能改变的。此外，常滤波参数有时会带来的另一个影响是运动平台的工作空间利用率较低。

本文提出了“闭环”洗出算法(CLWA)，直接消除了图 3 中的相位滞后，重新设计了倾斜坐标系通道的加速度源，并将由于角速度限制器的影响而损失的持续加速度补偿到平移运动通道中。

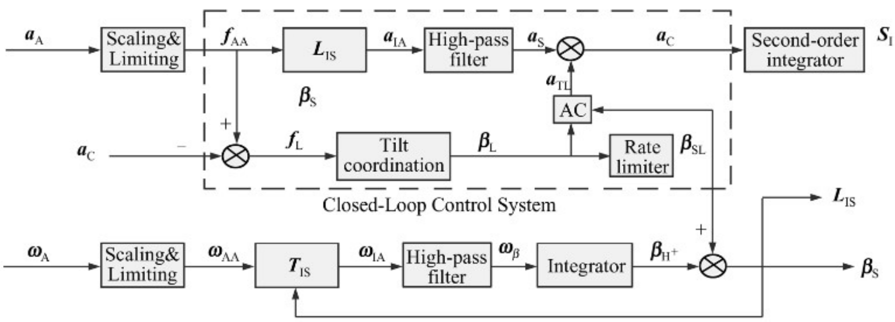

图 3“闭环”洗出算法 (“Closed-loop” washout algorith)

具体措施如下：

1) 对倾斜协调低通滤波器的改进：低通滤波器的使用不可避免地会丢失一些高中频部分被过滤掉的持续加速度，这是造成飞行模拟器中出现虚假模拟的根本原因。本文结合高通加速度通道和倾斜坐标系原理与人类前庭感知系统，重新设计倾斜协调渠道的来源来减少洗出算法里的滤波器参数，于此同时清楚了倾斜坐标系通道的相位滞后，进一步克服洗出过程中错误提示。高通加速度 a_C 是上层平台的绝对加速度，需要转换为相对加速度。公式如式(2)所示。

$$f_L = f_{AA} - (a_c - g_I) \tag{2}$$

2) 倾斜坐标系角速度限制器的改进：倾斜坐标系通道中角速度限制器的作用如图 4

所示(输入加速度如图 5 所示)。角速度的大部分超过了规定的半规管阈值。因此，不可避免

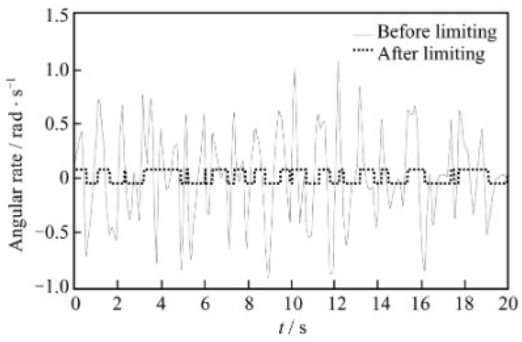

图 4 限制前后的角速度

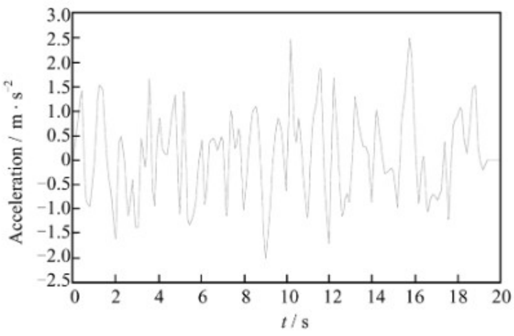

图 5 输入加速度

地要减小传入的倾斜角，这将导致无法模拟的部分加速度。加速度 a_{TL} 是通过加速度转换(AC)模块得到的，然后补偿给到高通加速通道，如公式(3)和(4)所示。

$$a_{TL} = (\beta_L - \beta_{SL}) \cdot g + g_I \tag{3}$$

$$a_C = a_{TL} + a_S \tag{4}$$

4. 模拟结果

在模拟飞行器飞行时，通常需要完成不同的加速度动作。选取强度为 1 dBW 的随机白噪声作为飞行模拟器的经度方向加速度，如图 5 所示。为了避免角速度的扰动，高通角速度的输入为零。在图 6 中，将 CLWA， CWA 与参考模型（飞机的飞行信号直接通过人体前庭感知系统）在倾斜坐标系通道中进行对比。可以看出，CWA 通过低通滤波器的整体相位滞后比较严重。它只能模糊持续加速的趋势，而且 CWA 的峰值跟踪性能极差。而 CLAW 算法采用了一种新的低通加速度源，大大降低了倾斜协调加速度的相位延迟，能够很好地逼近参考曲线的极值点，从而有效地克服了虚假模拟现象，提高了飞行模拟器的动态逼真度。图 7 是 CWA 和 CLWA 的位移曲线。CWA 工作空间保守，运动范围在±0.05 m 以内，运动平台

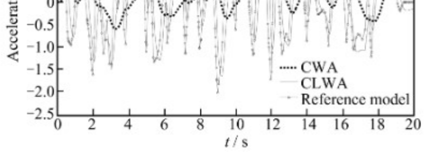

图 6 倾斜坐标系加速度

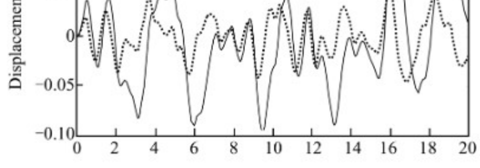

图 7 洗出位移

未充分利用。CLWA 在相同高通滤波参数下，冲刷出±0.12 m 内的位移范围，有效提高了运

动平台的空间利用率。

众所周知，半规管的角速度阈值在螺距方向上为 3.6° /s 或 0.062 8 rad/s。如果超过这个阈值，人们就会感受到倾斜坐标系运动，从而在洗出过程中产生感官角速度。可以看到从图 8，冲刷角速度经历 tilt-coordination 频道有限低于 0.062 8 rad / s，人们不能在纵摇方向上感觉角速度，这证明它有效地遵循人类前庭感知模型，此外，在倾斜坐标系通道的连续的加速度模拟也处于最大的程度。它比 CWA 更加可靠。从图 9 可以看出，CWA 和 CLWA 洗出的姿态角位移基本相同，与 CWA 相比，CLWA 的洗出角位移没有显著增加，这保证了在人类感知阈值范围内发生倾斜坐标系过程中，人们感觉不到由于重力的倾斜分量引起的连续加速度。结果表明，该算法的结构设计基本符合飞行模拟器的运动洗出性能要求。

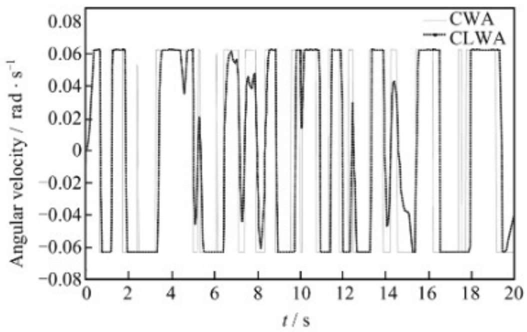

图 8 洗出角速度

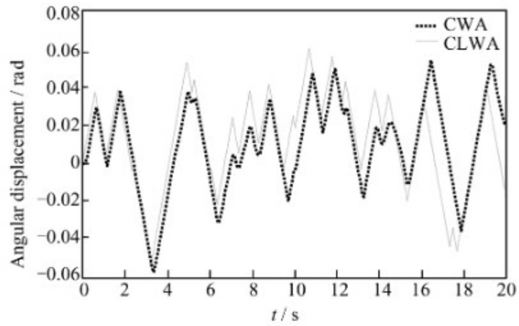

图 9 洗出角位移

洗出加速度由高通加速度通道的平移加速度和倾斜坐标系通道的连续加速度组成。在图 10 和图 11 中，由于低通滤波器和角速度限制器的影响，CWA 带来了较大的相位延迟和感官误差，反过来导致了 X 方向的加速错误体感模拟现象。CLWA 有效地克服了 CWA 的缺点，使得洗出过程中的感觉加速度产生非常小的相位延迟，5×10^{-3} m/s^2 以下的感觉加速度错误远远小于耳石阈值，使人感觉不到虚假体感模拟。结果表明，该设计具有较高的可靠性。

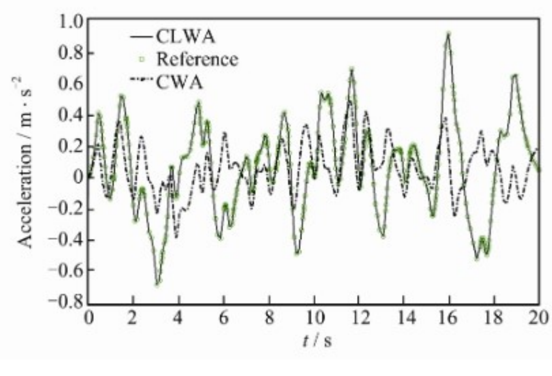

图 10 感知加速度

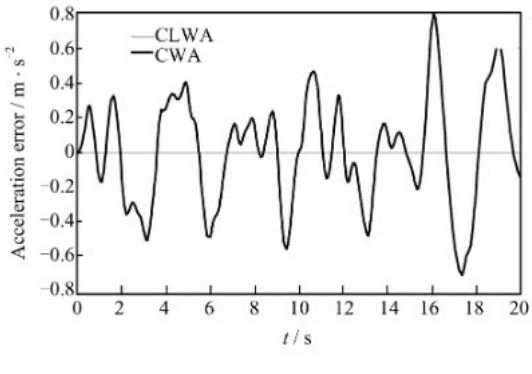

图 11 感知加速度错误

5. 结论

本文将人体前庭感知系统的运动特性与新型的“闭环”控制系统结构相结合，设计了

CLWA 算法。仿真结果表明，该算法能够有效地克服虚假模拟现象，减少相位滞后，提高洗出过程中感知加速度峰值的拟合程度，显著提高了飞行模拟器的洗出效果和动态逼真度。此外，“闭环”控制系统的设计可以减少洗出算法滤波器参数的数量，这有助于减少计算复杂度，并显著提高洗出算法的自适应性，同时提高了用于转换到高通加速通道用于提高运动平台空间利用率的那部分倾斜坐标系加速度，但是在未来的工作中，需要考虑位移峰值　的有限能力。

参考文献

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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 $\boldsymbol{a}_{\rm A}$ and angular velocity $\boldsymbol{\omega}_{\rm A}$) into the flight simulator to form specific force acceleration $\boldsymbol{f}_{\rm AA}$ and angular velocity $\boldsymbol{\omega}_{\rm AA}$ 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 $\boldsymbol{f}_{\rm AA}$ are

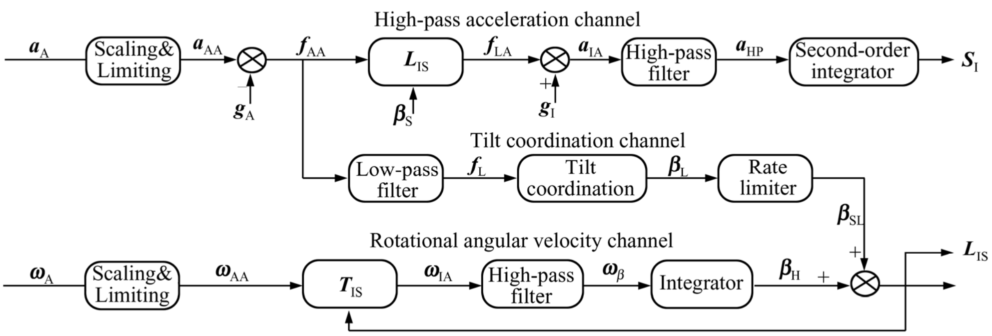

Fig. 1 Classical washout algorithm (CWA)

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

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.

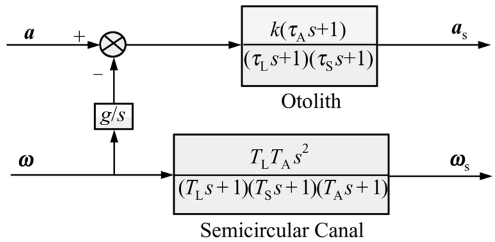

Fig. 2 Model of human vestibular perception system

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.

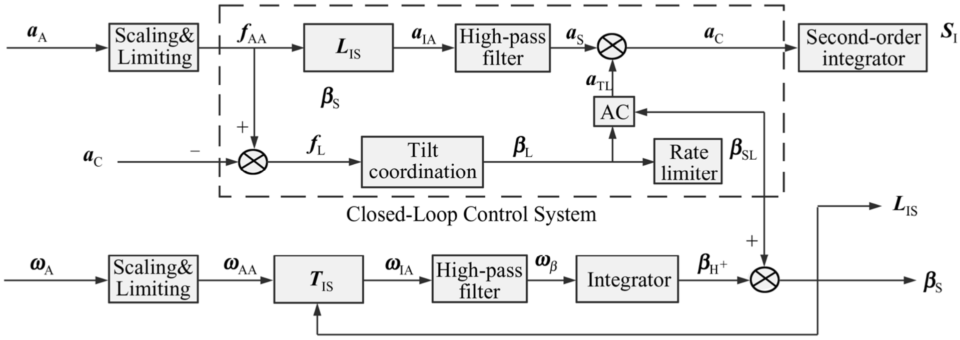

Fig. 3 "Closed-loop" washout algorithm (CLWA)

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

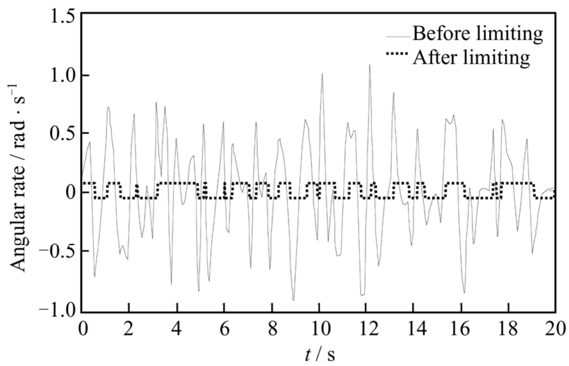

Fig. 4 Angular rate before and after limiting

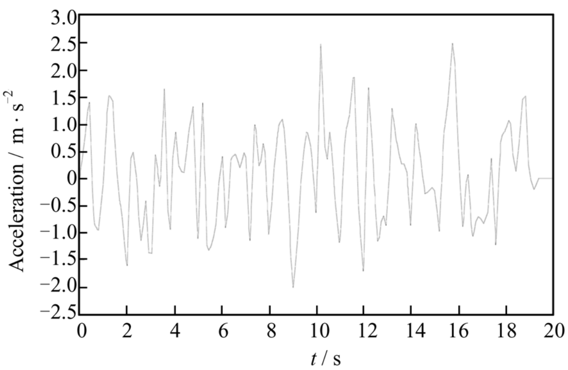

Fig. 5 Input acceleration

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.

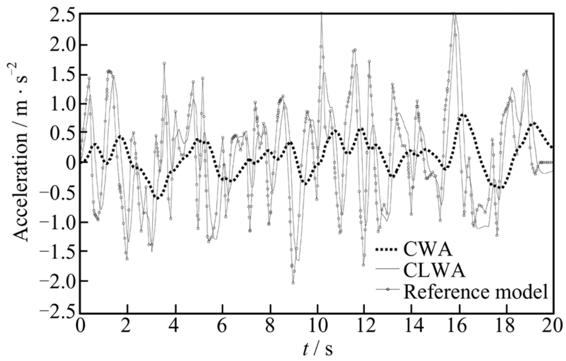

Fig. 6 Tilt-coordination acceleration

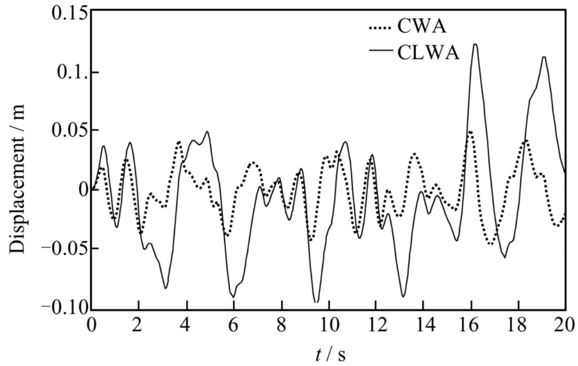

Fig. 7 Washout displacement

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.

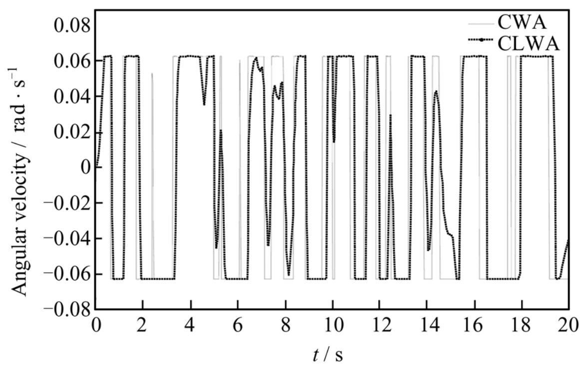

Fig. 8 Washout angular velocity

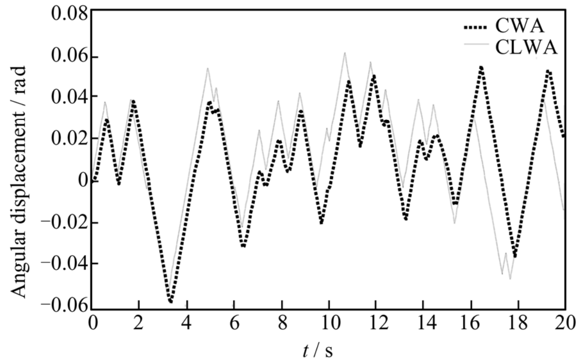

Fig. 9 Washout angular displacement

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.

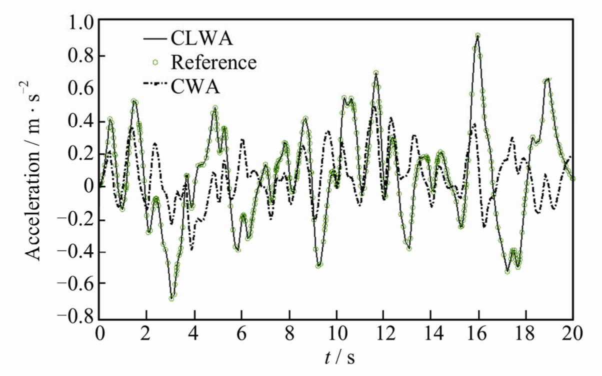

Fig. 10 Sensory acceleration

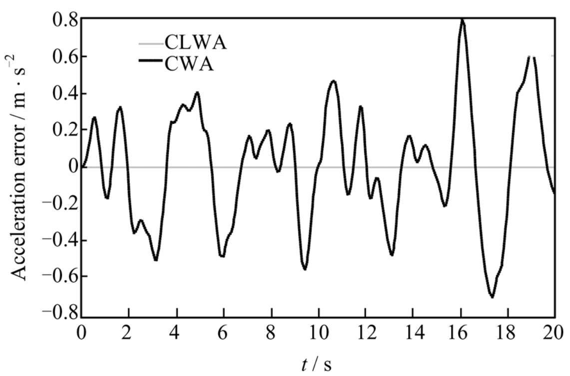

Fig. 11 Sensory acceleration error

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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