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THE RESEARCH ON CAB SIMULATOR OF QUAY CRANE CONTAINERS ON CLASSICAL WASHOUT ALGORITHM

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Abstract- The acceleration of the speed of the quay crane for containers has raised a higher demand to the dynamic simulation system which is the key part of the simulator in the coast container crane. So it is very necessary to do this research on it. This essay, aimed at the seat motion system of training simulator in the coast container crane, lays a study on the key points in the design of the proprioceptive simulation algorithm of the bridge crane simulator and proposes the realization method for it. This method can help to find the most proper washout point and optimizes the fixed parameter so as to be able to improve the simulation fidelity by offering a better system. It also establishes the simulation model by MATLAB on the basis of which it operates the simulation calculation and analysis on a group of practical motion data. The result shows that this algorithm provides an effective way for the application of the TDOF simulator.

Index terms*:* Training Simulator; Proprioceptive Simulation Algorithm; Motion Platform; TDOF.

I. INTRODUCTION

In order to obtain a real feeling as in the practical operation when being in the limited space of the simulator motion system, we need to introduce the washout algorithm into the instructions of platform motion and system motion so that we can ensure that after a gusty motion, the training simulator can return to the neutral position and have enough space for the next motion and during this process, we should also ensure that the driver would not feel the motion. To reach this requirement, the motion platform should fulfill the task in a mild form below the human sensation threshold (0.02g) to achieve the goal of gaining an infinite motion sensation in a finite space. So the quality of the washout algorithm has a direct influence on the fidelity of dynamic simulation. Proprioceptive simulation algorithm, as a kind of controlling software, being a reflection of the cab motion simulation , cannot only simulate a actual motion in a finite operating space but also give the driver a real feeling [1]. TDOF motion system, as a kind of hardware, is the carrier of the simulator cab and it can simulate the actual motion according to the drive parameters calculated by the motion simulation module in the cab to give the driver a real feeling. So the quality of the TDOF also has a direct effect on the fidelity of the dynamic simulation.

The washout algorithm is widely used as three kinds: classical washout algorithm [2], optimal control washout algorithm [3] and coordinated adaptive washout algorithm.

The classic filtering algorithm, featuring as concise, easily adaptive, fast in operation and feedback, is still widely used in dynamic simulation. Having the function of coordinating the washout, this algorithm can washout the linear motion and angular motion into dynamic coordination signal so that it can improve the simulator's reproduction ability to the low frequency dynamic signal [4].

MATERNAL to China's first independently Xiaoliang Wang developed targeted train driving simulator to study the washout location for train driving simulator fidelity effects [5]. Using MATLAB to washout by a different position after platform motion displacement and washout the classic algorithm and the sensory evaluation model simulation analysis to produce a feeling of comparison, the centroid of the platform to the position of the optimal wash conclusion, the position of other types of wash simulator also has the choice of reference effect. Therefore, the effect of exercise simulated the feeling is very limited.

Based on the analysis of three common somatosensory simulation algorithm deficiency in high-speed train driving simulator applications [6], Xiaoliang Wang studies high-speed train driving simulator somatosensory simulation algorithm design of the key issues on the proposed the design and implementation of high-speed train driving simulator method somatosensory simulation algorithm. In this method, washout the effects of different positions based on simulation fidelity, to find the most suitable washout position; based on genetic algorithms, to meet the movement of the platform and the rapid return of human motion sensory threshold required to optimize the high-speed train driving simulator somatosensory simulation algorithm with fixed parameters; based on fuzzy control, we propose two high-speed train driving simulator somatosensory simulation algorithm-fuzzy classical washout algorithm simulation and fuzzy adaptive washout algorithm, the new algorithm can not only meet the high-speed train driver Real-time computing requirements , but also to get a higher fidelity simulation.

Requiring linear acceleration motor sport and the angular velocity parameter handling in order to meet programming requirements by filtering somatosensory simulation algorithm, the algorithm needs to achieve through digital simulation algorithm based on the principles of classical somatosensory. Tang Yi made to achieve a feeling of movement in the car simulator [7]. Due to the movement of human type for vehicles, the simulation algorithm derived somatosensory filter transfer function and the orders: using bilinear transform method, the mapping of the analog filter frequency digital filter frequency transfer function is derived and differential equation expressions. Implements digital filtering application of this digital filter analog signals and digital signals output from the virtual car is filtered; the results show that the digital filter can be separated from the high-frequency and low frequency signals, which meet the filtering accuracy and real-time requirements to achieve the desired filtering effect.

From the Stewart platform providing a realistic guarantee dynamic angle of pilots within their workspace departure, the classical washout algorithm parameter selection methods have been studied by a analysis of first and second order linear first-order high-pass filter and a linear low-pass filter step response, Dr. Yang Yu put forward that filter parameters derived analytical relations between the step response and thus presents a time-domain response of the filter-based filtering parameter selection methods [8], namely the various parameters of the filter were fixed step search within a certain range. Thus the filter parameters are generated by the optimal time-domain response and the use of aircraft during takeoff the flight simulation data and Stewart platform for its experimental verification results show that the use of the parameters of the method chosen to take advantage of the Stewart platform workspace provides pilots with realistic movement.

WeiChunyu use the vehicle dynamics model Vortex software and parallel 6-DOF platform model for joint washout motion simulation platform visualization [9], who proposed a multi-body dynamics software use Vortex on 6 DOF platform simulation platform hydraulic cylinders initial posture modeling complex movement of the vehicle model is now determined, using the analytical method to achieve washout filter algorithm and inverse kinematics algorithm in simulink motion platform, then using the turn and line 2 typical movement simulation.

The parameters in the classical washout algorithm directly affect the quality of the algorithm. But at present, the parameters are mainly determined by the experience of the designer and the feeling of the driver. Due to the large amount of the parameters, the debug process is very complex and the reproduction ability of the motion platform is difficult to come into play. To solve this problem, the easy puts forward a new method of choosing the parameter: we may calculate the parameter according to the limiting conditions to the motion displacement, speed and acceleration from the motion platform by using the time-domain response analytical expressions of different kinds of linear filters and the way of traversal search.

II. THE ALGORITHM CONSTITUTE INPUT SIGNAL SOLVING

a. The composition of the classical washout algorithm

The general motion is divided into four modes: portrait mode (including vertical and pitch two degrees of freedom), the lateral mode (including horizontal and roll two degrees of freedom), yaw mode, and up and down mode in washout algorithm. The first two modes enable the simulator to tilt the pitch angle and roll angle which uses the component of the acceleration due to gravity in simulator body coordinate system to provide continuous acceleration feel for the driver. The following figure 1 is a schematic diagram of dynamic simulation of the motion simulator:

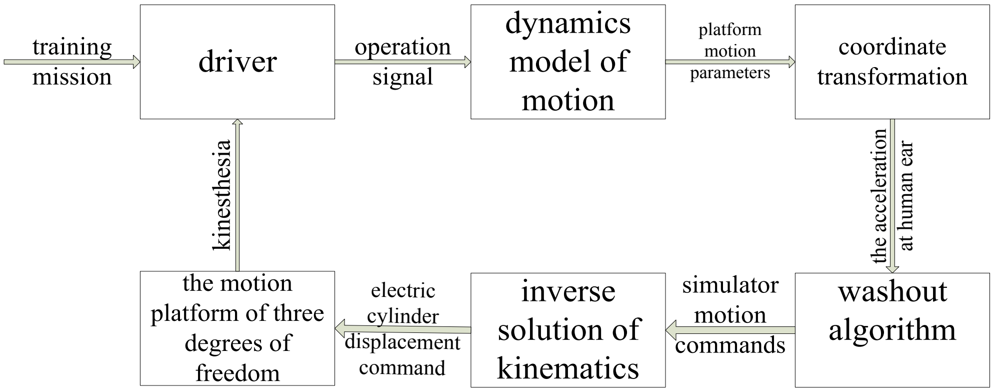

Figure 1 schematic diagram of dynamic simulation of the motion simulator

b. The establishment of coordinate system

F_o coordinate system: geodetic coordinate system, that is the earth -fixed inertial coordinate system. Its origin O is the geometric center of static platform in motion platform of three degrees of freedom, X_0 direction is the moving direction of the gantry, Y_0 direction is the moving direction of the trolley, Z_0 direction uses the right-hand rule to determine.

F_s coordinate system: Emulator coordinate system, due to requiring the frequent use of motion and force parameters of the coordinate origin, so the origin S is chosen as motion platform centroid in three degrees of freedom platform, X_s direction is the moving direction of the gantry, Y_s direction is the moving direction of the trolley, Z_s direction uses the right-hand rule to determine.

F_A coordinate system: corresponding to the coordinate system of the coordinate system of the emulator in the actual cab movement. Origin A in the platform is the position corresponding to the S coordinates origin in the emulator, each axis direction parallel to the axis in Fs coordinate system. The establishing position of the coordinate system is shown in Figure 2.

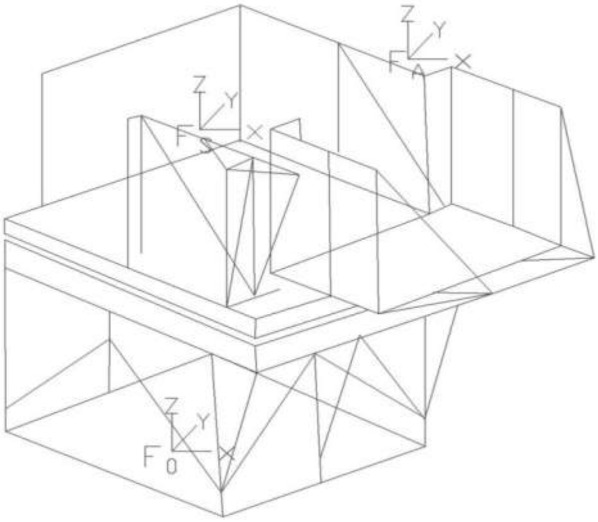

Figure 2 Driving Simulator diagram

c. Coordinate transformation

In the analysis and synthesis of space agencies, a special kind of homogeneous transformation matrix is widely used, that is D-H matrix.

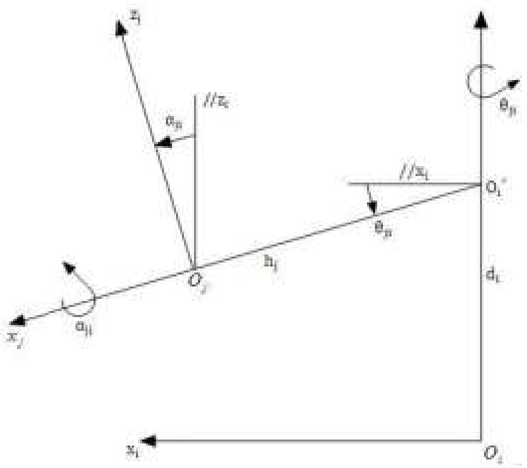

Figure 3 Coordinate transformation schematic

Shown in Figure 3, the configuration features of the coordinate system is: x_j axis is the common vertical line of the z_i axis and z_j axis, o'_1 and o_j are two foot drops. To express of homogeneous coordinates transformation relation between two coordinate systems, it is required to use four parameters: d_i、θ_{ji}、h_j and α_{ji}. Their meanings:

d_i ——the directed distance between x_i axis and x_j axis, $d_i = \overline{o_1 o'_1}$; When the directed line segment $\overline{o_1 o'_1}$ of the direction equal to the z_i axis positive phase, d_i is a positive value; On the contrary, di is negative.

θ_{ji}——the directed angel between x_i axis and x_j axis; Looking forward to the z_i axis, the x_i axis rotates to parallel level of the x_j axis around the z_i axis in the counterclockwise direction.

h_j——the directed distance between z_i axis and z_j axis , $h_j=\overline{o_1' o_j}$; When the directed line segment of the direction equal to the x_j axis positive phase, h_j is a positive value; On the contrary, h_j is negative.

α_{ji}——the directed angel between z_i axis and z_j axis; Looking forward to the x_j axis, the z_i axis rotates to parallel level of the z_j axis around the x_j axis in the counterclockwise direction.

In the above-mentioned four parameters, d_i and θ_{ji} describe the geometric relationship between the bifacial axis x_i and x_j, while h_j and α_{ji} describe the geometric relationship between the bifacial axis z_i and z_j. According to the definition of the four parameters, coordinate system O_j-$x_iy_iz_i$（y_i axis is omitted to paint, given by the right-hand rule, the same below）can viewed to obtain the coordinate system O_i-$x_iy_iz_i$ by two spiral motion. One is the helical motion of x_i axis along the z_i axis（d_i, θ_{ji}）; The other is the helical motion of z_i axis along the x_j axis（h_j, α_{ji}）. Therefore, the homogeneous transformation matrix of the coordinate system O_j-$x_iy_iz_i$ to O_i-$x_iy_iz_i$ coordinate system is:

$$T_{ij} = \begin{bmatrix} Rot(z_i, \theta_{ji}) & [r_{o'_i}] \\ 0 & 1 \end{bmatrix} \begin{bmatrix} Rot(x_j, \alpha_{ji}) & [r_{o'_j}] \\ 0 & 1 \end{bmatrix}$$

$$=\begin{bmatrix}\cos\theta_{ji} & -\sin\theta_{ji} & 0 & 0\\ \sin\theta_{ji} & \cos\theta_{ji} & 0 & 0\\ 0 & 0 & 1 & di\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0 & 0 & hj\\ 0 & \cos\alpha_{ji} & -\sin\alpha_{ji} & 0\\ 0 & \sin\alpha_{ji} & \cos\alpha_{ji} & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{1}$$

Expand the above equation, we get:

$$T_{ij}=T_{ij}(di,\theta_{ji},hj,\alpha_{ji})=\begin{bmatrix}\cos\theta_{ji} & -\sin\theta_{ji}\cos\alpha_{ji} & \sin\theta_{ji}\sin\alpha_{ji} & hj\cos\theta_{ji}\\ \sin\theta_{ji} & \cos\theta_{ji}\cos\alpha_{ji} & -\cos\theta_{ji}\sin\alpha_{ji} & hj\sin\theta_{ji}\\ 0 & \sin\alpha_{ji} & \cos\alpha_{ji} & di\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$=\begin{bmatrix}C_{ij} & [r_{oj}]\\ 0 & 1\end{bmatrix} \tag{2}$$

Where, C_{ij} is the（3X3）master matrix of T_i, i.e., the rotational transformation matrix from the j coordinate to the i coordinates system; [r_oj] is the coordinate array of the origin O_j in the i coordinates.

$$C_{ij}=C_{ij}(\theta_{ij}\alpha_{ij})\begin{bmatrix}\cos\theta_{ji} & -\sin\theta_{ji}\cos\alpha_{ji} & \sin\theta_{ji}\sin\alpha_{ji}\\ \sin\theta_{ji} & \cos\theta_{ji}\cos\alpha_{ji} & -\cos\theta_{ji}\sin\alpha_{ji}\\ 0 & \sin\alpha_{ji} & \cos\alpha_{ji}\end{bmatrix} \tag{3}$$

Therefore, the homogeneous coordinate transformation of the i coordinate system to the j coordinate system (D-H matrix) is:

$T_{ji}=T_{ji}(d_i,\theta_{ji}, h_j,\alpha_{ji})=T_{ij}^{-1}$

$$=\begin{bmatrix}\cos\theta_{ji} & \sin\theta_{ji} & \sin\theta_{ji}\sin\alpha_{ji} & -hj\\ \sin\theta_{ji} & \cos\theta_{ji}\cos\alpha_{ji} & \sin\alpha_{ji} & -di\sin\alpha_{ji}\\ \sin\theta_{ji}\sin\alpha_{ji} & -\cos\theta_{ji}\sin\alpha_{ji} & \cos\alpha_{ji} & -di\cos\alpha_{ji}\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{4}$$

The motion parameters for the platform provided by motion dynamics model are 3 axial linear acceleration of the centroid of the moving platform and the position of the head of the driver at the vestibular system related to the centroid of the motion platform in motion platform to calculate the linear acceleration of the driver's vestibular system.

The feeling of the human body to linear acceleration represents in the form of specific force. The definition of specific force is f=a-g, where: f means the body felt linear acceleration; a means the body's absolute linear acceleration; g is the acceleration due to gravity. Because people are used to taking themselves as reference, then the specific force experienced by the pilot on the plane should be measured using the coordinate system of the body. That is:

$$f = a - \hat{g} \tag{5}$$

Where: g is the acceleration due to gravity $g\{(0\ 0\ g)^T\}$ converted to the body coordinate system by the rotation matrix.

Assuming F_A coordinate system with respect to the four parameters of the Fo coordinate system are d,θ,h,α, so the transformation matrix of F_A coordinate system relative to the Fo coordinate system is:

$$T_{OA} = \begin{bmatrix} \cos\theta & -\sin\theta\cos\alpha & \sin\theta\sin\alpha \\ \sin\theta & \cos\theta\cos\alpha & -\cos\theta\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \tag{6}$$

Where the acceleration of gravity vector $g_o=[0;0;g], g=9.8m/s^2$.

So, $f_{AA} = a_A^A - g_A^A$

$$g_A^A = T_{AO} g_o = (T_{OA})^T g_o = \begin{bmatrix} \sin\theta\sin\alpha \\ -\cos\theta\sin\alpha \\ \cos\alpha \end{bmatrix} \tag{7}$$

Where f_{AA} represents the motion specific force of origin (A) in the F_A coordinate system.

The specific force of translation of different positions in driving emulator according to the method described above. When taking the specific force of translation at different locations as input, motion parameters are obtained at this position after washout algorithm, drive signals of motion system obtained based on these parameters input to the moving platform to make the emulator driver to produce the corresponding speed and acceleration sensation of movement in help of visual system. Thus, different positions of the motion signal for the input to the washout algorithm will directly affect the final driver's feeling of movement.

III. THE IMPROVEMENT OF CLASSICAL WASHOUT ALGORITHM AND THE ESTABLISHMENT OF SIMULATION MODEL

a. Classical washout algorithm principle

The input of classical washout algorithm is the specific force of the vestibule of the driver's head in the cab body coordinate system and the angular velocity in three cockpit directions. Three degrees of freedom motion platform is researched, so the angular velocity of three directions is zero. The specific force and angular velocity sensed by human body vestibular organ determine the movement. The output signal is the displacement of the emulator.

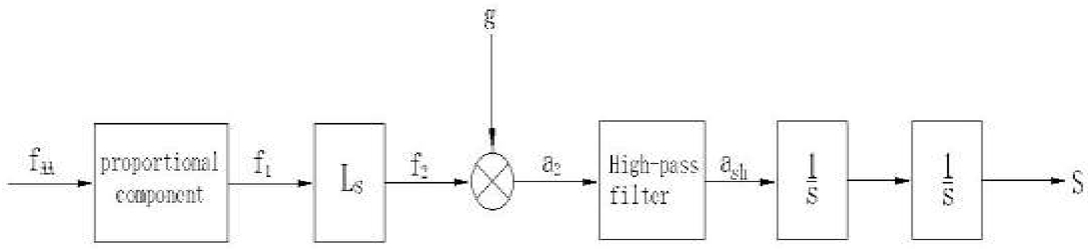

Figure 4. The composition schematics of classical washout algorithm

Figure 4 is the composition schematics of classical washout algorithm. The specific force at the vestibule simulated by cab driver's head which input to washout algorithm first passes through a proportional part of scaling to ensure maximum specific force input requirements [4]. It is converted into the specific force in the inertial coordinate system after a proportional component, the motion acceleration is obtained with the sum of gravity vector and increase acceleration filter out the low-frequency component of the motion of the platform after the high-pass filter which enables overrun platform translational acceleration, after twice integration platform translational position is gained. The algorithm consists of the translation channel simulator, in order to avoid the displacement of the low-frequency portion of the motion signal beyond the range of motion of the platform that causes mechanical damage, setting the high-pass filter module is used to stop the low-frequency portion of the motion signal, and eventually produce the translational platform movement. After low-pass filtering the specific force input to the tilt coordination module to the inclination of the platform to generate a continuous feeling of acceleration for driver, and ultimately producing the low-frequency portion of the Euler angles of emulator, setting speed limit module in order to prevent the platform tilt angular velocity exceeding the angular velocity of the body feeling threshold (0.0523rad/s) not to be found [12].

b. Algorithm derivation

Input signal f_{AA} through the channel scaling factor k respectively uses coordinate transformation matrix $\mathbf{T_{OA}}$ convert the specific force f_{AA} of emulator in coordinate system to geodetic coordinate system.

The set of point A is the contact between point V movement of the centroid of the cab and the movable platform centroid S, The motion of point A approximately simulate the movement of the point S in the actual cab movement. So the above derivation point A and point S in the formula are the same. Therefore, $T_{OA} = T_{OS}$。

As the Figure 4 shows, $a_c = T_{OS} f_{AA} + g_o$

Where, a_c is the acceleration of emulator platform centroid (point s) in Fo coordinate system.

In classic washout algorithm the equations of the common filter are as follows.

Translational high-pass filter: $HPt = \dfrac{s^2}{s^2 + 2\xi\omega s + \omega^2}$ (8)

Translational low-pass filter: $LPt = \dfrac{s^2}{s^2 + 2\xi\omega s + \omega^2}$ (9)

Where, ω, ω are the natural frequency of each filter respectively; ξ, ξ are damping ratio for each filter.

Specific parameters are shown in Table 2-1.

Table 2-1 Filter parameters of the classical washout algorithm

	ω	ξ
Translation	3.10	1.4

The acceleration, velocity, displacement and other relevant parameters of the motion platform can be obtained by washout algorithm [3].

c. The parameter selection of high-pass filter

The high-pass filter in algorithm ensure the output acceleration not beyond the range of motion of the motion platform, and the completion of a sudden dynamic simulation can be back to the platform neutral position by which is smaller than the acceleration human can detect.

Third-order high -pass filter is usually used in translational high-pass filter for the three-axis direction whose transfer function is:

$$\frac{a_{sh}}{a} = \frac{s^3}{(s+\omega_{hp})(s^2+2\xi_{hps}\omega_{hps}s+\omega_{hps}^2)} \tag{10}$$

Where, ω_{hp} 、 ω_{hps} ——the first and second aspects of the natural cut-off frequency, ξ_{hps}——damping ratio.

Step signal of $6\mathrm{m/s}^2$ is as the excitation signal for the parameters of the high-pass filter to select. Selecting principles are as follows: The acceleration in the process of secretly return is not greater than 0.02g and platform movement position cannot exceed the range of the platform ; Returning to the neutral position as soon as possible.

When ξ_{hps}>1, after the step response in time domain and its integral speed and position Formula (10) can be written as follows:

$$a_{sh} = 6 \times \left[\frac{p_1^2 \times e^{-p_1 t}}{(\omega_m - p_2)(p_1 - p_2)} - \frac{p_2^2 \times e^{-p_2 t}}{(\omega_m - p_1)(p_2 - p_1)} + \frac{\omega_m^2 \times e^{-\omega b t}}{(\omega_m - p_1)(\omega_m - p_2)}\right] \tag{11}$$

$$v_{sh} = 6 \times \left[-\frac{p_1 \times e^{-p_1 t}}{(\omega_m - p_2)(p_1 - p_2)} + \frac{p_2 \times e^{-p_2 t}}{(\omega_m - p_1)(p_2 - p_1)} - \frac{\omega_m \times e^{-\omega b t}}{(\omega_m - p_1)(\omega_m - p_2)} + C_o\right] \tag{12}$$

$$x_{sh} = 6 \times \left[\frac{e^{-p_1 t}}{(\omega_m - p_2)(p_1 - p_2)} - \frac{e^{-p_2 t}}{(\omega_m - p_1)(p_2 - p_1)} + \frac{e^{-\omega b t}}{(\omega_m - p_1)(\omega_m - p_2)} + C_o t + C_1\right] \tag{13}$$

Where,

$$p_1 = \left(\xi_{hps} - j\sqrt{1-\xi_{hps}^2}\right)\omega_{hps} \quad p_2 = (\xi_{hps} + j\sqrt{1-\xi_{hps}^2})\omega_{hps}$$

$$C_o = \frac{p_1}{(\omega_m - p_2)(p_1 - p_2)} - \frac{p_2}{(\omega_m - p_1)(p_2 - p_1)} + \frac{\omega_m}{(\omega_m - p_1)(\omega_m - p_2)}$$

$$C_1 = -\frac{1}{(\omega_m - p_2)(p_1 - p_2)} + \frac{1}{(\omega_m - p_1)(p_2 - p_1)} - \frac{1}{(\omega_m - p_1)(\omega_m - p_2)}$$

The acceleration, velocity and displacement have determined maximum for each group of ω_m、ω_{hps} and ξ_{hps} time domain response seen by formula (11)-(13)[5]. Single point iterative method is used to calculate the time $t_{a\max}$、$t_{v\max}$、$t_{x\max}$ of the derivatives that are zero of acceleration, velocity and displacement. The maximum value of the acceleration, velocity and displacement can be obtained by substituting into the formula (11)-(13).

According to the relationship between the above acceleration, velocity and displacement of the maximum value and the filter parameters, using fixed step method for ω_m、ω_{hps} and ξ_{hps} in (0,50) , (0,50) and (0,10) within the range of 0.1 step to search, finding the maximum secretly return acceleration range(-0.15m/s^2,-0.198m/s^2),the interval of the maximum speed (0.222m/s, 0.264m/s), parameter group of maximum displacement is in the range of (0.27m, 0.3m)[7]. The position of each set of parameters in response to the signal integrated over time, the selection of the shortest travel time parameters in the up position. Search results: When$0 < \xi_{hps} < 1$, ω_m=18.01 , $\omega_{hps} = 0.61$, $\xi_{hps} = 0.5$, When$1 < \xi_{hps} < \infty$,ω_m=0.4 ,$\omega_{hps} = 2.6$,$\xi_{hps} = 4.0$. The best parameters are selected as the set of parameters for the filter parameters after comparing, as is shown in Table 2-2.

Table 2-2 Translational high-pass filter parameters of portrait mode

ω_{hps}	ω_m	ξ_{hps}	a_{max}	V_{max}	x_{max}
0.61	18.01	0.5	-0.196m/s^2	0.295m/s	0.299m

The rotated high-pass filter for the three axis directions usually use the method described above. Since rotated high-pass filter for the direction of three axes is a second-order linear filter, the time domain solution given by the literature [2], only giving parameters select results, the parameters of the high-pass filter are shown in Table 2-3.

Table 2-3 High-pass filter parameters of portrait mode

ω_{hps}	ω_m	ξ_{hps}	$\omega_{hp\beta}$	$\xi_{hp\beta}$
0.61	18.1	0.51	0.22	0.26

d. Motor sensory evaluation of human

Simulation fidelity of the driving simulator and comprehensive evaluation of the effectiveness of the simulation is a complex multi-objective decision problem, this is mainly because :①The comprehensive evaluation issue involved in many evaluation factors, is a multi-level、multi-factor problem; ②The evaluation factors are mainly made of the driver's assessment and advice; many of evaluation factors are not directly quantitative evaluation. At present, there are a lot of the existing evaluation methods, Emulator analog fidelity model to measure the use of human feeling Liaosan Ping proposed method is simple , intuitive, and without having to actual driving and simulation driving case, only calculated by computer to complete the evaluation process, therefore, in the design phase of the emulator is supplied most. Specifically, the selected unit time human motor and sensory sum of squared errors “F” as the metrics, that is, under a set of parameters, motor and sensory integral of the square of the difference between the actual and simulated system per unit time.

$$F = \frac{\int_0 (f_{rt} - f_{st})^2 dt}{T} \quad (14)$$

In the formula: f_{rt} 、 f_{st} are the sensory value of the real system and the emulator of the driver at time “t”, T is total simulation time. If “F” is smaller, the error of human motion felling in unit time is smaller, the simulation fidelity is higher. Given the ambiguity of the human motor and sensory, it is difficult for us to measure the feeling of human motion precisely, but after a lot of human physiology research and after analysis of the results of human feeling, we acquire the approximation model formula of the feeling of human motion, through the formula, we can get the input the sensory value generated in the human body without actual driving and simulation.

Human perception kinesthetic or somatosensory receptors are located in the inner ear vestibular organ, including three semicircular canals, utricle and saccule, the latter two containing the otolith, since only considering the linear acceleration, angular acceleration can be ignored, it is simply to establish the appropriate otolith organ models as follows

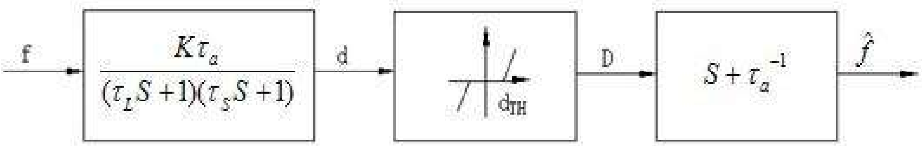

Figure 5 Otolith model

The otolith feels linear acceleration mainly composed by the utricle and saccule, which locates in the bottom of the semicircular canal; it feels the vector sum along the driver's brain orthogonal triaxial specific force component. As is shown in Figure 5 specifically, f is the specific force input at the center of the driver's brain vestibule, $\hat{f}$ is the specific force of driver's feeling. K is the gain factor, τ_L、τ_S、τ_a are the otolith model parameters which can derived by somatosensory simulation measurement and statistical analysis.

The first module for the otolith model that is equivalent to a linear accelerometer physically, its output d is the displacement of otoliths relative to the ear grouper in vestibular system, dimension is m/s^2. The second module is threshold module, d_{TH} is the otolith threshold for linear acceleration feeling whose output is the third module that is first-order lead compensation module [7].

$$D = \begin{cases} 0 & |d| \le d_{TH} \\ d - SGN(d)d_{TH} & |d| > d_{TH} \end{cases} \tag{15}$$

$$SGN(d) = \begin{cases} +1 & \delta > 0 \\ -1 & \delta < 0 \end{cases} \tag{16}$$

Accordingly, the otolith model transfer function is:

$$H_{OTO}(S) = \frac{L[\hat{f}]}{L[f]} = \frac{K\tau_a}{(\tau_L S+1)(\tau_S S+1)} \tag{17}$$

The parameters of otolith model are shown in Table 2-4.

Use the method of motor sensory evaluation of human to measure the effect of classical washout algorithm. The specific approach is: Algorithm will use washout algorithm to obtain acceleration through the centroid transformation at the center of the emulator driver vestibular system to specific force in washout position, which is taken as human motion sensor system input of emulator driver, emulator driver's motor sensory through the body feeling model is obtained. The actual cab acceleration is obtained after centroid transform the actual specific force at the center of driver’s vestibular system, as the actual driver of human motion sensory input, then using human sensory model to derive the actual driver's feeling of human motion [9]. It should be noted that classic washout algorithm from the motion signal respectively generate high and low human sensation of movement by the high-and low-pass channel, while in the actual driving process, the body movement is the overall feeling, therefore the emulator driver's high and low frequency motor sensory should be added to get the emulator driver's overall motor sensory, then comparing with the actual feeling of human motion.

Table 2-4: The otolith model parameters

The otolith model parameters			
	Longitudinal	Transverse	Vertical
$\tau_{[illegible]}(s)$	5.25	5.25	5.25
$\tau_{[illegible]}(s)$	0.56	0.56	0.56
$\tau_{[illegible]}(s)$	12.5	12.5	12.5
k	0.4	0.4	0.4
d_{TH}	0.15	0.15	0.30

IV. ANALYSIS OF SIMULATION RESULTS

a. Simulation results

According to simulation model constructed in Chapter II and selected parameters, the simulink module is used to simulation in MATLAB, simulation time is sequentially shown in Figure, the signal describes the quay crane acceleration, constant speed, deceleration, accelerating signal in course of the campaign is shown in Figure 8. The simulation results are shown in Figure 9-Figure 11. The dotted line indicates the actual movement curve; the solid line represents a motion curve of the emulator in figure. Figure 6 gives square wave signal of the movement, figure 7 is an analog signal of the motion platform in order to verify the somatosensory model.

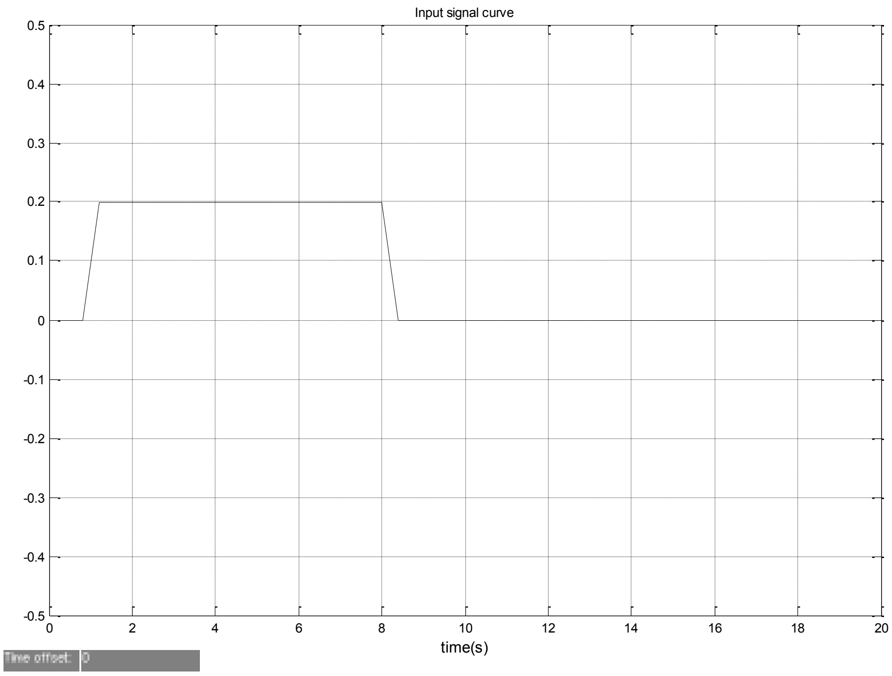

Figure 6 Input signal curve

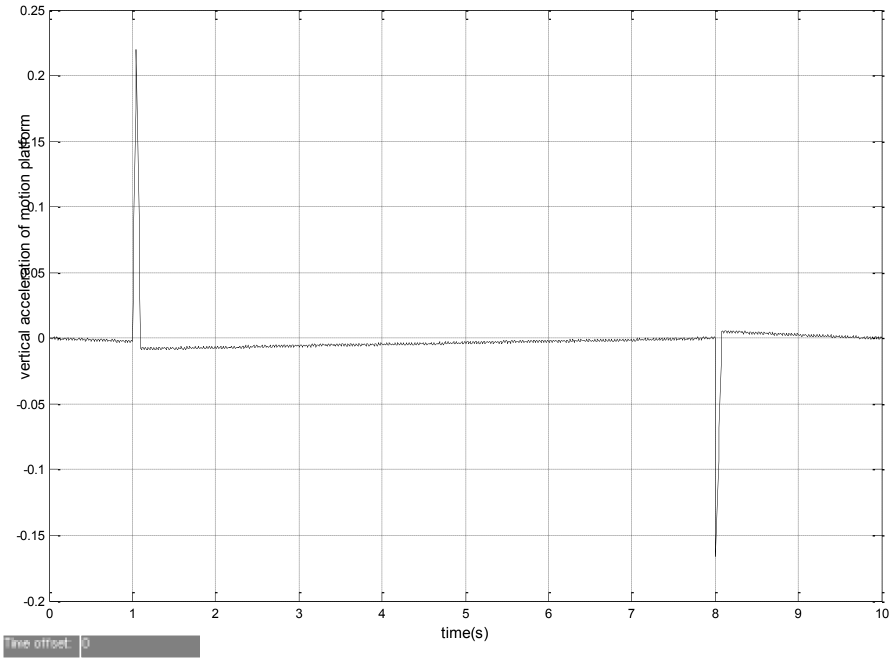

Figure 7. Motion platform acceleration

The main function of the channel of the high-pass filter is used to simulate the aircraft instantaneous acceleration feeling, because the low-frequency acceleration will result in a flight simulator motion beyond the workspace, so it needs to filter out low-frequency part of the direction of the translational acceleration by high-pass filter [13].

The low-pass filter channel is mainly used to simulating a continuous linear acceleration of the aircraft, which is achieved by moving platform tilted to simulate by using the gravitational acceleration component, inserting the inclination angular velocity limiting means , so that the angular velocity is less than the human perception threshold , which is also referred to tilt coordinate system technology. The tilt coordinate system technology is the use of the components of the gravity vector to simulate the continued acceleration of the translational direction. But it cannot use this technique in the vertical direction, so all wash out the algorithm cannot simulate the continuous vertical acceleration. Of course, the slow inclined platform will lead to the reduction of the linear acceleration of the z - axis direction of the simulator platform, but in a relatively small inclination angle this part of the impact can be ignored.

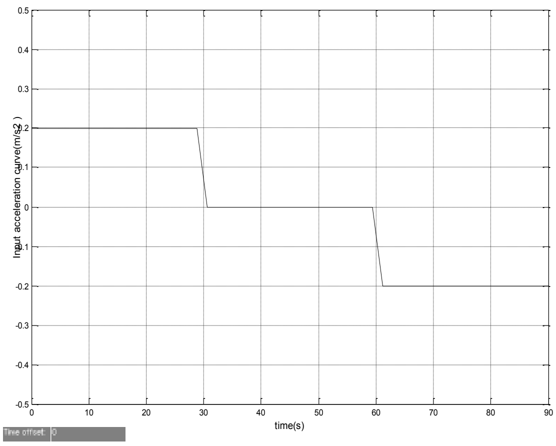

Figure 8 the actual input signal

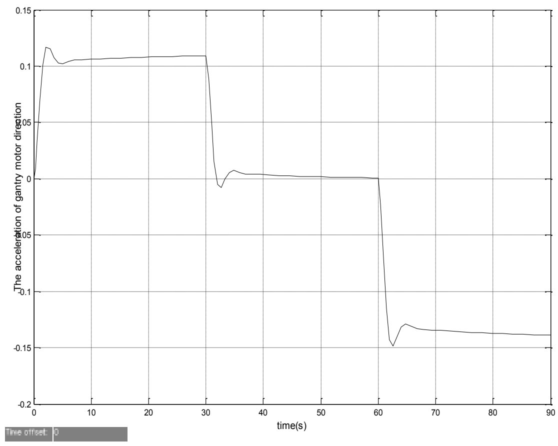

Figure 10 acceleration of trolley direction

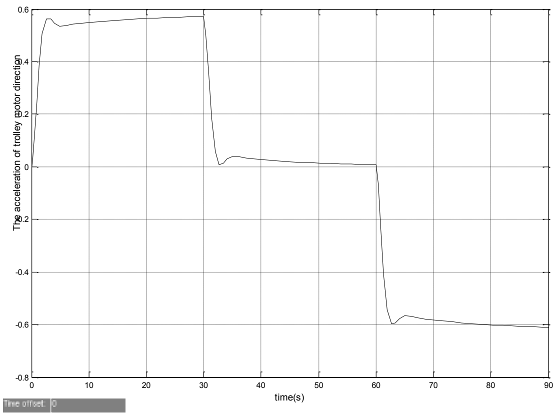

Figure 9 acceleration of gantry direction

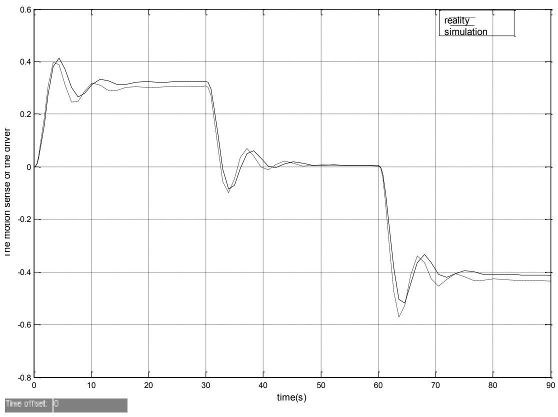

Figure 11 Human somatosensory specific force curve

From figure 9 to figure 11, platform translational movement only simulate the high frequency portion of the analog input signal, while the low-frequency part of the platform motion simulation is shown in Figure 11, this is the application of tilt coordinated approach, platform displacement does not return to 0 because of the lower high-pass filter order, when the order of filter is greater than or equal to 3, the platform displacement will gradually return to 0. Human motor sensory simulation in Figure 11, emulator driver motor sensory feeling is almost the same with the actual driver movement, this proves the classical washout algorithm is effective, But there are errors due to the type of algorithm, the parameter selection, which produces motor sensory error shown in Figure 11.

Classical washout algorithm has the following disadvantages by the above simulation:

(1) The order of washout filter in algorithm is low, so the simulation of high-frequency signal is limited.

(2) The algorithm parameters in the calculation is always the same which cannot be adjusted to meet with changes in external conditions.

(3) For longitudinal/tilt, horizontal/roll direction, the emulator can take advantage of the human body that is not possible to distinguish the influence of gravity and acceleration effects, according to the tilt coordination to simulate the continuous acceleration motion, good results have achieved, vertical motion simulation cannot use the tilt coordination technology, making errors in the simulation.

b. Experimental results

Using the washout algorithm training simulator during the movement of the horizontal acceleration and angular velocity signals to filter by the determined method, and the acceleration and angular acceleration command signal of the motion platform are obtained, then by integrating the command signal of the position and the angle to drive the movement platform, enabling motion platform in its work space for the driver to provide a realistic sensation of movement.

In this paper, the existing motion platform aims to authenticate the kind of parameter optimization algorithm. Three orthogonal accelerometers are mounted on the upper surface of the motion platform to measure the acceleration motion platform provided.

This calculated washout filter parameters ensure the complex exhibited a slight acceleration value or high frequency signal. However, for large values of the acceleration signal a low frequency motion of the platform due to motion of space limitations, the present algorithm can be used for moving the platform reproduction maximum capacity.

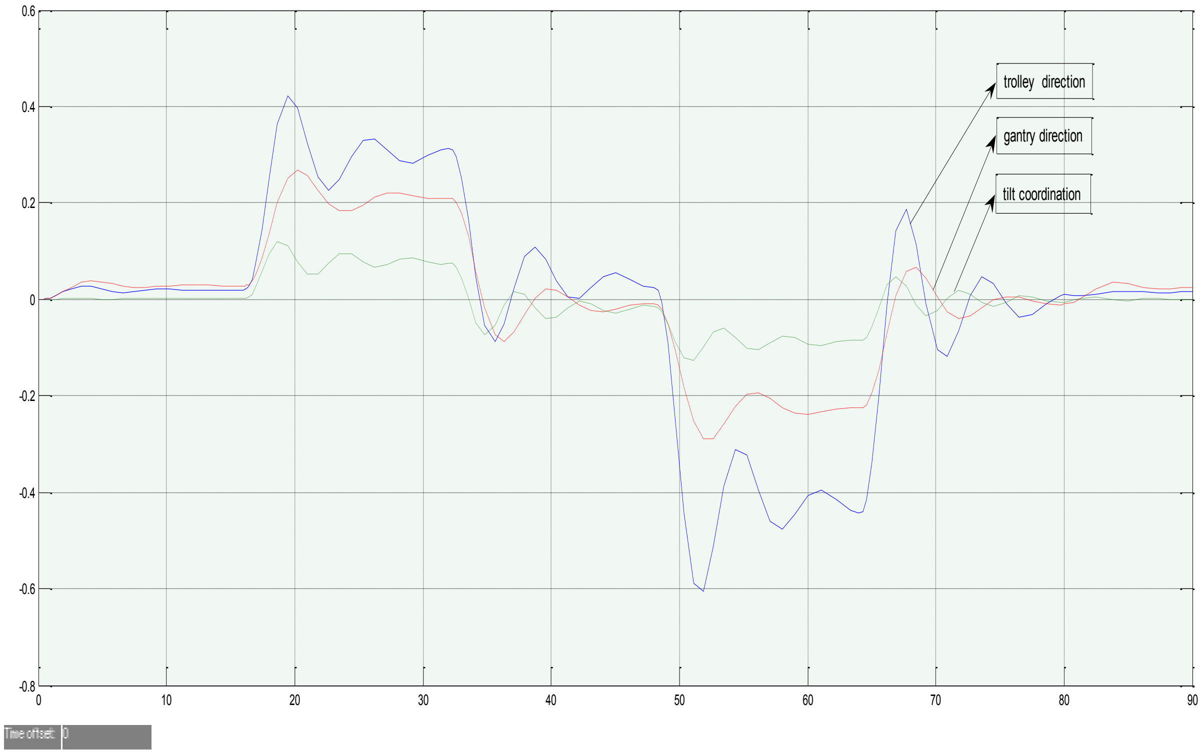

Figure 12 Electric cylinder displacements

c. Experimental evaluation

Due to the electric cylinder transmission process, linear actuator rod is divided into a number of compensation an average interval, which is performed by the PLC control of the power cylinder back to the zero-order, the rod zero of electric cylinder is Coordinate zero. From the initial position of the electric cylinder is adjusted to maximum position, so that the error reduces [19]. According to the experimental results, as is shown in Figure 12, during the washout the elongation of each of the electric cylinder does not exceed its maximum range of motion, and the three actuators are not close to the maximum stroke of the cylinder power stroke, if the readjustment washout algorithm parameters to increase the low frequency reproduction capabilities acceleration signal will cause the hydraulic cylinder stroke overrun, which does not work.

The maximal displacement of trolley direction is about 0.6m; major distribution of fluctuating values main appears in the process of acceleration and deceleration phase, these lines converges at a certain point. The maximal displacement of gantry direction is around 0.3m, which did not exceed the electric cylinder stroke, so it meets the requirements of platform.

Tilt coordination curve tends to be mild, which can effectively describe the libration in working condition.

Therefore, washout algorithm parameters identified in the article can take full advantage of the motion platform movement space for the driver to provide realistic movement.

V. CONCLUSION

This essay and its achievement offer a basis for the research and development of the dynamic simulation system in the coast container crane and lay a foundation for the further improvement of the fidelity of the simulator. Meanwhile, the essay is also a good reference for the design of other kinds of dynamic simulation systems. The fidelity of the dynamic simulation is an important index in examining the function of cab simulator and the quality of the washout algorithm is directly related to whether the driver can gain a real feel in the operation. Through the analysis of the human perceiving performance, this essay introduces the vestibular model into the algorithm and studies with computer the effect on the dynamic simulation from the linear filter. All in all, the classic washout algorithm cannot only help the motion system meet the requirements of the exiting platform, but also can achieve a comparatively real motion effect. The work hereafter will be on this basis and combine with the TDOF platform to carry out an integrated design for the whole motion system to make a further improvement on the dynamic simulation fidelity.

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