Research on Objective Evaluation Method of Flight Simulator Fidelity

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Abstract. As ground simulation equipment, flight simulator plays an important role in pilot teaching and airworthiness compliance verification with the continuous progress of simulation technology. Fidelity is an important index to measure simulator and real flight. This paper studies the objective evaluation of fidelity of flight simulator. Through establishing evaluation loop model and evaluation index, the method of fidelity calculation is obtained. Finally, the effectiveness of the evaluation method is verified through specific missions.

1. Evaluation loop composition and evaluation index

Objective testing is a quantitative comparison between the performance data of flight simulation training equipment and actual or predicted aircraft data to ensure that the performance of flight simulation training equipment is within the tolerance range specified in the appraisal performance standard\textsuperscript{[1]}. The study of fidelity can be carried out from two aspects: one is to perform the same task to observe the changes of the pilots' operation on the real plane and the simulator; the other is to ensure that the pilots' operation is the same under the two environments and observe the difference of the output curves between the aircraft and the simulator.

From the modeling experience, it is very difficult to observe the changes of pilots' operation and establish corresponding models. Moreover, even if there is inaccurate input feeling due to pilots' adaptability and experience operation, it is possible to maintain the operation actions consistent with real flight. Therefore, this paper chooses to establish two closed-loop circuits of the airplane and the simulator under the same operation of the pilot and compares the key information. As shown in figure 1 and 2.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure.png}
\caption{Pilot-aircraft closed loop}
\end{figure}
The essence of the objective evaluation method used in this paper is to compare the \( u(t) \) which represents the pilot's operation output in the pilot-aircraft and pilot-simulator circuits as an evaluation index to judge the fidelity. Hess analyzes the manipulation signal from the angle of frequency domain, and gives the formula for calculating the fidelity evaluation result based on the power spectral density relation of the signal\(^2\):

\[
P(\omega) = \frac{1}{K_n} \Phi_\delta(\omega)
\]

\[
FM = \sum_{i=1}^{n} \left[ \int_{0}^{\infty} \frac{d\omega}{P(\omega)_{nom} - P(\omega)_{sim}} \right]
\]

In the formula, \( \Phi_\delta \) represents the power spectral density of driver output; \( K_n \) represents the pilot correlation coefficient, dimensionless; \( nom, sim \) represents the closed loop of aircraft and simulator; \( n \) represents the number of control shafts.

2. Establishment of closed loop and evaluation results

According to the structure of the closed loop in the previous section, the modules involved in the closed loop are established and the fidelity evaluation based on the flight.

2.1. Pilot Model

According to people's feeling and control mechanism, a pilot structure model is established in practical application\(^3\). As shown in figure 3.

The significance of the model is to obtain a model that can accurately describe the influence of visual and vestibular stimuli on pilot's control behavior under the condition of aircraft movement, and through the weighting factor, the model can know the distribution of pilot's attention under the condition of mission execution. The controlled system \( Y_c \) represents the dynamics of the aircraft piloted by the pilot and outputs the attitude of the aircraft. Based on the research on pilot's motion perception and control behavior\(^4,5\), the transfer functions of vision and vestibular system are as follows:

The vision system is composed of attitude perception \((H_{C,att})\) and rate perception \((H_{C,rate})\), and the transfer functions are:

\[
H_{C,att}(\omega) = e^{-\tau_{att}}
\]

Figure 2. Pilot-simulator closed loop

Figure 3. Pilot structure model
\[ H_{Cr,rate}(\omega) = e^{-\tau_{rate}} \]  

In the formula, \( \tau_{att} \) represents the attitude sensing time delay constant, 0.05(s); \( \tau_{rate} \) represents the rate sensing time delay constant, 0.15(s).

The vestibular system is composed of semicircular canal \( (H_{SCC}) \) and otolith \( (H_{OTO}) \) structures, and the transfer function is[^6]:

\[ H_{SCC}(\omega) = \frac{(1+\tau_{SCC1})}{(1+\tau_{SCC2})(1+\tau_{SCC3})} \]  
\[ H_{OTO}(\omega) = \frac{(1+\tau_{OTO1})}{(1+\tau_{OTO2})(1+\tau_{OTO3})} \]

In the formula, \( \tau_{SCC1}, \tau_{OTO1} \) represents the advance time constant of semicircular canal model, 0.11(s) and otolith model, 1(s), respectively; \( \tau_{SCC2} \) and \( \tau_{SCC3} \) represents the Semicircular canal time delay constant, 5.9(s) and 0.005(s); \( \tau_{OTO2} \) and \( \tau_{OTO3} \) represents the otolith canal time delay constant, 0.5(s) and 0.016(s).

The perception, decision-making and output control system consists of neuromuscular system and its delay links. The transfer function is

\[ H_n(\omega) = e^{-\tau_n} \]  
\[ G_{nm} = \frac{\omega_n^2}{s^2 + 2\delta\omega_n s + \omega_n^2} \]

In the formula, \( \tau_n \) represents the neuromuscular system time delay, 0.08(s); \( \delta \) represents the neuromuscular damping ratio, dimensionless, 0.7; \( \omega_n \) represents the neuromuscular natural frequency, 9(rad/s).

In the pilot model, the sensory weighting coefficients \( W_{Cr,rate}, W_{Cr,att}, W_{SCC}, W_{OTO} \) which describing the attention distribution of pilots to each channel are determined by using Cost Function[^7].

\[ J = \sum \left( e^2 + Qu^2 + Ru^2 \right) \]

In the formula, \( e \) represents the tracking error; \( u \) represents the control signal; \( Q, R \) represents the Cost function control factor, the parameter value depends on the characteristics of the aircraft and the task performed.

2.2. Aircraft Dynamics
The aircraft dynamics model uses a linear approximation model of a general fly-by-wire aircraft model. Using this linear model can simplify the analysis process, reduce the execution time, and has wider application. The transfer function expression is[^8]:

\[ \frac{\Theta(s)}{F(s)} = \frac{7.481(s+0.035)(s+3.400)}{(s^2+0.009s+0.025s^2+5.842s+22.888)^2} e^{-0.195s} \]

2.3. Washout Algorithm Model
The washout algorithm used in this paper is a classical washout algorithm. According to the classical washout algorithm structure, the hexagonal washout algorithm model is established by using MATLAB/simulink as shown in the figure 4[^9].
2.4. 6-DOF Platform Model
In this paper, Stewart platform is used for modeling and simulation. The Simulink block diagram of the overall structure is shown in figure 5.

2.5. Closed Loop Establishment and Evaluation Results

2.5.1. Fidelity Evaluation of Pitch Tracking Task. The simulation input is set to a ramp signal of 0.01 rad/s. In the tracking task, since there is no vertical, horizontal or vertical input, the otolith model has no perceptual weighting assignment and the weighting value is 0. The Simulink model of the three-channel pilot-aircraft loop under this condition is shown in figure 6.

The unknown quantity in the pilot-aircraft closed loop is the weight value in each channel, and particle swarm optimization algorithm is used to optimize the cost function to complete the optimal solution of the weight value. The change of the pilot-aircraft loop after adding the cost function is shown in figure 7.
After setting the precision to 0.0001, the weight value $W_{C_{att}}, W_{C_{rate}}, W_{SCC}$ obtained by particle swarm algorithm is: 1.365, 0.541, 0.003, the value of cost function is 0.00754. The resulting input-output curves and cost function curves are shown in figures 8 and 9.

The slope of the output curve is basically the same as that of the input, indicating that the parameter can reach a good tracking level. Comparing the output curve with the input curve, it is found that the delay of about 1s is caused by the delay of the system itself.

The pilot-simulator closed loop and input-output curves of the loop are shown in figures 10 and 11.

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**Figure 8. Pilot-aircraft loop input-output curve**

**Figure 9. Cost function curve**

**Figure 10. Pilot-simulator closed loop**
The power spectral density of the signal $u(t)$ in the two closed loops is estimated by using the autocorrelation method, and the results are shown in figures 12 and 13.

The final evaluation result is obtained according to the power spectral density curve.

$$FM = \sum_{i=1}^{6} \left[ \int_{0}^{\infty} \left| P_i(\omega) - P_i(\omega)_{\text{ref}} \right| d\omega \right]$$

$$= \frac{191.8847}{451.2274} = 0.4253$$

2.5.2. Fidelity Evaluation of Interference Tasks. Interference items are added to the interference task loop to disturb the normal running of the aircraft to simulate the vibration of the aircraft caused by turbulence or mechanical movement. The input of the whole loop is zero and loop structure is shown in Figure 14.

Under the interference task, the weight values $W_{\text{C,att}}, W_{\text{C,rate}}, W_{\text{SCC}}$ of each channel are 0.131, 0, 0.814, and the cost function value is 0.00271. Since the aircraft is in cruise state and there is no acceleration signal input, the rate perception weight in the visual model is zero. The input and output curves of the pilot-aircraft and pilot-simulator loops under this weight parameter are shown in figures 15 and 16.
3. Analysis and summary

According to the calculation results of pitch mission and interference mission, it is shown that the objective evaluation results can be successfully obtained by using the power spectral density of pilot control output signal as the evaluation index, which shows that the method is true and effective, and the calculation results have high accuracy. The evaluation index can calculate and obtain evaluation results for different tasks, and has good universality. At the same time, it can be seen from the fidelity calculation formula that the simulator has no difference from the real situation when FM=0. From the calculation results, it can be concluded that on the basis of accurate model establishment, better simulation results can be obtained, and the motion system can also be shown to have higher fidelity.

By comparing the output results of the weight values of the pitching task and the disturbance task, it can be seen that under different missions, the requirements for completing the mission are different, resulting in different focuses for pilots. Under the pitch tracking task, the pilot mainly observes through vision and controls the aircraft to maintain the same output posture as the input, so the weight value in the vision loop is large. In the interference task, because there is no signal input, the pilot mainly senses the state of the aircraft through vestibular feedback, thus minimizing the disturbance caused by the interference signal to the attitude output of the aircraft. Therefore, the weight value in the vestibular loop is large in this task. By comparing the final fidelity results, it can be seen that different missions will affect the pilots’ attention and operation behavior, resulting in differences in the final results. Therefore, it is necessary to set up the missions in advance and reasonably select the missions in order to make the evaluation results more accurate.

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