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Design and Experiments of Model-free Compound Controller of Flight Simulator

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Abstract

A model-free compound controller design method is proposed to achieve the wide frequency bandwidth requirement of flight simulators. The method based on quantitative feedback theory, acquires system uncertainty under different working conditions through closed-loop identification with power spectrum estimation. Then in controller designing, it makes a tradeoff between the strict requirements for magnitude-frequency characteristics and those for phase-frequency characteristics of flight simulators, by converting the indices of magnitude-frequency characteristics of flight simulators into quantitative feedback theory-based tracking specification bounds and using feedforward controller to attain the required phase-frequency characteristics. Simulation and experimental results indicate that, when used to design inner frame controller of flight simulator, the proposed method can fulfill the requirements for wide frequency bandwidth indices. Compared with other controller design methods, it has the property of model-free and transparency.

Keywords: model-free; quantitative feedback theory; power spectrum estimation; flight simulators; closed-loop system identification

1. Introduction

The flight simulator is one of the key equipment for hardware-in-the-loop (HWIL) simulation, which can be used to verify performance indices of sensors, guidance systems, control systems and actuators. With unabated advancement of unit under test, wider frequency bandwidth of flight simulators that influences dynamic characteristic testing is required. The two main factors that decide frequency bandwidth of flight simulators, as it is known, are motor power and structure rigidity[1].

At present, the research on widening frequency bandwidth of flight simulators mainly concentrates on improving the control strategies on the assumption that motor power and structure rigidity have met requirements of simulators. Z. M. Li, et al.[2] introduced command shaping technique to suppress vibration and expand frequency bandwidth of flight simulators. L. A. DeMore, et al.[3] presented a state variable feedback control system architecture with feedforward techniques to improve the flight table's dynamic fidelity by significantly reducing the table's low frequency phase lag. M. Swamp, et al.[4] used acceleration feedback as a part of the axes servo system to improve dynamic fidelity in HWIL simulation. Q. Liu, et al.[5] suggested a novel feedforward control scheme on the basis of Padé approximation to deal with non-minimum phase digital servo system, which could ensure small phase errors and gain errors in the low frequency range. Q. Fu, et al.[6] developed a combined control method that implants the quantitative feedback theory (QFT) into the zero phase error tracking controller. It dispenses with flaws of QFT control system and achieves high performance robustness and wide frequency bandwidth. J. Y. Yu, et al.[7] worked out an improved QFT method that made tradeoff between frequency performance indices of nominal plant and those of system uncertainty.

All of the above-mentioned studies are carried out on the basis of given system uncertainty, which is not always tenable in actual controller design. This artical describes a model-free compound controller design method. It acquires QFT experiment plant templates from the measured time response data of simulators, while converts the indices of magnitude-frequency characteristics of flight simulators to QFT-based tracking specification bounds and uses feedforward controller to satisfy the requirements for phase-fre-

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quency characteristics.

2. Indirect Closed-loop Identification of QFT Experiment Plant Templates Using Power Spectrum Estimation

2.1. Principles of power spectrum estimation

Assume that H is a linear time-invariant system. The cross correlation function of input signal $X(n)$ and output signal $Y(n)$ is defined as

$$R_{XY}(m) = E\{X(n)Y(n+m)\} = R_X(m) * h(m) \quad (1)$$

where $R_X(m)$ denotes auto correlation function of $X(n)$, and $h(m)$ impulse response of system H. Its Fourier transform abides by

$$P_{XY}(\omega) = P_X(\omega)H(\omega) \quad (2)$$

where $P_{XY}(\omega)$ is the cross power spectrum function of input and output signals, and $P_X(\omega)$ the power spectrum of input signal. The identification result of transfer function $H(\omega)$ can be calculated by

$$H(\omega) = \frac{P_{XY}(\omega)}{P_X(\omega)} \quad (3)$$

Since the output to be measured is likely to be corrupted by noise $N(n)$, the cross correlation function of input signal and output signal can be defined as

$$R_{XY}(m) = E[X(n) * (Y(n+m) + N(n+m))] = R_X(m) * h(m) + R_{XN}(m) \quad (4)$$

Its corresponding Fourier transform is shown as follows:

$$P_{XY}(\omega) = P_X(\omega)H(\omega) + P_{XN}(\omega) \quad (5)$$

The reliability of Eq.(3) may then be estimated by computation of the coherence function given by[8]

$$\gamma^2(\omega) = \frac{P_{XY}(\omega)P_{XY}^*(\omega)}{P_{XX}(\omega)P_{YY}(\omega)} = \frac{|P_{XY}(\omega)|^2}{P_{XX}(\omega)P_{YY}(\omega)} \quad (6)$$

The results that stem from comparison of coherence function with the transfer function evaluated over the frequency range of interest are usually acceptable, if $\gamma^2(\omega)$ remains consistently high, i.e., 0.8< $\gamma^2(\omega)$ < 1.0.

2.2. Indirect closed-loop identification method

Fig.1 shows the closed-loop system under consideration in a block diagram form. $P(s)$ denotes the system plant under test with output being $Y(s)$, input $X(s)$ and disturbance $N(s)$. Mathematically, the system can be described by

$$Y(s) = \frac{G(s)P(s)}{1+G(s)P(s)}X(s) + \frac{1}{1+G(s)P(s)}N(s) \quad (7)$$

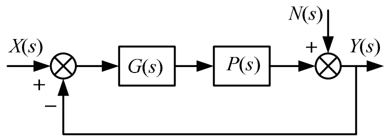

Fig.1 Schematic diagram of indirect closed-loop identification method.

The closed-loop system transfer function can be described by

$$H(s) = \frac{Y(s)}{X(s)} = \frac{G(s)P(s)}{1+G(s)P(s)} \quad (8)$$

Then, according to Eq.(8), the parameters of $P(s)$ can be estimated through open-loop system identification methods, in which the transfer function of controller in use is usually known. As for QFT experiment plant templates, the frequency data model that is built up with frequency responses in different frequency ranges is desirable. Hence, the estimated open-loop system frequency characteristic $\hat{P}(\mathrm{j}\omega)$ is given by

$$\hat{P}(\mathrm{j}\omega_i) = \frac{H(\mathrm{j}\omega_i)}{(1-H(\mathrm{j}\omega_i))G(\mathrm{j}\omega_i)} \quad (i = 1, 2, \cdots, n) \quad (9)$$

The advantage of indirect closed-loop system identification lies in its ability of converting closed-loop system identification into open-loop one, thereby avoiding the pitfalls inherent in closed-loop method.

2.3. Experimental conditions

In the experiments the test signal $X(t)$ is defined as

$$X(t) = A\sin\{2\pi t(f_i + 0.1F(t, t_i, f_i))\} \quad (f_i = 0.1, 0.2, \cdots, 40.1 \text{ Hz}) \quad (10)$$

where A is the amplitude of input signal, f_i the current signal frequency, t_i the shift time from f_{i-1} to f_i and t the present time.

$$F(t, t_i, f_i) = \begin{cases} 1 & (t - t_i - 4/f_i) \geq 0 \\ 0 & (t - t_i - 4/f_i) < 0 \end{cases} \quad (11)$$

The frequency of input signal that lasts for four times the period of every present frequency changes from 0.1 Hz to 40.1 Hz. In this way, steady-state output response can be ensured, which is very important for power spectrum estimation. Besides, the output response of system indicates that the frequency range of input signal, [0.1, 40.1] Hz, covers the interested frequency range of system.