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An error test and compensation method of infrared guidance hardware-in-the-loop system by self-calibration device

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HIGHLIGHTS

- We analyze the effect of system error in the HWIL simulation system.
- We propose an error test and calibration method using a self-calibration device.
- The self-calibration device can eliminate the error caused by mounting.

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ABSTRACT

An error test and compensation method of infrared guidance hardware-in-the-loop system by self-calibration device and flight motion simulator was proposed. The optical system of the unit under test and infrared scene projector were combined into a synthesis optical system. After the pupil function of synthesis optical system reconstructed, Fourier-optics method and ray-tracing method were adopted to analyze the effect on PSF and MTF caused by "offset error" and "tilt error". The analysis results showed that the MTF were higher than 0.4 in spatial frequency of 30 (lp/mm), when the system has offset error below 5 mm and tilt error below 0.3°. However, the tilt error would affect the position of the PSF, and it should be eliminated. To eliminate the tilt error, a self-calibration device was designed, and the tilt error compensation method by adjusting the flight motion simulator was described. Finally, the experiment results showed that the accuracy of the simulation results was improved obviously after the compensation.

1. Introduction

Hardware-in-the-loop (HWIL) system has played an important role for designing, testing, validating, and evaluating infrared guidance system. The HWIL system is composed by the infrared scene simulator (IRSS), five-axis flight motion simulator (FMS) and simulation control subsystem. As shown in Fig. 1, the five-axis FMS can be divided into two sections: inner three axes (roll, pitch, and yaw) and outer two axes (azimuth and elevation). The unit under test (UUT) is mounted on rolling axis of inner three axes which are used to simulate the flight attitude of the UUT. While the IRSS is mounted on the outer two axes which are used to simulate the relative line-of-sight angle between the UUT and the IRSS. Simulation control subsystem is used to solve the relative motion model and control the motion of each axis [1,2].

Although several infrared scene projection technologies have been used maturely, there still has the system errors caused by the reasons such as non-orthogonal axes, mounting interface deviations of each component and the errors will further determine the accuracy of the HWIL system [3]. Thus, rigorous test and compensation of the system errors is so significant that it has been researched by many scholars and engineers.

In 2003, Tomaszunas analyzed the system errors caused by the mechanical tolerances in the HWIL system [4]. The offset error and tilt error of the UUT and IRSS mounting on the FMS were defined. The errors calibration method and procedures were proposed and described. The errors could be eliminated by mechanical adjustment methods during the system integration.

In 2006, Mitchell defined the classification of system errors according to the error sources and combined the errors into one term named "pointing vector error". The error determined the

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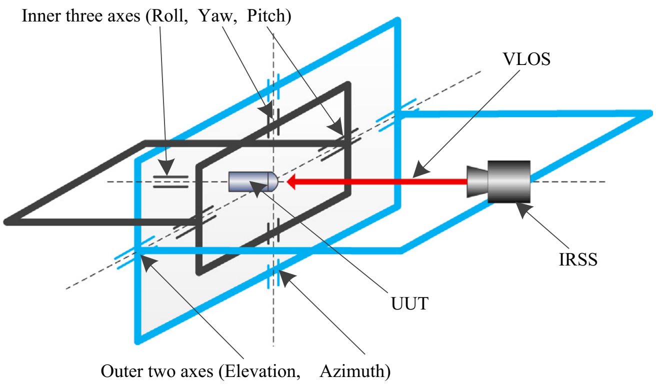

Fig. 1. Schematic layout of five-axis FMS.

accuracy of vector line of sight (VLOS) from the IRSS to the UUT, as shown in Fig. 1. The deterministic and random error sources were mainly caused by the various axes and mounting interface deviations [5,6].

However, those previous researches did not provide the detailed information about the performance degradation of HWIL system caused by the system errors. The error compensation methods have high precision but complex and time-consuming. Furthermore, the compensation methods above need to adjust the mechanical structure when the FMS is working. The FMS which is driven by high hydraulic pressure with extremely heavy rotational inertia will threat to the safety of engineer [7]. Thus, we propose a simple, feasible and efficient method to test and compensate the system error when HWIL system is in service, in order to balance the system performance and difficulties of compensation. We also provide an error analysis method which can obtain the performance degradation of HWIL system caused by the system error.

In this paper, the error of system was also classified as "offset error" and "tilt error". First, the optical system of UUT and IRSS were combined into a synthesis system. Then, the synthesis system pupil function with considering the energy distribution and the wavefront error was reconstructed. The performance degradation of HWIL system caused by "offset error" and "tilt error" were analyzed by Fourier-optics method and ray-tracing method [8–10]. The offset error would lead to slightly degradation of modulation transfer function (MTF). However, the position of the point spread function (PSF) in the image plane would not be affected by offset error. The tilt error between UUT and IRSS greatly affected the position of the PSF and it would not affect the MTF of HWIL system. Thus, the little influence by offset error could be ignored. Then, a calibration device was designed. Its installation error of calibration device could be eliminated through self-calibration. Furthermore, the process of error compensation was described which realized by adjusting the FMS. Finally, the system error test and compensation experiment was described in detail. Experiment results showed that the accuracy of the HWIL simulation can be improved obviously after the compensation.

2. System errors analysis

2.1. Error classification

The optical system of the UUT is a conventional IR imaging system, while the optical system of the IRSS is a projection optical system as shown in Fig. 2(a). They constitute a synthesis optical system. Simultaneously, the entrance pupil P_1 of UUT's optical system (the aperture of the imaging lens) should match well with the exit pupil P_2 of IRSS's optical system. Actually, the exit pupil size of IRSS's optical system is larger than the entrance exit pupil of UUT's optical system considering the design redundancy. At the same time, the size of the projection lens is determined by the entrance pupil of UUT, its field of view (FOV) and the distance between the UUT and IRSS. Assuming that the O′ is the center point of the object plane, the light emitted from O′ will be collimated by the projection lens and directed into the entrance pupil of the UUT, and it will be refocused on the center point O of the image plane. Both the UUT and IRSS are optical rotational symmetric system, and their optical axes should be co-axis as shown in Fig. 2(a). However, non-orthogonal axes and mounting interface deviations will lead to their pupil mismatch which means that there will be an error of VLOS.

The error of VLOS can be decomposed into two parts: offset error and tilt error from the geometrical optics viewpoint. Two kinds of errors are mutually independent. So, the error is considered respectively. The offset error d is the axes distance between the UUT and IRSS as shown in Fig. 2(b). And the tilt error θ is the intersection angle of the axes between the UUT and IRSS as shown in Fig. 2(c). The collimated light will be still refocused on the center point O of the image plane, even though there is an offset error. However, the collimated light will be refocused on the point S on the image plane, when there is a tilt error. So the synthesis optical system should be more sensitive to the tilt error than the offset error. In order to validate this and obtain the quantitative influence on the imaging quality of the UUT from the two kinds of errors, the MTF of the synthesis optical system with the each type of error is analyzed by Fourier optics and Geometrical optics method.

2.2. Error analysis methods and formulations

The Cassegrain structure which is an all reflective structure is adopted in the optical systems of the IRSS and UUT in order to eliminate the chromatic aberration. Therefore, the influence of chromatic aberration is ignored, when the MTF of the synthesis optical system is analyzed [11]. The pupil function of a Cassegrain optical system is a circular ring and it can be expressed as

$$P(\xi,\eta)=\begin{cases}1 & R_1\leqslant\sqrt{\varepsilon^2+\eta^2}\leqslant R_2\\ 0 & \text{others}\end{cases} \tag{1}$$

where the $(\xi,\ \eta)$ is the coordinate system of the pupil plane as shown in Fig. 2(a). The R_1 and R_2 is the radius of the primary mirror and secondary mirror, respectively.

The $P_1(\xi,\eta)$ represents the pupil function of the UUT. Due to the offset error, the pupil function of the IRSS can be express as $P_2(\xi+d_\xi,\eta+d_\eta)$. The d_ξ and d_η are the ξ and η components of the offset error d, as shown in Fig. 2(b). So, the d can be expressed as

$$d=\sqrt{d_\xi^2+d_\eta^2}. \tag{2}$$

When considering the influence of pupil offset, the pupil function $P_{12}(\xi,\eta)$ of the synthesis optical system can be expressed as:

$$P_{12}(\xi,\eta)=P_1(\xi,\eta)\times P_2(\xi+d_\xi,\eta+d_\eta). \tag{3}$$

The energy distribution on the pupil plane is uneven, because the Cassegrain optical system has a center shade. The $T_1(\xi,\eta)$ and $T_2(\xi+d_\xi,\eta+d_\eta)$ are used to express the normalized energy distribution of UUT and IRSS, respectively. They can be computed by ray-tracing method [12,13].

The tilt error θ will lead to the wavefront tilt as shown in Fig. 2(c). The equiphase surface of optical wave can be expressed as

$$\vec{k}\cdot\vec{r}=C \tag{4}$$