Research on the effect of vibration of aerial cameras on imaging quality under flight conditions

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Abstract. In order to make the structural design of the aerial camera meet the requirements of the imaging system, the influence of externally excited vibration interference on the imaging quality of the aerial camera optical system under the flying state of the UAV was studied. This paper adopts the optical-machine integrated analysis method (OIAM) to cause the vibration interference influence is studied. The MTF (modulation transfer function) is used as an evaluation index of imaging quality. The aerial camera dynamics simulation analysis is performed to extract the displacement of each node under vibration excitation. The lens deformation is fitted using the Fringe Zernike polynomial. The obtained data were used for optical performance evaluation. The analysis have showed that the optical system of the aerial camera has a 0.071% reduction in the MTF at a resolution of 91 lp / mm under the excitation of flight vibration, with little effect.

1. Introduction

As an important part of drones, it is an important way to obtain ground and aerial image information by using aerial cameras. With the continuous improvement of the imaging quality requirements of aerial cameras in the civilian and military fields, the development and research of aerial cameras has been rapidly developed. It can be used in terrain exploration, environmental disaster forecasting, military reconnaissance, etc., and it has received more and more attention from various countries. With the development of optoelectronic technology, aerial cameras are developing in the direction of higher resolution and larger coverage.

However, due to the vibration generated in various airborne platforms, the vibration of the aircraft will be transmitted to the optical system through the platform, causing optical System vibration. On the other hand, since the imaging system needs to expand the imaging range and image shift compensation through mechanical transmission [1-3], O. Hadar et al. Have done a lot of research and experiments on the effect of vibration on the optical imaging system [4-7]. This paper integrates the effects of mechanical vibration transmission on the aerial camera optical system from the vibration analysis of the drone's airborne platform in flight conditions. Uses the finite element analysis technology to analyze the stress and deformation of the main optical components in the optical system integrate the deformed surface data. Finally,input it into the optical system to analyze the imaging quality. Analyze the modulation effect on the optical transfer function and quantify its impact on the optical transfer function. The integrated modeling method combines the interference source and...
structure with the design of the optical system, and can perform the performance evaluation of the system requirements [8-10]. It should be considered in the design of drones, airborne platforms and aerial cameras to understand the overall MTF degree to which it is affected by vibration. The image quality of aerial cameras was evaluated by numerical calculation of MTF, some conclusions were summarized, and corresponding principles and measures of vibration isolation were proposed.

2. Optical-mechanical integration analysis

After the aerial camera is excited by the vibration load, the main optical components of its internal optical system will undergo rigid body displacement and surface distortion. The performance and imaging quality of the optical system will be affected to varying degrees.

Optical-mechanical integrated modeling analysis is to obtain the data of rigid element displacement and surface distortion of optical elements through structural finite element analysis. Use the Fringe Zernike polynomial conversion interface to process the extracted data, and use optical software to analyze optical imaging performance. By analyzing the data obtained by the optical analysis software, the degree of change of the imaging quality of the optical system after being excited by vibration can be evaluated. The data conversion algorithm is a key step in the OIAM. The Fringe Zernike function is used to realize the data conversion connection of structural analysis and optical analysis on this basis. In this way, the integrated analysis and simulation of the mechanical structure and the optical system is realized, and the design efficiency of the optical machine product is improved. The specific analysis process is shown in Figure 1.

3. Simulation analysis of integrated vibration modeling

3.1. Establishment of finite element model of aerial camera

The aerial camera has been specially developed to improve the imaging performance of optical-mechanical components in complex working environments.

The camera is an optical system composed of 6 groups of lenses. The fourth lens is aspherical. The lens and the lens are rigidly connected by a retaining ring. The lens and the lens barrel are connected by 4 uniformly distributed screws. The lens barrel is connected to the base through the internal interface. Tighten and fix with screws. The CCD is fixedly connected to the adapter plate by screws, and the adapter plate is fixedly connected to the base by bolts. According to the physical design dimensions of the aerial camera, a three-dimensional model is established as shown in Figure 2. The finite element model of the aerial camera is shown in Figure 3. The whole model has a total of 111,282 units and 141,953 nodes.
3.2. Modal analysis of aerial camera

In order to obtain the natural frequency and mode shapes of the optical camera system of the aerial camera, a modal analysis is performed on the optical camera system of the aerial camera. The first 2 order mode shapes of the aerial camera optical-mechanical system are shown in Figure 4. Table 1 is the description of the first 6 orders of natural frequency and mode shapes of the optical-mechanical system.

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**Figure 2.** 3D model of aerial camera.

**Figure 3.** Finite element model of aerial camera.

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As can be seen from Figure 4 of the aerial camera, the lens and CCD part have poor anti-vibration performance, and the vibration reduction performance needs to be improved. In the sixth-order modal, the CCD and the frame have large mode oscillations but their frequency has reached 2671.9 Hz, which has exceeded the normal operating frequency of the drone, without considering the impact on the imaging quality. The natural frequencies and mode shapes of the first six modes of the camera can be seen from Table 1.

3.3. Vibration simulation analysis under flight conditions

UAVs generate vibration during high-speed flight, causing rigid body displacements and surface distortions of the main optical components of the aerospace optical system. Analyzing the effects of vibrations in flight on aerial cameras. The rigid body displacement of the aerial camera optical-mechanical system is shown in Figure 5, and the lens node displacement data after fitting is shown in Table 2.

| Order   | Frequency /Hz | Mode shape     |
|---------|---------------|----------------|
| First-order | 430.6         | Swing around Y axis |
| Second-order | 997.1         | Swing around X axis |
| Third order | 1550.1        | Twist around X axis |
| Fourth-order | 1908.3        | Twist around Y axis |
| Fifth order  | 2242.4        | Twist around Z axis |
| Sixth-order  | 2671.9        | Twist around Y axis |

Figure 4. The first 2 order mode shapes of aerial camera optical-mechanical system.

Figure 5. Rigid body displacement of aerial camera optical-mechanical system.
Table 2. Lens node displacement data after fitting.

|   | \( \Delta x/(\text{mm}) \) | \( \Delta y/(\text{mm}) \) | \( \Delta z/(\text{mm}) \) | \( \alpha/(^\circ) \) | \( \beta/(^\circ) \) | \( \gamma/(^\circ) \) |
|---|---|---|---|---|---|---|
| 1 | -3.77E-04 | -3.94E-06 | -5.18E-04 | 7.5E-04 | 2.45E-05 | -8.34E-05 |
| 2 | -3.71E-04 | -3.91E-06 | -5.19E-04 | 5.34E-05 | 1.36E-07 | -2.45E-05 |
| 3 | -3.58E-04 | -3.85E-06 | -5.18E-04 | 8.38E-04 | 3.89E-05 | 7.44E-04 |
| 4 | -3.36E-04 | -3.64E-06 | -4.81E-04 | 4.17E-04 | -7.33E-05 | -3.69E-04 |
| 5 | -3.04E-04 | -3.61E-06 | -5.19E-04 | 2.69E-03 | -1.12E-04 | 2.74E-04 |
| 6 | -2.92E-04 | -3.55E-06 | -5.19E-04 | 2.76E-03 | -8.24E-05 | -1.27E-03 |
| 7 | -2.38E-04 | -3.31E-06 | -5.19E-04 | 2.17E-03 | -1.07E-04 | 2.00E-04 |
| 8 | -2.24E-04 | -3.24E-06 | -5.19E-04 | 2.54E-03 | -3.15E-05 | -1.40E-03 |
| 9 | -2.20E-04 | -3.23E-06 | -5.18E-04 | 2.38E-03 | 3.88E-05 | 1.03E-04 |
| 10 | -1.89E-04 | -3.11E-06 | -5.18E-04 | 4.09E-03 | 1.18E-04 | -8.80E-04 |
| 11 | -1.78E-04 | -3.07E-06 | -5.18E-04 | 1.59E-03 | 1.13E-04 | -1.06E-03 |
| 12 | -1.44E-04 | -2.87E-06 | -5.18E-04 | 1.28E-04 | -8.64E-05 | -1.67E-03 |

4. Optical simulation analysis of aerial camera

4.1. Aerial camera optical system
The object distance of the aerial camera optical system is infinite, the focal length is 80 mm, the caliber is 10 mm, the full field of view: 28°. The working band is visible light. Its lens grades are HZBAF50, HF13, HZK6, HZK20, F2, HZBAF50. The optical system model of the aerial camera is shown in Figure 6. When the spatial sampling Nyquist frequency is 91lp/mm, the MTF of the aerial camera optical system is better than 0.41 in the full field of view.

![Figure 6. Optical system model of aerial camera.](image)

4.2. Image quality of aerial cameras under vibration excitation
The 37 term Fringe Zernike polynomial coefficients of the 12 lens surfaces obtained by fitting are input into the optical design software. The MTF and image point map of the aerial camera under the excitation of flying vibration load are obtained.
The MTF of the optical system of the aerial camera is reduced after vibration excitation is shown in Figure 7. In the 18° field of view, the MTF value decreases from 0.419126 to 0.419055 at a resolution of 91 lp/mm. Figure 8 is a dot array diagram of the optical system along the optical axis direction. It can be seen from the Figure 8. that the radius of the Airy spot of the system before the vibration excitation is 5.728 μm. Airy spot radius. After the vibration load excitation, although the diffuse spot radius of the system image point map in each field of view still falls within the Airy spot radius. But the maximum beam radius in the system point map of each field of view is larger than before the vibration excitation. The GEO radius of the system can be seen in Table 3.

**Table 3.** GEO radius of the system before and after vibration excitation.

| Field of view | Before       | After         |
|---------------|--------------|---------------|
| 0°            | 2.72831078E+000 μm | 2.7718891E+000 μm |
| 8.4°          | 3.38957218E+000 μm | 3.42805772E+000 μm |
| 14°           | 3.28197520E+000 μm | 3.31710606E+000 μm |
| 18°           | 4.29496985E+000 μm | 4.32543799E+000 μm |
The analysis shows that after being excited by the vibration load, the image point array of the aerial camera optical-mechanical system will be shifted and dispersed to different degrees in different fields of view. Although it has a small impact on the imaging performance of the optical system. In order to better ensure the imaging performance of the camera a vibration isolation auxiliary device can be designed.

5. Conclusion
This paper adopts the OIAM to study the influence of vibration interference on the imaging quality of aerial cameras.

Research indicates, the aerial camera imaging is less affected by vibration. The analysis shows that the aerial camera optical system has a 0.071% reduction in MTF at a resolution of 91lp/mm under the high-speed cruising flight conditions, and the MTF value decreases from 0.419126 to 0.419055. This conclusion can be used to analyze the impact of vibration on imaging performance in the design of aerial cameras, and has important guiding significance for the vibration reduction optimization of aerial cameras.

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References
[1] Zhai L P, Liu M, Xiu J H 2006 Calculation of image motion velocity considering airplane gesture angle in oblique aerial camera[J] Opt. Precision Eng 14(3) 490-494 (in Chinese)
[2] Xu Y S, Ding Y L, Tian H Y, Dong B 2007 Calculation and compensation for image motion of aerial remote sensor in oblique situation[J] Opt. Precision Eng 15(11) 1779-1783(in Chinese)
[3] Zhang SH Q, Ding Y L, Yu CH F 2007 Attitude compensation of frame aerial camera based on spot model[J] Opt. Precision Eng 15(11) 1789-1795(in Chinese)
[4] Hadar O,Fisher M,Kopeika N S 1992 Image resolution limits resulting from mechanical vibrations. partIII : numerical calculation of modulation transfer function[J] Opt. Eng 31(3) 581-589
[5] Hadar O, Dror I, Kopeika N S 1992 Real-time Numerical calculation of Optical Transfer Function for Image motion and vibration Part1:Experimen-tal verification[J] SPIE 1971 412-435
[6] Hadar O, Dror I, Kopeika N S 1991 Numerical calculation of Optical Transfer Function for Image motion and vibration-a new method[J] SPIE 1533 61-74
[7] Hadar O, Fisher M, Kopeika N S 1991 Numerical calculation of Image motion and vibration modulation transfer function[J] SPIE 1482 79-91
[8] Lee, D. O., Yoon, J. S., and Han, J. H March 2012 Integrated Framework for Jitter Analysis Combining Disturbance, Structure, Vibration Isolator and Optical Model Proceedings of the SPIE 8341 Paper 834126
[9] Miller, D. W., Weck, O. L., and Mosier, G. E. July 2002 Framework for Multidisciplinary Integrated Modeling and Analysis of Space Telescopes Proceedings of the SPIE Integrated Modeling of Telescopes 4757 1–18
[10] Remedia, M., Aglietti, G. S. and Richardson, G. May 2015 A Stochastic Methodology for Predictions of the Environment Created by Multiple Micro vibration Sources Journal of Sound and Vibration 344 138–157