Research Article

A Study on the Structural Analysis of Ultra-Lightweight Two-axis Stabilizer for Multi-Purpose Tracking

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Abstract: This is a study on the structural analysis to improve the precise location tracking of the Electro-Optical Tracking System (EOTS), which is installed on a drone to monitor and track a target and calculate the coordinates of the target. The dynamic mass imbalance due to the difference between the center of gravity and the rotation center of the sensor module installed in the EOTS and the friction torque generated in the bearing connected to the BLDC motor to operate the EOTS adversely affects the control performance of the EOTS. However, it is difficult to accurately predict the EOTS stabilization error due to nonlinearity taking into account structural complexity and friction. Therefore, it is intended to minimize stabilization errors through predictable boundary conditions and vibration mode analysis due to disturbances using Ansys structural analysis program.

Keywords: Structural analysis, Ultra-lightweight gimbal, FEM, Line of sight, Structure optimization, Gyro-image Stabilizer

1. Introduction

Electro-optical tracking equipment (EOTS) is installed and operated on platforms such as rotary and fixed wing unmanned aerial vehicles, combat vehicles, and ships, and is mainly mounted on aircraft and used for reconnaissance purposes. Gimbal structure system consists of day / night camera module (EO / IR) and laser rangefinder (LRF) for detection, and includes a stabilizing function for stabilizing the line of sight (LOS). The stabilization drive apparatus is used for the purpose of directing or tracking the line of sight of the camera by performing rotational motion at elevation and azimuth. In addition, EOTS prevents the vibration generated from the platform from being transmitted to the camera module, so that stable images can be acquired in real time. And, EOTS includes automatic target tracking and navigation for aircraft cruising. In order for the gimbal structure system to operate stably, it is most preferable that the natural frequency does not exist within the external excitation range, but if it is unavoidably present in the structure, the vibration characteristics of the structure must be optimized as a control band capable of achieving stabilization performance. There are various external excitations such as periodic vibrations generated inside drone rotors, aerodynamics due to air viscosity and friction, inertia forces, and vibrations from aircraft. These external excitations have differences in amplitude and frequency depending on the disturbance. The amplitude is not a constant value, but an excitation having a frequency within a certain range. The resonance phenomenon of the gimbal structure becomes a decisive factor in the positioning accuracy of the camera and the camera's LOS, and in severe cases, the structure is damaged. For this reason, it is necessary to analyze the vibration characteristics of the gimbal structure against the excitation of all frequencies acting on the gimbal structure system through modal analysis and harmonic response analysis of the gimbal structure including the camera to detect the stable and accurate image of the target.

2. Electro-Optical Tracking System Structure Analysis

M. Chati., R. Rand.,& S. Mukerhjee. (1997) conducted study on the analyze the vibration characteristics of the structure through modal analysis and harmonic response analysis of the ultra-lightweight 2-axis EOTS gimbal for precision position tracking. The EOTS consists of a camera module(EO/IR/LRF) and an IMU sensor on the Tilt-axis, as shown in Figure.1 The Pan-axis consists of a BLDC(Brushless DC) motor for performing stabilization and tracking functions, a control board for controlling this motor, and position sensor. The Tilt-axis frame and the Pan-axis frame have a shape that is assembled and secured through a bearing on the drive shaft. The camera module and the BLDC motors are very complex in shape and configuration, but EOTS must be precisely controlled. Therefore, the center of gravity is balanced on the drive shaft of the Tilt and Pan-axis. Finite element analysis proceeded by applying point mass conditions to the mounting positions of components(Camera module, BLDC motors). **H. H Lee. (2019)** conducted study on the finite element method using Ansys 2020.

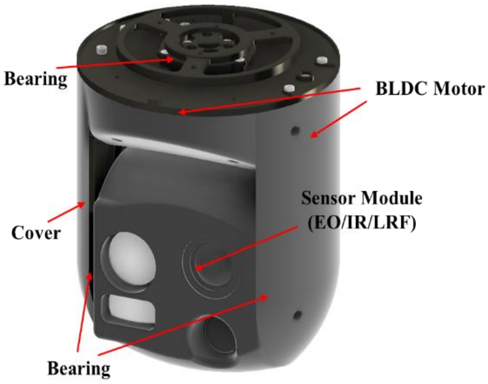
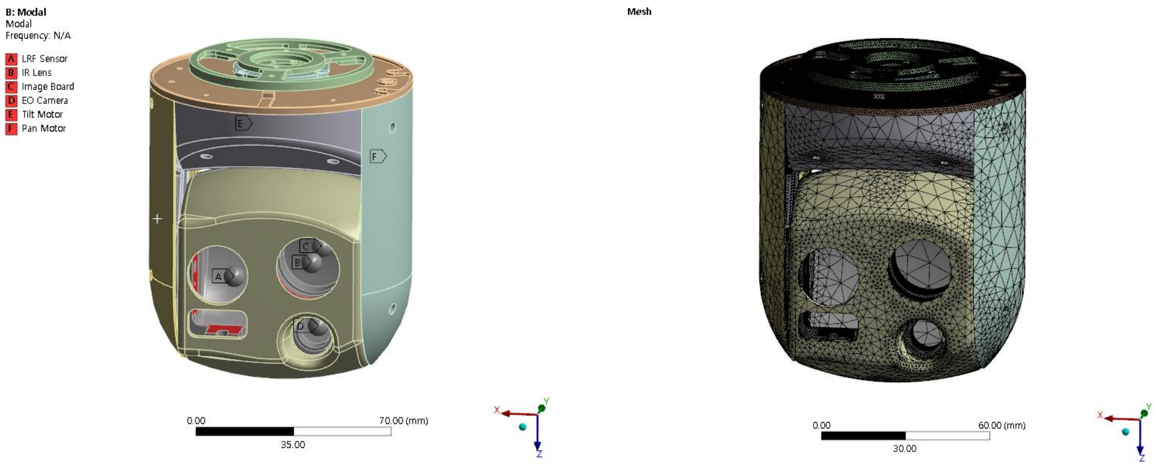


Figure.1 Components of EOTS Structure



(a) Point mass position (b) Mesh of EOTS

Figure. 2 Point mass position and mesh of EOTS

The analysis model is shown in Figure.2 and the components weighing 11g for EO module, 27g for IR modules, 51g for LRF sensor, and 16g for BLDC motor. The EOTS structure is supported by two angular contact ball bearings, the Tilt-axis structure including the camera module and sensor. In addition, the Pan-axis structure is supported by one angular contact ball bearing and has a structure in which bearings are constructed Pan, Tilt-axis to perform rotational motion. **J. P. Hong. (2017)** conducted a study that it withstands the axial and radial loads of angular contact ball bearings and has excellent high-speed precision. Angular contact ball bearing changes vibration characteristics under the influence of axial pre-pressure, radial load, and rotational speed during operation. Therefore, when each angle contact ball bearing is used, the axial pre-pressure is applied to increase the accuracy and bearing stiffness of the axis, allowing the control of the rotation to be controlled by sliding. In the analytical step, the boundary conditions are simplified by applying spring damper elements provided by Ansys, as the finite element modeling considering the inner ball contact of the bearing is limited, but the axial stiffness and radial stiffness obtained by pre-pressure are known. However, it is assumed that the bearing between the application of spring damper elements is completely fixed to the structure without causing friction, self-deformation, and attenuation. This bearing is manufactured by **Timken Company** with axial stiffness of 11,000kN/m and radial stiffness of 33,000kN/m. The material to which the EOTS structure is applied shall be rigid to withstand heat-induced thermal deformation and external force deformation that may occur in camera modules during UAV(unmanned aerial vehicle) operation. In addition, the weight should be light enough not to burden UAV. To this end, the EOTS structure was made of Aluminum 6061. **S. E. Lee., T. W. Lee.(2011)** conducted a study of the the damping ratio of the structure is set to 2%

Table. 1 Material Properties of Angular Contact Ball Bearing

Model Name	Axial Stiffness	Radial Stiffness
S2128	11,000kN/m	33,000kN/m

Table. 2 Material Properties of EOTS Structure

Material	Aluminum 6061
Density	$2770\ kg/m^3$
Young's Modulus	7,100 MPa
Poisson's Ratio	0.33
Bulk Modulus	69,608 MPa
Shear Modulus	26,692 MPa

The mesh shape of the analytical model applies the Tetrahedrons method and was constructed with Fig. 2. Mesh consists of 765,769 points and 443,798 elements. Referring to the research results of **J. W. Choi, D. G. Kwag. (2021),** through mesh analysis, the average element quality was composed of 0.78, and the standard deviation of the mesh was 0.15. The average element quality closer to 1 is better. The average element quality is small in error from above 0.7 and does not affect the analysis of vibration characteristics of the EOTS structure.

Table. 3 Finite Element Mesh Setting

Mesh Setting	Configuration
Mesh Type	Tetrahedrons Method
Number of Point	765,769
Number of Element	443,798
Element Quality	0.78
Element Standard Deviation	0.15

We analyze the vibration characteristics of transmission rates to disturbances using harmonic response analysis, an analytical technique that verifies the response when the material and boundary conditions of EOTS are applied. The governing equation for this finite element analysis can be finally expressed in equation (4) through the following theorem.

The harmonic response analysis is performed using the complex number/complex number plane theory. It is possible to express the vibration state by using Euler's equation for the real part and the imaginary part.

$$Z = x + iy = A \cdot e^{i(\omega t+\theta)} \tag{1}$$

Where $x = A\cos(\omega t + \theta)$, $y = A\sin(\omega t + \theta)$, $e^{i\varphi} = \cos\theta + i \cdot \sin\theta$.

Therefore, Assuming that $\{F\}$ and $\{u\}$ are harmonic functions of frequency Ω they can be transformed into complex number form as shown in equation (2).

$$Z = x + iy = A \cdot e^{i(\omega t+\theta)} = (A \cdot e^{i\theta})e^{i\Omega t} \tag{2}$$

$$\{F\} = \{F_{max}e^{i\theta}\}e^{i\Omega t} = (\{F_1\} + \{F_2\})e^{i\Omega t} \tag{2.1}$$

$$\{u\} = \{u_{max}e^{i\theta}\}e^{i\Omega t} = (\{u_1\} + \{u_2\})e^{i\Omega t} \tag{2.2}$$

Where $\{F_1\}$ is Real force vector, $\{F_2\}$is Imaginary force vector, $\{u_1\}$is Real displacement vector, $\{u_2\}$is Imaginary displacement vector.

Finally, a harmonic response analysis is performed by applying {F} and {u} of equation (2.1), (2.2) summarized in complex number form to general motion equation (3).

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F\} \quad (3)$$

where is Mass matrix, C is Damping matrix, K is Stiffness matrix, F is External force vector. and $\ddot{u}$ is Acceleration vector, $\dot{u}$ is V is Velocity vector, u is Displacement vector. The governing equation for the finite element analysis applied to perform this interpretation is as follows.

$$(-\Omega^2[M] + i\Omega[C] + [K])(\{u_1\} + i\{u_2\}) = (\{F_1\} + i\{F_2\}) \quad (4)$$

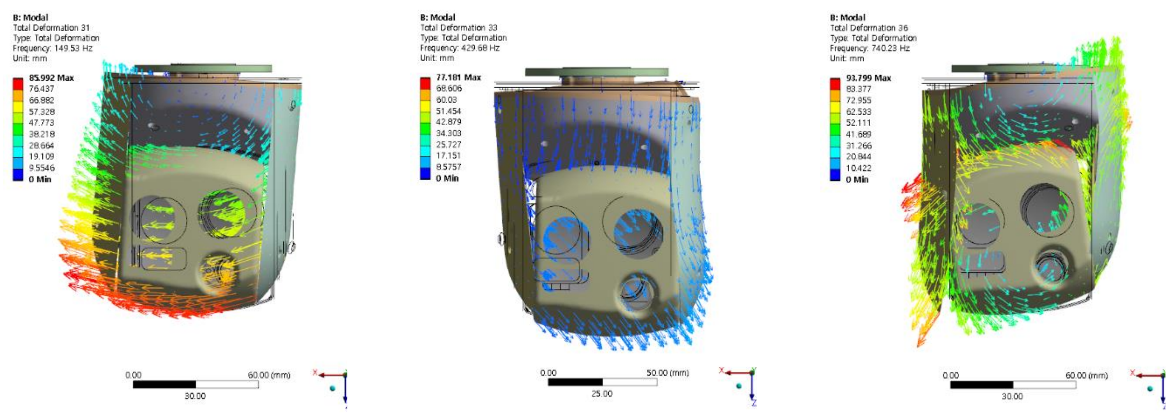
The external vector term in equation (3) corresponds to the acceleration applied by the EOTS structure and the acceleration of Sine-sweep from 0 to 1000 Hz is applied as base excitation condition. Through finite element analysis, we want to verify the response characteristics to the haves it determine the natural frequency of EOTS and the transmission rate applied to the Tilt-axis structure. The conditions for harmonic response interpretation implemented the base excitation condition to be applied to the mounting surface of the UAV(mounting platform) of the EOTS. The transmission rate for each direction of the X, Y, Z-axis of the Tilt-axis structure is analyzed for the acceleration input of the mounting plane.

3. Electro-Optical Tracking System Structure Analysis Result

This study analyzes the natural frequency and transmission rate by performing a modal analysis and a harmonic response analysis on acceleration inputs to analyze the vibration characteristics of EOTS structures for precision position tracking. EOTS performs image stabilization and tracking functions. Steady and accurate functional performance requires a stabilization design for structural stability and vibration. For the analysis of these properties, we first analyzed the natural frequency through modal analysis. To determine the characteristics at frequency from 0 to 1000Hz, we perform a harmonic response analysis that allows us to verify the transfer rate. The mode shape in the natural frequency within 0 to 1000Hz shown as a result of modal analysis were shown in Fig. 3~5. The natural frequency of Bending mode has 149.53 Hz in the first, 429.68Hz in the second, 740.23Hz in the third. The natural frequency of Lateral mode has 174.16Hz in the first, 439.15Hz in the second. The natural frequency of Torsion mode has 515.79Hz in the first, 776.6Hz in the second. The natural frequency are shown in Table. 4.

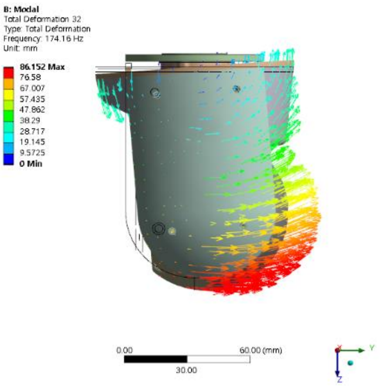
Table. 4 Natural Frequency of EOTS

Mode	Natural Frequency	Mode	Natural Frequency	Mode	Natural Frequency
1st Bending	149.53 Hz	1st Lateral	174.16 Hz	1st Torsion	515.79 Hz
2nd Bending	429.68 Hz	2nd Lateral	439.15 Hz	2nd Torsion	776.6 Hz
3rd Bending	740.23 Hz	-	-	-	-

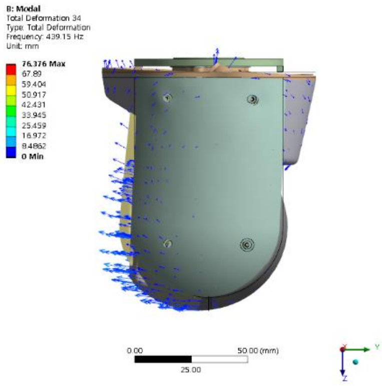


(a) 1st Bending mode(149.5Hz) (b) 2nd Bending Mode (429.6Hz) (c) 3rd Bending Mode(740.23Hz)

Figure.3 Bending Mode Shape

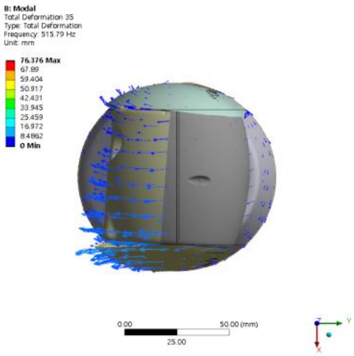


(a) 1st Lateral Mode (174.16Hz)

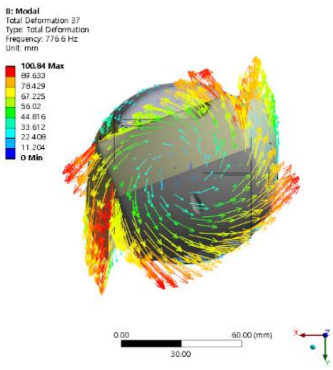


(b) 2nd Lateral Mode (439.15Hz)

Figure.4 Lateral Mode Shape



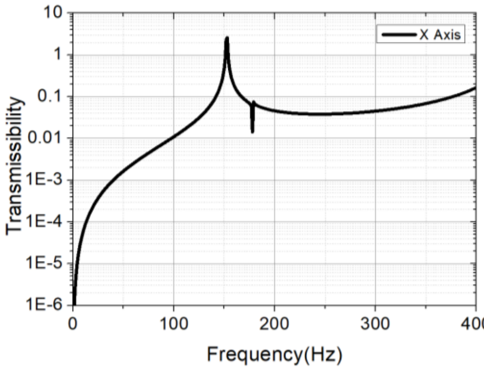
(a) 1st Torsion Mode(515.79Hz)



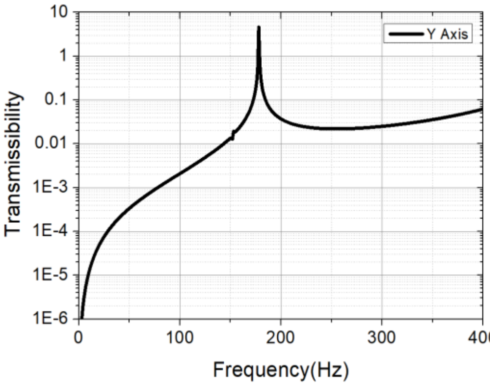
(b) 2nd Torsion Mode(776.6Hz)

Figure.5 Torsion Mode Shape

The acceleration transmissibility of the Tilt-axis structure was obtained through the harmonic response analysis, and a graph of the transmissibility for each direction was shown in Fig. 6. The transmissibility graph confirms that the operational frequency of EOTS will be suitable for operation at 0~400Hz. Within 0~400Hz, the maximum transmissibility in the X-axis direction is 2.59 at the first peak point, and the maximum transmissibility in the Y-axis direction is 4.65 at the first peak point. Finally, the maximum transmissibility in the Z-axis direction was found to be 3.12 at 400Hz. (No peak point with in 400Hz.) As a result, the first natural frequency of EOTS occurs at 149.53 Hz in the first bending mode. It was confirmed that the maximum transmissibility in the X, Y, Z directions was 4.65 for the Y-axis when first lateral mode occurred. The natural frequency and transmissibility in 0~400Hz are described in Table 5.



(a) Transmissibility of X Direction (EOTS)



(b) Transmissibility of Y Direction (EOTS)

Figure.6 Transmissibility Graph (0~400Hz)

4. Conclusion

In this study, a 2-axis EOTS structure is conducted for the purpose of structural analysis to obtain stable image data by performing stabilization functions and target tracking functions. Structural design requires a stabilization design for vibration as well as the strength of the structure. Therefore, we analyze natural frequency and transmissibility in the operating frequency band that can be caused by the disturbance. The vibration characteristics of EOTS structures have been concluded as follows :

1) It is believed that setting the EOTS operation frequency band within the 0~400Hz range will be stable for the structure during operation. When operating above the 400Hz frequency band , it can be seen that the transmissibility above the design requirement occurs.
2) The first natural frequency that occurs within the recommended frequency rage of 0 to 400Hz is 149.53Hz in first Bending mode. The maximum transmissibility was found to be 4.65 in the Y-axis direction at 174.16Hz in first lateral mode.
3) To meet the design requirements for the EOTS transmissibility analyzed in the study, the development of isolation structure for vibration attenuation should be added. Therefore, the design of vibration isolator to reduce vibration will have effect of reducing the transmissibility.

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