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Modal analysis of rotating mirror for ultra-high-speed cameras

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ABSTRACT

We theoretically and numerically investigated the modal properties of three different kinds of cross-section rotating mirrors. At the same facet size, the fundamental frequency of equilateral-triangle cross-section rotating mirror (ET-RM) was 8725.4 Hz, which was 1.81 times and 4.60 times higher than that of equilateral-square and equilateral-hexagonal rotating mirrors. The displacement response curves of the three kinds rotating mirrors show that the amplitude of the first peak is further larger than the second one. The first bending modal of rotating mirror is the main reason of the damage for rotating mirrors. The maximum working speed of ET-RM with face size of 17.32 mm × 36 mm is 44,400 rpm. That of the other two kinds of rotating mirror are 37,800 rpm and 27,000 rpm respectively. The equilateral-triangle cross-section as an ideal structure of rotating mirror for ultra-high-speed cameras based on the dynamic properties.

1. Introduction

Rotating mirror (RM)-based ultra-high-speed cameras, with their large frame area, large frame count, high spatial resolution, and wide dynamic range, are regarded as one of the important transient imaging techniques in the modern economy, scientific research, and the national defense industry [1–5]. These cameras have been extensively used to image the details of explosions, splintering, detonations, shockwaves, high-voltage discharges, supersonic wind tunnels, high-speed combustion, and so on [4,5]. In the RM ultra-high-speed camera system, the RM is not only as an imaging element in optical path, where imaging quality is affected by surface quality and plane deformation of the RM, but also as an element to implement ultrahigh speed, because performances of the ultra-high-speed camera system are mainly dependent on the edge linear velocity and dynamic mechanical properties of the RM [6–10]. Dynamic properties of RM are interested research subjects, and data computed by derived formula are expected to be coincident with results from experiments. The troublesome vibration is normal to the axis of rotation and is at an amplitude maximum when the speed of rotation is the same as one of the RM vibration frequencies. Ruptures of RM have occasionally occurred, which generally indicates that the RM is not strong

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enough for high-speed loading, or the fatigue crack is generated because of the accumulation of fatigue damage caused by torsion or bending vibration [11–17]. The vibrational characteristic of RM is immensely dependent on cross-section shape and lateral mass distribution of RM [18–22].

In this paper, the dynamic properities of mainly three cross-section shapes of RM, namely, equilateral-triangle RM (ET-RM), equilateral-square RM (ES-RM), and equilateral-hexagonal RM (EH-RM), were investigated by theoretically and numerically method. The first three natural frequencies of ET-RM are 8725.4 Hz, 8726.2 Hz, and 10,013.0 Hz. For ES-RM, the values are 4810.3 Hz, 7684.6 Hz, and 7688.3 Hz. For EH-RM, the modal parameters are 1895.5 Hz, 5288.2 Hz, and 5292.0 Hz. The fundamental frequency of ET-RM is 1.81 times and 4.60 times higher than those of ES-RM and EH-RM, respectively. The first bending modal of RM is the main reason of the damage for RMs. The maximum working speed of ET-RM with face size of 17.32 mm × 36 mm is the highest speed among the three different cross-section. Considering the dynamic properities, equilateral-triangle cross-section is an ideal cross-section construction of RM for ultra-high-speed cameras.

2. Theory of modal analysis

Assuming that the RM system is damped with viscous damping, the motion differential equation of the finite element can be expressed as [22–24]

$$[m_e]\left\{\ddot{x}\right\}+[c_e]\left\{\dot{x}\right\}+[k_e]\{x\}=\left\{f^e(t)\right\}, \tag{1}$$

where $[m_e]$ is the mass matrix of an element, $[c_e]$ is the damping matrix of the element, $[k_e]$ is the stiffness of the element, and $\{f^e(t)\}$ is the generalized force vector of the element. $\{x\}$ stands for the generalized displacement vector,

$$\left\{f^e(t)\right\}=\left\{f^{el}(t)\right\}+\left\{f^{eD}(t)\right\}, \tag{2}$$

where $\{f^{el}(t)\}$ is the physical strength matrix of the element, and $\{f^{eD}(t)\}$ is the damping force matrix of the element.

$$\left\{f^{el}(t)\right\}=-\int_{V_e}\rho[N]^T[N]\left\{\ddot{x}^e\right\}dV, \tag{3}$$

where ρ is the density of the element, and $[N]$ is the shape function matrix of the element,

$$\left\{f^{eD}(t)\right\}=-\int_{V_e}c[N]^T[N]\left\{\dot{x}^e\right\}dV, \tag{4}$$

where c is the damping coefficient of the element,

$$[m_e]=\int_{V_e}\rho[N]^T[N]dV, \tag{5}$$

$$[c_e]=\int_{V_e}c[N]^T[N]dV, \tag{6}$$

$$k_e=\int_{V_e}[B_e]^T[D_e][B_e]dV, \tag{7}$$

where $[B_e]$ is the strain matrix of the element, $[B_e]^T$ is the transformation matrix of an element strain matrix, and $[D_e]$ is the elastic matrix of the element.

$$[D_e]=\begin{bmatrix} \lambda+2G & \lambda & 0 & 0 & 0 & 0 \\ & \lambda+2G & \lambda & 0 & 0 & 0 \\ & & \lambda+2G & \lambda & 0 & 0 \\ symmetry & & & G & 0 & 0 \\ & & & & G & 0 \\ & & & & & G \end{bmatrix}, \tag{8}$$

λ and G are Lame constants of the RM material and can be expressed as

$$\lambda=\frac{E\mu}{(1+\mu)(1-2\mu)}, \tag{9}$$

$$G=\frac{E}{2(1+\mu)}, \tag{10}$$

where E is a constant called the Young's modulus, and μ is the Poisson ratio.