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Original research article

Strength reliability of rotating mirrors for ultra-high-speed cameras

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ABSTRACT

This study aims to identify numerical analysis methods for the reliability prediction of rotating mirror(RM) strength at the early-stage design. A mathematical model for the strength reliability analysis of RM is established based on the Monte Carlo method, small-sample theory, and reliability principle. Numerical analysis on the strength reliability of RM is conducted, and the results are experimentally verified according to small-sample theory. The spearman rank order correlation coefficients between structure parameters and the maximum stress is the circumradius of mirror body, and that of the material variable is the elastic modulus of high-strength aluminum alloy(Al). The skewness and kurtosis values of maximum stress and strain are all positive. Calculated statistical results obey normal distribution and are right skewed. At 95% confidence level, the strength reliability of the RM with a design speed of 70,000 rpm is 0.999. This finding shows that the strength reliability of the RM meets the required design in ideal state. No failure of RMs occurs among strength reliability experiment, proving the validity of the numerical model. This model provides an economic, feasible, and effective method for estimating the strength reliability of RM.

1. Introduction

In the high-speed photography, RM ultra-high-speed cameras are widely used in wind-tunnel tests, high-pressure physics, micromechanics, and other scientific studies with features of large format, large format numbers, high spatial resolution, wide spectral bands, and wide shooting-frequency bands [1–6]. RM is the core component of ultra-high-speed cameras, and the strength reliability of this component directly determines the reliability of ultra-high-speed cameras [3,7–10]. Meanwhile, RM has a large potential application value in the field of laser processing with a scanning speed 100 times higher than that of commonly used galvanometer mirrors [11,12]. The rotational speed of the RM of ultra-high-speed cameras ranges between 0 and 5.0×10^5 rpm, and that for laser processing is about 1.0×10^5 rpm. Due to the high rotational speed, the required mechanical properties of its materials are relatively high and are hardly met by traditional design methods. Current research on RM mainly focuses on dynamic characteristics, RM surface deformation, and RM strength [2,7,10,13–15]. Considering the complicated internal stress and strain of RMs, predicting their strength reliability at the early-stage design of such mirrors is difficult.

In this letter, the performance functions of RMs are taken as research objects to establish a mathematical model for the strength

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reliability analysis of RMs according to the probability density distribution function of basic variables, such as the structure sizes. Numerical analysis on the strength reliability of the RM is conducted at the rotational speed of 70,000 rpm, and results are experimentally verified according to small-sample theory. The performance function values of the RM are found to be far below allowance value. The spearman rank order correlation coefficients between circumradius of mirror body (R_1), radius of shaft segment 1 (R_2) and maximum stress of the RM are 0.406 and 0.304, respectively. R_1 is the parameter that has the greatest influence on the maximum stress in the structure sizes of RM. And that of the materials' is the elastic modulus of Al. The skewness and kurtosis values of the maximum stress and strain probability distribution curves are all positive. The strength reliability of the RM meets design requirements. No failure is observed among the 10 RM samples in the reliability tests. These findings indicate that the validity of the RM strength reliability model and provides theoretical basis for the design of RM.

2. Theoretical basis

According to strength reliability theory, the stress and strength of the RM obey normal distribution. The probability density distribution functions [16–20] are

$$f(S) = \frac{1}{\sigma_S\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{S-\mu_S}{\sigma_S}\right)^2\right], -\infty < S < +\infty \tag{1}$$

$$g(\delta) = \frac{1}{\sigma_\delta\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{S-\mu_\delta}{\sigma_\delta}\right)^2\right], -\infty < \delta < +\infty \tag{2}$$

in the formula, σ_S, σ_δ, and μ_S, μ_δ are the standard deviation and mean value of the stress S and strength δ, $f(S)$ is the stress probability density function, and $g(\delta)$ is the strength probability density distribution function.

The strength reliability [21,22] of the RM is

$$R = P(y>0) = \int_0^{+\infty}\frac{1}{\sigma_y\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{y-\mu_y}{\sigma_y}\right)^2\right]dy \tag{3}$$

in the formula, $y = \delta - S$ is the strength reliability performance function of the RM. Formula (3) shows that the strength reliability of the RM is a multidimensional issue with a complicated domain of integration, and no analytical solution exists for the integral formula of the performance function. Thus, a numerical method must be introduced to solve the issue of the RM strength reliability. The parameters of the RM's stress, strength, elastic modulus, density, and structure size are the random basic variables of the strength reliability analysis, which meet certain mathematical statistic laws. The law of large numbers states that when a sample is large, the statistical law of the parent can be replaced by the sample. Thus, sample values can be drawn within the probability density distribution function of the basic variable of the RM. Each sample value can be substituted into the reliability probability formula to calculate the reliability of the sample value and finally obtain the reliability of the RM through statistical analysis. With a sufficiently large sample value, which is extracted within the range of the probability density distribution function of the RM, the strength reliability of the statistically obtained sample is infinity approximation to that of RM.

In this letter, we used the Monte Carlo method [23,24] for solving the strength reliability of RM. First, a probability analysis model for the strength reliability of the RM is established according to the probability density distribution function of the basic variables of the RM. Then, the percentage of the maximum stress of the RM under a certain value is statistically analyzed through multiple random samplings. With sufficient samples, the percentage approximates the strength reliability of the RM. We initially suppose that N random samples of the basic variable $x_j (j = 1, 2, \cdots N)$ are produced by the probability density distribution function $f_{X_i}(x_i)$ of the basic random variable of the RM, and that these N random samples are substituted into the performance function y. Sample numbers N_f falling into the failure domain $F = \{x: g(x) \le 0\}$ are then calculated, and the failure probability P_f is approximately replaced by the frequency of the failure N_f/N. Thus, approximate values $\hat{P}_f$ of the failure probability of the RM are approximated. The expectation of the estimated value of the failure probability $\hat{P}_f$ is [22,25]

$$E[\hat{P}_f] = E[\frac{1}{N}\sum_{j=1}^{N} I_F(x_j)] \tag{4}$$

$I_F(x_j) = \begin{cases}1, x \in F\\ 0, x \notin F\end{cases}$ is the indicator function in failure domain.

Given that sample x_j and the parent x of the RM are independent and identically distributed random variables [21,22,26], then

$$E[\hat{P}_f] = \frac{1}{N}E[\sum_{j=1}^{N} I_F(x_j)] = E[I_F(x_j)] = E[I_F(x)] = P_f \tag{5}$$

where $\hat{P}_f$ is an unbiased estimator of P_f.

Due to the independent and identically distributed of the samples, the variance of the failure probability estimated value $\hat{P}_f$ is