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Analysis and Prediction of Effect of Turning Marks Diffraction on Image Quality of Optical System

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Abstract

Single-point diamond turning (SPDT) is widely used in the machining of infrared materials and metal-based mirrors. Diamond tips can scratch material, replicate the shape of the tip, and create annular turning marks on optical surfaces, which can have unpredictable adverse effects on imaging. In order to predict the effect of turning marks diffraction on the degradation of imaging quality, a model of the influence of SPDT processing parameters on the reduction of system imaging MTF under the influence of ideal grating turning marks diffraction was established. The results show that the depth of the turning mark will lead to the decline of MTF, especially the low frequency information. Finally, a method is proposed to reduce the effect of turning marks diffraction through changing the processing parameters.

Keywords

Single-Point Diamond Turning, Diffraction, MTF, Blaze Grating

1. Introduction

With the continuous improvement of optical system manufacturing requirements, high-precision optical surface processing technology continues to develop. SPDT is a fabrication technique which used for producing infrared material lenses, aspheric metal-based mirrors, and other precision metal optical components. Diamond blades score glass or metal surfaces, and removes unwanted material. The turning tool generally travels along the Archimedes spiral. Since the feed speed of the tool is very slow, each revolution is about 10 μm, forming concentric annular-shaped grooves. When the light is incident on the surface of the metal mirror, according to the grating equation, the turning marks may produce diffracted light in a certain direction beside the mirror light. When the diffracted light continues to propagate to the image plane, it will interfere with the imaging quality, which reduces the imaging performance of the optical system.

In order to explain and suppress the degradation of imaging quality caused by the high-order diffracted light of SPDT mirrors, relevant fields have made great efforts in theory and experiment. Wu, D. [1] realized the diffraction optical characterization of the diamond-turned surface based on the vector diffraction theory, and revealed the distribution characteristics of the diffraction spots by using the finite difference time domain method. It is also proved that the height and spacing of the nano-surface topography have different effects on the intensity and angle of the diffraction spot. J. E. Harvey [2] proposed and developed the generalized Harvey-Shack surface scattering theory based on linear system theory, and proposed that low spatial frequency components, that is, shape precision will cause wavefront aberrations, while high spatial frequency components, that is, wide surface roughness will redistribute the radiation energy angle diffraction effect. Church [3] argued that the residual surface roughness of diamond-turned optical surfaces contains an important periodic component, and explored the performance of diamond-turned optics using the Rayleigh-Rice vector scattering theory, and the theory was applied to periods where the vertical amplitude is much smaller than the wavelength of light sexual roughness. In 2020, P. Zhou [4] proposed a mathematical model to reveal the relationship between the diffraction efficiency of harmonic diffractive optical elements, tool radius, feed rate, microstructure zone period width and the refractive index of the substrate material for HDOE diamond turning diffraction efficiency evaluation.

C. L. He established a three-dimensional surface topography model [5] for single-point diamond turning in 2018, and simulated the effect of tool edge waviness on SPDT diffraction through rigorous coupled wave analysis in 2019, proving that as the tool waviness deteriorates, The diffraction efficiency of specular light is reduced, but the high-order diffracted light is concentrated in the horizontal direction on the receiving screen [6]. A new approach to control tool edge quality, material defects, and machining parameters is proposed to directly eliminate diffraction effects in diamond turning [7].

L. Li [8] studied the properties of diamond-machined surfaces and found that the normalized first-order diffracted light was caused by tool marks and decreased as the turning marks degenerated. Additionally, they state that the slow-turning servo technology enables high-quality optical surfaces. Sheng [9] proposed a method to find the turning parameters that can directly produce an optical surface without diffraction effects by coupling the surface microtopography model of the turned surface with scattering theory in 2021. F. Fang [10] used the interferometry and integral method to theoretically analyze the relationship between the optical defects of the steering mirror, the surface micro-topography and the turning conditions, and obtained the relationship between the surface finish, the optical defects and the turning conditions. P. Wang. [11] analyzed the helical sinusoidal trajectory airbag polishing removal of SPDT tool marks, and proposed a helical sinusoidal polishing trajectory. Experiments have proved that the improvement effect of micro-nano texture is good under this trajectory.

C. Du [12] proposed a high-efficiency turning mark removal process combining ion beam sputtering and smooth polishing, which improved the removal efficiency of turning marks. J. Chen [13] proposed a model to predict surface roughness R_a in single-point diamond turning based on the analysis of relative vibration and expansion effects. The model is closer to the actual turning process than previous models and shows higher surface roughness prediction accuracy.

However, Existing research mainly focuses on the analysis of the diffraction characteristics of the turning marks diffraction surface and the processing experiment verification of turning marks removal. It is difficult to give a quantitative estimate of the image quality degradation caused by turning marks diffraction in the existing technology. The impact of turning marks texture on the imaging quality of the optical system can only be treated by blindly polishing the processed surface after processing, which not only increases the processing cost, but also may cause damage to the surface.

In this paper, the effect of turning mark diffraction on the degradation of imaging quality is studied. Based on the linear theory of optical system [14], we use the characteristic that the diffraction of turning marks has the greatest influence on the coaxial field of view, and the turning grating can be locally approximated as a linear grating. From the worst case, the structure of turning marks completely conforms to the Kinoform type diffraction grating, the impact of turning marks diffraction on image quality is estimated, and a program for quickly estimating the impact of SPDT turning marks on image quality degradation is developed. Taking the reduction of MTF by turning marks diffraction as one of the predictions of final image quality puts forward new requirements for the optical design stage, so that the optical design can regularly derive the optical manufacturing tolerances required to meet specific image quality requirements during the design stage of the project. That is, integrating optical metrology and manufacturing into the optical design process [15], and by observing and comparing the MTF decline trend under different processing parameters, a method to reduce the effect of turning marks diffraction is given.

2. Methods

The optical system can be regarded as a linear system, so the turning marks grating diffraction can be decomposed into the superposition of different orders of diffracted light images.

$$\mathcal{L}\left\{a_1 f_1(x)+a_2 f_2(x)\right\}=a_1 g_1(x)+a_2 g_2(x) \tag{1}$$

Based on this basic theory, the proposed calculation method flow chart is shown in **Figure 1**.

Based on the optimized optical system, the surface of interest (usually the primary mirror) is modeled as a grating. Here we have a variety of modeling methods, including building a annular grating structure, or directly assigning the

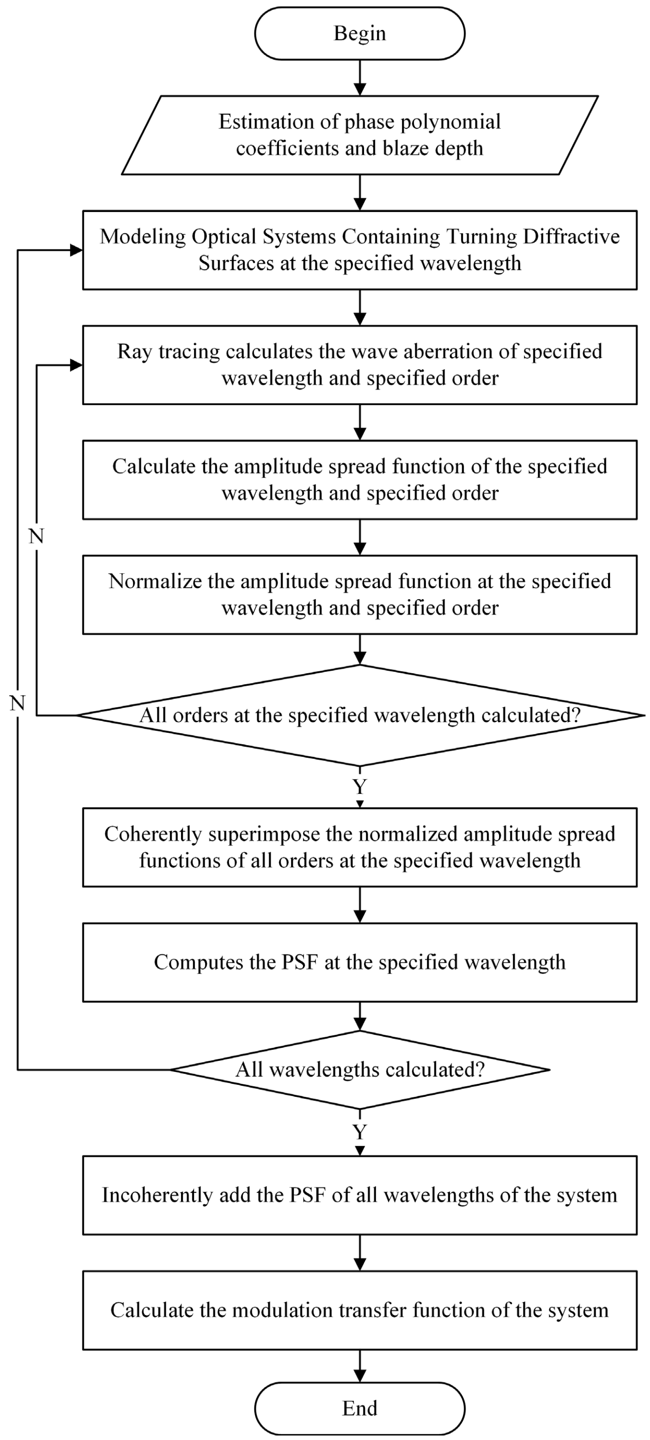

Figure 1. The calculation process of MTF under the influence of turning marks diffraction.

corresponding phase of the annular grating on the surface, the latter will be simpler in terms of calculation. The annular grating on the entire mirror surface can be regarded as a linear grating locally, and a fixed phase difference will be introduced between adjacent periods. When the gradient of the mirror sagittal height is not large, we can approximately consider that the grating adds a phase to the ±1 order diffracted light. Therefore, the additional phase of the turning marks diffraction grating to the incident light can be expressed by the following formula,

$$\phi = \mathrm{f}\left(r\right) \tag{2}$$

where $r = \sqrt{x^2 + y^2} > 0$, f( ) is the function of the grating on the phase. Here, we approximate that the stepping distance of each circle of the diamond cutter head is consistent, that is, the annular grating period is constant. When the plane wave is incident along the optical axis,

$$\phi = Cr \tag{3}$$

That is, the phase increases linearly with the radius, and the coefficient C is related to the processing parameters.

Since the tool mark annular grating can be locally regarded as a linear grating, as shown in **Figure 2**, the fixed optical path difference introduced between adjacent cycles is

$$OPD = nd\left(\sin\theta_i \pm \sin\theta_m\right) \tag{4}$$

where n is the mirror immersion refractive index, generally air (n = 1), d is the grating period, θ_i and θ_m are the angle of incidence and the angle of diffraction, respectively. When the incident light and diffracted light are on the same side of the grating normal, take +; if the incident light and diffracted light are on different sides of the grating normal, take −. Therefore, the coefficient C of the phase polynomial is

$$C = \frac{2\pi}{\lambda}\left(\sin\theta_i \pm \sin\theta_m\right) \tag{5}$$

where λ is the wavelength of light.

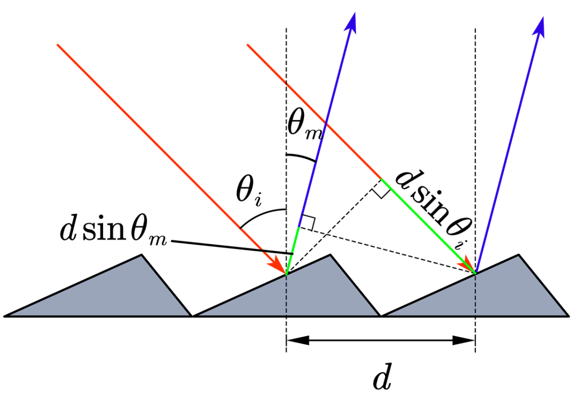

Figure 2. Phase tilt introduced by grating.

Another parameter relevant to grating modeling, blaze depth b is a processing-related parameter estimated as,

$$b=(-1)^r\frac{m\lambda}{\left(n_1-n_2\right)} \tag{6}$$

where r is an integer representing the number of reflections before diffraction. The blaze depth is measured along the surface normal.

After assigning grating properties to the surface of interest, it needs to be analyzed as a part of the optical system. Since the high-order diffraction energy greater than 1th is extremely low, we only need to pay attention to the diffracted light of the three orders of −1th, 0th, +1th, of which the 0th order is in the same direction as the normal refracted/reflected light, and the −1th and +1th orders deviate slightly. For a diffractive surface characterized by phase, the direction of the outgoing light after passing through the surface is calculated by the following formula.

$$\begin{aligned} l' &= l+\frac{\lambda}{2\pi}\frac{\partial\varphi}{\partial x} \\ m' &= m+\frac{\lambda}{2\pi}\frac{\partial\varphi}{\partial y} \end{aligned} \tag{7}$$

where l and m are the cosines of the direction of the incident light, and l' and m' are the cosines of the direction of the outgoing light.

From the entrance pupil of the optical system, trace the ray grid with the number of uniformly arranged rays of $N\times N$, and record the optical path difference OPD_w^m of each ray from the entrance pupil to the exit pupil spherical surface.

$$OPD_w^m=\Sigma_{i=1}^S n_i OPL_i \tag{8}$$

where S is the number of surfaces in the optical system, n is the refractive index before the ith surface, OPL_i is the optical path from the i-1th surface to the ith surface . Calculate the amplitude spread function (ASF) on the image plane,

$$ASF_w^m=\mathcal{F}\left\{\exp i\frac{2\pi}{\lambda_w}OPD_w^m\right\} \tag{9}$$

where λ_w represents the w wavelength, OPD_w^m represents the wave aberration of the m order at the w wavelength, and ASF_w^m represents the w wavelength The amplitude spread function of the mth order on the image plane, $\mathcal{F}$ represents the Fourier transform, namely

$$\mathcal{F}(\xi,\eta)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}f(x,y)e^{-i2pi(x\xi+y\eta)}dxdy \tag{10}$$

However, the ASF_w^m calculated by the Equation (9) has not been normalized, and cannot represent the energy proportion of the corresponding order. The ASF complex amplitude should be normalized, the diffraction efficiency of each order needs to be calculated. After diamond turning across the substrate material, a Blaze grating [16] is formed. The calculation of the grating efficiency can be compared to the Kinoform Blaze grating structure. The diffraction efficiency of the mth diffraction order is given by the following formula:

$$\eta_m = \left\{ \frac{\sin\left[\pi\left(\beta - m\right)\right]}{\pi\left(\beta - m\right)} \right\}^2 \quad (11)$$

where $\beta = b\left(n_1 \cos\theta_1 - n_2 \cos\theta_2\right)/\lambda$, n_1 is the front refraction index of the surface, n_2 is the back refraction of the surface rate, λ is the wavelength, θ_1 is the incident angle, and θ_2 is the diffraction angle. The amplitude spread function calculated by the Equation (9) is normalized by the diffraction efficiency of the corresponding order to obtain the normalized amplitude spread function as

$$ASF_w^{m'} = \frac{ASF_w^m}{\max\left(ASF_w^m\right)} \times \eta_m \quad (12)$$

On the image plane, since different orders of light of the same wavelength come from the same light source, the fluctuations of different orders of light are related, that is, interference can occur between complex amplitudes of the same wavelength [17], so the amplitude spread functions of different orders at the same wavelength should be coherently superimposed. The amplitude spread function at the same wavelength after superposition is

$$ASF_w^{sum} = \Sigma_m ASF_w^{m'} \quad (13)$$

The design wavelength of the optical system usually selects several representative wavelengths in the spectral band as the sampling wavelength. Since the electromagnetic frequencies of different wavelengths are different, no interference will occur, so incoherent superposition is used. The system sampling wavelength is repeatedly calculated to obtain the amplitude spread function at each wavelength, and the corresponding intensity spread function (PSF) is calculated by the following formula

$$PSF_w = ASF_w^{sum} \times ASF_w^{sum*} \quad (14)$$

The monochromatic intensity transfer function is obtained by incoherent superposition of the following formula to obtain the complex color point spread function,

$$PSF_{sum} = \Sigma_w PSF_w \quad (15)$$

Further, the modulation transfer function (MTF) of the optical system is calculated by the following formula,

$$MTF = \left|\mathcal{F}\left\{PSF_{sum}\right\}\right| \quad (16)$$

Through the above steps, the estimated value of the worst impact of turning marks diffraction on the intensity spread function and modulation transfer function of the optical system is obtained through calculation under the specified processing parameters. Therefore, it can be judged whether the optical design and processing parameters are reasonable, and can guide the further optimization of the design.

3. Results

Taking the Ritchey-Chrétien reflective optical system as an example, the layout of the optical system is shown in **Figure 3**. The optical system works in the visible light band, and the wavelengths are sampled at 656 nm, 587 nm, and 486 nm, and the weights of the wavelengths are equal.

The influence of turning marks diffraction on image quality degradation is analyzed, and on this basis, the influence of phase coefficient and blaze depth on image quality is studied. Analyzes were calculated and presented by MATLAB R2017a. The calculated −1th, 0th, +1th order PSF is shown in **Figure 4**.

Through the above steps, under the specified processing parameters, the estimated value of the worst impact of turning marks diffraction on the intensity spread function and modulation transfer function of the optical system is obtained. The MTF curve is shown in the **Figure 5**, and the black curve is the diffraction limit. The red curve is the design MTF when the turning marks diffraction is not considered. Because the design image quality is better, it coincides with the black curve. The blue curve is the MTF after considering the turning marks diffraction, and it can be seen that there is a certain decrease compared with the design MTF. From the degree of decline of the MTF curve from the turning marks diffraction, we can judge whether the optical design and processing parameters are reasonable, and guide the further optimization of the design.

When the design scheme is determined, turning parameters, material properties, and tool parameters all play an important role in tool mark diffraction. There are two parameters that directly affect the tool mark diffraction, namely, the distance traveled by each turn of turning, which affects the period length of the tool mark grating, and the tool wedge angle affects the tool mark depth of the tool mark grating. The period length of the turning marks grating can be controlled by the phase tilt coefficient C, the larger C is, the denser the turning marks are, and the stronger the deflection effect on the light is. The turning marks depth is controlled by the blaze depth b. By changing these two parameters and comparing the decline of MTF under different parameters, the analysis results are shown in **Figure 6**. According to the analysis of the curve, the decrease of MTF is more sensitive to the depth of the tool mark. Therefore, at the end of the machining, the tool with a larger tool tip angle should be replaced, and the tool movement should be controlled by a slow turning.

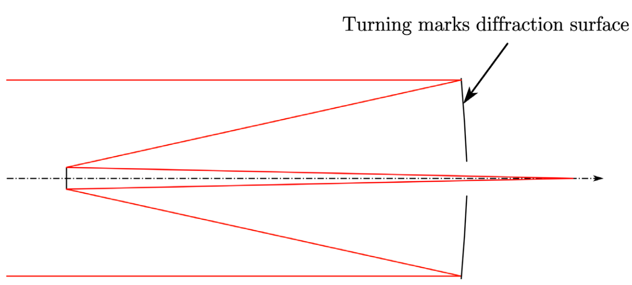

Figure 3. Ritchey-Chrétien reflective optical system layout.

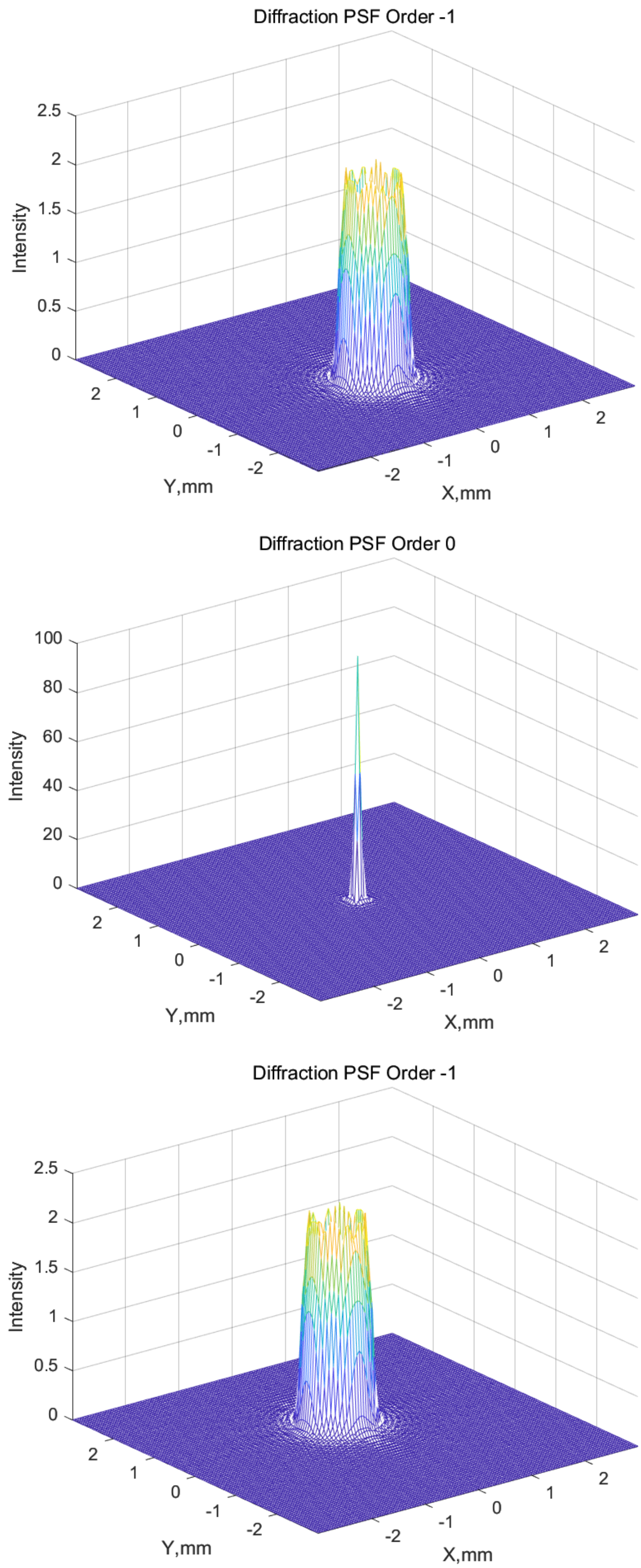

Figure 4. PSF under different diffraction orders.

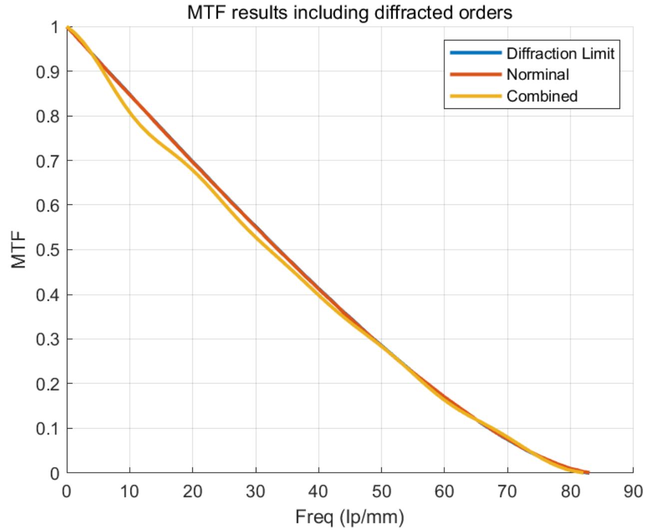

Figure 5. Estimation of the worst impact of turning marks diffraction on MTF.

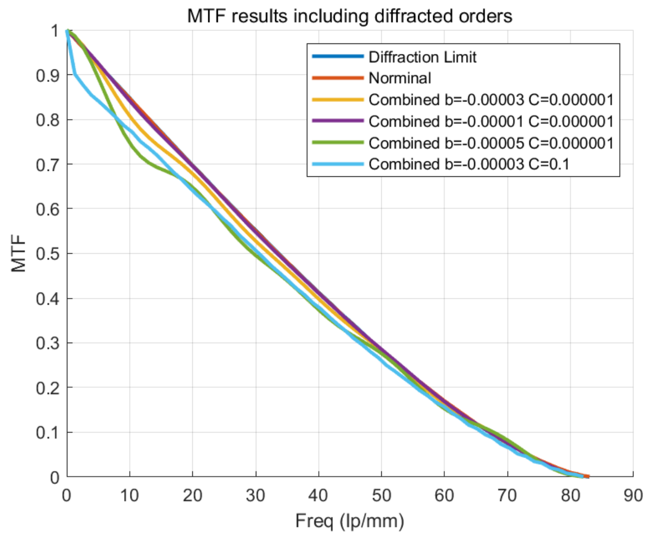

Figure 6. MTF drop curve of optical system under different processing parameters.

4. Discussions

This paper proposes a method based on scalar diffraction theory to quickly evaluate the impact of SPDT turning marks diffraction on imaging quality. This method has high computational efficiency and does not require electromagnetic solutions such as strict coupled wave analysis. In the field of scalar theory, an approximate estimate of the image degradation caused by turning marks diffraction is given. Through theoretical analysis and numerical calculation, the worst estimate of the impact of turning marks diffraction on image quality is directly given, without multiple processing and test iterations, it can be used as a part of digital modeling in actual design and manufacturing, saving high costs such as processing and testing, and the image quality degradation caused by turning marks diffraction is included in the image quality index analysis during design. In the next work, the author will further carry out experimental verification and study the impact of coating filling turning marks.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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