Automatic clocking optimization for compensating two-dimensional tolerances

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Abstract: Clocking of lens elements is frequently used as an effective method of compensating for two-dimensional tolerances such as material inhomogeneity and surface figure errors. Typically, the lens designer has to determine the optimum angles of rotation by manually modeling lens element clocking in the commercial optical design software because the nature of errors resolved by lens clocking does not lead to good convergences for clocking optimization. In this paper, a method of automatic clocking optimization is developed. The method is implemented using a combination of particle swarm optimization algorithm and commercial optical design software. The optimum angles of rotation and predicted imaging performance are automatically calculated using this method. Methods of implementation and optimization examples are also given.

OCIS codes: (080.3620) Lens system design; (220.1000) Aberration compensation.

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1. Introduction

Clocking of lens elements is frequently used to achieve a near-perfect image quality of lithographic lens with a high numerical aperture (NA). Lens clocking is a special method used to compensate for the low spatial frequency of material inhomogeneity and surface figure errors, even when the index homogeneity of the lens element is <1 ppm and the surface figure error (root–mean–square, RMS) is ~1 nm [1,2]. The lens designer has to determine the optimum angles of rotation by manually modeling the clocking of lens elements in commercial optical design software because conventional software tools have poor optimization ability for compensating for material inhomogeneity and surface figure errors. The two main reasons are as follows. First, commercial optical design software cannot

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generate an accurate set of tolerances for material inhomogeneity and surface figure error tolerances. Second, the nature of errors resolved by clocking lenses does not give good convergence for clocking optimization.

In this paper, we classify the tolerance parameters into two classes: tolerances with one dimension such as refractive index, radius, thickness, and element tilt; and tolerances with two dimensions such as material index inhomogeneity and surface figure errors. Compared with one-dimensional (1D) tolerance parameters, knowing only the peak or RMS of two-dimensional (2D) tolerances is insufficient. However, knowing the shapes of 2D distribution of index inhomogeneity and surface figure error is necessary. We use interferograms in terms of Zernike circle polynomials to model the shape distribution of index inhomogeneity and surface figure error exhibiting low spatial frequency [3]. We can use a 2D tolerance generator to generate an artificial set of interferograms in accurately modeling 2D tolerances, but this topic is beyond the scope of this paper. Interferograms of material inhomogeneity from material suppliers and interferograms of surface figure errors from lens fabricators can also be used.

Commercial optical design software such as CodeV and Zemax applies singular value decomposition algorithm to determine the most effective alignment compensators and uses an alignment optimization feature to determine the magnitude and direction of allowed system adjustments (compensators) to recover as much nominal system performance as possible [4]. This process is called computer-aided assembly adjustment, which is very effective in compensating for almost all 1D tolerances but not 2D tolerances. Commercial optical design software has poor capability in determining the optimum rotation angles of lens elements and predicting imaging performance. In the 1980s, PerkinElmer Corporation performed clocking optimization by manually rotating various combinations of elements about the optical axis [5]. In 2000s, Canon and Nikon corporations performed clocking optimization with their own in-house software [6,7]. In the current paper, we propose a method of clocking optimization using a combination of particle swarm optimization (PSO) and commercial optical design software. Using this method enables the automatic calculation of the optimum rotation angles and predicts imaging performance.

2. Clocking Optimization

A series of stages of image performance compensation is used in manufacturing lithographic lens, such as spacer recomputation, clocking optimization, computer-aided assembly adjustment, fine-surface figuring, and real-time adjustment using a deformable mirror.

Spacer recomputation attempts to compensate for 1D fabrication tolerances such as radius, thickness, and index of lens elements. The optimum spacer thickness can be easily calculated through a damped least-squares optimization algorithm widely used in commercial optical design software. Clocking optimization attempts to compensate for 2D fabrication tolerances, such as low spatial frequency of material inhomogeneity and surface figure error. In this paper, we focus on the 2D tolerance of the material inhomogeneity error.

For a mathematical set of expressions, the figure of merit associated with the lens performances is denoted by M, and the number of lens elements is denoted by N. $\theta_1, \theta_2, \ldots \theta_N$ are the rotation angles for each lens element, and N interferometric material inhomogeneity errors are denoted by $s_1, s_2, \ldots s_N$. If interferometric material inhomogeneity errors associated with the rotation angle are denoted by $s_1(\theta_1), s_2(\theta_2), \ldots s_N(\theta_N)$, an expression for the merit function can be written as Eq. (1):

$$M = f[s_1(\theta_1), s_2(\theta_2), ..s_N(\theta_N)]. \quad (1)$$

where f is the relationship between the figure of merit and lens rotation angles. Clocking optimization aims to find an optimum set of rotation angles of the lens elements with the best lens performance. However, getting an analytical expression for the merit function is impossible, which makes clocking optimization similar to the black-box optimization problem. Thus, the damped least-squares optimization algorithm used in commercial optical

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design software does not work well in clocking optimization. No sophisticated and automatic clocking optimization algorithms have been reported. In this paper, we propose to use the PSO algorithm to automatically calculate the optimum rotation angles of lens elements.

2.1 Particle swarm optimization (PSO)

PSO is originally attributed to Kennedy, Eberhart, and Shi [8] and was first intended for simulating social behavior as a stylized representation of the movement of organisms in a bird flock or fish school. Compared with traditional nonlinear optimization algorithm such as damped least-squares optimization, PSO does not use a problem's gradient; thus, PSO can be used in optimization problems that are partially irregular, noisy, changing over time, etc.

PSO optimizes the problem of clocking optimization by having a population of candidate solutions (dubbed here as particles) and moving these particles around in the search-space according to simple mathematical formulae over the position and velocity of a particle. The movement of each particle is influenced by its best known local position and is guided toward the best known positions in the search space, which is updated when better positions are found by other particles. Thus, the swarm is expected to move toward the best solutions.

2.2 Two methods of clocking optimization

We compared two different methods of clocking optimization in this study. Optimum rotation angles of lens are obtained using a complete trial-and-error method that we call "manual clocking optimization (MCO)." Optimum rotation angles of lens are also obtained using PSO, which we call "automatic clocking optimization (ACO)." Figure 1 shows the traditional MCO. Figure 2 shows the flow chart of the proposed ACO, wherein an outer loop is added for automatic adjustment of clocking angles through PSO.

MCO is implemented through the CodeV and custom macros. The steps in MCO are described below:

Step 1: The as-built imaging performance is determined and evaluated based on specifications. For lithographic lens, the two most important metrics are wavefront error and centroid-based distortion.

Step 2: The lens is loaded and the interferograms of material inhomogeneity error from material suppliers or the inhomogeneity error generator is attached.

Step 3: All lens elements (interferograms are actually rotated) with random clocking angles and the imaging performance are evaluated. Results are recorded and the process cycle is repeated through the macro. The exit condition is checked after each cycle.

Step 4: The optimum rotation angles are obtained according to the best as-built imaging performances.

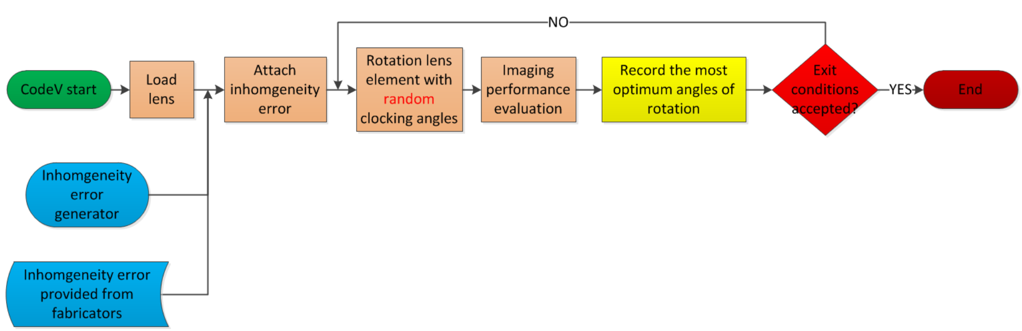

Fig. 1. Flow chart of manual clocking optimization.

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From the process description, the MCO is semi-automatically implemented using macros; thus, the MCO is actually a semi-automatic method for clocking optimization. The use of CodeV is essential in manual MCO for create samples of lens with random clocking angles and then manually finding the best solution from the samples.

ACO is implemented with Matlab and CodeV. Matlab with PSO toolbox (PSOt) is developed by Brian Birge. The Windows COM standard interface allows CodeV to be run in Matlab. We demonstrate automatic ACO capability on the Matlab implementation. The steps in ACO are described below:

Step 1: Matlab and PSOt are initialized, and the merit function and variable dimensions of the problem are defined. A single value of the merit function is calculated based on imaging performance such as RMS wavefront error and centroid-based distortion, and the variable dimension is equal to the number of clocking lens elements.

Step 2: The PSOt sets a number of particles that fly through the hyperspace of the problem. Each particle represents a candidate solution for clocking optimization. After each cycle of optimization, the position of a particle is updated both by the previous best position of the particle and the best overall position of the entire group. The updated particle representing a new set of clocking angles is automatically passed to CodeV.

Step 3: CodeV is commanded using the COM interface. The lens is loaded and the interferograms of material inhomogeneity error from material suppliers or the inhomogeneity error generator are attached.

Step 4: CodeV is commanded to rotate the lens elements with certain clocking angles provided from the PSOt, and the merit function is calculated based on the imaging performance evaluation. The merit function value is returned to the PSO.

Step 5: PSO records the relationship between clocking angels and merit function values that are returned from CodeV. The best position of the particle and the best overall position of the entire group are updated. A new set of clocking angles is updated according to the PSO algorithm and automatically passed to CodeV.

Step 6: Steps 4 and 5 are repeated cycle by cycle. The exit condition is checked after each cycle.

Step 7: The optimum rotation angles of lens elements are automatically listed at the end of the Matlab implementation.

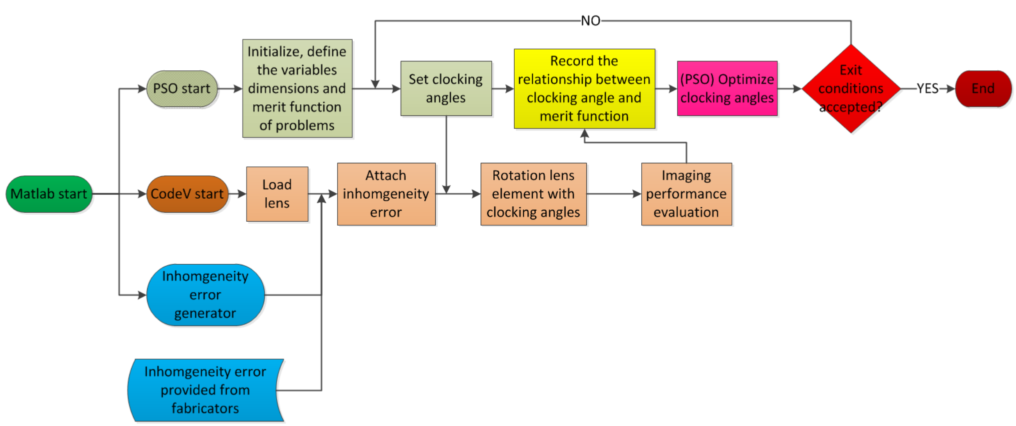

Fig. 2. Flow chart of automatic clocking optimization.

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From the process description, defining the clocking angles and imaging performances as inputs and output is essential. CodeV is used to calculate the relationship between inputs and output, and then the PSO algorithm is used to automatically find the best solution.

3. Examples of clocking optimization

In this section, a lithographic lens with material inhomogeneity errors is used to demonstrate the effectiveness of ACO method. Figure 3 shows the starting point of the lithographic lens with 20 interferometric material inhomogeneity errors.

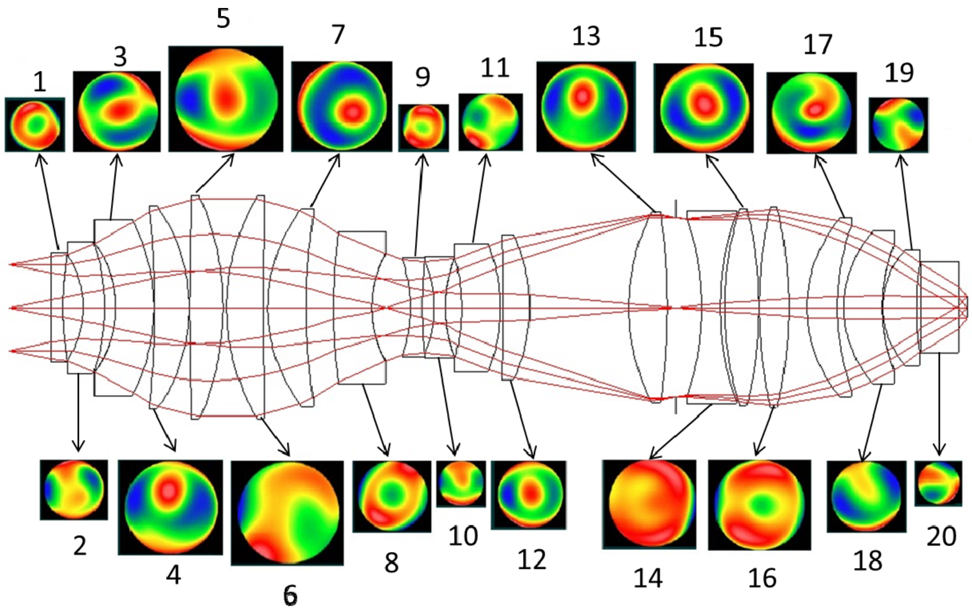

Fig. 3. Layout of lithographic lens with interferometric material inhomogeneity errors.

The lithographic lens is a patented lens with 20 lens elements [9]. The numbers in Fig. 3 represent the order of the element in the lithographic lens. The main specifications of this patented lithographic lens are shown in Table 1.

Table 1. Specifications of the lithographic lens

Parameter	Specifications
Central wavelength of spectral band	193.368 nm
Numerical aperture (NA)	0.75
Field of image	26 mm × 8 mm
Magnification	0.25
Resolution	<100 nm
Wavefront error (nominal design)	<0.8 nm RMS
Distortion (nominal design)	<1.0 nm PV
Number of lens elements	20

It should be noted that all the lens elements in the lithographic lens should be rotated because the rectangular shape of image field.

Interferometric material inhomogeneity errors are obtained from the material supplier. The shapes of distribution of material index inhomogeneity of the elements are shown in Fig. 3, and the magnitudes of the index inhomogeneity, sizes of diameter, and center thickness of 20 lens elements are given in the Table 2.

#192472 - $15.00 USD Received 18 Jun 2013; revised 26 Aug 2013; accepted 27 Aug 2013; published 12 Sep 2013

Table 2. Index inhomogeneity and dimension sizes for each lens element

Element number	Diameter (mm)	Center thickness (mm)	Inhomogeneity[a] (nm RMS)
1	138.01	15.00	0.55
2	166.69	27.38	0.41
3	223.62	50.00	1.08
4	258.53	44.91	1.44
5	283.44	43.09	0.80
6	283.10	47.58	1.51
7	251.23	50.00	1.22
8	192.84	50.00	0.82
9	123.79	15.00	0.46
10	127.35	15.00	0.46
11	161.57	50.00	0.48
12	182.92	35.00	0.86
13	242.83	50.00	2.17
14	244.58	24.11	1.50
15	250.01	44.38	2.74
16	254.88	38.17	1.15
17	227.40	39.24	1.22
18	194.19	50.00	0.98
19	146.43	43.61	0.52
20	114.47	50.00	0.23

[a]Tilt and power are removed.

It is worth noting that adding such two-dimensional interferometric inhomogeneity errors in a lens model just provides an approximate way to calculate the performance of the actual lens with three-dimensional inhomogeneity errors.

Before clocking optimization, we define a simple calculation method for the single merit function value according to our previous experiences as Eq. (2):

$$M = \sqrt{a \bullet W^2 + b \bullet D^2}. \tag{2}$$

W and D are the worst wavefront error and distortion, respectively, across the image field and are expressed in nanometers, and a and b are the imaging performance weights for the wavefront error and distortion, respectively. A balanced imaging performance between the wavefront error and distortion can be obtained by adjusting the values of a and b. For instance, we set $a = 1$ and $b = 0.25$ in this paper.

Rotation angles are the optimum using MCO and ACO. MCO is implemented through our custom macro in CodeV, whereas ACO is implemented through Matlab and CodeV. The most critical control parameter in the ACO is the population size of particles, and we set the population size equal to 20 just according to our previous experiences. Both clocking optimization methods have 20 variables expressed in degree angles, and each input variable is from −180° to 180°. Convergences of merit function value obtained using the clocking optimization methods are plotted in Fig. 4.

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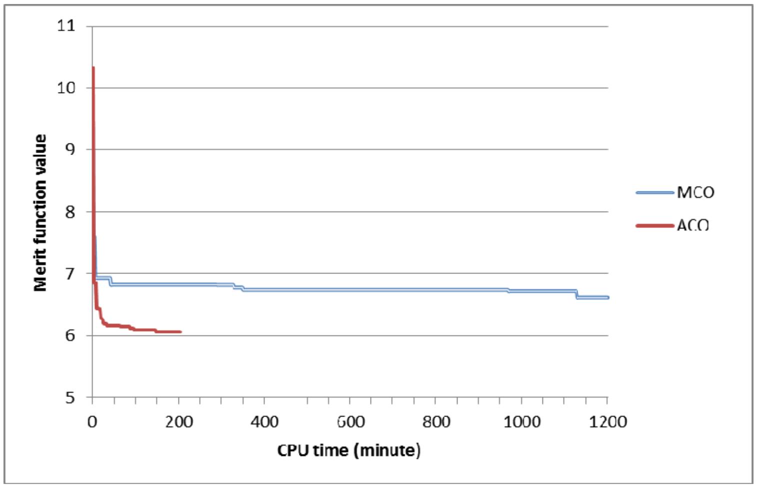

Fig. 4. MCO vs. ACO convergence for lithographic lens with NA = 0.75.

The merit function value of MCO converges to 6.61 with a CPU time of 1200 min on a 2.8 GHz CPU. The optimum results for MCO are actually selected from the ten thousands of lens samples with all lens elements rotated in random clocking angles. The merit function value of ACO converges to 6.06 with a CPU time of only 201 min on a 2.8 GHz CPU. Compared with MCO, ACO obtains a better solution with a smaller wavefront error and distortion across the image field. The details of the optimum results for the two clocking optimization methods are shown in Table 3.

Table 3. Comparison between the optimum results of the two clocking optimization methods

Element number	Angles of element rotation (in degrees)		
	Before clocking optimization	After manual clocking optimization	After automatic clocking optimization
1	0.0	−26.7	9.6
2	0.0	−79.8	6.7
3	0.0	−104.7	18.6
4	0.0	113.5	70.8
5	0.0	−131.4	72.2
6	0.0	−146.7	180.0
7	0.0	−147.9	−2.7
8	0.0	58.8	−98.9
9	0.0	110.9	172.2
10	0.0	−31.0	12.0
11	0.0	−13.6	3.4
12	0.0	−176.0	−180.0
13	0.0	−4.8	54.0
14	0.0	−156.4	180.0
15	0.0	−130.5	−75.5
16	0.0	154.6	−92.2
17	0.0	−57.4	−124.5
18	0.0	178.9	−13.1
19	0.0	32.6	−81.7
20	0.0	11.3	−135.0
Worst wavefront error across the image field (nm RMS)	7.97	5.52	5.25
Worst distortion across the image field (nm PV)	13.12	7.28	6.05
Value of merit function	10.32	6.61	6.06
CPU time (min)	/	1200	201

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4. Conclusion

We perform simulations for ACO and compare the results with those of MCO for compensating material index inhomogeneity in lithographic lens. Results show the advantages of ACO in terms of convergence speed and efficiency. ACO is implemented using a combination of PSO in Matlab and CodeV. This method contributes to the reduction of inadequacies of traditional optimization algorithm for compensating 2D tolerances such as surface figure error and material birefringence. The method can also be extended to complementary optimization tools in lens design software. Beside the PSO, other optimization algorithms that do not make use of derivatives of the merit function, i.e., downhill simplex, simulated annealing, genetic algorithms and so forth [10], all have the potentials to solve the problem of automatic clocking optimization.

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