A study on the optomechanical tolerance model for lens assembly

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ABSTRACT

Optomechanics is defined as the science or engineering of maintaining the proper shapes and positions of the functional elements in an optical system. At the optomechanical interface, manufacturing tolerances affect the shape and position of the surface in a lens system. Even very small variations will cause extra aberrations which degrade the optical performance of a lens system. The traditional approach to the optomechanical tolerance design is a top-down process. The optical designers typically designate the critical to quality parameters, such as tolerances of tilts, decenters, and locations of optical elements. A significant drawback of this top-down process is that the tolerances determined by optical designers do not take the real manufacturing and assembly process into consideration. As a result, some tolerances are too tight for the manufacturing, and the yield rate of the production is difficult to improve. The objective of this study is to develop a surface based optomechanical tolerance model that calculates the variation of the critical to quality parameters for a lens system. The distribution of these parameters can be treated as inputs to the optical design. Therefore, the optical performance will be predictable than the top-down approach, and the manufacturability of the optical system can be improved.

Keywords: Optomechanics, tolerance, assembly, lens system

1. INTRODUCTION

The lens is a typical optical system. In general, optomechanical design plays as important role as optical design does in the optical system design. Optomechanics is defined as the science or engineering of maintaining the proper shapes and positions of the functional elements in an optical system. At the optomechanical interface, manufacturing tolerances affect the shape and position of the surface in a lens system. Even very small shape or position variations will cause extra aberrations which degrade the optical performance of a lens system dramatically. As a result, tolerance is a critical design issue in the optomechanical design of a lens system.

1.1 Literature Review

Variation is a physical result of manufacturing process. Parts and assemblies always differ from each other and from what we want them to be. Tolerance refers to the amount of variation that designers can tolerate in a part or assembly. Tolerance analysis plays an important role in reducing variation in the manufacturing process so as to improve the quality, cost, and the deliver time. For an optical system, the variation will lead to certain image quality degradation that will be a serious problem. Hilbert stated that the objective of the optical tolerancing is to determine the combination of dimensional ranges for optical elements, and their relative position in assemblies. It will minimize manufacturing costs when satisfying performance requirements[1]. Drake realized the drawback of traditional top-down optomechanical design process and developed a new bottom-up approach to automate the design process of optical system. The software program with Monte Carlo analysis integrates design parameters, constraints, mechanical dimensions, process capabilities, and manufacturing requirements to predict the performance of optomechanical design[2]. Sasaki had developed a statistical tolerancing system that enables the quantitative analysis of the optical performance, productivity, and sensitivity analysis prior to manufacturing[3]. Magrill chose twelve primary parameters to simulate the variations of lens mounting assembly caused by manufacturing errors[4]. Lee had studied the factors which affect surface tilt and

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decentration during the mounting cell. Some useful formulas which provide the tilt and decenter of optical components in mounting cell were summarized[5]. Thompson had developed a theory to represent fabricated optical components by a set of simple local coordinate systems linked by physically relevant stationary pivot points. The properties of optical elements, mechanical spacers, and the techniques for their characterization are developed[6]. De Witt IV had presented a means of characterizing the rigid body motions of optical element from their nominal positions as caused by manufacturing tolerances and thermal effects. Several cases of element tilt or decenter effect caused by mechanical mounting components were discussed[7]. However, the details of the toleancing system still remain ambiguous. A surface based tolerance model is necessary to calculate the stack-up variations of the optomechanical critical to quality parameters.

1.2 Objective and study method

The performance of a lens system is greatly influenced by the tolerances of the optical and mechanical components. Currently the tolerance requirement of a lens system is determined by optical designer. The real manufacturing process capability and the variation occur in assembly process are not considered. That makes some of the lens development project is found difficult to improve the yield rate before or during mass production. In the real world, the resultant positional variation of the optical component is determined by the tolerance stack-up of the optical component itself and the mechanical components used to mount the optical element. The dimensional and geometric variations of the optical and mechanical component are determined by the capability of the manufacturing processes. If the optical performance is analyzed by the resultant tolerances that are derived from the actual optomechanical stack-up, it is reasonable for engineers to predict the mass production yield rate of a lens system. Then, the design can be modified or improved to meet the requirements for mass production. The cost and delivery of a development project can be minimized, and the quality will fit for use. This is the concept of “Design for Manufacturing” (DFM).

The objective of this study is to develop an optomechanical tolerance model that calculates the variation of the critical to quality parameters for a lens system, such as the lens element tilt, decenter and despace within a cell. The distribution of these parameters can be an input to the optical design. Therefore, the optical performance will be predictable than the top-down approach, and the manufacturability of the optical system will be improved. The optomechanical tolerance model is implemented by VSA-3D®[8] software. First, all the optical and mechanical components is represented as the point geometry that is derived from the engineering specifications of the component, and from some geometric calculation and vector operation. Second, the tolerances are assigned to the corresponding location points of each component. Third, the system is assembled by defining the stationary points and the rolling limit conditions. Parameters which are critical to the quality such as the stack-up element tilt, decenter and despace within a cell are defined as the output.

2. TOLERANCE ANALYSIS

Tolerance analysis and tolerance allocation are the central issues of tolerance design. The difference between these two problems is illustrated in Figure 1. In tolerance analysis, the component tolerances are all known or specified and the resulting assembly tolerance is calculated. In tolerance allocation, on the other hand, the assembly tolerance is known from design requirements, while the component tolerances are unknown.
Measurement and data collection is necessary for applying tolerance analysis to calculate the variation (or distribution) of the target dimension. In general, it is difficult to modify the design to improve a product’s performance by looking at the raw data collected from manufacturing process. The data must be organized into a useful form for building knowledge and for drawing conclusions that carry out the product or process performance improvement.
Statistics is the fundamental knowledge for engineer to properly gather and process sample data in tolerance analysis. These data will come directly from the manufacturing process, from an experiment on a product, or from the random number generator. Data that are a sample from a population can be mathematically processed into descriptive values called “sample statistics”. Data that comprise an entire population can be mathematically processed into descriptive values called “population statistics”. Some population statistics can never be quantified because they are large amount and uncountable, or they are in process, so that it is not possible to gather the entire data set. For example, if the manufacturing process data come out from a production line, it is only possible to manage sample data from populations.

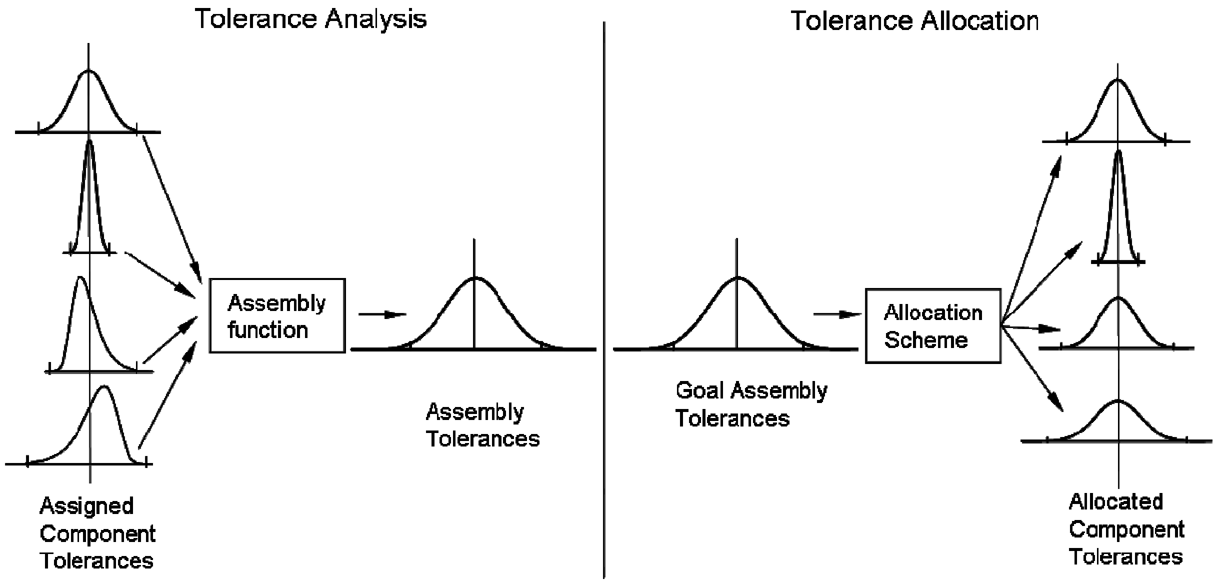


Fig.1 Comparison of tolerance analysis and tolerance allocation

3. VARIATIONS IN LENS SYSTEM

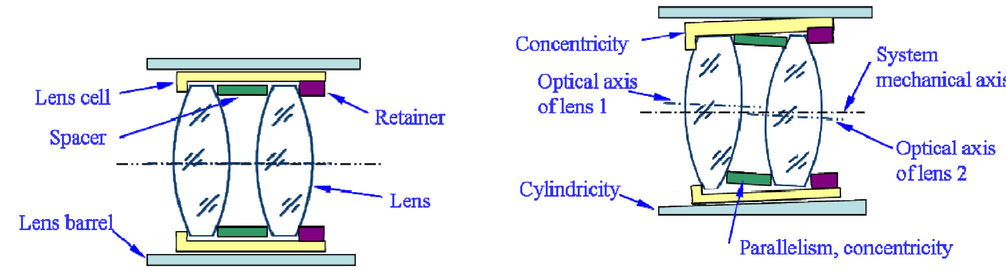
3.1 Variations in Lens Element

ISO 10110 Standard[9] had defined the specification in drawing of the characteristics, especially the tolerances, of optical elements and system. First, there are the purely optical specifications which are primarily materials related. Second, there are optomechanical specifications such as surface form, radius, thickness, and centering. Third, there are surface texture and surface imperfections specifications. Finally, there are surface treatment and coating specifications. The optomechanical specifications are the items that will cause lenses positions errors in an assembly.

3.2 Variations in Lens Assembly

A typical lens mounting assembly is illustrated in Figure 2. Lens element is mounted inside the lens cell and rest on the shoulder of cell. Lens elements are separated by a carefully machined spacer to obtain the required air space between surface vertices. Then a retainer is inserted into the cell to hold the lenses. The optical designer assumes that individual lenses are centered on the imaginary straight line which coincides with the axis of cell and lens barrel as shown in Figure 2(a). However there are several places where variations may occur. The major assembly variation sources consist of lens-to-cell clearances, cell-to-barrel clearances, concentricity between the ID and OD of the cell, the cylindricity of the inside bore of lens barrel, and the geometrical accuracy of the spacer as shown in Figure 2(b). The mechanical engineer must control the tolerances stack-up attributed to the individual component variations to meet the requirements specified in optical design. The mechanical engineer must also provide the resultant tolerance stack-up distribution information to optical designer.

Manufacturing and assembly variations that make one or more surface centers move away from the optical axis will cause extra aberrations. It is the reasons for optical performance degradation. There are many factors causing variations. The resultant position variations of optical elements can be classified as element tilt, decenter and despace. These are the major critical to quality parameters which will be modeled and simulated in this study.



(a) Idea case of lens assembly (b) Components and assembly variation in real world

Fig. 2 Lens mounted in barrel

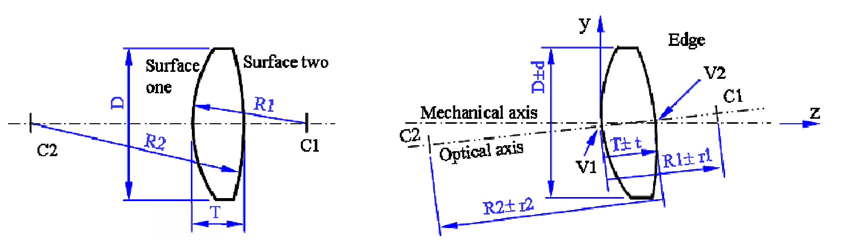
4. OPTOMECHANICAL TOLERANCE MODEL

4.1 Tolerance modeling

Tolerances on linear and angular dimensions are assumed to be in normal distribution, and the tolerance spans a 3 sigmas range distribution with its mean value at the midpoint of the range. The GD&T symbols can be modeled by two basic types of the tolerance zone. They are perpendicular tolerance zone and circular tolerance zone. In a perpendicular tolerance zone the position of points are varied along a direction normal to the feature surface within a specified total width zone. In a circular tolerance zone the position of points are varied radially on the feature surface within a specified total diameter zone.

4.2 Tolerance model on lens element

The surface tilt variation of a lens element is caused in the edging process, it is appropriate to simulate the surface tilt tolerance of a biconvex lens by varying the vertex of a surface. Circular tolerance zones are created at the vertexes. Figure 3(a) illustrates an ideal centered biconvex lens. The optomechanical tolerance model of the lens is shown in Figure 3(b). Similar method can be applied to meniscus convex lens, biconcave lens and meniscus concave lens. For an aspheric surface, determining the local center of curvature is necessary.



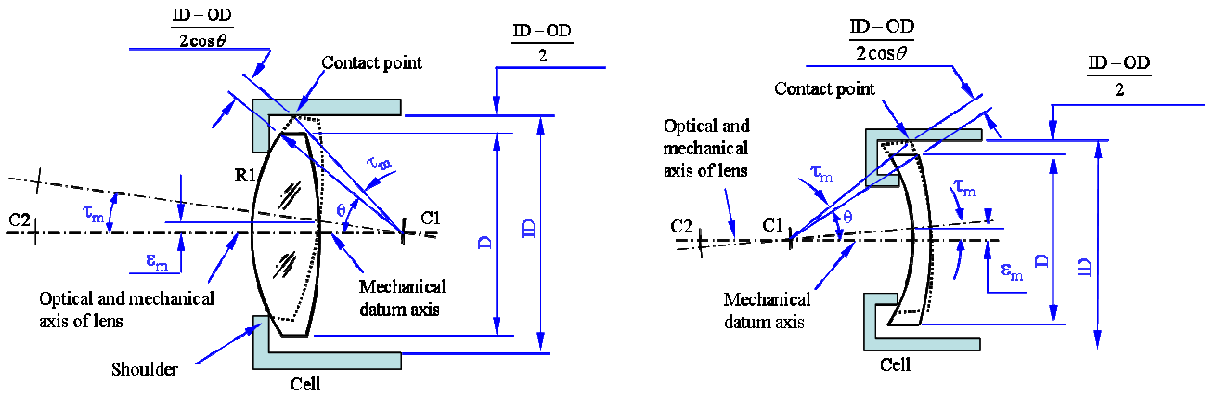
(a) Idea centered lens (b) Lens with dimensional tolerances and surface tilt

Fig. 3 Tolerance model of a convex lens

4.3 Assembly variations in lens assembly

Rolling center in assembly

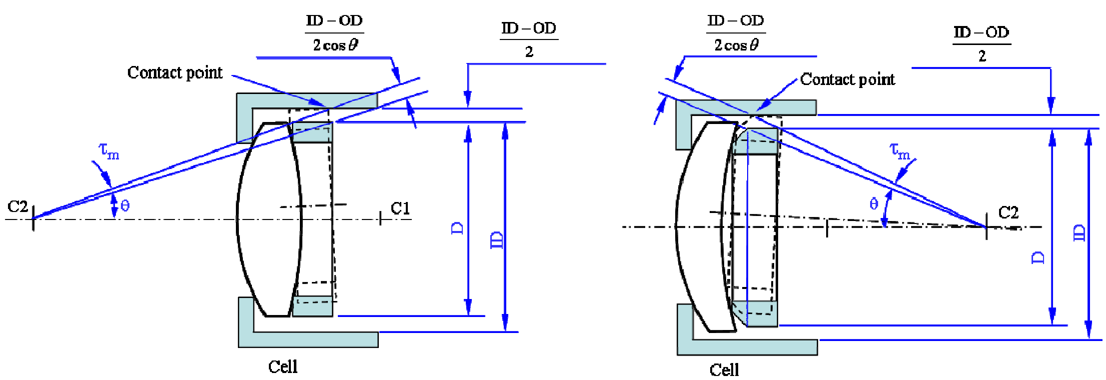
For a “drop-in” assembly, the real position of optical elements and mechanical elements within a cell are random. The determination of element tilt and decenter due to assembly variation is described as following. In Figure 4(a) a typical centered bi-convex lens is mounted on the shoulder of an ideal cell perfectly. The optical and mechanical axis of the bi-convex lens coincides with the axis of the bore of cell. The dotted line depicts the lens in a maximum tilted condition due to the assembly variation. The motion of lens caused by assembly variation seems that the element rolls on its surface again the shoulder of cell. The center of curvature of surface one C1 is also the rolling center of lens element. That is the only point belongs to the coordinate system of the lens remains stationary in the coordinate system of the cell despite how much tilt the lens is. As a result, the resultant element tilt τ_m and element decenter ε_m of the lens can be calculated. In the same way, a lens with concave front surface mounted on the shoulder of a cell is shown in Figure 4(b). The center of curvature of the concave surface is the rolling center of the lens and is a stationary point belongs to lens when assembly variation occurs.



(a) Rolling center of convex surface on cell shoulder (b) Rolling center of concave surface on cell shoulder

Fig. 4 Rolling center of optical surface on cell shoulder

In "drop-in" assembly design, spacer is usually loaded between two lenses to have the designed air space. The determination of the position of the spacer in a lens assembly system is straightforward. In Figure 5(a), a typical spacer is attached to a biconvex lens within a cell. The dotted line depicts the spacer in maximum element tilted situation due to the assembly variation. The motion of the spacer caused by assembly variation is that the spacer rolls on the surface which it attaches on. The center of curvature of surface 2 of the lens is the rolling center of the spacer. Again, this is the only point belongs to the coordinate system of the spacer retains stationary in the coordinate system of the lens or cell despite how much element tilt the spacer is. Similarly, the assembly variation of a spacer which is attached to a concave surface of a lens in a cell is shown in Figure 5(b).



(a) Rolling center of spacer on convex surface (b) Rolling center of spacer on concave surface

Fig. 5 Rolling center of spacer on lens surface

The lens loaded in the assembly after the spacer can be considered as mounting a lens on the shoulder of the spacer. This is the same situation as a lens mounted on the shoulder of the cell. As a result, the rolling center of each component in a cell can be determined. The rolling center will be the target point in the assembly simulation when moving the coordinate system of a object component to the coordinate system of the target component.

Rolling limit in assembly

In Figure 4 and Figure 5, the maximum rolling angle of the rolling component is limited by the contact point. Contact point is the intersection point of the bore boundary on the cell and the rolling arc on the lens or spacer as illustrated in Figure 6. Rolling arc is usually found at the rim of rolling component and is the farthest point away from the rolling center. The maximum rolling distance away from the axis of the bore approximately equals to $(ID-OD)/2\cos\theta$. In other words, the position variation of the lens surface center in the cell is a circular variation zone with radius $(ID-OD)/2\cos\theta$. In case of spacer, the position variation can take account of the variation of the chord of the arc. The radius of the circular variation zone at the chord center is $(ID-OD)/2$. By creating a circular tolerance zone at the corresponding point in cell, the position of components which is randomly located within the cell can be simulated.

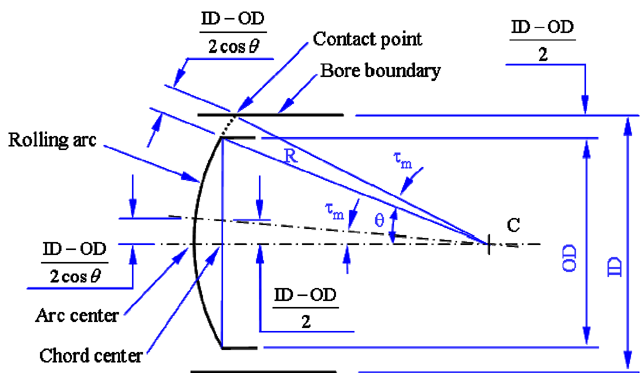


Fig. 6 Components rolling limit within cell

4.4 Tolerance model of mechanical components

The mechanical components in a lens assembly are spacers, retainers, cells, and lens barrels. The dimensional and geometrical tolerances are simulated by the general mechanical tolerance simulation techniques. In addition, some virtual points must be added into the tolerance model according to the dimensions and tolerances of the optical elements which are attached to the mechanical components. For instance, the optomechanical tolerance model of the cell in Figure 4(a) is shown in Figure 7. The first virtual point C is the stationary rolling center for the attached optical element. The position of point C is determined by the dimensions and tolerances of the attached optical element and cell itself. The second virtual point U is the radial variation center of the attached optical element. Point U is located on the bore axis of the cell and is at a distance R1 from point C. A circular tolerance zone parallel to x-y plane with radius $(ID-OD)/2\cos\theta$ is created on point U as the locating point of the attached optical element. During the execution of Monte Carlo simulation, all the dimensions are generated randomly according to the specifications of tolerances; the position of point C or point U of each observation is different in the sample.

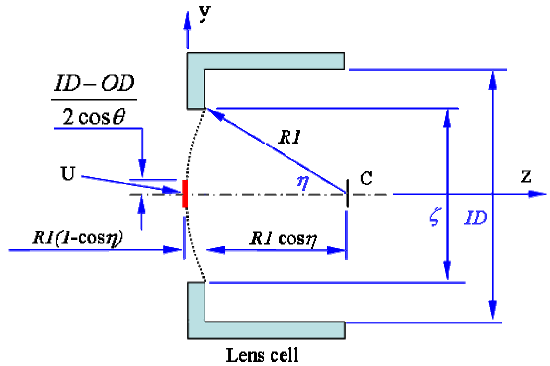


Fig. 7 Tolerance model of cell

In the same way, the virtual point of stationary rolling center is necessary to add into the mechanical tolerance model of spacers. Figure 8(a) shows the mechanical tolerance model of the spacer in Figure 5(a). It is assumed that the optical element attached on the right side of the spacer is a convex surface. Point C2 is the stationary point in the coordinate frame of the space when it is assembled within a cell. The position of point C2 is determined by the dimensions of the spacer and the lens that the spacer is attached on. Point C1 is the rolling center for the lens attached to the right side of the spacer. The position of point C1 is determined by the dimensions of the spacer itself and of the lens which is attached on the spacer. The tolerance model of spacer in Figure 5(b) is shown in Figure 8(b). It is also assumed that the optical element attached on the right side of the spacer is a convex surface.

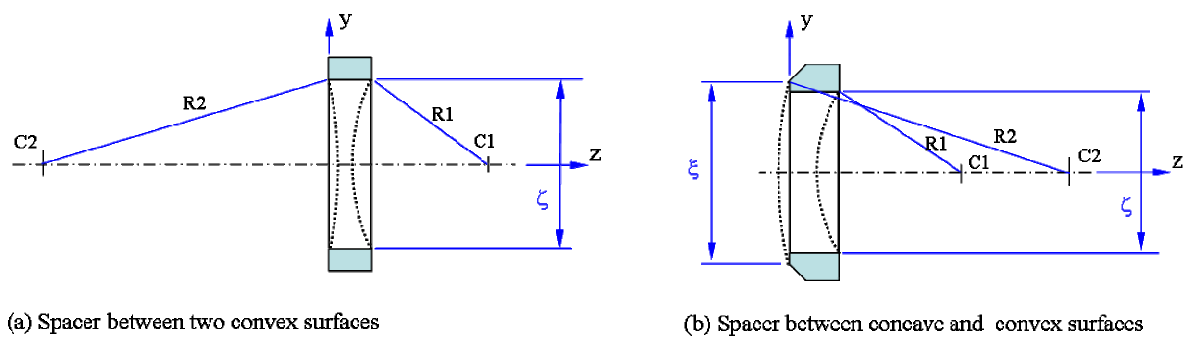


Fig. 8 Tolerance model of spacers

4.5 Assembly model

The assembly model is the method to position and orient parts in space with respect to each other. The mathematical models of assemblies make use of the matrix transformation[10]. An assembly is a chain of coordinate frames on parts designed to achieve certain dimensional relationship, the critical to quality parameters, between some of the components or between features on these parts. Figure 4(a) is the assembly of the lens in Figure 3(a) and the cell in Figure 6. The frame relationship can be defined by the following procedures. First, move the frame of the lens and let the center of curvature C1 of the lens coincides with the virtual point C of the cell. Then, align point M of the lens with point U of the cell. As a result, the frame of lens is constrained with respect to the frame of cell. Similar procedure can be applied to the assembly of spacer and the lens which attaches to the spacer.

5. CONCLUSIONS

The element tilt, decenter and desapce of a lens within a cell are the critical to quality optomechanical parameters of a lens system. In this study, an optomechanical tolerance model for lens assembly has been developed and implemented by VSA-3D® software to simulate the distribution of these parameters by Monte Carol method. The model integrates the tolerances of optical elements, the tolerances of mechanical component, and the variations of the assembly process. The model is represented as point geometry. Because the point geometry of the optical surfaces is derived by the mathematical equation of the surfaces and the dimensions of mechanical component that attached to it, a surface based optomechanical tolerance model is obtained. The outputs of the model are the statistical information about the element tilt, decenter and desapce of a lens or the resultant error of the optical axis of a lens within a cell. With this tolerance model the performance of an optomechanical system can be anticipated. The analysis results also can be an input to optical design software. As a result, a "Design for Manufacturing" optical system can be accomplished.

REFERENCES

1. R. S. Hilbert, , "Semi-automatic modulation transfer function (MTF) tolerancing", Optical System Engineering, SPIE Vol. 193, pp. 34-43, San Diego, 1979.
2. P. Drake, "Auto-tolerancing on optical system", Lens Design, Illumination, and Optomechanical Modeling, SPIE Vol. 3130, pp. 136-147, San Diego, 1997.
3. T. Sasaki, M. Shinkai, K. Higashiyama, F. Tanaka, and T. Kishinami., "Development of Statistical Tolerancing System for Optical Product. – Virtual PT System and Mass Product Simulation", International Optical Design Conference, SPIE Vol. 3482, pp. 528-537, Kona,1998.
4. S. Magarill, "Optomechanical sensitivity and tolerancing", Optomechanical Engineering and Vibration Control, SPIE Vol. 3786, pp. 220-228, Denver, 1999.
5. K. J. Lee, Y. Yoon, and J. Maxwell, "Creative Optomechanical Tolerancing in Lens System", International Optical Design Conference, SPIE Vol. 3482, pp. 187-220, Kona, 1998.
6. K. P. Thompson, "Techniques for characterizing optical system fabrication", Selected Papers on Optomechanical design, SPIE Vol. 770, Ed. O'Shea D. C., pp. 89-95, 1987.
7. F. De Witt IV, G. Nadorff, "Rigid Body Movements of Optical Elements due to Opto-Mechanical Factors", Optical Modeling and Performance Predictions II, Proc. Of SPIE Vol. 5867, Ed. Kahan, 2005.
8. VSA-3D® software, Variation Systems Analysis Inc., St. Clair Shores, MI, USA, 2000.
9. ISO 10110, "Optics and optical instruments preparations of drawing for optical elements and system", 1996.
10. D. E. Whitney, *Mechanical Assemblies*, Oxford University Press, New York, 2004.