Integrated opto-mechanical tolerance analysis

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ABSTRACT

Optical tolerance analysis is a very important step in optical systems development. It ensures that appropriate optical performances will be achieved considering all the manufacturing errors involved in the assembly. To perform an accurate tolerance analysis, a realistic optomechanical tolerance model and appropriate perturbations simulation are required in the optical design code. Most of the time, optomechanical lens mounting is not taken into account accurately in classical optical tolerancing method. To improve optical system tolerancing process, an integrated opto-mechanical tolerance analysis is proposed. This paper first describes typical tolerancing process and iteration performed between optical designers and optomechanical engineers in the development of optical systems. Then, the optomechanical tolerance analysis that involves interactions between lenses and mounts, as well as manufacturing errors is presented. Simulation methods to consolidate optical and optomechanical tolerance analysis are discussed. Finally, an integrated opto-mechanical tolerance analysis is described, and a new optomechanical tolerancing software is introduced. The intent of this new modeling method is to perform accurate optical simulations that are representative of the optomechanical mounting and centering methods. This result in a more efficient allocation of the tolerances and a more accurate prediction of the optical system performances.

Keywords: Tolerance analysis, tolerancing, simulation, integrated model, error budget, lens mounting, optomechanics, centering, alignment, optical design

1. INTRODUCTION

Performance, manufacturability, and cost are most often the key requirements to be conciliated in the development of optical systems. Unfortunately, a perfect optical system cannot be built due to limitations of fabrication and alignment methods. These errors tend to degrade the expected optical performances as predicted by the optical design code through simulations performed on the nominal optical layout. To create an appropriate tolerance budget, i.e., the allocation of the manufacturing uncertainties on each of the optical component and mechanical part, a realistic optomechanical tolerance model is required. To do so, a thorough understanding of the interactions between lenses and mounts is mandatory. The lens geometry, the mounting interface, and the centering method must be considered to define the appropriate simulation methods in the optical design code. This very important task is often neglected due to the complexity and misunderstanding of the optomechanical theory of interactions between lenses and mounts. Therefore, the default tolerancing parameters on optical design software, that do not consider real optomechanical design behaviors, are most of the time used. As a result, unrealistic mounting and alignment cases are simulated. Thus, there is a need for an integrated model where the optomechanical tolerance analysis is linked with the optical model. In the proposed tolerance analysis, the optical layout from the optical design software is imported in the optomechanical tolerance analysis software. Mounting type, centering method, and manufacturing tolerance are defined. According to these optomechanical tolerance analysis inputs, the software computes the perturbations to be applied in the optical design software. This allows to simulate a more realistic optomechanical design, providing an accurate tolerancing model.

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2. CLASSICAL OPTICAL TOLERANCING PROCESS

Even with the modern available level of manufacturing sophistication, optical and optomechanical components always have dimensional and geometric errors. These errors tend to degrade the expected optical performances as predicted by the optical design code through simulations performed on the nominal optical layout. Considering this, an important task for the optical designers is to perform a comprehensive tolerance analysis in order to determine the level of precision required for the manufacturing of the optical elements, and for the positioning of those elements in the layout. Collaboration between optical designers and optomechanical engineers is required at this stage since a complete tolerance analysis involves both optical and optomechanical tolerances analyses. This process requires iterations between the two disciplines and the goal is to create a realistic tolerance budget, i.e., the allocation of the manufacturing uncertainties on each of the optical component and mechanical part. This step of the design process is very important because the results of the tolerance analysis directly impact the optical system cost and complexity in terms of manufacturing tolerance and alignment [1]. In typical tolerancing process, optical designers use simulation software to evaluate the acceptable manufacturing and positioning error on each optical component while meeting the optical performance requirements. These positioning error requirements are often specified in tables containing allowable decenter, tilt, and axial location of the optical components. In traditional approach, these positioning requirements are then transferred to the optomechanical designer as design inputs and for the mechanical tolerance budget allocation. This process is summarized on Figure 1 from Drake [2].

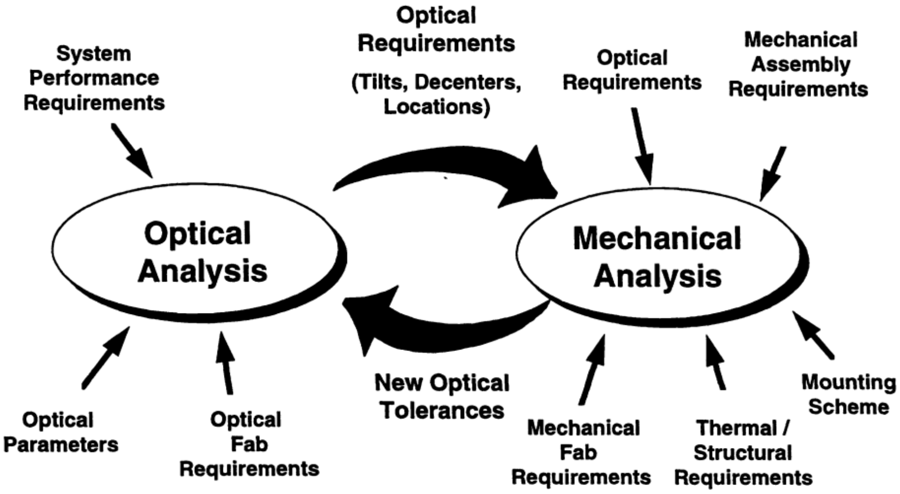

Figure 1. Traditional optical systems tolerancing process [2].

There are several drawbacks with this traditional tolerancing approach. Since the optical tolerance analysis is performed as a first step, the mechanical mounting strategy and the manufacturing process capabilities are not considered in the optical components positioning error requirements. This will either result in an optical system that will be difficult to manufacture, or in several iterations between optical and optomechanical designers to provide an optimized tolerance budget allocation. Also, the allowable lens positioning error given by the optical designer is often specified in terms of lens vertex decenter and tilt, where the lens vertex is defined by the point where the lens optical axis intersects the first lens surface in the optical path. However, real tilt perturbations on the optical component are almost never located at the lens vertex. This results in optical component positioning perturbations that are not representative of the real optomechanical lens mounting and alignment. To perform realistic simulation in the optical design software for the tolerance analysis, the positioning perturbations applied on optical surfaces and on optical elements shall be consistent with the mounting and centering strategy. Most of the time, the realistic optical component positioning error cannot be modeled simply by using the default tolerancing parameters in the optical design software. Figure 2 shows how tilt and decenter perturbations are applied by the optical design software using the default tolerancing parameters. First, a rotation is applied on the vertex of the first lens surface. Then, a translation is applied to the vertex to simulate the lens decenter.

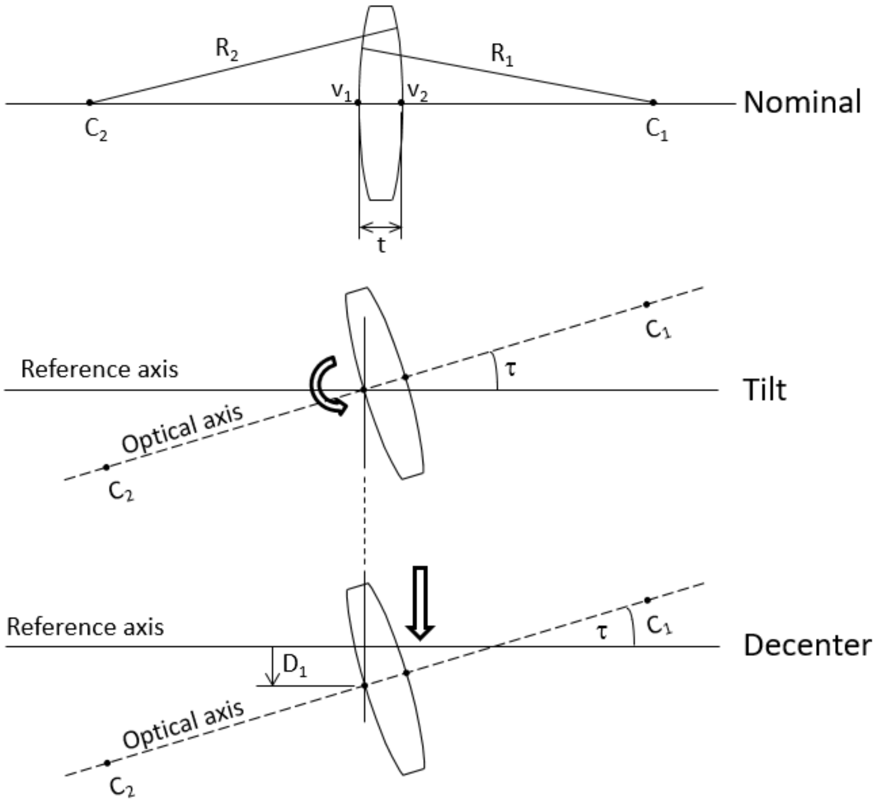

Figure 2. Tilt and decenter variation applied on lens by optical software for tolerancing.

This kind of perturbation may result in poor tolerancing model accuracy as well as major lens positioning error requirements misunderstanding. For example, suppose that an optical tolerance analysis is performed with the default tolerancing parameters results in a lens positioning requirement of 25 µm in decenter (D_1 in Figure 2) and 0.05 deg in tilt (τ in Figure 2). If we consider a lens mounted in a barrel and centered using the rim-contact method, an optomechanical designer may interpret these requirements as a maximum radial clearance of 25 µm between the lens OD and the barrel ID, and a tilt of the lens mounting seat in the barrel of 0.05 deg. But in fact, the lens positioning errors in the barrel are more complex. The positioning errors will be the result of the seat concentricity error (Figure 3), the seat tilt error (Figure 4), and the lens roll in the barrel (Figure 5). Thus, the lens positioning errors involve more parameters than the radial clearance and the seat tilt. Also, the simulation as depicted on Figure 2 that uses default tolerance parameters do not provide the correlation between the lens decenter and the lens tilt generated by the lens roll motion, resulting in a less accurate model. Moreover, the lens manufacturing wedge shall also be included properly in the optical tolerancing model. To do so, the lens geometry, the centering method, the lens mounting surface, and the lens datum features used for the lens wedge manufacturing tolerance shall be considered. For example, the perturbation from the lens wedge error to be applied in the optical tolerance model would be different for a bi-concave lens mounted on a non-optical flat surface (also called flat bevel) than for a bi-convex lens mounted on a spherical optical surface. Also, the lens wedge error will not affect the optical performance and shall not be modeled in the same manners if the lens is centered using rim-contact, surface-contact, or active alignment using a centering machine.

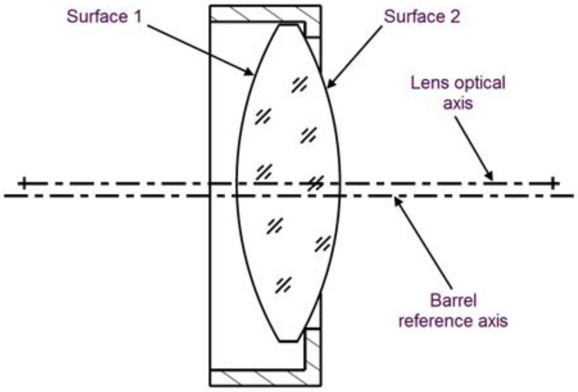

Figure 3. Effect of the barrel lens seat decenter manufacturing error on the lens positioning.

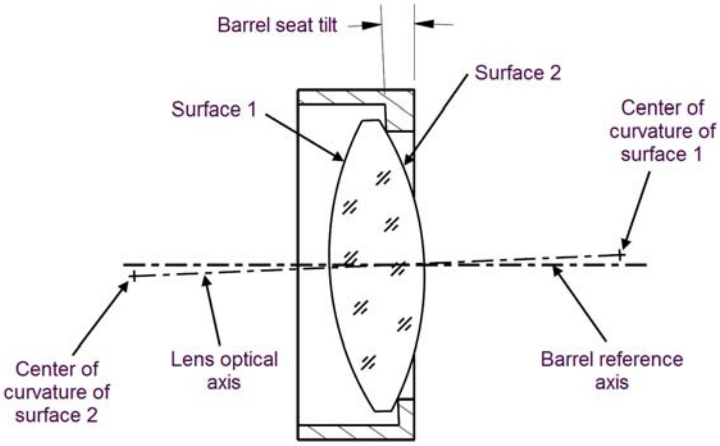

Figure 4. Effect of the barrel lens seat tilt manufacturing error on the lens positioning.

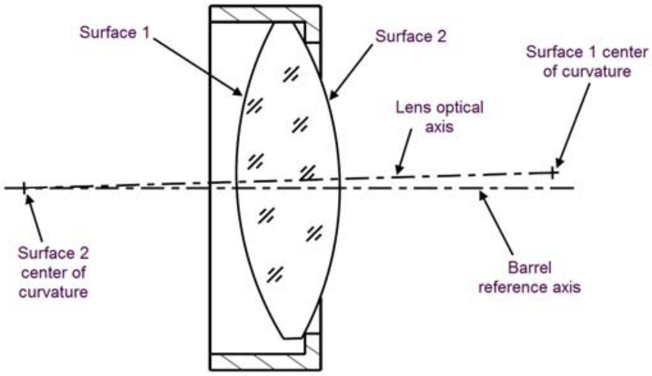

Figure 5. Effect of the lens roll on the lens positioning.

If we consider another example with the same lens positioning requirement as in the previous example where the lens is centered using active alignment inside the barrel, the technician that will perform the assembly may interpret that the lens centering requirement is 25 µm. Since most of the optical centering methods are based on the displacement of an image produced by the optical surface being aligned as shown on Figure 6 [4], the centering of 25 µm will be performed by the technician on the center of curvature of the surface opposite to the barrel seat, which is different than the 25 µm centering error (D_1 in Figure 2) simulated at the lens vertex. In some case, even a perfect centering of the center of curvature of the optical surface opposite to the barrel seat may result in vertex centering error that is larger than the requirement [3]. In the examples shown on Figure 7, we can see that the centering error of the lens vertex is present even with a perfect centering of the center of curvature of the optical surface opposite to the barrel seat. This occurs because of the lens seat manufacturing errors and, in some case, because of lens manufacturing error on a non-optical flat mounting surface, as it is often the case with concave optical surfaces. Thus, mounting seat and lens manufacturing errors induce centering error on the center of curvature of the optical surface located on the barrel seat side. Once the center of curvature of the optical surface opposite to the barrel seat is centered by the technician on a centering machine, the lens vertex is decentered as per the geometrical relationship of the different parameters involved. As a result, there is no direct link between the lens centering error simulated at the lens vertex in the tolerance analysis and the residual alignment centering error performed on the lens surface that is opposite to the barrel seat.

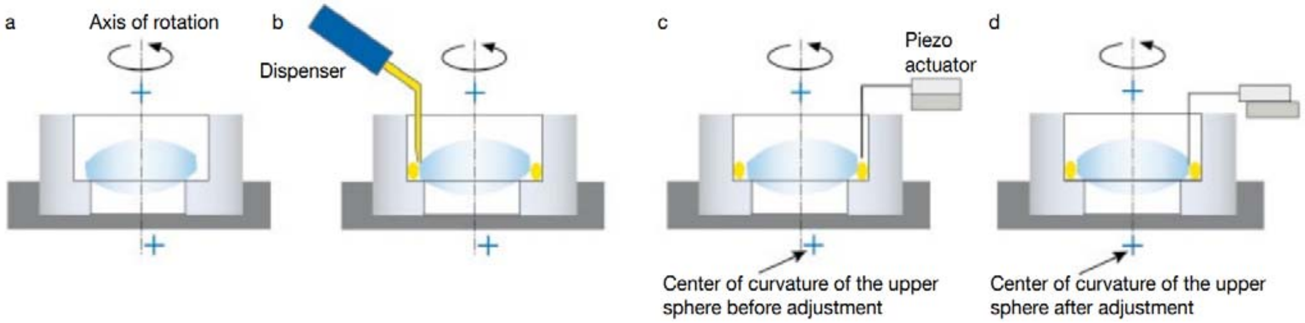

Figure 6. Alignment and bonding process in two degrees of freedom [4].

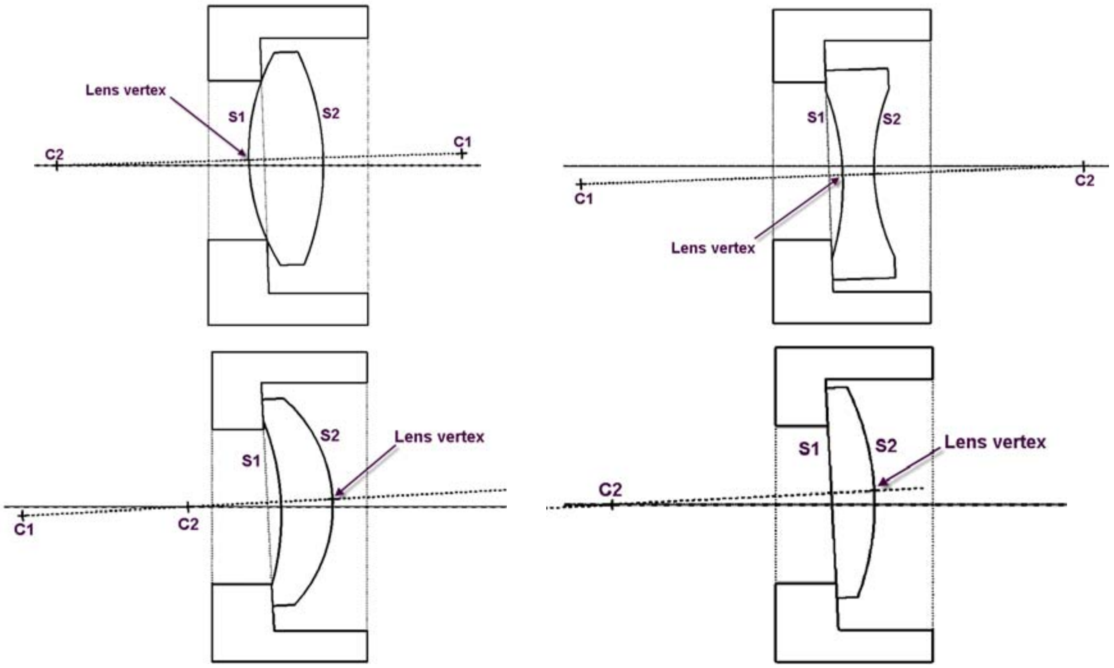

Figure 7. Centering of the first lens surface seen by the autocollimator considering error on the lens seat [3].

These two examples show some of the disadvantages in terms of simulation accuracy and in terms of possible misunderstanding of using classical optical tolerancing process and the default parameters for the tolerance analysis in the optical design code.

3. OPTOMECHANICAL TOLERANCE ANALYSIS

To provide an accurate tolerancing model, it would be more efficient to define for each lens the perturbations to be applied in the optical design software as per the optomechanical mounting and alignment strategy. This means that the optomechanical designer specifies the perturbations to be applied in the optical design software rather than try to allocate a tolerancing budget to mechanical parts and assembly based on requirements resulting from the tolerance analysis performed by the optical design software. By doing so, it is possible to build a more realistic tolerance model in the optical design software, avoid misunderstanding, and be more efficient for the tolerance budget allocation. The optomechanical tolerance analysis must consider manufacturing tolerances of optical and mechanical parts, as well as interactions between optical components and mounts. The specificity of the optomechanical tolerance analysis, compared to standard mechanical tolerance analysis, lies mainly in the interactions between optical components and mounts. A realistic optomechanical tolerance analysis involves several parameters, such as the lens geometry, the mounting interface, the centering method, and the manufacturing tolerances on the optical component and mechanical mount. Depending on the centering method, the radial clearance between the lens and the barrel may need to be considered. In many cases, the lens wedge error also affects the lens centering relative to the barrel axis. If the lens is mounted on a non-optical surface, the geometrical error between the mounting surface and the optical axis of the lens will also affect the centering. Another contributor to the lens centering is the manufacturing errors of the barrel. Perpendicularity and concentricity of the lens seat, as well as the concentricity of the barrel inner diameter relative to the barrel reference axis are among the main contributors. Moreover, when the lens is mounted on a spherical surface instead of a planar surface, the lens rolls rather than translates, causing a centering error of the lens plus a tilt. In the case of aspheric surfaces, the manufacturing error of the aspheric axis must also be considered. The following sections illustrate how these most typical manufacturing and assembly errors affect the lens positioning error for specific cases.

3.1 Lens Wedge

Once mounted in an optical mount, the lens wedge manufacturing error of a bi-convex lens results in a centering error of the optical surface opposite to the lens mounting seat as depicted on Figure 8. Since the lens mounting surface is a spherical optical surface, the lens wedge does not affect the centering error of this surface because it is fully constrained by the mechanical seat. In the case of a bi-convex lens, the lens wedge error shall be considered in the lens positioning error for rim-contact lens centering. However, for surface-contact and active alignment lens centering method, it does not affect the final lens positioning error.

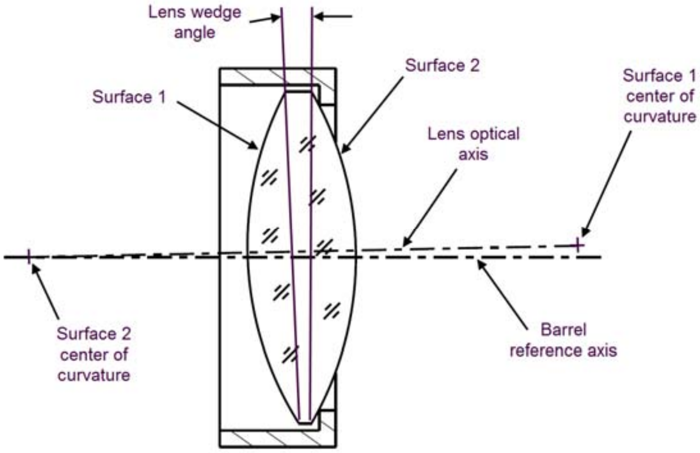

Figure 8. Wedged bi-convex lens mounted in a barrel.

For a lens mounted on a non-optical surface as shown on Figure 9, the manufacturing error between the optical axis and the lens mounting surface affects the lens positioning error of both optical surfaces. Once again, the lens wedge error shall result in different perturbation simulation in the optical model depending on the lens centering method that is used.

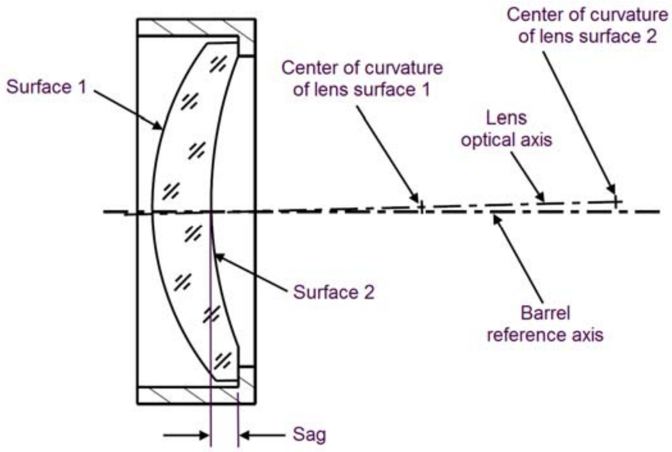

Figure 9. Effect of non-optical mounting surface manufacturing error on the lens centering.

3.2 Radial Clearance

The radial clearance between the lens and the mechanical mount inside diameter (ID) shall be considered for rim-contact centering method. It is the result of the nominal radial clearance required for the assembly and thermal effect, as well as the diameters manufacturing tolerance on the lens and the mount ID (Figure 10).

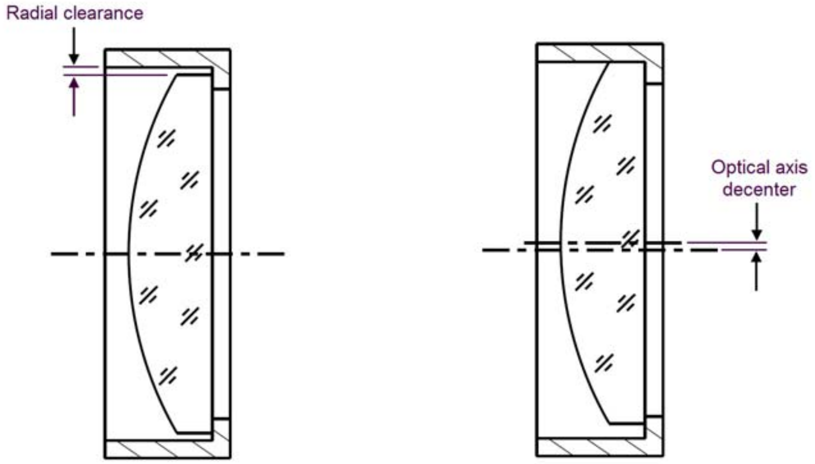

Figure 10. Radial clearance effect on a plano-convex lens. (Left) Centered lens, (Right) Decentered lens.

3.3 Lens Roll

When a lens is mounted on a spherical surface, the radial clearance results in a roll rather than in a translation as for a lens mounted on a planar surface. For rim-contact lens centering, the lens roll is the result of the total radial clearance (Figure 11). If the lens is centered using surface-contact mounting or active alignment, the lens roll is the result of the residual centering error of the center of curvature of the optical surface that is centered.

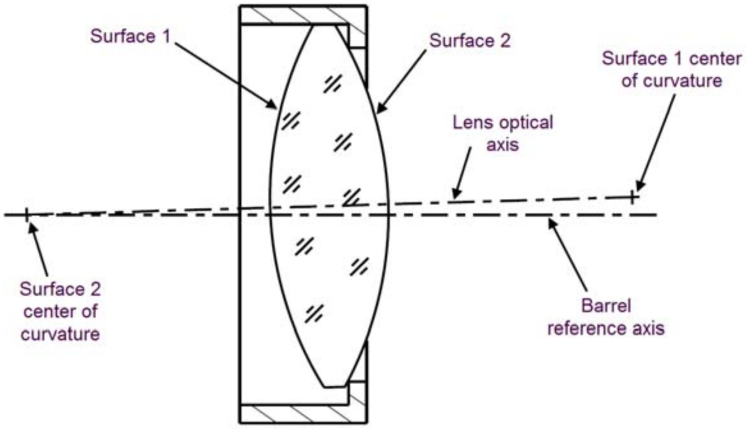

Figure 11. Effect of the lens roll on the lens centering.

3.4 Barrel Manufacturing Error

For a lens mounted on a spherical surface, the centering error of the mechanical mounting seat will directly affect the lens centering error. The lens surface mounted on a decentered barrel lens seat has the same centering error as the barrel lens seat (Figure 12 left). A tilt of the barrel seat also results in a centering error of the lens surface in contact with the mounting seat (Figure 12 right). Depending on the lens centering method used, the lens surface opposite to the mounting seat will be decentered differently and the perturbation to be implemented in the optical tolerancing model shall be applied correctly.

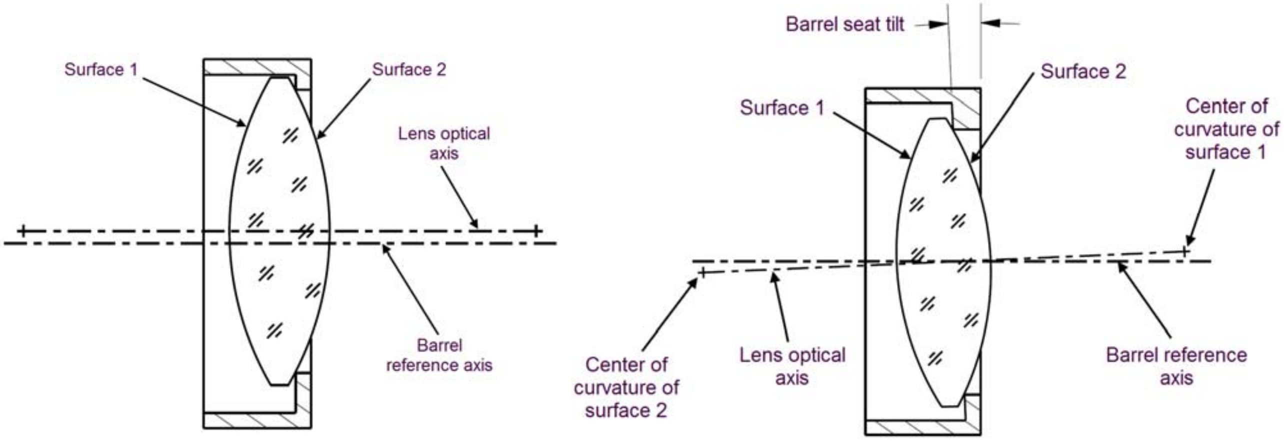

Figure 12. Barrel lens seat decenter (left) and tilt (right) manufacturing errors.

3.5 Aspheric Lens

In addition to the centering error described above for spherical surfaces (sections 3.1 to 3.4), the manufacturing error of an aspheric surface relative to the lens reference axis must also to be considered for the calculation of an aspheric surface positioning error (Figure 13). As per ISO 10110 standard [5] [6], aspheric surface centering tolerances are specified as the distance between the aspheric surface center point and the lens reference axis, and by the tilt angle of the aspheric surface axis with respect to the lens reference axis. In opposition to spherical lens, the manufacturing error between the aspheric surface and the second optical surface of the lens cannot be compensated by a further alignment of the lens. Thus, these errors specific to aspheric lenses shall be considered in the tolerance model. Also, local aspheric surface mounting and centering radii shall be used properly in the optomechanical tolerancing model to provide accurate simulations.

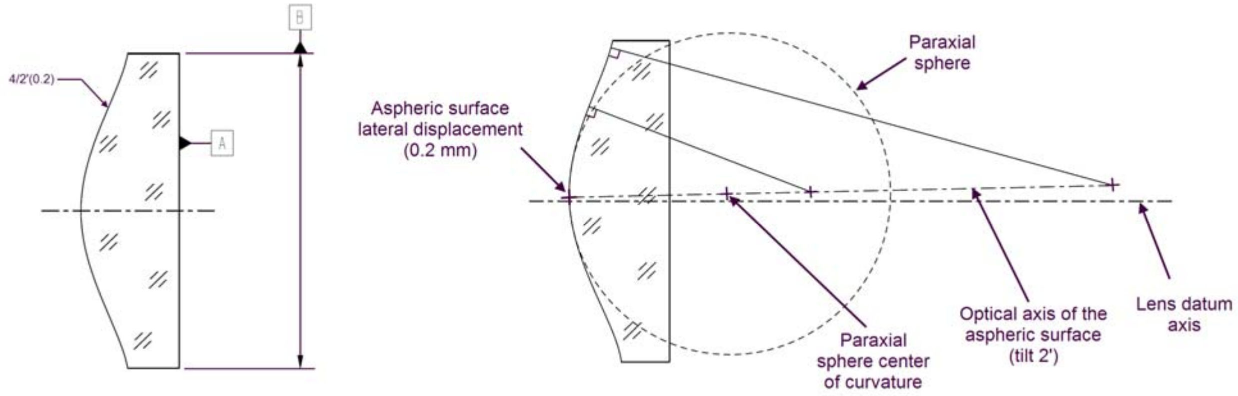

Figure 13. Aspheric lens decenter and tilt manufacturing errors.

3.6 Lens Centering Errors Considering all Contributors

Figure 14 shows a bi-convex lens mounted on the right optical surface, centered with rim-contact, and including all the manufacturing and assembly error that affect the lens positioning error.

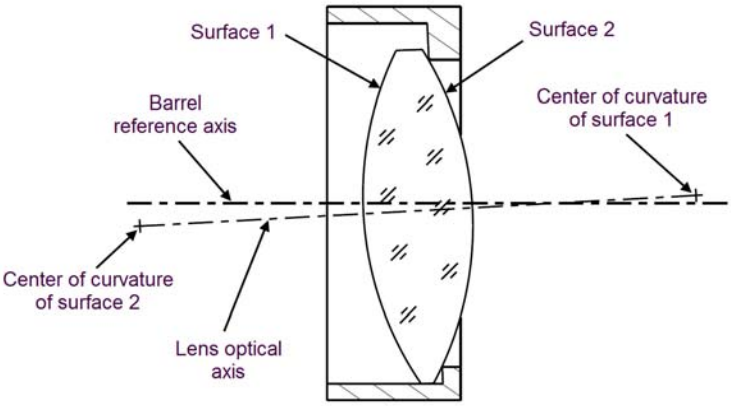

Figure 14. Lens positioning error considering all main contributors.

The perturbations would have been different for another lens geometry, such as a meniscus lens. The perturbations would also have been different for another centering method or if the mounting surface had been the left surface rather than the right surface. More complex perturbations would have been required for aspheric lenses or doublet elements. Thus, optomechanical tolerance analysis must consider several parameters to be accurate. It requires several calculations that are dependents of the lens geometry, the mounting surface, and the centering method. Moreover, for each lens, a simulation method that is representative of the real optomechanical perturbations shall be implemented in the optical design code. Considering that several optical simulations are often required to select the appropriate lens centering method and to optimize the tolerance budget allocation, such kind of optomechanical tolerance analysis would be very time consuming to be implemented in the classical optical tolerance analysis process.

4. INTEGRATED OTPO-MECHANICAL TOLERANCE ANALYSIS

To perform realistic tolerance analysis simulations in the optical design software, the positioning perturbations applied on optical surfaces and optical elements shall be consistent with the mounting and centering strategy. Building an accurate model that is representative of the real optical components mounting and alignment strategy requires an extensive knowledge of the interactions between lenses and mounts theory, several calculations from the optomechanical designer, and a lot more effort for the optical designer. To perform efficiently and accurately the tolerance analysis in the optical design code, an integrated tolerance analysis method has been developed to conciliate the optomechanical and the optical tolerance analysis. This integrated tolerance analysis first used geometric input parameters from the nominal optical design, such as the number of lenses, the lens diameter, the radii of curvature, the center thickness... Then, a mounting and centering strategy is defined for each lens. According to the lens geometry, the mounting surface and the centering method, it is possible to define a simulation sequence to be implemented in the optical design software. Each perturbation of the simulation sequence is then computed as per the optomechanical tolerance analysis. The pivot positions are also computed to apply tilt to the optical surfaces and element at positions that are in accordance with the real optomechanical mounting and centering. Finally, the perturbation value in terms of tilt, decenter, and axial error of the optical surfaces and element, as well as the pivot positions are then sent to the optical design software to perform the optical tolerance analysis.

An important step of this integrated tolerance analysis is the perturbation simulation sequence to be implemented in the optical design software. It basically replaces the default tolerancing parameters in the optical design software by perturbations and pivot positions that are representative of the real mounting and centering of the lenses. The perturbation sequences have been defined for different lens geometries (plano-convex, bi-convex, bi-concave, meniscus, doublet, triplet, aspheric), different types of mounting (right or left surface, optical or non-optical surface lens mounting), and different centering method (rim-contact, surface-contact, active alignment). For each case, the mounting surface, the centering surface, and the element perturbations and their respective pivot positions have been defined. Each of these perturbations is the result of manufacturing and assembly errors. Several equations are used to translate the manufacturing tolerances into tilts and decenters perturbations. Thus, the perturbation simulation sequence to be applied in the optical design software has been defined for each type of lens geometry, mounting and centering method. For each perturbation simulation sequence corresponds a set of equations. These equations are used to compute the perturbation resulting from manufacturing and assembly errors as per the optomechanical tolerance analysis described in section 3. Finally, the pivot positions that depend on where the manufacturing and assembly errors affect the surface or element tilt are also computed to be used in the optical design software. Since there are a lot of different possible cases of lens geometries and mounting methods, many equations are required to compute the resulting perturbations to be simulated in the optical design software. To ease the optomechanical tolerance analysis calculations and the time required to generate the information to be used in the optical design software, a standalone application has been developed. It is therefore possible to perform this integrated tolerance analysis very easily and rapidly. Optimization between optical performance and manufacturability can be performed in a way that was nearly impossible until now. For example, it is possible to converge towards an optimized design solution in terms of mounting method, centering technique, and tolerance level for each contributor involved. More details about this powerful standalone application for realistic optical tolerancing are the subject of another paper [7].

5. CONCLUSION

This paper has discussed some drawbacks of classical optical system tolerancing process where optical and optomechanical tolerance analysis are performed separately. To improve the tolerancing process efficiency and accuracy, an integrated opto-mechanical tolerancing method where the optomechanical tolerance analysis is linked with the optical model has been presented. In the proposed tolerance analysis, the optical layout from the optical design software is imported in a new optomechanical tolerance analysis software. Mounting type, centering method, and manufacturing tolerance are defined. According to these optomechanical tolerance analysis inputs, the software performs the optomechanical tolerance analysis and computes the perturbations to be applied in the optical design software. This allows to perform accurate simulations in the optical design software that are representative of the optomechanical mounting and centering methods, resulting in a more efficient allocation of the tolerances and a more accurate prediction of the optical system performances.

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