Coupling Multibody Dynamics and Optical Simulations to Reduce Dynamic Aberrations in Lens Systems

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Abstract

In high precision optics the dynamical behavior of lenses and mirrors often reduces the quality of a projected image. To develop methods for decoupling the image quality from external influences like noise excitations, the interaction between lens motion and image projection has to be understood. Coupled dynamical-optical simulations are a good possibility to investigate this issue.

Keywords: multibody dynamics, vibrations, coupled fields

1. Introduction

Image aberrations are a main problem in designing any optical system. In high precision optics very high accuracy demands are necessary to keep the aberrations small. However, this condition leads to a high susceptibility to failures. In particular, this regards lithographic projection lenses [1] which are used in manufacturing semiconductor devices, see Fig. 1.

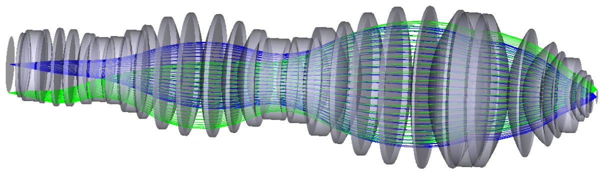

Figure 1: Lithographic projection lens

To reduce image aberrations due to the dynamical behavior of optical systems, the correlation between vibrating optical components and resulting aberrations must be known. After outlining some basics for coupling dynamics and optics, some methods are introduced to investigate both lens systems with rigid lenses and with flexible lenses by means of multibody system dynamics.

2. Ray Tracing and Aberrations in Dynamical Lens Systems

The most common areas in applied optics are geometrical optics and wave optics. In the following, only the geometrical aberrations are discussed. In geometrical optics, light propagation gets simplified to rays which describe the propagation direction. Snell's law is used to calculate the path of rays in lens systems. This procedure is called ray tracing. See Fig. 2 for an example and some important terms and definitions.

Aberrations at the image plane are a main criteria to evaluate the design of an objective lens, both the optical part and the mechanical part. In case of observing the dynamical behavior of an optical system, the common way of handling aberrations is adapted and expanded. In such systems, two kinds of aberrations have to be distinguished: blurring and chief ray deviation. The first one is the same as in static cases, but it is treated more general. That means, if an image is blurred, one usually differentiates between spherical aberrations, coma, astigmatism, etc., e.g. [2]. Here these single types are not interpreted individually but as a whole. The second aberration never occurs in static cases and it describes the movement of the chief ray of a light source. Those two types of aberration consider all monochromatic errors.

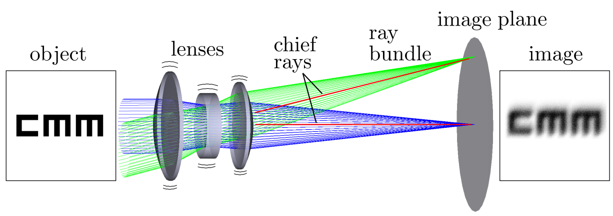

Figure 2: Lens triplet and blurred image due to vibrating lenses

It is complicated to quantify the blurring directly from an image. For this, wavefront aberrations provide a better and more efficient way for a quantification. A wavefront is a surface, where all waves of one point light source have the same phase [2]. Or in geometrical optics, this is a surface where all rays cover the same optical distance.

3. Coupled Dynamical-Optical Simulations

Dynamical Lens systems can be modeled with rigid lenses or flexible lenses. Combinations are possible, of course, but first of all, procedures for both cases have to be developed independently. Recent developments are introduced in the following subsections.

3.1. *A Reduced Method for Rigid Lenses*

For coupled simulations, a step-by-step procedure seems most promising. Firstly, in a dynamical simulation the move-

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ments of the lenses are calculated at discrete time steps. These results are transferred to a ray tracing simulation where, secondly, at each time step the aberrations are calculated.

The individual displacements at a certain time step, including both translational and rotational movements, can be seen as a state of displacement. Simulations have shown that aberrations of any state of displacement may be superposed, see Fig. 3. They also are proportional to the magnitude of a displacement state. So each displacement state has an aberration sensitivity. Thus each mode shape of the lens system produces characteristic aberrations which are declared to so-called modal sensitivities. A multiplication of the modal sensitivities with the associated modal coordinate $\tilde{\boldsymbol{q}}$ will yield the actual aberrations.

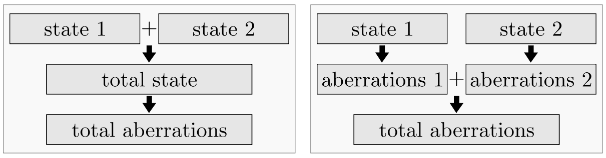

Figure 3: Superposition of aberrations

In other words, modal coordinates lead directly to the dynamical aberrations of a lens system. Hence a reduced method can be defined which comprises a modal transformation [3] within the dynamical simulation. Based on the differential equations of motion with the generalized coordinates $\boldsymbol{q}$

$$\boldsymbol{M}\cdot\ddot{\boldsymbol{q}}+\boldsymbol{D}\cdot\dot{\boldsymbol{q}}+\boldsymbol{K}\cdot\boldsymbol{q}=\boldsymbol{B}\cdot\boldsymbol{u}$$
$$\boldsymbol{y}=\boldsymbol{C}\cdot\boldsymbol{q} \tag{1}$$

the modal transformation with $\boldsymbol{q}=\boldsymbol{\Phi}\cdot\tilde{\boldsymbol{q}}$ reads

$$\boldsymbol{\Phi}^T\!\cdot\boldsymbol{M}\cdot\boldsymbol{\Phi}\cdot\ddot{\tilde{\boldsymbol{q}}}+\boldsymbol{\Phi}^T\!\cdot\boldsymbol{D}\cdot\boldsymbol{\Phi}\cdot\dot{\tilde{\boldsymbol{q}}}+\boldsymbol{\Phi}^T\!\cdot\boldsymbol{K}\cdot\boldsymbol{\Phi}\cdot\tilde{\boldsymbol{q}}=\boldsymbol{\Phi}^T\!\cdot\boldsymbol{B}\cdot\boldsymbol{u}$$
$$\tilde{\boldsymbol{y}}=\tilde{\boldsymbol{C}}\cdot\tilde{\boldsymbol{q}}. \tag{2}$$

The modal matrix $\boldsymbol{\Phi}$ contains the eigenvectors listed next to each other. The outputs $\boldsymbol{y}$ in Eqn. (1) are the movements of the lenses, whereas the outputs $\tilde{\boldsymbol{y}}$ in Eqn. (2) are the aberrations calculated by the modal sensitivities in the modified output matrix $\tilde{\boldsymbol{C}}$.

The reduced method is almost as exact as the full step-by-step procedure and in most cases more efficient. And, above all, it makes evaluations of the design quality possible. This refers to the conclusion that, if there is a detectable excitation with a certain frequency range, the aberrations of all mode shapes within that range have to stay small to keep the overall aberrations small.

Regarding the duration of the time integration in the dynamical simulation, the advantage of the reduced method is due to the modal transformation which simplifies the structures of the matrices in the system equation. Since in the reduced method the aberrations of all mode shapes are calculated, the optical simulation will be more efficient, too, if there are more time steps than degrees of freedom (DOF). The count of the DOF is always equal to the count of the modes. For the development of a good dynamical behavior for a given lens design, the masses m_i and stiffnesses k_i have to be optimized to improve the mode shapes, compare Fig. 4. For this, an adequate optimization procedure has to be set up.

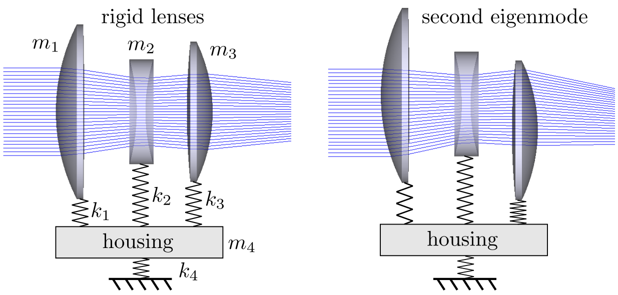

Figure 4: A lens triplet with its mechanical connection to the environment and its second eigenmode

3.2. *Preparing Deformable Lenses for Ray Tracing*

If the eigenfrequencies of the individual lenses are in the range of the excitation frequencies, their surfaces deform and stress within the lens occurs. In ray tracing simulations, surface deformations are handled like aspheric surfaces for which lots of simulation methods exist. Usually, an aspheric surface is described by a reference sphere and a sag which is parallel to the lens axis. In optical simulation software, e.g. Zemax, the sag can be specified by Zernike polynomials. Zernike polynomials are defined over a circular support area and are therefore useful in combination with the Finite Element Method for deviations of nodes on a lens surface. One advantage is that these polynomials smooth the discretized surfaces to avoid artifacts in optical simulation results. Another big advantage regards transient analyses. The polynomials can be attached to any shape functions which are calculated by any model order reduction technique for Elastic Multibody Systems. The precalculations for the application of the polynomials is shown in Fig. 5 with the first shape function for a modal reduction. The figure below shows the calculated sag which subsequently gets expanded by Zernike polynomials.

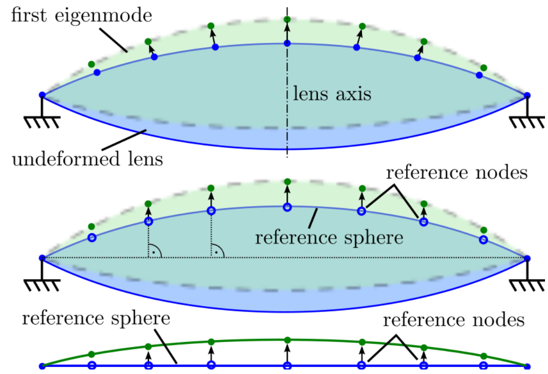

Figure 5: Nodal displacements for the first eigenmode of a lens

To return to transient analyses, the coefficients for the Zernike polynomials are directly received as results from a time integration. So nodal movements need not to be calculated and plenty of computation time is saved.

4. Outlook

Though coupling rigid lenses with geometrical optics is in good progress, compare [4], it still has to be improved for industrial applications. A main goal, regarding flexible lenses, is to find correlations to aberrations in a similar way as it has been achieved for rigid lenses. However, this requires many investigations to be done. Furthermore, stress has to be considered due to deformations both in static and dynamic cases. Stress changes the refraction index of the lens material, like thermal effects do, too.

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