1 Overview

1.1 Design requirements and independent variables

When lens data are given, various characteristics of the lens can be evaluated with optical theory. The typical independent variables of lens design are

- total surface number,
- material between surfaces,
- curvature of surface,
- distance between surfaces,
- clear aperture of surface,
- surface number to be aspherized,
- shape of asphere,
- stop surface number,
- stop surface diameter, and so on.

The typical dependent variables of the lens design are

- effective focal length,
- back focal length,
- distance from the object surface to the image surface,
- imaging magnification,
- ray aberration,
- root mean square optical path difference (RMS OPD),
- modulation transfer function (MTF),
- distortion,
- relative illumination,
- ghost image intensity,
- total track length,
- maximum surface height,
- glass weight,
- transmittance,
- glass cost,
- tolerance sensitivity, and so on.

A major part of lens design is optimization, defined as the process of achieving the values of independent variables that realize the target values of dependent variables.

1.2 Problem of sensitivity and tolerances

The problems of tolerance sensitivity and the determination of tolerances are important in lens design. The as-built performance of a sensitive design is low if the ordinary tolerances are applied. If tight tolerances are applied to get a high as-built performance, then the cost is high. It might seem that the
evaluation of the tolerance sensitivity takes a lot of time and cannot be included in the optimization. This Spotlight will explain how to evaluate the tolerance sensitivity within a short time and how to control it systematically during optimization. The loss of nominal performance depends on the choice of the tolerances, which affects the manufacturing cost.

The goal of tolerance optimization is to choose the best tolerance. However, this is not the same as the minimization of tolerance sensitivity. When the lens design is finished, the tolerances need to be determined for manufacture. Tight tolerances result in high performance and high cost. Loose tolerances cause low performance and low cost. If a tolerance set is given, the performance of the product can be estimated statistically and the production cost can be evaluated. However, it seems very difficult to prove that a given tolerance set is optimal and to find the optimal tolerance set. This Spotlight formulates this problem as the optimization problem and proposes a simple and rapid method to solve it (culminating in Section 6.3).

2 Lens Design Optimization Principles

2.1 Merit function

Generally speaking, if the number of dependent variables is larger than the number of independent variables, then the target values of the dependent variables cannot be fulfilled simultaneously. In this situation, the problem needs to be a least-squares problem. The merit function $\Phi$ is defined as

$$
\Phi = \sum_{i=1}^{n} w_i (f_i - t_i)^2,
$$

where $f_i$ is the value of the $i$'th-dependent variable, $t_i$ is the target value, $w_i$ is the weight, and $n$ is the number of dependent variables. There is a case where a dependent variable $f_i$ is allowed to be in an interval $[c_i, d_i]$. In this case, the weight $w_i$ and the target value $t_i$ change with the value $f_i$:

- If $f_i < c_i$, then $t_i = c_i$;
- If $c_i \leq f_i \leq d_i$, then $w_i = 0.0$; and
- If $d_i < f_i$, then $t_i = d_i$.

The problem is to minimize the merit function $\Phi$ in the space of the independent variables. The weight $w_i$ is chosen to express the importance of each dependent variable. The minimum point of $\Phi$ changes with the values of $w_i$ changing the residual values of $f_i$. The choice of $w_i$ is critical to the performance of the design result.