Deformable Grating Design Optimization for Large-Aperture Pulse Compressor Systems

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1. Abstract

The Matlab global optimization toolbox was used to optimize actuator positions for designing a deformable grating. It is desired to amend the pulse compression system in the OMEGA EP laser to use 1.5 m monolithic diffraction gratings to temporally compress previously stretched and amplified light. Due to gravity, internal stresses, and temperature drops acting on the glass substrate during the coating process, deformations in the grating inevitably form, resulting in surface wavefront errors. The ANSYS® modeling program, whose finite element capabilities enable it to more accurately model irregular surfaces, is used to analyze grating substrate deformations. An adaptive optical system using pressurized actuators has been devised to limit the size of these irregularities with an effective seven-actuator configuration already established. A genetic algorithm provided by the Matlab global optimization toolbox is used to optimize the locations of individual actuators. A location-optimized seven-actuator design has been achieved using a two dimensional, centrally constrained model, with the final wavefront having a root-mean-square (RMS) error of 0.0013 μm, improved from an inititial wavefront RMS of 0.28 μm. Future actuator designs will develop alongside the grating model.

2. Introduction

The OMEGA EP (extended performance) laser system was designed to be an addition to the original OMEGA laser system. Through chirped pulse amplification [1], the OMEGA EP system is capable of achieving picosecond pulse widths and petawatt powers. The laser sends out an initial short pulse that is too weak for fusion but too strong to pass through glass amplifiers. As shown in Fig. 1, the beam is sent through a stretching system that stretches the pulse temporally before it is run through an amplification system. Once amplified, the beam is sent through a compressor consisting of four sets of tiled grating assemblies, each having three interferometrically aligned grating tiles measuring 0.47 m x 0.43 m x 0.1 m [2, 3].

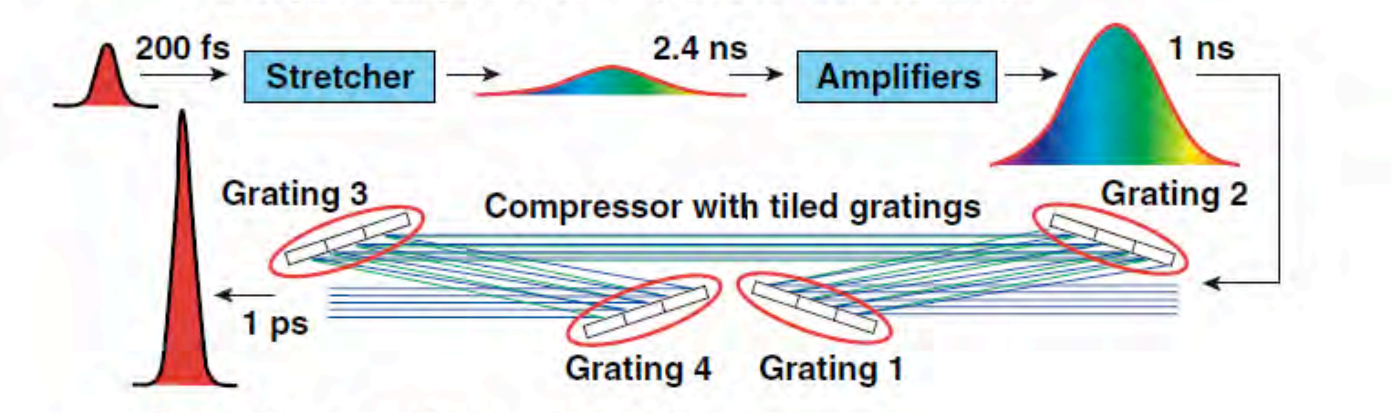

Fig. 1: The OMEGA EP short pulse system. A short pulse of light is stretched and amplified before being sent through a compression system.

The current short pulse system uses tiled-grating compression due to the size limitation of the available gratings, which requires shadowing the input beam across grating-tile gaps, resulting in an energy loss of almost 18%. As a solution, meter-sized monolithic diffraction gratings are desired to eliminate the energy lost and the challenging tile-to-tile sub-microradian alignment associated with manufacturing the three-tile gratings.

While the monolithic large-aperture gratings would eliminate energy loss and make installation and maintenance easier, these tiles are more prone to deformations due to gravity and temperature gradients along the grating. Such deformations cause laser beam irregularities and spatially varying temporal distortion, resulting in a beam that is less concentrated both spatially and temporally and, therefore, less powerful. A system of actuators along the back of the grating may be an effective solution to the problem of grating deformations. A seven-actuator design has been proposed [5] that corrects a grating with an initial RMS of 0.28 μm, as seen in Fig. 2, resulting in a corrected wavefront with an RMS of 0.0028 μm.

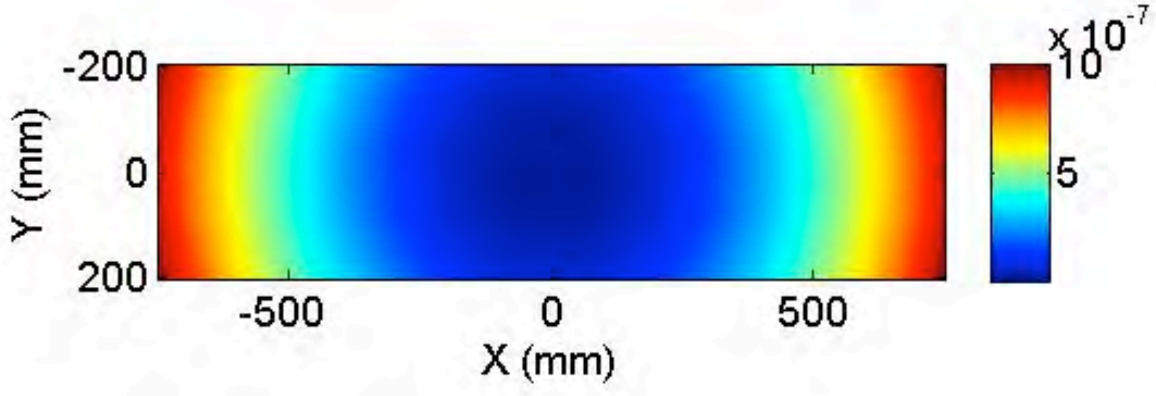

Fig. 2: The initial wavefront to be corrected. The deformed wavefront had a peak-to-valley of 1 μm and an RMS of 0.28 μm. The contour levels are given in m.

The goal of this work was to use the MATLAB global optimization toolbox to optimize the location of actuators along the grating to best minimize wavefront deformations. A genetic algorithm was used to position seven actuators along the grating, resulting in an RMS lower than that of the previous seven-acuator set up.

3. Grating deformations modeled with ANSYS

ANSYS (Analysis System)[4] is a modeling program that was used to model the deformable compression gratings proposed for the OMEGA EP compression system. ANSYS uses finite-element analysis to give a more accurate realization of the grating and its deformations. It breaks down a complex geometry into many small elements through a meshing tool. While the surface as a whole cannot be modeled polynomially, these smaller elements can, with the sum of the elements giving an accurate shape of the grating.

To determine grating deformations, ANSYS analyzes the stress acting on the grating from some external force. Such stress in a given dimension is illustrated by the equation for the stress σ_x along the x direction:

$$\sigma_x = \frac{E}{(1+v)(1-2v)} \bullet ((1-v)e_x + ve_y + ve_z) - \frac{E\alpha\Delta T}{1-2v}$$

where E is the Young's modulus, which is the stiffness of a material (for BK7, the grating's substrate material, the Young's modulus is 82 GPa); *v* is the Poisson's ratio, or how much a material moves in one direction when pushed in the orthogonal direction (equal to 0.21 for BK7); α is the coefficient of thermal expansion (equal to $7.1\text{x}10^{-6}$ for BK7); ΔT is the temperature change on the gradient; and e is the strain acting on the grating in the x, y, or z direction. This method of analysis was used to calculate the grating deformations due to temperature gradients, gravity and stress from actuator displacements.

To analyze grating deformations, a model of a multilayer dielectric (MLD) grating, which consists of a BK7 substrate and 20 dielectric layers of alternating high and low refractive index layers, here HfO_2 and SiO_2, respectively, was created in ANSYS (Fig. 3).

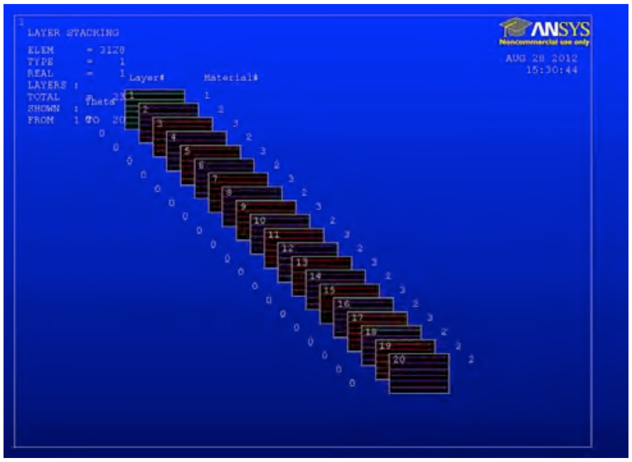

Fig. 3: An ANSYS model of a MLD grating, used to analyze the deformations of the grating from external stresses.

The model was held at the central node in the center of the substrate, and the deformations caused by temperature gradients and gravity were inspected. Temperature changes caused the grating to deform due to the nature of the materials the grating is composed of. The BK7 substrate (thermal expansion coefficient = $7.1x10^{-6}$) has a higher thermal expansion coefficient than that of HfO_2 ($3.8x10^{-6}$) and SiO_2 ($0.7x10^{-6}$). Therefore, as the temperature drops from 200 degrees Celsius (the temperature at which the MLD layers are coated) to 20 degrees

Celsius, the substrate layer contracts more than the coatings, pulling the grating into a parabolic shape (Fig. 4 (a)). In a similar manner, because the mass of the substrate makes up a majority of the grating's total mass, it bends under gravity more than the substrate layers, once again pulling the grating into a parabolic shape. After testing a number of substrate thicknesses, it was apparent that surface deformation decreases as the substrate thickness increased, as seen in Fig. 4 (b).

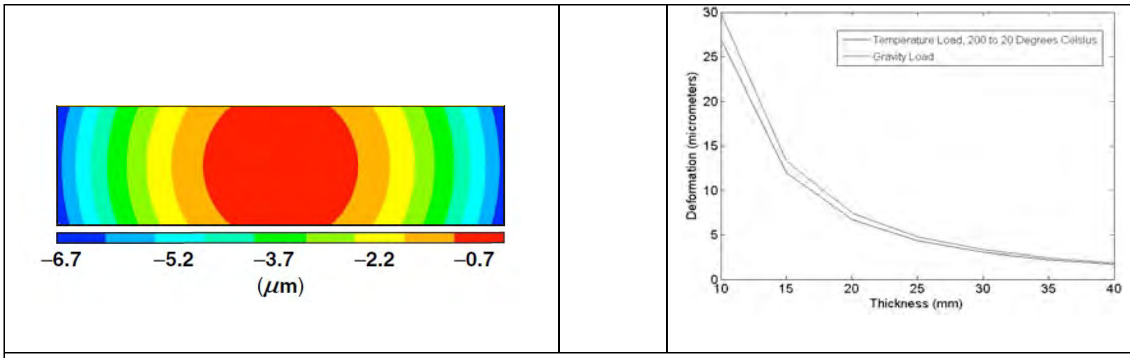

Fig. 4 (a) Thermally-induced surface deformation of a 1.5 m x 0.41 m grating exhibiting a convex-shaped parabola; (b) Defromation due to gravity and thermal loads, both decreasing as the substrate thickness increases.

4. Use of ANSYS and Matlab routines to optimize actuator positions

The initial seven-actuator design that was proposed to correct a 1 micron parabolic wavefront error on a 1.5x0.41x.020 m BK7 substrate was used as the starting point for optimization. Boundary conditions were set for the actuators, allowing each to move 200 mm to the left or right along the grating and 50 mm up and down. The starting positions for each actuator are shown in Fig. 5:

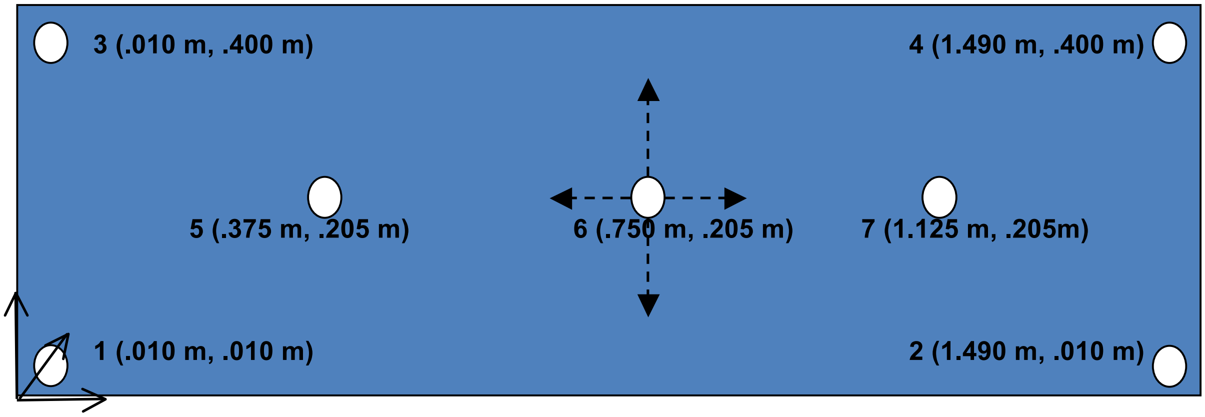

Fig. 5: Diagram of the initial actuator design. A seven-actuator configuration was the starting point for optimization. Each actuator's movement was constrained.

For every actuator configuration, Matlab runs the locations through ANSYS, which then determines the influence function for that design. The influence function is the response of each node – the points on the substrate – to the movement of a particular actuator. It varies depending on the geometrical layout of all the actuators and constraints of the substrate on which the actuators are attached. The required actuator displacements for a desired wavefront can be calculated by:

$$\begin{bmatrix} \boldsymbol{D_1} \\ \vdots \\ \boldsymbol{D_M} \end{bmatrix} = \begin{bmatrix} \boldsymbol{P_1A_1} & \cdots & \boldsymbol{P_1A_M} \\ \vdots & \ddots & \vdots \\ \boldsymbol{P_NA_1} & \cdots & \boldsymbol{P_NA_M} \end{bmatrix}^{-1} \begin{vmatrix} \boldsymbol{Z_1} \\ \vdots \\ \boldsymbol{Z_N} \end{vmatrix}$$

where D_1 through D_M are the displacements of each of the M actuators; P_1A_1 through P_NA_M are the influence of each actuator M on each node N on the surface, and Z_1 through Z_N are the surface deformations at each node specified by the inverse of the wavefront to be corrected. The determined actuator displacements D_1 to D_M can be used to subsequently create a surface that cancels out the uncorrected wavefront and minimizes the grating deformations.

The Matlab genetic algorithm, part of the Matlab global optimization toolbox that contains routines for finding the global minimum of the output of a user-defined merit function, was used to optimize the actuator locations. The objective of the optimization was to minimize the merit function, which was defined as the RMS of the difference between the surface figure generated by the actuators and the wavefront to be corrected. The input variables were the initial actuator locations and their boundary conditions. From these inputs, the Matlab global optimization toolbox would create an initial “population” of randomly generated actuator configurations, as seen in Fig. 6 . The Matlab genetic algorithm would then run each of these configurations in ANSYS through the merit funtion and would determine which configurations generated surface figures that best cancelled out the initial deformation. The most “fit” configurations would then reproduce – either by combining with another fit configuration or by altering itself – creating a new generation of configurations. This process continues until some stopping criterion is met – this could be a time limit, a certain number of generations, or a minimum difference in average values from one generation to the next. Matlab eventually narrows in on one configuration that best minimizes the merit function.

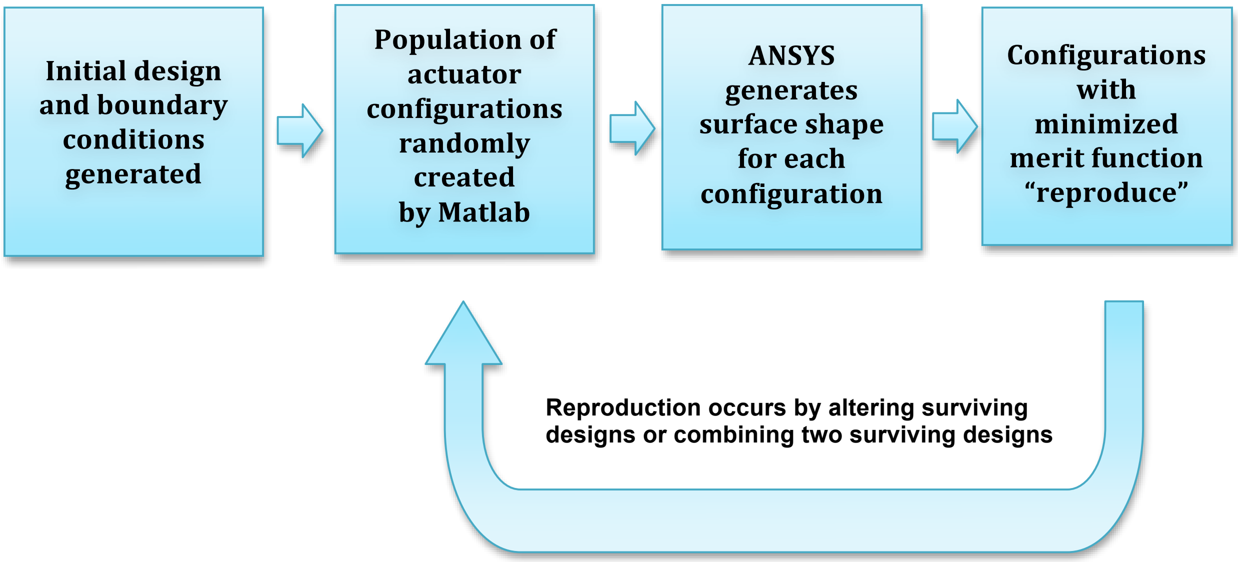

Fig. 6: Algorithm used to optimize actuator positions. The algorithm was looped through until one of a number of criteria was met.

5. Results

The Matlab global optimization toolbox optimized the initial seven-actuator design to minimize the RMS of a deformed-grating wavefront. The configuration was used to correct the wavefront error of a parabolically deformed grating held at its center node with an RMS of 0.28 μm and a peak-to-valley of 1 μm. The final RMS and peak-to-valley after optimization were 0.0013 μm and 0.15 μm, respectively. The final wavefront is shown in Fig. 7.

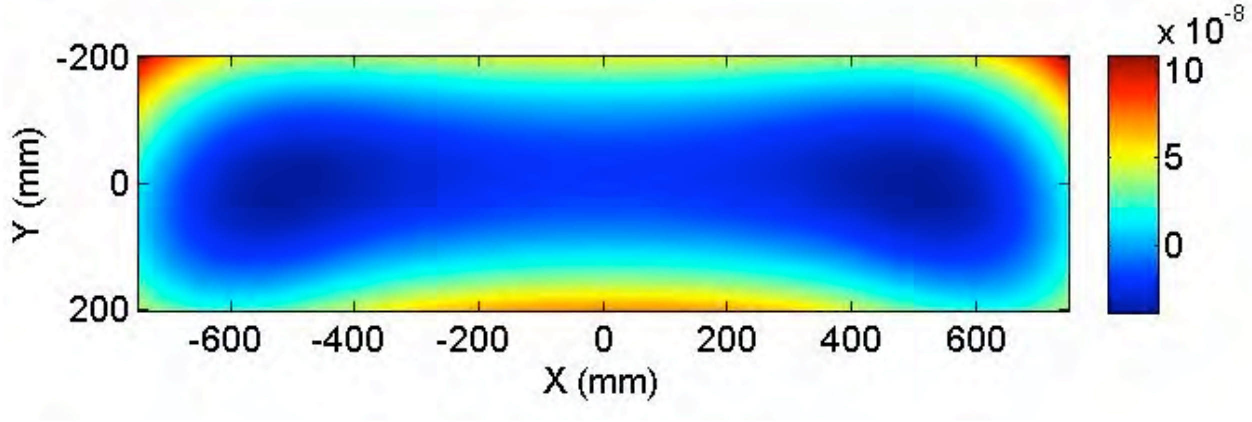

Fig. 7: The final corrected wavefront after optimization of the seven-actuator design. The configuration achieved a wavefront RMS of 0.0013 µm. The contour levels are given in meters.

The optimized actuator set up better minimized the deformable grating RMS than the initial seven-actuator design, which achieved a final RMS of 0.0028 µm and a final peak-to-valley of 0.094 µm and whose wavefront can be seen in Fig. 8:

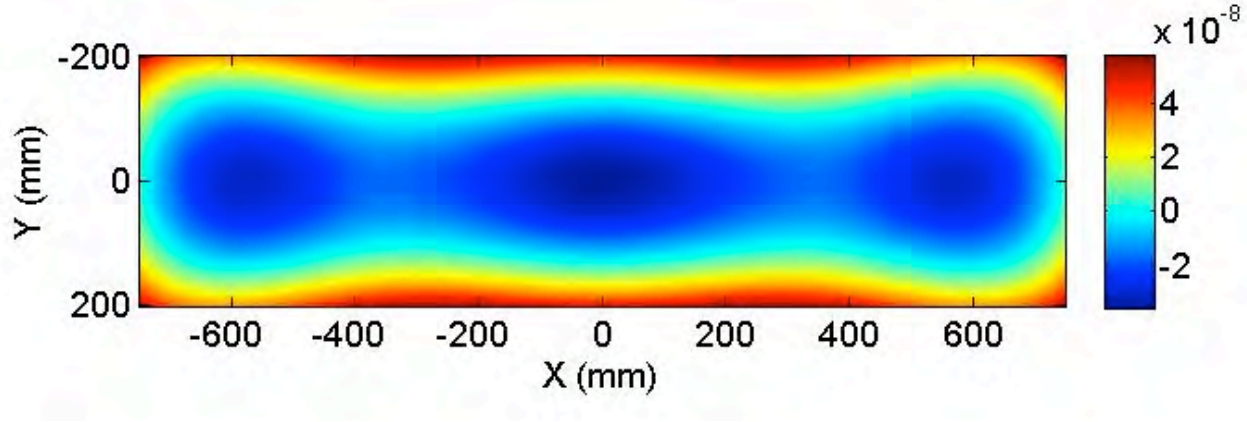

Fig. 8: The wavefront created by the initial seven-actuator design. The configuration achieved a wavefront RMS of 0.0028 µm.

While the initial design achieved a lower peak-to-valley than the optimized design, the most drastic deformations on the optimized corrected surface occur in the upper corners. These are above the beam, which takes up the central ± 185 mm of the grating vertically.

6. Conclusion

ANSYS was used to model deformations of a 1.5 m x 0.41 m x 0.02 m compression grating caused by gravity and temperature change. An initial seven - actuator design was optimized using Matlab's global optimization toolbox with a user-defined merit function to minimize the RMS of the grating deformation. While the optimized design achieved a final wavefront with an RMS of 0.0013 µm, down from 0.0028 µm from the initial design, the optimized final wavefront had a peak-to-valley of 0.15 µm, higher than the intial design's 0.094 µm.

As seen in Fig. 7, the optimized set up was not a symmetrical pattern of actuators, contrary to what one would expect. Most likely the boundary conditions were not optimum or the optimization time was not long enough to allow the model to reach a symmetrical design. Future research could focus on expanding the finite-element analysis to include internal nodes of the substrate for internal stress analysis, improving the specifications for boundary conditions, and a longer run-time for optimizing the actuator locations.

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