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Model-based analysis of highly dynamic laser beam shaping using deformable mirrors

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Abstract

Deformable mirrors show large potential for the dynamic beam shaping in high power laser applications. A model which is based on influence functions is used to systematically investigate the beam shaping capabilities of several deformable mirrors based on the underlying technology and the number of actuators.

Keywords: dynamic beam shaping; deformable mirror; high power; influence functions; membrane mirror; piezoelectric mirror

1. Introduction

Modern laser-based surface treatment processes take full advantage of application-specific intensity distributions to tailor the temperature profile to the process requirements and to increase the processing speed [1]. But in particular the processing of 3D-surfaces requires an adaptation of these distributions with sufficient temporal and spatial dynamics. That is to say that the distributions must be changed fast enough to keep up with the feed speed of the process. Likewise, the possible changes must be large and precise enough to compensate for the distortions introduced by the scanner and the topography of the work piece [2]. Furthermore, high-power applications like laser polishing and thin-film processing require power handling capabilities of ≥ 500 W.

Deformable mirrors (DMs) were initially developed to minimize dynamic aberrations in optical systems especially for earth-bound telescopes. The possibility to coat DMs with highly reflective coatings, switching times < 5 ms and decreasing production costs raised the importance of DMs for laser-based material processing. [3]

This work extends on the results shown in [2,4], where a measurement-based model of a 37-actuator DM was integrated into a commercial optics design software to find the best mirror control signals to produce a predefined intensity distribution. Together with the adaptive optics manufacturer *Flexible Optical B.V.* a theory-based model for several DMs was implemented. Based on a beam-mapping algorithm the ability of the DMs to shape extended flat-top intensities is systematically investigated and the results are discussed.

2. Investigated types of deformable mirrors

In this work, two different types of DMs are considered: Micromachined Membrane Deformable Mirrors (MMDM) and Piezoelectric Deformable Mirrors (PDM). MMDMs consist of a thin (~1 µm) coated membrane mounted over an array of electrodes. Any potential applied between the membrane and any number of electrodes leads to an electrostatic attraction between membrane and electrodes and the deformation of the former. Note that the membrane can only be pulled towards the electrodes producing concave mirror shapes. A PDM consists of a solid plate bonded onto an array of piezoelectric actuators. A deformation of the actuators via the inverse piezoelectric effect leads to a global deformation of the plate. As the

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actuators are bonded to the plate they actively push and pull the plate. A more detailed discussion of these and other DM technologies can be found in [2,5].

For both mirror types, the influence of different amounts of electrodes/actuators (in the following universally called actuators) is investigated. The considered mirrors are listed in Table 1 based on the mirrors available from *Flexible Optical B.V.* Mirrors optimized for the compensation of low-order aberrations are not considered.

Table 1. List of investigated mirrors from *Flexible Optical B.V.*

Mirror Type	# Actuators
MMDM	37, 39, 59, 79
PDM	19, 37, 69, 79

3. Modeling of mirror surfaces

To approximate the shape of the DMs, i.e. the deflection $S(x,y)$ for every (x,y) within the boundaries of the mirror, a set of influence functions $\mathcal{A}_i$ is used:

$$S(x,y) = \sum_i \mathcal{A}_i(x,y) \cdot v_i + S_0(x,y) \tag{1}$$

where i denotes the actuator number and $v_i \in [0,1]$ is a normalized scaling factor that reflects the voltage applied to the actuator. Each influence function describes the maximum response of the DM to the i-th actuator. S_0 defines the initial mirror shape. This allows to describe the mirror shape as a function of the applied voltages V_i as long as the influence functions and the conversion function $f(V_i) = v_i$ are known.

3.1. MMDM

Small displacements of a thin (thickness $\ll$ diameter) membrane with surface tension T based on an external pressure $P(x,y)$ are well described via the Poisson equation

$$\Delta S(x,y) = P(x,y)/T. \tag{2}$$

When the influence of the membrane deformation on the pressure can be neglected, the solutions to equation (2) are linear in pressure and a general solution is given by equation (1). For MMDMs, this approach is well documented in the literature. The influence functions $\mathcal{A}_i$ can be derived analytically for simple mirror and actuator geometries, numerically calculated for arbitrary geometries or simply measured. [2,4,5,6]

3.2. PDM

The deflection of PDMs on the other hand is better described via a small-deflection thin-plate model [5]:

$$\Delta\Delta S(x,y) = P(x,y)/D \tag{3}$$

with the pressure $P(x,y)$ and the cylindrical stiffness D of the plate. This model again assumes a thickness much smaller than the diameter of the plate and deflections much smaller than the thickness of the plate. In [7] the analytical solution for the surface shape of a circular thin plate with free edges and load $P(x,y)$ acting on that plate is derived. As the solution is rather extensive it is not repeated here. However, assuming that the total pressure $P(x,y)$ enacted by the actuators can be written as a sum of point forces at the positions (x_i, y_i) of the respective i-th actuator

$$P(x,y) = \sum_i p_i \cdot \delta(x_i, y_i) \tag{4}$$

the solution to equation (3) can again be written in the form of equation (1) with an analytical form of the influence functions as shown in [5,7]. Note that this solution again assumes a negligible influence of the deflection on the external pressure.

3.3. Discussion of the model

The assumptions made above are often very simple. Cross-effects between the actuators due the influence of the deflection on the external pressure can usually not be ignored, notably for the PDM. More accurate models are usually based on a finite element method (FEM). Especially when the technical details regarding the DM are available from the manufacturer, FEM methods can produce very accurate results. However, these methods are computationally extensive and must be repeated for every set of actuator voltages. For an iteratively solved optimization problem as discussed in section 4, such methods are not viable [8]. One should also note that as long as the real mirror shapes can be well enough approximated in a basis of the influence functions, i.e. via equation (1), the subsequent analysis is still valid. Only the relation between the scaling factors v_i and the actual required voltages V_i may then be more complicated.

4. Simulation and analysis of beam-shaping capabilities

To investigate the beam-shaping capabilities of the selected DMs, an idealized optical system is set up within the optical design software *Zemax OpticStudio*: A Gaussian beam ($M^2 = 1$) with a diameter (1/e² intensity) of 10 mm and a wavelength of 1064 nm is expanded or compressed

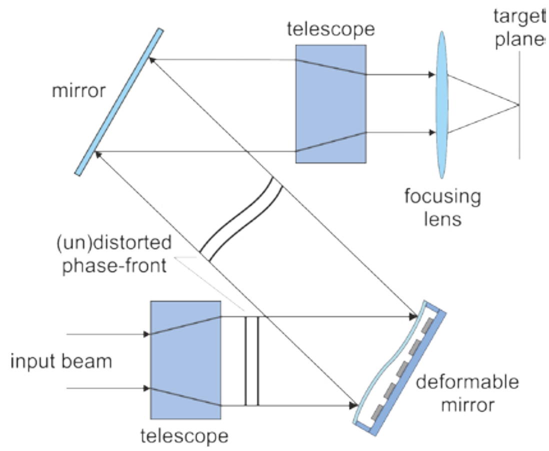

Fig. 1. Schematically drawing of the simulated optical system.

via an ideal Galilean telescope (cf. Fig. 1). The zoom factor of the telescope is a free parameter for the subsequent optimization and allows for an optimal illumination of the DM. After the telescope, the beam illuminates the DM with an incidence angle of 10°. The rotation of the mirror around the normal through the center of the mirror is also a free parameter as the best orientation generally depends on the relation between the actuator distribution and the target intensity distribution. For rotational symmetric intensity distributions, the rotation has no effect. After the reflection from the DM, the beam is compressed or expanded via a second telescope with the inversed magnification of the first telescope. This guarantees a fixed beam size on the following ideal focusing lens and thus the same diffractive effects for all mirrors. The lens has a focal length of 400 mm. Beam shaping systems usually benefit from small focal lengths as diffraction effects are then smaller and e.g. edges of a flat-top distribution are sharper. However, this is only valid when the amplitude of the phase shift introduced by the optical element is not limited. The required phase shift for a fixed target distribution increases with decreasing focal lengths. Due to the limitation of the stroke of the DMs a compromise between beam shaping capabilities and acceptable diffraction effects must be found.

The optical system is schematically shown in Fig. 1. The second mirror is only a fold mirror to show the system in a more compact form.

4.1. Integration of mirror models and optimization criteria

The DMs are integrated into *Zemax OpticStudio* via a dynamic-link library (DLL). This DLL accepts an array of values between 0 and 1 corresponding to the v_i in equation (1). The DLL then reads in the precalculated influence functions and calculates the corresponding mirror shape according to equation (1) which is used for the ray-tracing and beam propagation in *Zemax OpticStudio*.

To optimize the mirror shapes, the desired intensity distributions must be defined as part of a merit function that is iteratively minimized by varying the available variables. Here, a geometric beam-mapping algorithm is used based on the analytical calculation of the required energy redistribution from a Gaussian beam to the desired intensity distribution. The algorithm and its implementation are discussed in more detail in [2,4]. Based on that merit function, each DM is then optimized for the creation of a round flat-top with 500 µm diameter and a square flat-top with 500 µm side length.

Compared to other analyses that calculate the required phase-front to form a certain intensity distribution within a fixed optical system and fit equation (1) to that phase-front [6], this approach has the advantage of a variable optical system. That is to say that the remaining optical system can be optimized together with the shape of the DM to overcome the limitations of the DM. For example, while it may be intuitive to place the image plane in the focal plane of the focusing lens, much better results for shaping extended distributions can be achieved when the distance to the focal plane can be varied (cf. Fig. 4). As the beam (without DM) is larger outside of the focus region, the DM (or any optical element) only needs to redistribute the energy and not also enlarge the intensity distribution.

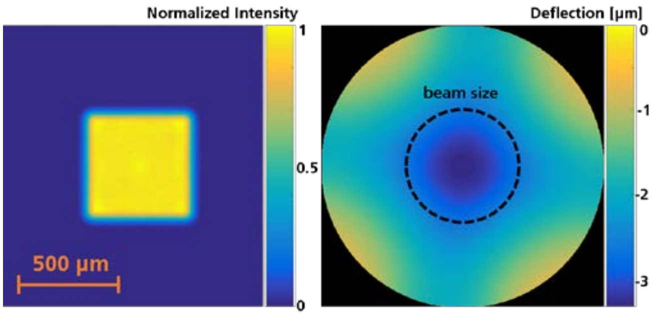

Fig. 2. Flat-top shaped with 79-actuator PDM and corresponding surface.

4.2. Evaluation of results

The results of each optimization are analyzed via the physical optics model of *Zemax OpticStudio* to include diffractive effects. The beam-shaping results and the corresponding mirror surface for the 79-actuator PDM and the square flat-top are shown in Fig. 2. The $1/e^2$ intensity diameter for the impinging beam is also depicted. To compare the achieved intensity distributions, the normalized RMS deviation from the ideal intensity distribution is calculated:

$$RMS = \frac{1}{I_{flat-top}} \cdot \sqrt{\frac{1}{N}\sum_i \left(I_i - I_{i,ideal}\right)^2} \quad (5)$$

The sum represents the sum over all N considered pixels with I_i being the intensity in the i-th pixel and $I_{i,ideal}$ being the expected intensity for the ideal distribution. For normalization, the RMS is divided by the ideal (constant) intensity within the flat-top. It should be noted that the evaluation criterion is different from the criterion used for optimization. While small values of the merit function usually lead to "good" intensity distributions, the optimization particularly ignores diffraction effects as it is only based on ray tracing. This sometimes leads to systems where the beam diameter after the first telescope is so large that diffraction at the aperture of the DM heavily distorts the achieved intensity distribution. Generally, apertures with diameters less than twice the beam diameter ($1/e^2$ intensity) are to be avoided when working with single-mode lasers for beam-shaping to minimize noticeable diffraction effects [9]. Thus, the magnification range of the telescopes must be limited to avoid too large beam sizes. Even in the best case scenario, diffractive effects always smear out the edges of the flat-top distribution. With the here chosen focal length, beam size and target distributions, RMS values of less than 20 % are not possible when considering the whole intensity distribution. As the RMS calculates the mean quadratic deviation from the target, the edges have a very strong influence as the target value jumps directly from the maximum value to zero (or vice versa). This leads to large quadratic deviations in the whole transition region (here defined as the region where the intensity falls from 90 % to 10 % of its maximum value). As the diffraction effects are similar for all mirrors in this test case, the RMS is only calculated for regions outside the transition region. The width of the transition region is roughly the diameter of a diffraction limited spot (without the DM) (here: 52 µm) [9].

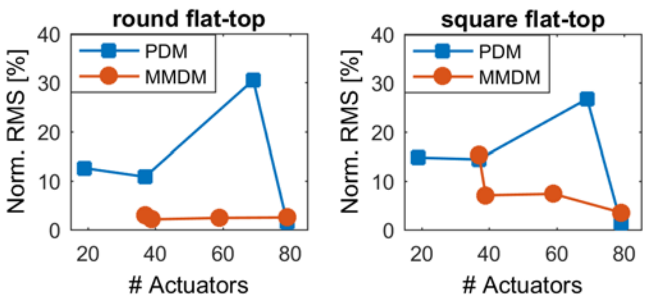

Fig. 3. Norm. RMS values for shaping a 500 µm round and square flat-top

4.3. Discussion of results

Fig. 3 shows the RMS values for both target distributions based on the mirror technology and the number of actuators.

MMDMs seem to be ideal for creating round flat-top distributions. As their edges are fixed they naturally create almost ideal, round surface shapes when the middle of the membrane is pulled down. This also explains why the number of actuators has basically no influence here. PDMs on the other hand struggle to create round distributions especially with a low number of actuators. But while the 79-actuator PDM even surpasses the best MMDM, the 69-actuator PDM is a heavy outlier. A possible explanation is that the actuators in the 69-actuator PDM are positioned in a square grid while the other mirrors usually have hexagonal actuator geometries [5].

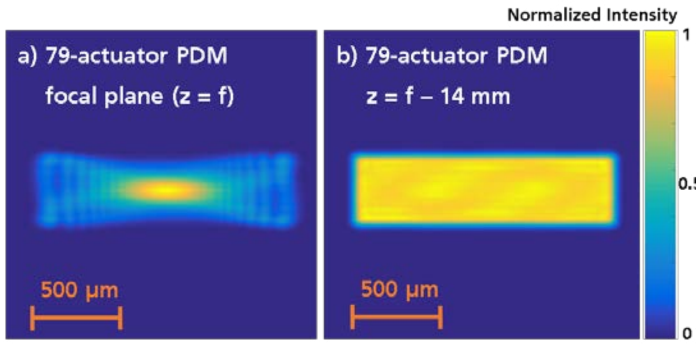

Fig. 4. 1500x400 µm² flat-top shaped in (a) and outside of (b) the focal plane

For the square flat-top distribution, the fixed edges of the MMDMs seem to be an issue as it is more difficult to create surface shapes that break the rotational symmetry. However, the more actuators the MMDM has the better this can be compensated. The 79-actuator PDM is again able to create a basically diffraction limited flat-top while the other PDMs fail to create a real flat-top distribution. Noticeably, the 69-actuator PDM is again an outlier even though the target intensity has now the same symmetry as the actuator geometry.

The 79-actuator PDM is also able to shape even larger intensity distributions with aspect ratios > 3:1 as shown exemplarily in Fig. 4. The figure also shows the best-effort optimization when the target plane is fixed in the focal plane of the focusing lens (cf. section 4.1).

5. Conclusion and Outlook

While the demand for adaptive beam shaping systems for high power laser systems (≥ 500 W) is rising, the beam shaping capabilities of DMs with different technologies and actuator numbers were not yet systematically investigated.

Within this work, a set of different membrane mirrors and piezoelectric deformable mirrors are modelled and their beam shaping capabilities to form an extended round and square intensity distribution are analyzed. Membrane mirrors show very good results for shaping round distributions, due to the inherently round shape of the deformed membrane, but struggle to shape square distributions with high uniformity. Piezoelectric deformable mirrors seem to show better results for both round and square distributions at least when a sufficient number of actuators is used. As a result, piezoelectric deformable mirrors with a sufficient number of actuators seem to be the favorable choice for the creation of arbitrary shapes.

Future work will need to validate the results within experimental setups. To better understand any possible shortcomings of the models used to describe the deformable mirrors, an interferometric setup will be used to directly measure the surface shapes of a deformable mirror. This may allow to improve the used model without the need for computational more expensive modeling methods.

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