SF2A 2010
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SPACE ACTIVE OPTICS: IN SITU COMPENSATION OF LIGHTWEIGHT PRIMARY MIRRORS' DEFORMATIONS

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Abstract. The need for both high quality images and light structures is a constant concern in the conception of space telescopes. The goal here is to determine how an active optics system could be embarked on a satellite in order to correct the wave front deformations of the optical train. The optical aberrations appearing in a space environment are due to mirrors' deformations, with three main origins: the thermal variations, the weightlessness conditions and the use of large weightlighted primary mirrors. We are developing a model of deformable mirror as minimalist as possible, especially in term of number of actuators, which is able to correct the first Zernike polynomials in a specified range of amplitude and precision. Flight constraints as weight, volume and power consumption are considered. Firstly, such a system is designed according to the equations from the elasticity theory: we determine the geometrical and mechanical characteristics of the mirror, the location of the forces to be applied and the way to apply them. Then the concept is validated with a Finite Element Analysis, allowing to optimize the system by taking into account parameters absent from the theory. At the end, the mirror will be realized and characterized in a representative optical configuration.

Keywords: active optics, elasticity, aberrations correction, deformable mirror, space telescope

1 Introduction

The need for both high quality images and light structures is a constant concern in the conception of space telescopes. In this paper, we present an active optics system as a way to fulfill those two objectives. Indeed, active optics consists in controlling mirrors' deformations in order to improve the images quality (Freeman 1982). The two main applications of active optics techniques are the in-situ compensation of phase errors in a wave front by using a corrector deformable mirror (Wilson 1987) and the manufacturing of aspherical mirrors by stress polishing or by in-situ stressing (Hugot 2009). We will focus here on the wave-front correction. Indeed, the next generation of space telescopes will have lightweight primary mirrors; in consequence, they will be sensitive to the environment variations, inducing optical aberrations in the instrument.
An active optics system is principally composed of a deformable mirror, a wave-front sensor, a set of actuators deforming the mirror and control/command electronics. It is used to correct the wave-front errors due to the optical design, the manufacturing imperfections, the large lightweight primary mirrors' deflection in field gravity, the fixation devices, and the mirrors and structures' thermal distortions due to the local turbulence (Kendrew 2006). Active optics is based on the elasticity theory (Lemaitre 2009); forces and/or load are used to deform a mirror. Like in adaptive optics, actuators can simply be placed under the optical surface (Wilson 1987), but other configurations have also been studied: a systems simplification, inducing a minimization of the number of actuators can be achieved by working on the mirror design (Lemaitre 2009). For instance, in the so called Vase form Multimode Deformable Mirror (Lemaitre 2005), forces are applied on an external ring clamped on the pupil. With this method, there is no local effect due to the application of forces on the mirror's back face. Furthermore, the number of actuators needed to warp the mirror does not depend on the pupil size; it is a fully scalable configuration.
The insertion of a Vase form Multimode Deformable Mirror on the design of an optical instrument will allow correcting the most common low spatial frequency aberrations. This concept could be applied in a space telescope. A Finite Element Analysis of the developed model has been conducted in order to characterize the systems behavior and to validate the concept.

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2 Vase form Multi-mode Deformable Mirror

2.1 Needs in space

Lightweight primary mirrors of space telescope will loose their best shape mainly because of the thermal dilatation and the weightlessness conditions (Kendrew 2006). It will induce Optical Path Differences (OPD) in the instrument corresponding to the first optical aberrations.
Following previous studies in close collaboration with the French space agency (CNES) and space industry, we can assume that correcting the first 9 optical modes Spherical3, Coma3, Astigmatism3&5, Trefoil5&7 and Tetrafoil7&9 is enough to significantly improve the wave-front quality. The rms amplitude of the wave-front to be corrected is chosen on the order of $\lambda = 632.8$ nm with a required precision of $\lambda/20$ rms in Wave-Front for each mode. The design of the correcting mirror for such an application has also to consider some particular constraints such as the weight, the volume, the power consumption or the resistance to the launch vibrations (CNES 1998).

2.2 Principles of deformation and design

A Vase form Multi-mode Deformable Mirror (VMDM) is composed of a circular meniscus, an outer ring of biggest thickness and k_m arms regularly clamped on the ring. The deformation of the pupil is obtain by applying a set of $2k_m$ forces located on the ring and at the end of each arm.
As demonstrated by Lemaitre (2005), such a system can compensate a set of Zernike polynomials verifying $n = m$ or $n = m + 2$ (with n and m the radial and azimuthal orders).Given the symmetry of the modes needed to be generated to meet our specifications, we have chosen to use a mirror with 12 arms, allowing creating the deformations in several orientations. Furthermore, in order to correct the spherical aberration, a central clamping on the back face of the mirror, fixed at its base, is added relatively to the usual VMDM design (Fig.1).
In order to have a light system, the dimensions of the studied mirror have been reduced to a minimum: the diameter of the equipped mirror (including the arms) is set to 130 mm. All the mirror's characteristics have been optimized to obtain the most efficient system possible. For that purpose, a Finite Element Analysis (FEA) has been performed.

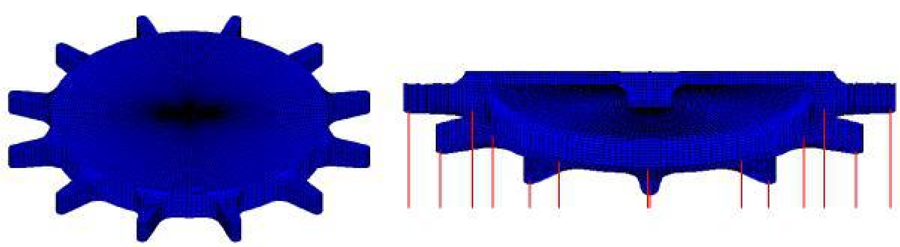

Fig. 1. Finite Elements model of the studied VMDM (77879 nodes, 63708 hexaedrical elements)

3 Correcting system performances

3.1 Influence Functions and Eigen Modes

Leaning on a VMDM's FEA model (Fig. 1), we develop a method to determine the needed forces using the phase decomposition on the mirror's influence functions base (Gray 2008; Paterson 2000). The influence function of an actuator, ϕ_i^{IF}, is the resulting mirror surface shape when that actuator is given a unit command. For a VMDM configuration, there are two types of influence functions: the deformation maps when we push the end of the arm, and when we push on the ring. The influence functions base gives also access to the system's eigen modes. They are shown in Figure2 They are very close to optical aberrations and represent an orthogonal base of the system: linear combinations of them give all the deformations that the system is able to produce. The modes are classified from the less to the more energetic.
The decomposition on the mirror's influence functions or eigen modes allows characterizing the mirror in a fast and accurate way. In the FEA model, we acquire the $2k_m$ influence functions. The decomposition of a phase map on this characteristic base permits to reconstruct the deformation that the system is able to generate. Comparing it to the initial phase, the precision of the correction is determined.

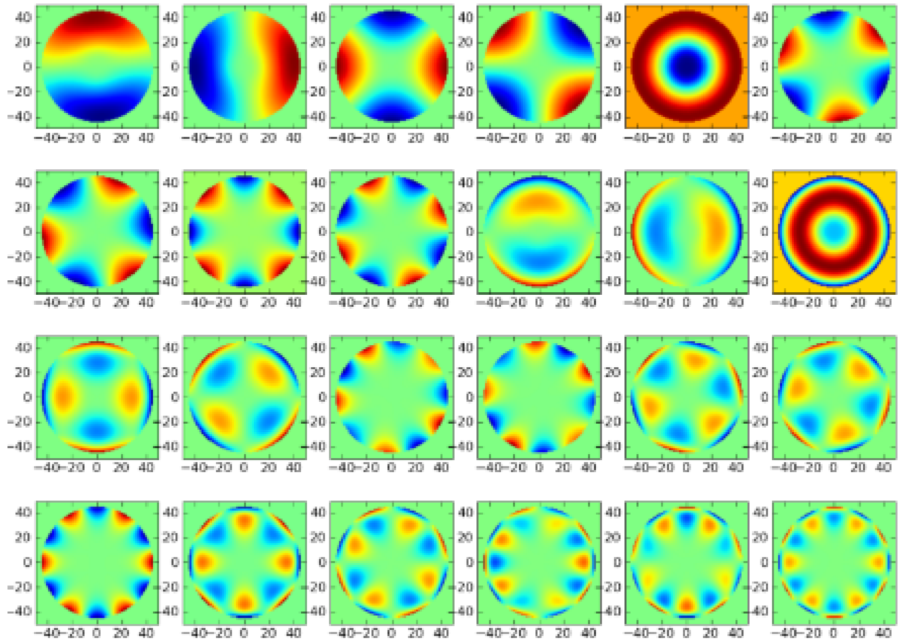

Fig. 2. Mirror's Eigen Modes

3.2 Precision of correction

The purity of each mode is determined by calculating the residues obtained when the aberration is corrected with an amplitude of λ. The results are presented in Figure3, left. With less than 2% of residues, the Coma3, Trefoil5 and Astigmatism3 are precisely corrected (WFE< $\lambda/60$ rms). Trefoil7, Tetrafoil7 and Astigmatism5 can be generated with 5% of residues and they are just at the $\lambda/20$ specification. On the other hand, the Spherical3 and Tetrafoil9 aberrations induce more residues (around $\lambda/8$). We can note that residues mainly come from the presence of the central clamping and from the difference between the modes' symmetry and the mirror symmetry. The residues projection on the Zernike polynomials base shows that they are composed of harmonics of the considered aberration.
The projection on the influence functions base gives the values of displacement to be applied in order to generate the given phase. Applying those values in the FEA model we can visualize the mirror deformation (Fig3, right). This last step allows us to validate the decomposition method and to study the system behavior (displacements, stress in the material etc.).

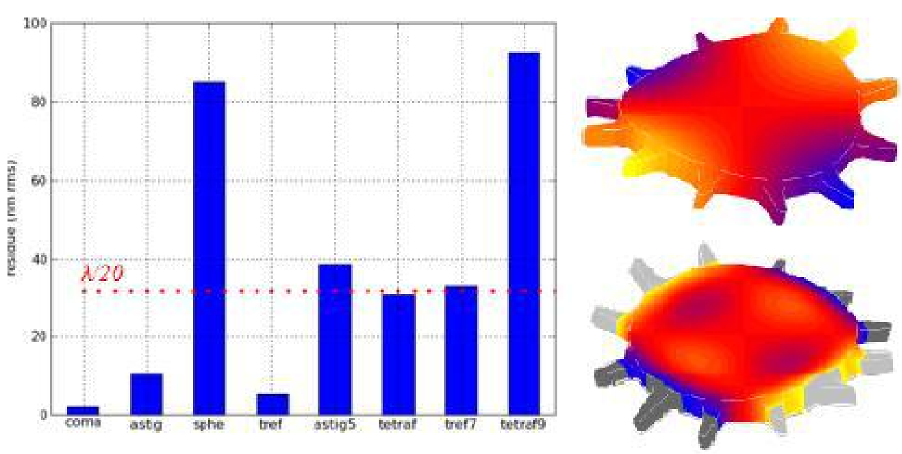

Fig. 3. Left: Residues for a modal correction of 1λ - Right: Mirror deformation corresponding to Astigmatism3&5

It is important to study the mirror's performances in a situation close to the real functioning of this correcting system. In such a case, the wave-front to be corrected will be a combination of the 8 modes presented before plus others minors terms. Because the generation of Spherical3 and Tetrafoil9 induces a too much residues, we decide to correct them only up to an amplitude of $\lambda/3$, so that the amount of residue is lower than $\lambda/20$ for each mode.
Firstly, we consider the worst case: the incident phase is composed of the 8 aberrations at their maximum amplitude. The residual error is then about $\lambda/8$ rms.
To have a representative idea of what the system can achieve, we calculate the residues after the correction of a random phase map. The OPD map is created by adding all the modes, balancing them with a random coefficient between 0 and their maximum corrigible amplitude. Studying the statistics after several random draws gives the expected mean precision achievable by the system. For 1000 random maps, the mean precision correction achieved is around $\lambda/15$ rms with a standard deviation of $\lambda/60$.

4 Conclusions

The very simple concept of Vase form Multimode Deformable Mirror seems to be applicable and very efficient to improve the wave-front quality in a space telescope. We have seen in this paper that it allows correcting, with a good quality, the first Zernike polynomials: Comas, Astigmatisms, Trefoils and Tetrafoils. The spherical aberration can also be generated with the presence of a central clamping on the mirror's back face. In addition, this holds the entire system. A system with 12 arms is preferred because it can easily create shapes of several symmetries. To characterize the system, we have considered the mirror's influence functions and eigen modes. Knowing these characteristics, the correction capabilities have been determined for each mode separately and for more representative phases. With this work, we have defined some specifications for the amplitudes that can be corrected in an efficient way.
The Comas3, Astigmatisms3&5, Trefoils5&7 and Terafoils7 are easily generated at amplitudes around 1λ rms with a precision better than $\lambda/20$ rms. The corrections of Spherical3 and Tetrafoils9 require more energy and are less precise; we choose to correct them at a maximal amplitude of $\lambda/3$ rms to obtain the same precision. The element inducing a significant part of the residues is the central clamping, but it allows the generation of Spherical3 despite the absence of an uniform load. Simulating the correction of random phase maps, the mean residual phase is around $\lambda/15$ rms.
Those results are promising for the application of such a concept to the compensation of the deformations in a large space telescope. The next step is to realize a prototype of this correcting mirror and test it in a representative configuration.

Acknowledgments
This study is performed with the support of a Ph.D grant from CNES (Centre National d'Etudes Spatiales) and Thales Alenia Space, within a project of the Research and Industry Optical Cluster 'PopSud/Optitec'.

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