Active optics and corrective holographic gratings: a general recording method applied to COS/HST 2003

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A general recording method applied to COS / HST 2003

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1. Multimode Deformable Mirrors

Aberration corrected gratings are useful to design spectrographs having the minimum of optical surfaces, thus minimizing light loss such as needed for astronomical instruments. For instance, many space orbiters spectrographs for the uv and euv are using as sole optics a single concave grating. Basically, the holographic recording process requires the formation of an interference pattern which is frozen into the photosensitive layer of the grating substrate. One of the two recording wavefronts must be aspheric in order to obtain aberration corrections. Up to now, the formation of an aspheric wavefront requires to design and built a special optical system providing the opposite shape of the wavefront to be corrected. Generally, such a compensating system is complex, expensive and only usable for making a particular grating. Also, various type of aberrations cannot be simultaneously achieved with such optical systems, therefore leading to great difficulties for correcting high order aberrations with holographic gratings.

A general method for recording corrected diffraction gratings without requiring to the above sophisticated optical systems, has been conceived (Duban & Lemaître 1998). This uses a plane multimode deformable mirror (MDM) (Lemaître & Wang 1995). The MDM provides a quasi-all-order optical path compensator which should give rise to a universal recording method.

As an exemple of the method, one have considered the recording of the three holographic gratings of the HST Cosmic Origins Spectrograph (COS) (Green 1998, Morse et al. 1998). Very substantial improvements in the image quality has been found (Duban 1998, Lemaître & Duban 1998) by use of a MDM as recording compensator. The result is that i) much higher order aberrations can simultaneously be corrected, and therefore ii) the residual blur images of the spectra occupy \( \approx 25-30 \) times smaller areas than those obtained up to now. Thus, this new method provides large 2D gains i.e. both in spectral resolution and in limiting magnitude.

The elasticity design, object of the present analysis, has been investigated at the Laboratoire d’Optique de l’Observatoire de Marseille (LOOM) and has been followed up by the construction and performance evaluation of active vase form mirrors fitted with radial arms. This concept provide the basic features of multimode deformable mirrors. Drum form mirrors have been suggested in the past by Couder (1931) for making lighten mirrors. Vase form mirrors are quite similar to those mirrors. With the first 12-arm MDM design and optical evaluation (Lemaître & Wang 1995 and Moretto & Lemaître 1995), the analysis shows the strong mathematical link between the elasticity theory i.e. Clebsch’s polynomials and the optical theory of aberrations i.e. the wavefront polynomials or Zernike’s polynomials. We propose to name this active optics modes Clebsch-Zernike polynomials.

Active optics methods, pioneered by B. Schmidt, already lead to high performance concepts for large telescopes (ESO NTT and VLT primaries, CFHT, THEMIS and TEMOS 4 secondaries, Keck primary segments, LAMOST primary and secondary segments), for astronomical interferometry in the visible (highly variable curvature mirrors for the delay lines of the VLTI), as well as for focal instrumentation (axisymmetric and non-axisymmetric aspherized mirrors and gratings).
2. Elasticity design of a vase form MDM in the CTD class

Active MDM compensators for new grating recording methods have to realize the coaddition of many deformation modes such as, for instance, a 1st order curvature mode Cu1, 3rd order modes Sphe3, Coma3, Astm3, and 5th order modes Astm5, and Tri5, the latter mode being of tertiary symmetry. This contracted denotation is useful and usual in opticians’ terminology. If needed, higher order modes could be compensated by an adaptive system. However, the elasticity theory shows that higher order modes could also be generated.

Given the number of modes to be generated and the difficulty of easily superposing more than two modes with mirrors belonging to the Variable thickness distribution (VTD) class (Lemaitre 1989), a mirror belonging to the Constant thickness distribution (CTD) class has been investigated. A preliminary goal was to match up the number of actuators with the geometrical modes to achieve. It has been found that forces applied onto discrete azimuths equally distributed along the mirror perimeter would be optimal for generating axi and non-axisymmetry modes. An important aspect of the design is the fact that the discrete position actuators have to generate, in both radial and tangential directions, a smooth and continuous deformation at the proximity of the boundaries. The shear component of the deformation due the punctual forces provide a slope discontinuity at position where the force apply. This component has a much more local effect and is of much smaller amplitude than the bending component of the deformation, but nevertheless it is preferable to minimize the shear component by avoiding puntual forces directly applied onto the optical surface even at the mirror edge. For continuity reasons, these punctual forces has to be applied at some distance from the optical surface such as presented here.

Following the Saint-Venant’s principle (see Germain & Muller 1994) led to the design of a vase form, i.e. a mirror having two concentric zones of constant rigidity (Lemaitre 1980). The outer zone is thicker than that of the clear aperture which is the inner zone. The two zones are clamped together and punctual forces are applied onto the outer ring. Apart from minimizing the shear deformation to a negligible value at the optical surface, another advantage a thicker ring is to provide a regular modulation of the tangential deformation generated by discrete forces. Because of large axial forces and important tangential moments to apply on the outer ring, several radial arms have been found preferable to complete the mirror design.

Fig. 1 - Elasticity design of a multimode deformable mirror - MDM - showing a two-zone rigidity and radial arms. The clear aperture zone is built-in at \( r = a \) into a thicker ring. The holosteric shape allows one to achieve the Clebsch-Zernike deformation modes i.e. \( Cu1, Sphe3, Coma3, Astm3, Astm5, Tri5, Tri7, Squa7, Squa9, ... \) by the action of axial forces \( F_{a,k} \) and \( F_{c,k} \) applied to the ring inner radius \( r = a \) and to the outer end \( r = c \) of each arm (here \( k_m = 12 \) arms). Except for the mode \( Sphe3 \) which is achieved by addition of uniform air pressure or depressure \( q \), all other above modes, obtained with \( q = 0 \), belong to the central and upper-adjacent diagonals of the optics triangular matrix.

Figure 1 displays the basic design of a multimode deformable mirror. The clear aperture zone \( 0 < r < a \), is built-in into a thicker outer ring \( a < r < b \), so that the mirror can be easily machined as a holosteric piece. Both axial forces and tangential torques will be applied to the discrete positions of the outer ring. Each actuator is able to generate a positive or a negative axial force. The forces applied at the internal circle \( r = a \) are denoted \( F_{a,k} \); those applied at the external circle \( r = c \) are denoted \( F_{c,k} \) with here \( k_m = 12 \) arms i.e. \( k \in [1, 2, \ldots, 12] \). In addition, positive or negative uniform loads \( q \) can be superposed into the vase inner zone by mean of air pressure or depressure.

Let us consider a plane MDM and denote \( E \) and \( \nu \) the Young’s modulus and the Poisson’s ratio respec-
tively, $t_1, t_2$ and $D_1, D_2$ the thicknesses and associated rigidities for inner and outer zones respectively. In cylindrical coordinates, the deflected surface $Z$ is given by the Poisson’s equation (Timoshenko & Woinowsky-Krieger 1959)

$$\nabla^2 \nabla^2 Z(r, \theta) = q/D \quad \text{with} \quad D = E\tau^3/[12(1 - \nu^2)] = \text{constant},$$

and $\nabla^2 = \partial^2/\partial r^2 + \partial/\partial r \partial r + \partial^2/\partial r^2 \partial^2$ the laplacian, $D = D_1$ for $0 < r < a$, $D = D_2$ for $a < r < b$.

- On the inner zone of the vase mirror, a polynomial representation of the deformation in cylindrical coordinates is expressed as

$$Z = \sum z_{nm} = \sum A_{nm}r^n \cos m\theta,$$

where $n$ and $m$ are positive integers, $(n + m)$ is even and $A_{nm}$ coefficients belong to the triangular matrix expressing the optical path differences, i.e. $m \leq n$. For a given mode $z_{nm}$, substitution in Eq. (1) leads to

$$A_{nm}(n^2 - m^2)(n^2 - 2) = \sum q/D \quad \text{with} \quad n \geq 2. \quad (4)$$

- For $q = 0$ in Eq. (1), one finds two classes of solutions, $m = n$ i.e. $A_{22}, A_{33}, A_{44}, \ldots$ terms and $m = n - 2$ i.e. $A_{20}, A_{31}, A_{42}, A_{53}, \ldots$ terms.

- For $q = \text{constant}$, one finds $n = 4$ simultaneously with $m = 0$ i.e. the $A_{40}$ term.

This shows that the generation of $A_{20} - C_{u1}, A_{40} - S_{pe3}, A_{31} - C_{oma3}, A_{22} - A_{st2}, A_{42} - A_{st4}, A_{33} - T_{ri5}, A_{53} - T_{ri7}, A_{44} - S_{qua7}, \ldots$ modes is obtained, while it is found not possible to generate the $A_{31} - C_{oma5}$ or $A_{60} - S_{pe5}$ modes by using a uniform loading $q = \text{constant}$. A parabolic loading would be required in this case so that $A_{40}, A_{60}$ and $A_{31}$ could not be simultaneously set at any given values.

- On the outer zone of the vase mirror, a uniform load is never applied, so that the equation to be solved for $a < r < b$ is Eq. (1) with $q = 0$. The solutions are

$$Z = \sum z_{nm} = R_{n0} + \sum_{m=1}^{\infty} R_{nm} \cos m\theta + \sum_{m=1}^{\infty} R'_{nm} \sin m\theta,$$

in which $R_{n0}, R_{n1}, \ldots, R'_{n1}, \ldots$ are function of the radial distance only. In our case, one considers the same azimuth of the deformation as that given by Eq. (4), so that the third functions $R'_{nm}$ vanish. The functions $R_{nm}$ are Clebsch’s solutions of

$$\left(\frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr} - \frac{m^2}{r^2}\right)\left(\frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr} - \frac{m^2}{r^2}\right) = 0. \quad (6)$$

For $m = 0, m = 1$ and $m > 1$, the functions $R_{nm}$ have the following forms

$$R_{n0} = B_{n0} + C_{n0} \ln r + D_{n0}r^2 + E_{n0}r^2 \ln r,$$

$$R_{n1} = B_{n1} + C_{n1}r + D_{n1}r^2 + E_{n1}r^3 \ln r,$$

$$R_{nm} = B_{nm}r^m + C_{nm}r^{-m} + D_{nm}r^{m+2} + E_{nm}r^{m+2}. \quad (7)$$

The boundaries between the two zones at $r = a$ must provide a continuity of the flexure $z_{nm}$, slope $dz_{nm}/dr$, bending moment $M_r$ and shearing force $Q_r$

$$M_r = -D \frac{\partial^2 z}{\partial r^2} + \nu \left(\frac{1}{r} \frac{\partial z}{\partial r} + \frac{1}{r^2} \frac{\partial^2 z}{\partial \theta^2}\right), \quad Q_r = -D \frac{\partial}{\partial r} (\nabla^2 z). \quad (8)$$
Denoting $\gamma = D_1/D_2$ as the rigidity ratio between the two zones ($\gamma < 1$), for $\forall \theta$, the four continuity conditions provide the coefficients $B_{nm}, C_{nm}, D_{nm}$ and $E_{nm}$ in Eqs. 7 by respect to $A_{nm}$ and allow the determining the distributions of bending moments $M_{r}(r, \theta)$ and shearing forces $Q_{s}(r, \theta)$, applied to the ring and namely at its edge $r=b$. These determinations are done for each considered mode.

For example, one finds for the 5th order astigmatism mode, i.e. $n=4, m=2$, $A_{42} = A_{s} m 5$

$$B_{42} = 3(1-\gamma)a^2 A_{42}/2,
C_{42} = -(1-\gamma)a^4 A_{42}/2,
D_{42} = \gamma A_{42},
E_{42} = 0,$$

$$M_{r}(b) = -2D_{2}[1-(1-\nu)B_{42} + 3(1-\nu)C_{42}/b^4 + 6D_{42}b^2 - 2\nu E_{42}/b^2],
Q_{s}(b) = -8D_{2}[3D_{42}b + E_{42}/b^2].$$

In order to realize $M_{r}$ and $Q_{s}$ at $r=b$, it is to be noticed that the MDM design gains in compactness by applying the axial forces at $r=a$ and $r=c$ instead of at $r=b$ and $r=b$. With this choice, the axial forces are denoted $F_{a,k}$ and $F_{c,k}$ (cf. Fig. 1) and defined by the statics equilibrium relationships

$$F_{a,k} + F_{c,k} = b \int_{\pi(2k-1)/k_m}^{\pi(2k-1)/k_m} Q_{s}(b, \theta) \, d\theta,$$

$$Q_{s}(b) = -8D_{2}[3D_{42}b + E_{42}/b^2].$$

with $k = 1, 2, ..., k_m$ for a MDM having $k_m$ arms.

The $F_{a,k}$ and $F_{c,k}$ are determined for each mode $A_{nm}$ by starting from the corresponding equation set $B, C, D, E$ provided by the continuity conditions and then allowing to express $M_{r}(b), Q_{s}(b)$.

3. A 6-arm MDM elasticity design for a Clebsch-Zernike 6-mode coaddition

A 6-arm multimode deformable mirror has been designed which is able to provide the coaddition of 6 Clebsch-Zernike modes. This is for developing the new recording method of holographic gratings and particularly to the case of the Cosmic Origins Spectrograph of HST 2002.

Compared to glass or vitroceram materials, metal mirrors present several features that are of interest in the achievement of large deformation active surfaces. The gain in flexibility-ratio $\sigma_{lm}/E$, is larger than 100. This is basically due to the much higher yield strength $\sigma_{lm}$ of metal alloys. Two other selective criteria for selecting metal substrates are a perfect stress-strain linearity in the sense of Hook's law and a broad elastical range. With respect to these criteria, quenched FeCr13 is well known, otherwise metal alloys such CuNi18Zn20 or TiAl6V4 could be experimented, but Al predominant alloys show more restrictive linear ranges and are impossible to polish without metal overcoat.

A performance evaluation has been carried out with two prototype MDMs. Their optical figure were flat while at rest and having a clear aperture of 8 cm. The selected metal alloy was FeCr13, since this is a material that has a long term experience at LOOM. After this selection, the optimization of a convenient flexibility has been done by determining the rigidities $D_1$ and $D_2$ i.e. the thicknesses $t_1$ and $t_2$, with respect to the maximum stress. The maximum stress has been kept lower than the yield strength of the FeCr13 material which is 1200 N/mm$^2$. This does not take into account a possible quenching process of this material that could substantially increases this limit if necessary in a further stage. In order to respect the 3D homogeneity of the substrate, the 6 radial arms were not added to the vase mirror but machined into the substrate in a one piece device by a numerical command machine. The deformations are obtained by control of the rotation of 9 differential screws linked between the arms and the support; the 3 remaining screws located at $\theta = 0, \pm 2\pi/3$ and $r = a$ are not active since defining the reference plane of the deformations. The geometrical parameters of the 6-arm MDM are displayed by Figure 2.
The elastic constants are $E = 2.05 \times 10^4$ daN.mm$^{-2}$ and $\nu = 0.305$ for the Young's modulus and the Poisson's ratio respectively. The mirror geometry is defined by the thicknesses $t_1 = 5$ mm and $t_2 = 14$ mm for the central plate and outer ring respectively. The radial parameters are $a = 40$ mm, $b = 54$ mm and $c = 80$ mm. This geometry provides a rigidity-ratio $1/\gamma = D_2/D_1 = (14/5)^3 \approx 22$ and an aspect ratio $2a/t_1 = 16$. The axial forces $F_{a,k}$ and $F_{c,k}$ are applied to the ring inner radius $r = a$ and to the outer end $r = c$ of the radial arms ($k_m = 6$) built-in to the ring.

The axial distribution of forces $F_{a,k}$ and $F_{c,k}$ applied to the MDM has been determined for each of 6 Clebsch-Zernike modes having a PtV deformation of $1 \mu m$ at $r = a = 40$ mm for $\theta \in [0, 2\pi]$. This result is displayed by Table 1.

### TABLE 1 - Axial distribution of forces $F_{a,k}$ and $F_{c,k}$ applied to a 6-arm MDM.

The amplitude of the modes $z_{nm} = A_{nm} r^n \cos m\theta$ has been set for a PtV deformation of $1 \mu m$ at $r = a = 40$ mm for $\theta \in [0, 2\pi]$, thus corresponding to $A_{20} = 6.260E-7$, $A_{40} = 3.90628E-10$, $A_{22} = A_{20}/2$, $A_{31} = 7.8125E-9$, $A_{33} = A_{31}$ and $A_{42} = A_{40}/2$, in mm$^{-n}$

<table>
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<tr>
<th>$\theta / \pi$</th>
<th>$k$</th>
<th>$F_{a,k}$</th>
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<th>$F_{a,k}$</th>
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* The required uniform loading for producing the Sph3 mode is $q = 0.0018886$ daN.mm$^{-2}$

### 4. Optical design of the COS gratings and MDM, recording parameters

The three COS gratings must correct the residual spherical aberration of the Hubble Space Telescope (HST). Therefore it is not possible to keep the grating substrates purely spherical. Thus we have introduced fourth and sixth degree deformations on the grating substrates, i.e. $z_{40}$ and $z_{60}$ terms.

Since the COS incident beam is located 5.40 arcmin off the HST optical axis, we also have been led to correct the HST astigmatism which produces an astigmatism length of 1.20 mm. The three holographic gratings use the Optimized Rowland Mounting (Duban 1987, Duban 1991) in such a way that the recording parameters cancel the astigmatism at two points $P1$ and $P2$ of the spectrum. We have demonstrated that, as a very general result which is also valid for the COS gratings, this mounting is the only one really suitable for obtaining the Astm3 compensation.

Table 2 displays the spectral data in Å and Table 3 displays the grating parameters, where $N$ is the groove density in $l$.mm$^{-1}$, $R$ the radius of curvature of the grating substrates in mm, $\lambda_0$ the laser recording wavelength, $i$ the incidence angle at the HST, $\alpha$ and $\beta$ the recording angles in deg. Table 4 displays the deformation coefficients of the grating substrates in mm$^{-n+1}$. Substrates of gratings #1 and #2 are identical. Table 5 displays the deformation coefficients in mm$^{-n+1}$ and the incidence angle $i_{MDM}$ upon the MDM in deg. For the recording, the distance from the laser source 1 to the MDM is 1100 mm for gratings #1 and #2, and 1000 mm for grating #3. Of course, all the parameters can easily be modified slightly, if necessary, in order to exactly match the COS geometry of detector positioning.
Spot diagrams are calculated at five wavelengths for each grating as displayed in Figs. 3, 4 and 5. The wavelengths in Å are those listed in Table 2 and correspond - from left to right - to $\lambda_{\text{min}}$, $P_1$, the middle of the spectrum $\lambda_{\text{med}}$, $P_2$, and $\lambda_{\text{max}}$. The correction of astigmatism at points $P_1$ and $P_2$ is evident. The resolving power of the f/24 HST images at the input of COS is $1.22 \lambda f/d = 3.8 \mu m$ at 1300 Å and the concave gratings provide a magnification $\approx -1$. Despite of the simplification here provided by axisymmetric

grating substrates, the images given by gratings #1 and #2 are diffraction limited with respect to the resolution over the main part of the spectral range, and are very nearly diffraction limited at the extremities. In addition, the image heights have a similar size compared to our precedent studies. With
6. MDM tuning of the 3-mode coaddition for COS / HST

Figure 7 displays views of MDM #1 in its mounting and of the rear side of MDM #2 alone. Figure 8 displays single modes $Cu_1$, $Astrom_3$, $Coma_3$, $Tri_5$ and $Astrom_5$ obtained with the 6-arm MDM #2. In accordance with Table 1, the mode $Sphe_3$ could be obtained by applying some air pressure or depressure inside the MDM vase form. This equipment is not necessary for COS.

Fig. 7 - Views of MDM #1 in its mounting - with the nine differential screws and three reference points onto the inner ring - and of MDM #2 alone.

Fig. 8 - He-Ne interferograms of MDM #2 at full aperture 80mm showing single modes $Cu_1$, $Astrom_3$, $Coma_3$, $Tri_5$ and $Astrom_5$. By respect to Table 1, $Sphe_3$ could be obtained by air pressure or depressure inside the MDM vase form.

From the data such as given by Table 5, a fringe map can be drawn in order to provide theoretical model of the deformation to achieve. For the case of the COS grating #1, this reference map at $\lambda_{HeNe}=632.8$ nm is displayed by Figure 9. The $F_{a,k}$ and $F_{c,k}$ forces such as given by Table 6 have been generated to the MDM by use of a dynamometric wrench. The forces are applied to 9 differential screws that provide 100$\mu$m displacement for a $2\pi$ rotation. The 3 remaining points at $r=a$ and $\theta=0$, $\pm 2\pi/3$ are not actuated but provide the reference plane of the deformation. In the case of COS grating #1, the obtained MDM shape at $\lambda_{HeNe}$ is displayed by Figure 9.
Fig. 9 - Full aperture He-Ne interferograms (80 mm) of MDM #1 tuned as optical path compensator for the holographic recording of the COS grating #1 (3800 l/mm). The three modes Coma3, Tri5 and Astm5 have been coadded by generating forces $F_{c,k}$ and $F_{o,k}$ such as given by Table 6. [Up] Obtained shape, [Down] Theoretical shape.

A 80 mm circular aperture of COS gratings - which is larger than the $73.2 \times 68.8$ mm$^2$ area lighten up by the f/24 HST incident beam for $i=20^\circ$ - corresponds to a recording beam at the MDM of $42.9 \times 53.3$ mm$^2$ for gratings #1, and little smaller for #2 and #3. On this MDM recording area, the PtV deviation of the interferogram is better than $0.2 \lambda_{HNe}$. This can be partly checked by the reader in making a convenient scaled up transparent from the synthetic interferogram.
7. Conclusion

Although the deflexure of a concave or convex MDM will not be exactly identical to the present case of plane MDMs, the analysis remains valid for curved optical surfaces up to f/4 or f/3. The elasticity design is very similar to that of active Cassegrain mirrors in vitroceram glass already developed at LOOM, since using a two-zone rigidity design of the vase form. The outer ring provides the respect of Saint Venant’s principle by avoiding slope discontinuities of the shear component that would be caused at the optical surface by punctual force applications. The linked arms provide the most accurate distribution of the tangential deformations with a minimum of actuators. In addition to the particular case for \( A_{40} \) which is not used for COS, the generation of two families deformation modes \( A_{nm} \) has been found. The first family of solutions is given by \( m = n \) i.e. \( A_{22}, A_{33}, ... \) modes and the second by \( m = n - 2 \) i.e. \( A_{20}, A_{31}, ... \) modes. We have named these active optics polynomials *Clebsch-Zernike modes*.

Plane and 6-arm MDMs designed as *aberration path compensators* provide easily the first six Clebsch-Zernike modes \( A_{20}, A_{40}, A_{31}, A_{22}, A_{42} \) and \( A_{33} \). As presently shown and compared to the state of the art, our active optics method provides very effective 2D gains in resolution and sensitivity:

- for all three gratings, *the COS spectral resolution \( \lambda/5\lambda \) would be increased by a factor 10*, and
- in addition, for the two more dispersive gratings, the limiting magnitude (perpendicular direction) is higher, *i.e. the COS sensitivity on the sky appears to be increased of \( \approx 1-1.2 \) mag*.

Plane MDMs are useful for developing a new and *universal* method of producing high order corrected gratings by holographic recording. They will certainly bring a milestone to the constructing technology of holographic gratings. The MDM #1 has been cordially made available to the COS team and Jobin Yvon Corp. At the moment, COS is expected to be mounted on the HST in 2003.

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