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LETTER

Letter to the Editor

A general method of holographic grating recording with a null-powered multimode deformable mirror

The case of the Cosmic Origins Spectrograph for HST 2002

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Abstract. A new general method for recording high resolution holographic gratings by using a null-powered multimode deformable mirror is described. Up to now, the principle of this active method has been applied only to make gratings correcting a single aberration mode. The extension of the method to gratings correcting several aberration modes is proposed. An analogy between Clebsch modes (Clebsch 1861, Saint Venant and Flamant 1881) in elasticity, and Zernike modes in optics, allows generation and coaddition of aspherical surfaces up to a high order in aberration compensation. To illustrate the efficiency of the method in a difficult case, the three gratings for the Cosmic Origin Spectrograph have been computed. Their working conditions take into account the compensation of the HST residual spherical aberration. The image quality obtained are *nearly diffraction limited* in the direction of the dispersion and also in the other direction for the third, less dispersive, grating. The three grating substrates are aspherical but retain *rotational symmetry*, thus being easily achievable by an active "vase form" and by spherical polishing. Only *three optical modes* have to be coadded onto the multimode deformable mirror. We propose to call such an active mirror form a "multimode mirror" or a "Clebsch-Zernike mirror". This general method will greatly simplify grating manufacturers' holographic recording mountings.

Key words: holographic gratings – grating recording – high resolution – active optics – elasticity – multimode mirrors – Clebsch-Zernike mirrors – aberration compensators

1. Introduction

Achieving high resolution over a large spectral range with a diffraction grating requires good correction of astigmatism, coma, spherical aberration and higher order aberrations. In the case of instruments requiring diffraction gratings and few optical surfaces, these corrections are generally obtained by combining the use of aspheric grating substrate and aspheric recording waves during the holographic recording process (Lemaitre 1974, Lemaitre 1980, Duban 1987, Huber et al. 1988, Duban 1991, Duban 1993).

By using grating subtrates with or without rotational symmetry, the new idea is to generate gratings when one of the two laser recording sources is aberrated by reflection onto a plane multimode deformable mirror (hereafter MDM) actively controled by force distributions applied at its perimeter (Lemaitre 1989, Lemaitre and Wang 1995).

As a typical example, this method has been found particularly promising for the difficult case of recording the gratings for the Cosmic Origins Spectrograph (COS) presently investigated (Green 1997, Green 1998, Morse and Green 1998) as a Hubble Telescope replacement instrument for the 2002 reservicing mission.

Compared to our previous studies on the recording conditions of the COS gratings (Duban et al. 1998a, Duban et al. 1998b, Duban et al. 1998c) leading to fully diffraction limited images but requiring numerous aspherical coefficients for both the MDM and grating substrates, the main interest of the present study is the simplification of grating substrates now having *rotational symmetries*, and the ease with which the null-powered MDM can provide very nearly diffraction limited images with only *three single modes* of aberration. This will allow reduction of fabrication costs and schedules as well as spectrograph designs of improved performance.

2. A multimode or "Clebsch-Zernike" deformable mirror

Active optics methods are particularly efficient in generating *very smooth aspherical surfaces* (Lemaitre 1974, Lemaitre 1980, Huber et al. 1988, Lemaitre 1989). When a large variety of optical modes have to be simultaneously generated, it has been shown (Lemaitre and Wang 1995) that the

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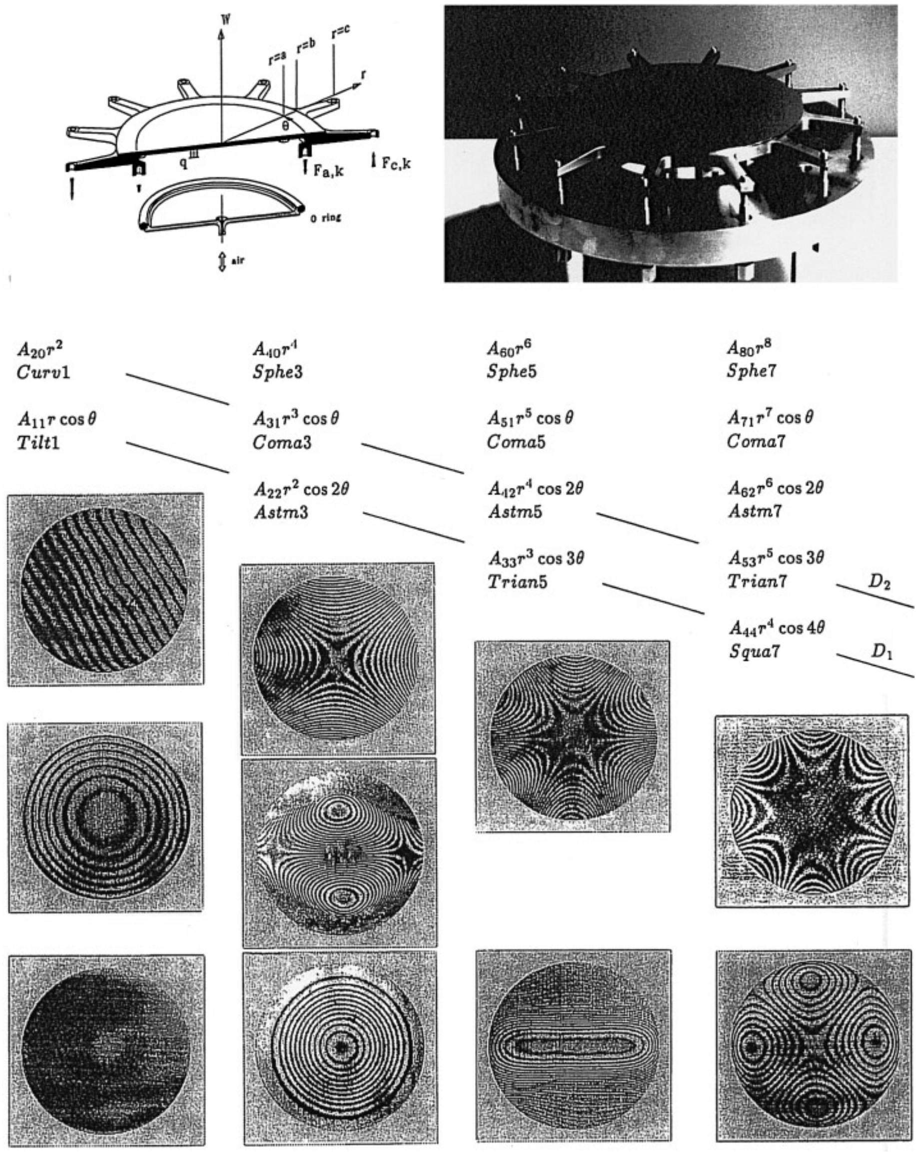

Fig. 1. He-Ne wavefronts obtained with a prototype Multimode Deformable Mirror (MDM) also proposed to be called a "Clebsch-Zernike mirror". Clear aperture d=160 mm. Aspect ratio $d/t = 40$.

Clebsch's elasticity modes are in a *perfect analogy* with the Zernike's optical modes. Following this concept, a MDM has been designed, built and tested, as shown by Fig. 1.

In this case, the elasticity analysis has led us to design a plane deformable mirror having a two-zone rigidity. The inner zone, which is the optical clear aperture, has a *built-in* link to a thicker outer ring. Discrete radial arms are distributed onto the ring rear face. With respect to the ring's mean radius, the small angular size of each arm allows us to achieve the best continuity of axial and slope deformations when forces $F_{\mathrm{i},k}$ and $F_{\mathrm{o},k}$ act on the inner and outer ends of each arm respectively. The ring allows the continuity transfer of required flexions to the inner zone boundary. We have proposed to name such configurations "*multimode mirrors*" as well as "*Clebsch-Zernike mirrors*". In active optics, they belong to the vase mirror class[9] that we already developed (see also Sect. 5).

It has been shown (Lemaitre and Wang 1995) that two multimode families can be generated by perimeter axial forces and radial moments. Denoting, in cylindrical coordinates, $Z = \sum z_{nm} = \sum A_{nm}\, r^n \cos m\theta$, a polynomial series defining a surface where n and m are positive integers, $(n + m)$ even and $A_{n,m}$ the matrix coefficients, the theory of optical path differences restrict the terms to those of a triangular matrix, i.e. $m \leq n$. The co-addable solutions z_{nm} are thus obtained by solving $\nabla^2\nabla^2\, Z(r, \theta) = 0$. These are:

– the matrix terms $m = n$ of the lower diagonal D_1 of Fig. 1, i.e. for the first modes

$$A_{11} \equiv Tilt\,1,\ A_{22} \equiv Astm\,3,\ A_{33} \equiv Tri\,5,$$
$$A_{44} \equiv Squa\,7\ldots,$$

– the matrix terms $m = n - 2$ of the upper diagonal D_2 of Fig. 1, i.e. for the first modes

$$A_{20} \equiv Cv\,1,\ A_{31} \equiv Coma\,3,\ A_{42} \equiv Astm\,5,$$
$$A_{53} \equiv Tri\,7\ldots,$$

– and further, if a uniform load (air pressure or partial vacuum) is applied to the inner zone of the MDM, which correspond also to its clear aperture, a particular solution of $\nabla^2\nabla^2\, Z(r,\theta) = q/\mathrm{D}$, where D is the rigidity of the inner zone, is obtained by a linear combination of z_{20} and z_{40}. This later mode is

$$A_{40} \equiv Sphe\,3\ .$$

By actively substracting $z_{20} = A'_{20} r^2$ with the perimeter forces, i.e. varying the curvature by an opposite value $A'_{20} = -A_{20}$, a pure z_{40} mode is obtained. This solution, characterized by the term $Sphe\,3$, can be coadded to those of the two previous families.

The MDM prototype displayed in Fig. 1 was designed for another application (off-axis telescope corrector) having a 160 mm clear aperture diameter, 4 mm thickness (aspect ratio d/t=40), FeCr12 alloy and with 12 arms, permitting coadditions up to $m + n = 8$, i.e. 9 modes including two 7th-order aberrations. The analytic determination of force distributions $F_{i,k}$ and $F_{o,k}$ has been done for $k = 1, 2, .., 12$ and $q = 0$ or $q \neq 0$ (Lemaitre and Wang 1995). Detailed testing of large amplitude deformations has been carried out for $Astm\,3$, which has shown no plastic effect for a 2mm PtV deflection. Interferometrical testing of single modes and of some coadded modes have demonstrated the validity of the elasticity analysis and design.

A tolerance analysis has shown that a multimode deformable mirror made using this technique will meet the COS requirements for use in the proposed method of recording holographic gratings. An elasticity design of an MDM for recording the COS gratings has been optimized with a 70 mm clear aperture where only 6 arms, i.e. $k = 1, 2, ..6$, have been found sufficient.

3. Gratings and mounting parameters in the COS-HST case

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 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 astigmatism compensation ($Astm\,3$).

Table 1 displays the spectral data in Å and Table 2 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, λ_0 the laser recording wavelength, i the incidence angle, α and β the recording angles in deg. Table 3 displays the deformation coefficients of the grating substrates in mm^{-n+1}.

Table 1. Spectral data in Å.

Grating	$\lambda_{\min}$	$P1$	$\lambda_{\rm med}$	$P2$	$\lambda_{\max}$
#1	1150	1185	1295.5	1382	1449
#2	1405	1456	1589.5	1684	1774
#3	1230	1320	1615.0	1810	2000

Table 2. Grating and geometrical recording parameters.

Grating	N	R	λ_0	i	α	β
#1	3800	1652.0	3511	19.886	−36.089	48.171
#2	3052.6	1652.0	3511	19.538	−25.750	39.592
#3	380	1613.4	4880	2.106	−4.025	6.618

Table 3. Substrate coefficients [deformations in μm].

Grating	A_{40}	A_{60}
#1	1.913E-9	9.14E-14
	[2.68]	[0.15]
#2	1.913E-9	9.14E-14
	[2.68]	[0.15]
#3	1.822E-9	1.03E-13
	[2.33]	[0.15]

Table 4. MDM coefficients and incidence angle.

Grating	A_{31}	A_{33}	A_{42}	$i_{\rm MDM}$
#1	4.821E-8	−5.582E-8	−2.172E-9	29.96°
#2	1.880E-8	−2.671E-8	−2.360E-9	16.92°
#3	0.512E-8	−0.003E-8	−0.180E-9	10.00°

Substrates of gratings #1 and #2 are identical. Table 4 displays the deformation coefficients in mm^{-n+1} and the incidence angle $i_{\rm MDM}$ 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.

4. Results with such gratings for COS

Spot diagrams are calculated at five wavelengths for each grating as displayed in Figs. 2, 3 and 4. The wavelengths in Å are those listed in Table 1 and correspond – from left to right – to $\lambda_{\min}$, $P1$, the middle of the spectrum $\lambda_{\rm med}$, $P2$, and $\lambda_{\max}$. The correction of astigmatism at points $P1$ and $P2$ is evident. Despite of the simplification of the substrates and of the MDM, the images given by gratings #1 and #2 remain diffraction limited with regard 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 grating #3, of low dispersion, both the widths and the heights of the images remain diffraction lim-

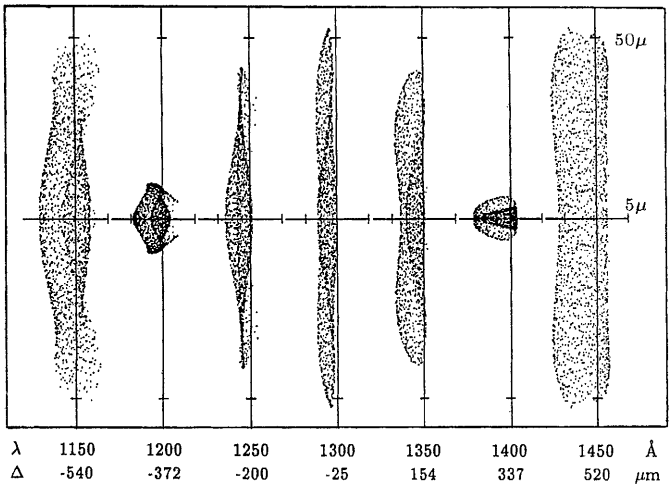

Fig. 2. Spot-diagram given by grating #1, 3800 l.mm^{-1}.

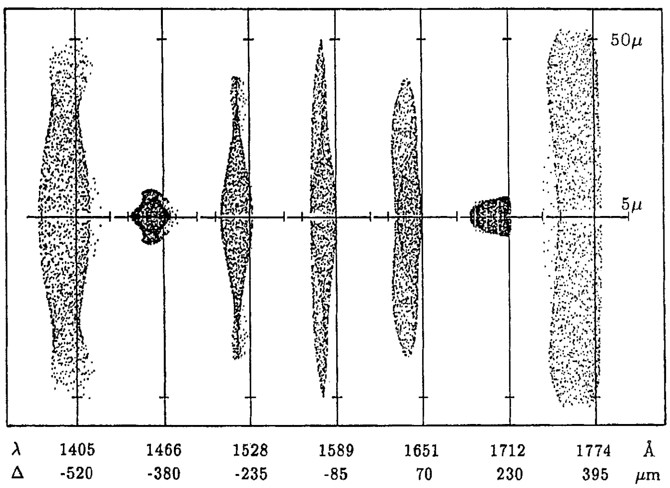

Fig. 3. Spot-diagram given by grating #2, 3052.6 l.mm^{-1}.

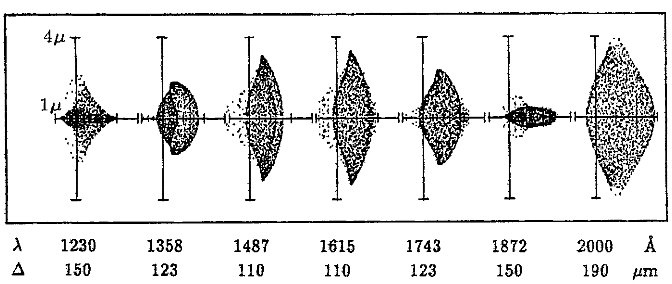

Fig. 4. Spot-diagram given by grating #3, 380 l.mm^{-1}.

ited. In Figs. 2, 3 and 4 and for each color, Δ is the focusing onto the principal ray with respect to the Rowland circle. A positive Δ means an increase of the image distance to the grating vertex.

5. Vase form grating substrates

The asphérization of rotationally symmetric optics has been extensively used with "*vase form*" vitro-ceram substrates as well as metal substrates. Such substrates are designed with a meniscus of quasi-constant thickness built-in into a stiff outer ring (Lemaitre 1980). NC command machines currently make the required shape within a correct accuracy. The aspherization is obtained by air pressure or depressure depending whether the spherical polishing is done

– during the deformation: parabolization and hyperbolization of telescope secondary mirrors [GI3T (Lemaitre 1980), THEMIS (Lemaitre 1989)],

– before the deformation: ellipsoid secondary mirrors shaped in situ for a telescope with a spherical primary [TEMOS (Lemaitre and Wang 1995)] or active substrates for the replication of aspherized gratings of many faint-object spectrogaphs under collaborations with Jobin-Yvon Corp. and Hyperfine Corp. (Lemaitre 1981, Lemaitre and Kohler 1990, Lemaitre and Richardson 1998).

This is a low cost technology providing very smooth optical profiles and twice-lighter substrates than more conventionnal ones, which is particularly appropriate for the COS grating substrates.

6. Conclusion

This new and general method appears as useful and efficient for nearly all types of grating spectrographs. In particular, we have examined the applicability of these technique to the Cosmic Origins Spectrograph recently selected for use aboard the Hubble Space Telescope and to be launched in 2002.

In this proposal, *the grating substrates are all of rotational symmetry*, the substrates for grating #1 and #2 are identical. Even for the highest groove density of 3800 l.mm^{-1}, the computed deformations are at least forty times smaller than the maximum achievable with the existing MDM. Further, *only three odd modes have to be coadded onto a new* 6-*arm* MDM. These are namely $Coma\,3$, $Tri\,5$ and $Astm\,5$. Such a MDM has been designed for making the COS gratings that would provide optical tolerances, as a recording compensator, fully within achievable practice. Thus, the COS spectrograph aberrations have been reduced to the *diffraction limit* in resolution for gratings #1, 2 and 3, and in a much smaller number of pixels in the perpendicular direction to the dispersion for gratings #1 and 2.

The method, particularly promising for the COS gratings, will greatly simplify grating manufacturers' holographic recording mountings. It appears to be powerful and of general interest since MDM compensations remain efficient even under the difficult conditions of correcting much more aberration modes than those to be corrected by the grating mounting itself.

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