International Journal of Scientific & Engineering Research Volume 8, Issue 7, July-2017 1752
ISSN 2229-5518

Optical method for measurement of radius of curvature of large diameter mirrors

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Abstract. An optical method is presented for measurement of radius of curvature of large diameter metal mirrors and lenses. This method is based on 3D profile measurements through the aperture of optics. Measurements also provide information about positive or negative curvatures on optical surfaces. The method was used for measurement of radii of curvatures of optical surfaces involving both opaque as well as transparent optics, mirrors and lenses. The results are compared with those obtained by Twyman-Green interferometer. In all measurements, the measured value was found within ±2% of designed value for respective optics.

Index Terms: laser resonator mirrors, ROC measurement, 3D profiles measurements, Twyman-Green interferometer, Characterization of mirrors and lenses.

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1 INTRODUCTION

The determination of Radius of Curvature (ROC) of curved optical surfaces such as mirrors and lenses plays a vital role in design and manufacturing of optical components. There are applications where curvature of optical surface is required to be maintained to high degree of accuracy to meet the objectives. Some of these applications include large diameter optical telescopes and laser resonators, specifically unstable resonators that utilize curved mirrors as end reflectors with curvature tolerances within ±5% or even better depending upon the application. For example, unstable con focal resonators in much high power laser systems employs spherical metallic OFHC copper mirrors with radii of curvature ranging from few meters to tens of meters. Radii of curvature of these mirrors are required to be maintained with precession to meet the objectives. Any deviation in ROC from its designed value during mirror fabrication, leads to violation of confocality of resonator which ultimately results in reduced peak intensity of the beam in far field. For a typical 3m long resonator involving beam magnification of around 2.0, the fabrication tolerance of radii of curvature of mirrors must be within ±2%. Accurate determination of radii of curvature of resonator mirror is therefore essential for evaluating the performance of resonators. A number of optical and mechanical methods are reported in the literature [1]-[4],[7], [8] for measurement of radii of curvature of laser mirrors. Twyman-Greens interferometer [5] and Newton's rings methods are widely used in industries and optical shops for measurement of radius of curvature for characterization of mirrors.

In Twyman-Green interferometer, the light is collimated by means of a lens to form plane wave fronts. The wave front is then divided by a beam splitter to produce reference and source wave fronts. The two wave fronts are then combined after reflection from two flat mirrors to form an interference pattern. One of the flat mirrors is replaced by the test sample that is a mirror or a lens for measurement. The interference pattern thus obtained provides the measurement of radius of curvature of test sample. In Newton's ring method, the test sphere is placed in contact with test sample and the interference of light reflected between two surfaces separated by a small air gap forms interference pattern called Newton rings. The measurement of radius of n^{th} ring provides radius of curvature of test sphere. Interferometer methods are indirect measurement methods for radius of curvature measurement. There are many other methods for Radius of curvature measurements like zone plate interferometer [6], spherometer, computational holography etc. In mechanical methods, the curvature of spherical surface is measured by a spherometer where separation between the vertex and curvature center of mirror is measured by a precision translation stages. In the present paper, a non contact optical method is presented for measurement of ROC for large radii mirrors. This method utilizes a high precision compound microscope of large magnification to generate a high resolution 3-D surface profile of test sample for measurement. The measurement data are then analyzed through Quadra check software in PC to compute the curvature profile of test sample along its principal diameter of by the method of best curve fit.

2 MEASUREMENTS PRINCIPLE

The radius of curvature of mirror is the radius of sphere from where a part of spherical surface is removed for mirror fabrication. In case of large ROC, the mirror is fabricated by profiling the front surface by diamond turning in such a way so as to fit it in to a sphere. In this method the curvature of spherical optical surface is measured by measuring the Z co-ordinate of a point along the diameter of mirror. This is achieved by focusing the microscope objective at various points along the diameter of mirror.

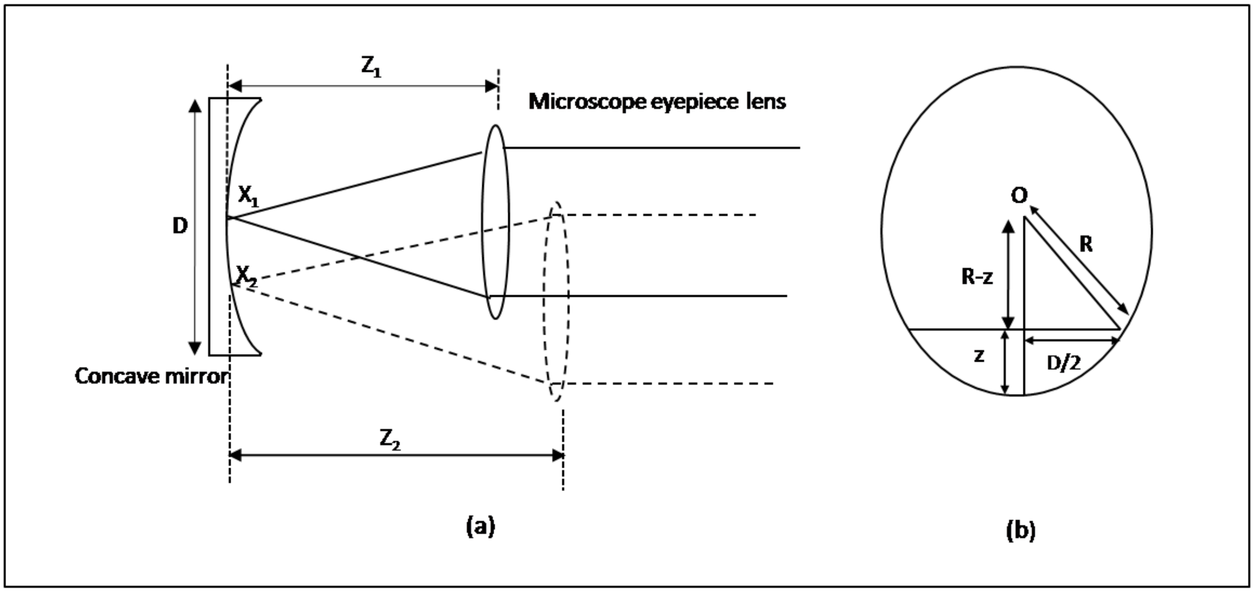


Fig.1 Principle of ROC measurement for curved spherical mirrors

The principle of measurement of radius of curvature is illustrated in Fig 1(a). Here x_1 and x_2 are the points along the diameter of the mirror whose z coordinates are z_1 and z_2. Mirror under measurement is placed on to a translation stage which is free to move along horizontal and vertical directions in X-Y plane. The objective of microscope is focused at mirror center and mirror is scanned along one of its principal diameter along x axis. The corresponding X-Z coordinates of number of points of mirror surface are recorded. The surface curvature profile of the mirror is then generated through Quadra- Check software by feeding X-Z coordinates of various points along the diameter of mirror. Fig- 1(b) represents test sphere a part of which is has been used for fabrication of mirror under measurement. If D represents the diameter of a spherical mirror with sag of Z at the center, the radii of curvature of mirror from Fig 1 (b) given by:

$$R^2 = (R - Z)^2 + \left(\frac{D}{2}\right)^2 \qquad (1)$$

The X-Z surface profile measurements provide a mean for determination of radii of curvature for mirror.

3. MEASUREMENT SET UP

The measurement set up employs a high magnification compound microscope the, Vision 3 -D measurement system from Vision Engineering Ltd, UK with facility of performing 3-D measurements on samples. Such microscope works on principle of magnified image. Unlike the conventional microscope having a small exit pupil to produce high resolution image of an object, camera based profile projection systems of vision 3D measurement system have very large exit pupil and is easy to use but resolution, contrast and brightness suffers. In the present system, the optical path is redefined with multi lens rotating array which expands the exit pupil by more than a factor of 100X. The optical scheme of this system is presented in Fig-2.

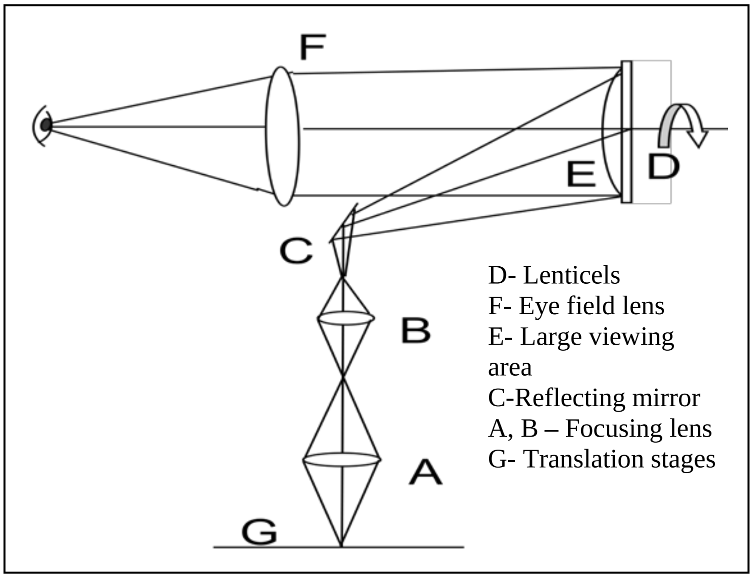


Fig. 2 Optical scheme of measurement

The essential part of the system is a multi lenticular disc surface D comprising of millions of individual lenticels. Each lenticel measures few microns in diameter. This disc spins at very high speed so as to merge millions of individual optical paths and delivers a smooth expanded-pupil stereo image having a generous depth of focus along with wide field of view. The multi-lenticular disc, thus serves to expand the intrinsic pupil of the system. The resultant image is observed through the field lens F to the operator's eyes and a high-resolution image is projected onto a large viewing area, E for maximum viewing comfort. System consists of an illuminating light source, a translational platform, a microscope, and the interface with quadra- check software. The mirror under measurement is placed on precision X-Y translation stage G, which has linear translation accuracy of 2µm. The microscope is arranged normal to mirror surface with liner translation accuracy of 2 µm along Z-axis. The objective is focused at various points on mirror surface along its principal diameter by moving the objective along z direction. The movement along 3 axes X, Y and Z generates 3D images of object. The measurement data of position coordinates in XZ plane along the diameter are acquired and processed in PC through quadra-check software. The curvature profile of mirror is then generated by analyzing and plotting of data through software. The radius of curvature of mirror is computed by the method of best curve fit. The software requires initial adjustment to set reference for coordinate system. This is achieved by setting initial reference coordinates (0, 0, 0) along X, Y, Z axis of the machine. The object, like an optical mirror for which the measurements to be performed, is placed on the translational stage and the reference plane is set by adjusting Z-axis at 4 points on mirror surface in a cyclic order. The linear translation stage is pre aligned and calibrated with an optical flat.

The number of points to be selected for measurements depends upon the diameter of the mirror. A large number of points should be selected for best curve fit on measured data. For measurement in X, Z plane along the diameter of mirror care should be taken so that Y axis is not disturbed. The measurement accuracy is dependent on magnification of compound microscope and the accuracy of translation of microscope objective along Z direction. The accuracy can be enhanced by employing large magnification for microscope objective. Maximum dimension and size of optics for measurement is restricted by the dimensions and movement of linear translation along horizontal and vertical directions which is restricted to 150mm for the present system of measurement.

4 RESULTS AND DISCUSSION

Measurements were performed to measure the radii of curvature for both opaque as well as transparent glass and Zn-Se optics. These mirrors are meant for application in optical resonators for laser generation. The results of theoretical sag calculated by equation (1) and experimental sag measured with vision 3 -D measurement system are shown in table 1. The first set of mirror comprises 15330mm radius of curvature OFHC concave mirror with diameter 90mm and 13330mm

ISSN 2229-5518

radius of curvature OFHC convex mirror with diameter 70mm for 1000mm long resonator with magnification of 1.15. The measured curvature profiles of mirrors for this set of mirrors are shown in Fig. 3 (a) and 3 (b) respectively.

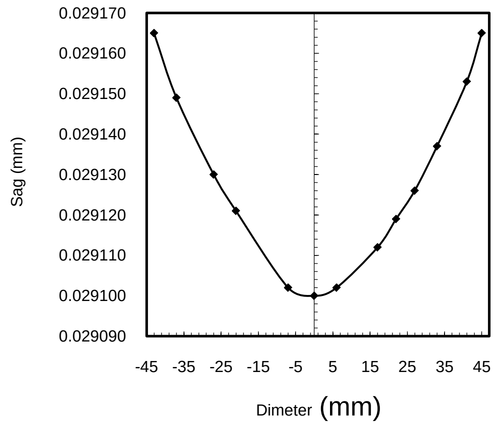


Fig. 3(a) Measurement data for concave mirror

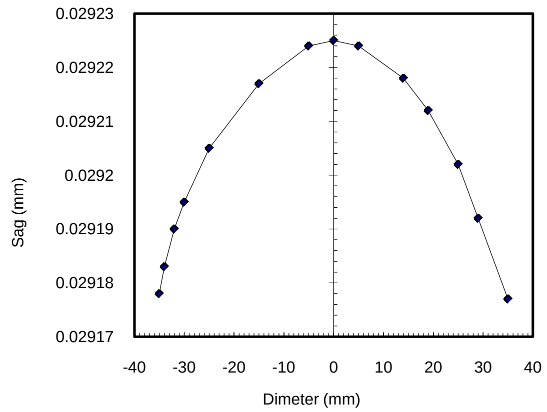
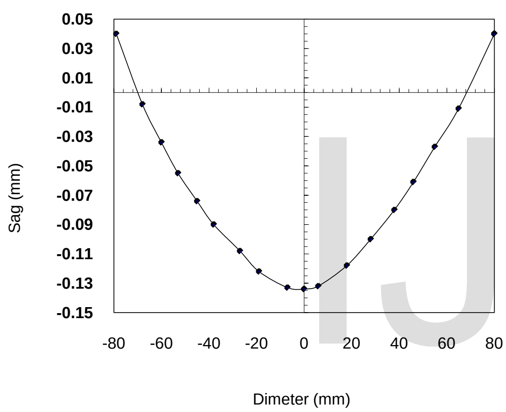


Fig. 3(b) Measured data for convex mirrors

The second set of mirrors comprises of concave and convex mirrors of radii of curvatures 8400mm and 14275mm and diameters 88 mm and 150 mm respectively for 3000m long resonator magnification of 1.7.



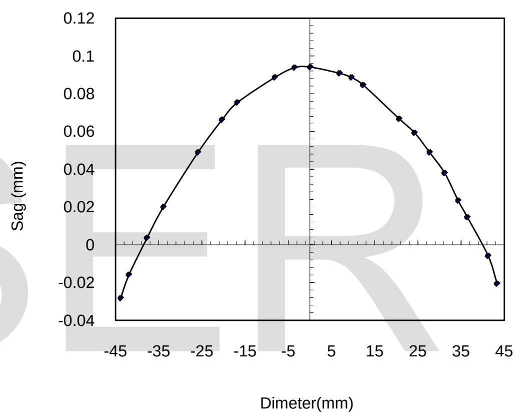


Fig. 4(a) Measurement data for concave mirror

Fig. 4(b) Measured data for convex mirrors

Corresponding curvature profiles are shown in Fig. 4 (a) and 4 (b) respectively.

The third set of measurements were performed on similar mirrors with radii of curvatures 16020mm concave and 10020mm convex mirrors with diameters 150mm and 94mm respectively for resonator magnification of 1.6. Corresponding profiles are shown in Fig. 5(a) and 5 (b) respectively. Measured mirror profile gives information regarding positive and negative curvature and mirror bowing at the center of the mirror.

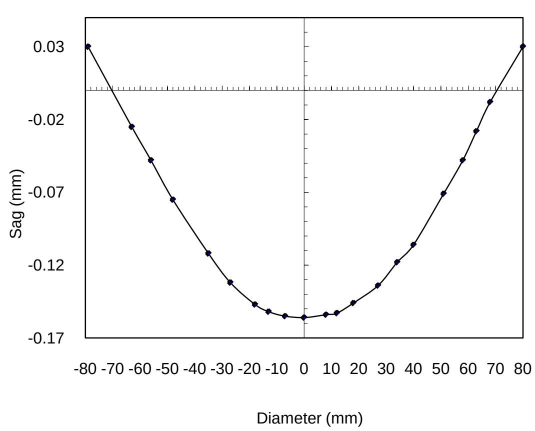


Fig. 5(a) Measurement data for concave mirror

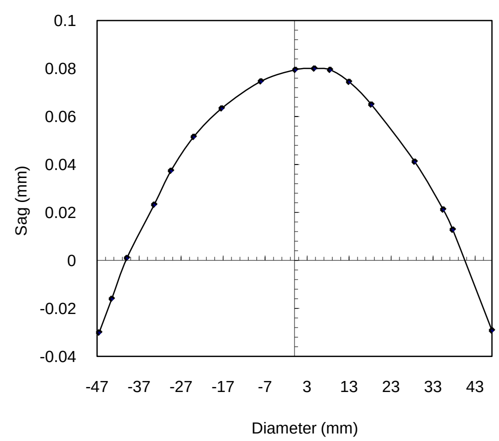


Fig. 5(b) Measurement data for convex mirrors

From these experiments, it is evident that the measured sag values are negative for concave mirror and positive for convex mirror.

The results of theoretically calculated and experimentally determined value of sag at the center and the corresponding values of ROC are summarized in Table 1.

TABLE 1

MEASUREMENT OF RADIUS OF CURVATURE OF CONCAVE AND CONVEX MIRRORS

Set No	Type of Mirror	Diameter (mm)	Calculated sag (µm) at centre	Theoretical ROC (mm)	Experimental determined ROC (mm)	Measured sag (µm)	Deviation in Roc (%)
1	Concave mirror	90	66	15330	15513	65	1.19
	Convex mirror	70	46	13330	13144	46.6	1.39
2	Concave mirror	150	197	14275	14315	196	0.28
	Convex mirror	88	115	8400	8342	116	0.6
3	Concave mirror	150	175	16020	16145	174	0.78
	Convex mirror	94	110	10020	10072	109	0.5

The results of measurements for first set of mirrors were compared with results obtained by Twyman Green interferometer. These measurements are presented in Fig. 6.

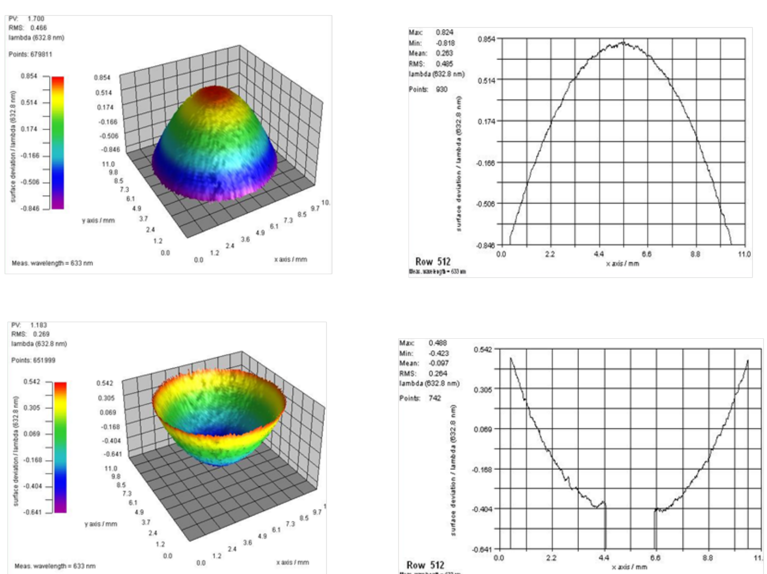


Fig. 6 Measurement of radii of curvature from Twyman Green interferometer

The radii of curvature measurements by Twyman Green interferometer for first set of mirrors in table-1that is concave of diameters 90 mm with radius of curvatures 15330mm and convex mirrors of diameter 70 mm with radii of curvature 13330mm respectively revealed a value for radius of curvature of 14518 mm for concave mirror and 13982 mm for convex mirror. This gives measurement accuracy within ±5% for both mirrors by Twyman Green interferometer method. This is indicative of superiority for the present methods over Twyman Green interferometer method.

5. CONCLUSIONS

In this paper, we report a direct non-contact optical method for measurement of the radius of curvature for large diameter mirrors. The superiority of this method over conventional interferometer methods is the method provides a direct non contact measurement for delicate optical surfaces across the entire clear aperture of optics. The method does not require any standard optical flat or test spheres for measurements. The method is much simpler and do not require complicated test procedures for measurements. The real advantage of this method is determination of radii of curvatures for large diameter optics with small curvatures where it is difficult to make standard test spheres to perform measurements over the entire optical surface. The method offers better measurement accuracy for such measurements.

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Acknowledgements

The authors are extremely grateful to Sh. H B Srivastava, Director, Lastec for providing all facilities and support for publishing this work.