HIGH STABILITY OPTO MECHANICAL MIRROR MOUNTS FOR UNSTABLE RESONATOR

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ABSTRACT

This paper presents design methodology of a set of high stability opto mechanical mirror mounts with provision for auto alignment of unstable resonator mirrors for high energy laser system. Both mirror mounts have provision for manual and auto alignment of resonator. The mounts with mirror assembled at the opposite ends of a resonator supporting frame provide alignment and in situ check for misalignment of resonator with accuracy better than 20 arc seconds for a 3 m long linear unstable resonator. The optical method for alignment of resonator and check for alignment accuracy is described.

Key words: High Stability, Mirror Mounts, Opto Mechanical, Auto Alignment, Gear Wheels, Position Sensing, Parallelism, Alignment Accuracy, Unstable Resonator, High Power Lasers, Gas Dynamics, Coarse and Fine Alignments.

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1. INTRODUCTION

High mechanical and thermal stability is an important consideration for design of optical resonator for high power laser (HPL) systems [1]. In much high power gas flow and chemical laser systems such as, TEA excited CO$_2$ Lasers, Chemical Oxy Iodine Laser, HF-DF and gas dynamic lasers, the conditions for laser generation are created by electrical, chemical or thermal excitations in laser gain medium [2]. For example, in gas dynamic lasers gas mixture containing carbon dioxide, nitrogen and water vapor is produced by combustion of suitable fuel and oxidizer in a combustor. The gas mixture at high pressure and temperature is subsequently passed through a supersonic nozzle for creating conditions for laser generation in the medium. The laser is then extracted from medium by optical resonator placed downstream of the nozzle. Initiation of combustion in the combustor and supersonic flow of gases through laser cavity cause intense shock and vibrations in the system and may cause misalignment of resonator. Though optical resonator in such high power
laser system is totally isolated from laser cavity, the possibilities of transmitting shock and vibrations to the resonator system through coupling between resonator and laser cavity containing gain medium cannot be ruled out. Moreover, high thermal conductivity of laser mirrors and the heat flowing through mirror mounting block during extraction of laser from resonator also results in misalignment for resonator mirrors. This paper presents the design of high stability opto mechanical mirror mounts for a linear unstable resonator in high energy laser system for operation under harsh environments. The mounts also provide an in situ check for alignment of resonator with provision for realignment so that the laser could be repeatedly fired in short succession in case of misalignment [3, 5].

2. DESIGN OBJECTIVES AND REQUIREMENTS

A high power laser system utilizing Unstable Resonator for laser generation requires a higher order of optical and mechanical stability for extracting high quality laser beam from resonator. A low rigidity and stability of mirror mounts in resonator results in the misalignment of mirrors that leads to the degraded performance of laser in terms of reduced output power and beam quality from resonator. Misalignment of resonator also results in loss of directionality of laser. The tolerance for mirror misalignment in a resonator is dependent on number of factors such as geometry of laser resonator, resonator length, diameter of mirrors etc. There are several causes for misalignment of resonator in high energy laser systems as mentioned above. Sometime the laser systems are required to be mounted on mobile platforms that are subjected to large mechanical shock and vibrations and to be operated under harsh industrial and military environments. All these factors may cause misalignment of resonator. Moreover lasers for directed energy applications are required to be operated in succession within a time interval of few seconds. This restricts the in situ check and the manual realignment of resonator for intended laser application within the time available between successive laser operations. This necessitates the requirement of high stability opto mechanical mirror with following design objectives:

1. Alignment of resonator for required alignment accuracies of the order of 10-20 arc sec for 3 m long linear unstable resonator.
2. Provision for alignment of both mirrors for all combinations of (x,y) coordinates.
3. High stability for mirror mounts to take care of shock and vibrations in the system.
4. High rigidity for mirror mounts for positioning of laser system and/or Resonator on mobile platform.
5. The In situ check for misalignment of resonator within required alignment accuracy.
6. Provision for both manual and auto alignment of resonator.
7. Maintaining the directionality of output beam from resonator for successive intended laser operations.

3. DESIGN OF MIRROR MOUNTS

The set of resonator mirror mounts consists of mirror mount for concave mirror and convex mirror for extraction of laser beam from resonator.

Each mirror mount assembly consists of following sub assemblies:

1. Assembly for mirror holding plates.
2. Coarse alignment assembly.
3. Mirror alignment rings for finer alignment of mirror.

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3.1. Design of concave mirror Mount

The base material of fabrication for both mirror mounts is INVAR due to its low coefficient of thermal expansion making it suitable for operation at elevated temperatures. Low coefficient of thermal expansion provides high thermal stability for mirror mounts. The material properties of INVAR are presented in table 1.

<table>
<thead>
<tr>
<th>Sr No.</th>
<th>Properties</th>
<th>Invar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Elastic modulus</td>
<td>1.44x10^11 N/m²</td>
</tr>
<tr>
<td>2</td>
<td>Poisson ratio</td>
<td>0.23</td>
</tr>
<tr>
<td>3</td>
<td>Shear modulus</td>
<td>7.5x10^10 N/m²</td>
</tr>
<tr>
<td>4</td>
<td>Thermal expansion</td>
<td>1.8x10^-6 /Kelvin</td>
</tr>
<tr>
<td>5</td>
<td>Mass density</td>
<td>8150 kg/m³</td>
</tr>
<tr>
<td>6</td>
<td>Thermal conductivity</td>
<td>13 W/m.K</td>
</tr>
<tr>
<td>7</td>
<td>Specific heat</td>
<td>480 J/kg.K</td>
</tr>
<tr>
<td>8</td>
<td>Yield strength</td>
<td>2.75x10^8 N/m²</td>
</tr>
<tr>
<td>9</td>
<td>Tensile strength</td>
<td>4.5x10^8 N/m²</td>
</tr>
<tr>
<td>10</td>
<td>Compressive strength</td>
<td>0 N/m²</td>
</tr>
</tbody>
</table>

The design schematic of concave mirror mount is shown in figure 1. The mirror mount assembly consists of:

1. The main stationary plate 1 of dimensions 340x340 mm and thickness 11 mm. This plate has 4 holes of diameter Φ11 mm for its attachment on resonator flange, 2 holes M20 for brad and 3 holes of diameter Φ13 mm for attachment of coarse alignment screws. This plate has rectangular opening of dimensions 161x221 mm for exposure of mirror to laser cavity.

2. A circular ring of diameter Φ164 mm, 7 & a circular disc, 8 of diameter Φ120 mm. The inner circular disc has attachment with ring through a special pair of bush arrangements and can slide over the ring in a vertical plane. The outer ring has attachment with mobile plate through another pair of special brushes. This ring can rotate with respect to mobile plate in horizontal plane. The mirror is implemented at the centre of disc through 4XM6↓10 bolts at PCD70.

3. Two stepper motors with a gear assembly, 3 with provision for attachment of motor with gear wheels. Design and construction of gear wheels is given in section 3.1.4.
Four. Three symmetric coarse alignment assemblies, 4 at 120° on centre of mobile plate for rotation of mobile plate in horizontal and vertical planes for coarse alignment of mirror. The design of coarse alignment assembly is given in section 3.1.1.

5. Quadrant detector assembly, 5 for sensing the misalignment of convex mirror held at the opposite end through a diode laser beam originating from diode laser assembly implemented on mobile plate 6. Quadrant detector assembly is described in section 3.1.2.

6. Laser diode assembly, 2 for installation and alignment of diode laser beam reflected from convex mirror on quadrant detector.

The assemblies 2 and 5 are firmly attached to the mobile plate 6. The mobile plate can be turned with respect to stationary plate through coarse alignment adjusting module and ball joint. This arrangement provides the alignment of mirror in both horizontal and vertical planes in the range ±2° with accuracy better than 10 arc-minute.

The pusher of motor has elastic connection with internal disc and the outer ring. The rotation of internal disc and the ring through motor in conjunction with gear wheel and card and joint the alignment of mirror in the range 1/3° with accuracy better than 2 arc sec is possible in both horizontal and vertical directions.

3.1.1. Design of Coarse alignment adjusting module

The mobile plate of both convex and concave mirror mounts can be turned in horizontal and vertical planes with the help of three coarse alignment adjusting modules. The schematic of coarse alignment adjusting module is shown in figure 2.
The assembly for coarse alignment adjusting module consists of a hemispherical barrel 4, a guiding pin 1, and the bolt 7, and the lock nut 6, special spacers 3 & 2 and the insert 5. The guide pin is strongly push fitted on to stationary plate while the thread insert have connection with mobile plate 6. The guide pin is centrally located inside the barrel. The insert and barrel make threaded connections. When the lock nut is not screwed on the bolt, it is possible to screw the barrel in the insert. Due to this the mobile plate moves with respect to stationary plate. Special spacers 2 and 3 are designed with one end flat and the other with curvature of R-30 for smooth movements over spherical ends of barrel. The curvature of barrel matches with curvatures of special spacers and decide the maximum slew between them. The inner diameter of barrel and the diameter of guiding pin decide the maximum angular tilt of mobile plate. Lock nut 6 is provided to lock the position of mobile plate on bolt and hence the aligned position of mirror. With coarse alignment adjusting module it is possible to align mirrors in both planes up to ±2° with accuracy 10 arc minutes. This accuracy and range is determined by the thread pitch of 70 TPI at the external surface of barrel and the space available between the guiding pin and the inner walls of hollow cylindrical barrel.

3.1.2. Design of quadrant detector assembly

The quadrant detector known as position sensing element is required to be rigidly mounted on to mobile plate 6 in a suitable housing for sensing the misalignment of convex mirror at the opposite end. The schematic of quadrant detector assembly is given in figure 3.
Design of quadrant detector assembly (figure 3) comprises of hollow cylindrical body 2, lock ring 3 for lens assembly, holder plate for shutter assembly 1, a shutter guiding plate 4, motor holding plate 5, shutter plate 6, stepper motor 7, casing for PCB plate 8 and quadrant detector holder plate 9. The detector housing consists of a hollow cylinder of diameter 53 mm and length 66 mm having a wall thickness of 2 mm. At the rear end of cylinder, the quadrant detector is installed through detector holder plate. The inner wall of cylinder has matching threads with threads on detector holder plate. At the front end of cylinder, a gradium lens is rigidly mounted with the help of a lens holder ring for focusing of diode laser beam reflected from convex mirror at the centre of quadrant detector. The cylinder is fixed on to holder plate of shutter assembly for its positioning on mobile plate of mirror mount assembly. A shutter assembly, 10 is incorporated in front of lens aperture for protection of lens and quadrant detector. This shutter is driven by an electric motor on control panel during operation of resonator. The on off time for shutter is controlled by three parameters that is speed of motor, total travel length of shaft for shutter attachment and TPI of lead screw. The biasing circuitry of quadrant detector is placed inside rectangular casing mounted over the cylinder.

3.1.3. Design of Laser diode assembly
A semiconductor diode laser producing laser beam at 630 nm and output power of 3 mW with divergence 1 mrad is utilised for recording the position coordinates of convex mirror onto quadrant detector in order to measure misalignment of mirror. The laser diode assembly is installed on to mobile plate 6 to avoid relative shift between laser diode and quadrant detector due to transmission
of shock and vibrations on to mirror mount. The design of laser diode mounting assembly is shown in the figure 4.

![Figure 8 Laser diode mounting assembly](image)

3.1.4. Design of Gear Wheel Assembly for stepper motor

The finer alignment of mirror is achieved through rotational motion of ring and circular disc driven through a pair of stepper motors with gear wheels. This arrangement provides high accuracy of alignment to resonator mirrors. The gear wheel assembly along with stepper motor is shown in figure-5. The whole assembly consists of Gear wheel plate spacer 1, lower plate of gear box 2, the upper plate of gear box 3, ball bearing stopper plate 4, lock nut 5 threaded bolt for alignment ring attachment 6, stepper motor 7, flexible coupling 8, hex spacer 9, spacer for stepper motor 10, first gear wheel 16, second gear wheel 12, third gear wheel, 11 grub screw 13. A two stage spur type gear assembly is designed for stepper motor with gear ratio of 1:6, the axial gear, 16 connected with the shaft of motor have radius 7 mm with central hole of diameter 8 mm. this is push fit onto the shaft of motor. This wheel drives the second wheel having diameter of 40 mm and is designed in such manner so that the first wheel of second stage is co axial with it.
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The smaller wheel of second stage have radius 7 mm and drives final wheel 11 of gear assembly. The final wheel 11 have central hole of diameter 8 mm through which a special axial nut having inside threading is push fit with it. Threaded bolt for alignment ring attachment, 6 moves inside special axial nut. This gear wheel assembly consisting of four wheels is fixed between two parallel plates with a gap of 14 mm. Plates are held in position by three hex spacer 9. Threaded bolt have slot of length 19mm which limits the movement of bolt. A manual lock through a grub screw restricts the movement of threaded bolt of alignment ring attachment. At the extreme end, the movement of bolt is further stopped by a special washer which performs the function of clutch and sets the wheel free. The threaded bolt has connection with mirror alignment rings through elastic coupling. When the motor is driven through gear wheel, the alignment rings are pulled or pushed depending on the direction of motor. Due to this the fine alignment of mirror is possible in both horizontal and vertical planes. The required torque of motor for constant speed is given by [6]:

\[ T_{\text{const}} = \frac{F_a L}{2\pi \eta} \times 10^{-3} \times A \]

Where \( F_a \) is the total external load, \( L \) is total movement of screw, \( A \) is reduction ratio of gear, \( \eta \) is the efficiency of screw. The required torque is 1.16 N-m whereas for accelerating movement, the required additional torque is 0.018 N-m. The total torque for acceleration is 1.178 N-m. The gear wheels are made of bronze for smooth rolling of wheels for movement through motor.

3.2. Design of convex mirror Mount
Design schematics of convex Mirror mount is presented in figure 6. This mirror mount assembly consists of:

![Figure 5 Gear wheel and motor mounting assembly](image-url)
Figure 6 Design schematics of convex mirror mount

1. The main stationary plate 1 of dimensions 380X380mm and thickness 11mm. This plate have 4 slots of dimensions 19X10 mm for its attachment with resonator flange, 2 holes for brads and 2 holes for screws. This plate has two slots for shifting of this plate vertically upward. This plate has attachment for coupling of module 9 on resonator flange, for provisioning of its shifting along vertical axis in the range of ±5mm.

2. Mobile plate, 6 of dimensions 350X330 mm. This plate has three holes of diameter Φ13mm for attachment of coarse alignment modules and two slots horizontal slots for provisioning of its shifting along horizontal axis in the range of ±5mm through module 8. This plate have rectangular window of dimensions 220X160 mm for exposure of mirror to laser cavity and extraction of laser beam from resonator.

3. Mobile plate, 7 with provision for attachment of coarse adjusting modules at 120°. The mobile plates 2 and 3 are connected together through coarse alignment adjusting modules.

4. Two rectangular frames 150X190mm and 250X275mm named internal and external rotational frames respectively. On the internal frame convex mirror is implemented on a central disc of diameter attached to the internal frame through spiders. The mirror is implemented on central disc with the help of 4MX6.10 bolts at 40PCD. The inner frame has attachment with mobile plate through external frame.

Design schematic of internal frame with curved spider is shown in figure7. The laser beam from resonator is extracted through diffraction over the edges of convex mirror from the space between central convex mirror mounting disc and rectangular internal frame [4]. The central convex mirror mounting disc is attached to the rectangular frame by three symmetric spider legs as shown in the figure. The design of spiders is such that each spider forms a crescent shaped spider leg to minimize the Fraunhofer diffraction effects in the far field of beam as compared to straight edge spider legs. It is evident that the half angle of subtends for each curved spider legs to be maintained at 30° to minimize diffraction peaks of secondary maxima in far field. The spiders are rapped with a thin sheet of copper of thickness 1 mm for preventing misalignment of external
rings due to heat conduction through spiders during extraction of high power laser beam from resonator. It is inferred that such construction provide virtually nil thermal loading on spider legs.

**Figure 7** Curved spider schematics

1. Two stepper motors with a gear assemblies as described in 3.1
2. Three symmetric coarse alignment assemblies at 120° with respect to the centre of mobile plate for coarse alignment of mirror in horizontal and vertical planes as per description under section 3.1.1.
3. Quadrant detector assembly for sensing the misalignment of concave mirror held at concave mirror mounting assembly.
4. Laser diode assembly for installation and alignment of diode laser beam reflected from concave mirror on quadrant detector.

The external frame rotation axis is torsion, which is connected with mobile plate 2 through bush arrangement. Second rotation axis is made analogues. The internal frame rotates inside the external frame. On the internal frame two collectors are fixed. On these collectors output mirror is established. The pushers of motor have elastic connection with internal frame through reducer. Similar arrangement has been provided for external frame. With the help of card and joint and gear wheel, it is possible to align output mirror in two planes. The accuracy for repositioning of each mirror is mainly governed by three parameters the step angle of stepper motor, pitch of lead screw and the gear ratio. The stepper motor with a typical step angle of 0.3° (half angle) when driven through gear wheel with gear ratio 1:6 provide repositioning accuracy better than 2 arc sec for each mirrors.

4. ALIGNMENT AND TEST PROCEDURE FOR ALIGNMENT ACCURACY

A test set up for alignment of resonator and check for alignment accuracy is shown in figure 8. A He-Ne Laser producing a visible red beam of light with output power of 2 mW and divergence 1 mrad is utilised in the set up. For alignment of resonator, two transparent screens with central hole of diameter 1 mm were installed on each resonator flange. Laser is adjusted so that the beam passes
through holes on screen. This sets the initial axis of resonator. Now a flat mirror is installed at the
centre of beam axis at the rear side of flange 2. The mirror is adjusted so that reflected beam from
mirror is centred on He-Ne laser. The screen 1 is removed and the concave mirror fixed on to
concave mirror mount is installed on resonator flange 1 (Figure 8) such that the beam pass through
central hole of 1 mm diameter on the concave mirror. The mirror is adjusted in both planes until
the spilled over portion of the beam reflected around the hole on concave mirror coincide with
laser spot on flat mirror. The mirror position is now locked through lock nuts provided in concave
mirror mounting assembly. The flat mirror is now removed and convex mirror fixed on to convex
mirror mount is installed on resonator flange 2. The mirror is adjusted for its centre on beam axis
with the help of horizontal and vertical adjustment modules and paper screen in front of mirror.
The transparent screen 2 is now removed from resonator flange 2. The convex mirror is adjusted
in both planes until the multiple light spots of He-Ne laser beam reflected from convex mirror
merges with light spot at the centre of concave mirror. The mirror position in convex mirror mount
is then locked through lock nuts provided on convex mirror mount assembly. In the perfect aligned
position of resonator concentric interference fringes of equal slope are seen at the centre of concave
mirror. The concentricity of fringes with respect to alignment laser beam spot at the centre of
concave mirror can be visualised through space between convex mirror and rectangular alignment
rings on convex mirror mount.

Figure 8 Test set up for resonator alignment

The method provides alignment accuracy of 10-20 arcs second for resonator. The accuracy of
alignment can be monitored against uniform illumination on screen at the exit of resonator.
Alternatively one also can monitor accuracy of alignment by observing the shift of fringe centre
with respect to laser beam spot at the central 1mm diameter hole provided on concave mirror. The
offset between the two provide accuracy of alignment for resonator. The output beam from
resonator perform several round trips within resonator before it exits from it. The minimum one
round trip is required for beam escaping from resonator. The same is true for the alignment laser
beam too. The accuracy of alignment may be easily measured either by observing uniform
illumination on screen placed at the exit of resonator or by visualising displacement of fringe centre
from central hole on concave mirror. For the present resonator of length 3 meters, an offset of
fringe centre within 0.5 from central hole on mirror which is easily visualized by naked eyes
ensures accuracy of alignment not worse than 20 arc sec for one round trip travel of alignment
laser beam inside the resonator. For short resonator lengths the accuracy of alignment can be
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quantified by focusing of fringe pattern at the exit of resonator by a perfect focusing mirror and measure the offset in the focal plane as shown in figure 8. Once the initial alignment is accomplished, the misalignment of resonator mirrors if any, is measured by a pair of diode laser and quadrant detector placed on each mirror mount either during operation of laser or between successive laser shots. It is achieved by centring the diode laser beam on quadrant detector in pre aligned resonator and measuring the shift of beam position on quadrant detector due to misalignment of resonator mirrors. For example the misalignment of convex mirror can be monitored by laser diode and quadrant detector placed on to concave mirror mount and vice versa. Realignment of each mirror with respect to their pre aligned positions is then achieved by a pair of stepper motors run through gear wheel assembly.

5. CONCLUSIONS

In this paper we have presented the requirements, objectives and design methodology of resonator mirror mounts for high energy lasers system. The basic design and configuration of mirror mounts is described. Figure 9 presents an engineered view of mirror mounts with all embedded hardware for manual and auto alignment of mirrors.

![Figure 9 Engineered view of mirror mounts](image)

Each mirror mount when integrated on resonator support structure provide information of misalignment for resonator mirror structured at other end of resonator. The error signals received from respective quadrant detector due to misalignment of mirror are then processed in a feedback control system for realignment of mirrors. These mirror mounts were designed for metallic concave and convex mirrors of diameters 160 mm and 88 mm respectively for operation of 3 m long liner confocal unstable resonator in high power laser system. The resonator has misalignment tolerance of nearly 60 arc seconds. An Optical method for alignment of resonator and the verifying the accuracy of alignment is described. The mirror mounts were successfully tested for both manual and automatic alignment of said resonator within accuracy of alignment not worse than 20 arc seconds.
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