

Elliptically framed tip-tilt mirror optimized for stellar tracking

James H. Clark III^a, F. Ernesto Penado^b, and Jeremy Petak^b

^aNaval Research Laboratory/NPOI, 10391 W Observatory Road, Flagstaff, AZ, USA 86001;

^bNorthern Arizona University, Department of Mechanical Engineering, Flagstaff, AZ, USA 86011

ABSTRACT

We compare a design innovation of an elliptically framed tip-tilt optical tracker with an existing circularly framed tracker for the Navy Precision Optical Interferometer. The tracker stabilizes a 12.5 cm stellar beam on a target hundreds of meters away and requires an increase in operational frequency. We reduced mass and size by integrating an elliptical mirror as one of the rotating components, which eliminated a rotating frame. We used the same materials as the existing tracker; however, light-weighted both the aluminum frame and Zerodur® mirror. We generated a computer-aided design model, converted it into a finite element model and performed modal analysis on two load cases. In load case 1, we tied down three points on the bottom surface of the tracker corresponding to the tie-down points of the comparison tracker. This reveals a first mode (lowest) frequency of 140 Hz, a factor of two over the baseline tracker's first mode frequency of 67 Hz. In load case 2, we constrained four additional points inboard of the corners of the tracker base, for a total of seven tie-downs, simulating a firmly bolted and secured mount. The first mode of vibration for this case is 211 Hz, an increase over load case 1 by a factor of 1.5 and more than three times the fundamental frequency of the existing tracker. We conclude that these geometrical changes with the additional tie-down bolts are a viable solution path forward to improve steering speed and recommend a continuation with this effort.

Keywords: optical interferometry, optomechanical tracker, elliptical flat mirrors, frequency response, natural frequency, NPOI

1. INTRODUCTION

1.1 Background

The Navy Precision Optical Interferometer (NPOI) in Flagstaff, Arizona uses discrete smaller telescopes spaced along a Y-array and used simultaneously to simulate an equivalent single large telescope. Figure 1 shows an aerial view of the Y-array. We transport 12.5 cm diameter starlight beams from each telescope station through an evacuated feed beam system to a beam combiner and superimpose them interferometrically. Each star beam, up to six, is generated at a telescope station and relayed and transported through an array arm, a long delay line, precision delay line and a beam combiner station. The beam combiner station generates optical fringe data for later analysis and post-processing, resulting in star positions, orbits, diameters and synthesized images. The trajectory of each stellar beam from each telescope is steered to and steadied at the beam combiner station, up to 800 m distant, where the optical fringes are generated and recorded. Unwavering star beams create crisper fringe contrast and correspondingly improved results. Relentless atmospheric disturbances alter the beam trajectory vectors at each telescope and must be effectively cancelled, or tracked. We attenuate these atmospheric effects by steering and stabilizing the transported starlight with a flat reflective tip-tilt optical mirror. We will call this device the tracker. We guide and steady the star beam on a target at the beam combiner station up to 800 m distant from the telescope. A feedback signal, representing an error from the ideal target center, is sent to the tracker at each telescope to steer it and reduce the error¹. The response and speed of this tracker is a limiting factor in the performance of the NPOI.

1.2 Purpose

Our new elliptically framed tip-tilt mirror design described herein can increase the frequency response of the tracker by a factor of three over the current NPOI tracker. In this paper, we compare our design innovation of an elliptically framed tip-tilt optical tracker with the existing circularly framed tracker. The circular tracker, or baseline tracker, has a first

* jhc29@nau.edu; phone 1 928 779-9567

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mode of vibration of 67 Hz^2 , which is a limiting factor in the quality and quantity of fringe data³. Our elliptically framed tracker design has a first mode (lowest) frequency of vibration of 211 Hz. This increase in fundamental structural frequency allows a corresponding reduction in servo response time; we command the tip-tilt steering actuators faster and improve the stability of each stellar beam at the beam combiner station under the continuously changing atmospheric conditions. In addition, we believe we can observe a larger number of fainter objects with this faster tracker.

Improvement in performance over the baseline tracker is achieved through a reduction in mass and size of the components, as opposed to material changes. The elliptical flat reflective mirror measures 15.2 cm by 20.3 cm. We found that additional tie-down points further increase the first mode of vibration and are therefore included in the results. Tie-down points are simply the fastener locations of the tracker to its base. The tracker components include an aluminum yoke and ring, glass Zerodur®⁴ mirror, piezoelectric (PZT) actuators and stainless steel flexure pivot bearings⁵.

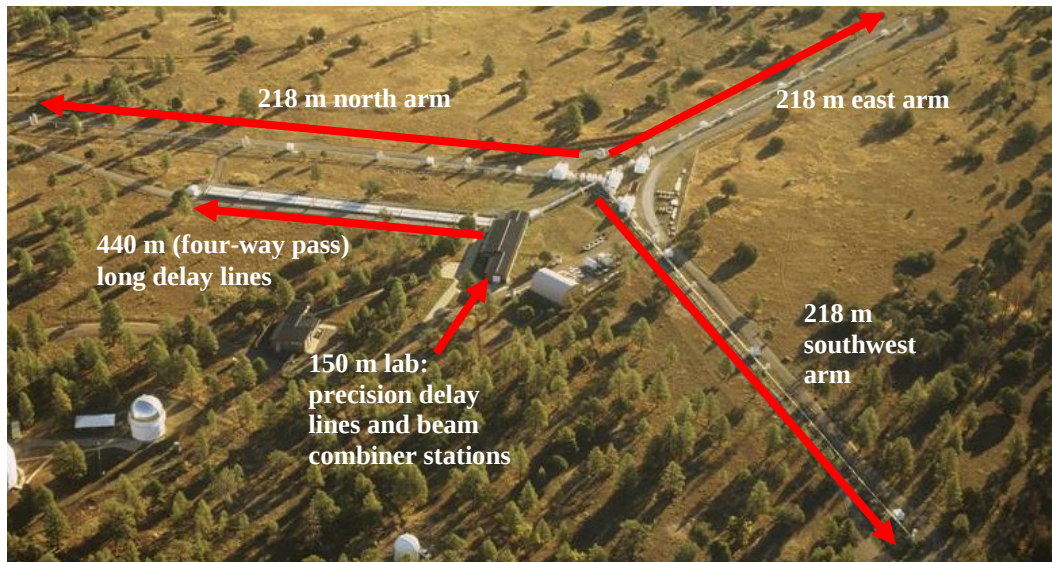


Fig. 1. NPOI site, Flagstaff, AZ (Photo courtesy of Michael Collier). Ten imaging telescope stations per arm offer a variety of baselines to satisfy specific observing programs. Tip-tilt mirrors (trackers) at each station steer and stabilize its stellar beam to the beam combiner, a distance up to 800 m.

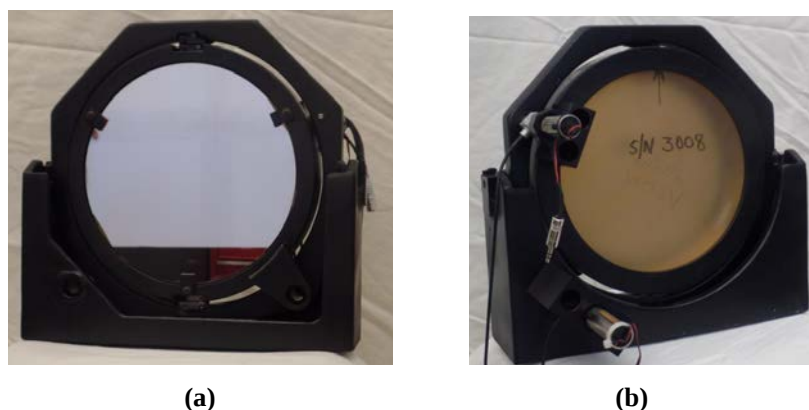


Fig. 2. Current 20.3 cm circular tip-tilt tracker. (a) front view, (b) rear view. The tracker components consist of a circular 20.3 cm diameter, 3.8 cm thick glass Zerodur® mirror, aluminum yoke, frame and mirror ring, two piezoelectric (PZT) actuators for fine positioning and motion control and two precision electric positioning screws for feed system alignment.

2. COMPUTER AIDED DESIGN MODEL

We generated a computer aided design (CAD) model of the elliptically framed tracker using SolidWorks 14.0. This volumetric representation maintains the fundamental critical dimensions and fastener locations of the circular baseline tracker. These are important features for integration and alignment into the existing optomechanical infrastructure of the NPOI. In addition, for comparison purposes between the current baseline tracker and our proposed elliptically framed tip-tilt tracker, the materials for the yoke, ring and mirror are maintained, and flexure pivot bearings, piezoelectric actuators and precision electric positioning screws are identical. Figure 3 illustrates the overall shape and actuator locations of the elliptically framed tracker. The yoke is the same as the one used in the circular version. Figure 3a shows the front reflective side of the elliptically shaped flat mirror. The mirror is a structural rotating component and attaches to the ring with two flexure pivot bearings. The ring, also a structural rotating component, rotates perpendicular to the mirror and attaches to the yoke with two flexure pivot bearings.

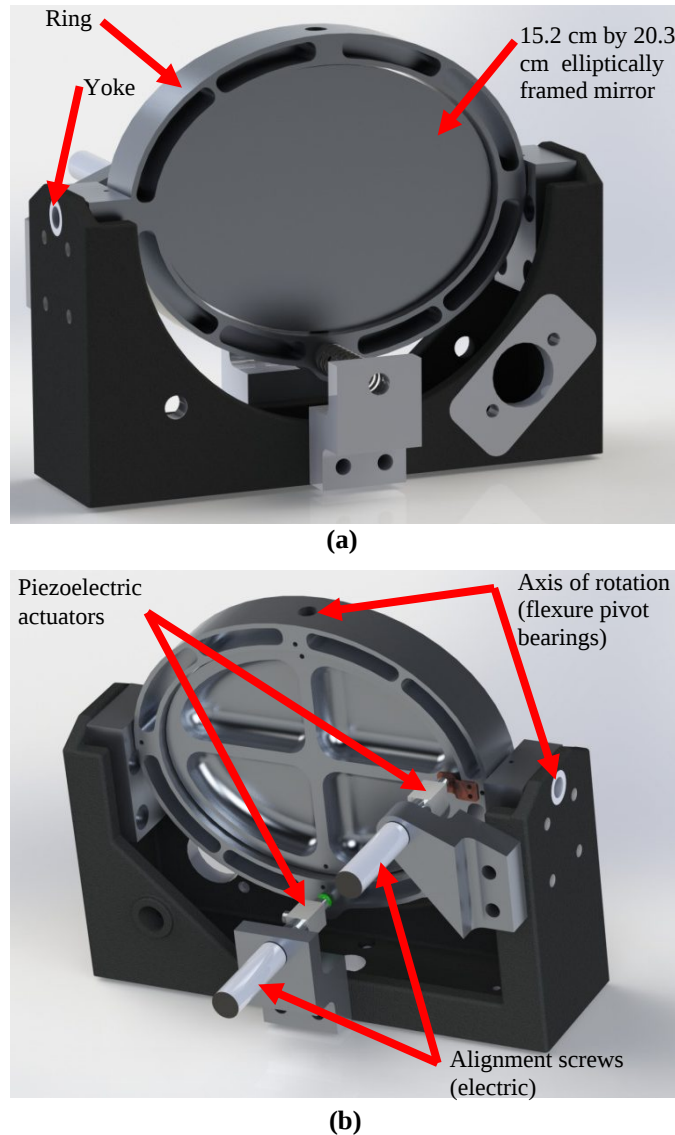


Fig. 3. Computer aided rendering of a 15.2 cm by 20.3 cm elliptically framed tip-tilt tracker assembly. (a) front reflective view, (b) rear view showing pocketed mirror.

Figure 3b shows the rear view of the tracker. Two flexure pivot bearings, one located at the top and the other at bottom, fasten the mirror/ring assembly together. The upper location is shown in the figure. Two flexure pivot bearings, one on

the left, the other on the right, fasten the ring/yoke assembly. The right-side location is shown in the figure. Also shown is the pocketing of the backside of the mirror for weight reduction purposes. The piezoelectric actuators and precision electric positioning screws are stacked in-line for each axis of rotation. The positioning screws are fixed at one end to the yoke in both cases and therefore do not rotate with the structural ring and mirror components. This reduces the mass moment of inertia of the rotating components and increases the first mode of vibration frequency.

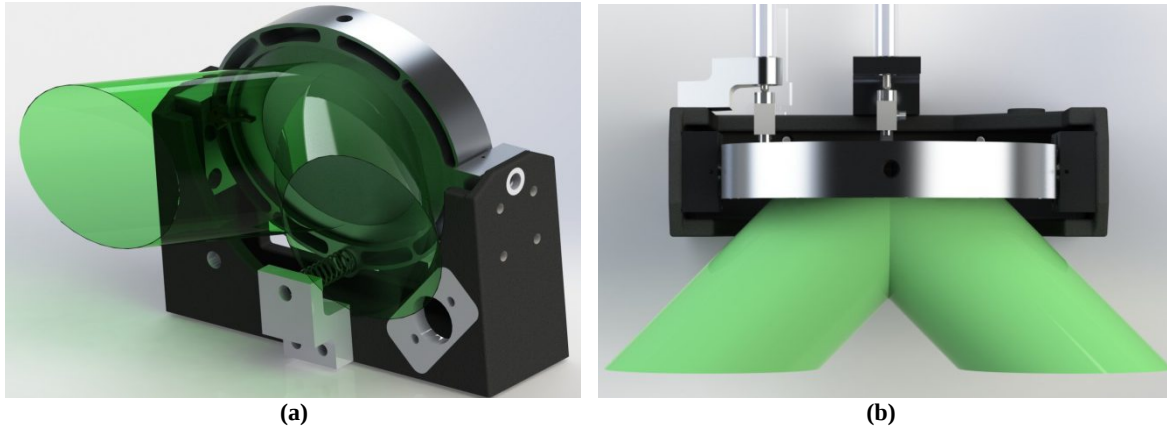


Fig. 4. Computer aided rendering of elliptically framed tip-tilt tracker showing 12.5 cm diameter reflected light beam. (a) front perspective view, (b) top view.

3. FINITE ELEMENT MODEL

In order to determine the natural frequencies and modes of vibration of the design, a finite element model of the tracker was built and run using ANSYS Mechanical APDL R15.0⁶. The geometry and mesh used are shown in Figure 5. The components and dimensions are the same as with the CAD model described in the previous section.

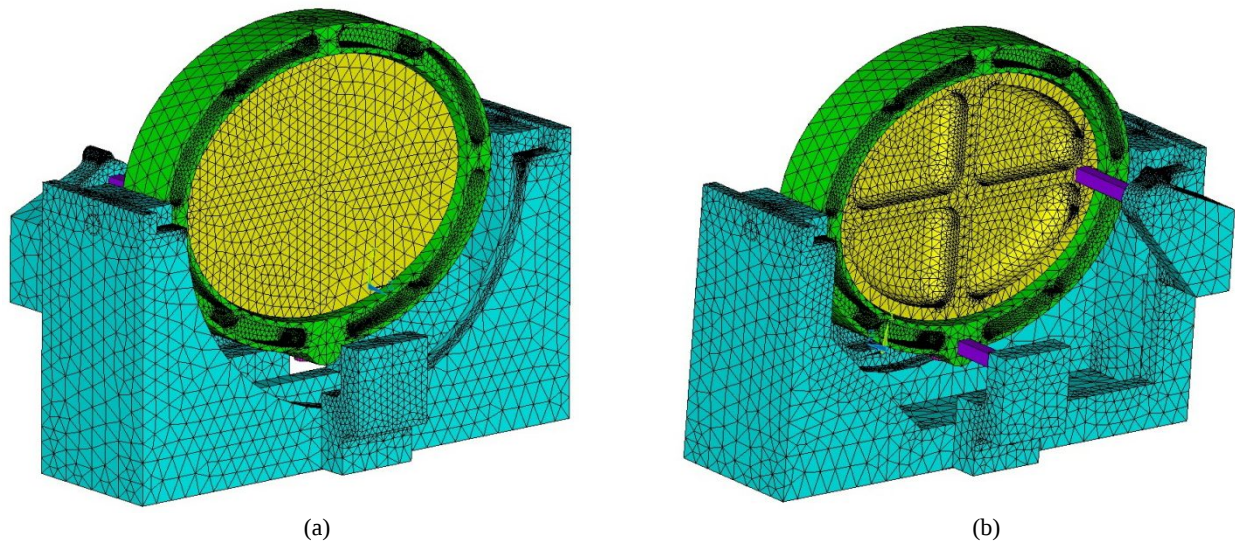


Fig. 5. Geometry and finite element mesh used in the model, (a) front view, (b) rear view.

Figure 6 shows a rear view of the mesh geometry with labels for the different components. This mesh was used for both load cases in the present analysis. At the bottom of the base, shown in Figure 7, the nodal displacements were set to zero at the nodes corresponding to the bolt hole locations in the actual tracker yoke.

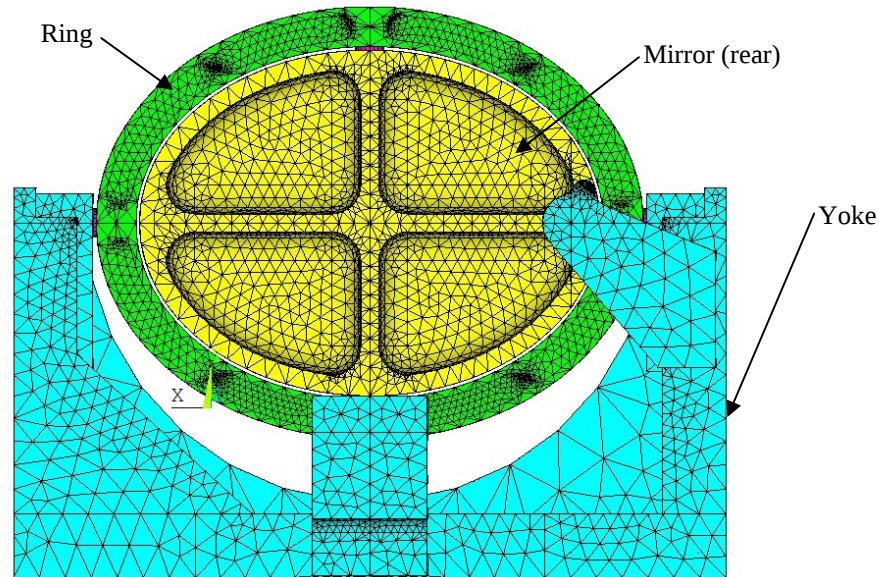


Fig. 6. Rear view of tracker assembly mesh.

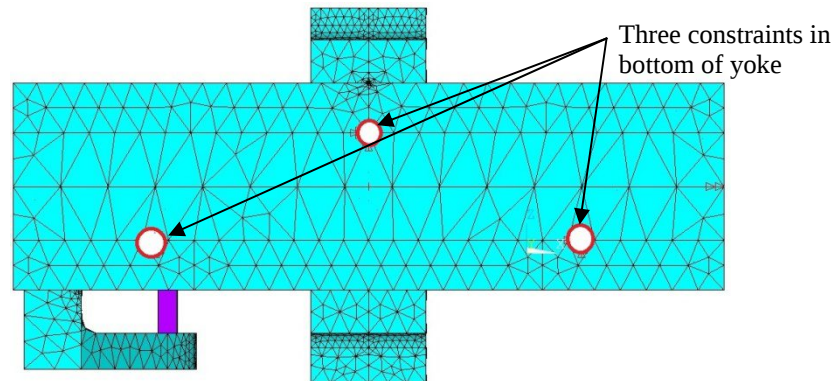


Fig. 7. Bottom view of mesh showing three bottom constraints (load case 1: same constraints as the baseline case with circular mirror).

The bottom constraints in load case 1, shown in Figure 7, correspond to the three tie-down points (i.e. the mounting bolt holes) of the baseline load case from the circular tracker. Nodes at these locations are constrained to zero translation in the three coordinate axes. Analysis of this configuration provides a direct comparison with the baseline circular mirror case.

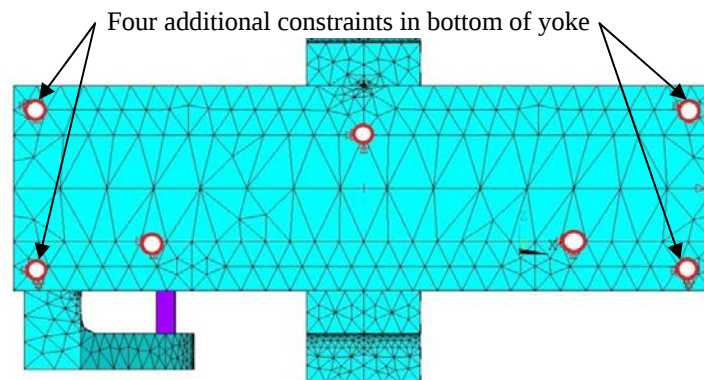


Fig. 8. Bottom view of mesh showing seven bottom constraints (load case 2: baseline case plus four inboard corner constraints).

Figure 8 shows the additional four inboard corner constraints for the model. These additional tie-downs, or fastener locations in the bottom of the yoke more firmly attach the tracker to its mounting platform. Nodes at these locations are constrained to zero translation in the three coordinate axes. Inboard corner constraints aid in reducing bending of the yoke when it vibrates.

The model in both load cases consisted of 127,963 elements. There were 127,949 3-D 10-noded tetrahedral structural solid elements, 12 2-noded beam elements, and two 2-noded truss elements. The 10-noded tetrahedral elements (SOLID187) were used for the mirror, ring and yoke. The beam elements (BEAM188) were used for the attachment pivots connecting the mirror to the ring and the ring to the yoke. The truss elements (LINK180) were used for two piezoelectric actuators. The properties used for the tracker components and their element types are shown in Table 1.

Table 1. Properties of materials and element types used in the analysis.

Component	Material	Modulus of elasticity, E (msi)	Poisson's ratio, ν	Density, ρ (lb-sec ² /in ⁴)	Finite element type (ANSYS)
Ring	Aluminum	10.4	0.33	0.000262	10-noded tetrahedral solid (SOLID187)
Mirror	Zerodur®	13.1	0.243	0.0002367	10-noded tetrahedral solid (SOLID187)
Yoke	Aluminum	10.4	0.33	0.000262	10-noded tetrahedral solid (SOLID187)
Attachment pivots (axle bearings)	Stainless steel	27.6	0.30	0.000725	2-noded beam (BEAM188)
Piezoelectric actuators	Lead zirconate titanate (PZT)	5.0	0.35	0.000725	2-noded truss (LINK180)

4. ANALYSIS OF BASELINE CIRCULAR TIP-TILT TRACKER

The baseline case, consisting of an all-aluminum structural framework and circular Zerodur glass mirror, was analyzed and reported in an earlier paper⁷. The material properties used are shown in Table 1. This model served the goals of verifying the model by comparing against experimental results and providing frequency results to compare against the modified designs to be discussed in the next section. The geometry, component labels, and basic dimensions of the circular baseline model are shown in Figure 9.

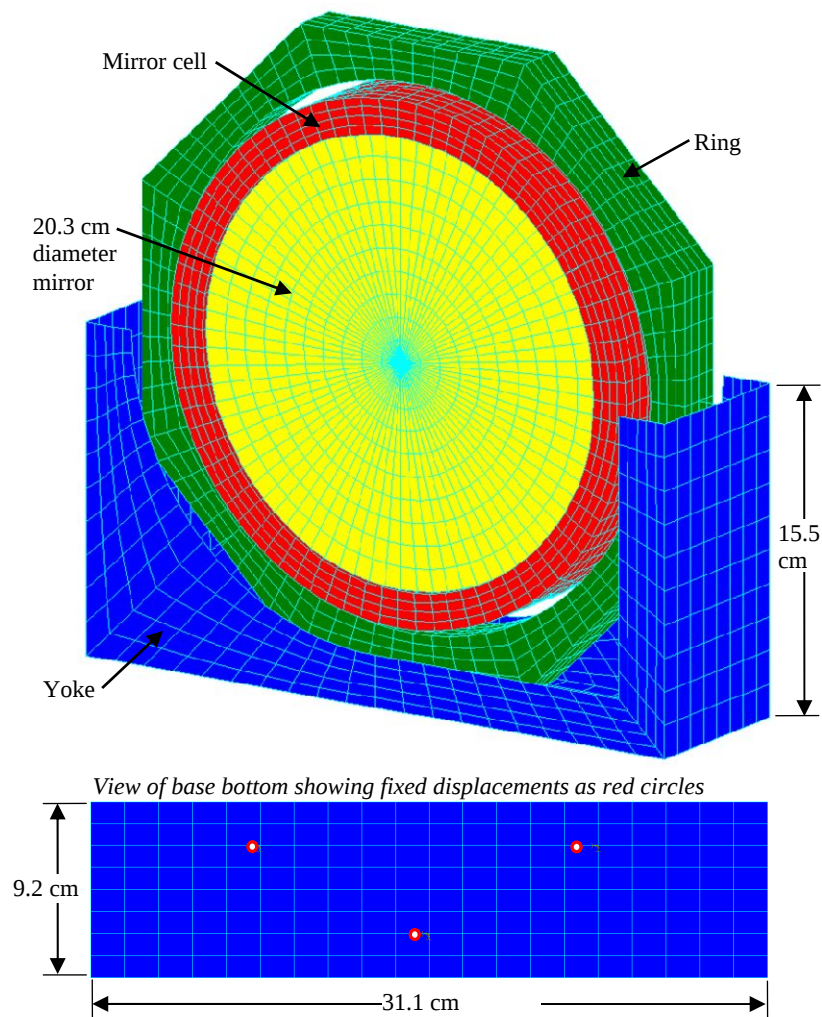


Fig. 9. Geometry, components and boundary conditions used in the baseline circular tracker.

The results for the first five frequencies are shown in Table 2. The experimentally obtained value of the fundamental frequency was 66 Hz², which compares well with the 67.6 Hz value obtained from the analysis (the FEA value is 2.4% higher). This result provides confidence in the ability of the model to capture the main features of the actual structure.

Table 2. Lowest five frequencies of the baseline model.

Frequency #	Finite Element value (cycles/sec)	Experimental value (cycles/sec)
1	67.6	66
2	128.3	---
3	158.4	---
4	209.0	---
5	256.0	---

The mode of vibration for the lowest frequency is shown in Figure 10. This figure indicates that torsion of the ring and sideways bending of the yoke play important roles in the vibration of the tracker. Therefore, stiffening of the ring in torsion and of the yoke in bending would be expected to increase the fundamental frequency of vibration.

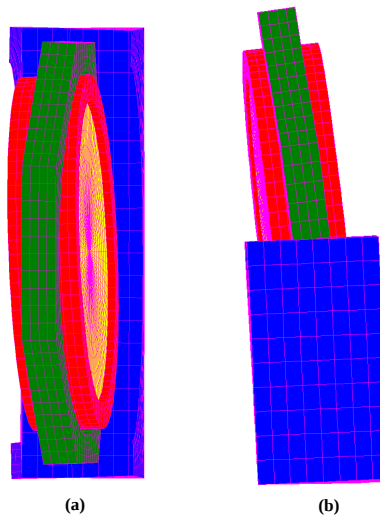


Fig. 10. First mode of vibration of the baseline circular tracker assembly. (a) Top view, (b) Side view.

5. DESIGN MODIFICATIONS TO INCREASE NATURAL FREQUENCIES

The frequencies of vibration of the structure increase with increasing stiffness and decreasing mass. We modified the geometry of the components to reduce mass and size and retained the baseline materials (aluminum, Zerodur® mirror, stainless steel pivots and lead-zirconate-titanate [PZT] piezoelectric actuators). We changed the mirror from circular to elliptical and pocketed the rear furthering its mass reduction. We further reduced size and mass by eliminating a mounting ring and incorporated the elliptical mirror as one of the rotating structural members. The other rotational component, the ring, is also pocketed for weight reduction purposes. We apply additional tie-down points, or constraints, to stiffen the yoke in bending.

In order to consider the effect of the various component changes on the frequencies of vibration, the properties were varied progressively. Three different cases, including the baseline case, were considered. Following is a summary of each case. The results for the lowest five frequencies for each case are given in Table 3. In addition, Table 3 shows tracker component weights for the mirror, mirror cell, ring, and total in each case. The yoke, piezoelectric actuators and precision electric positioning screws are common to all cases and not included in Table 3.

Table 3. Lowest five frequencies of the baseline model.

	Load case		
	Baseline	1	2
Freq. #	Frequencies (cycles/sec)		
1	67.6	140.3	210.8
2	128.3	185.0	413.3
3	158.4	307.5	499.0
4	209.0	392.9	577.9
5	256.0	528.1	688.2
Tracker component	Weights (lb)		
Mirror (Zerodur®)	6.9	2.1	2.1
Mirror cell (aluminum)	3.5	0	0
Ring (aluminum)	2.3	1.3	1.3
Total	12.7	3.4	3.4

Load case Baseline: Circular mirror and three tie-down constraints on bottom of yoke. All aluminum structural frame (ring, mirror cell and yoke) with Zerodur® circular glass mirror of constant thickness. This case corresponds to the current design of the tracker, as shown in Figure 9.

Load case 1: Elliptically framed tip-tilt tracker with three tie-down constraints. All aluminum frame (ring and yoke) with Zerodur® pocketed, elliptical glass mirror. This case uses the same material as in the baseline case and the same three tie-down locations to attach the assembly to a base mount. The side view of the deformed assembly, as seen in Figure 11, suggests additional bottom constraints that reduce yoke bending can increase the frequency of the first mode of vibration.

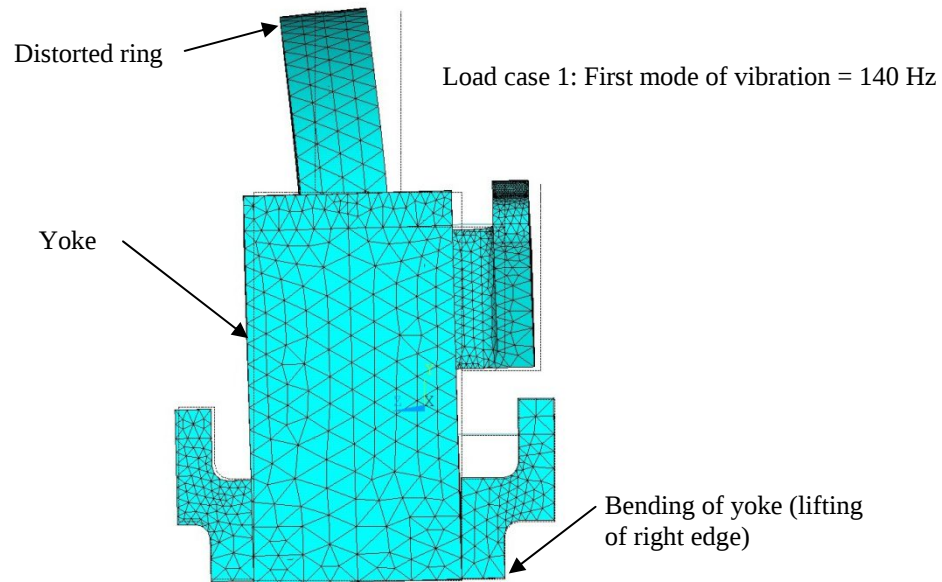


Fig. 11. Side view of assembly in case 1 showing bending of yoke. Lowest frequency of vibration is 140 Hz.

Load case 2: Elliptically framed tip-tilt tracker with three baseline and four inboard tie-down constraints. This is similar to load case 1, except that we added four additional tie-downs inboard of the actual corners. This model has seven bolt hole locations through the bottom surface of the yoke as shown in Figure 8. The side view of the deformed assembly is shown in Figure 12.

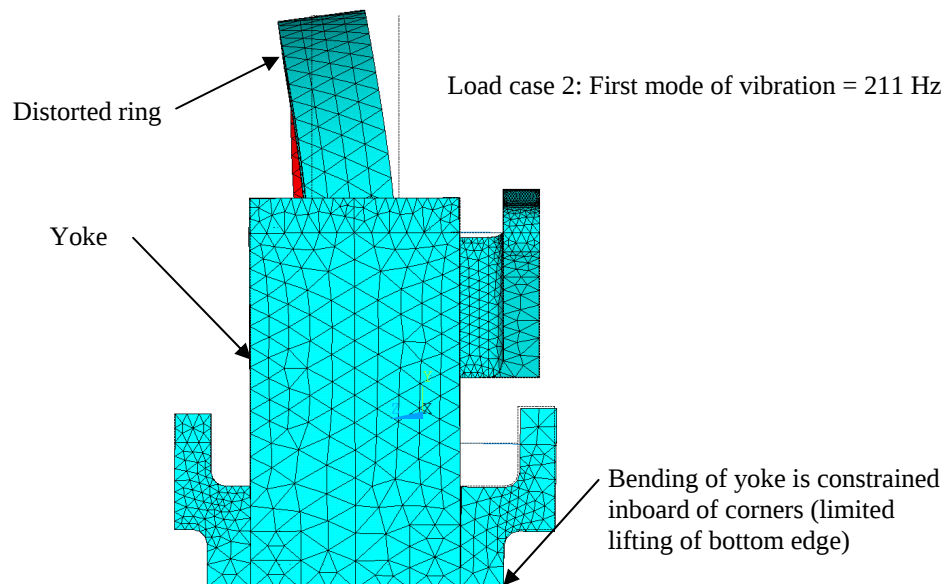


Fig. 12. Side view of assembly in case 2 showing bending of yoke is constrained. Lowest frequency of vibration is 211 Hz.

6. CONCLUSIONS AND RECOMMENDATIONS

Reducing the size and mass and optimizing the shape to an elliptical, pocketed, flat-framed mirror and mounting ring can result in a significant increase in the fundamental frequency of vibration of the tracker over the baseline case made of cast aluminum with a circular glass (Zerodur®) mirror. We integrated the mirror as one of the rotating components, which further reduced mass and eliminated a rotating frame. The increase in the fundamental frequency of vibration is due to the higher stiffness, lighter weight and reduced inertia of the components. The recommended design, corresponding to load case 2, is based on manufacturability and performance and incorporates additional mounting holes in the bottom of the tracker, which reduces bending of the yoke. This design has a natural frequency of 211 Hz, which is 3.1 times greater than the 67.6 Hz frequency of the baseline assembly, currently in operation at the Navy Precision Optical Interferometer. In addition, the weight of the rotating tracker components, including the mirror, was decreased from 12.7 lb in the baseline case to 3.4 lb in the recommended design, or a factor of 3.7.

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