Supports Analysis of the Fast Steering Secondary Mirror Prototype for Giant Magellan Telescope

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KEYWORDS : mirror, mount, support, opto-mechanics, GMT, tip-tilt, Magellan, mirror cell

Korea Astronomy and Space Science Institute (KASI) is developing a prototype of the fast steering secondary mirror (FSM) for the Giant Magellan Telescope (GMT) that is one of the largest telescopes in the world. The FSM mirror forms a single secondary with seven lightweighted concave mirrors, and each one has a diameter of 1.06m.
A FSM assembly, FSM secondary consists of one FSM mirror, three axial supports, one lateral support and one mirror cell. The axial supports and the lateral support are the most important parts to control the performance of the FSM mirror. The axial component of the mirror weight is supported by three axial supports, and the lateral component is done by one lateral support mounted at the center of one FSM mirror while both supports are decoupled. The mirror cell is the base structure on which one the mirror and these supports are mounted. This paper will discuss analysis results for axial and lateral supports and effects of these supports on one FSM segment.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

NOMENCLATURE

E = Young's modulus
ν *= Poisson's ratio*
ρ *= density*
YS = yield strength
ζ *= damping ratio*

1. Introduction

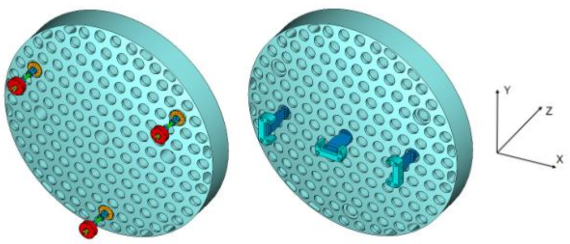
Giant Magellan Telescope (GMT) will be one of the largest telescopes in the world. Total diameter of primary mirror composed of seven 8.4m segments is 25.4m, and that of secondary mirror having the same number of primary segments is 3.2m. The seven segments of secondary mirror are conjugated 1:1 to the segments of the primary as shown in Fig. 1. GMT secondary has two types. The first type is Adaptive Secondary Mirror(ASM) to compensate atmospheric blurring with deformable thin mirror. The second type is Fast Steering Mirror(FSM), conventional mirror to compensate wind vibration and tracking jittering as shown in Fig. 1. KASI(Korea Astronomy & Space Science Institute) is developing a prototype of GMT FSM mirror with several institutions. Particularly, the supports of FSM were collaboratively researched with National Optical Astronomy Observatory(NOAO). The initial model files for the center segment of FSM secondary were provided from GMTO(GMT office). The files were updated by KASI and NOAO.

Fig. 1. Giant Magellan Telescope(left) and GMT FSM secondary(right).

Supports of Magellan secondary were pre-researched to understand supports of GMT FSM secondary, because the concept design of GMT FSM secondary starts from Magellan secondary. The diameter of one FSM, 1.06m, is simillar, to that of Magellan, 1.3m. It is the same that three axial supports with vacuum system is used. But, the number of lateral support is different. In case of GMT FSM secondary, there are six off-axis segments surrounding a center segment. When one lateral support is used, off-axis segments have a symmetric axis. However, if three lateral supports are used, four of six off axis segments no longer have the symmetric axis. Moreover, to decide the position of lateral support hole will be too hard, while lightweighted hole patterns are considered. The analysis of Magellan supports helped the support mechanism of GMT FSM mirror understood. The design goal of supports of the FSM mirror was set to enable the surface RMS(Root Mean Square) value of the mirror to be less than 20 nm under kinematic mount system and to enable the tip-tilt motion of the mirror to be possible, in reference to GMT Conceptual Design Review[1]. To perform supports analysis, NX I-DEAS for Finite Element Analysis, Solidworks 2010 for CAD(Computer Aided Design) and Fortran program for data analysis were conducted.

2. Supports of Magellan secondary mirror

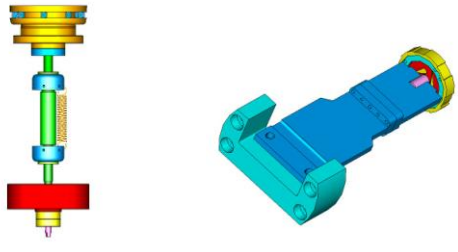
The Magellan secondary mirror, whose material is Zerodur($E = 9.2 \times 10^{10} N/m^2$, $\nu = 0.24$, $\rho = 2530 kg/m^3$), is supported by three axial supports and three lateral supports as shown in Fig. 2(a) and 2(b) under the kinematic mount system which restricts only six degree of freedoms. Under the coordinate system as shown in Fig. 2, the axial(Z axis direction, optical axis direction) component of the mirror weight is supported by three axial supports and the vacuum system. The vacuum system operates over the back surface of Magellan secondary mirror, so that it makes the axial component of the mirror weight to zero. At this time, axial supports work just as reference position.



(a) (b)

Fig. 2. Supports of Magellan secondary mirror; (a) Three axial support with Magellan secondary mirror, (b) Three lateral support with Magellan secondary mirror.

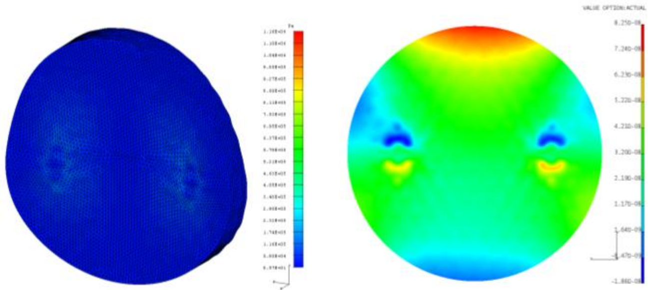
Three axial supports support translation along Z axis(Tz), rotation along X axis(Rx) and rotation along Y axis(Ry). An axial support as shown in Fig. 3(a) includes an actuator for the tip-tilt operation which compensates vibration by wind and jittering by telescope tracking. Meanwhile, the lateral(Y axis direction, X axis direction) component of the mirror weight is supported by three lateral supports. A lateral support as shown in Fig. 3(b) has a lateral flexure of the blade configuration. When a force loads on the horizontal plane of the lateral flexure, the stiffness is strong, but it is relatively weak in case of loading on vertical plane. Three lateral flexures support translation along X axis(Tx), translation along Y axis(Ty) and rotation along Z axis(Rz). Under these constraints, axial supports and lateral supports are decoupled each other. Axial supports are mounted on the back surface of the mirror. The lateral flexure is mounted at the C.G(center of gravity) position of the mirror, otherwise the bending moment occurs as distance off from the C.G.



(a) (b)

Fig. 3. Supports of Magellan secondary mirror; (a) One axial support (b) One lateral support.

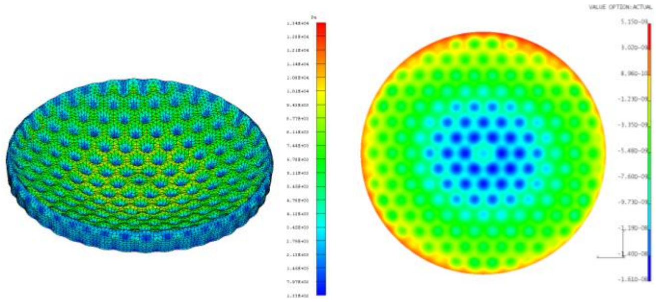
A telescope changes elevation angles for astronomical tracking, so that mirror position is also changed. In case of Magellan secondary, at zenith angle = 0°, axial supports fully support the mirror with vacuum pressure. At zenith angle = 90°, lateral support fully supports the mirror weight. Under above support mechanism, performance of Magellan secondary mirror was analyzed through FEA. The mass of FE model is about 215kg. Fig. 4(a) shows stress distribution with deformed configuration at zenith angle = 90°. Here the maximum stress was calculated to 1.2MPa, when compared to yield strength of Zerodur, 75MPa, there are no problems on stress. Fig. 4(b) shows the deformation map of the mirror surface through the correction of tip, tilt and piston which mean the rigid body motion, because the deformation of the mirror surface only affects the performance of the mirror. At this zenith angle, surface P-V(Peak to Valley) is 83.3nm, and RMS is 13.3nm(< 20nm, design goal of GMT FSM mirror).



(a) (b)

Fig. 4. Performance analysis of Magellan secondary mirror at Zenith angle = 90°; (a) Stress distribution and deformed configuration(Max. stress=1.2MPa) , (b) Deformation map of the mirror surface with correction for rigid body motion(P-V=83.3nm, RMS=13.3nm).

At zenith angle = 0°, the vacuum pressure makes the reaction force at the axial support position to nearly zero, and then the mirror deformation is greatly reduced as lightweighted pattern is shown in Fig. 5(a). Reaction force is calculated to 0.47N, and three axial supports are the same as the reference position. The maximum stress, 13.4KPa is very small when compared to yield strength of Zerodur. Through the correction of tip, tilt and piston, the deformation map of the mirror surface was obtained as shown in Fig. 5(b). Surface P-V is 20.4nm, and RMS is 4.25nm(< 20nm, design goal of GMT FSM mirror).



(a) (b)

Fig. 5. Performance analysis of Magellan secondary mirror at Zenith angle = 0°; (a) Stress distribution and deformed configuration(Max. stress=13.4KPa, Reaction force=0.47N), (b) Deformation map of the mirror surface with correction for rigid body motion(P-V=20.4nm, RMS=4.25nm).

At 0° < zenith angle, θ° < 90°, the mirror is supported by the combination of lateral supports and axial support. Lateral supports support cosθ component of the mirror weight, W, and axial supports have its sinθ component. Therfore, at each zenith angle vacuum pressure should be controlled as Wsinθ. Actually, axial supports include the load cell which measures the reaction force acting to axial supports, so vacuum pressure is mediated to zero the reaction force. In case of zenith angles = 30°, 45° and 60°, the mirror surface P-V and RMS were summarized in Table 1. The closer zenith angle becomes at zero, the more RMS values are reduced due to compensation by vacuum pressure. Consequently, all RMS values are less than 20nm at all zenith angles.

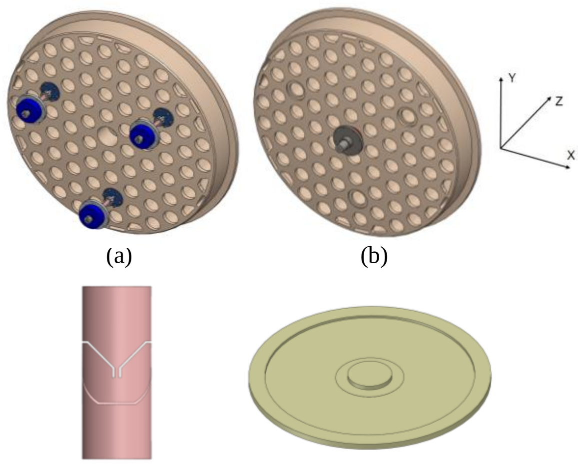
Table 1. Peak to Valley and RMS of the mirror surface at variable zenith angles.

Zenith Angle, θ	0°	30°	45°	60°	90°
P-V(nm)	20.4	47.5	61.6	74.1	83.3
RMS(nm)	4.3	7.7	9.9	11.7	13.3

3. Supports of GMT FSM secondary mirror

Fig. 6(a) and 6(b) shows three axial supports and one lateral support which form kinematic mount system with FSM center mirror. Like Magellan secondary mirror, the FSM center mirror, whose material is Zerodur, has the same axial supports with the vacuum system, and they support the axial component of the mirror weight. One lateral support fully supports the lateral component of FSM mirror weight.

It is possible that axial supports and lateral supports are decoupled by axial flexure tip and lateral flexure. Under the coordinate system as shown in Fig. 6, the axial flexure tip as shown in Fig. 6(c) including the blade is weak for Rx, Ry, Tx, and Ty, but stiff for Tz. The lateral flexure as shown in Fig. 6(d) including the thin plate whose thickness is 0.4mm is stiff for Tx and Ty, but weak for Rx and Ry. The lateral flexure is mounted in center hole of back surface of the mirror whose diameter is 100mm. GMT FSM secondary includes the tip-tilt system to compensate vibration by wind and jittering from telescope tracking. The tip-tilt system compensates tip-tilt angle of ±20 arc-seconds, and its operating frequency is about 20Hz to 30Hz. Therefore, the natural frequency of supports with the FSM mirror should be larger than this frequency. The tip-tilt system is operated through actuators of axial supports, and then when actuating the FSM mirror, the axial flexure tip and the lateral flexure should accept to rotate Rx and Ry.



(a) (b) (c) (d)

Fig. 6. Supports of GMT secondary mirror; (a) Three axial support with the FSM center mirror, (b) One lateral support with the FSM center mirror, (c) An axial flexure tip of axial support, (d) The lateral flexure of lateral support.

The natural frequency of supports should be larger than that of tip-tilt actuation, but smaller than the FSM mirror. Through FEA(Finite Element Analysis), The FE model of the mirror, whose natural frequency becomes 717Hz and depth is 140mm, was developed[3],[4] with shell element, and it was analyzed under free-free boundary condition. When considered the mass of mirror FE model is about 100kg, dynamic stiffness of the mirror was much improved by lightweighting. Fig. 7 shows 1st mode shape of horse saddle configuration. With considering this stiffness, the axial flexure tip and the lateral flexure should be designed flexibly enough, so that they should be deformed before the mirror is deformed. As a result of that, just rigid body motion, which does not affect the mirror performance, occurs.

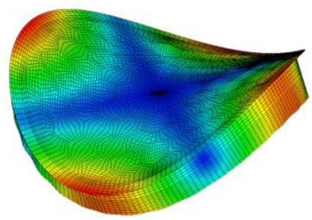
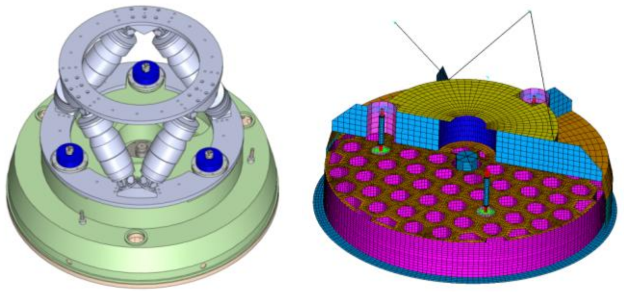


Fig. 7. The 1st mode shape of the FSM mirror; frequency = 717Hz.

4. FE model for center segment of GMT FSM secondary

The center segment of GMT FSM secondary, assembly as shown in Fig. 8(a) consists of one FSM mirror, six axial flexure tips, three actuators and three load cells in three axial supports, one lateral flexure, one lateral sleeve and one sleeve support in one lateral support, one mirror cell and one hexapod actuator. The mirror cell is a base structure which axial supports and lateral supports are mounted. Moreover, it should be stiff for tip-tilt actuation as well as vacuum pressure. The lateral sleeve and the sleeve support are parts connecting the lateral flexure to mirror cell. The hexapod actuator makes seven FSM segments aligned to co-phasing, and it supports weight of each FSM segment. The FE model as shown in Fig. 8(b) was developed by using several elements with materials in Table 2.



(a) (b)

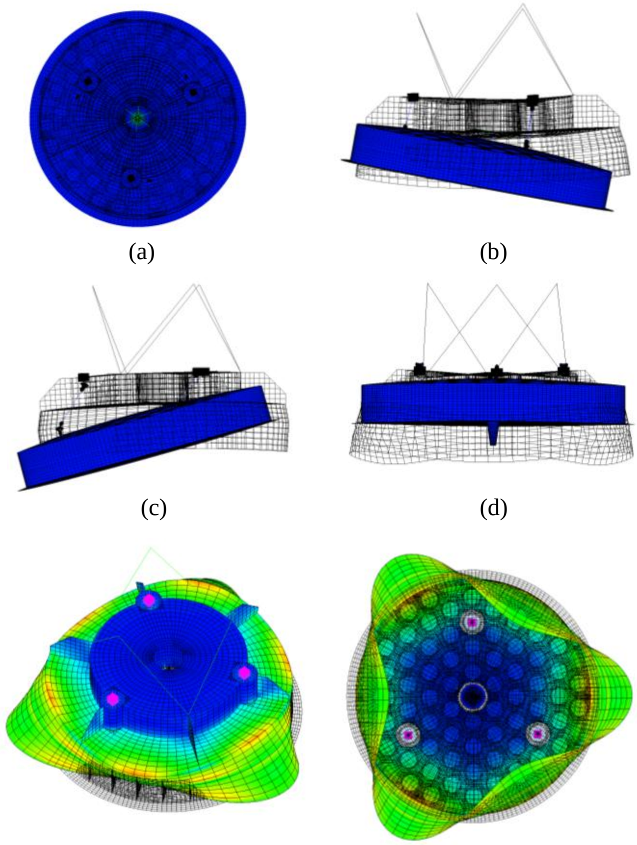
Fig. 8. (a) The center segment of GMT FSM secondary, (b) The FE model for center segment of GMT FSM secondary.

Table 2. Materials properties of each part

Material	E (N/m^2)	ν	ρ (kg/m^3)	YS (MPa)
Al6061-T6 (Mirror cell)	6.9×10^{10}	0.33	2700	275
ST, Ferrite (Axial flexure tip)	0.2×10^{12}	0.28	7800	172
ASTM A36 steel (Sleeve support)	0.2×10^{12}	0.26	7850	250
AISI 304 (Lateral sleeve)	1.9×10^{11}	0.29	8000	206.8
Invar 36 (Lateral Flexure)	1.47×10^{11}	0.29	8050	276
Zerodur (FSM Mirror)	9.2×10^{10}	0.24	2530	75

5. Modal analysis for center segment of GMT FSM secondary

The stiffness of supports was calculated through the modal analysis for center segment of GMT FSM secondary. Under the coordinate system as shown in Fig. 6, torsion, Rz occurred as the 1st mode as shown in Fig. 9(a). In fact, additional parts will be added to improve stiffness for torsion, because it was already predicted that current lateral flexure is not stiff enough for torsion. They will be mounted on the outside radial surface of the FSM mirror. The 2nd and 3rd mode are Rx and Ry motion(tip and tilt motion) as shown in Fig. 9(b), and the 4th and 5th mode are Tx and Ty motion, with rotation as shown in Fig. 9(c). This rotation occurred by the local deflection of region where sleeve support and lateral sleeve are mounted. The 6th mode is translation along Z axis as shown in Fig. 9(d). The frequency of the 2nd to 6th mode is 102Hz ~ 141Hz. Tip-tilt actuation to compensate wind vibration and tracking jittering is operated in range of 20Hz to 30Hz. Therefore, if stiffness for torsion is complemented, the stiffness of supports of the mirror will not affect tip-tilt actuation. The last motion of supports with the FSM mirror occurs at 141Hz. If the vibration of supports with mirror is regarded as excitation by support vibration, to limit amplitude of the mirror cell from the excitation, the natural frequency of the mirror cell should become more than √2 times of excited frequency. This is the amplitude of mirror cell by 141Hz excitation limits in the range of √2 and 2 times regardless of damping ratio, ζ. Therefore, the natural frequency of the mirror cell should be more than 200Hz. The mirror cell the 1st frequency becomes 224Hz as shown in Fig. 9(e) and 9(f) was designed. If supports design is updated, so that the stiffness of the supports is changed a little, the stiffness of the cell will be also updated to √2 times of that.

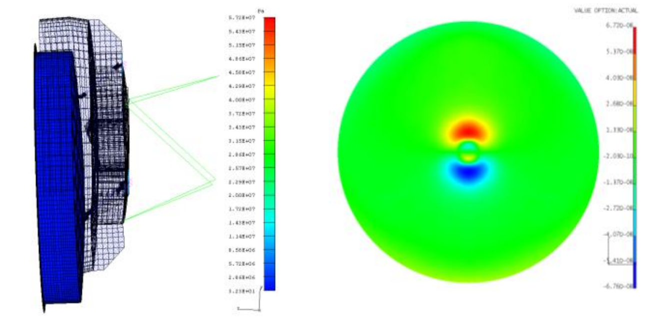


(a) (b) (c) (d) (e) (f)

Fig. 9. Mode shapes for center segment of GMT FSM secondary; (a) 1st mode(7.25Hz): Rz, (b) 2nd and 3rd mode(102Hz): Rx and Ry, (c) 4th and 5th mode(117Hz): Tx and Ty, (d) 6th mode(141Hz): Tz, (e) and (f) 7th mode(224Hz): The deformation of mirror cell.

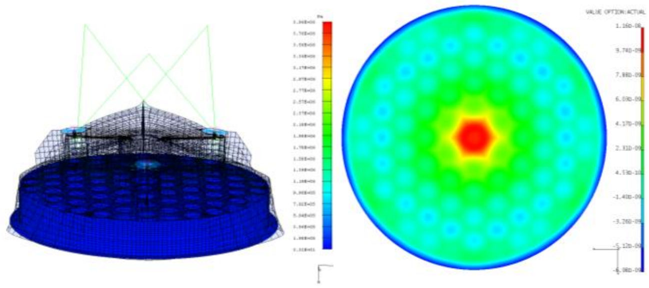
6. Gravity analysis and mirror performance prediction for center segment of GMT FSM secondary

Through gravity analysis for center segment of GMT FSM secondary, it was confirmed if supports can support the FSM mirror and if when the FSM mirror is mounted by actual supports and mirror cell, the performance of the FSM mirror is maintained. In case of Gravity –Y(at zenith angle = 90°), maximum stress value, 57MPa occurred on lateral flexure because it fully supports the FSM mirror weight as shown in Fig. 10(a). When compared to yield strength of Invar 36, 276MPa, safety factor becomes about 5. The maximum displacement magnitude is 24μm. As rigid body motion, tilt for x axis is dominant, and the value is 7E-4 degrees. After rigid body motion made by supports with mirror cell was removed, mirror surface RMS value was obtained to 11.2nm as shown in Fig. 10(b). In case of gravity +Z(at zenith angle = 0°), vacuum pressure is acted to the inside of mirror cell and backplane of the FSM mirror. The mirror weight is fully compensated by vacuum pressure, so that deflection of mirror becomes to a minimum. The maximum stress value, 4MPa occurred on the inside of mirror cell by vacuum pressure, but it is also very small when compared to yield strength of Al6061-T6, 275MPa as shown in Fig. 11(a). The maximum displacement magnitude is 6μm. Piston as rigid body motion is dominant in this case, and the value is 3μm. Through correction, surface RMS was gotten to 3.2nm as shown in Fig. 11(b). Both cases are satisfied with design goal, which is surface RMS value of the FSM mirror is less than 20nm.



(a) (b)

Fig. 10. Gravity –Y(at zenith angle = 90°) analysis of the FSM center segment ; (a) Stress distribution and deformed configuration of FSM center segments(Max. stress=57MPa, Max. displacement magnitude=24μm) (b) When mounted by actual supports and mirror cell, deformation map of the mirror surface with correction for rigid body motion(P-V=134.9nm, RMS=11.2nm).



(a) (b)

Fig. 11. Gravity +Z(at zenith angle = 0°) analysis of the FSM center segment ; (a) Stress distribution and deformed configuration of FSM center segments(Max. stress=4MPa, Max. displacement magnitude=6μm) (b) When mounted by actual supports and mirror cell, deformation map of the mirror surface with correction for rigid body motion(P-V=19.2nm, RMS=3.2nm).

7. Conclusions

Analysis of supports for GMT FSM secondary was performed with the FSM center mirror and the mirror cell. In analysis results, three axial supports and one lateral support could support the FSM center mirror within safe stress distribution for gravity –Y and +Z. At these angles, surface RMS value of the FSM mirror has values less than 20nm, design goal of the FSM mirror when rigid body motions by the supports and the mirror cell were removed. This means the supports are successfully supporting the FSM mirror under kinematic mount system by decoupled supports. Through analysis results of Magellan secondary mirror, we can also predict that the mirror can be supported within 20nm by the combination of one lateral support and three axial supports at 0° < zenith angle, θ° < 90°.

The frequency of the 2nd to 6th mode of supports with the FSM mirror is about 100Hz to 140Hz. When considered that tip-tilt actuations are operated within 20Hz to 30Hz, if stiffness for torsion is improved, the supports of the FSM mirror will not affect tip-tilt actuation. To prevent the torsion, parts which do not affect other motions except torsion will be added.

After the final design and analysis, KASI will manufacture and evaluate a prototype of FSM secondary, FSM assembly which consists of one FSM mirror, three axial supports, one lateral support and one mirror cell by 2012, the time of the GMT system design review.

REFERENCES

[1] GMT Organization, Giant Magellan Telescope Conceptual Design Review, GMTO, 2006.

[2] Magellan telescopes, Technical Specifications for Polishing the #2 Magellan Project f/11 Secondary Mirror, Document No. 98SE0023, 1998.

[3] Cho, M., Park, K., "K-GMT FSMP PDR", Korea Astronomy and Space Science Institute, May 2010.

[4] Cho, M., Park, K., "K-GMT FSMP PDR- II", Korea Astronomy and Space Science Institute, November 2010.

[5] R. Yoder, Jr., "Opto-mechanical system design", Marcel Dekker, 1993.

[6] Y. Bely, " The design and construction of large optical telescope", Springer, 1993.

[7] Cho, M., Ming, Douglas R., "Performance Prediction of the LSST Secondary Mirror", SPIE 7424-06, San Diego, August 2009.

[8] T. Thomson, "Theory of Vibration with Application", Prentice Hall, 1998.

[9] Mack, B. "Deflection and stress analysis of a 4.2m diam. primary mirror on an altazimuth-mounted telescope", Applied Optics, 19(6), 1001-1010, 1980.