Solving a Performance Limiting Resonance Frequency Problem of the SOFIA Secondary Mirror Mechanism by Structural Modifications

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Abstract

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is a 2.7-m infrared telescope built into a Boeing 747 SP. It reached its full operational capability in 2014 and takes off about three to four times a week to explore the infrared sky from stratospheric altitudes above most of the atmosphere’s water vapor content. Since its installation in 2002, the active Secondary Mirror Mechanism (SMM) has proven to be a reliable part of the telescope assembly. However, its performance is limited by a strong structural resonance at a frequency of about 300 Hz. Solving this resonance on the hardware level would lead to a wider actuation bandwidth and therefore a faster transition time for infrared chopping and pointing corrections. Based on finite element simulations, a ring-shaped reaction mass made of aluminum has been identified as the main cause of this mode. Concepts have been developed to eliminate the resonance by changing the mass distribution along the ring shape and by implementing a parallel kinematic suspension. An end-to-end simulation including the mechanical finite element model and a model of the control algorithm was used to predict the final system performance of the developed concepts. Based on the simulation results, a prototype of the new reaction mass was designed and manufactured. An extreme mass redistribution along the ring shape by combining tungsten and AlSiC ring-segments shows the best results. The new ring was integrated and thoroughly tested on a mockup of the SMM confirming the predicted performance improvement. The closed-loop actuation bandwidth is improved by 80%. Based on this prototype, two flight units will be manufactured for future SOFIA science missions.

Introduction

After reaching its full operational capability in 2014, the Stratospheric Observatory For Infrared Astronomy (SOFIA) takes off several times a week to explore the universe. This, today’s largest airborne observatory, consists of a 2.7-m-diameter infrared telescope mounted in the aft fuselage of a modified Boeing 747SP aircraft. Maximizing the scientific output requires successive optimizations of the telescope performance while not interfering with science.

One of the most complex systems of the observatory is the Secondary Mirror Mechanism (SMM) providing fast mirror steering capability for image stabilization and infrared square wave chopping. The SMM is mounted 446 mm before the focus of the primary mirror, close to the cavity opening and exposed to harsh environmental conditions (see Figure 1). After more than 10 years of use and 400 flights, this mechanism, designed and manufactured by CSEM in Switzerland, proves to be a reliable part of the observatory. However, since its integration in 2002 the performance of the SMM is limited by a strong structural resonance at a frequency of 300 Hz. For more information about SOFIA and the SMM refer to [1], [2] and [6].
Figure 1. Location of the Secondary Mirror Assembly on the SOFIA observatory. The SMA is mounted between three spider arms positioning the secondary mirror below the focus of the primary mirror, close to the cavity opening exposed to harsh environmental conditions.

The Secondary Mirror Assembly

The Secondary Mirror Assembly (SMA) is a three-stage system that enables mirror movements in seven degrees of freedom. The design can be separated into three subsystems, the light weight silicon carbide mirror, the Tilt Chopping Mechanism (TCM), and the Focus Center Mechanism (FCM). The FCM is a hexapod platform, attached to the spider arms of the telescope structure and enables mirror movements in two rotational degrees of freedom (DoF) (tip-tilt) and three translational DoF to setup the M2 collimation and focus position. The TCM is mounted on top of the FCM and enables high-frequency tip-tilt M2 motions for infrared chopping and pointing corrections. When chopping (1125 arcsec max), the mirror is alternating the field of view by following a square wave pattern up to 20 Hz at a settling time of about 10 ms. Stationed in the Mojave Desert and flying in stratospheric altitudes, the typical mission temperature range is between -60°C and 30°C.

Figure 2 shows a schematic 120-deg section cut through the TCM presenting the main moving components and all flexure elements of the mechanism. The system is driven by three moving magnet linear actuators. The lever arm assembly amplifies the actuator force and reduces the stroke to allow high precision positioning. Three pivot rods are transferring the actuator load to the mirror holder. A set of force sensors is measuring the induced load. The mirror cell is suspended by a combination of a central pivot rod and a membrane that allows the holder to rotate in the tip and tilt domain. The rod provides stiffness and prevents motion in the focal direction. The membrane prevents side movements of the mirror holder and locks the rotational degree of freedom around the focal axis. The silicon carbide mirror is mounted to the aluminum mirror cell by three bipods to prevent stress due to thermal expansion.

A set of three eddy current sensors is used to measure the mirror position indirectly by tracking the motion of the mirror cell. To eliminate any load induction to the telescope structure when chopping, the lever arm assembly is tilting a ring-shaped reaction mass, the ‘compensation ring’, in the mirror’s opposite direction. This ring is mounted to the three lever arms by a set of flexures. All moving components of the TCM are suspended in their center of mass to prevent any excitation due to external loads.

The main structural mode of the SMA is the chop motion of the TCM at about 32 Hz. The first dominant unwanted resonance that results in mirror jitter is at 300 Hz. So far, this resonance is addressed by the controller, reducing the unwanted mirror motion at the expense of mirror steering performance (refer to [3], [4] and [5] for further information). Constraining this resonance on the hardware level would not only lead to a wider actuation bandwidth and therefore a faster transition between the two chop positions but also reduce the image jitter introduced by external disturbances acting on the active mechanism itself. From
experimental modal analysis and finite element simulations, the compensation ring was identified as the main cause of the 300-Hz mode, from here on referred to as CBEND. The mode shape presented in Figure 3 shows a deformation of the ring geometry and lateral shift of the ring on its soft serial-kinematic suspension. Mirror motion results from this coupled mode.

Figure 2. Schematic 120-degree section cut of the Tilt Chopping Mechanism showing the main moving components. Flexure elements are used throughout the whole system to reduce friction, backlash, and wear out.

Figure 3. Mode Shape of the 300-Hz resonance (CBEND). Left: Deformation of the compensation ring (cyan) and the coupled tip-tilt motion of the mirror (magenta). Right: A lateral shift of the compensation ring is the result of the soft serial-kinematic mount and the soft compensation ring. The compensation blade flexure (green) and the lever pivots (cyan) show deformations.
Solving the 300-Hz Resonance Problem

Concepts have been developed to constrain the 300-Hz resonance. The goal is to find a minimal invasive solution providing maximal performance gain to not interfere with the ongoing science campaigns. One approach that has been followed is the implementation of a parallel kinematic suspension to stiffen the non-operational degrees of freedom of the compensation ring as shown in Figure 4 (left). The original ring is supported by a serial kinematic suspension as shown in Figure 3. Here the loads are transferred from the ring over the compensation blades, the lever arm, and the lever pivots to the FCM interface. Serial kinematic suspensions are to be avoided when seeking high stiffness since the flexibility and positioning error of each element adds up. The other approach is to stiffen the compensation ring itself and to concentrate mass at the suspension points (nodes of mode shape). Taking strain energy out of the mode will reduce its magnitude. Please note that the inertia tensor of the ring has to remain unchanged to retain its original functionality.

![Image of two design concepts](image)

Figure 4. Two design concepts to eliminate the 300-Hz structural resonance. Left: Parallel kinematic suspension to constrain in plane deformations of the compensation ring as well as in plane translational motion of the ring on top of the suspension. Right: Concentrating mass at the suspension points (nodes of mode shape) will take strain energy out of the mode. Selecting stiffer materials will additionally push the resonance to higher frequencies.

Both concepts, the new suspension architecture and the compensation ring with optimized mass distribution (material combination) have been analyzed in a finite element model to predict the new system response. The results are shown in Figure 5 where the system response is plotted over the frequency range of interest. The dominant resonance (CBEND) is clearly visible for the original configuration. Another structural resonance is present at about 430 Hz (SWAY), a sideways motion of the mirror coupled with a deformation of the compensation ring. Different material combinations are shown combined with the serial kinematic suspension (SKS) and the parallel kinematic suspension (PKS). A clear improvement is visible for both concepts. The CBEND magnitude is decreasing and the mode is pushed to higher frequencies. Applying the parallel kinematic suspension while keeping the original aluminum ring results in a magnitude drop of about 35%. Applying an extreme mass concentration at the suspension points using a material combination of tungsten and aluminum while keeping the SKS results in a CBEND magnitude drop of about 90%.
Combining both concepts can basically result in an elimination of the CBEND mode but promotes the SWAY resonance as shown for PKS W-AL. Using stiffer material combinations (less damping) results in a moderate reduction of the CBEND mode without amplifying SWAY (see PKS W-SiC and SKS W-SiC). In general, it can be observed that the more strain energy is taken out of the ring by concentrating mass at the suspension points, the lower the positive effect of the parallel kinematic mount becomes.

Even though a general improvement for most configurations is visible, predicting the new system performance from the open-loop frequency response is not trivial. Does a reduced magnitude or a displaced resonance frequency result in a larger actuation bandwidth? Therefore, these transfer functions were implemented in a control simulation developed in [3] and [4]. It was determined that the parallel kinematic suspensions in combination with an extreme mass redistribution (PKS W-SiC and PKS W-AL) show the largest performance improvement of about 95%. Silicon carbide benefits from its high specific stiffness while aluminum benefits from its good damping behavior. When combining the extreme mass redistribution with the original serial kinematic suspension (SKS W-SiC and SKS W-AL), there is still an improvement of around 80%. Considering the hardware changes required to implement the parallel kinematic suspension to the extra 15% performance gain, the decision was made to retain the original suspension. A detailed description of the end-to-end simulation used to predict the new closed-loop mechanism performance is covered in [7].

Manufacturing of a Prototype

Even if the combination of tungsten and silicon carbide showed a slightly better performance, the SKS W-AL is selected for manufacturing a prototype. Making a complex structure from pure silicon carbide is very challenging and expensive. Furthermore, once installed to the aircraft, the compensation ring is inaccessible for periodic inspections so very fragile materials should be avoided.
Nevertheless, joining two very divergent materials such as tungsten and aluminum can be challenging as well. Due to their diverse material properties, classical brazing or welding is not an option. Consequently, a mechanical joint has to be designed that is stiff and able to compensate the divergent thermal expansions. Figure 6 shows an approach of using flexure elements for the thermal expansion compensation. The heavy tungsten compensation mass (material at the node location) and the lightweight aluminum bridge element (material at the anti-node location) are bolted at the lower joint. A tempered steel flexure connects the two bodies on the upper joint allowing vertical thermal expansion. All other degrees of freedom are blocked keeping a high stiffness of the compensation ring assembly.

Figure 6. CAD model of the new compensation ring showing the segmentation. To compensate the vertical thermal expansion, the bridge element and the compensation mass are connected by a flexure joint shown on the right.

A heavy tungsten alloy (97%W, 2.1%Ni, 0.9%Fe) is used for the compensation masses shown in Figure 7a. Along with its high density (18.5 g/cm³) this tungsten alloy comes with a very high Young’s modulus (365 GPa) providing stiffness at three of the weak cross sections of the ring. Solid carbide tools with polychrome coating were used to machine this tough material. A dynamic trochoidal milling approach was applied to reduce the tool wear and machining loads. To reach a very precise planarity and parallelism of the contact surfaces, they have been precision ground.
To maintain a high stiffness but at a low density in between the tungsten parts, the light weighted bridge elements (Figure 7c) are made from an aluminum-based metal matrix composite (MMC Al70-SiC30). This material has a low density of 2.9 g/cm$^3$ and provides a high stiffness of about 120 GPa. It combines the advantages of aluminum (fracture toughness, damping behavior, density) and silicon carbide (stiffness, density) at a manageable machinability. To reduce secondary machining, the main geometry has been cast. A prototype casting approach was selected based on the thin wall geometry, the deep pockets, and the small quantity ordered (10 pieces). A wax model was 3D printed and invested into a ceramic mold (see Figure 8a-c). After burning out the wax, liquid AlSiC is poured into the resultant cavity forming the final part (Figure 8d). Hot Isostatic Pressing is used to reduce the porosity of the cast as well as to improve the chemical and mechanical bonding of the SiC phase in the metal matrix. This leads to improved material properties and prevents the harder SiC from breaking off during machining and use. Due to the high ceramic content of the material, post machining of the joints has been performed using diamond-coated tools (Figure 8e). Complex fixtures were prepared to enable a steady and defined positioning of the cast part on the milling machine.

To compensate the thermal expansion in the operational temperature range between -60°C to 30°C, flexure elements made of high strength steel are used, shown in Figure 7b. The flexure geometry is optimized in a
way to minimize local stress concentrations during cool down. The assembled compensation ring is shown in Figure 7d.

![Figure 7d](image)

**Performance Testing**

To prove the new design concept and to verify the resulting in-flight performance, extensive testing has been performed on a mockup of the Secondary Mirror Assembly (test bench) (Figure 7e). The test bench is a true scale rebuild of the TCM plus FCM suspension mounted on a heavy optical table. Flight electronics (controller boards, amplifier) were used to operate the test bench for better comparison with the actual SMA. For more information on the test bench please refer to [7]. Figure 9 shows the open-loop system response of the original and the new compensation ring tested on the testbench. The system was driven by applying a white noise excitation to the voice coil actuators while measuring the mirror movements with the eddy current sensors.

Compared to the original aluminum ring, a significant improvement is visible. The CBEND amplitude dropped by approximately 80% while the frequency increased by about 33 Hz. As predicted by the finite element simulations, the frequency of the SWAY mode drops. Fortunately, an increase in SWAY amplitude is absent, which can be credited to the SiC phase in the MMC bridge element when comparing to the SKS W-AL and SKS W-SiC curve in Figure 5. Please note that due to the stiff suspension of the test bench
(mounted on an optical table), the resonance of higher frequency modes (CBEND, SWAY) is amplified compared to the spider arm suspended system of the flight hardware (applied in FE simulations).

Figure 9. Open-loop frequency response of the original and the new compensation ring mounted on the test bench. A noticeable deviation between the new hardware and the simulation result is visible, which is mainly caused by the stiffer suspension of test bench (optical table vs. spider arms of the telescope) and by simplifications of the contact stiffness in the FE model.

Adjusting the controller to the new open-loop system response leads to the closed-loop response shown in Figure 10. Again, the system was driven by a white noise actuator input while measuring the mirror position. The controller gains are changed in a way to adjust the controller to its new stability limit. Based on the -90° cutoff frequency, the actuation bandwidth was improved by 80% (from 50 Hz to 90 Hz). Figure 10 additionally shows a closed-loop simulation result from [8] using the material properties of Al70-SiC30 for the bridge elements. Here a closed-loop bandwidth of about 95 Hz (90%) is predicted. The deviation of 5 Hz can be explained by simplifications in the finite element model such as assuming a rigid behavior of the frictional contacts. Also the stiff suspension of the test bench (optical table) as described above is expected to have an influence on the closed-loop bandwidth.
Figure 10. Closed-loop frequency response of the original and the new compensation ring mounted on the test bench. Zoom of magnitude and phase plot presenting the bandwidth improvement based on the -3 dB and the -90° cutoff frequency.

Conclusion

As a conclusion, the 300-Hz structural resonance of the SOFIA secondary mirror mechanism has been solved by redesigning the ring-shaped compensation mass in a way that its mass is concentrated at the suspension points while keeping the same inertia tensor. Tungsten and AlSiC ring segments are combined to achieve the extreme mass redistribution. The high elastic modulus of the tungsten and the SiC phase of the metal matrix composite additionally provide an improved overall stiffness. Eliminating the resonance enables a more aggressive controller design. Adjusting the control gains to the new stability limit, a significant improvement in actuation bandwidth of 80% was determined from testing the prototype on a full-scale system mockup. Based on this prototype design, two flight units will be manufactured for future SOFIA missions. The improved actuation bandwidth will provide faster mirror steering capability for image stabilization and infrared square wave chopping.
References

7. Yannick Lammen, Andreas Reinacher, Rick Brewster, Benjamin Greiner, Friederike Graf, Alfred Krabbe, "A new test environment for the SOFIA secondary mirror assembly to reduce the required time for in-flight testing", Proc. SPIE 9906, Ground-based and Airborne Telescopes VI, 99064T (27 July 2016); doi: 10.1117/12.2232152

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