53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference

# MOIRE Gossamer Space Telescope – Structural Challenges and Solutions

William D. Tandy Jr.[1]
*Ball Aerospace & Technologies, Boulder, CO, 80301*

Paul Atcheson[2] and Jeanette Domber[3]
*Ball Aerospace & Technologies, Boulder, CO, 80301*

*and*

Aaron Seltzer[4]
*Ball Aerospace & Technologies, Boulder, CO, 80301*

The views expressed are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

Distribution Statement “A” (Approved for Public Release, Distribution Unlimited) – Approved by DARPA on 3/21/12

**The MOIRE optical space system, being designed by Ball Aerospace and its partners for DARPA, is a gossamer structure featuring a 10 meter diameter membrane optical element at a distance 50 meters away from the spacecraft bus, with traceability to a 20 meter primary optic diameter system. During launch, the system is tightly packed to fit within the payload fairing and, once on station, it relies on intricate mechanism design to deploy to its final configuration. Pointing control, optical stability, weight, and stiffness requirements drive efforts in finely optimized structural design. This paper reviews these challenges and focuses on those pertaining to membrane stability and survivability and the novel solutions developed to meet them.**

## I. Introduction

THE Membrane Optical Imager Real-time Exploitation (MOIRE) program is sponsored by the Defense Advanced Research Projects Agency (DARPA), as seen in the initial program Broad Area Announcement[1]. Figure 1 depicts a conceptual approach. The MOIRE system seeks to take advantage of recent developments related to large, low cost, lightweight deployable space telescope technologies to provide geosynchronous based earth observation capabilities. Ball Aerospace & Technologies Corp., with its partners Lawrence Livermore National Laboratory, NeXolve Corporation, and ATK, are working to design a 10-m aperture demonstration telescope (ultimately traceable to a 20 meter aperture system[2,3]) with real-time video downlink capability. The concept exploits the benefits of diffractive optics, which allow for about 3 orders of magnitude relaxation in out-of-plane tolerances in the primary optic when compared to a reflective system. The design is stowed for launch and deployed on orbit. Therefore, the use of deployable booms and optics are integral to the success of the mission. The nature of this large, flexible, deployed structure introduces significant design and structural challenges. This paper seeks to address some of those challenges and the methodologies used to reduce their risk.

Phase I was completed in September 2011, culminating in a Preliminary Design Review. The program is now a little more than a third of the way through a Phase II study to ground validate the telescope design. Ground testing includes building the full optic path, measuring performance relative to changing environmental laboratory

---

[1] Senior Engineer, Structural Analysis, 1600 Commerce Street, Boulder CO 80301, AIAA Senior Member

[2] Staff Consultant, Pointing, Tracking and Sensor Technologies, 1600 Commerce Street, Boulder CO 80301

[3] Senior Engineer, Payload Systems Engineering, 1600 Commerce Street, Boulder CO 80301, AIAA Senior Member

[4] Director of Space Control and Special Missions, National Defense, 10 Longs Peak Drive, Broomfield CO 80021

conditions, calculating margins based on collected data, and creating manufacturing processes and mechanical designs to lay the groundwork for a flight system. Ultimately, the Phase II program seeks to image scene data on a real time basis using the complete optical system.

To accomplish these objectives an end-to-end metrology system is being developed. Taking into account jitter, turbulence, temperature and humidity changes, and other such environmental factors, the closed loop control system will keep the optics aligned over the imaging period. The metrology system is being designed into each optic and in situ data is being collected in advance so that the system will be best positioned at the start of integration and test. Indeed, a significant achievement of the Phase II program will be a finely tuned understanding of the environmental challenges and how to overcome them to achieve results.

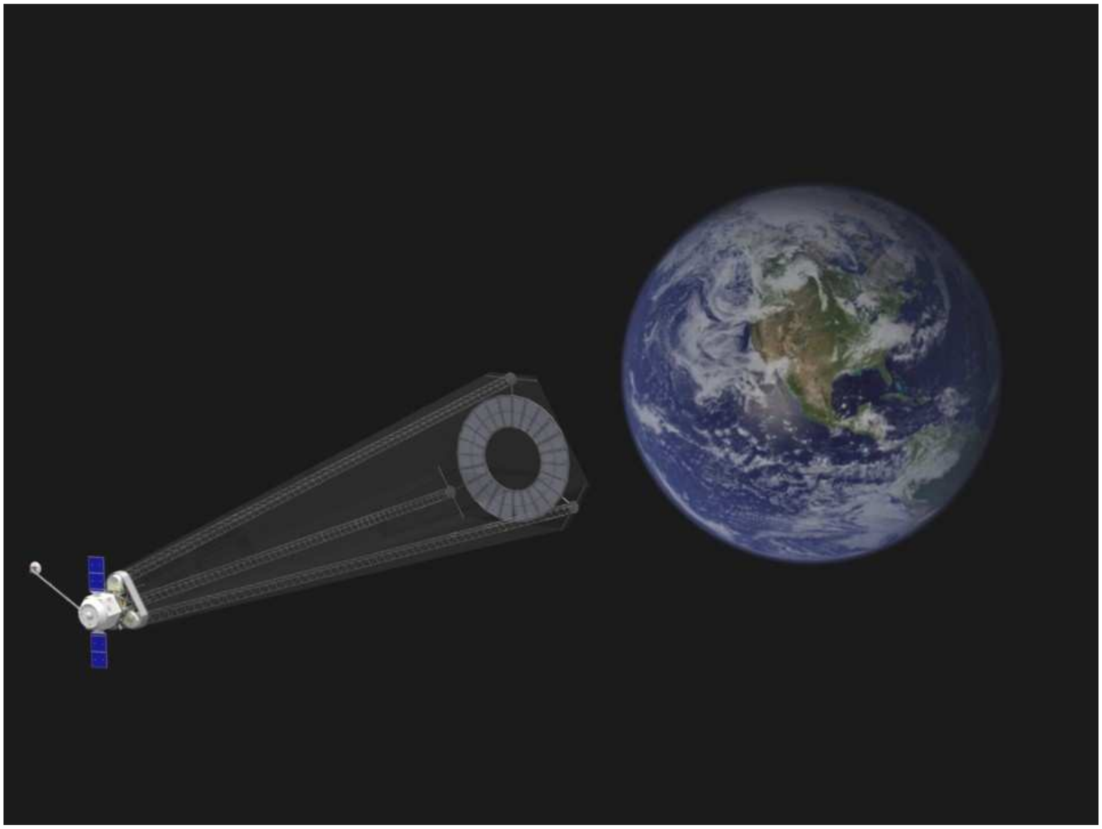

**Figure 1. Artist's concept of MOIRE based on early efforts in system design**

## II. Membrane Overview and Analysis

The design team is working to achieve an areal density of 5 kg/m$^2$ for the primary collection optic. Areal density is used by optical engineers to describe the mass of an optics system including all support structure and local control mechanisms. MOIRE's target optical telescope element (OTE) areal density, which includes all of the optomechanical components and support structure, improves on that of the James Webb Space Telescope[4] by a factor of about 4. To meet the challenge, Ball Aerospace, in conjunction with NeXolve Corporation and Lawrence Livermore National Labs, is developing phase etched membrane optical components, in a process similar to the manufacturing process of silicon processors. The etching produces a Fresnel diffractive optical element (DOE) that is not only exceptionally light, but is three orders of magnitude less sensitive to surface figure control than traditional reflective optical systems. However, there are two serious challenges introduced by using membranes: material stability and membrane acoustics.

### A. Mechanical Design Overview

At the membrane level, the concept is to keep the design as simple and lightweight as possible. To meet the optical performance objectives, the membrane needs to be held dimensionally stable. Wrinkles are an obvious problem that needs to be addressed, but performance can be diminished well before wrinkling starts if in-plane deformations are allowed. This need to minimize the distortion of the etched pattern has lead to Ball designing a frame that holds the membrane around its entire boundary. Figure 2 shows several concept frames that Ball has built and tested to measure various metrics such as manufacturability, stability under loading, handling, and optic throughput. Each framed membrane is tested individually for performance and then many of these frames are combined into an assembly to create the primary DOE akin to what was shown in Figure 1.

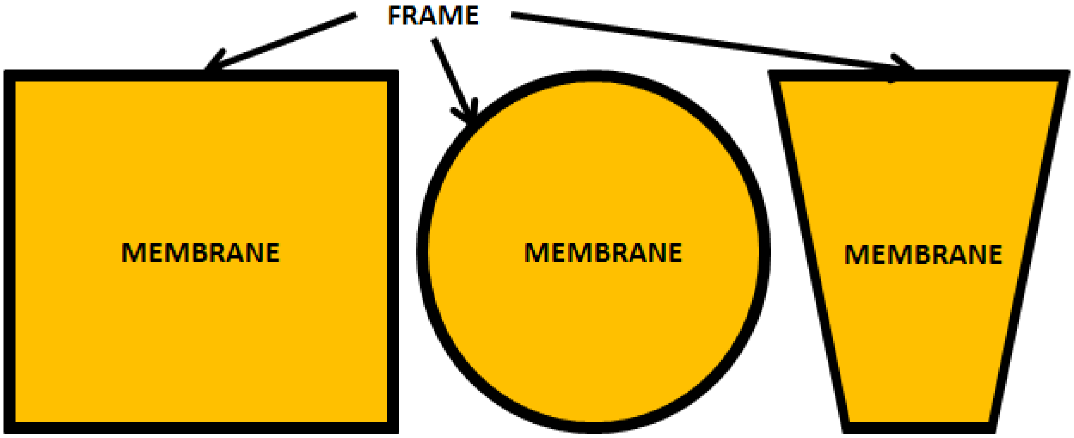

**Figure 2. Frame and Membrane labeling with a sample of the various shapes analyzed for performance.**

## B. Material Stability

The polymer material selected by the team features low CTE values, but there is some known variation within a sheet due to the nature of polymers. Over a large area and through a significant temperature change these variations could potentially lead to unacceptable optical performance degradation. For instance, without analysis non-uniform in-plane displacements due to CTE differences might distort the Fresnel pattern causing image blurring or, in extreme cases, might cause wrinkling and permanent deformations. To move forward, a process to analyze a material with random internal mechanical peoperties was created. The custom set of code for this process was developed in Matlab to import finite element models, apply random distributions based on measured material samples, and export the resulting material maps for downstream analysis. This random material property distribution process was repeated a large number of times to create a curve of probable performance. The predicted curve was then used to compute a sensitivity analysis and budget for image wavefront error (WFE). More than one material property can be assigned a random map so that dual analyses, such as modulus and CTE variations, can be simultaneously investigated.

The process for a CTE variation study that investigates the impact of membrane temperature changes on WFE is demonstrated in Figures 3 and 4. In Figure 3 the image shows a random map generated by the code. Code inputs include the number of seed points to use, the minimum distance between seed points, mean and standard deviation material property values, and material dimensions. After the raw map is generated a smoothing algorithm is applied to generate the contoured peaks and valleys seen in Figure 3. Next, element centers are calculated using the node locations. Finally, the material properties are interpolated onto the element centers. When the user exports the new model deck and runs it in a FE solver package results such as those seen in Figure 4 are produced. By data mining the results over a large number of iterations a surface figure pattern begins to emerge. Analyses such as these are being used in early design efforts and to develop membrane uniformity requirements that directly support the full system performance requirement.

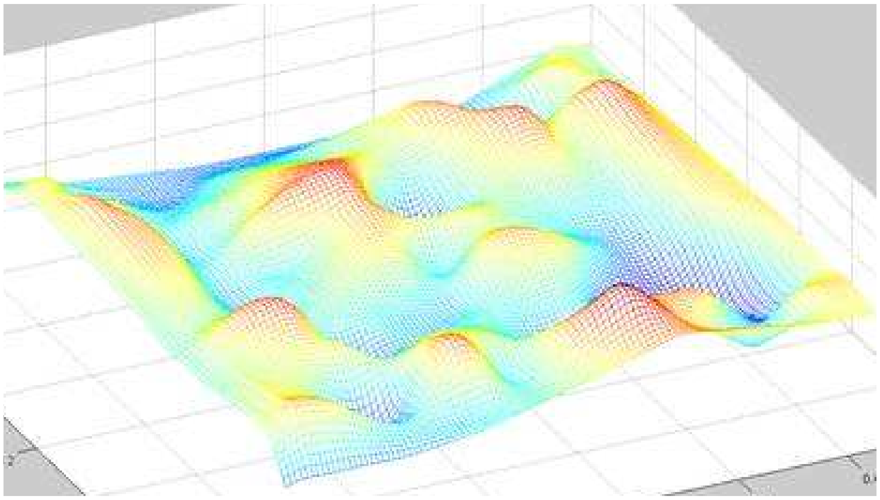

**Figure 3. An example material properties map where the elevations represent CTE values**

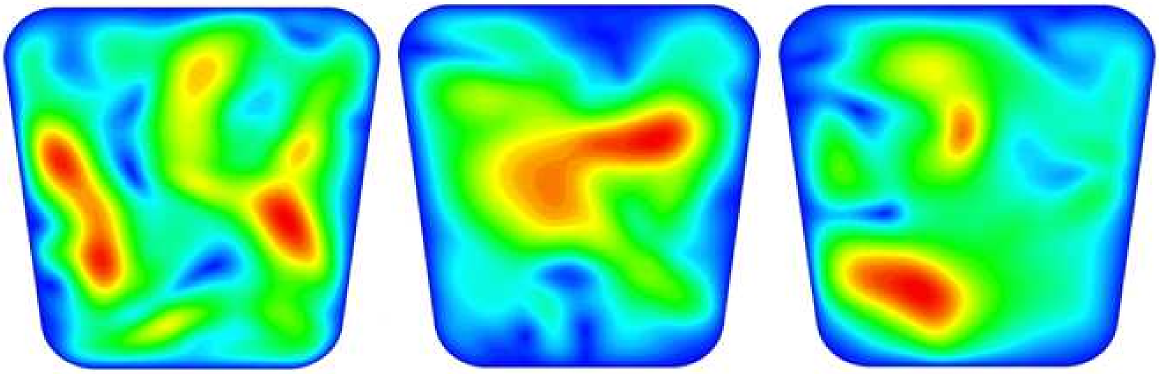

**Figure 4. Example displacement maps created using random material properties.**

When determinging what is good or acceptable the displacement maps above are converted to equivalent WFE and compared to the allowable. The equations used in this process take into account the radial distortion of the Fresnel pattern, the focal length of the refractive membranes, and then weight each node's displacement according to the radial distance from the optic center. From these calculations the allowable changes due to environmental loading are derived. However, while the objective is a flight design the Phase II focus is on ground testing. For ground testing environmental loading means taking into account both temperature and humidity changes and determining allowed deltas for each.

### C. Manufacturing Loads

Before other environmental loads can interact with the frame and membrane there are initial manufacturing loads to consider. The membrane, as delivered from NeXolve, is mounted to a hoop with constant force springs. The springs keep the aperature region of the membrane wrinkle free during the shipping process. An initial manufacturing plan looked at bonding the frame directly to the membrane in the shipping hoop and then cutting the frame free. However, it was expected that the residual tension in the membrane would warp the frame. Figure 5 demonstrates the process and the source of the expected deformation loads.

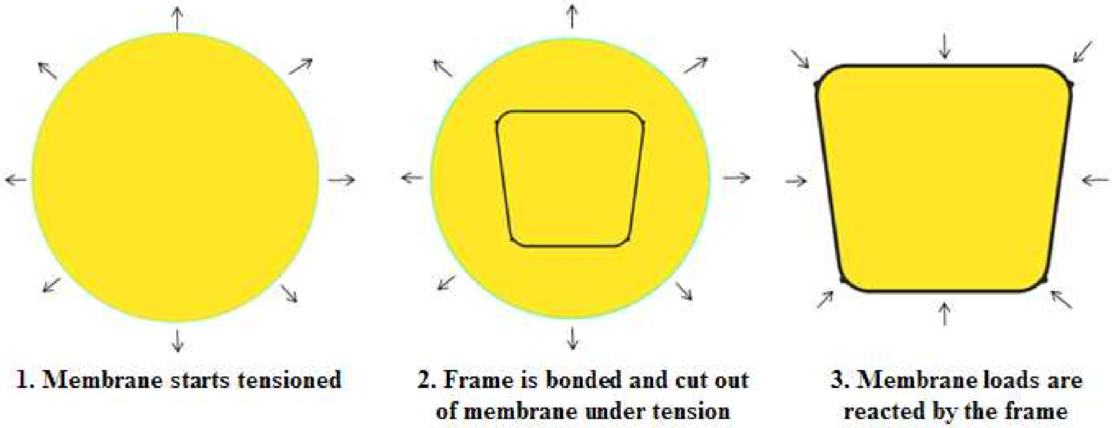

**Figure 5. Membrane to frame mounting process that introduces residual tension into the final product.**

To correctly analyze the deformation, the boundary conditions on the frame needed to be captured. Because the loads on the frame change with where in the hoop the frame is bonded, it was not sufficient to simply apply a thermal load to the membrane in the frame. Instead, the actual internal forces of the full membrane while in the hoop needed to be determined and then exported to the frame's model. To determine the internal forces, a membrane model with the frame's outline embedded at a proposed bonding location was created. The hoop's spring loads were then simulated with a thermal load on the membrane. In most finite element solvers the node force balances can be exported to show that the sum of forces on a node is zero. These nodal force balances were imported into Matlab. Custom software then extracts the correct nodes for the frame's boundary and their forces. These force balance values are then converted into external node forces on a model of the frame. The final model can then be run in a finite element solver to determine actual frame deformations. The process allows for varying hoop loads, frame placements, and frame designs. Figure 6 demonstrates the process.

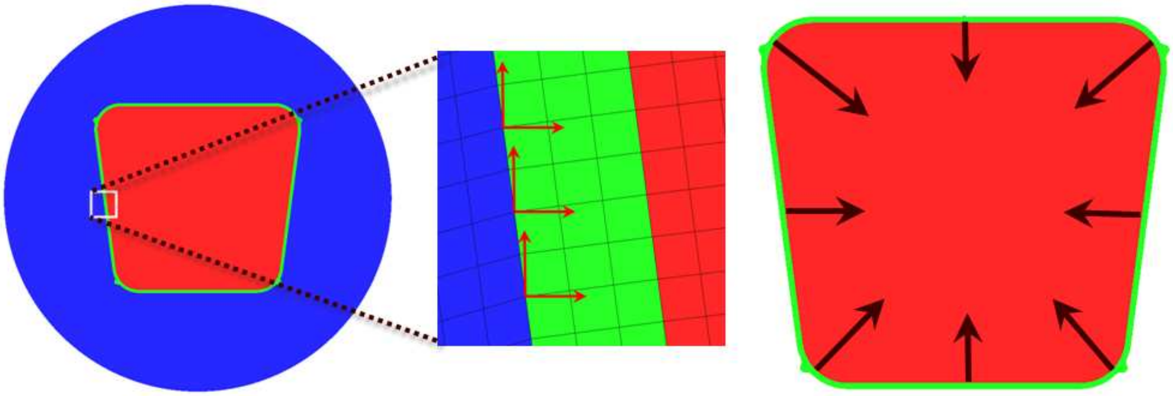

**Figure 6. Process overview for finite element model results converted in Matlab to boundary loads.**

### D. Acoustic Loads

A major concern introduced by using large membrane surfaces is acoustic damage during the launch event. To a lesser extent, air turbulence during ground testing can cause drum head like constant motion of the membrane which raises a potential concern about material durability over time. Besides the potential for catastrophic failure there is a concern about micro-yielding (yield below the traditional yield stress limit) affecting optical performance. Unfortunately, the highly non-linear stiffness of the membrane as a function of displacement makes traditional acoustic analysis unusable. Specifically, most acoustic analyses rely on a FE package to solve for the stiffness matrix which is then used to apply increasing static pressure levels in a linear solution. Because the stiffness matrix of a membrane changes as a function of pressure levels it would be necessary to solve for a new stiffness matrix at each pressure level step. However, this is still inadequate because the launch environment does not step up in even pressure levels, but in random blasts of acoustic energy.

Ball Aerospace is engaging in a multi-part analysis and test cycle to address the concerns. When funded in a future phase of the contract, the analysis will solve a large number of time-domain based acoustic energy profiles. Using the curves provided by potential launch vehicles, random acoustic profiles will be created that have equivalent RMS values, time spans, and mean/peak energy values. Similar to the random material properties discussion in the previous section the goal will be to run enough cases so that a curve of probable outcomes is developed. Efforts along this path have already shown good potential. Figure 7 shows a simple time domain based pressure curve and the membrane’s response. Note that no damping has been included in the analysis so that the oscillations at the static pressure level are expected. These tests were repeated at increasing pressure loads using two different explicit solvers. Figure 8 shows the results of these non-linear displacement responses as the membrane’s out-of-plane stiffness increases with pressure.

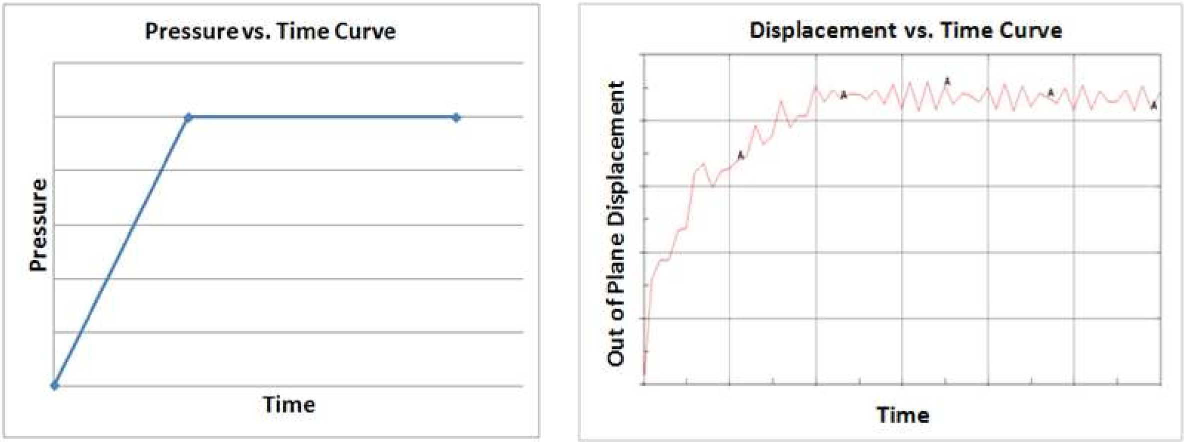

**Figure 7. Example pressure vs. time curve and the resulting out-of-plane displacements**

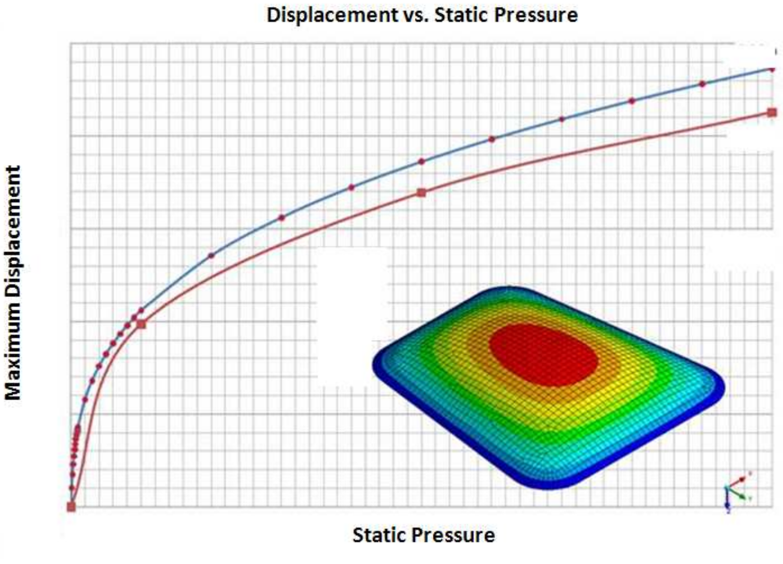

**Figure 8. The membrane’s non-linear displacement response under increasing pressure.** *Results are from two explicit FE solver packages*

### E. Analysis Verification Through Fiducials

The analysis to date has looked closely at what happens when statistical variations occur within the membrane. These variational properties that are being fed into the finite element solvers have come from two sets of initial test data on smaller samples. However, moving forward, bulk membrane properties will be captured through the use of in situ fiducials. The fiducials will primarily be used to align optics in the telescope, but deformations over time will also be captured during the ground testing phase of the program. By mapping these displacements against the measured environment variables, such as temperature and humidity, and against the nominal membrane stress, the analysis will be refined to more closely match the actual membrane properties. This process will help validate the membrane models.

## III. System Level Considerations

While the membrane optic introduces new technology to the space environment the system supporting the membrane carries its own set of novel things to consider. First and foremost is ensuring accurate pointing and control. The large nature of the system (roughly 1,300 cubic meters) means the first modes will be low so the control system will need to accommodate accordingly. The thermal environment also commands attention.

### A. Structural Modes

The deployed MOIRE structure will become one of the largest known on-orbit structures to date making fine-tuned control a delicate balance. Ball Aerospace has designed a control system that will meet the pointing requirements of the system as long as the first modes of the fully deployed spacecraft are above 0.1 Hz. As the system essentially consists of two sets of masses connected by long booms the focus is on making these structures as stiff and light as possible. With ATK, Ball went through a trade study to characterize available boom geometries in order to find the minimum diameter required to meet the control loop needs while still leaving room around the optical bench and fitting within the payload fairing of the launch vehicle. Figure 9 shows the first mode of the system, which is a torsional mode about the telescope's primary axis at 0.2 Hz. In fact, the boom modes dominate nearly all of the modes of the system up to around 100 Hz.

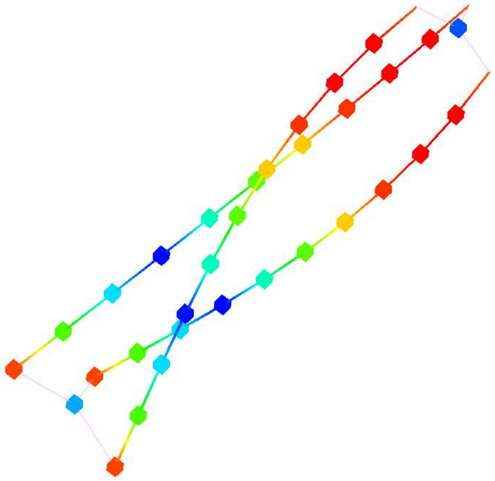

**Figure 9. The first mode of the system is a twisting about the optic axis.**

### B. Thermal Environment

The system structure is currently being designed with active thermal control to tight requirements. Additionally, a sun shade will cover most of the telescope making internal radiation the dominant source of energy transfer. However, the primary optical element will be largely exposed to the ambient thermal environments. Although the current concept of operations prohibits pointing the primary optic directly at the sun, there are potential scenarios where the sun will induce thermal gradients across the DOE.

The first structural decision to combat these concerns was use of a composite framing structure with a tailored CTE profile. In choosing the CTE value a delicate balance is called for as there is concern of membrane wrinkling due to CTE mismatches. As a result, for optical performance reasons, it is necessary to have a frame with a CTE that is slightly lower than the membrane CTE so that as the temperature decreases the membrane tightens relative to the frame. It is also desirable to design the frames with low thermal mass so that it warms and cools as close to the same rate as the membrane as possible. The outcome will be a small tightening of the membrane as the telescope goes from the room temperature test environment to the operational cold environment.

### C. Control System Trade Study

After the first modes of the structure were identified through the boom study discussed above, a full finite element model was built including all optics, the bus structure, and the expected distribution of masses from various subsystems. The optical engineers then provided jitter and pointing requirements that were combined with the finite element model to determine limits on where loads could be applied and their magnitude. Figure 10 below shows a response of the structure when inputs from a proposed thruster configuration were applied. For each potential configuration it was first verified that the force was sufficient to meet pointing requirements within a given time frame. From there the expected jitter that would be input to the system was determined as well as the amount of energy absorption that would be required between the input sources and the optics. Through the comprehensive study of potential pointing configurations a consensus was reached on a path forward. Additional work to verify and extend the analysis will be accomplished in future phases of the program.

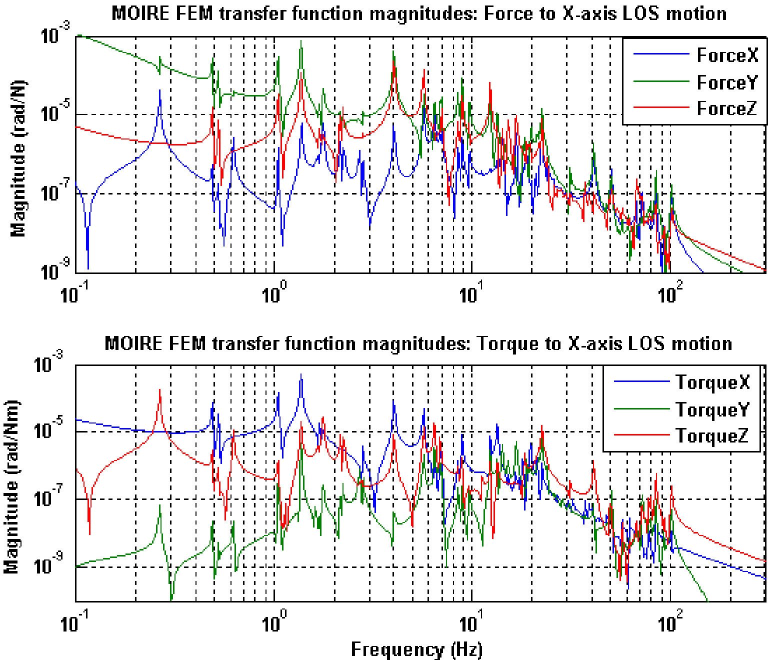

**Figure 10. Early transfer function analysis showing major structural modes reacting to example input control loads during a trade study.**

## IV. Conclusion

The MOIRE program promises significant reduction in large optical areal density over currents systems while being more resistant to the influence of jitter. It also has very high volume to mass ratios and exceptionally cost effective membrane optics. With these and other desirable benefits it hints at the future of space based gossamer systems. However, to make the entire system work requires pushing boundaries in non-linear analysis and creative problem solving. Ball Aerospace and its partners will be pursuing additional fidelity in variational material properties, time domain based acoustic analysis, tight thermal control and mitigation, and careful mechanism design and testing.

## Acknowledgments

The authors would like to express our appreciation for all the hard work provided by the MOIRE team – at Ball Aerospace, DARPA, and our partners Nexolve and ATK.

## References

[1] Solicitation Number: DARPA-BAA-10-51, "MOIRE - Membrane Optic Imager Real-Time Exploitation", URL: https://www.fbo.gov/index?s=opportunity&mode=form&id=5dea37072f51f629ef3f152128856c5b&tab=core&_cview=1

[2] R.A. Hyde, "Eyeglass. 1. Very large aperture diffractive telescopes," Applied Optics, Vol. 38, No. 19, July 1999, pp. 4198-4212

[3] J. Early, R. Hyde and R. Baron, "Twenty meter space telescope based on diffractive Fresnel lens," Proc. SPIE, Vol. 5166, 2004, pp. 148-156.

[4] P.A. Lightsey, "James Webb Space Telescope – A large deployable cryogenic telescope in space," Proc. SPIE, Vol. 6720, Paper 6720-22, 2007.