AMTD - Advanced Mirror Technology Development In Mechanical Stability

J. Brent Knight*[a]
[a]NASA Marshall Space Flight Center, AL, USA 35812

Abstract

Analytical tools and processes are being developed at NASA Marshal Space Flight Center in support of the Advanced Mirror Technology Development (AMTD) project. One facet of optical performance is mechanical stability with respect to structural dynamics. Pertinent parameters are: (1) the spacecraft structural design, (2) the mechanical disturbances on-board the spacecraft (sources of vibratory/transient motion such as reaction wheels), (3) the vibration isolation systems (invariably required to meet future science needs), and (4) the dynamic characteristics of the optical system itself. With stability requirements of future large aperture space telescopes being in the lower Pico meter regime, it is paramount that all sources of mechanical excitation be considered in both feasibility studies and detailed analyses. The primary objective of this paper is to lay out a path to perform feasibility studies of future large aperture space telescope projects which require extreme stability. To get to that end, a high level overview of a structural dynamic analysis process to assess an integrated spacecraft and optical system is included.

Motivation

NASA Marshall Space Flight Center engineers supporting AMTD are evolving engineering methodologies and tools with which future space telescope programs can perform quick turnaround parametric studies of proposed mirror designs. The efforts documented herein are focused on outlining a high level plan to perform structural dynamic analyses to address mechanical stability facet of such programs. The intended audience includes space telescope program managers, principle investigators, and perhaps systems engineers. The primary motivation of this paper is to facilitate meaningful mechanical stability feasibility studies associated with proposed future programs.

Mechanical Stability - General Discussion

The barrage of tasks imbedded within predictions of what is herein labeled "mechanical stability" is complex. Although, at the highest level the task is that of "simply" determining the motion, with all things considered, of the optical system. As simple as that may sound, doing so entails predictions of both rigid body motions as well as flexible body motions of the mirror itself, its immediate support structure, and the spacecraft. Any vibratory motion, rigid and flexible, applied at the optical system to spacecraft interface is a dynamic excitation and the optical system's response to that is a perturbation to stability. Sited stability requirements for a future large aperture space telescope are on the order of 10 pm RMS over ten minutes.

In most other, not space optics, engineering efforts it is commonplace to proactively err on the side of conservatism. By and large it is reasonable and categorically "good engineering" to use the minimum envelope of pertinent damping data, for example, in structural loads analyses. Doing so will result in structural design loads that are acceptably conservative. That is, predicted dynamic loads that hardware would be sized to would be known to be higher than what would be experienced in service, but not too much so. It is always categorically imprudent to be un-conservative. However, in this arena with pm level stability requirements, with no known conservatism in mechanical stability analyses it will be challenging to demonstrate feasibility and thereby secure resources for a future project. For this reason, it is recommended that extreme caution be exercised prior to incorporating some common engineering philosophies. It is also recommended that care be taken to not underestimate assumptions utilized in feasibility studies and thereby lose credibility. These conflicting philosophies are always present but with the order of magnitude of target requirements being what they are, perhaps selected disturbance data, for example, used in feasibility analyses be given more thought than would be typical.

With the challenge of future large aperture space telescope performance requirements in hand, all dynamic characteristics and excitations have to be accounted for and considered as well as any quasi-static loads. Ultimately, accurate damping data has to be available for each element in the design between each excitation and the optical system as well as that of the optical system itself. In summary, with the structural/mechanical design of the spacecraft and the optical system, detailed damping data, detailed accurate models of the dynamic excitations and their phasing one can accurately predict motion that results in Wave Front Error (WFE) and alignment errors.

It is unreasonable to think that one could ever know the precise phasing of dynamic disturbances on board a spacecraft while in service. That is, one cannot, for example, realistically predict when the reactions wheels are going to be spinning at a known frequency and know when something in the active thermal control system is going to turn off or on creating a simultaneous disturbance. For that reason, it is likely that effects of multiple disturbances will be combined via root sum squares. This is common in efforts to predict the composite dynamic (vibratory and transient) environment due to multiple mechanical systems and similar things occurred in the International Space Station micro-gravity arena which is very similar in nature. Predicted peak responses from all disturbances could be linearly superimposed but doing so would likely be overly conservative the vast majority of the time.

A high level depiction of the dynamic mechanical system to be assessed for stability is depicted in Figure 1. Ultimately, the entire integrated system has to be analyzed to predict overall performance. However, to get to the desired end, parametric studies of potential piece part designs of that system can be performed independently determining each sub-system's dynamic characteristics and sensitivities. One such step is to perform analyses of potential or proposed mirrors to determine transfer functions that represent the sensitivity of the mirror itself to unit dynamic inputs at its interface. This would result in determining the influence of the primary mirror in the stability of the overall optical system. As something to talk to in this paper, a Finite Element Model (FEM) of a 4 m hypothetical mirror is utilized in this effort.

A block diagram of a simplified analysis process for performing a mechanical stability analysis is presented in Figure 2.

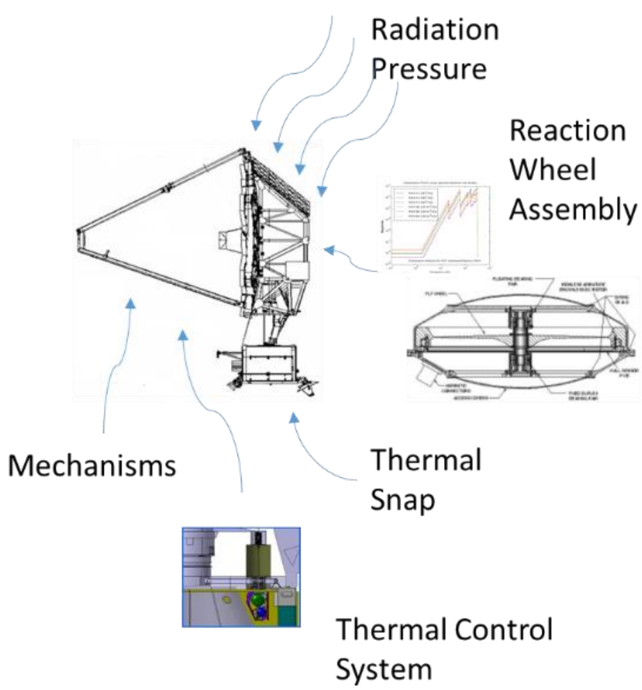

Figure 1: Dynamic Mechanical System

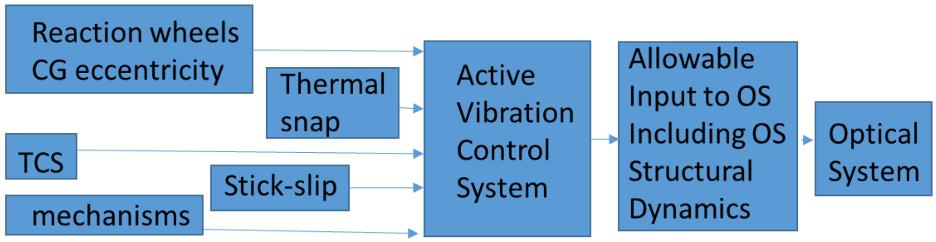

Figure 2: Mechanical Stability Analysis Block Diagram

Spacecraft and Optical System Support Structure Design

As is always the case in dynamics, the structures in question, the spacecraft and telescope systems, are as much players in the source of the subject deformations as are the dynamic environments that initiate them. For example, the magnitude and frequencies of dynamic loads associated with motion in a reaction wheel system that excites the mirror to spacecraft interface includes dependence on the modal frequencies and mode shapes of the spacecraft structural design itself. Similarly, the alignment of and deformations of the mirror surface are, with that input at its interface, dependent on the modes of the optical system's structural design.

The design of the spacecraft structure as well as the optical system support structure can contribute much relative to mitigating disturbances or amplifying them. In the absence of the global structural architecture of a proposed future program, perhaps use of transfer functions derived from models of the James Webb Space Telescope (JWST) spacecraft and optical system support system would serve as a good start for feasibility studies.

Dynamic Disturbances

Any mechanical system on board the integrated spacecraft that includes moving parts (compressors, mechanisms, reaction wheels, etc.) or fluid flow will create dynamic excitations that to some degree perturb mechanical stability. Dynamic excitations, "forcing functions", can be modeled in the time domain or the frequency domain. A sudden impulse might be considered a short duration time domain event and considered a short step function and a rotating component of a reaction wheel system would likely be considered a harmonic frequency domain disturbance. The latter could be assessed in the frequency or time domain analytically. In any case, the accurate mathematical representation of the comprehensive list of disturbances is paramount. The challenge now is to devise an accepted means to quantify that to the extent necessary to demonstrate feasibility of a future project.

Conversations with JWST dynamics analysts have been held in an effort to at least qualify what disturbances are the most significant in that program. At that time, the consensus was that the reaction wheel assembly (RWA) is the big hitter. Figure 3 shows a depiction of the JWST RWA disturbances and is included for qualitative purposes only. This is to highlight the point that by the end of JWST development efforts, and in fact now, there should be significant/pertinent space telescope disturbance data available for use in feasibility studies. ***It would be optimum for that data to be organized and stored with all pertinent engineering data (drawings, models, operational data, etc.) necessary for future engineers to readily utilize it. Ideally, this would be done real time.*** It may be a significant number of years before that data needs to be utilized and current personnel working JWST will likely be long since detached from pertinent details.

At first glance, one may think that the RWA needs a requirement to avoid modal frequencies and thereby prevent coupling and therefore circumvent the potential for an amplified response. However, an RWA can have multiple wheels that each sweep through frequencies from DC up to 70 or 80 Hz. It is also probable that the rate of sweep will be slow enough for modes to reach their potential peak. Therefore, dynamic coupling will occur.

Other phenomena that can result in dynamic excitations include thermal snap and stick-slip. Ultimately, any intended or not intended motion of any part in the integrated spacecraft/telescope system will to some degree be an excitation and will carry the potential to take away from error budgets. On the upside, since requirements relative to the RMS of deformations over 10 minutes where many of these sources are potentially averaged out of the picture and the subject analyses would bear that out.

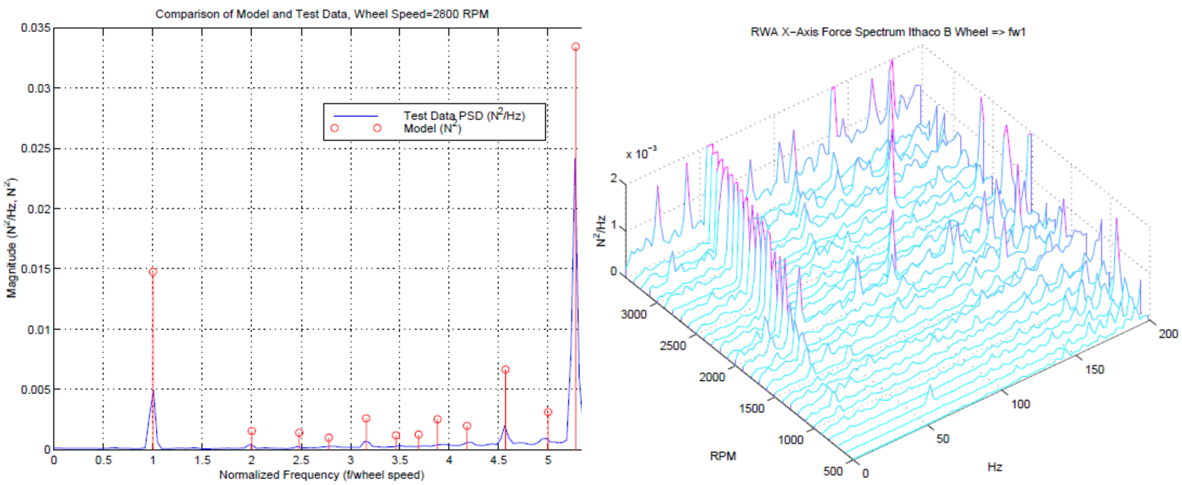

Figure 3: JWST RWA Disturbance Data Samples

Within this arena of extreme precision and accuracy, unlike other mechanical engineering circles, the effort associated with “capturing” an adequate mathematical representation of pertinent dynamic disturbances can be a feat in and of itself. An RWA will have multiple sinusoidal forces acting simultaneously and cryo-fluid impacting a bend in a fluid line will likely be represented as a random input and potentially input to the analysis process as a power spectral density. Compressors powering up will be a transient as will be their spinning down. While operating nominally they will input sinusoidal disturbances. The imbedded message here is that developing forcing functions for the stability assessment will be as much an exercise in modeling as is the creation of pertinent FEM’s. To try to get to that end for at the feasibility level of effort is not possible As said previously, due to target levels being at the extreme that they are, a comprehensive set of disturbances is essential in feasibility studies. So, ideally, one would use that which already exists from a mature program.

A first cut may be to single out the thought to be worst disturbance or forcing function and predict the WFE based on that alone. If that is promising then a next good metric would be to look at the complete set of forcing functions and perform the analyses with that set of disturbances.

Damping

A mechanical systems vibration damping characteristics are unique to that system. Materials have their own level of structural damping. Joints between structural members can result in another component of the overall damping. A systems damping has to be measured to know it with any level of accuracy and certainty.

Conversations with JWST personnel have brought out that damping at cryo temperatures is much lower than originally considered. That stands to reason in that at colder temperatures structural members seemingly lose ductility. With lower ductility flexural motion decreases, therefore, damping would go down. The effect of that is that actual and predicted responses (dynamic motion) would be higher than anticipated.

It is common in many circles to use conservative numbers for damping in structural dynamic analyses associated with design. It is also likely common to not measure damping after a system is built since in many circles conservative methodologies cover any potential small damping data discrepancies. However, with the order of magnitude of current target stability requirements, use of un-necessarily conservative damping assumptions may contribute to less than desirable feasibility study results.

Vibration Isolation Systems

As has been stated multiple times in this paper, with the order of magnitude of the target stability requirements being what they are, an upper end system or method to isolate the optical system from spacecraft disturbances to the greatest extent possible is paramount. To know how much isolation will be required requires insight into the levels of disturbances, dynamics of the spacecraft and dynamics of the optical system.

A point of caution is that actual isolation needed and/or provided between two flexible bodies may vary greatly from that predicted with rigid bodies modeled on either side of the isolated interface. Perhaps using the dynamic characteristics of the JWST SC in pertinent feasibility studies will better estimates or point the optical system structural design in a meaningful direction.

A 4 m Mirror "Case Study"

MSFC has developed a FEM tool tailored for quick turnaround creation of mirror FEMs. The Arnold Mirror Modeler (AMM) was utilized to create a FEM of a hypothetical 4 m monolithic ULE mirror that is used here as a talking point. The FEM is shown in Figure 4.

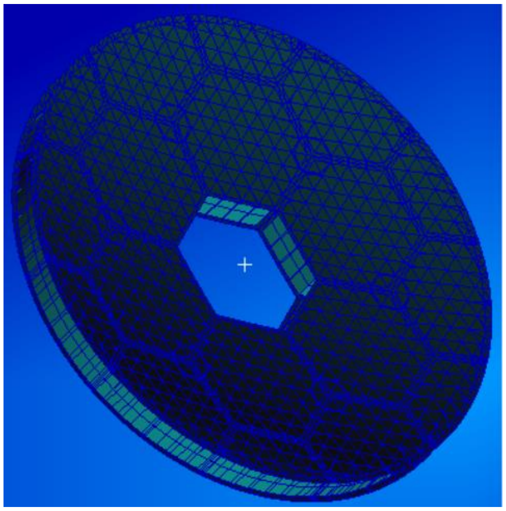

Figure 4: Finite Element Model

The mirror design is arbitrary and utilized solely to be the subject of pertinent discussions. The FEM in this effort is basically comprised of shell elements and rod elements, it has material properties associated with ULE and its mass is 1,941 Kg. A model summary is presented in Table 1.

FEM	**Quantity**
Grids	4734
Concentrated Mass Elements	12
Shell Elements	9348
Rod Elements	1014
Rigid Elements	132

Table 1: Finite Element Model Summary

Analyses performed were done in the frequency domain using the described FEM. A unit input (1m/s^2) from 1 to 250 Hz was applied and responses were predicted. Mirror surface nodal responses in the mirror axis direction (Z direction in the FEM coordinate system) were doubled to estimate WFE, then root mean squared (RMS) and potted as a function of frequency. These results serve as a set of transfer functions that can be factored by frequency domain disturbances to predict the estimated WFE due to that disturbance.

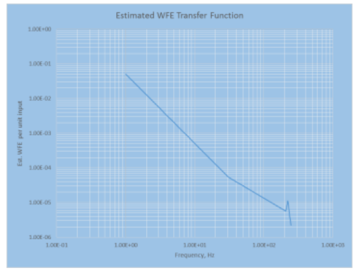

Figure 5: Transfer Functions

Knowing that forcing functions, at least on JWST, can go down to DC (RWA) it is important to note that even though there are no mirror modes that low, there is still motion. Looking at 25 Hz on the above plot the TF is on the order of 10^{-4} WFE/(m/s^2 excitation) and at above 200 Hz where the mirror modes begin it is 10^{-5}. The point to be made is that for any oscillating input, at a modal frequency or not, there is resulting motion of the optical system. From another perspective, the RMS of the WFE TF in frequency band $210 \leq f \leq 250$ is on the order of $7 * 10^{-6}$ and for the entire spectrum shown it is $7 * 10^{-3}$. In this very simplified example it is clear that the contribution of the modal regime is relatively small.

Verification and Measurements

Notable concern is perceived relative to being able to measure motion at the target order of magnitude levels. While being able to do so may necessitate advancing pertinent measurement system technologies, in the interim, comparing FEA results to the lowest possible measured levels would certainly add value to feasibility studies. If current technology can facilitate measuring motion to the 500 pm level, for example, and that compares favorably to FEA results then that would add notable credence to the FEA efforts in this arena.

Relevant conversations have by and large included the subject of isolation and/or active corrections. Knowing our performance target, going there is intuitive. However, one cannot actively isolate or correct or impose motion at levels beyond that which we can with prudent accuracy and certainty measure. Advancing relevant technologies is paramount.

Summary of Points Made

1. One cannot predict dynamic responses or WFE without knowledge of what creates it, the disturbances. In an arena that pursues extreme results, much more than superficial insight into those disturbances is paramount.
2. It is accepted that significant vibration isolation is necessary to achieve the target goal. As good a representation of the flexible nature of the two bodies in question (SC and optical system) need to be included in vibration isolation system feasibility studies. To estimate the level of isolation needed considering the two bodies as rigid may be misleading.
3. Due to the spectral nature of the structural sensitivities and therefore pertinent TF’s, it is not meaningful to utilize the TF to derive a single scalar TF and base studies on that. Doing so could unnecessarily over constrain engineering efforts as well as conservatively or un-conservatively skew the picture.
4. Furthering low pm level measurement capabilities is seemingly paramount.

Proposed Future Work

Proposed future efforts include acquiring and compiling JWST disturbance, isolation, SC TF and damping data. Then deriving from that as simple a set of inputs as possible to facilitate large numbers of quick turnaround parametric analyses but that is comprehensive enough to capture the effect of the major contributors to performance. That would be utilized in feasibility studies incorporating a conceptual optical system structure and a broad range of conceptual mirror designs. The results of that would be representative of the order of magnitude of WFE due to those parameters.

Conclusions

Meaningful feasibility studies of a future space telescope system that can achieve the target stability is clearly possible but necessitates the compilation of detailed disturbance data and dynamic characteristics of an expected similar SC. The effort of gathering that data has initiated and progress has been made. A set of transfer functions similar to those discussed is as simple a model as one should utilize to perform trade studies of this nature.

The target stability requirement is seemingly beyond the normal level of extreme. Nonetheless, meaningful feasibility studies are achievable with the suggested data available and with appropriate measurement and control capabilities achieving the target requirement seems plausible.