AMTD - Advanced Mirror Technology Development In Mechanical Stability

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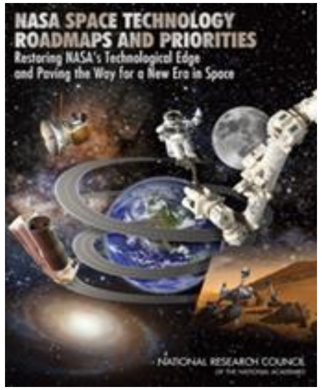
J. Brent Knight
NASA/MSFC/ES22

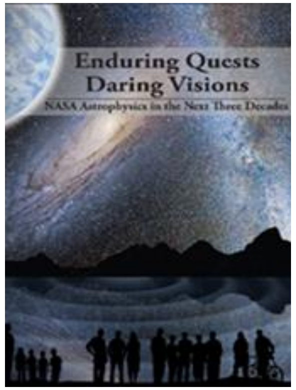
Agenda

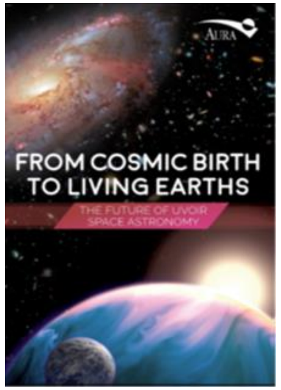
- Advanced Mirror Technology Development (AMTD)
- Arnold Mirror Modeler
- Objective
- Optical System Stability Big Picture
- Mechanical Stability
- A 4 m segmented mirror case study
- Dynamic Disturbances
- Vibration Isolation
- Summary

AMTD

- Efforts associated with this presentation are performed as part of the Advanced Mirror Technology Development (AMTD) program
- Larger aperture space telescopes are required to answer our most compelling science questions.





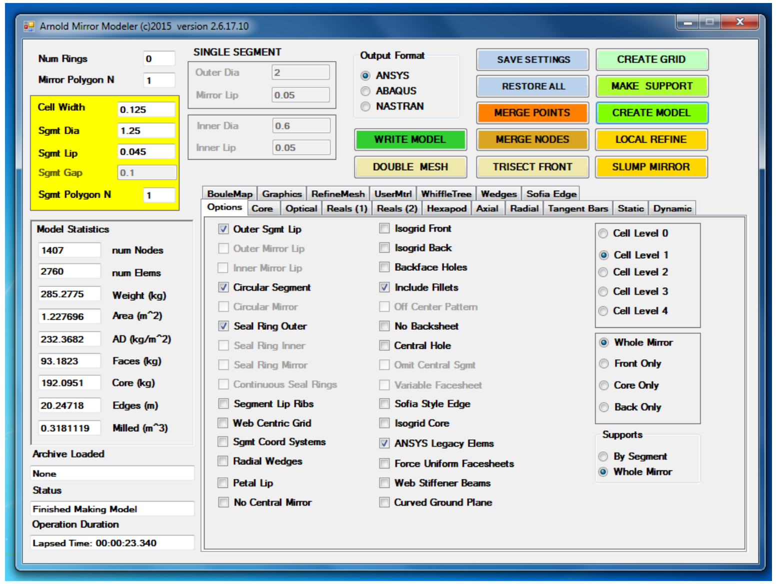


- AMTD's objective is to mature to TRL-6 critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

- To accomplish our objective, we:
  - Use a science-driven systems engineering approach.
  - Mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

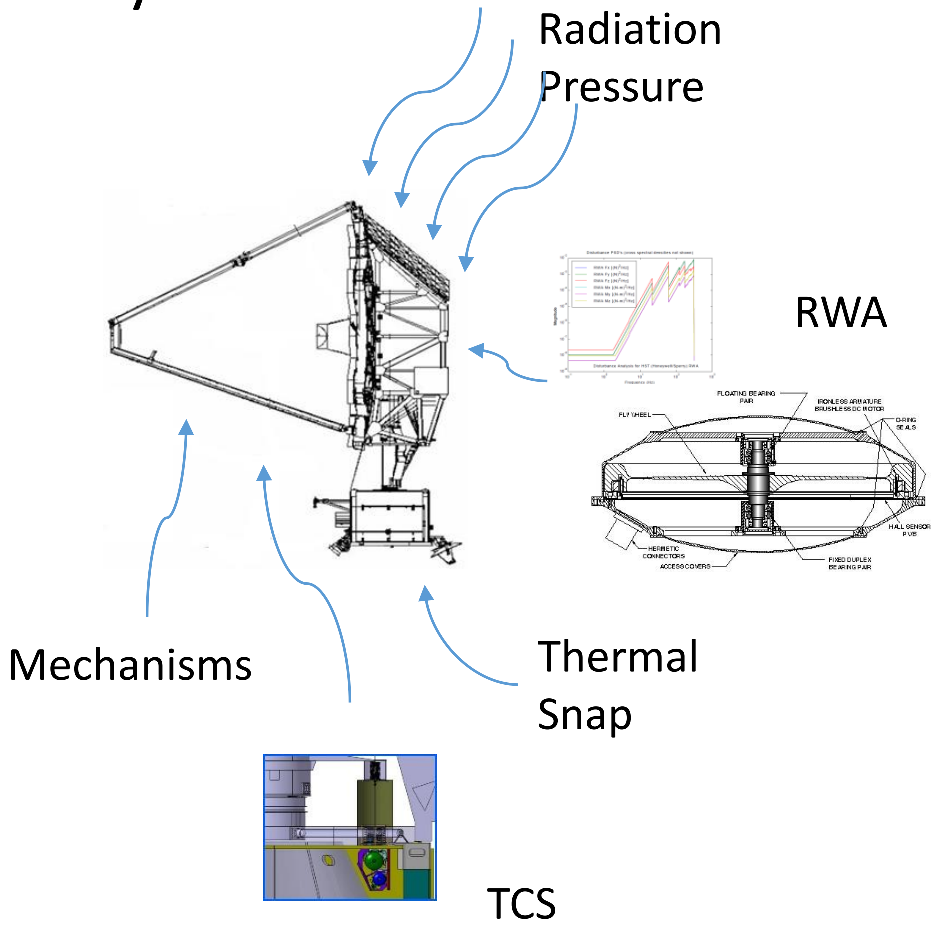
Arnold Mirror Modeler

- From the engineering analysis perspective, a key element of AMTD is the development of the Arnold Mirror Modeler (AMM)
  - Interested parties are referred to presentations by Mr. Bill Arnold
- The purpose of this talk is not to discuss the AMM per se but it is certainly worth introducing that here
- The AMM is an analysis tool that very quickly (few minutes) creates a Finite Element Model of a circular or hexagonal mirror of any size.
  - Literally, 10's of FEM's of large mirrors can be created and run to predict a stress field or modes, for example, in only hours
  - Structural design parameters such as mirror thickness or rib thickness can be varied extremely quickly to asses the impact/sensitivities of those parameters
- It was originally created to quickly assess mirrors for launch environments
- FEMs created with the AMM are now being utilized in efforts to evolve quick turnaround optical performance (mechanical & thermal stability) analysis tools



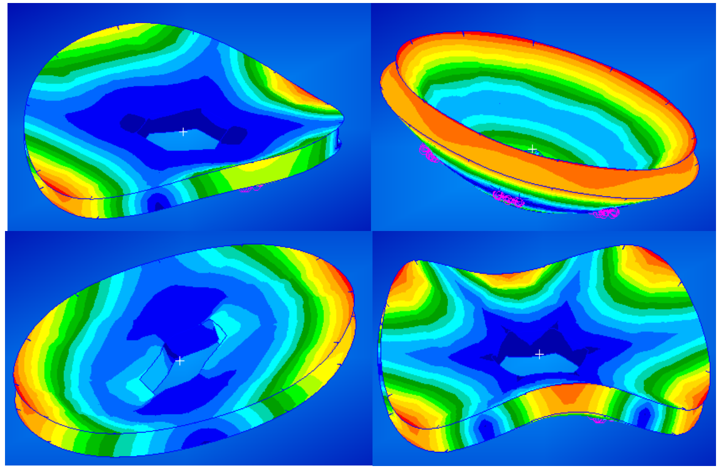
Objective

- The objective of this presentation is to outline a path to provide the science communities future required level of optical performance relative to Mechanical Stability (MS) using a 4 m mirror case study
    - 10 pm RMS over 10 minutes
- The pertinent parameters to achieve that end are
    - Structural dynamics
        - Mirror, Mirror support structure & Spacecraft
        - Mode shapes, frequencies, damping, etc.
    - Dynamic disturbances
    - Vibration Isolation System
    - Radiation Pressure
- <u>With the exception of radiation pressure the source of perturbations to MS are man made</u>
    - <u>Therefore, the potential to design them out exists</u>

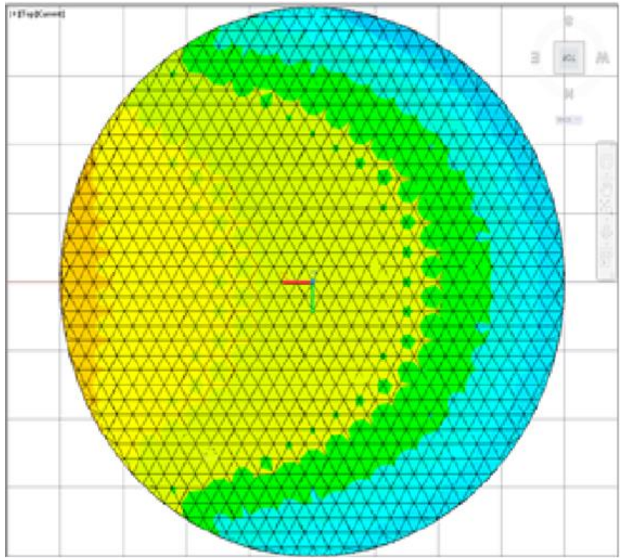


Optical System Stability Big Picture

- Optical System Stability (OSS) is a measure of how motionless the system is.
  - Sources of motion include structural deformations due to thermal gradients and motion, flexible (structural deformation) or rigid, due to structural dynamics
    - Thermal extremes in space are known
    - Dynamic/vibratory environments are not known
      - They are a function of the mechanical systems on board the space craft and the spacecraft structure itself
        - Reaction wheels
        - Thermal control systems
        - Thermal snap …
    - The absence of clear bounds on the Dynamic Disturbances adds a level of complexity to pertinent engineering



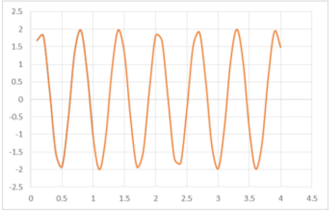
Mirror vibratory mode shape

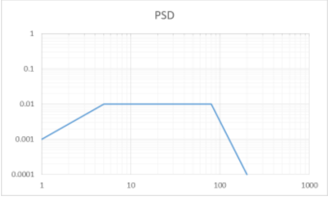


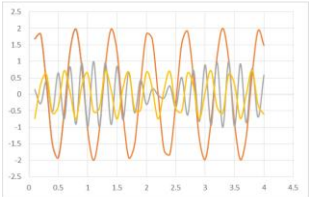
Mirror Thermal Gradient

Optical System Stability Big Picture

- Dynamic Disturbances
  - Once all dynamic disturbances are identified for a given spacecraft/telescope system they have to be modeled for use as inputs to structural dynamic analyses
    - Some modeled in the frequency domain and some in the time domain
    - Some in the frequency domain may be modeled with an enveloping power spectral density and some as discrete tones
      - The latter could be numerically represented by a time domain signal in a transient analysis or by a frequency and amplitude in a frequency response analysis
  - Initially, very early in a future space telescope program, equipment specifications and judgment may be used to get initial estimates of dynamic disturbances
  - Or, use measured data from previous programs such as JWST







Optical System Stability Big Picture

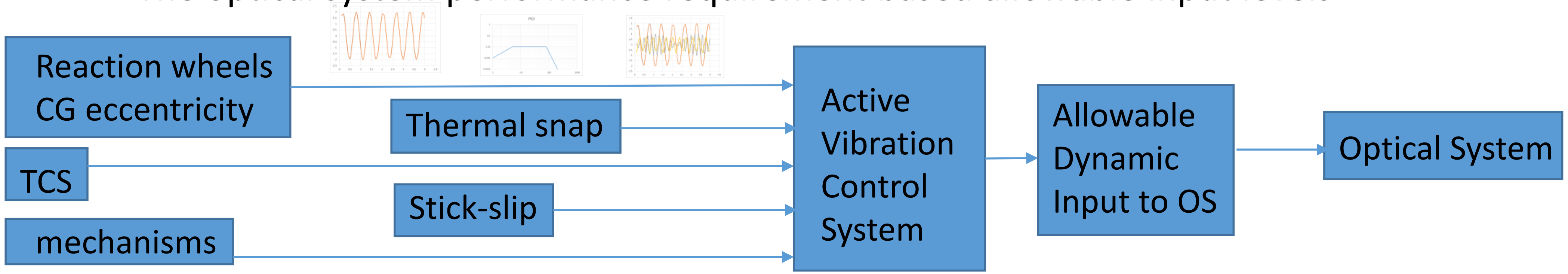
- Combining effects of multiple dynamic disturbances to stability
  - The effect of each of the known dynamic inputs (reaction wheels, thermal control systems, transients….) has to be considered to represent the overall effect on optical performance
    - In particular, the wave front error associated with each dynamic/vibratory source of excitation has to be considered
  - Knowing that many, maybe all, of the disturbances can occur simultaneously how are they to be handled?
    - Consider their effect individually? This is non-conservative
    - Linear superposition? This is overly conservative
    - RSS? Probably the best approach

$$wfe_{tot-dyn} = \sqrt{\sum_{i=1}^{n} wfe_i^2}$$

n= number of disturbance sources

Optical System Stability Big Picture

- Vibration Isolation
  - With the order of magnitude of future space telescope Optical System (OS) performance requirements being what they are, a cutting edge active vibration isolation system will be paramount
    - Overall performance presumably better than JWST - pm levels of stability
  - Two parameters are needed to define vibration isolation requirements
    - The vibratory signature associated with all disturbances at the spacecraft to isolation system interface
    - The optical system performance requirement based allowable input levels

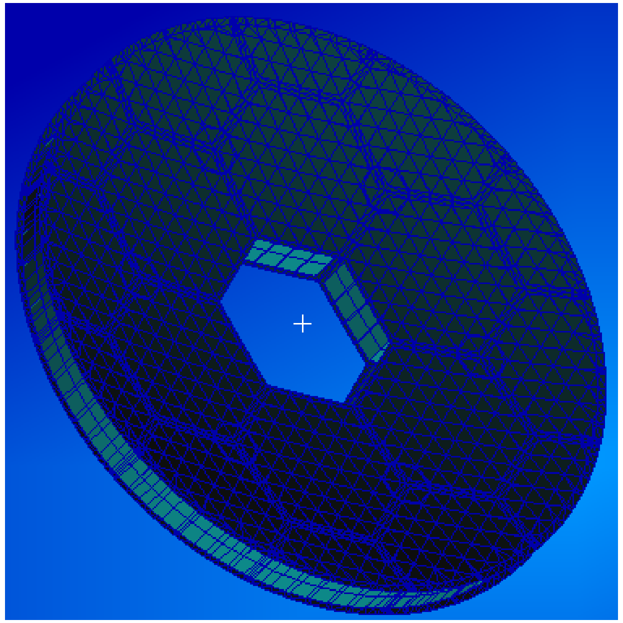


- It’s worth saying that more isolation or less disturbance can yield the desired result

Mechanical Stability

- Knowing the science required mechanical stability, one can derive mirror interface requirements for a given mirror design
  - Requirement will be in the form of

    a set of Transfer Functions (TF)



Simplified Approach

Resultant of all vibratory disturbances at isolation system to telescope interface	*	Analytically derived mirror System transfer functions	≤	Stability requirement levied by the science community

A 4 m Segmented Mirror Case Study

- Analyses done and presented here are relative to the derivation of transfer functions represented in block 2

Resultant of all vibratory disturbances at isolation system to telescope interface	*	Analytically derived mirror System transfer functions	≤	Stability requirement levied by the science community

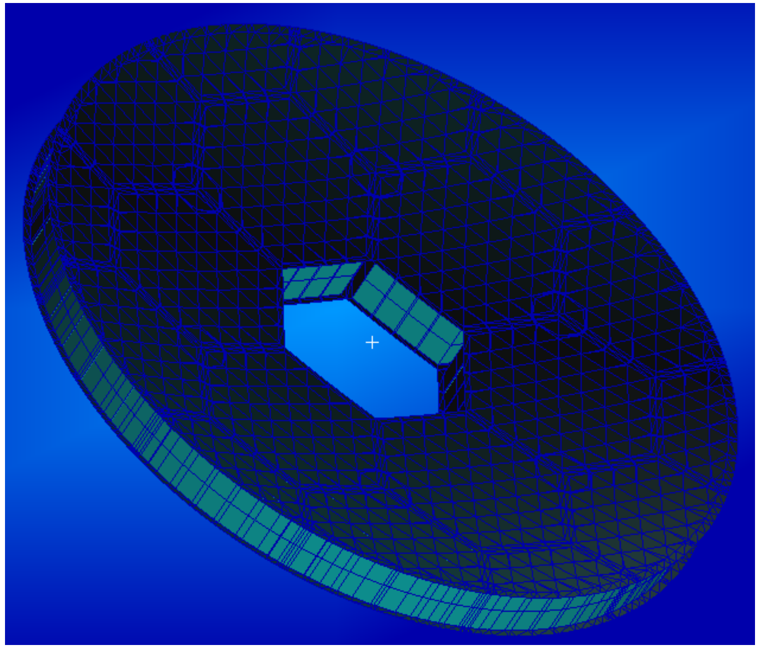
- The dynamics of a mirror's suspension system are a huge player in the overall system performance
- However, since there are many potential mirror suspension system designs and they would strongly influence results, analyses performed were of the mirror only (w/o a suspension system)

A 4 m Segmented Mirror Case Study

- An AMM generated FEM of a 4 m was acquired
- Suspension system was removed
- Bonded pads retained
- Suspension system to pad interface was fixed
- Model summary:

M O D E L   S U M M A R Y

ENTRY NAME	NUMBER OF ENTRIES
CONM1	6
CONROD	1008
CQUAD4	2568
CTRIA3	6780



A 4 m Segmented Mirror Case Study

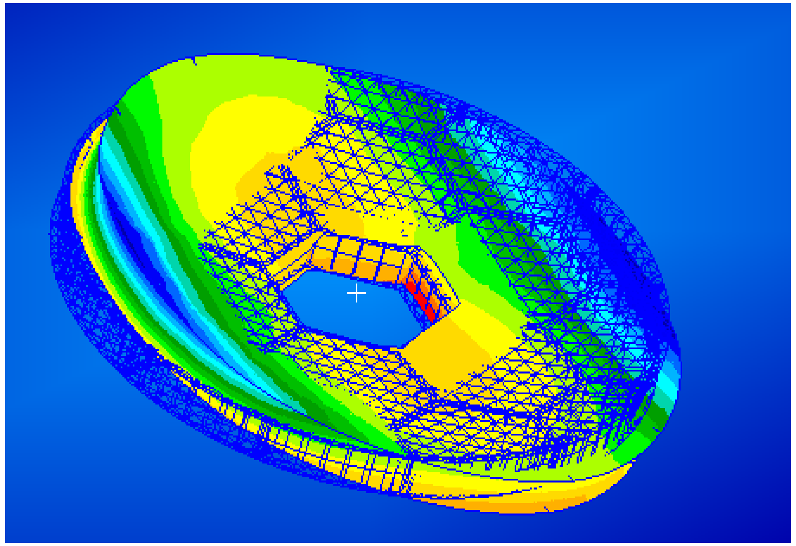
- FEM mass = 1,938 Kg
- Predicted Modes and Modal Effective Mass (MEM)
  - Modes up to 250Hz were captured

Mode No.	Frequency (Hz)	Modal Effective Mass					
		X	Y	Z	θ_x	θ_y	θ_z
1	214	0.04	0.06	0.00	0.38	0.26	0.00
2	214	0.06	0.04	0.00	0.26	0.38	0.00
3	222	0.00	0.00	0.32	0.00	0.00	0.00
4	240	0.00	0.00	0.00	0.00	0.00	0.00
5	240	0.00	0.00	0.00	0.00	0.00	0.00

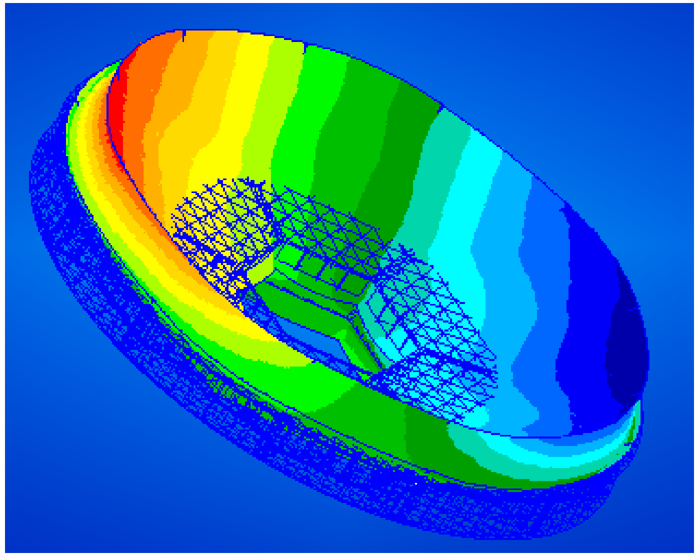
- MEM is a measure how readily modes are excited by base excitation
  - Global modes are considered easily excited by base excitations
  - High MEM is indicative of a global mode and low MEM is indicative of a local mode

A 4 m Segmented Mirror Case Study

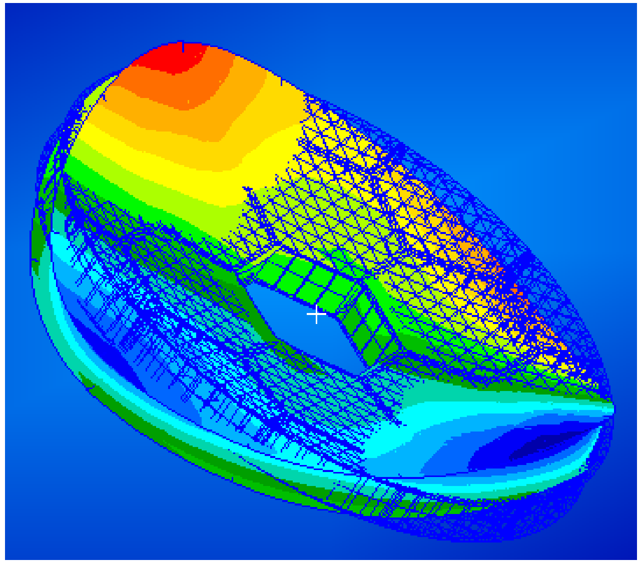
- Mode Shapes



Modes 1 and 2



Mode 3



Modes 4 and 5

Modes 1 – 3 can contribute to the overall RMS WFE but with practically no MEM acting in 4 & 5 it is not likely that they will be big players in the overall WFE

A 4 m Segmented Mirror Case Study

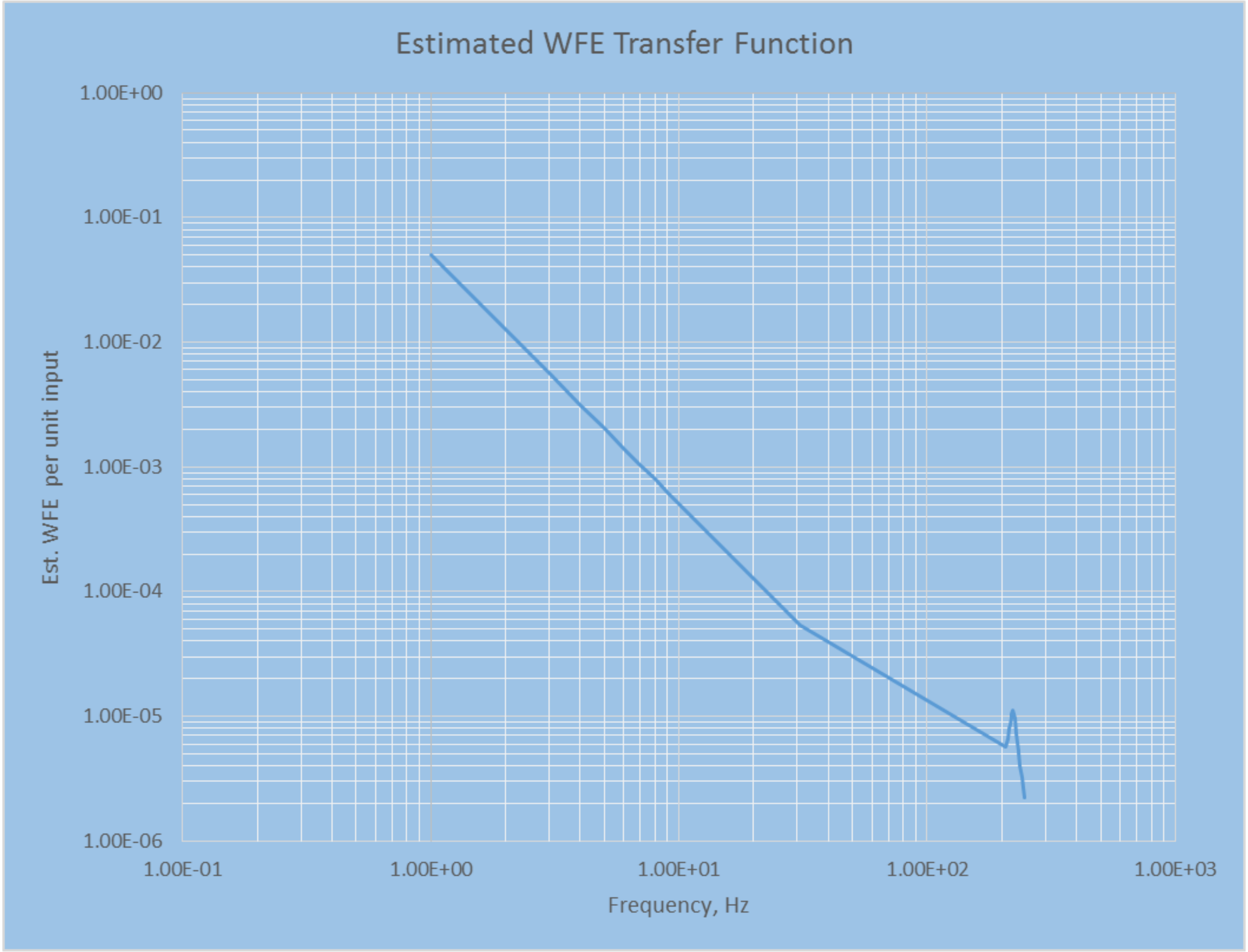
- For the analysis performed:
  - Assumed damping ratio of .03
  - The FEM is fixed at the suspension system to pad interface
    - All 6 DOF's are fixed
  - Unit input from 1 – 250 Hz
    - 1 m/s^2
  - Results are displacements
  - Z direction, optical axis, displacements are assumed to be normal surface deformations
  - WFE is assumed to be displacements factored by 2

$$WFE_{est} = \sqrt{\frac{1}{n}\sum_{i=1}^{nf}\sum_{j=1}^{ng}(2z_{ij})^2}$$

ng= on the surface of the mirror FRM
Z = displacement in the z direction
nf= number of frequencies considered
n = nf * ng

A 4 m Segmented Mirror Case Study

- Frequency Response Analysis was performed using the 4 m case study FEM
- The WFE TF results order of magnitude are deceptive
  - This is not the predicted WFE
  - Results are TF's that would be factored by a known disturbance level
  - TF is an estimated WFE per unit (1 m/s^2) input per frequency

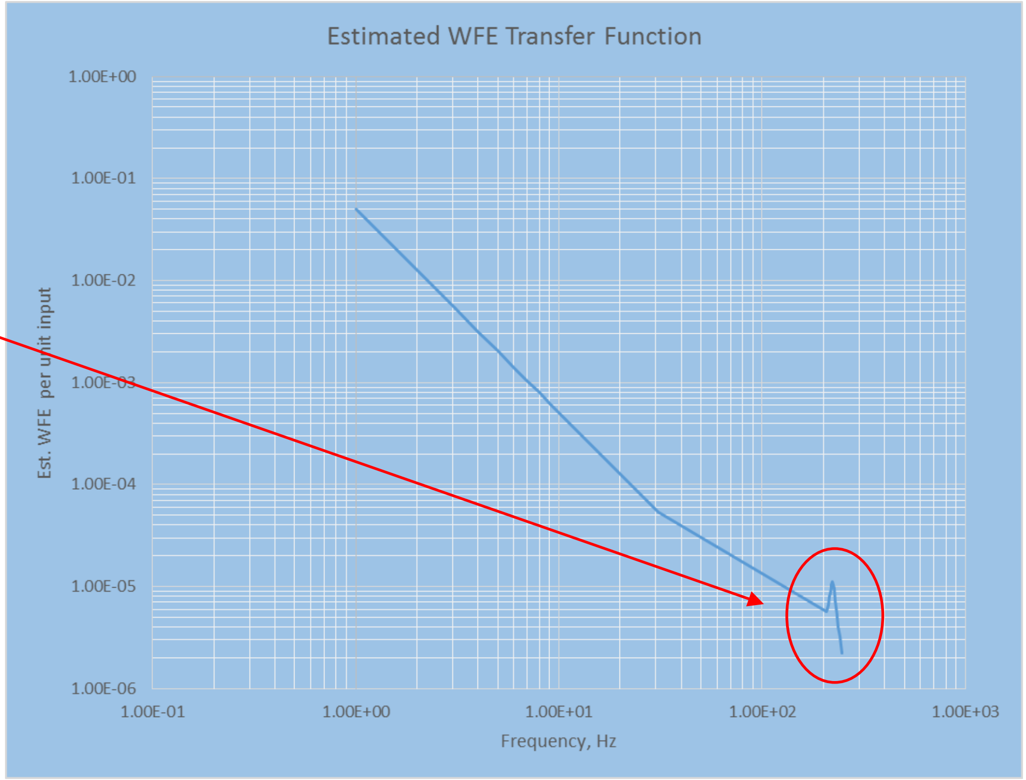


A 4 m Segmented Mirror Case Study

- The RMS of the WFE TF's is on the order of 7 *10^{-3} across the frequency range
- The region in which the mirror has modes (captured in this analysis),

  210 Hz ≤ f ≤ 250 Hz

  has an RMS on the order of 7.3 *10^{-6}
- So those modal responses contribute little to the overall potential response
- Obviously, those frequencies at which there are no dynamic disturbances would be factored by 0 when computing the WFE

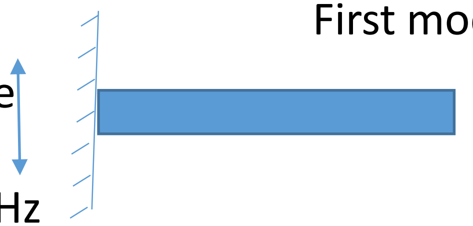


A 4 m Segmented Mirror Case Study

- Potential misconception
  - Minimizing the effects of structural modes of vibration is paramount
  - But that alone will likely not be enough to meet future performance requirements
  - The point to make is that in the complete absence of vibratory modes, forced vibratory motion will always be there
    - The magnitude of this is perceived as significant relative to the need for pm level stability
    - Of course, everything is significant relative to pm requirements
  - Example:

First mode is @ 80 Hz

Input base
Excitation
1 g @ 50 Hz



Cantilever beam

The beams natural frequency of 80 Hz will not couple with the 50 Hz excitation so resonance (amplified response) will not occur

But the beam still exhibits the 50 Hz forced motion
So, to reiterate, to limit concerns to modal responses will likely not suffice

A 4 m Segmented Mirror Case Study

- How would one go from here, with the set of transfer functions to predict the WFE?
  - In an existing program disturbance/vibration data associated with all known disturbance sources (RWA, compressors, mechanism,…) would be in hand (or in work)
  - Those disturbances modeled in the frequency domain would be used to factor the transfer function and output the actual WFE due to that disturbance

Frequency Domain Disturbance $(m/s^2)/Hz$

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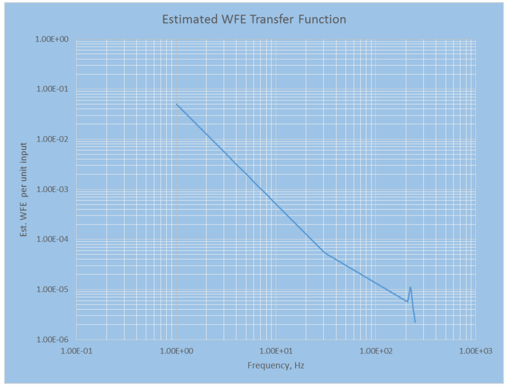

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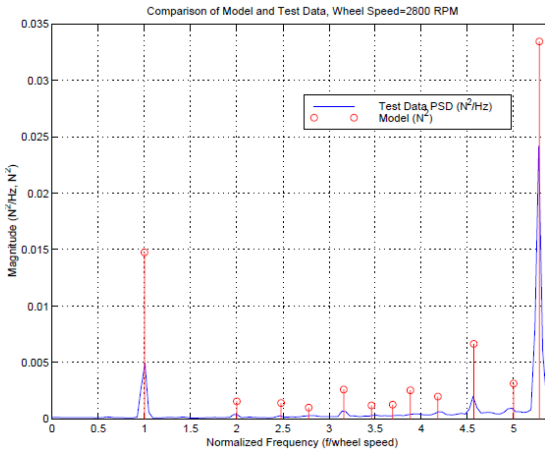
WFE for that Disturbance Over the spectrum

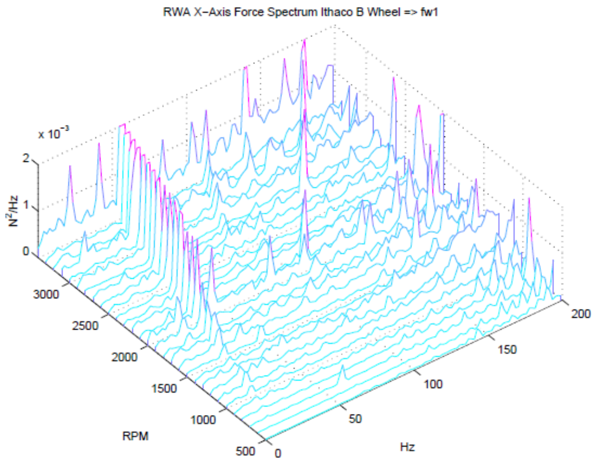
  - WFE from all sources would have to be combined and the cumulative result compared to the science levied requirement

Dynamic Disturbances

- In the proposal phase of a program, or very early in a program, existing disturbance data from the current in service programs would be a great first cut
  - For feasibility studies and proposal efforts for a proposed post JWST program, for example, use the JWST disturbance data
    - It is assumed that since the new program wouldn't manifest until years after JWST
    - Seemingly, RWA technologies, for example, would have advanced by that time so assuming that those disturbance levels are conservative is reasonable



Samples of JWST Disturbance Data

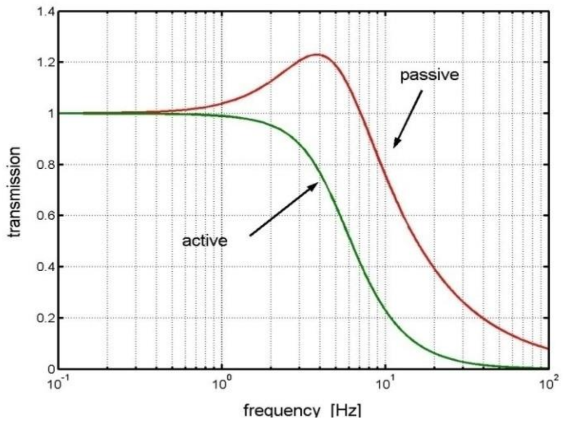


Vibration Isolation

- With future performance requirements being in the in Pico meters, a state of the art vibration isolation system will be paramount
- How much isolation is needed?
  - While a given vibration system can advertise that they can isolate to some level or provide a level of reduction, one cannot know how much isolation they will need in a future system without knowing the net disturbance level
- Example of isolation system transmissibility
- Transmissibility is output/input

$$disturbance * Transmissibility = output \leq stability\ requirement$$

- *w/o the input disturbances one cannot know how much reduction is needed*



From reference 2

Summary Points

- In early efforts to lay out a future space telescope program, a tool such as the AMM will add enormous efficiency
- The effect of all dynamic disturbances can not be assessed w/o a first cut at the disturbance levels
- One cannot know how much vibration isolation will be needed w/o the above
  - So again, a first cut at the dynamic disturbances has to be included in the assessment
  - Perhaps start with the resultant (loosely stated) of all JWST disturbances
- With the exception of radiation pressure, perturbations to MS are man made
  - Therefore the potential to design them out exists
- It is likely not adequate to simply focus on controlling the modes of the structures in question since forced vibrations will be an input
  - To mitigate this, disturbance levels at all frequencies need to be minimized