Design optimization with system level adaptive optical performance

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Objective

- Enable optimization with system level requirements rather than sub-system level requirements
  - Allows early feasibility studies with one system level model
  - Helps with budget flowdown for later detailed sub-system design efforts

System Level Requirements

Sub-System Level Requirements

- Thermal Stability Wavefront Error 20.0 nm
  - Primary Mirror 14.1 nm
    - Design Cycle
  - Secondary Mirror 6.3 nm
    - Design Cycle
  - Focal Plane 4.5 nm
    - Design Cycle
  - Metering Structure 7.7 nm
    - Design Cycle
  - Margin 8.9 nm

- Gravity Release Wavefront Error 60.0 nm
  - Primary Mirror 42.4 nm
    - Design Cycle
  - Secondary Mirror 19.0 nm
    - Design Cycle
  - Focal Plane 13.4 nm
    - Design Cycle
  - Metering Structure 23.2 nm
    - Design Cycle
  - Margin 26.8 nm

- Nonoperational Wavefront Error 30.0 nm

System Wavefront Error 70.0 nm
Implementation Overview

Start

MSC.Nastran™ Solution 200
Design Optimization

Evaluate Design
Calculate Responses

Converged?

Redesign

Sigmadyne
SigFit
DRESP3
Server

Compute Sensitivities

Stop

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Space Administration.

5/5/2005
System Adaptive Control Simulation

- Actuator influence functions $\Phi_m$ decomposed into rigid body motions and Zernike polynomials, $B_{jm}$, for $m$th actuator and $j$th rigid body motion or Zernike polynomial
- Matrix of system sensitivities, $S_{kj}$, transforms actuator influence surface functions, $B_{jm}$, to system wavefront influence functions, $U_{km}$
  $$U_{km} = S_{kj}B_{jm}$$
- Similar transformation for $i$th disturbance
  $$Z_{ki} = S_{kj}C_{ji}$$
- Corrected system wavefront error is disturbance plus actuation
  $$E = \sum_{k}^{Z} w_k \left( Z_{ki} - \sum_{m}^{M} U_{km}A_m \right)^2$$
- Minimizing $E$ w/r to actuator input $A_m$ gives linear equations for actuator inputs
  $$\begin{bmatrix} H \end{bmatrix}\{A\} = \{F\} \quad H_{qm} = \sum_{k}^{Z} w_k U_{qk} U_{km} \quad F_q = -\sum_{k}^{Z} w_k Z_k U_{kq}$$

Reference 1
Implementation in MSC.Nastran™ DRESP3

- MPCs compute rigid body motions and Zernike coefficients for each surface for actuator influence functions and disturbances
- Subcase specific DRESP1s reference GRID and SPOINT data
- DTABLE stores user selections, optical sensitivities, and constants
- Data passed to precompiled DRESP3 server for computation of system level corrected performance as synthetic response
- All bulk data cards written by SigFit as preprocessing step
- DRESP3 server is subroutine form of SigFit

Reference 2

5/5/2005
Example 1: Telescope Model

Primary Mirror
Aft Metering Structure
Mounting Struts
Outer Shell
Secondary Mirror
Example 1: Primary Mirror Model

- Core wall thicknesses allowed to vary near mounts and force actuators
Example 1: Optimization Statement

- **MINIMIZE**: Primary mirror weight
- **DESIGN VARIABLES**:  
  - Optical facesheet thickness: 0.18 inch < $t_f$ < 0.25 inch  
  - Back facesheet thickness: 0.10 inch < $t_b$ < 0.25 inch  
  - Interior core wall thicknesses: 0.04 inch < $t_c$ < 0.25 inch  
  - Inner and outer core wall thicknesses: 0.08 inch < $t_c$ < 0.25 inch  
  - Core depth: 0.25 inch < $t_c$ < 5.0 inch
- **SUBJECT TO**:  
  - Thermally induced system wavefront error < 20 nm RMS  
  - Gravity release induced system wavefront error < 60 nm RMS  
  - Peak launch induced stress in PM < 1000 psi  
  - First mounted PM natural frequency > 200 Hz
Example 1: Optimization Results

- Optimization adjusts core walls and faceplate thicknesses to meet all requirements and dramatically reduce weight.

<table>
<thead>
<tr>
<th>Response</th>
<th>Initial Design</th>
<th>Optimized Design</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermally Induced Wavefront Error</td>
<td>9 nm</td>
<td>20 nm</td>
<td>20 nm</td>
</tr>
<tr>
<td>Gravity Release Induced Wavefront Error</td>
<td>54 nm</td>
<td>60 nm</td>
<td>60 nm</td>
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<tr>
<td>Peak Launch Stresses</td>
<td>1000 psi</td>
<td>1000 psi</td>
<td>1000 psi</td>
</tr>
<tr>
<td>First Natural Frequency</td>
<td>231 Hz</td>
<td>221 Hz</td>
<td>200 Hz</td>
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<tr>
<td>Weight</td>
<td>20.8 kg</td>
<td>9.9 kg</td>
<td>Minimum</td>
</tr>
<tr>
<td>Areal Density</td>
<td>53.0 kg/m²</td>
<td>25.2 kg/m²</td>
<td>Minimum</td>
</tr>
</tbody>
</table>
Example 2: SPOT Optimization

- **Objective**
  - Develop a back surface profile to allow optimum correction of ±2 mm change in radius-of-curvature
  - Residual surface error of 5 nm RMS desired

- **Baseline Design**
  - 225 nm RMS corrected surface
  - Relatively good control of azimuthally varying residual error
  - Considerable primary spherical in the residual error
  - Primary spherical can be substantially removed with proper profile

Courtesy NASA Goddard Space Flight Center

Corrected Surface Error of Baseline Design
Example 2: SPOT Optimization

- Optimized Design
  - Coefficients of two-dimensional polynomials used as shape design variables
    \[
    f(r, \theta) = a_0 + a_1 \frac{(r - 127)}{310.728} + a_2 \left( \frac{(r - 127)}{310.728} \right)^2 + a_3 \left( \frac{(r - 127)}{310.728} \right)^3 + a_4 \left( \frac{(r - 127)}{310.728} \right)^4 + \]
  - Central flat area required for processing
  - 33 nm RMS corrected surface down from 225 nm RMS
  - 21 nm RMS corrected surface with no central flat
  - Residual surface contains high-order deformations driven by only local actuator attachment behavior

Courtesy NASA Goddard Space Flight Center
Example 2: SPOT Hardware
Summary

- MSC.Nastran™ DRESP3 allows optimization using higher level optical performance metrics
  - Early trade studies compare concept optimums vs. point designs
  - Error budget and rough design flow down to sub-assemblies based on true combined optical and mechanical behavior; not guesswork and prior experience
  - Optimizations take advantage of system level interactions
- Implemented in next SigFit version (Summer 2005)
References