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Collaborative Design and Modeling of Complex Opto-mechanical Systems

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Abstract: In this article, we propose a concurrent design methodology that employs physics-based high fidelity computational models together with analysis methods to predict the performance of complex opto-mechanical systems. For this purpose, we developed a web-based collaborative design and modeling environment for the simulation of complex opto-mechanical systems (SIMCOMS). The analysis tools and the methodology presented in this article provide a systematic and quantitative way to investigate the end-to-end system performance of such systems, perform sensitivity analysis, and identify the critical components of the system that degrade the performance. The SIMCOMS integrates all the modeling and analysis tools in a common MATLAB computational environment and it can be accessed through standard web browsers. Through the use of structural, optical, and controls modules, SIMCOMS allows modeling and SIMCOMS. The analysis modules of SIMCOMS provide the means for predicting the performance of such systems and diagnosing the problematic components that degrade the performance. The web interface of SIMCOMS provides a flexible and robust environment for designing such complex opto-mechanical systems and keeps an archive of models to compare different design configurations. The design can be conducted concurrently by multidisciplinary teams located physically at different sites, which leads to savings in time and cost. We demonstrated the use of SIMCOMS through a case study which includes the redesign process of a siderostat mirror; one of the main optical components of the SIM PlanetQuest (formerly called Space Interferometry Mission). SIM will determine the positions and distances of stars several hundred times more accurately than any previous program. SIM provides a good example case for testing the functionality of SIMCOMS since the precise tolerance required by the SIM instrument facilitates the investigation of many design options, trades, and methods for minimizing interaction between the actively controlled optics and the structure.

Key Words: integrated modeling, collaborative design, opto-mechanical systems, performance prediction, multidisciplinary teams.

1. Introduction

Designing complex opto-mechanical systems is a highly challenging activity that involves multi-disciplinary teams work together to achieve the optimal design. In this study, we developed a web-based modeling and simulation environment (SIMCOMS), which allows a collaborative design environment for multidisciplinary teams. The teams, each working simultaneously at distant locations and on different platforms, can access the SIMCOMS using standard web browsers. In the proposed approach, multidisciplinary design of complex opto-mechanical systems can be conducted concurrently.

During the design phase of a project, addressing the major technological challenges at the system-level could be very difficult, time consuming, and costly due to the complexity of the design problem. In those cases, computer-based models and simulations become an integral part of the development process to test and verify the system level performance. System-level simulations, performance verification, design changes could be easily performed using the computer-based models until the design becomes mature. All these processes get even more complicated when designing complex multidisciplinary systems since these systems are composed of subsystems from different fields. Space systems are good examples of such multidisciplinary systems since they combine structures, optics, and controls in order to meet their stringent requirements.

There are already a few modeling and design tools available for the integrated design of complex space systems, which include TRW’s Integrated Concept Design Facility (ICDF) [1], Jet Propulsion Laboratory’s (JPL) Project Design Center [2], Boeing’s Concurrent Integrated Engineering Laboratory (CIEL) [3], Aerospace Corporations’s ‘Concept Design Center’ (CDC) [4], and European Space Agency’s ‘Concurrent Design Facility’ (CDF) [5]. The models used in these facilities are not heavily based on physics and mathematics. They are mostly used for ‘back in the envelope’ calculations, which can give quick and rough estimates of the system performance during the conceptual design phase. Considering the need for higher fidelity models, the Aerospace Systems Design Laboratory (ASDL) at
Georgia Tech has launched their own facility ‘The Collaborative Design Environment (CoDE)’ [6]. The CoDE will enable researchers to develop, test, and apply new approaches to conceptual design by utilizing high-fidelity modeling, simulation, and analysis tools in a collaborative team-centered environment.

There are also various collaborative design and manufacturing tools that has been developed for various engineering systems. Chang et al. [7] has developed a web-based collaborative system for integrated design and manufacturing of mechanical parts using JAVA and VRML. They focused on the framework of the collaborative system and discussed how it was implemented in the design and collaboration modules. Another concurrent design and manufacturing tool has been developed by Chang et al. to employ physics-based computational methods together with computer graphics techniques for product design of mechanical systems [8]. Their modeling and simulation tools were tested on an airplane engine to simulate product performance, reliability, and manufacturing cost. Distributed object-based environment (DOME) is another modeling tool that is developed by MIT CAD-Lab that concentrates on integrating various tools that can be used for product development [9]. It provides the links between the design, manufacturing, and marketing departments. Different from the other design tools, DOME allows detailed analysis options but its main focus is to develop the architecture that facilitates the integration of the commonly used commercial products. Kalsi et al. [10] introduced a technique to reduce the effects of uncertainty or variation in design parameters and incorporate flexibility into the design of complex systems involving multi-disciplinary teams. They use the concepts of robust design to reduce the effects of decisions made during the design of one subsystem on the performance of the rest. Another technique developed by Chen and Lewis [11] integrates game theoretic models of the design process with robust design techniques in order to reduce the effect of the coupling between the subsystems and improve the performance of the overall system. A computer program, developed by Ollinger and Stahovich [12], uses model-based reasoning to generate and evaluate proposals of redesign plans for engineered devices. These proposals describe how the design parameters could be changed to achieve a specified performance goal.

The lack of high fidelity tools for design of complex space structures spurred the growth of two MATLAB-based software packages at JPL: a structural package called integrated modeling of optical systems (IMOS) and an optics package called modeling and analysis for controlled optical systems (MACOS) [13,14]. Over the years more and more applications and capabilities are added to these packages and they have evolved into a sophisticated modeling environment to conduct end-to-end performance analysis for complex opto-mechanical systems. The modeling methodology has been validated at JPL by comparing model predictions with the test-bed measurements [15,16].

In this study, we expanded the capabilities of the IMOS and MACOS by developing new analysis tools first and then integrating all these tools into a web-based modeling and simulation environment. SIMCOMS can be used to conduct concurrent engineering through virtual testing of complex opto-mechanical systems. The result is a multi-disciplinary tool that enables a user to integrate models from different disciplines and conduct performance analysis that would otherwise be exceedingly difficult with the real hardware. The simulation environment is a collection of functions that operates in the MATLAB environment. The SIMCOMS integrates structural, optical, disturbance, and control system modeling into a common MATLAB computational environment and provides various analysis options to construct “what-if scenarios” for attacking various design questions through simulations, thus minimizing hardware tests. The SIMCOMS also incorporates several graphics functions that enable visualization of structural assembly, structural deformations, and elementary optical layouts. The SIMCOMS can be further expanded by the user by writing his/her own MATLAB functions. The simulation and visualization tools allow the identification of the critical components that degrade the performance of the system and also the evaluation of the design tradeoffs very efficiently.

SIMCOMS is accessed via a web-browser through a ‘point and click’ graphical user interface (Figure 1). Working within the design environment, the analysts and design engineers can easily exercise the main system and the components under various conditions, performing the same tests they would normally run in the test laboratories that would take months or years. Target users of such a modeling and simulation tool include design engineers, system engineers, analysts, and at some level, project managers. SIMCOMS is intended for use during the design phase of a project, when engineers need to make quick, yet accurate assessment of the overall effects of a particular design change. The framework combines a collection of user interface programs and external MATLAB routines. The user inputs provided through a web-interface invoke MATLAB code or externally defined functions. While understanding the basic theory employed in the programs is required, the users may not be intimately familiar with the program’s input syntax and all the details of the MATLAB functions. Users can animate component or system dynamics on-screen, display graphs or important parameters, save and print their analysis results directly from their local computer.
They can progressively refine and retest their designs until the required performance is achieved. The web-interface can include a library of models of the current project and components that can be also used as an archive to make comparisons between recent and previous design configurations. The web-based environment also provides means for communicating the information among different disciplines, groups, and organizations, which is especially crucial in large-scale collaborative projects. The platform independent framework makes all kinds of knowledge available to anyone, located anywhere, at any time.

To demonstrate the use of SIMCOMS, we selected a case study, which involved the redesign process of a siderostat mirror, which is one of the main optical components of the SIM PlanetQuest (formerly called Space Interferometry Mission). The interferometer collects the starlight from two physically separated collectors and via a series of mirrors, brings the light to a beam combiner where they are interfered. It is comprised of a complex optical train composed of numerous collecting and actively steered optics. The optical elements are mounted on a lightweight truss structure subject to dynamic, quasi-static, and static disturbances produced during the course of on board operations.

Fundamental interferometer operation requires that the two independent telescopes view the same star [17–19]. The pointing control system is responsible for providing this function (Figure 2). This system adjusts four degrees of freedom: wave front tip and tilt (WFT) of the two incoming beams by articulating the siderostat mirrors with feedback from angle tracking cameras. In this study, we investigated the effect of differential WFT jitter resulting from the reaction wheel assembly (RWA) disturbances, which is the largest anticipated disturbance source on the SIM spacecraft. The model predictions of the baseline design showed that the WFT performance of the SIM instrument was above the requirement specified by the SIM science team [19]. Utilizing the analysis tools of the SIMCOMS, we were able to identify that one of the mode shapes of the siderostat mirror mount coupled with the overall system dynamics and degraded the WFT performance. Then we went through a redesign process and stiffened the siderostat mirror mount, which eventually improved the performance of the SIM instrument significantly. Considering the multidisciplinary components of the SIM: the optical instrument, the structure, and the way the opto-mechanical system couples with the RWA disturbances, it would not be possible to identify the problematic components in such a complex system if we did not use the integrated modeling methodology and the analysis tools of SIMCOMS. The systematic and the quantitative approach presented in this article make it possible to pinpoint the critical design parameters in the design space.

The case study presented in this article, the redesign scenario of the siderostat mirror mount includes the following steps (Figure 3): first we develop the integrated model of the baseline system. The integration process involves the multidisciplinary teams create their own models. This is where the structural, optical, and control models are built according to the current system specifications. The structural model is first integrated with the optics model to construct the state-space model.
of the integrated opto-mechanical model (see Section 3). The next step is to predict the WFT performance of the SIM instrument when the pointing control system is active and the spacecraft is subjected to the anticipated disturbance sources. This process is called the ‘disturbance analysis’ and the transfer functions of the integrated model are used as the input for this step. The empirical reaction wheel disturbance models of the previous missions are used in this case study. A MATLAB code, which propagates RWA disturbances through the integrated model, is developed and integrated into SIMCOMS to perform the disturbance analysis. The root-mean-square (RMS) values of the optical performance metric of the WFT are calculated as a function of wheel speed. If the requirements are met, the design is considered as candidate for further analysis and testing. If the performance is not met, the sources of the unwanted dynamics are identified.

Figure 2. Schematic of the SIM pointing control system to adjust four degrees of freedom, tip and tilt of the two incoming beams to perform interferometry.

Figure 3. End-to-end performance analysis and a typical redesign scenario using SIMCOMS.

Optical, structural, control & disturbance components model library

Identify the critical components & component/subsystem redesign

Model integration

Disturbance model (reaction wheel disturbances)

Opto-mechanical full model (state-space form)

Reduced model (state-space form)

Control model

Optical performance

Pointing requirement – 0.03 arcsecond

Tip and tilt angle of the siderostat mirror

Analysis & visualization tools

- Modal gain analysis
- Critical frequency analysis
- Strain energy analysis
- Sensitivity analysis
- Visualization of critical modes

Meet the requirement? Yes

Further analysis and testing

Open & closed loop optical pointing performance

No
using the analysis tools and the design is revisited at the component level until the overall system performance satisfies the desired requirements. Before proceeding with further analysis tools, the full size model is reduced to decrease the computational costs without losing the accuracy of the model. The disturbance analysis is repeated with the reduced model to verify that the reduction algorithm did not eliminate the modes that are significant to the system dynamics. All the analysis tools developed during the course of this study complement each other to first identify the problematic areas and components for redesign and then to improve the overall system performance. The ‘modal gain analysis’ calculates the modal participation factors from the RWA disturbance input to WFT as a function of frequency and uses the entries of the state-space model matrices as the inputs. The ‘critical frequency analysis’ tool enables us to identify the critical modes of the structure (i.e., the dynamics that appear to be the major contributors to the RMS metric) by convolving the transfer functions of the opto-mechanical model with the broadband power spectral densities (PSDs) of the corresponding force or torque. The transfer functions of the integrated model and PSD of the RWA disturbances are the inputs for this analysis. The ‘strain energy analysis’ tool allows us to identify the critical components that have the highest strain energy. Strain energy of each component is calculated at the component level where the structural model is developed. The ‘visualization’ tools in SIMCOMS are used to animate the critical modes and components to identify the problematic subcomponents and verify the results of the earlier analyses. The ‘sensitivity analysis’ tool enhances the understanding of the system by exploiting the sensitivities of physical parameters and performance information around the local neighborhood of a particular design. The details of these analysis tools are given in Sections 5–10.

2. Architecture of SIMCOMS

The SIMCOMS makes use of Tcl/Tk and Tcl extensions [20]. Tcl is a powerful and flexible scripting language, and Tk is a graphical user interface (GUI) toolkit working with Tcl. The SIMCOMS works by taking advantage of Expect [21], a Tcl extension, which sets up pseudo-terminals to interact with MATLAB. Figure 4 shows a brief description of how the client/server Web application works. The Expect server...
first spawns out MATLAB, and then listens on a TCP/IP socket port, waiting for Web Browser client connections. TCP is a connection orientated internet protocol for inter-process communication. A socket port, together with its host, forms the address of the providing service, in our case, our Expect MATLAB server tool. When a client connects and sends commands to the Expect, the server routes the command to the spawned MATLAB process, which then executes the command and returns the result back to the Expect server via pseudo-terminals. The Expect server then sends the result back to the client via TCP/IP socket connection. The result can be either text outputs from the MATLAB process or images generated from MATLAB plotting routines. However, in some client commands, the results from MATLAB are movie animations and, in these cases, the movies are pushed back to the client via the ‘Content-Type: multipart/x-mixed-replace’ technology that allows the transfer of the movie clips through the Common Gateway Interface (CGI) program. CGI is the part of the Web server that can communicate with other programs running on the server [22]. After all the GIF images are created by MATLAB, Expect sends a signal to the web browser client to tell it to open a new browser window that points to the web link containing the CGI. The CGI program tells the browser to mark a certain area of the web page and give it an internal name. After the page is initially displayed, the CGI can send updated information to that page. In this case, the CGI program sends several GIF files, each one is displayed immediately by the browser before the next one is received, and when the next one is received, it overwrites the previous one. This is a faster way to view the animations since we can see each frame right away as it is received rather than downloading all the frames before we can start to view it.

To install the client side of SIMCOMS, the user has to obtain and install Tcl/Tk web browser plug-in [23]. Once the Tcl plug-in is installed, the user can view the Tcl applet at a specified web address, which is the user front-end for the SIMCOMS. The Tcl applet consists of a few pull-down menus and sub-windows. The pull-down menus allow the user to bring up other popup GUI interfaces to perform different analyses. The results of the analyses are displayed on the lower left ‘MATLAB console’ window. In some analysis, resulting 2D/3D plots also return in separate windows, which the user then can zoom-in, pan, or change viewing angles. The user can also drag-n-drop these plots into the ‘blue canvas’ in the Tcl applet and resize, annotate, save, reload, and print them. The SIMCOMS can be easily linked to other applications such as Microsoft Excel. The returned results can be in the form of Excel spreadsheets, and in these cases, the Tcl applet can launch Excel to view the results.

3. Integrated Modeling Approach

The integrated modeling methodology combines structural, optical, disturbance, and control system modeling into a common computational environment and enables end-to-end performance evaluation of the SIM instrument before the system is built. The integrated model of the SIM instrument consists of a structural finite element model and a linear optical model. The structural model is developed using IMOS, whereas both IMOS and MACOS are used to create the optical model. The user can select the required structural models and assemble them using the SIMCOMS sub-menus.

To demonstrate the use of SIMCOMS, we selected a case study, which involved the redesign process of one of the main optical components of the SIM instrument. Although one case study has been presented in this article to demonstrate the capabilities of the SIMCOMS, previously various studies has been done [15,16,24,25] that utilizes the tools of the SIMCOMS to predict and improve the optical performance of opto-mechanical systems.

The following section describes the details of the structural and optical models and how they are integrated. Later, we describe a redesign scenario where we utilize the different modules of SIMCOMS to identify the problematic components and go through the redesign process, which eventually improved the performance of the instrument significantly.

3.1 Structural Model of SIM

The finite element model of SIM structure has 27,000 degrees of freedom (dof) and it is constructed using IMOS functions within the SIMCOMS structural module. This geometry consists of plate, beam, and rigid body elements, modeling the spacecraft and the instruments. Sub-structuring and component mode synthesis techniques are used to reduce the size of the finite element model to 1200 modes. The governing equation of the original system generated by the finite element analysis is

\[ M\ddot{d} + C\dot{d} + Kd = Fu \]  \hspace{1cm} (1)

where, \( M \), \( K \) and \( C \) are the mass, stiffness, and damping matrices, respectively. The vector \( d \) is the nodal displacements, \( u \) is the control input, and \( F \) is the influence matrix for \( u \). Then the system in Equation (1) is transformed to the modal coordinates as

\[ M_p\ddot{\eta} + C_p\dot{\eta} + K_p\eta = F_pu \]  \hspace{1cm} (2)

where \( M_p \), \( C_p \), and \( K_p \) are diagonal modal mass, damping, and stiffness matrices, respectively and \( \eta \) is the
vector of modal coordinates [26]. Once these matrices are calculated, they are integrated with the matrices obtained from the optical model to form the state-space model of the SIM instrument.

3.2 Optical Model of SIM

The optical model is generated using the optics module of the SIMCOMS environment. The optical model begins with the design specification of the optical elements in all four interferometers. This specification includes the shapes, positions, and orientations of the 128 optical elements distributed along the baselines of the four interferometers. Once the optical requirements are specified, they are exported to MACOS, where a linear optical model is generated. The linear optical model is developed by performing an analytic differential ray trace [14]. The result is a model of the form:

$$y = C_{\text{opt}}d_{\text{opt}}$$  \hspace{1cm} (3)

where $d_{\text{opt}}$ is a vector of optical element perturbations (i.e., a subset of $d$ in Equation (1)), $y$ is a vector of optical output, and $C_{\text{opt}}$ is the optical sensitivity matrix giving the change in ray state due to the perturbations of the optical elements. The optical output is the WFT performance of the SIM instrument.

3.3 Structural-Optical Model

First, the structural model is truncated to remove modes above the bandwidth of expected disturbances (i.e., above 1000 Hz). Then, the structural and optical models are integrated using the SIMCOMS sub-menus to form a structural-optical model in first-order, state space form, such that:

$$\dot{x} = Ax + Bu$$

$$y = Cx$$  \hspace{1cm} (4)

The state-space form in Laplace domain allows the calculation of the transfer functions $H(s)$, that relates the output WFT, $Y(s)$, to the given RWA disturbance inputs, $U(s)$, such that [27]

$$H(s) = \frac{Y(s)}{U(s)}$$  \hspace{1cm} (5)

Inputs are defined at disturbance locations and actuated degrees of freedom for the articulated optical surfaces, whereas outputs are measured at the fringe detectors and the wave front tilt cameras. These transfer functions depict how the disturbance propagates from the disturbance source to the optical sensor.

3.4 Integrated Model Validation

The performance measurements are not feasible on systems such as SIM spacecraft since the flight hardware are not ready until the end of the implementation phase of the project. But instead, one can build an integrated model of the SIM spacecraft using the integrated modeling methodology presented in this article and predict the optical performance of the SIM instrument. However, these techniques have to be validated in order to have confidence in our modeling methodology. The validation methodology uses the Micro-Precision Interferometer (MPI) testbed, which is a ground-based, representative hardware model of SIM. In previous studies by Basdogan et al. [15,16], the integrated model of the MPI testbed was used to calculate the transfer functions from RWA input to optical performance output. The model-predicted transfer functions were then compared with the MPI testbed measurements, and the accuracy of the integrated model was quantified using a metric that was based on output power of the transfer functions. It was shown that the integrated model predicts the optical performance within a factor of two over the entire 4–1000 Hz range. The model predictions overbound the measured transfer functions and then the results can be interpreted as being conservative.

4. Control Design

Control design begins once the input and the output matrices are specified in the state-space form of the integrated model. Feedback control involves designing a dynamical system that takes the sensor information as the input and produces the control signal as the output. The objective of the control design in SIM instrument is to shape and modify the transfer function from the input disturbance to the output. The control design and analysis emphasis is on improving the performance of the optics by suppressing the disturbances transmitted through the structure that affects the optics most. This could be achieved either by suppressing the vibration source at the location where it occurs or by correcting the critical components via active control.

The control system in SIM enables measurement of the interference fringe by adjusting four degrees of freedom: WFT of the two incoming beams. Once acquired, the stars must be tracked continuously by the control system with an accuracy of 0.03 arcsecond in the presence of the reaction wheel disturbances. In this study, the control system is emulated by a second-order high pass filter with a roll-off frequency at 100 Hz, which is the estimated disturbance rejection capacity of the actual pointing control system [28]. The controls’ module of SIMCOMS allows the user to
adjust the control system parameters (e.g., roll-off frequency) to investigate the design trades in order to improve the end-to-end performance of the SIM instrument.

5. Open and Closed Loop Disturbance Analysis

After developing an integrated model of the system, the next step is to assess the performance of the SIM instrument when the model is subjected to the anticipated disturbance sources. In this study, a reaction wheel model is used to assess the effect of the disturbances on the differential WFT performance. The disturbance model was based on the experimental data collected from eight different RWA units when the wheels were mounted to a rigid base [28]. SIMCOMS includes a library of various reaction wheel models used in the previous space missions. The user can utilize any of these wheel models to investigate their effect on the performance. Using the experimental data obtained from the reaction wheels, disturbance forces and torques are modeled as discrete harmonics of the reaction wheel speed, \( f_{\text{rwa}} \), with amplitudes proportional to the square of the wheel speed \([29,30]\)

\[
m(t) = \sum_{i=1}^{n} C_i f_{\text{rwa}}^2 \sin(2\pi f_{\text{rwa}} t + \phi_i)
\]

where \( m(t) \) is the disturbance torque or force, \( C_i \) is an amplitude coefficient, \( h_i \) is the harmonic number, and \( \phi_i \) is a random phase (uniform over \([0, 2\pi]\)). The model includes the axial force (along the wheel spin axis), two radial forces (normal to the spin axis), and two radial torques (causing the wheel to wobble). Disturbance torque about the axis of rotation is considered to be insignificant.

Each transfer function obtained from the integrated model of SIM maps the contribution of that particular force or torque direction to differential WFT as a function of frequency. Since a reaction wheel contains disturbances in three force directions and two torque directions, the contributions of all these disturbances to the WFT jitter is determined using linear superposition. The WFT performance PSD is calculated as:

\[
\Phi_{\text{WFT}}(\omega) = \sum_{j=1}^{5} |H_j(\omega)|^2 \Phi_m j(\omega)
\]

where \( |H_j(\omega)|^2 \) is the transfer function relating the particular disturbance force or torque to WFT and \( \Phi_m j(\omega) \) is the PSD of the corresponding force or torque [31]. The discrete disturbance analysis approach uses the principal of superposition for the estimation of the WFT performance. The area under the discrete performance PSD gives the WFT variance for a given wheel speed. Expected WFT jitter at each wheel speed is calculated by taking the square root of the WFT variance at that particular wheel speed. After the disturbance models are built, the transfer functions obtained from the SIM integrated model are inputted to the disturbance algorithm in order to determine the WFT error as a function of the wheel speed. The wheel speed is expected to vary between 10 and 50 revolutions per second (rps) for the open- and closed-loop configurations (Figure 5). The requirement for SIM is shown with a straight solid line on the plot [32].

![Figure 5. Disturbance analysis showing the WFT variation as a function of wheel speed.](image)
As it can be seen from Figure 5, SIM Baseline Design meets the requirement for the closed-loop configuration at all wheel speeds. For the open-loop configuration, this plot provides valuable information about the critical wheel speeds (i.e. ~14, 28, and ~42 rps) that would cause WFT errors be higher than the requirement. The RMS WFT at each wheel speed includes the effect of all the wheel harmonics as it is indicated in Equation (7). When the RWA model has more than one harmonic, it is difficult to map the results in Figure 6 to the frequency domain. Further investigation is required to identify the cause of these undesired behavior which couple with the RWA dynamics. The following sections will discuss the analysis tools of SIMCOMS that are used to identify the cause of these high peaks at the RMS metric plot.

5.1 Disturbance Analysis Method Validation

The MPI testbed can also be used to validate the disturbance analysis methodology, which is described in the previous section [16]. The same RWA disturbances were propagated through the modeled and measured transfer functions to predict the optical performance of

![Figure 6](image-url)

**Figure 6.** Full scale and reduced model disturbance analysis comparison: (a) open-loop configuration, (b) closed-loop configuration (note that the results of the reduced model overlaps with the results of the original model).
the MPI testbed. At the same time, the actual optical performance of the instrument can be measured directly while the wheel is spinning on MPI. The model predictions were then compared with the actual (measured) optical performance of MPI, measured with the RWA mounted to MPI, to evaluate the accuracy of the disturbance analysis method. The results show that this method can accurately calculate the optical performance of MPI when disturbance boundary conditions are corrected with ‘force filters’ that depend on estimates of the interface accelerances of the RWA and the MPI structure to represent the coupled RWA–MPI interface.

The actual optical performance measurement is not feasible on the SIM spacecraft since the flight hardware will not be ready until the end of the implementation phase of the project. But instead, one can build an integrated model of the SIM spacecraft using the modeling methodology presented in this article and apply the same disturbance analysis method to predict the optical performance of the SIM instrument under the same type of RWA disturbances as described in the previous section.

6. Model Reduction & Disturbance Analysis with the Reduced Model

Model reduction capability is also included in the SIMCOMS analysis module. The motivation behind the model reduction is to reduce the computational expense in performing the further analysis. The goal is to reduce the size of the system while maintaining the important dynamics. The first step is to create a balanced realization of the state space system. The technique was introduced in the control community by Moore [30]. We use MATLAB balancing function ‘balreal’ [33]. The algorithm creates a system with identical diagonal controllability and observability gramians. The criterion for a balanced system is that both the observability and controllability gramians are diagonal and equal.

The Gramian values (diagonal of Gramian matrix) that correspond to modes of low controllability/observability can be removed from the model without significantly affecting the retained dynamics [34]. SIMCOMS menus allow the user to select the desired number of states and also make a comparison between the reduced model and the original one. In our case, the first 304 states corresponding to the largest singular values are retained. This reduced model is subsequently used for the discrete RWA disturbance analysis and the results are compared. Figure 7(a) and (b) shows the comparison of the RMS metric using the original and the reduced model for the open-loop and closed-loop configurations, respectively. In both cases, the reduced model disturbance analysis overlaps with the results of the original model, which demonstrates that the reduced model captures all the significant dynamics to predict the WFT performance.

![Figure 7](http://cer.sagepub.com)

**Figure 7.** Model gain analysis showing the (a) normalized modal gains, (b) top 10 model gains.
7. Modal Gain Analysis

The modal gains or the modal participation factors from the RWA disturbance input to WFT are calculated as a function of frequency (Figure 8(a)). The equation for the modal gains is derived in Ref. [35].

\[ \sigma_i^2 = \frac{[b_i b_i^T c_i^T c_i]^{1/2}}{4\xi \omega_i^2} \]  \hspace{1cm} (8)

\( \sigma_i \) is the modal gain of the \( i \)th mode and the entries of the state-space matrices are used to obtain \( b_i, c_i, \xi_i, \) and \( \omega_i \).

The first 10 critical modes that have the largest modal participation are shown in Figure 8(b). For the WFT performance, the highest modal gains appear to be clustered between 1 and 24 Hz where 14.1 Hz has the maximum value. Further analysis is required to identify the problematic component that causes the highest peak at 14.1 Hz. Although modal gain approach provides the information regarding the problematic frequency range, it only includes the state-space model of the opto-mechanical system and does not consider the effect of the disturbances. The ‘critical frequency analysis’ will be presented in the following section.

8. Critical Frequency Analysis

The ‘critical frequency analysis’ tool is based on the broadband disturbance model of the reaction wheel disturbances, which was developed by Gutierrez [31]. The stochastic broadband model is based on the discrete frequency model which was introduced in Section 5 and assumes that the wheel speed is a uniform random variable over the interval 10–50 rps. This approach facilitates the broadband frequency analysis leading to a frequency domain model that can be propagated through the SIM integrated model. WFT PSDs are still calculated in the same way as shown in Equation (8) by convolving the transfer functions of the opto-mechanical model with the broadband PSDs of the corresponding force or torque. But now the PSD of the WFT is a continuous function of the frequency [Figure 6(a)], Figure 6(b) is the cumulative RMS and it is obtained by integrating under the PSD and taking the square root. The RMS error tends toward a value of RMS = 0.065 arcsecond which is high above the requirement. As it can be observed from the figure although there are small jumps in the cumulative RMS curve between 1 and 24 Hz, the biggest jump is at 14.1 Hz, which also agrees with the previous results from the ‘modal gain analysis.’

9. Strain Energy Analysis

The ‘strain energy analysis’ tool identifies the fraction of total strain energy due to component modes. Strain energy is a measure of the deformation of the structure and it is proportional to stiffness. We can identify the critical components that degrade the system...
performance by analyzing the fraction of total strain energy at the given mode numbers (e.g., mode numbers are obtained based on the frequency sorting of the mode shapes) and/or frequency range utilizing the SIMCOMS plotting options. Figure 9 shows the strain energy distribution for different components of the SIM instrument. If we concentrate on the frequency range between 13 and 16 Hz range, it can be observed that the main contributor to the total strain energy at 14 Hz is the siderostat bay component. This analysis shows that the problematic component at 14.1 Hz is located at the siderostat bay (Figure 10 – Note that there are eight siderostat bays in the SIM instrument which explains the eight modes in the strain energy diagram clustered around 14 Hz). The most critical component in the siderostat bay is the siderostat mirror, which is one of the major optical components in the optical ray trace. Additionally, we used the animation capabilities of the SIMCOMS and verified that the 14.1 Hz mode was a rotational mode of the siderostat mirror about the $x$ and $z$ axes. Based on these results, we decided to focus on the siderostat mirror and perform a sensitivity analysis on the structural parameters of the mirror support to improve the performance.

10. Sensitivity Analysis

Determining sensitivity of design parameters can provide useful information, especially when the system
Sensitivity information can provide useful information especially when there are many design parameters. Among the design parameters perturbed one at a time in the finite element analysis, the state-space model is reconstructed for the perturbed system, the disturbance analysis is performed, and the new performance RMS value, $\sigma_{zi}$, is computed using the approach described in [31]. The performance difference between the perturbed system and the original system is then divided by the amount of change in the design parameter $\Delta p$ and the sensitivity value is approximated. In order to compare the sensitivities calculated with respect to the parameters of different units or magnitudes, normalized values are computed as follows.

$$\left(\frac{\sigma_{zi, \text{perturbed}} - \sigma_{zi, \text{original}}}{\sigma_{zi, \text{original}}}\right) \approx \frac{\% \text{ change in } \sigma_{zi}}{\% \text{ change in } p}$$

(9)

The sensitivity analysis of the siderostat mirror mount is performed for the following design parameters: $I_{xx}$, $I_{yy}$, and $I_{zz}$, the moment of inertia about the $x$-, $y$-, and $z$-axes, respectively.

Table 1 tabulates the sensitivities of physical parameters for the siderostat mirror mount. Among the computed sensitivities, the greatest sensitivity belongs to $I_{xx}$ and $I_{zz}$, the moment of inertsias about the $x$- and $z$-axes. When disturbances are effective on the system, 1% increase in the moment of inertia $I_{xx}$ results in a decrease of 1.87% in the RMS performance of the instrument. Similarly, 1% increase in the moment of inertia $I_{zz}$ results in a decrease of 1.24% in the RMS performance of the instrument. A decrease in the RMS value can be interpreted as improved performance for the instrument. As expected, 1% increase in the moment of inertia $I_{yy}$ does not change the results significantly.

Sensitivity information can be used as a starting point for developing the isoperformance methodology, which was previously studied by de Weck and Miller [24]. Their methodology is based on the idea of holding a performance metric or value of an objective function constant and finding the corresponding contours to perform multidisciplinary optimization. However, the sensitivity analysis presented in this study only focus on few design parameters and identifies which parameters should be the focus of the redesign. The redesign scenario presented in the following section does not represent the optimal solution.

### 11. Model Refinement and Redesign of the Siderostat Mirror Mount

Based on the above analysis, we update the mirror parameters and stiffen the mirror mount and the first frequency of the siderostat mirror becomes 33 Hz, which was originally at 14.1 Hz. Updating is performed utilizing the options in the SIMCOMS structural module without changing the optics model. The disturbance analysis is repeated for the open- and closed-loop configurations using the new model and the new WFT performance as a function of wheel speed plot, which can be seen in Figure 11. As it can be observed from the figure, the WFT requirement can be met even with the open-loop configuration, which relaxes the control design for the pointing control system.

Although the preliminary results show that the SIM instrument can meet the requirements for open-loop configuration, detailed analysis is required to verify this conclusion. Some of the modeling assumptions have to be revisited and validated by supporting experimental studies.

### 12. Conclusion and Future Studies

We have demonstrated an end-to-end performance analysis and a virtual redesign process of SIM instrument using the web-based modeling and simulation environment, SIMCOMS. SIMCOMS is a concurrent design tool for predicting the performance of complex opto-mechanical systems especially when experimental testing is not viable or expensive. It integrates control, structural, and optic models to predict the optical performance of the instrument under the effect of disturbance sources. It can support a cross-functional team to simulate and design complex opto-mechanical systems concurrently in the early design stage.

The analysis and simulation modules of SIMCOMS allow testing various design scenarios very efficiently to improve the instrument performance. Engineers and
scientists can run ‘what-if’ scenarios to test the validity of developed models. SIMCOMS provides a shared platform for distributed engineers and scientists to work on the same problem together. The web-based architecture provides flexibility and robustness that allows the access of multiple users at the same time. Moreover, the users do not need local computers with high computational capabilities to use SIMCOMS. All the computations are performed by a computational engine at the server site. However, results can be visualized, saved, printed, or stored locally. SIMCOMS could be also used as an archive of the various design models until the design is mature. Although, the SIMCOMS is designed to fit the simulation needs of the complex opto-mechanical space systems, the philosophy and the performance prediction approach and analysis tools are suitable for other mechanical systems as well. The architecture of SIMCOMS is flexible and can be easily linked to other application programs and utilized to perform collaborative design projects between various disciplines.

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References

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