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INTEGRATED DESIGN OF THE CSI EVOLUTIONARY STRUCTURE: A VERIFICATION OF THE DESIGN METHODOLOGY

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OBJECTIVE

- To develop and validate integrated controls-structures design methodology for a class of flexible spacecraft which require fine pointing and vibration suppression with no payload articulation
  - Integrated design methodologies using various optimization approaches have been developed (CSI-DESIGN CODE)
  - Validation through fabrication and testing of an integrated design structure is warranted

One of the main objectives of the Controls-Structures Interaction (CSI) program is to develop and evaluate integrated controls-structures design methodology for flexible space structures. Thus far, integrated design methodologies for a class of flexible spacecraft, which require fine attitude pointing and vibration suppression with no payload articulation, have been extensively investigated. Various integrated design optimization approaches, such as single-objective optimization, and multi-objective optimization, have been implemented with an array of different objectives and constraints involving performance and cost measures such as total mass, actuator mass, steady-state pointing performance, transient performance, control power, and many more [1–3].* These studies have been performed using an integrated design software tool (CSI-DESIGN CODE) which is under development by the CSI-ADM team at the NASA Langley Research Center. To date, all of these studies, irrespective of the type of integrated optimization posed or objectives and constraints used, have indicated that integrated controls-structures design results in an overall spacecraft design which is considerably superior to designs obtained through a conventional sequential approach [1–3]. Consequently, it is believed that validation of some of these results through fabrication and testing of a structure which is designed through an integrated design approach is warranted. The objective of this paper is to present and discuss the efforts that have been taken thus far for the validation of the integrated design methodology.

* References 1–6 are cited in text.

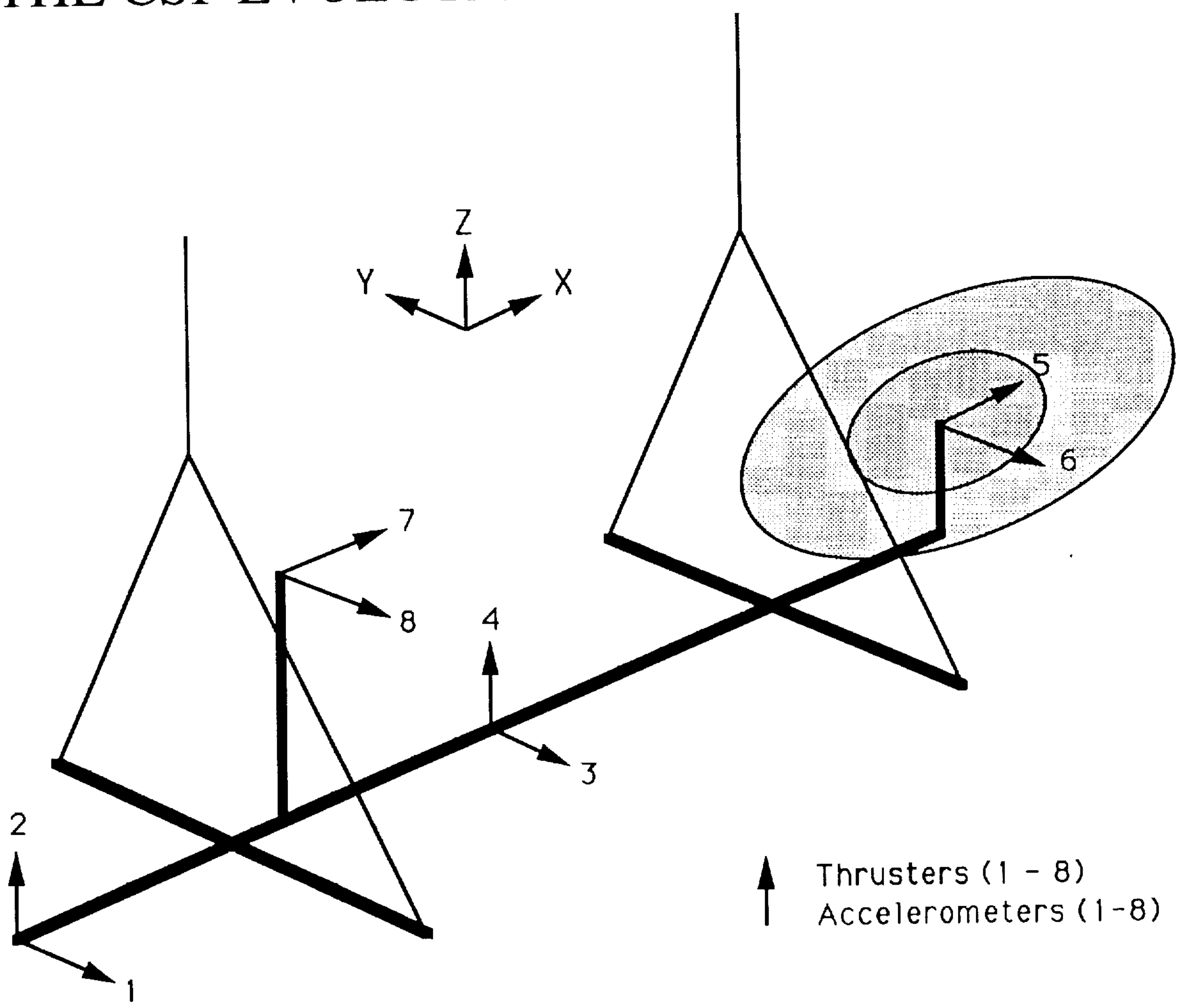
APPROACH

- Pose an integrated design optimization problem for the current CSI Evolutionary Structure (phase-0 structure)
- Design optimal controllers for the phase-0 structure
- Obtain an optimal integrated design structure (phase-1 structure)
- Fabricate the closest structure to the phase-1 design
- Validate the integrated design methodology by comparing phase-0 and phase-1 designs

The approach taken here is to use the CSI Evolutionary Structure for the validation of the integrated controls-structures design methodology. First, an integrated design optimization problem for the current CSI structure, referred to as the Phase-0 structure, is considered. Next, an optimal integrated design structure is obtained (which is optimal with respect to both the structure and control design variables). This structure is referred to as the CSI Phase-1 structure. Since it may not be practical or possible to build a structure to the exact specifications that come out of the integrated design process, the closest buildable structure to the Phase-1 design is fabricated. Meanwhile, optimal controllers for the Phase-0 structure are obtained in order to have a fair comparison with the Phase-1 design. Finally, the integrated controls-structures design methodology is validated through comparison of the overall performance of the Phase-0 and Phase-1 designs.

CSI Evolutionary Model is a laboratory testbed designed and constructed at the NASA Langley Research Center for experimental validation of the control design methods and the integrated design methodology [6]. The Phase-0 Evolutionary Model, shown in the figure, basically consists of a 62-bay central truss, with each bay 10 inches long; two vertical towers; and two horizontal booms. The structure is suspended using two cables as shown. A laser source is mounted at the top of one of the towers, and a reflector with a mirrored surface is mounted on the other tower. The laser beam is reflected by the mirrored surface onto a detector surface 660 inches above the reflector. Eight proportional, bi-directional, gas thrusters provide the input actuation, while collocated servo accelerometers provide output measurements.

THE CSI EVOLUTIONARY STRUCTURE



The basic problems in control systems design for flexible spacecraft arise because i) the order of a practically implementable controller is generally much lower than the number of elastic modes, and ii) the parameters, i.e., frequencies, mode-shapes and damping ratios, are not known accurately. The type of controller used in the integrated design should be robust (i.e., should maintain stability, and possibly performance) to unmodelled dynamics and parametric uncertainties mentioned above. In addition, it should be practically implementable, as well as be amenable for inclusion in an optimization process. One class of controllers which has these desired properties is the dissipative controllers [5], and includes "static" and "dynamic" dissipative controllers. The static (or constant-gain) dissipative controller employs collocated and compatible actuators and sensors, and consists of feedbacks of the measured attitude vector y_p and the attitude rate vector y_r using constant, positive-definite gain matrices G_p and G_r. This controller is robust in the presence of parametric uncertainties, unmodelled dynamics and certain types of actuator and sensor nonlinearities [4]. However, the performance of such controllers is inherently limited because of their structure.

CANDIDATE CONTROLLERS

Static Dissipative Controllers

$$u = -G_r y_r - G_p y_p$$

- Collocated sensors and actuators
- Positive definite gain matrices
- Robust in presence of model uncertainties
- Limited performance

In order to improve the performance of static dissipative controllers, an additional dynamic outer loop can be introduced as shown below, where z is the compensator state vector. The matrices A_c, B_c, *and* G denote the compensator system, input, and output matrices, respectively. These matrices satisfy certain additional conditions to establish dissipativity (A_c has to be strictly Hurwitz and Kalman-Yacubovich relations must hold) as described in [5]. The resulting controller is called a "dynamic dissipative controller", and is guaranteed to be robustly stable in the presence of unmodelled dynamics as well as parametric uncertainties. It should be noted that standard high-performance model-based controllers (e.g., $H_2(LQG)$ or H_∞ designs) are generally not robust to real parametric uncertainties [5], which makes dynamic dissipative controllers distinctly advantageous.

CANDIDATE CONTROLLERS

Dynamic Dissipative Controllers

$$\dot{z} = A_c z + B_c y_r \quad ; \quad u = -Gz$$

- Collocated sensors and actuators
- A_c is strictly Hurwitz, and the following Kalman-Yacubovich relations hold:

$$A_c^T P + P A_c = -Q \quad ; \quad G = B_c^T P$$

- Robust in presence of model uncertainties
- Enhanced performance

Here, two of the eight available actuators were used to generate persistent white-noise disturbances, while the remaining six actuators were used for feedback control. The static dissipative controller uses a 6 x 6 diagonal rate-gain matrix with no position feedback (since this system has no zero-frequency eigenvalues, position feedback is not necessary for asymptotic stability). Thus, in the integrated design with the static dissipative controller, the total number of design variables was 27 (21 structural plus 6 control design variables). The dynamic dissipative controller used in the design was a 12th-order controller consisting of six 2nd-order compensators (one for each control channel). Each of the 2nd-order compensators were defined in a controllable canonical form as shown below. There are four control design variables associated with each control channel, resulting in a total of 24 control design variables and 45 combined (structural and control) design variables.

CONTROL DESIGN VARIABLES

- Static dissipative controller: elements of the Cholesky factor matrix of the rate gain matrix

$$G_r = L_r L_r^T$$

- Dynamic dissipative controller: elements of the compensator state and gain matrices (in a controllable canonical form)

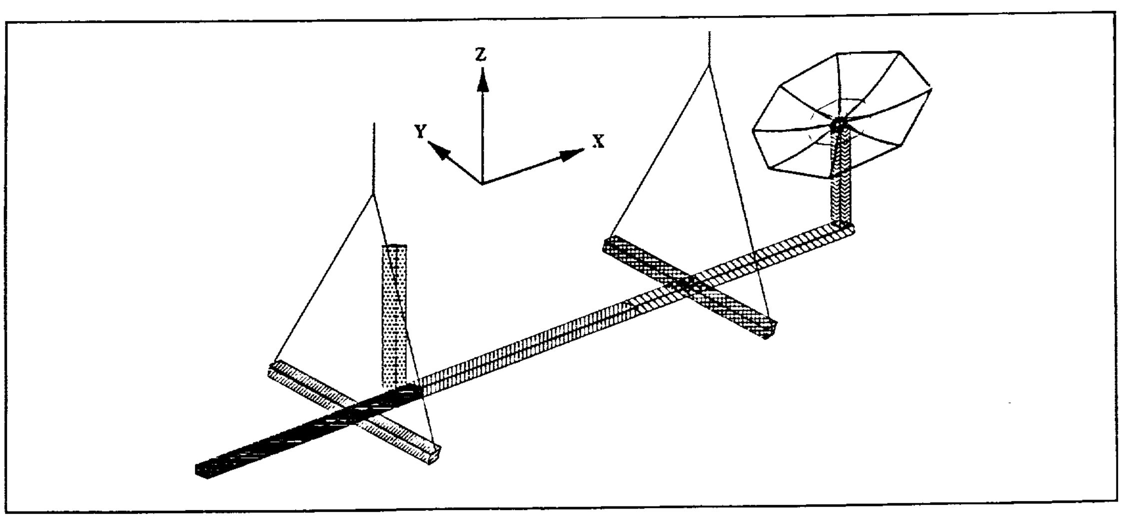
$$A_c = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 1 \\ \vdots & \vdots & \vdots & & \vdots \\ -\alpha_n & -\alpha_{n-1} & -\alpha_{n-2} & \dots & -\alpha_1 \end{bmatrix} \quad ; \quad B_c = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}$$

$$A_c^T P + P A_c = -Q \quad ; \quad G = B_c^T P$$

To perform the integrated design, the structure was divided into seven sections, three sections in the main bus, and one section each for the two horizontal booms and two vertical towers. The main bus structure is divided into three sections. Three structural design variables were used in each section; namely, the effective cross-sectional area of the longerons, the battens, and the diagonals, making a total of 21 structural design variables.

STRUCTURAL DESIGN VARIABLES

- Structure is divided into seven sections
- The effective cross-sectional areas of longerons, battens and diagonals are chosen as design variables
- Total of 21 structural design variables



An integrated controls-structures design was obtained by minimizing the steady-state average control power in the presence of white noise input disturbances with unit intensity (i.e., standard deviation intensity = 1 lbf.) at actuators No. 1 and 2 (located at the end of the main bus nearest to the laser tower), with a constraint on the steady-state rms position error at the laser detector (above the structure) for reasonable steady-state pointing performance, and a constraint on the total mass to have a fair comparison with Phase-0 design. Both static and dynamic dissipative controllers were used in the integrated design of the CSI Evolutionary Model. The six remaining actuators were used in the control design, along with velocity signals (required for feedback by the dissipative controllers) obtained by processing the accelerometer outputs. Additional side constraints were also placed on the structural design variables for safety and practicality concerns. Lower bound values were placed on these variables to satisfy structural integrity requirements against buckling and stress failures. On the other hand, upper bound values were placed on these variables to accommodate design and fabrication limitations.

DESIGN PROBLEM

- Pose the integrated controls-structures design as a simultaneous optimization problem
- Minimize the average control power

$$J \equiv Trace\{E\{uu^T\}\}$$

subject to

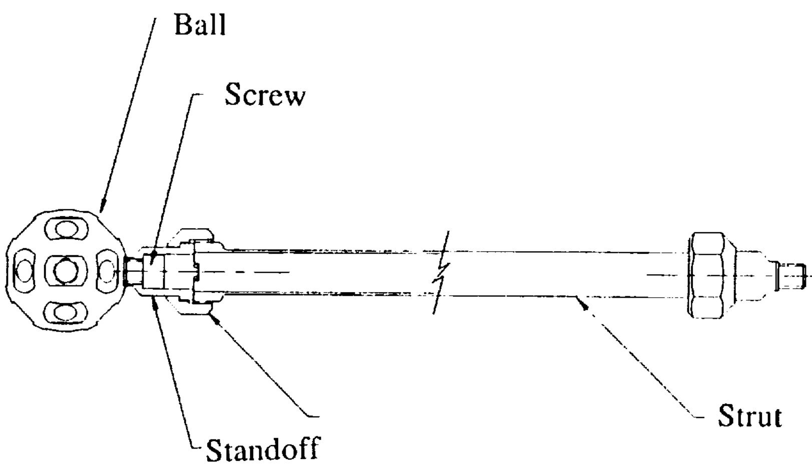
$$Trace\{E\{y_{los}y_{los}^T\}\} \leq \epsilon$$

$$M_{tot} \leq M_{budget}$$

- side constraints on the structural design variables to accommodate safety, reliability, and fabrication issues

A typical strut of the Phase-1 design is shown in the figure below. The strut is composed of three sections, namely, ball, joint and tube. In an ideal design, the effective density of the strut (which is the density for an equivalent uniform and homogeneous strut) remains roughly constant. Here, however, the effective density varies considerably with the effective cross-sectional area of the strut (which is the cross-sectional area for an equivalent uniform and homogeneous strut) . The main reason for this variation is that due to the short bay size and strut length, this strut design is rather joint-dominated with respect to mass, i.e., a large portion of the total strut mass is concentrated at the joints. As for the stiffness of the strut, its upper bound value is limited due to the ball and joint stiffnesses, whereas its lower bound value is governed by tube size limitations in fabrication.

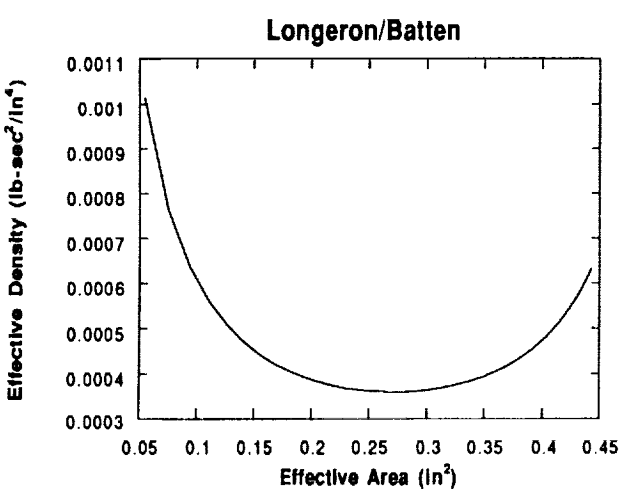
STRUT DESIGN

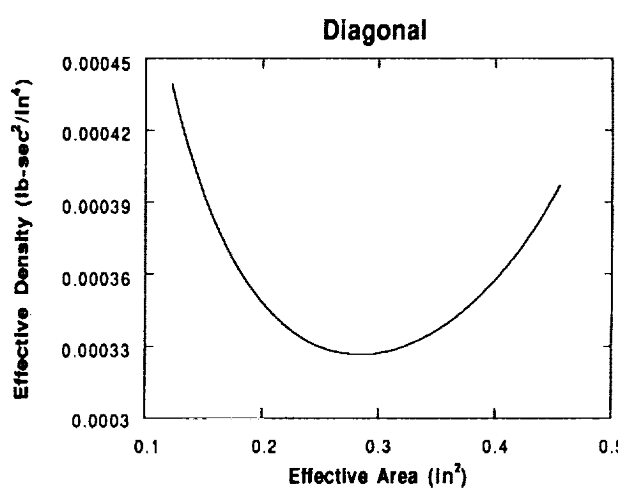


- Ideal Design: the effective density remains roughly constant
- Actual Design: the effective density varies considerably with the effective area
- The design is rather joint-dominated with respect to mass

In order to ensure that the design that comes out of the integrated design process is realizable, i.e., it is close to a structure that can be fabricated, strut design guides have been developed based on the strut shown in the preceding figure. The strut design guides for longerons, battens and diagonal are shown in the figures below. The curve on the design guide represents the lightest strut which can be manufactured for a given strut stiffness. These strut design curves have been developed assuming that the mass and stiffness properties of the ball and joint sections of the strut remain unchanged; and only the cross-sectional area of the tube portion of the strut changes. The beginning of the curve, corresponding to the lowest effective area, is governed by the load capacity of the tube portion, while the upper end of the curve is governed by the stiffness of the ball and joint sections.

STRUT DESIGN CURVES





Using a constraint on the maximum rms pointing error of 2.4 inches and a constraint on the total mass of 1.92 lb-s^2/in (nominal mass of the CSI Phase-0 Evolutionary Structure), a conventional ''control-optimized'' design was performed first (with the structural design fixed at the initial values) using both the static and dynamic dissipative controllers, where the average control power was minimized with respect to the control design variables only. The static dissipative controller gave an average control power of 7.11 lb^2, while the dynamic dissipative controller gave a better average control power of 6.41 lb^2. The open-loop rms pointing error for the Phase-0 structure was 22.54 inches. Next, an integrated design with the static dissipative controller was performed, wherein the average control power was minimized with respect to both control and structural design variables. The integrated design reduced the average control power by about 40 percent to 4.21 lb^2. This integrated design (Phase-1 design) gave an open-loop rms pointing error of 18.34 inches, which, although better than the open-loop performance of the Phase-0 design, indicates that the task of achieving satisfactory pointing performance cannot be achieved through structural redesign alone. Using the same initial design, another integrated design using the dynamic dissipative controller was also performed. This design gave an almost 43-percent reduction in the average control power compared to its corresponding control-optimized design. These results clearly demonstrate the advantage of integrated design over the traditional sequential design.

CONVENTIONAL VS. INTEGRATED

	RMS Displacement	Control Power
Open Loop (Phase-0)	22.54	0.00
Open Loop (Phase-1)	18.34	0.00
Control-Optimized (S) Design	2.4	7.11
Control-Optimized (D) Design	2.4	6.41
Integrated Design (S)	2.4	4.21
Integrated Design (D)	2.4	3.64

The effective cross-sectional areas of the longerons, battens and diagonal are presented in the table for both the Phase-0 structure and the Phase-1 structure that was designed using the static dissipative controller. Keeping in mind that the tube cross-sectional areas of the nominal CSI Evolutionary structure are 0.134 in^2 for the longerons and battens and 0.124 in^2 inches for the diagonal, it is observed that the longerons of all three sections of the main bus, particularly the section closest to the disturbance sources, and the laser tower are considerably stiffened; while the horizontal booms and the reflector tower became more flexible, partly to satisfy the mass constraint. Generally, all the diagonals and the battens decreased in size, mainly because the design optimization has to satisfy a constraint on the total mass, i.e., the mass of Phase-1 design must be less than or equal to the mass of Phase-0 design. Consequently, mass was taken from the battens and diagonals and was redistributed to the longerons of some sections because they are quite more effective in increasing the stiffness of a section. This behavioral trend may be attributed to a trade-off between structural controllability, observability, and excitability. The areas near the disturbance sources (actuator locations) were stiffened in order to reduce the sensitivity of the structure to external disturbances at those locations, while ensuring that no appreciable loss of controllability and/or observability occurred.

STRUCTURAL DESIGN VARIABLES

(Static Dissipative Controller)

	Design Var.	Phase-0 Areas	Phase-1 Areas
Longerons	1	0.134	0.330
	4	0.134	0.085
	7	0.134	0.173
	10	0.134	0.260
	13	0.134	0.257
	16	0.134	0.095
	19	0.134	0.096
Battens	2	0.134	0.082
	5	0.134	0.083
	8	0.134	0.082
	11	0.134	0.082
	14	0.134	0.081
	17	0.134	0.081
	20	0.134	0.081
Diagonals	3	0.124	0.082
	6	0.124	0.085
	9	0.124	0.082
	12	0.124	0.081
	15	0.124	0.079
	18	0.124	0.079
	21	0.124	0.082

The optimal values of the structural design variables for the integrated design structure with the dynamic dissipative controllers are presented below. Generally, quite similar trends to those for the static dissipative controller design are observed. In fact, the effective cross-sectional areas of this integrated design are roughly within 20 percent of the design obtained using the static dissipative controller, thus indicating that the optimal structures for both the static and dynamic dissipative designs are essentially the same. Consequently, the integrated design with static dissipative controller was chosen for fabrication.

STRUCTURAL DESIGN VARIABLES

(Dynamic Dissipative Controller)

	Design Var.	Phase-0 Areas	Phase-1 Areas
Longerons	1	0.134	0.330
	4	0.134	0.080
	7	0.134	0.142
	10	0.134	0.295
	13	0.134	0.258
	16	0.134	0.100
	19	0.134	0.117
Battens	2	0.134	0.077
	5	0.134	0.087
	8	0.134	0.086
	11	0.134	0.080
	14	0.134	0.078
	17	0.134	0.077
	20	0.134	0.083
Diagonals	3	0.124	0.098
	6	0.124	0.087
	9	0.124	0.082
	12	0.124	0.066
	15	0.124	0.066
	18	0.124	0.066
	21	0.124	0.083

It is not practical to expect that the optimal design that comes out of the integrated design process can be fabricated to exact specifications, mainly due to manufacturing and cost limitations. Consequently, any feasible design should allow for perturbations in the structural design variables (effective cross-sectional areas and effective mass densities of the struts). In order to evaluate the sensitivity of the optimal design with respect to perturbations in the structural design variables, the line-of-sight (Los) function and the control power function are approximated by a first-order Taylor's Series expansion. Then, upper bound values for Los pointing error and the control power are obtained for a maximum perturbation limit following a worst-case-scenario approach based on steepest ascent.

PERTURBATION ANALYSIS

- The integrated phase-1 design cannot be fabricated to exact specifications due to manufacturing and cost limitations
- Any viable integrated design should allow for possible perturbations in the structural design variables
- Carry out a post-design sensitivity analysis:

$$LOS(d+\delta) = LOS(d) + [\partial LOS/\partial \rho]^T \delta + \ldots$$

$$POW(d+\delta) = POW(d) + [\partial POW/\partial \rho]^T \delta + \ldots$$

- Upper bound values for the rms pointing error and control power

$$LOS_U = LOS(d) + |[\partial LOS/\partial \rho]^T| \delta_{max}$$

$$POW_U = POW(d) + |[\partial POW/\partial \rho]^T| \delta_{max}$$

The table below compares the rms pointing error and control power values of the nominal integrated design (with static dissipative controller) with a perturbed design and the final fabricated Phase-1 design. The perturbed design which allows for a 10–percent perturbation in the structural design variables gave a worst-case value of 4.42 for the control power (5–percent more than the nominal) and a worst-case value of 2.56 for the rms pointing error (7–percent more than the nominal), thus implying that the nominal integrated design is rather insensitive to structural parameters perturbations and, therefore, is a feasible design. The fabricated design which refers to the design that was chosen for fabrication gave a control power of 4.34 (3–percent off from the nominal) and an rms pointing error of 2.38 (1–percent off from the nominal) which are quite close to the nominal design values.

PERTUBATION ANALYSIS (CONT'D)

	Control Power	RMS Pointing Error
Nominal Design	4.21	2.40
Perturbed Design	4.42 (5%)	2.56 (7%)
Fabricated Design	4.34 (3%)	2.38 (1%)

The effective cross-sectional areas chosen for the fabrication of each of the 21 struts (corresponding to the 21 structural design variables) are presented in the table below. Out of the 21 possible struts, six unique struts were chosen for fabrication, with four for the longerons, one for the battens, and one for the diagonals. The reasons behind choosing only six unique struts are essentially cost limitations and/or closeness of the optimal design values. Most of the effective cross-sectional areas of the struts in the fabricated design are within 10–percent of the chosen integrated design (with static dissipative controller) and all are within 20–percent of the nominal values.

STRUCTURAL DESIGN VARIABLES

(Fabricated Structure)

	Design Var.	Phase-0 Areas	Phase-1 Areas
Longerons	1	0.134	0.347
	4	0.134	0.106
	7	0.134	0.182
	10	0.134	0.274
	13	0.134	0.274
	16	0.134	0.106
	19	0.134	0.106
Battens	2	0.134	0.094
	5	0.134	0.094
	8	0.134	0.094
	11	0.134	0.094
	14	0.134	0.094
	17	0.134	0.094
	20	0.134	0.094
Diagonals	3	0.124	0.087
	6	0.124	0.087
	9	0.124	0.087
	12	0.124	0.087
	15	0.124	0.087
	18	0.124	0.087
	21	0.124	0.087

An integrated design of the CSI Evolutionary Structure (Phase-0 structure) has been performed as a step in the validation of the integrated controls-structures design methodology. The integrated design structure (Phase-1 structure) provides the same Los pointing performance as the Phase-0 structure with around 60 percent of the control power requirement. Because of the dissipative nature of the controllers used in the integrated design, it is expected to have good stability robustness characteristics. Moreover, linear perturbation analysis indicates that the Phase-1 structure should also have good performance robustness characteristics. The Phase-1 structure is currently being fabricated, and is scheduled for testing and comparison with the Phase-0 structure in mid FY 92, at which time the process of validating the integrated design methodology will commence.

CONCLUDING REMARKS

- Phase-1 integrated design provides the same LOS performance as the phase-0 design with 60 percent of the control power requirement
- The integrated phase-1 design demonstrates good performance and stability robustness characteristics
- Phase-1 design is scheduled for testing and comparison with phase-0 in mid FY 92

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