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Control System Design for Flexible Structures Using Data Models

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Abstract

The dynamics and control of flexible aerospace structures exercises many of the engineering disciplines. In recent years there has been considerable research in the developing and tailoring of control system design techniques for these structures. This problem involves designing a control system for a multi-input, multi-output (MIMO) system that satisfies various performance criteria, such as vibration suppression, disturbance and noise rejection, attitude control and slewing control. Considerable progress has been made and demonstrated in control system design techniques for these structures. The key to designing control systems for these structures that meet stringent performance requirements is an accurate model. It has become apparent that theoretically and finite-element generated models do not provide the needed accuracy; almost all successful demonstrations of control system design techniques have involved using test results for fine-tuning a model or for extracting a model using system ID techniques.

This paper describes past and ongoing efforts at Ohio University and NASA Marshall Space Flight Center (MSFC) to design controllers using "data models". The basic philosophy of this approach is to start with a stabilizing controller and frequency response data that describes the plant; then, iteratively vary the free parameters of the controller so that performance measures become closer to satisfying design specifications. The frequency response data can be either experimentally derived or analytically derived. One "design-with-data" algorithm presented in this paper is called the Compensator Improvement Program (CIP). The current CIP designs controllers for MIMO systems so that classical gain, phase, and attenuation margins are achieved. The center-piece of the CIP algorithm is the constraint improvement technique which is used to calculate a parameter change vector that guarantees an improvement in all unsatisfied, feasible performance metrics from iteration to iteration. The paper also presents a recently demonstrated CIP-type algorithm, called the Model and Data Oriented Computer-Aided Design System (MADCADS), developed for achieving H_∞ type design specifications using data models. Control system designs for the NASA/MSFC Single Structure Control Facility are demonstrated for both CIP and MADCADS. Advantages of design-with-data algorithms over techniques that require analytical plant models are also presented.

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Introduction

The performance objectives in the design of controllers for flexible structures (FS's) include vibration suppression, disturbance rejection, and attitude control. FS's are characterized by having many low frequency, closely spaced, lightly damped structural modes. For controller designs to meet specifications, several structural modes must lie within the control system bandwidth. Because the structural modes of FS's are inherently lightly damped, they can cause vibrations problems once excited, and they provide paths of propagation between disturbances and quantities being controlled or regulated. The controller design process must either dampen or suppress (notch) these modes.

Because the modes for many FS's are closely spaced in frequency, the design process, e.g., LQG, H_∞, loop-at-the time, μ-synthesis, etc., used to dampen and/or suppress these modes, typically produces controllers with lightly damped characteristics in the frequency range of those modes inside the control system bandwidth. This produces significant problems of robustness to model inaccuracy. Experience has shown that models developed either from physical laws or finite element methods (FEM's) do not provide sufficient accuracy for controller designs for FS's with stringent vibration/disturbance/attitude performance specifications. It is not anticipated that significant breakthroughs will occur in control system model development from either physical laws or FEM's in the next decade.

An alternative is to develop control system design models from test results. The normal approach is to fabricate the FS, perform testing, and extract an analytical control system design model from the test data. The last step is called system identification (ID), and the results can either be a time domain or frequency domain model. This process is not trivial and is greatly complicated by FS's being inherently multi-input, multi-output (MIMO) in nature. In fact, system ID for FS's is still more of an art than a science and is time consuming and numerically intensive. Furthermore, for the MIMO case the order of the resulting model of the system can easily exceed one hundred. Numerical techniques used to design controllers cannot normally handle orders of this magnitude. To circumvent the order problem, the model is reduced, using model reduction schemes. The model reduction schemes "throw things away", and some produce models with different modes and mode shapes than were produced by system ID. The consequence is a design model that is significantly different from that identified. A controller

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design based on the reduced model may or may not produce a closed loop system satisfying design specifications. If the design does not meet specifications, the designer must either find a better model or fine-tune the design.

Alternate approaches are obviously needed. Approaches that directly utilize data models, i.e., test data or frequency response data obtained by operating upon test data by an FFT, to design controllers or fine-tune reduced order controllers, can avoid or circumvent the pitfalls of the system ID, model reduction, controller design process.

The philosophy of designing controllers using data models is not new. One of the most successful ventures in the development of an automated approach to the design of controllers for complex aerospace vehicles using frequency response data models is the Compensator Improvement Program (CIP) developed for NASA/MSFC in the 1970's for aiding in the design of controllers for the ascent flight control systems of the Saturn V and the Space Shuttle [1,2].

In this paper the description of the control system design problem as an abstract mathematical programming problem is presented. This is followed by a brief description of a straightforward algorithm used to find the solution to this problem using data models. Next, the basic features of two software programs, the CIP and the Model and Data Oriented Computer-Aided Design System (MADCADS) that implement variations of this algorithm are described. The application of these programs to the design of controllers for a flexible structure are then presented. Finally, plans for future enhancements to CIP and MADCADS are described, followed by concluding remarks.

An Algorithm for Design with Data Models

This section illustrates how the control systems design problem can be cast as a mathematical programming problem and presents a viable, iterative algorithm for its solution. Two software programs using this iterative algorithm are then described.

Problem Statement and Solution

The problem of designing a controller to meet various specifications can be stated abstractly as a mathematical programming problem of the form: Find $x \in \mathbf{R}^n$ to satisfy

$$f_i(x) \geq 0, \quad i = 1,2,\ldots,N_f \tag{1}$$

where each f_i is a function corresponding to a design specification and x is a vector of design variables that correspond to the free parameters of a controller representation. An approach to solving this problem using data models that has been proven effective is the Constraint

Improvement Technique (CIT). The CIT is based upon the fundamental principles of optimization in finite dimensional spaces under the assumption that the constraint functions are differentiable functions of the controller's parameters. The CIT has the following algorithmic structure. Let $x^{(k)}$ denote the value of the parameter vector at the k^{th} iteration. Set $k = 1$.

Step 1: [Test for convergence.] If all the constraints are satisfied, stop. Set the solution equal to $x^{(k)}$.

Step 2: [Calculate a search direction.] Compute a nonzero $d^{(k)} \in \mathbf{R}^n$ that has the possibility of improving some function of the constraints.

Step 3: [Calculate a step length.] Compute a nonnegative $\alpha^{(k)}$ such that when the constraint functions are evaluated at $x^{(k)} + \alpha^{(k)}d^{(k)}$ a measure of algorithm progress is improved.

Step 4: [Update parameters.] Set $x^{(k+1)} = x^{(k)} + \alpha^{(k)}d^{(k)}$ and $k \leftarrow k + 1$. Go to Step 1.

The key step in determining performance for this algorithm structure is the calculation of the search direction. The search direction as determined by CIT is calculated by finding $d^{(k)}$ such that

$$\nabla f_i^T(x^{(k)})d^{(k)} = c_i^{(k)}, \quad \forall\ i \in T^{(k)} \tag{2}$$

where ∇f_i is the gradient of the i^{th} constraint function, $c_i^{(k)}$ is a positive scalar and $T^{(k)}$ is a set denoting the constraints violated at the k^{th} iteration. If the number of elements in $T^{(k)}$ is less than or equal to the dimension of the parameter space and all the $\nabla f_i(x^{(k)})$ are linearly independent then there exists a $d^{(k)}$ to satisfy Equation 2. The requirement that each $c_i^{(k)} > 0$ insures that all the violated constraints can be "theoretically" improved at each iteration. Equation 2 is actually an underdetermined system of linear equations that can be written in the form

$$J^{(k)}d^{(k)} = c^{(k)} \tag{3}$$

where $J^{(k)}$ is a matrix with rows formed from the gradients and $c^{(k)}$ is a vector formed from the $c_i^{(k)}$'s. The angle between the search direction and the i^{th} gradient is given by

$$\theta_i^{(k)} = \operatorname{acos} \frac{c_i^{(k)}}{\| \nabla f_i(x^{(k)}) \|_2 \| d^{(k)} \|_2} . \tag{4}$$

Minimizing the 2-norm solution for $d^{(k)}$ in Equation 3 keeps this angle as small as possible for each i. Experience has shown that choosing

$$c_i^{(k)} = \| \nabla f_i(x^{(k)}) \|_2$$

(which causes $\theta_i^{(k)} = \theta_j^{(k)} \ \forall \ i,j \in T^{(k)}$) provides good algorithm performance.

CIP Overview

The first software program to employ CIT has been CIP; a viable candidate for improving or augmenting control system designs for FS's. It can be used to recover lost performance caused by spillover in state space or transfer function designs or to fine-tune loop-at-the-time designs. The essence of CIP is to start with an initial stabilizing design and iteratively increment the design parameters so as to improve open loop performance measures. The initial version of CIP was developed to improve designs of controllers for single input, multiple output systems [1]. Later CIP was extended to handle true MIMO systems [2].

CIP views the connection of the controller/plant as a multiple loop system. The general block diagram for which CIP has been tailored is shown in Figure 1. The design philosophy implemented in CIP is to iteratively increment the parameters of the controller so that *simultaneous* improvement of the open loop frequency responses of each loop occurs with all other loops closed. For complex systems, such as FS's, this task is pragmatically impossible by manual design techniques. In regard to Figure 1 the loops are broken between the controller and the plant.

The prominent features and characteristics of CIP are described as follows:

(1) The plant or system is assumed to be described in the form of a transfer function matrix. CIP requires frequency response data of each element of this matrix for a system description. By using frequency response data as a system model, numerical problems in handling large order systems are eliminated, and experimentally determined frequency responses can be directly accommodated.

(2) Performance specifications can be made frequency dependent. This accommodates different specifications for phase and gain stabilization regions.

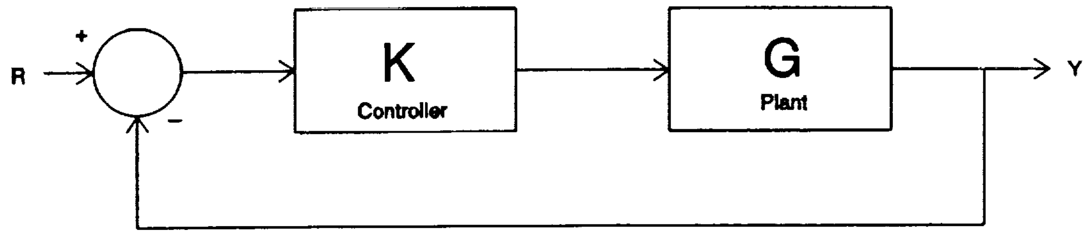

Figure 1: General Block Diagram for which CIP is Designed

(3) The controller is described as a transfer function matrix in which each element is represented as a ratio of first and second order factors. For continuous controllers these are s-plane functions, whereas for digital controllers these are w-plane functions. The coefficients of these factors are varied by CIP to improve the system performance. By constraining the variations in certain coefficients, restrictions can be placed on a controller element. For example, the D.C. gain of an element can be held constant to assure steady-state error performance, the coefficients of first order factors can be constrained to be positive in order to avoid first order right-half plane poles and zeros, or the damping ratios of second order factors can be specified to be above minimum values in order to assure robustness of the controller.

(4) CIP can test for system stability on each iteration.

(5) The coefficient change vector computed by CIP assures from iteration to iteration that an improved design results.

The code is started by specifying the system with frequency response data for each element of the transfer function matrix, the initial compensation, the desired design specifications, etc. At each iteration the performance measurements of the system are evaluated by opening each feedback loop, with all other loops closed, and determining stability and attenuation margins. The performance measurements are compared with respect to the design specifications; if all specifications are satisfied, the design is complete, and the process is terminated. Otherwise, the controller coefficient change vector (search direction) is computed using the gradients of the unsatisfied performance measurements with respect to the free parameters of the controller. A step is then taken along the search direction to compute a new compensator such that an improved solution is assured. If a step cannot be found that improves the performance measures above some user specified minimum, convergence is assumed. Otherwise, the iterative process is repeated.

As discussed previously, a property of the search direction computed by CIT is that it has a positive inner product with all gradient vectors; as a consequence, it is theoretically possible to simultaneously improve all unsatisfied performance measurements. However, from a practical point of view small degradations in some performance measurements are greatly outweighed by large improvements in one or more of the others. Such a philosophy has been incorporated into CIP.

MADCADS Overview

Recently, MADCADS, a code similar to CIP and based upon CIT, has been developed to use frequency domain data models to design controllers to meet H_∞-type multivariable control system design constraints [3]. An example of a typical constraint is the shape of the frequency response of the maximum singular value of the sensitivity function which can be written as

$$\sigma_{\max}\left[(I + G(\omega)K(\omega))^{-1}\right] \leq c(\omega) \quad \forall\ \omega \in [\omega_0, \omega_f] \tag{5}$$

where c is a function defined so as to achieve desired closed loop specifications.

In contrast to CIP, MADCADS uses a state-space realization to parameterize the controller in order to provide more flexibility in the controller's structure. Since the number of parameters in an arbitrary state-space realization is rather large (more than n^2 for an n^{th} order controller), it is necessary for computer memory limitations and algorithm performance to limit the number of parameters that are free to change at each iteration. In the current MADCADS the number of free parameters is limited by restricting the "A" matrix of the realization to be in upper-Hessenberg form. This does not pose any serious limitations on the structure of the controller. MADCADS also differs from CIP in that controllers for sampled-data systems are designed directly in the z-plane rather than in the w-plane. The current version of MADCADS does not assume any particular block diagram; rather the user must code subroutine modules to calculate constraints and gradients as they are needed. A large library of these modules has been developed for frequency dependent singular value constraints for various control system configurations.

Applications to the SSC Facility

This section describes the application of CIP and MADCADS to a flexible aerospace structure ground test facility. The details of the controller design procedures and experimental results of the implementations are also presented.

Description of the SSC Facility

A schematic of the NASA Marshall Space Flight Center Single Structure Control (SSC) Facility is shown in Figure 2. The SSC Facility is suitable for the study of line-of-sight (LOS) and vibration suppression control issues as pertaining to flexible aerospace structures. The primary element of the SSC Facility, a spare Voyager magnetometer boom, is a lightly damped beam measuring approximately 45 feet in length and weighing about 5 pounds.

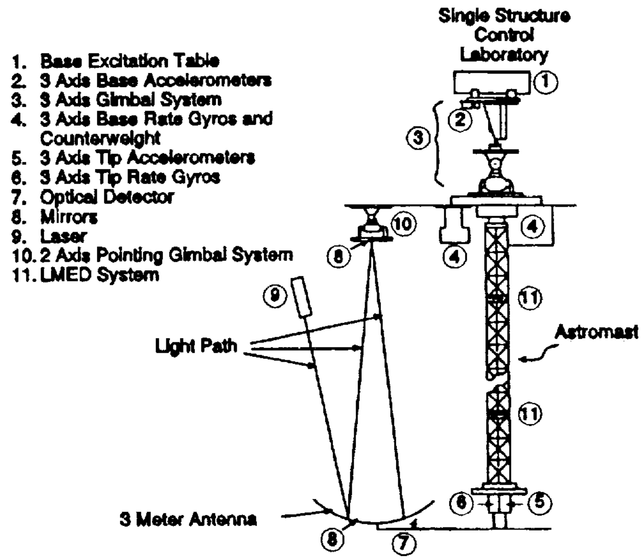

Figure 2: Schematic of the ACES Structure

The goal of the control system design is to maintain the reflected laser beam in the center of the antenna (location of the detector) in the presence of disturbances introduced by the base excitation table (BET). The digital controller is to be implemented on the HP9000 computer located at the facility using the fixed sampling rate of 50 Hertz and a fixed, one sample period computational delay. The results of other controller designs for the SSC Facility have been reported in the literature [4].

The experimental open loop frequency response from the y-axis of the Image Motion Compensation (IMC) gimbals to the x-axis LOS error is shown in Figure 3. The effect of the computational delay is quite apparent from analysis of the phase characteristic. The frequency responses of the other axes of the IMC-to-LOS are similar, although the cross-axis terms have less gain. The open loop frequency response from the y-axis Advanced Gimbal System (AGS) gimbal to the y-axis base gyro is shown in Figure 4. This response reveals the numerous lightly damped modes of the structure. The frequency responses of other elements of the AGS-to-base gyros transfer function matrix are similar. Mathematical modeling of the structure does not provide a model with sufficient fidelity to accomplish the above stated design goal. The frequency responses shown in Figures 3 and 4 were obtained by first exciting the system with pseudo-random inputs applied by the IMC and AGS, respectively, collecting the time response data and then using FFT techniques to compute the frequency response data. Averaging techniques were

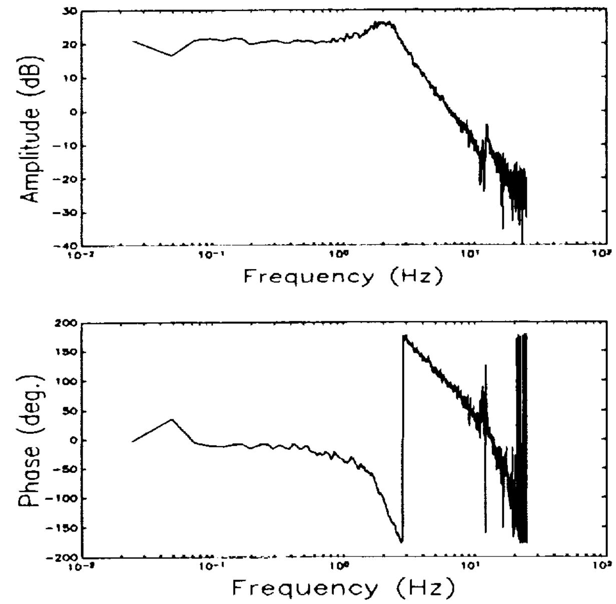

Figure 3: Experimental Frequency Response from y-Axis IMC to x-Axis LOS Error

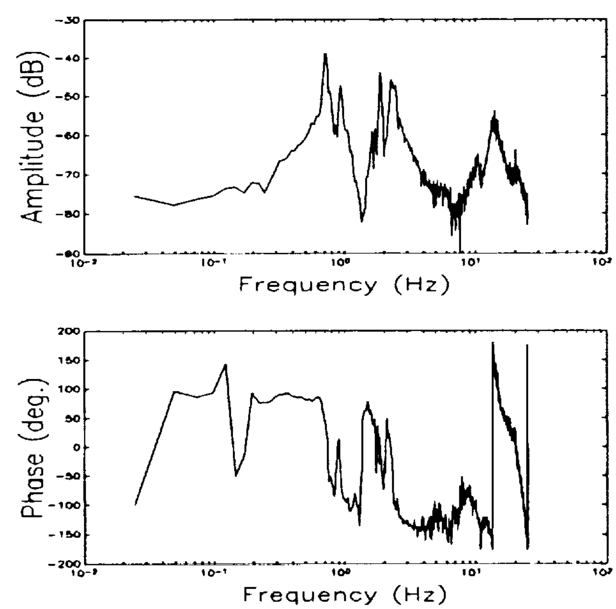

Figure 4: Experimental Frequency Response from y-Axis AGS to y-Axis Base Gyro

used to minimize the effects of noise and environmental disturbances. The error in the AGS magnitude data is estimated to be 10 dB or less for frequencies above 0.5 Hz.

There is a pendulum mode in the axis represented by Figure 4 with a frequency of roughly 0.15 Hz. As can be seen, the data does not show a lightly damped mode at this frequency. This is a resolution problem caused by a limitation in the data acquisition system hardware preventing the storage of a sufficient number of data points for accurately computing the frequency response characteristics of this mode. In fact, from other studies it is known that the frequency response data should show a peak of roughly 40 dB above the value shown.

Application of CIP

Since it is felt by the authors that an important factor in achieving a successful design for the system is the attainment of increased damping of the modes of the structure, the design using CIP has been limited to this goal. From Figure 4 it is seen that all the modes up to 5 Hz are reasonably phase stabilized. The first 180 degree crossing is roughly at 8 Hz. The design strategy is to gain stabilize all modes above 3 Hz, leave the modes below 3 Hz phase stabilized, and close the loop with a D.C. compensator gain of at least 60 dB. It is expected that significant damping will be added to all modes less than 3 Hz. The major difficulty in carrying out the design strategy is to roll-off (gain stabilize) the modes above 3 Hz while not adversely affecting the phase of the modes below 3 Hz, viz., minimizing phase lag spillover.

As a start, a low pass elliptic filter is designed with a break frequency of 6 Hz. The elliptic filter is chosen in order to minimize the phase lag spillover in the frequency range less than 3 Hz and to provide satisfactory attenuation of modes above 6 Hz. The stability and attenuation margins with this compensation are shown in Table 1.

CIP was run for 18 iterations and converged without satisfying all the design constraints, although significant improvements had been made. A third order factor with unity frequency response with poles near the frequencies where the constraints were not satisfied was placed in cascade with the resulting compensator. CIP then ran for 24 more iterations and satisfied the design constraints. The resulting margins are given in Table 2.

The resulting compensator was transformed to the time domain and down-loaded to the control computer of the SSC Facility. As expected significant improvements in performance were observed. In fact, test results showed that the damping of the pendulum mode more than tripled. It was assessed that more damping could be obtained if the D.C. gain could be raised; it was also realized that the loop gain could be doubled without jeopardizing the stability of the loop. The gain was raised conservatively to 1500, and a two cycle sine pulse at 0.15 Hz was applied. The results are shown in Figure 5. If this is closely compared to the open loop response with the same excitation, shown in Figure 6, several observations can be made. The pendulum mode damping has been increased by a factor of three, as estimated from comparison of the logarithmic decrements. The modes with frequencies of roughly 0.58, 0.76 and 1.9 Hz are not detectable. A closed loop mode with a frequency of roughly 2.4 Hz is observed. This results from a mode not being sufficiently phase stabilized with the increase in gain. This could not be predicted due to the fact that there is roughly 10 dB and 25 degrees uncertainty in the frequency response at this frequency. Further design work would involve performing more extensive identification studies at the appropriate frequency, possibly utilizing the closed loop response.

Minimum Gain Margin		
Frequency (Hz)	Margin Value	Specification
5.38	0.1 dB	8 dB
Minimum Phase Margin		
2.76	15.2°	45.0°
Maximum Attenuation Margin		
13.05	0.0317	0.5

Table 1: Design Constraints at Iteration 1

Minimum Gain Margin		
Frequency (Hz)	Margin Value	Specification
2.82	8.6 dB	8 dB
Minimum Phase Margin		
0.91	47.2°	45.0°
Maximum Attenuation Margin		
7.48	0.2529	0.5

Table 2: Design Constraints at Iteration 42

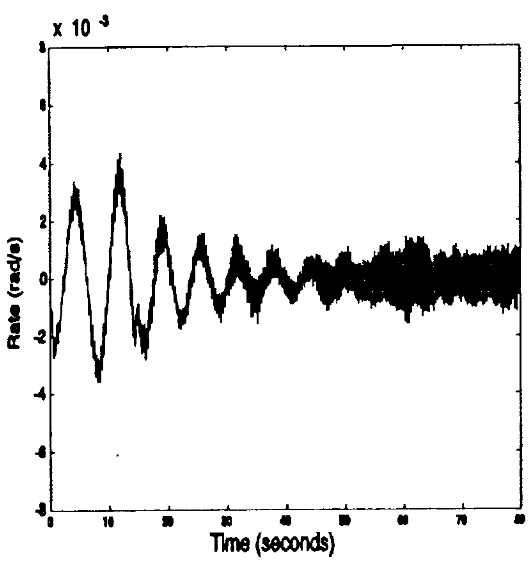

Figure 5: Closed Loop Response to a Two-Cycle Sine Pulse Input

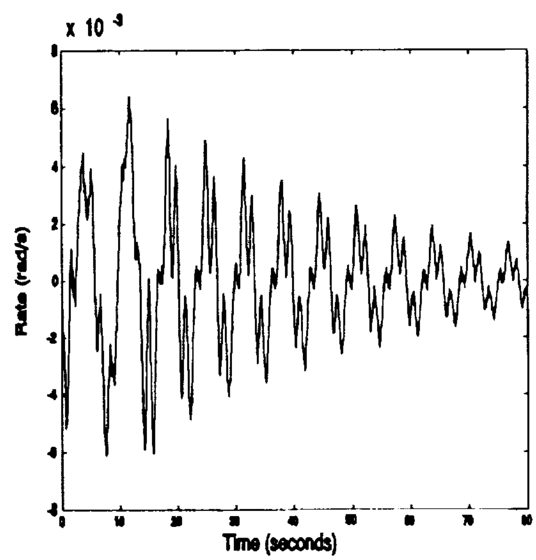

Figure 6: Open Loop Response to a Two-Cycle Sine Pulse Input

Application of MADCADS

In the application of MADCADS, a complete multivariable design is performed. The basic design philosophy is to dampen the pendulum modes and the bending modes of the structure by using feedback from the base gyros to the AGS while using the IMC gimbals with feedback from the detector to maintain the laser beam at the center of the detector. Due to sufficient decoupling, each two-input, two-output subsystem (AGS and IMC) is designed separately. One concern is the impact of disturbances that reach the IMC gimbals through the connecting arm that is attached to the base (as opposed to disturbances impacting the detector). Due to the inherently high optical gain from the IMC to the detector these disturbances can have a significant impact on the LOS error. To compensate for the effects of these disturbances it is not only necessary to maintain high loop gain over the frequency band of interest but to also maintain high IMC controller gain as well. Analysis of Figure 3 reveals that achieving high controller gain while also maintaining acceptable stability margins is difficult because of the combination of the high optical gain and the additional phase lag introduced by the computational delay. Fortunately, the impact of these disturbances can also be reduced by increasing the damping of the modes of the structure using the AGS; thereby reducing the motion of the base and the arm supporting the IMC gimbals. It is also desired to maintain reasonable levels of stability robustness.

The first step of the design procedure is the determination of a set of closed loop constraints consistent with the design philosophy such as those given in the first column of Table 3. Next, initial controllers are designed for the IMC-to-LOS and AGS-to-base gyro subsystems using a classical one-loop-at-a-time technique with the experimental frequency response data. Although the attempt was made to satisfy the constraints when designing the initial controllers, they are not satisfied as can be observed by comparing the first and second columns in Table 3. The initial controller for each subsystem is 10^{th} order. It should be noted that recently developed high fidelity models are 60^{th} order for the AGS-to-base gyro loops alone [5]. Design techniques such as LQG and H_∞ would yield controllers of at least this order (excluding weighting).

The multivariable design (i.e., taking cross-axis coupling within each subsystem into account) is then performed for each subsystem using MADCADS. The code is started with the initial 10^{th} order controllers described above, with no restrictions other than stability placed on the structure of the controllers. After approximately 100 iterations on each subsystem MADCADS converges without satisfying all the constraints. The final values of all the constraint functions are provided in the third column of Table 3.

Rather than trying to improve the design further, it was decided to implement the resulting 20^{th} order controller. The open loop x-axis LOS error due to an x-axis BET pulse disturbance intended to simulate the effect of spacecraft crew motion is shown in Figure 7. The dominant behavior in the response is the lightly damped 0.15 Hz pendulum mode. As shown in Figure 8, closing the loop with the resulting controller considerably reduces the impact of the pendulum mode and the first bending mode. The y-axis LOS error was negligible. The crew motion disturbance was applied to the y-axis of the BET yielding similar results.

Constraint	Initial Value	Final Value
$\sigma_{min}[I+GK(z)]_{IMC} \geq 0.5,\ f\in(0,25)$	0.2289	0.5090
$\sigma_{min}[I+KG(z)]_{IMC} \geq 0.5,\ f\in(0,25)$	0.2276	0.5056
$\sigma_{min}[I+(GK(z))^{-1}]_{IMC} \geq 0.6,\ f\in(0,25)$	0.2827	0.6072
$\sigma_{min}[I+(KG(z))^{-1}]_{IMC} \geq 0.6,\ f\in(0,25)$	0.2805	0.6112
$\sigma_{min}[I+GK(z)]_{IMC} \geq 18,\ f\in[0.14,0.16]$	10.0020	14.1000
$\sigma_{min}[I+GK(z)]_{AGS} \geq 0.6,\ f\in(0,25)$	0.3649	0.5996
$\sigma_{min}[I+KG(z)]_{AGS} \geq 0.6,\ f\in(0,25)$	0.3585	0.5988
$\sigma_{min}[I+(GK(z))^{-1}]_{AGS} \geq 0.7,\ f\in(0,25)$	0.3600	0.6719
$\sigma_{min}[I+(KG(z))^{-1}]_{AGS} \geq 0.7,\ f\in(0,25)$	0.3589	0.6712
IMC represents IMC subsystem; AGS represents AGS subsystem G represents plant; K represents controller $z = e^{j2\pi fT}$, $T = 0.02$ sec		

Table 3: Summary of MADCADS Design Constraints and Results

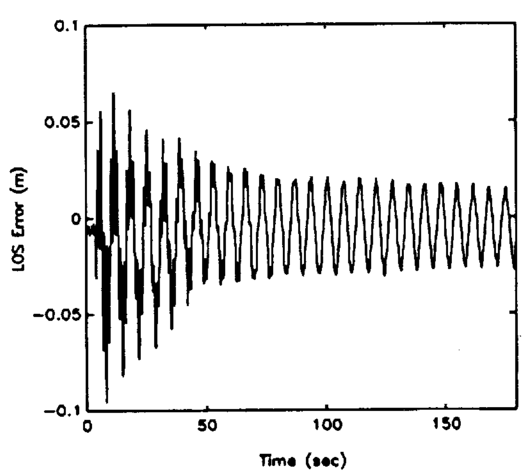

Figure 7: Experimental Open Loop x-axis LOS Error due to Crew Motion Disturbance

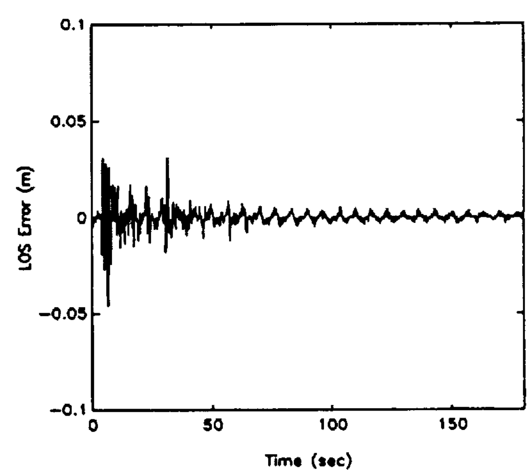

Figure 8: Experimental Closed Loop x-axis LOS Error due to Crew Motion Disturbance

Future Enhancements Planned for CIP and MADCADS

Both CIP and MADCADS have been demonstrated to be viable control system candidates for large space structures. There are ongoing programs at Ohio University and NASA/MSFC to refine and enhance these codes. This section briefly discusses these refinements and enhancements. These modifications fall into two basic categories: algorithm improvements and user interface improvements.

Algorithm Improvements

In order to increase the utility of CIP and MADCADS it is planned to increase the variety of constraints that can be handled. Current plans for CIP include the incorporation of constraints on the shapes of closed loop frequency responses and the use of state-space realizations to parameterize the controller. The ability to perform designs directly in the z-plane is currently being incorporated into CIP. Current plans for MADCADS include incorporation of constraints on the shapes of frequency responses of individual I/O pairs, operator 2-norm constraints (H_2-type constraints), as well as constraints on the damping ratios of the controller's poles and the zeros of individual I/O pairs of the controller. Other improvements for both CIP and MADCADS include better methods for calculating search directions and the application to the more general block diagram shown in Figure 9.

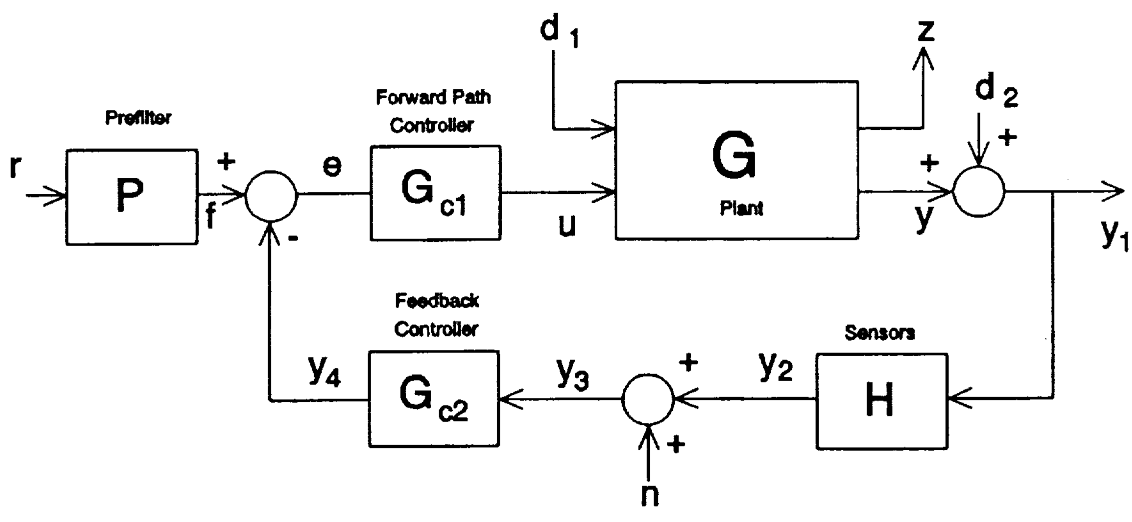

Figure 9: Proposed Block Diagram for CIP and MADCADS

User Interface Improvements

Current versions of CIP and MADCADS run in batch environments; hence user interaction is very limited and tedious. Experience has shown that the ability for the user to monitor algorithm performance and make design tradeoffs during code execution is needed. Therefore, work is in progress to develop versions of CIP and MADCADS that operate in a professional graphics workstation environment. It is planned to include in the codes the ability to monitor the progress of the design constraints in real-time by automatically updating graphics windows containing plots of the constraint functions. Other planned features include the ability to specify constraints graphically through the use of a mouse (this is especially convenient for specifying frequency domain constraints), single-step execution, and the ability to change the design constraints between iterations.

Conclusions

A review of ongoing research efforts in the area of multivariable controller design using data models at Ohio University and NASA Marshall Space Flight Center has been presented. The results of the application of two software programs, the Compensator Improvement Program and the Model and Data Computer Aided Design System, to the design of controllers for a flexible aerospace structure ground test facility was also presented. Both applications provided promising results. Future plans for expanded versions of CIP and MADCADS were also discussed.

References

1. J. R. Mitchell, "An Innovative Approach to Compensator Design," NASA Contractor Report, CR-2248, May 1973.

2. J. R. Mitchell, W. L. McDaniel, Jr., and L. L. Gresham, "Compensator Improvement for Multivariable Control Systems," Final Report, Contract No. NAS8-31568, NASA/MSFC, August 1977.

3. W. G. Frazier and R. D. Irwin, "A Numerical Approach to Controller Design with an Application to a Space Structure Test Facility," *Proceedings of the American Control Conference*, June 1992.

4. E. G. Collins, D. J. Phillips and D. C. Hyland, "Robust Decentralized Control Laws for the ACES Structure," *IEEE Control Systems Magazine*, vol. 11, no. 3, pp. 62-70, April 1991.

5. E. A. Medina, *Multi-input, Multi-output System Identification from Frequency Response Samples with Applications to the Modeling of Large Space Structures*, M. S. Thesis, Ohio University, November 1991.