

N94-35889

AN OPTIMIZATION-BASED APPROACH FOR
INTEGRATED CONTROLS-STRUCTURES DESIGN OF
FLEXIBLE SPACECRAFT

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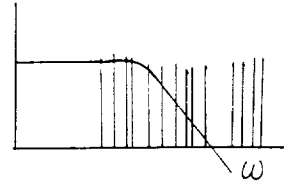
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MOTIVATION

- Control of flexible spacecraft is a difficult problem
 - Large number of elastic modes
 - Low value, closely-spaced frequencies
 - Very small damping
 - Uncertainties in math models



- Traditional design approach:
 - Design structure first
 - Design control system next
- Best achievable performance with traditional approach is limited
- **New Approach:** Design structure and control system *simultaneously*

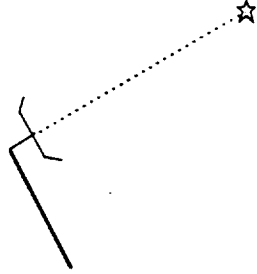
OBJECTIVE

Conceive and develop methodology for spacecraft design which

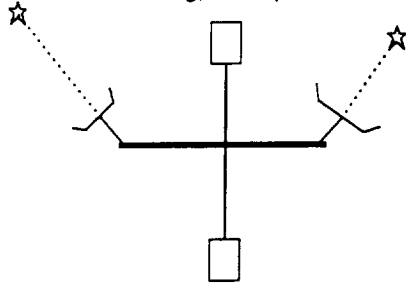
- addresses control/structure interaction issues
- produces technology for simultaneous control/structure design
- translates into algorithms and computational tools for practical integrated computer-aided design

PROBLEM CLASSIFICATION

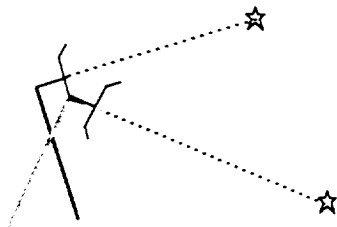
Class 1: Pointing, vib. sup., no articulation



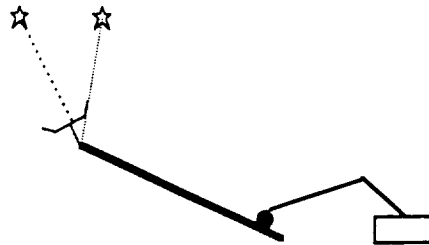
Class 2: Pointing, vib. sup., with articulation



Class 3: Nonlinear version of class 1



Class 4: General nonlinear with robotics



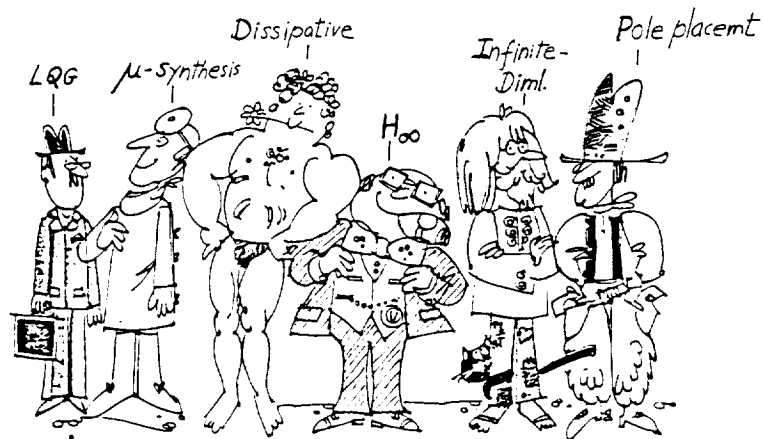
APPROACH

- Formulate integrated design problem as an optimization problem
 - Define objective function
 - Define design variables
 - . Structural parameters
 - . Control system parameters
 - Define constraints
 - Perform numerical optimization
- Validate the methodology through an integrated design of the CSI Evolutionary Model

INTEGRATED DESIGN METHODOLOGY VALIDATION

- Design and test optimal controllers for Phase Zero CEM
- Synthesize an optimal integrated design (Phase One CEM)
- Fabricate the closest structure to Phase One design
- Validate integrated design methodology by comparing Phase Zero and Phase One test performances

CONTROLLER ALTERNATIVES



APPROACHES TO LSS CONTROL

o MODEL-BASED CONTROLLERS (MBC):

- State estimator/observer "tuned" to a low-order design model
- Control gains via LQ regulator or eigensystem assignment, etc.

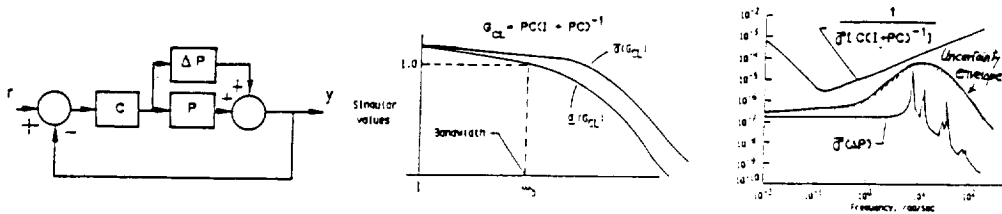
o DISSIPATIVE CONTROLLERS:

- Utilize collocated/compatible actuators and sensors (e.g., attitude and rate sensors and torque actuators)
 - CONSTANT-GAIN dissipative controllers
 - DYNAMIC dissipative controllers

MODEL-BASED DESIGN

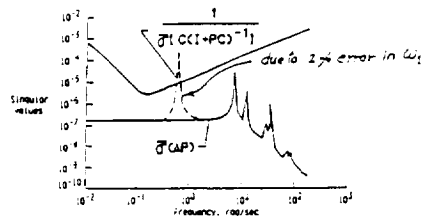
A Loop-Shaping Procedure loosely based on LQG/LTR:

Iterate on KBF and LQR to satisfy performance specs and robustness cond.



PROBLEM: Design robust to unmodeled dynamics, but NOT to parametric uncertainty

Small error in the design model frequency can destabilize the system!



Robustness of MBC's to real parametric uncertainties is an unsolved problem

CONTROLLER REQUIREMENTS FOR INTEGRATED DESIGN

- Must be **robust** to:
 - Unmodeled dynamics
 - Parameter uncertainties
 - Nonlinearities and failures
- Must be **implementable**
- Must be amenable to inclusion in an optimization loop
- ♦ *Dissipative controllers (developed in-house) satisfy these requirements*
- ♦ *More research is needed to obtain even higher performance*



STATIC (CONST.-GAIN) DISSIPATIVE CONTROLLERS

- o Use collocated/compatible actuators and sensors
- o Control **attitude** and **vibration** (i.e., **rigid** and **flexible** modes)
- o Constant-gain dissipative controllers:
$$u = -G_p y_p - G_r y_r,$$
where G_p, G_r are symmetric and pos. def.
- o Robust stability is guaranteed in the presence of
 - a) Unmodeled elastic modes
 - b) Parameter uncertainties
 - c) Monotonically increasing actuator nonlinearities
 - c) $(0, \infty)$ sector sensor nonlinearities
 - d) First-order actuator dynamics

DYNAMIC DISSIPATIVE COMPENSATORS

- o Constant-gain dissipative controllers give limited performance
- o Next logical step is to use *dynamic* dissipative compensators
 - Stability robustness is preserved in presence of
 - unmodeled elastic modes
 - parameter uncertainties
- o The transfer function from torque input to *attitude-rate* output is:

$$G(s) = \frac{J^{-1}}{s} + \sum_1^n \frac{\Phi_i \Phi_i^T s}{s^2 + 2\rho_i \omega_i s + \omega_i^2}$$

DYNAMIC DISSIPATIVE CONTROLLERS WITH DIRECT OUTPUT FEEDBACK INNER-LOOP

- o $u = -Gz - G_p y_p - G_r y_r$
- o $z = A_c z + B_c y_r$
- o Robustly stable if

G_p, G_r are symmetric and posdef, and

$C(s) = G(sI - A_c)^{-1} B_c$ is strictly positive real

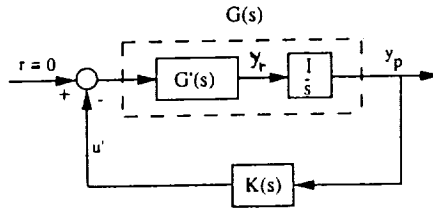
Easy to enforce via Kalman-Yakubovich lemma:

$C(s)$ is SPR if $\exists P, Q > 0$ such that

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

- o When zero-freq. modes are absent (e.g., test article), G_p, G_r can be zero--degenerates to "positivity" controller

DYNAMIC DISSIPATIVE CONTROLLER W/O DIRECT OUTPUT FEEDBACK



Theorem- Suppose $K(s)$ is asymptotically stable (a.s.) and min. phase, and $[K(j\omega)/(j\omega)] > 0 \forall$ real ω . Then the closed-loop system is a.s.

(Joshi, Maghami, Kelkar, GNC Conf, 1991)

$K(s)$ not strictly proper, but can be implemented as strictly proper using feedback of y_p and y_r .

CONDITIONS FOR DIAGONAL $[K(s)/s]$ TO BE STRONGLY PR

- o Suppose $K(s) = \text{diag}[K_1(s), K_2(s), \dots, K_m(s)]$

$$\text{where } K_i(s) = k_i \frac{s^2 + \beta_{1i}s + \beta_{0i}}{s^2 + \alpha_{1i}s + \alpha_{0i}}$$

Then $K(s)/s$ is strongly PR if

$$\alpha_{1i} - \beta_{1i} > 0$$

$$\alpha_{1i}\beta_{0i} - \alpha_{0i}\beta_{1i} > 0$$

- o For higher order $K_i(s)$, Sturm's theorem can be applied to get such conditions

DESIGN PROBLEM

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

$$J = E\{u^T u\}_{t \rightarrow \infty}$$

subject to:

$$E\{y_{\text{los}}^T y_{\text{los}}\}_{t \rightarrow \infty} \leq \varepsilon$$

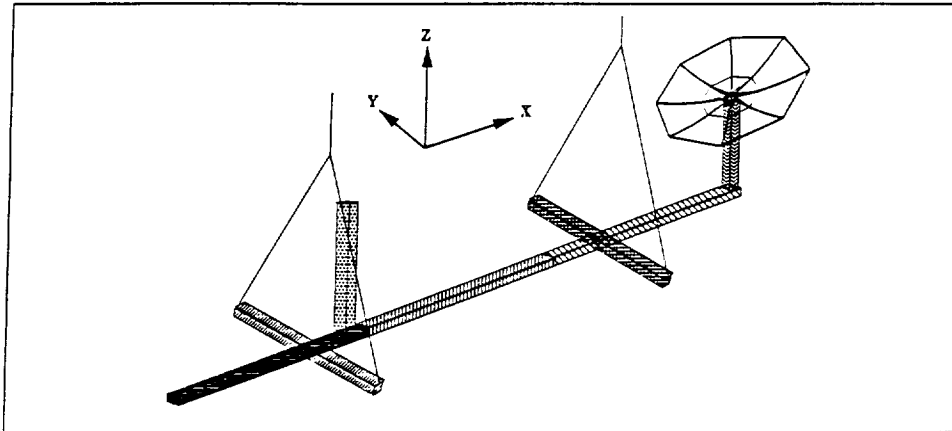
and

$$M \leq M_{\text{budget}}$$

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

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



CONTROL DESIGN VARIABLES

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

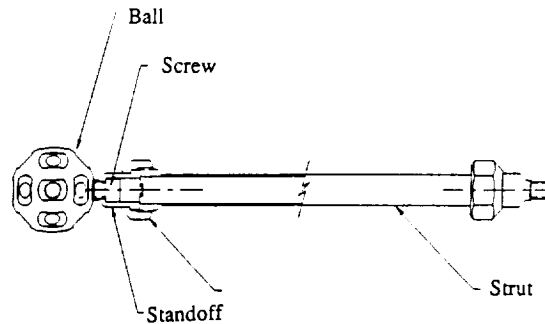
$$G_r = L_r L_r^T$$

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

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

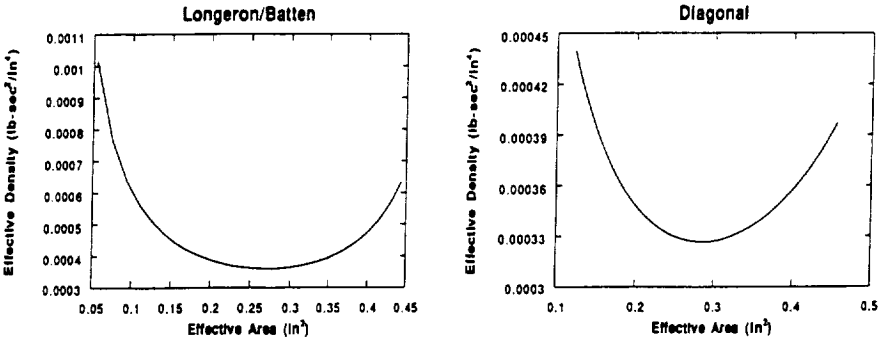
$$A_c^T P + P A_c = -Q ; \quad G = B_c^T P$$

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

STRUT DESIGN CURVES



CONVENTIONAL VS. INTEGRATED

	RMS	Control
	Displacement	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

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

STRUCTURAL DESIGN VARIABLES (Dynamic Dissipative Controller)

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

PERTURBATION ANALYSIS

- The integrated phase-1 design can not 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:

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

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

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

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

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

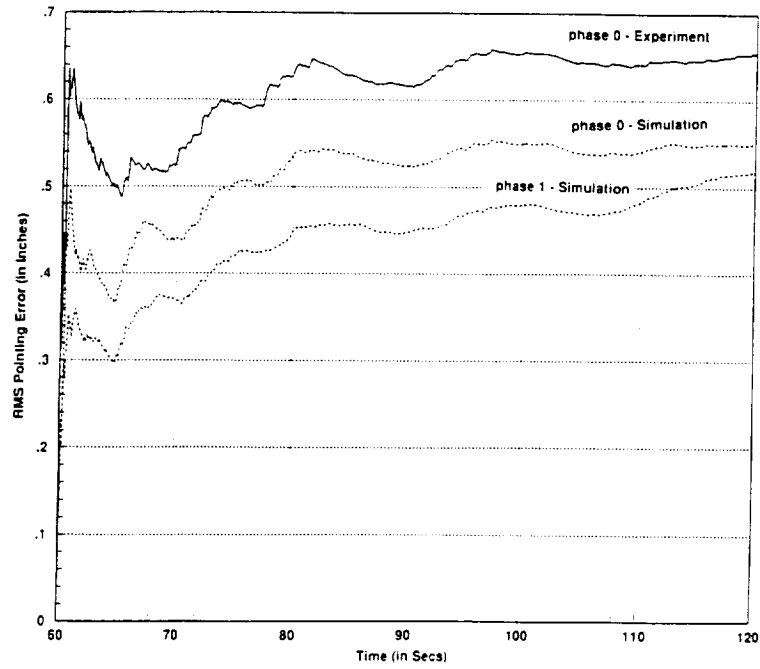
PERTURBATION ANALYSIS (CONT'D)

	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%)

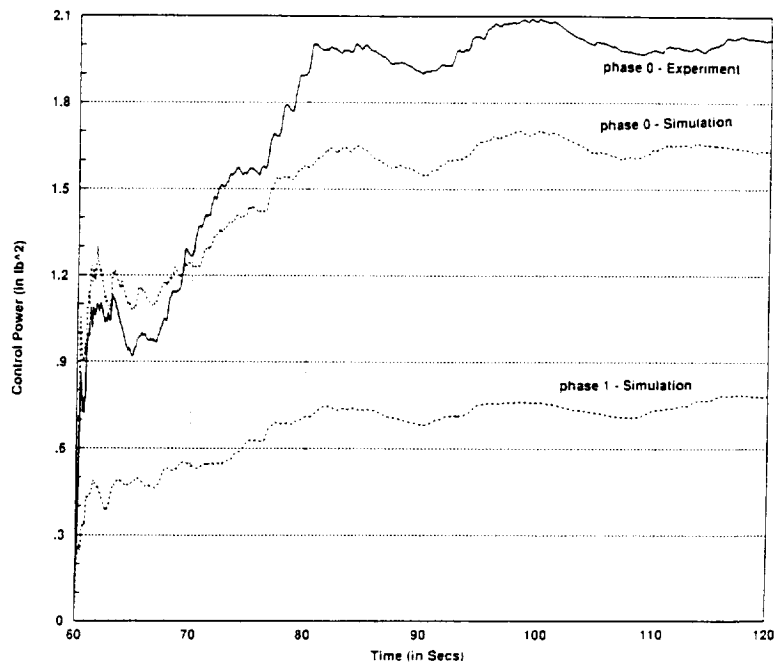
STRUCTURAL DESIGN VARIABLES (Fabricated Structure)

	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

SIMULATION AND EXPERIMENTAL RESULTS Static Dissipative Controller

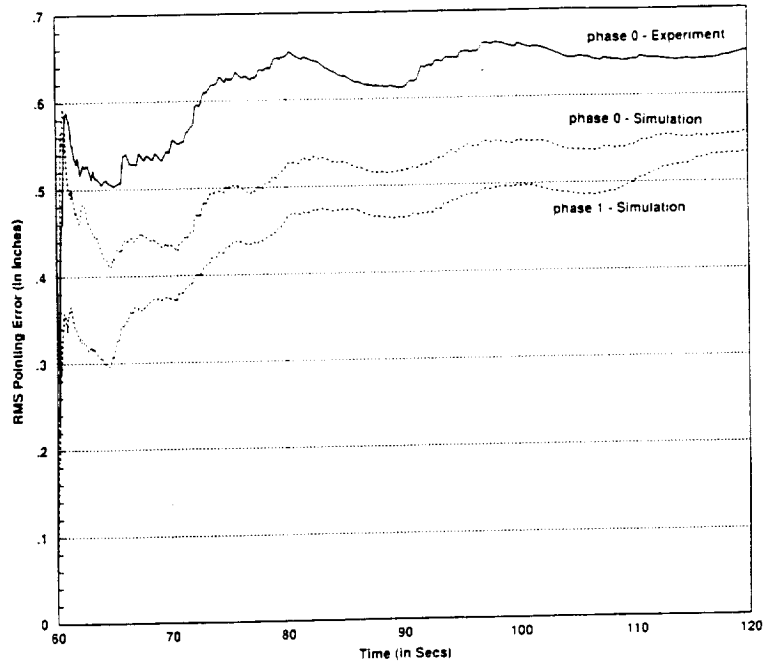


SIMULATION AND EXPERIMENTAL RESULTS Static Dissipative Controller



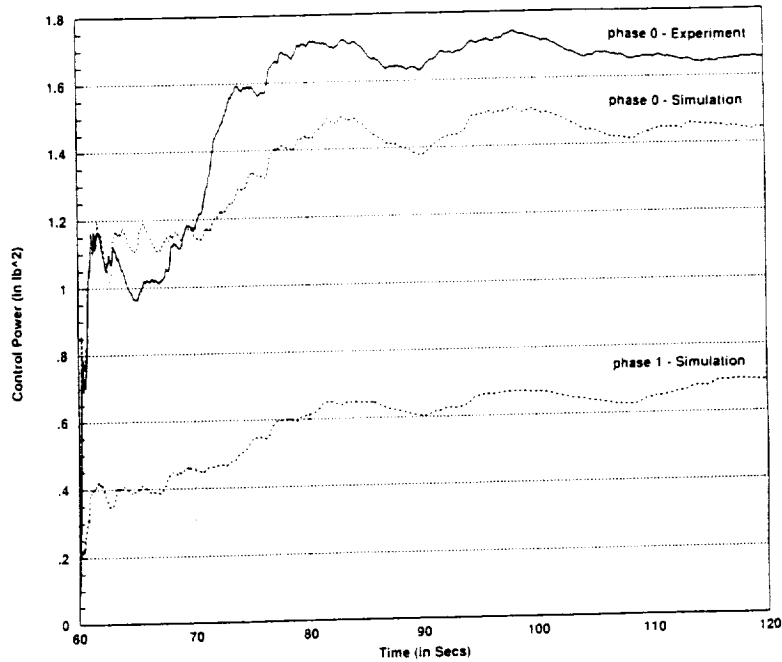
SIMULATION AND EXPERIMENTAL RESULTS

Dynamic Dissipative Controller



SIMULATION AND EXPERIMENTAL RESULTS

Dynamic Dissipative Controller



CONCLUDING REMARKS

- Basic integrated design methodology and software tool developed for Class I CSI problems
- Integrated redesign of evolutionary structure completed:
Provides same LOS performance with 40% less control power
- Integrated controls-structures design is a feasible and practical design tool for modern spacecraft
- Additional studies (theory and experiment) are in progress to improve and extend the methodology

