N94- 35889

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

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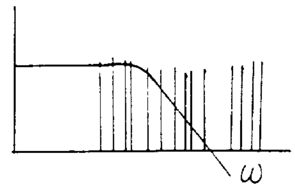
p. 17

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

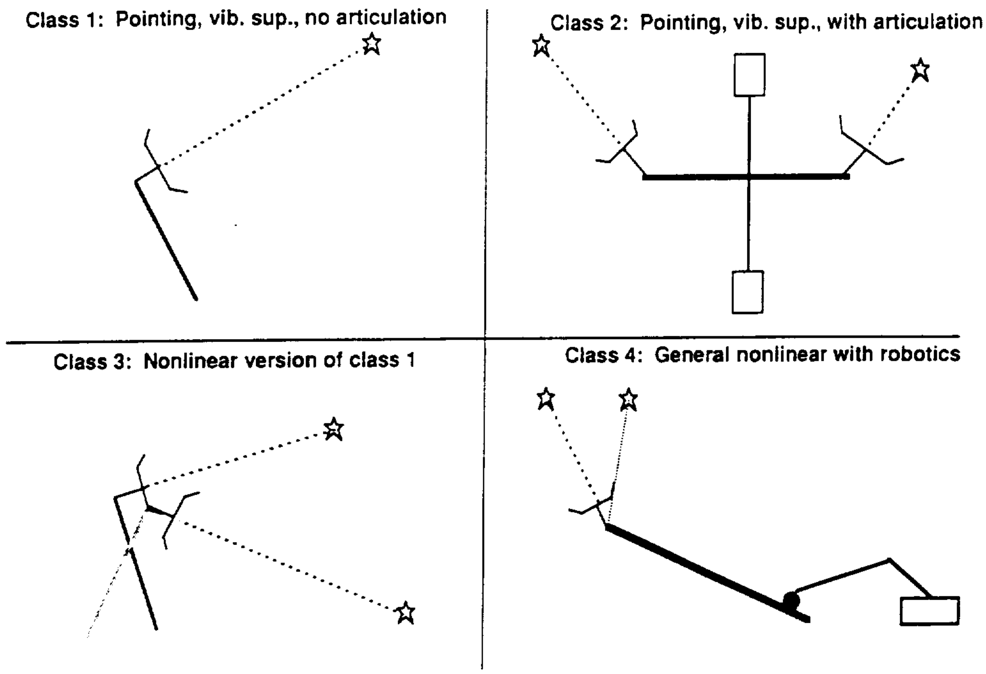
Conceive and develop methodology for spacecraft design which

- 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



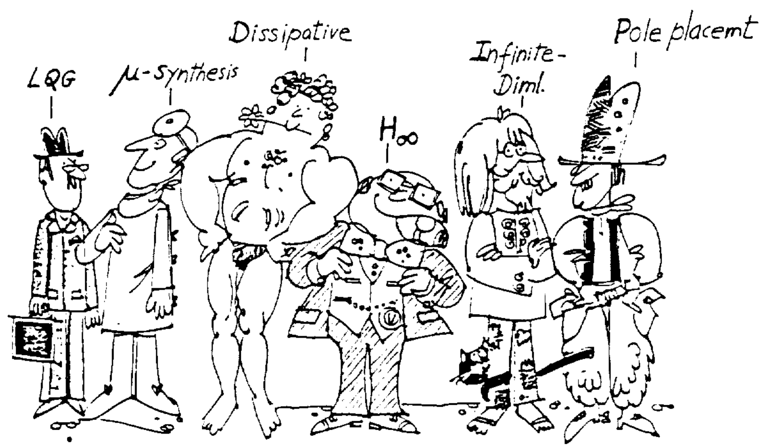
APPROACH

- 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)

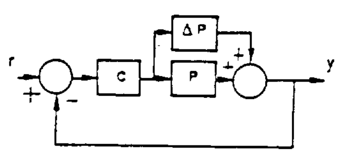
-CONSTANT-GAIN dissipative controllers

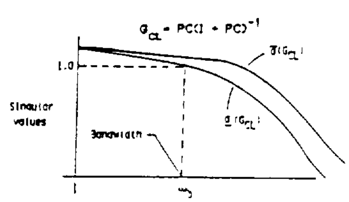
-DYNAMIC dissipative controllers

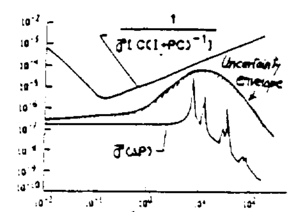
MODEL-BASED DESIGN

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

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

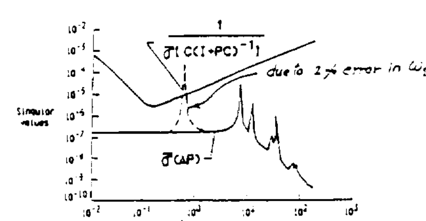






<u>PROBLEM: Design robust to unmodeled dynamics, but NOT to parametric uncertainty</u>

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

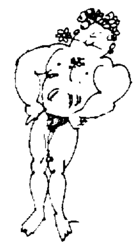


Robustness of MBC's to real parametric uncertainties is an unsolved problem

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:

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

DYNAMIC DISSIPATIVE CONTROLLERS <u>WITH</u> 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

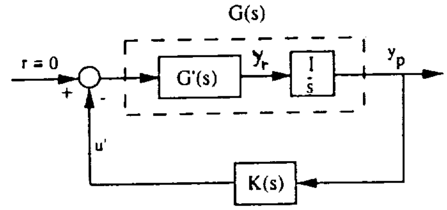
  Easy to enforce via Kalman-Yakubovich lemma:

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

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

- 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

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

  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

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

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

- 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

$$J = \underset{t \to \infty}{E}\{u^T u\}$$

subject to:

$$\underset{t \to \infty}{E}\{y_{los}^T \, y_{los}\} \le \varepsilon$$

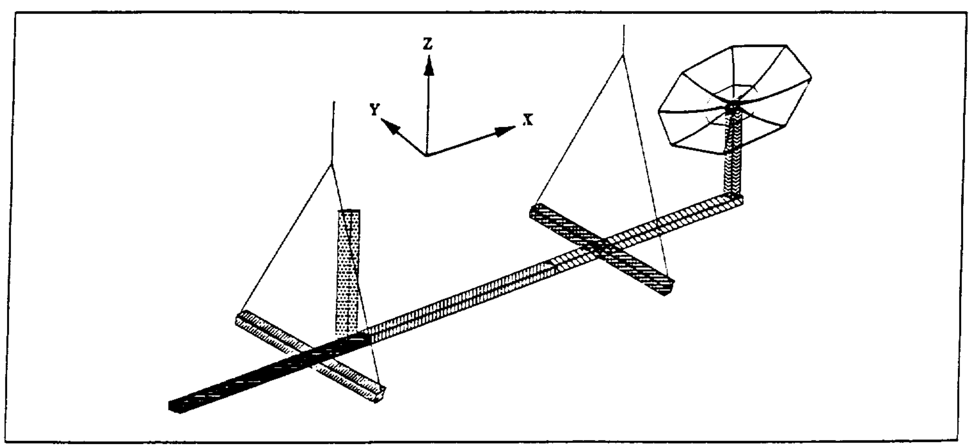
and

$$M \le M_{budget}$$

- 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

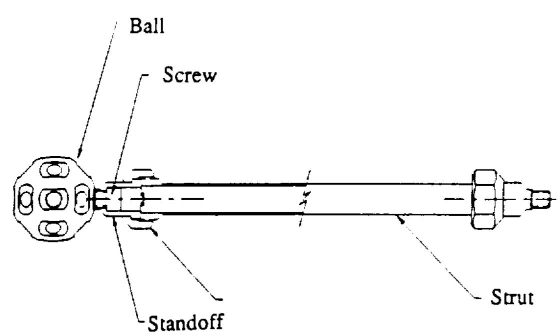
$$G_r = L_r L_r^T$$

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

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

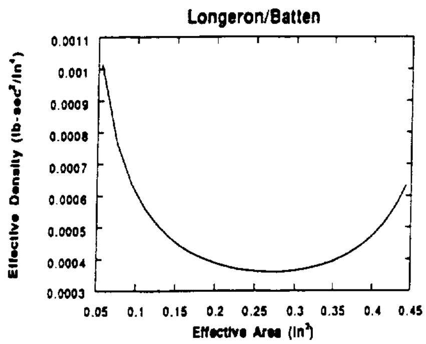
$$A_c^T P + P A_c = -Q \quad ; \quad G = B_c^T P$$

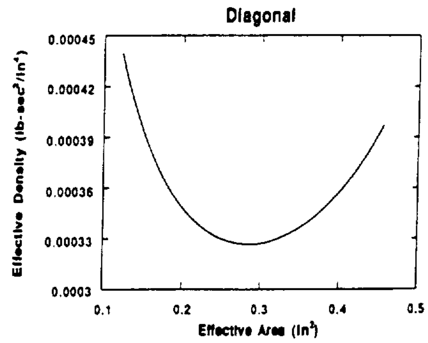
STRUT DESIGN



- 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 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

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 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

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)

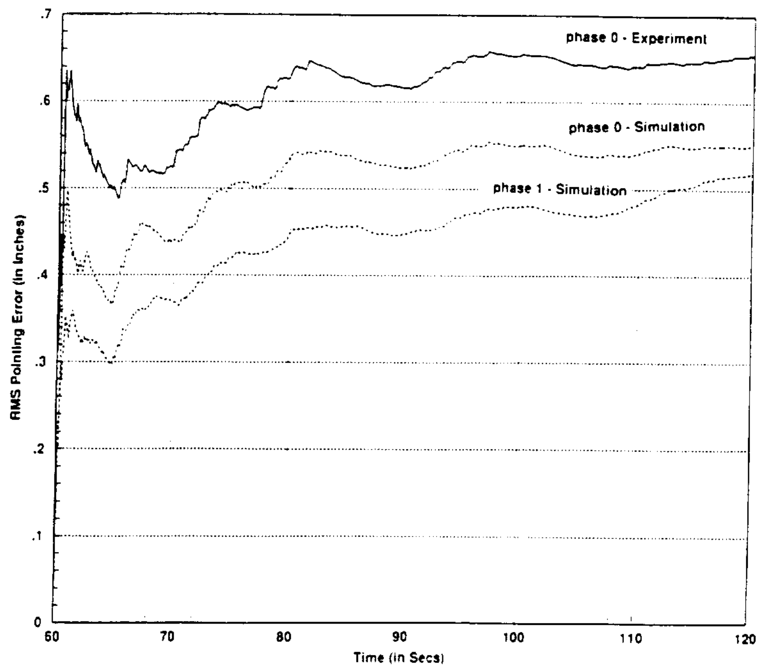
	Control Power	RMS Pointing Error
Nominal Design	4.21	2.40
Perturbed Design	4.42 (5%)	2.56 (7%)
Fabricated Design	4.34 (3%)	2.38 (1%)

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
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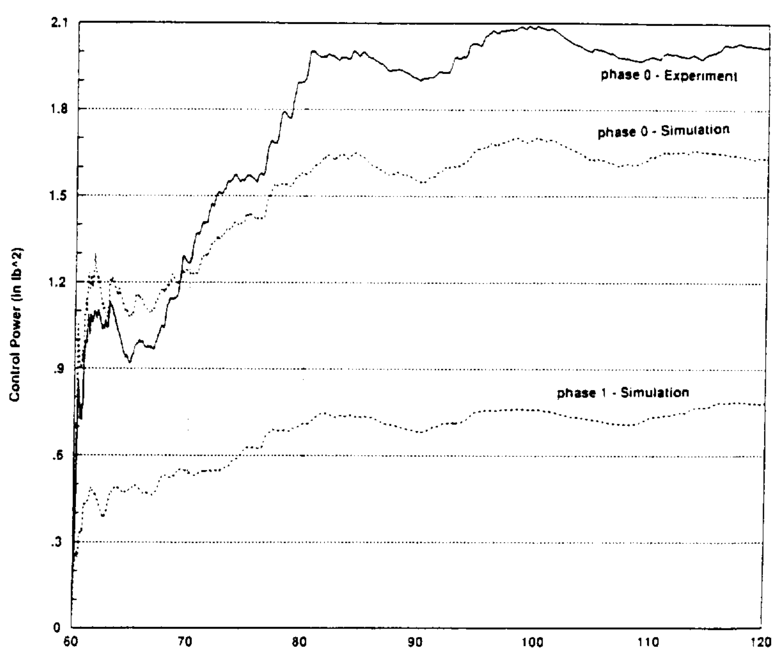

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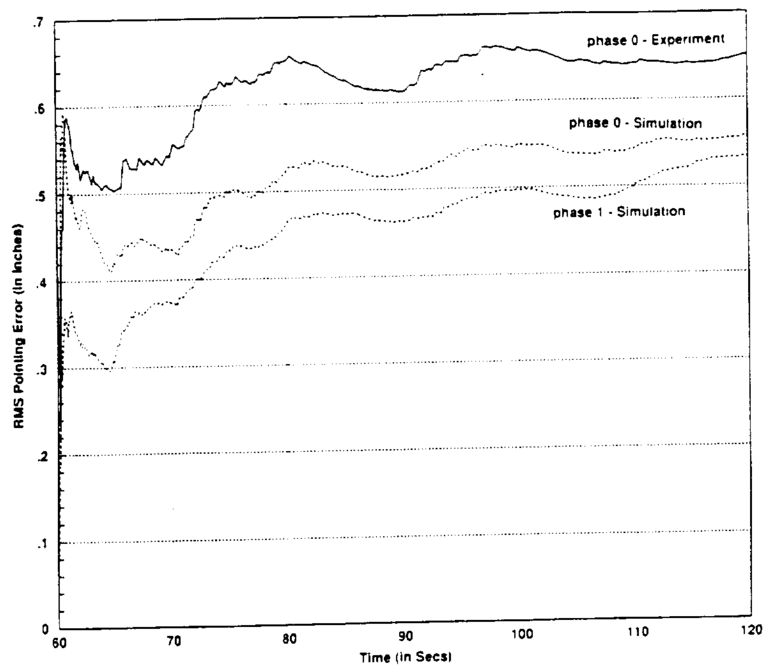
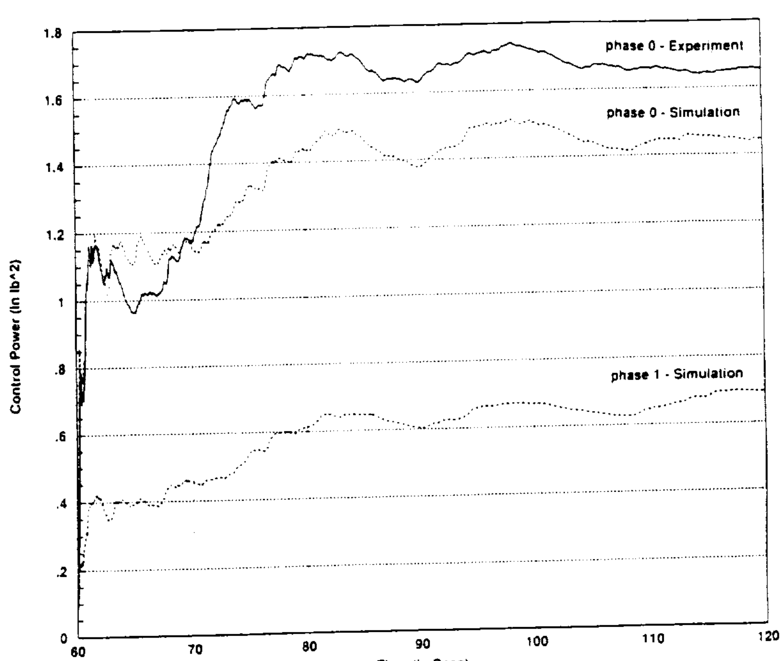
Dynamic Dissipative Controller



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