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PRECISION POINTING AND CONTROL OF FLEXIBLE SPACECRAFT

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BOEING AEROSPACE COMPANY

Large Space Structure Control

Precision Pointing and Control of Flexible Spacecraft

The problem and long term objectives for the precision pointing and control of flexible spacecraft are shown on the facing page. The four basic objectives are stated in terms of two principle tasks. Under Task 1, robust low order controllers, improved structural modeling methods for control applications and identification methods for structural dynamics are being developed. Under Task 2, a lab test experiment for verification of control laws and system identification algorithms is being developed. The following presentation highlights work in the following areas. For Task 1, work has focused on robust low order controller design and some initial considerations for structural modeling in control applications. For Task 2, work has focused on experiment design and fabrication, along with sensor selection and initial digital controller implementation.

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Precision Pointing and Control of Flexible Spacecraft

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- Problem
  - Current NASA and DoD plans call for large multiply connected flexible space structures (LSS) with requirements for unprecedented vibration and figure regulation accuracy
  - Resulting LSS control problems are multivariable, highly coupled with large model uncertainty
  - Controllers must be of relatively low order for implementation

Objectives

Task 1: Large Space Structure Control

- Develop low order robust, high performance controllers using modern techniques
- Develop improved structural modeling methods for control applications
- Develop methods for identification of structural dyanamics

Task 2: Flexible Spacecraft Control Simulator

- Develop lab test experiment for verification of control laws and systems identification algorithms

Large Space Structure Control
Fixed Order Controller Design

A flow diagram for comparing fixed order controller synthesis techniques is shown in the facing page. All methods begin with the definition of a continuum structure of theoretically infinite dimension. An evaluation model is derived by finite element methods of order N which is too large for controller design purposes. Model reduction methods are then employed to reduce the structure to various dimensions compatible with the chosen controller design scheme. Four fundamental approaches are discussed as follows. In each case, the objective is to provide a low order controller of dimension r << N.

In the first case (path A), the structure is reduced directly to dimension r and LQG methods derive a controller which is optimal for the r order structure. In the second case (path B), the structure is reduced to order s which is somewhat greater than r but much less than N. Parameter optimization using a nonlinear programming technique is used to synthesize the controller of dimension r. In the third case (path C), the structure is reduced to a large dimension n such that LQG controllers can be synthesized without exceeding the available computing capability viz., to "Riccati solvable" dimension. The resulting large order controller is reduced to dimension r by projection methods. In the fourth case (path D), a structure of dimension n is employed and the projection is calculated from the solution of coupled sets of Lynapunov and Riccati matrices of dimension n. The resulting projection is optimal because it is derived from a direct optimization of steady state quadratic performance index for the closed loop system equations including the controller. The resulting nonlinear matrix forms solve the first order necessary conditions of optimality but convergence is not guaranteed and the resulting solution is not guaranteed to be globally optimizing.

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Fixed Order Controller Design

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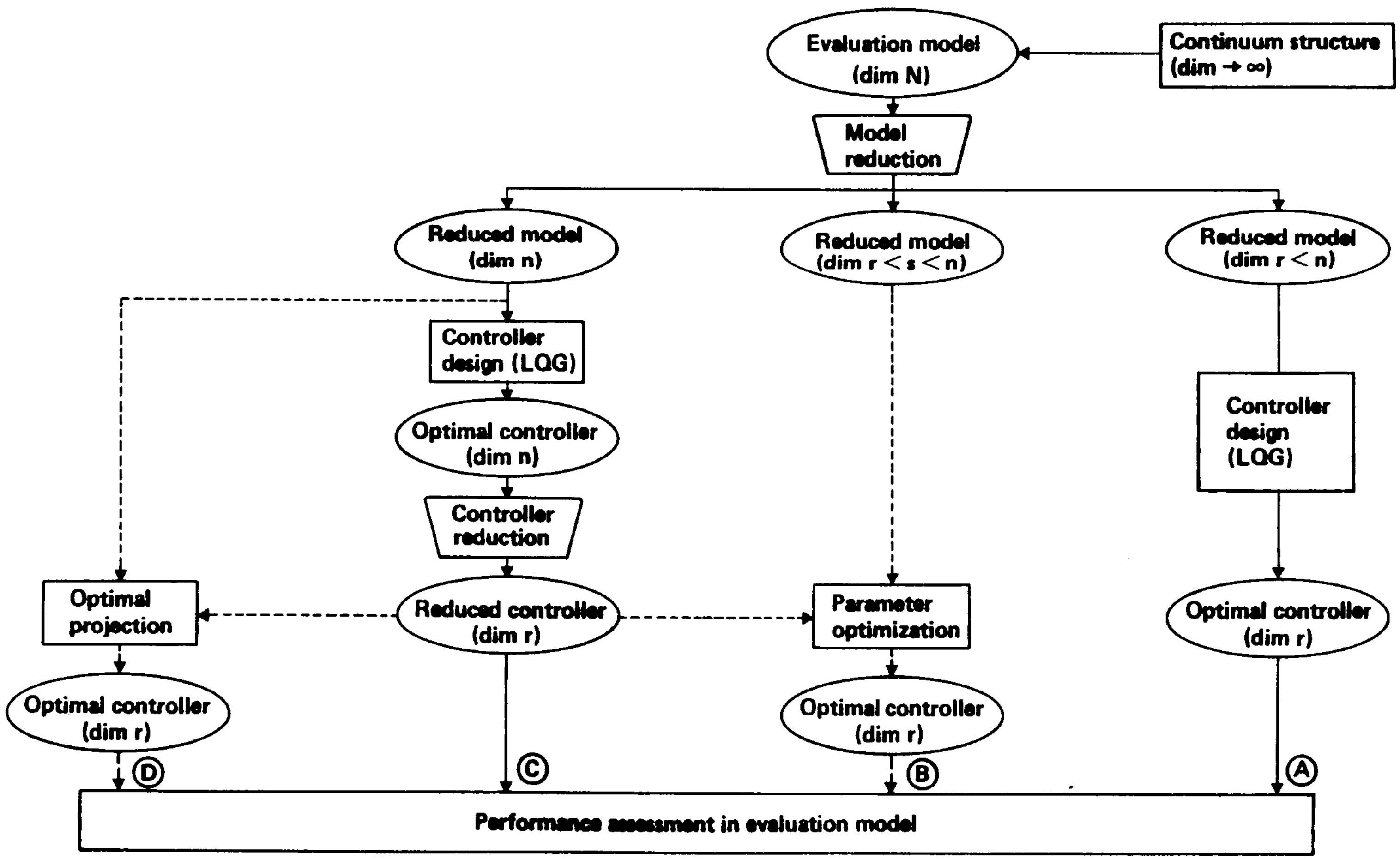

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Low Order Controller Methods/Attributes Comparison

The methods and attributes comparison for the controller synthesis techniques of the previous chart is shown on the facing page. This chart should be viewed and discussed in juxtaposition with the previous chart. The key points for each of the attributes are highlighted as follows.

Model Order

Model order refers to the order of the structural model used in controller design. The model order should be high enough to accommodate the dynamics which significantly impact the control objectives. This usually implicates a model of very high dimension when the controller pass band has strong interaction with the structure over a wide range of frequency.

Controller Structure

Controller structure refers to the various dynamic functions the controller will accommodate viz., integral control, proportional plus derivative, direct output feed back, etc. In a parameter optimization scheme, virtually any controller structure can be realized. In a standard LQG structure, additional variety is best obtained by frequency shaping the quadratic criteria in the integral expression for the cost index.

Controller Stability

The controller is stable if all of its poles are in the left half of the s plane. This criterion is important because it is generally observed that systems with unstable controllers do not exhibit good robustness properties and are particularly sensitive to parameter variations.

Computing Burden

In the synthesis of a controller, it is desirable that the algorithm not utilize numerical search procedures that require special expertise. This is tantamount to the requirement for user friendliness. If the control problem is difficult (because of coupling and ill conditioning) and the initializing guess is poor, numerical procedures do not represent a viable cost effective tool.

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Large Space Structures Control Low Order Controller Methods/ Attributes Comparison

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Methods / Attributes	Closed loop			Open loop
	D Optimal projection	C Sub-optimal projection	B Parameter optimization	A Low order LQG
Model order	High	High	Low	Low
Controller structure	Limited	Wide range with frequent shaping	Unlimited	Wide range with frequent shaping
Closed loop stability guaranteed	Yes	No	Yes	No
Controller stability guaranteed	Yes	Yes	No	No
Computing burden	Medium	Low	Very high	Low

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Fixed Order Robust Controller Design Techniques

The diagram on the facing page shows various methods for introducing uncertainty into the controller synthesis procedure. The methods are succinctly stated in the comments accompanying the diagram. The competing methods are also identified as closed loop or open loop. Methods B, C, D include uncertainty as part of controller synthesis and therefore constitute closed loop methods. Robustness analysis after controller synthesis (Method A) is an open loop procedure.

The design procedure described in this discussion is summarized as follows. Structure model reduction is accomplished by the method of component cost analysis with white noise introduced at the inputs. The noisey inputs may constitute either disturbance or actuator forcing terms. Model surveys should be performed with both types of inputs to properly identify the important modes with respect to disturbability, controllability, and observability. Internal balancing with respect to the "abilities" is also effective and should be used in conjunction with component cost analysis to give a comprehensive model survey.

Controller synthesis is accomplished by the method of suboptimal projection. The preferred method is q-COVER which is an acronym for Covariance Equivalent Realization of order q. This method will be highlighted in the presentation to follow.

Controller design with uncertainty is most effectively accomplished by introducing the variation of parameters into the reduced order model. This is accomplished by deriving additional states which model state trajectory perturbations or state sensitivities with respect to the set of parameter variations. The objective is to design a controller using quadratic synthesis which is "desensitized" with respect to the parameter variations. The resulting controller should give the best tradeoff between performance degradation and sensitivity to uncertainty.

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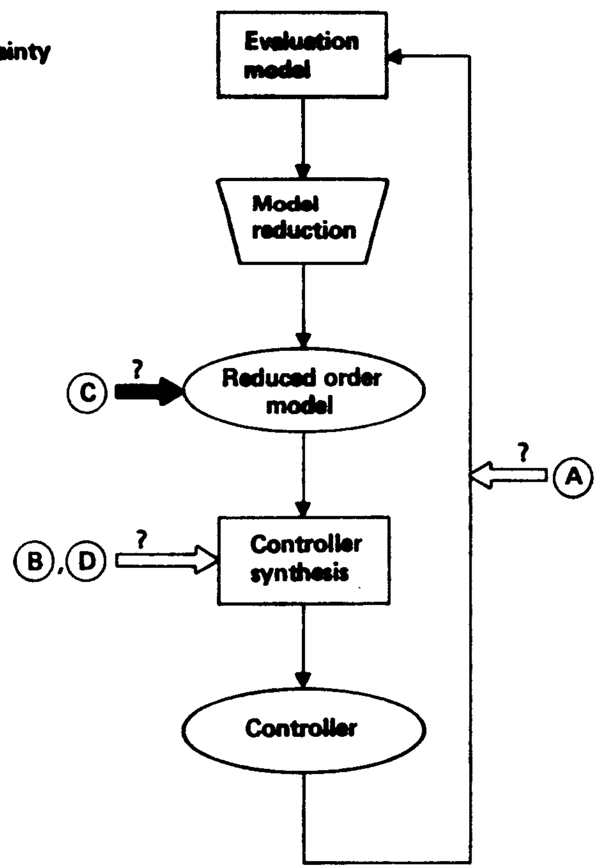
Robust Controller Design Techniques

? = uncertainty



Open loop	(A) Robustness analysis after nominal controller derived
Closed loop	(B) Weight discrete cost function with probability of a given plant state (C) Introduce trajectory sensitivity (parameter gradient states) and standard LQG format along with nominal control and state variables (D) Introduce probability density of parameter variations in LQG format

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Generalized LQG Compensator Design

The diagram on the facing page shows a generic configuration for the flexible structure with compensator along with the dynamics of the compensator. Also shown are the realization equations for the flexible structure and the compensator along with generalized quadratic criteria used to synthesize the regulator and filter. The LQG design methodology exploits the separation principle which states that the regulator and filter can be designed as independent elements in the event that process and measurement noises w and n are additive. The key matrices emerging from the synthesis are the Riccati matrices for the regulator and filter designated P_r and P_f, respectively.

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Generalized LQG Compensator Design

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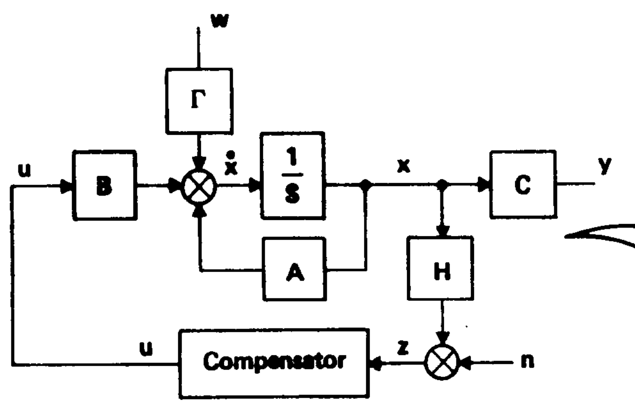
$$\dot{x} = Ax + Bu + \Gamma w$$
$$y = Cx$$
$$z = Hx + n$$

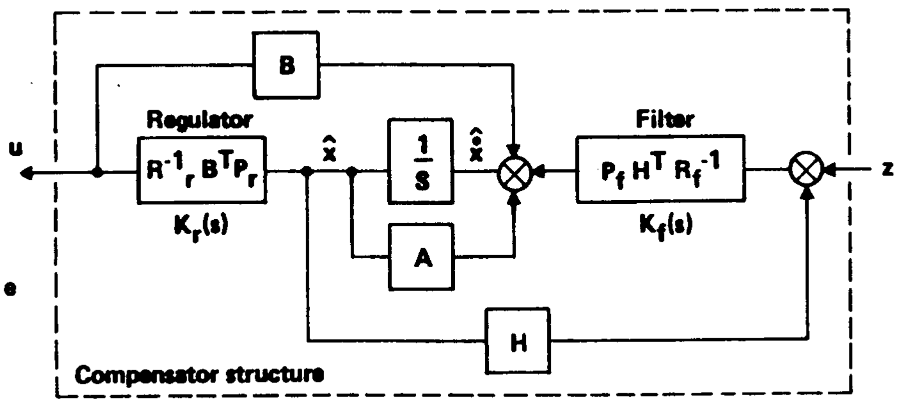


Regulator design

$$J_r = \min_u \int_0^\infty (y^T Q_r y + u^T R_r u)\, dt$$

Filter design

$$J_f = \min_w \int_0^\infty (z-Hx)^T Q_f (z-Hx) + w^T R_f w \, dt$$



$$\dot{\hat{x}} = A_c \hat{x} + K_f e$$
$$u = -K_r \hat{x}$$
$$A_c = A - BK_r$$
$$e = z - H\hat{x}$$

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Large Space Structure Control

Projection Defined

The method of controller reduction by projection is outlined on the facing page. The objective is to compute matrics T_L (qxn) and T_R (nxq) such that the full order compensator [A_c, K_f, K_r] of order n is reduced to [A_{cq}, K_{fq}, K_{rq}] of order q by the transformation indicated. The matrix $H = T_R T_L$ is called a projection matrix, and is such that its rank i.e., the number of independent rows (columns) is exactly q, the order of the reduced compensator.

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Large Space Structure Control
Projection Defined

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Purpose
- Distill maximal performance from the full order and project into a space of smaller dimension

Projections
- Given the compensator realization $\left\{ A_c, K_f, K_r \right\}$ order n

$$A_{cq} = T_L A_c T_R \qquad T_L \in R^{q \times n} \quad T_R \in R^{n \times q}$$

$$K_{fq} = T_R K_f \qquad T_L T_R = I_q$$

$$K_{rq} = K_r T_L \qquad \text{Rank} \left\{ T_R T_L \right\} = q$$

- Realization $\left\{ A_{cq}, K_{fq}, K_{rq} \right\}$ is of order $q < n$

$H = T_R T_L$ the "projection" matrix

Large Space Structure Control

Projection Methods

The selection of a projection algorithm is required in order to compute matrics T_R, T_L. In projection theory, it is desired that the reduced system preserve certain attributes of the full order system. The two methods outlined on the facing page are excellent examples of what is considered to be the most efficient open and closed loop model reduction algorithms. The Riccati balancing method derives a transformation S which balances disturbability and observability measures P_f and P_r to the extent that the singular values in the transformed coordinates are equal. The transformation then isolates those states which are most difficult to control and observe. The method is open loop because the states retained may not contribute to the closed loop control objectives.

The q-COVER method derives a transformation S that renders (A_c, K_f) and (A_c, K_r) disturable and observable. The reduced order system resulting from this process guarantees to match q covariance derivatives and the first q Markov parameters of the full order system. Thus, both the steady state covariance response and the high frequency system response are preserved up to order q. The method is closed loop because the matching process is performed on the entire controller as an entity, which was derived from closed loop objectives.

Large Space Structure Control Projection Methods

Ricatti balancing (open loop)

- Derive a transformation S such that

$$S^{-1} P_f S^T = S^T P_r S = \Sigma$$

$$\Sigma = \text{diag} [\sigma_1, \ldots, \sigma_n]$$

- Compensator is balanced with respect to disturbability (P_f) and observability (P_r)
- Construct T_L, T_R from S corresponding to largest σ's
- Open loop because states retained may not contribute to closed loop control objectives

q-COVER (closed loop)

- Derive a transformation S that renders (A_c, K_f), (A_c, K_r) controllable and observable
- Derive T_L, T_R such that (A_{cq}, K_{fq}, K_{rq}) matches q steady state covariance derivatives and the first q Markov parameters of the full order system

Large Space Structure Control
Tetrahedron Open Loop Frequency Response

The goal in the design of this model was to emulate the characteristics of a typical space structure while keeping the order of the problem small (less than 20 modes). The performance criterion for this system is the transverse (x,y) motion of node 1 at the apex of the tetrahedron. This is analogous to the line-of-sight error performance measure of typical large space structure optical systems. The tetrahedron is supported by six legs, which are pinned to the ground. Masses are lumpted at nodes 1 through 4, and the truss elements are capable of supporting only axial loads.

The resulting structure has 12 modes of vibration. The open-loop disturbance response at the apex, to transverse forces F_x, F_y is shown for the first eight modes on the facing page. The last four modes were considered unknown so that robustness to neglected high-frequency dynamics could be evaluated. Control and observation were limited to placement of linear force actuators and rate and position sensing in the supporting legs.

This is a difficult control problem because the vibration modes dominating apex motion are only weakly controllable and observable from the base structure. The modes which dominate apex transverse vibration are the first, second and fourth as shown.

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Large Space Structures Control
Tetrahedron Open Loop Frequency Response

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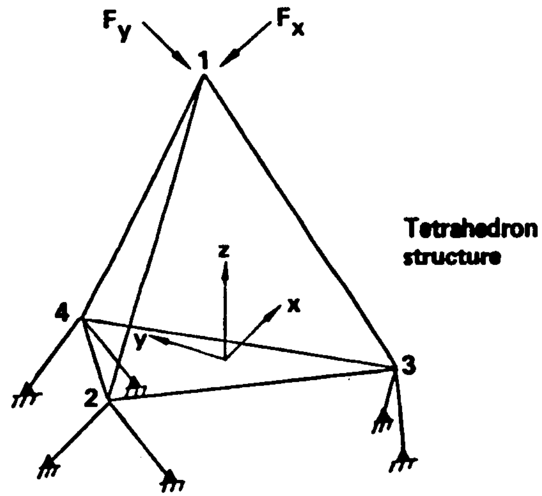
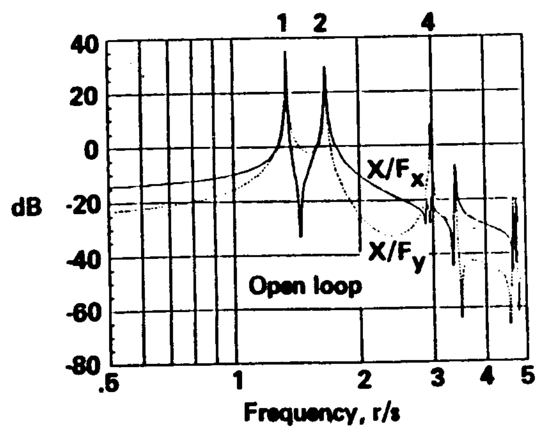
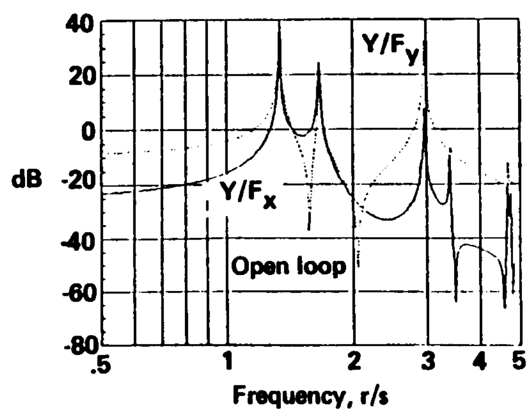
Mode	W_n
1	1.342
2	1.665
3	2.891
4	2.957
5	3.398
6	4.204
7	4.662
8	4.755
9	8.539
10	9.251
11	10.285
12	12.905



Tetrahedron structure





Large Space Structures Control
Tetrahedron Component Cost Analysis

Modal rankings as a function of mode number for V_n and V_δ are drawn on the facing page. Sensors (position + rate) and actuators are colocated in all cases. It is noted that with the exception of Mode 4, the impulsive and white noise evaluations give similar results for observation and control in two legs. For control and observation in multiple legs, cancellations in the row elements of the B matrix induce dropouts in the modal rankings of V_δ. Modal rankings for white noise measure V_n clearly give the correct indication of controllability and observability and analysis of Mode 7 shows that V_δ gives erroneous conclusions regarding these measures. The modal matrix in conjunction with the B matrix shows that Mode 7 is highly controllable and is dominated by z translations of masses 3 and 4 <u>in opposite directions</u>. Therefore to induce the presence of Mode 7 in V_δ for control at nodes 2, 3 and 4, the impulses would require appropriate scaling. For a complex structure with multiple controls, choice of the weights on the delta functions is not straight-forward.

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Tetrahedron Component Cost Analysis

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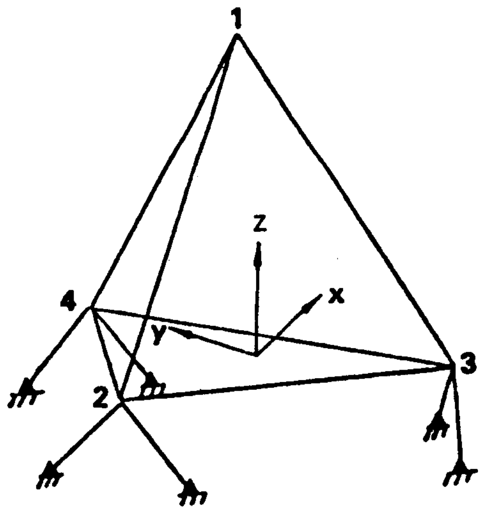

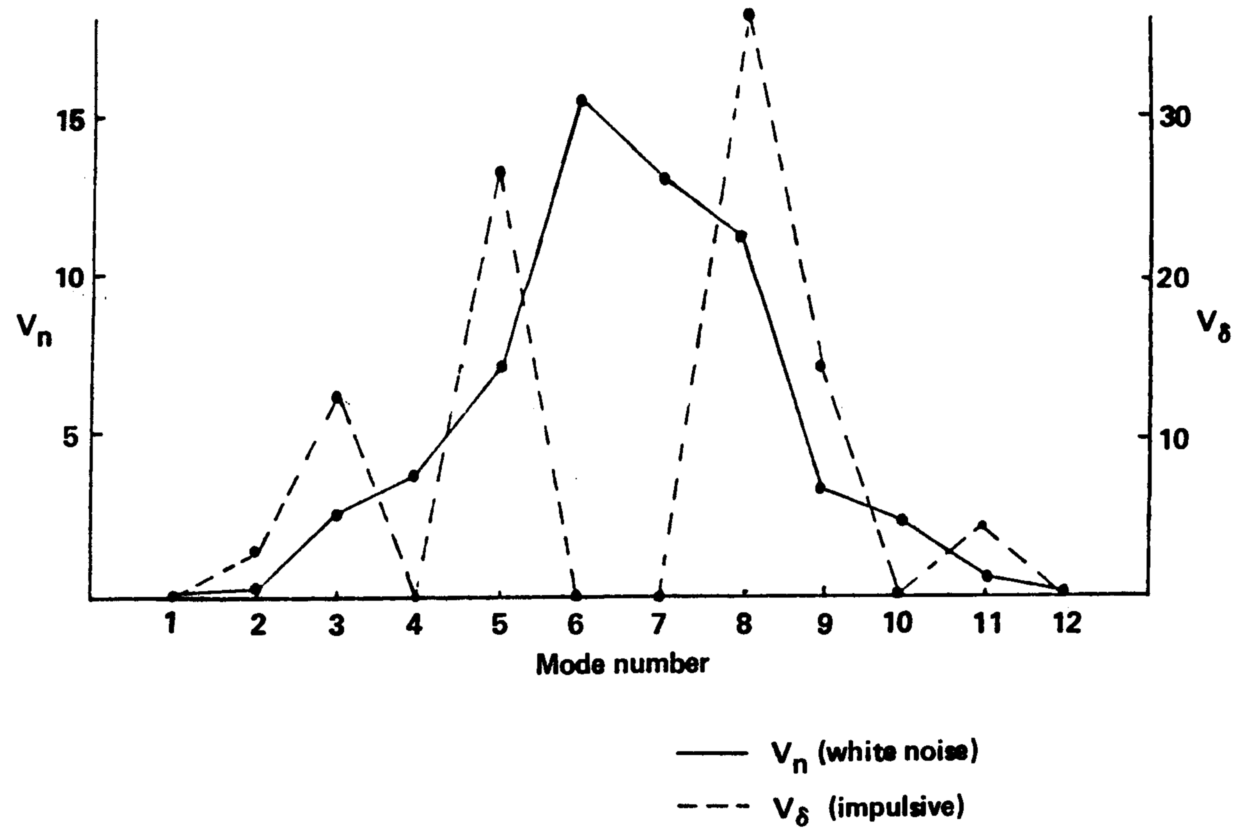

Large Space Structures Control

RMS Comparison of Low Order Controllers

The rms performance comparison for the balancing technique (RB) developed from the separat theorem (certainty equivalence principle) and COVER theory is shown on the facing page. Performance is quantified in terms of rms output at the apex of the structure vs. rms control effort. The plot on the left shows the performance of RB relative to the full 16^{th} order LQG controller, for RB controller orders of 6 and 4. The 6^{th} order controller closely matches the full order LQG. However, the performance 4^{th} order controller is poor and closed loop response was unstable for gain slightly greater than 10. The plot on the right shows the performance of RB relative to COVER with LQG as the standard for absolute comparison. This data is very revealing and the following conclusions are highlighted. It is noted that closed loop response for both the 4^{th} and $6t^{h}$ order COVER controllers is stable even for high gains where there is essentially no improvement in output performance for additional expenditure of controller effort. Additionally, for high gains the 6^{th} order controller requires more control effort than the 4^{th} order controller to achieve essentially the same rms performance. Clearly the 6^{th} RB gives superior performance for this particular application. Comparing the 6^{th} order COVER results with that of the 6^{th} order RB shows that the COVER controller performed poorly for low gain. However, near the knee of the curves the 6^{th} order COVER performance is comparable with the 6^{th} order RB and the 4^{th} order COVER closely matches the 6^{th} order COVER performance.

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RMS Comparison of Low Order Controllers

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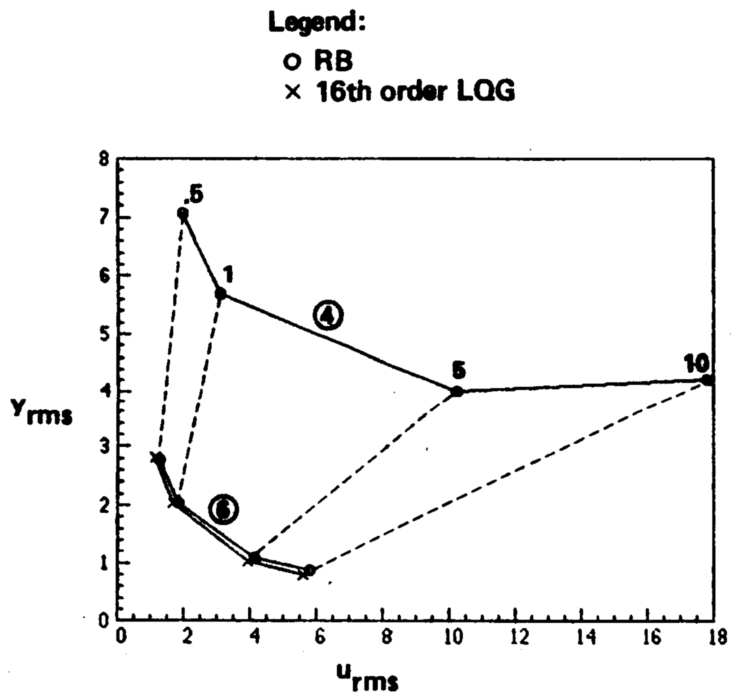

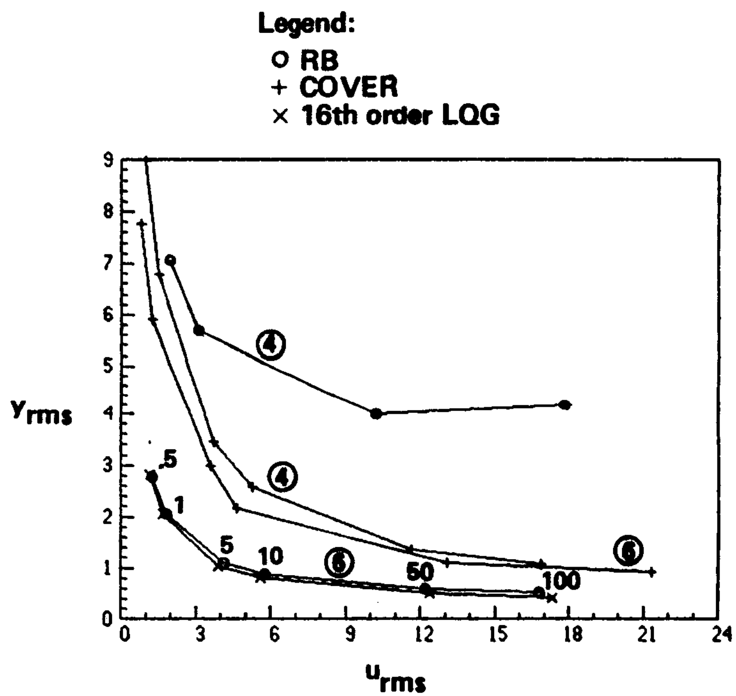

Large Space Structures Control

Comparison of Low Order Controllers

The closed loop frequency response of 6^{th} order RB and 4^{th} order COVER for a gain of 10 is shown on the facing page. Again the comparison is made with respect to the 16^{th} order LQG controller. The data indicates that the 6^{th} order RB controller matches the 16^{th} order LQG very closely. However, the 4^{th} order COVER controller exhibits considerable residual with respect to the controlled modes.

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Comparison of Low Order Controllers

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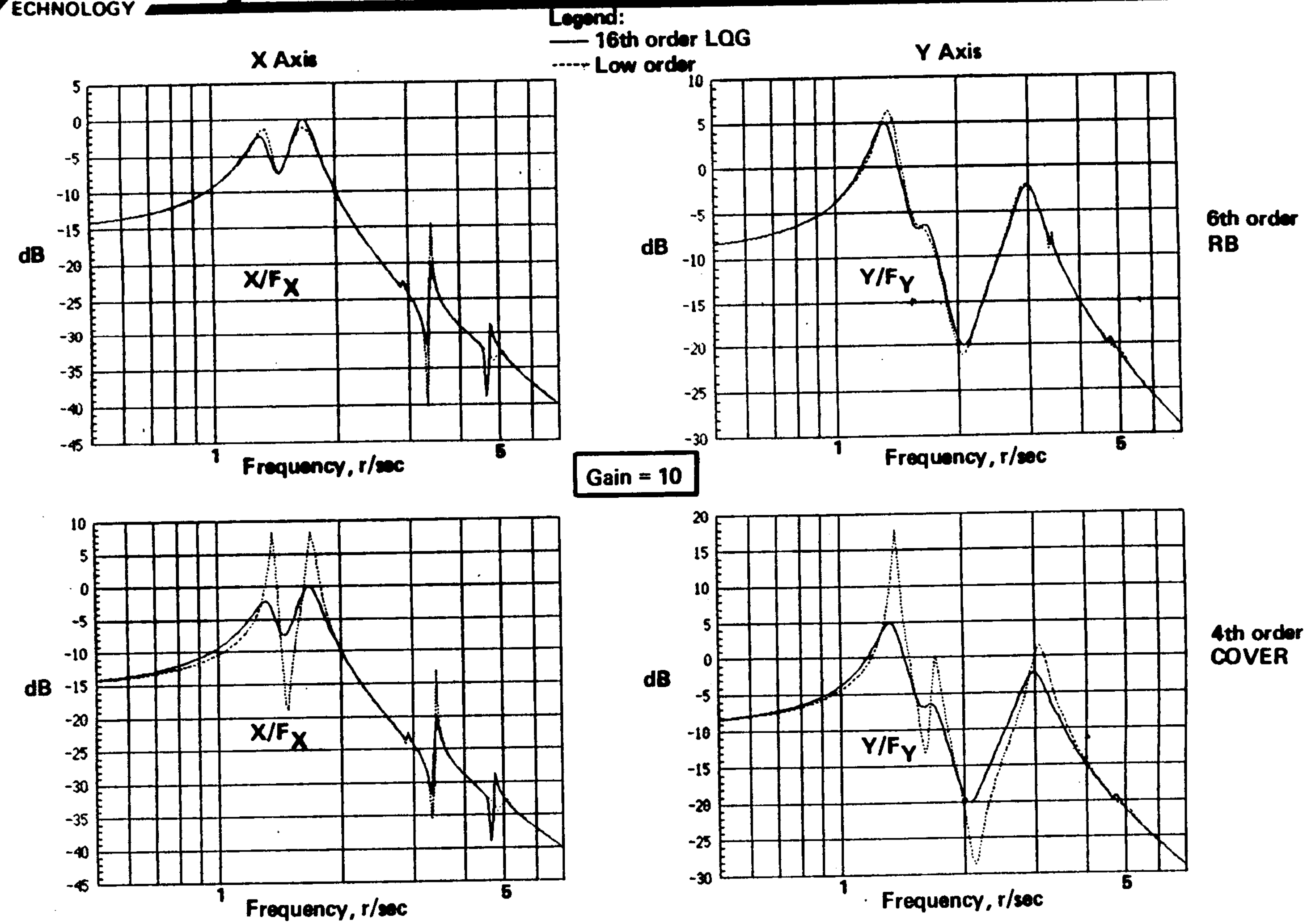

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Comparison of Low Order Controllers

The closed loop frequency response of 6^{th} order RB and 4^{th} order COVER for a gain of 100 is shown on the facing page. The comparison is made with respect to the 16^{th} order LQG controller. It is noted that as the gain increases the COVER controller is improving relative to 16^{th} order performance; the 6^{th} order RB is correspondingly degrading.

Comparison of Low Order Controllers

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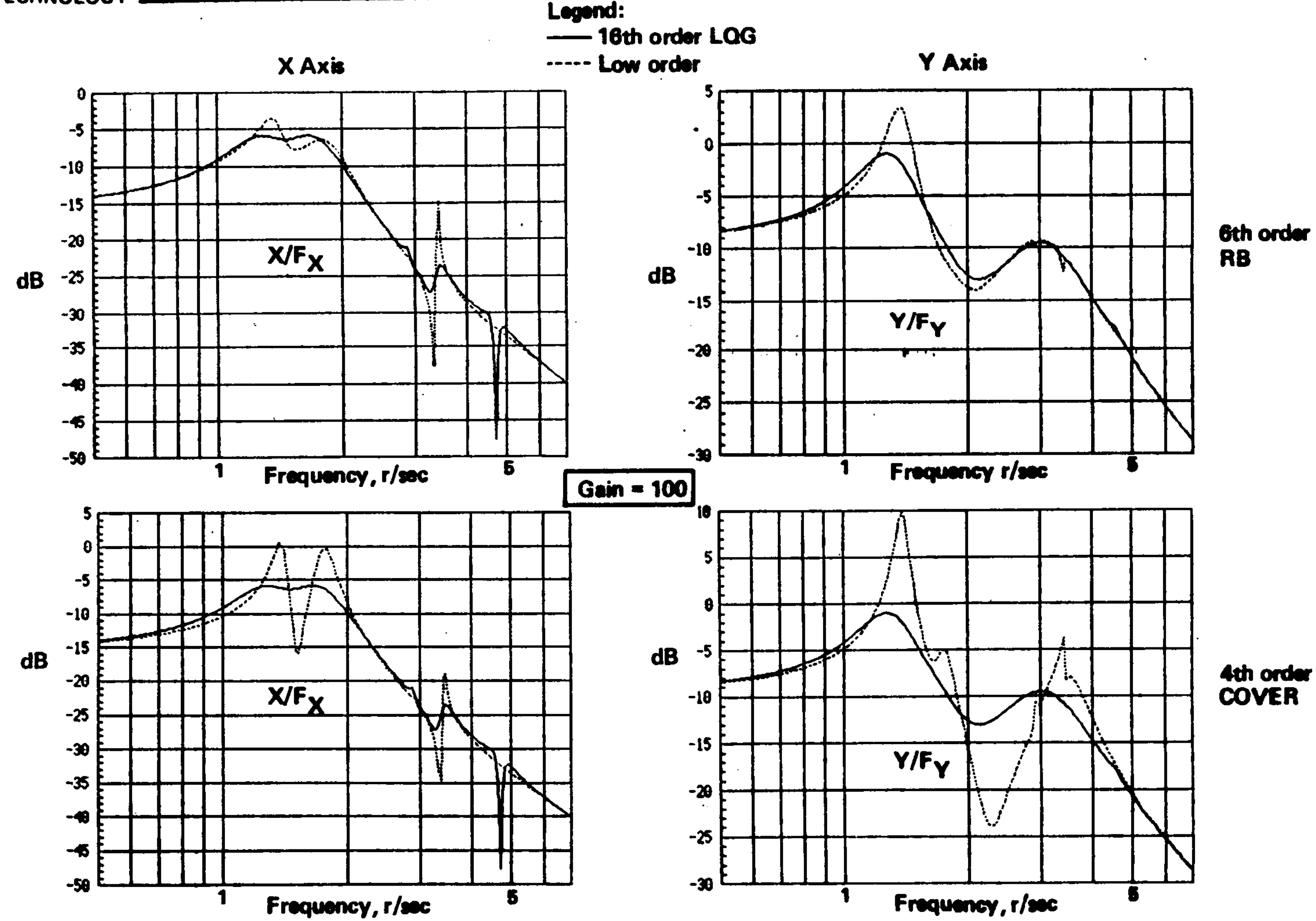

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Comparison of Low Order Controller

A singular value comparison of the 4^{th} order COVER and 6^{th} order RB controllers with respect to the 16^{th} order LQG is shown on the facing page. Singular values of $I + (KG)^{-1}$ give a sufficient condition for stability for multiplicative uncertainty. In particular, the proximity of the minimum singular value ($\underline{\sigma}$) of $I + (KG)^{-1}$ to zero gives an indication of impending instability. This measure is extremely conservative, However, controller design comparison can be made with meaningful results. The comparitive results indicate in a general sense that over the range of frequency fcr which the controllers were designed, the low order controller is more robust to multiplicative uncertainty than the full order controller. The exception is the large peaks at frequencies indicated in the frequency response plots. These are modes that do not contribute to the motion of the apex. However, the data indicates a significant degradation in robustness at these frequencies.

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Comparison of Low Order Controllers

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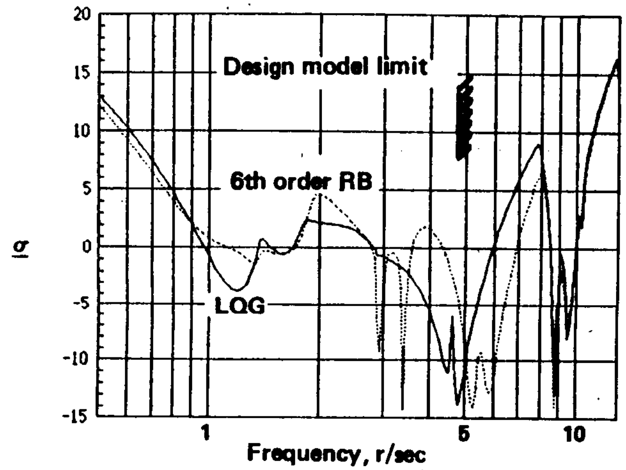

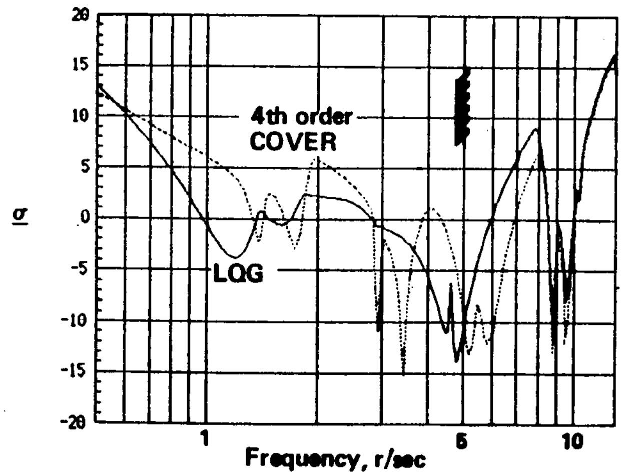

Gain = 100

$\underline{\sigma} = \min_{sv} [\, I + (KG)^{-1} \,]$

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Time Response Comparison

A time response comparison for the low order controllers of interest are shown on the facing page. The key item to note is that increasing the gain from 10 to 100 brought no increase in rms performance. However, the settling time is significantly improved. It is noted however, that the disturbance environment for structures that require CSI technology is usually wide band and random in nature. Thus rms performance considerations make more sense than criteria developed from impulsive or constant frequency disturbance sources.

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Time Response Comparison

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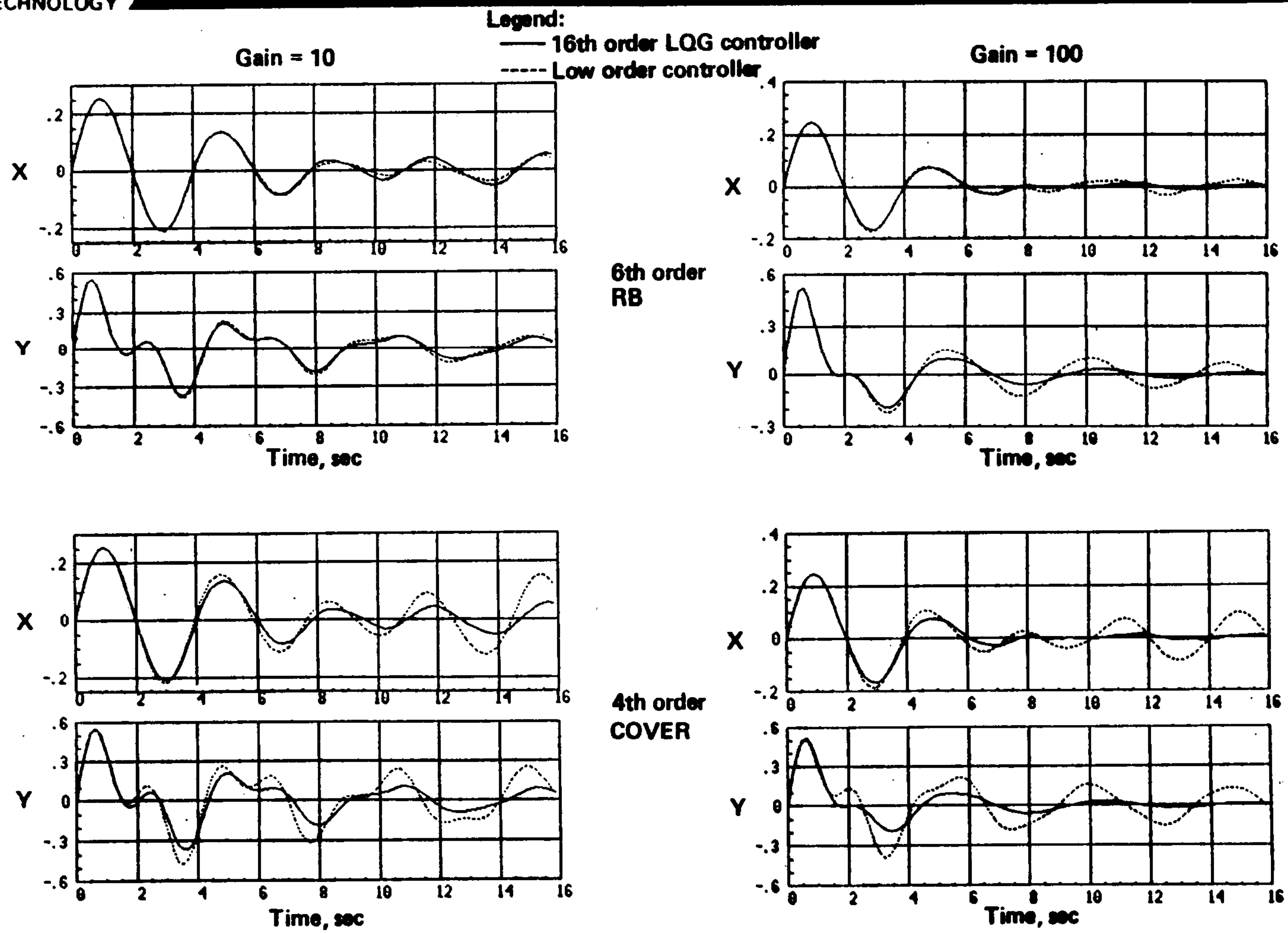

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Singular Value Comparison

The singular value plots on the facing page give a relative performance comparison of 6^{th} order RB controllers for a gain of 10 and 100 respectively. It is noted that the low gain controller is absolutely more robust than the high gain controller. However, the low order controller for the high gain case is relatively more robust to the full order LQG controller than the low gain counterpart.

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Singular Value Comparison

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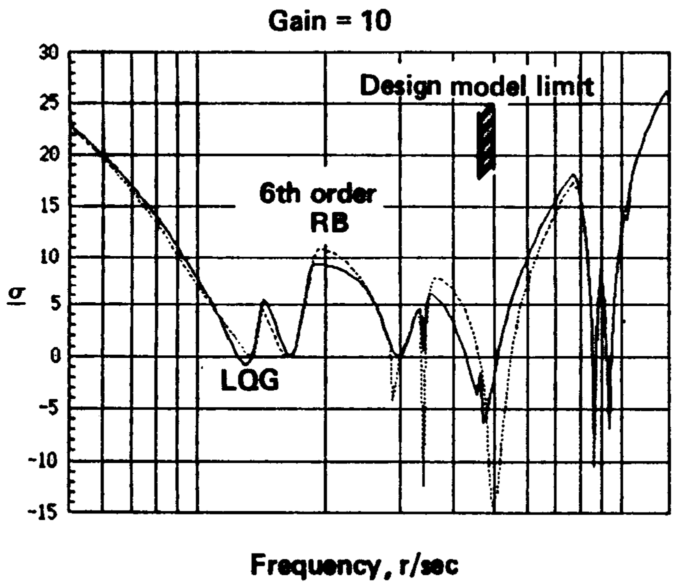
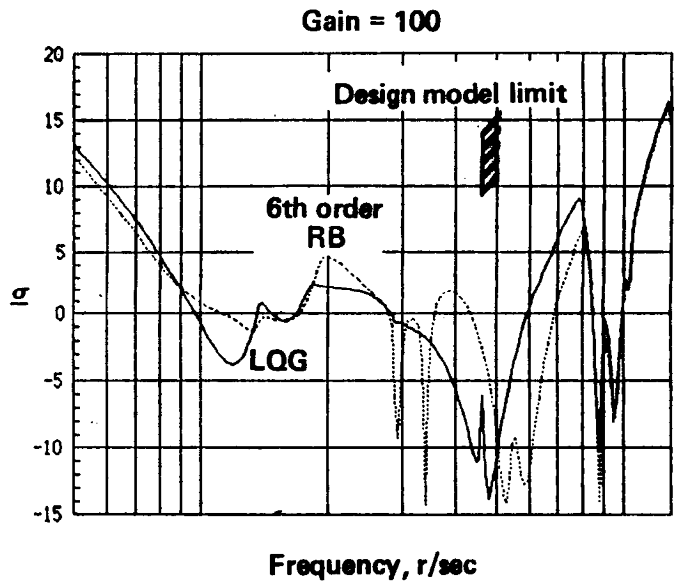
$$\underline{\sigma} = \min_{sv} \left[I + (KG)^{-1} \right]$$





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Conclusions

The conclusion of the study regarding fixed-order controller design along with basic considerations and observations for structural modeling in control applications is given on the facing page.

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Control of Flexible Structures
Conclusions

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Fixed order controller design

- Model reduction crucial to performance and robustness of closed loop system
- Preferred controller synthesis for highly complex structures is to design high order controller and reduce by projection methods
- q-COVER is the preferred suboptimal projection method for controller reduction
- Frequency shaping in quadratic synthesis of the compensator structure can substantially improve efficiency and performance of LQG designs
- Classified SISO do not accurately represent stability and performance characteristics of structures as multivariable systems
- Singular value decomposition effective for comparative controller robustness assessment but is not a good diagnostic tool