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SYSTEM IDENTIFICATION AND MODELING
FOR CONTROL OF FLEXIBLE STRUCTURES

Edward Mettler

and

Mark Milman

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

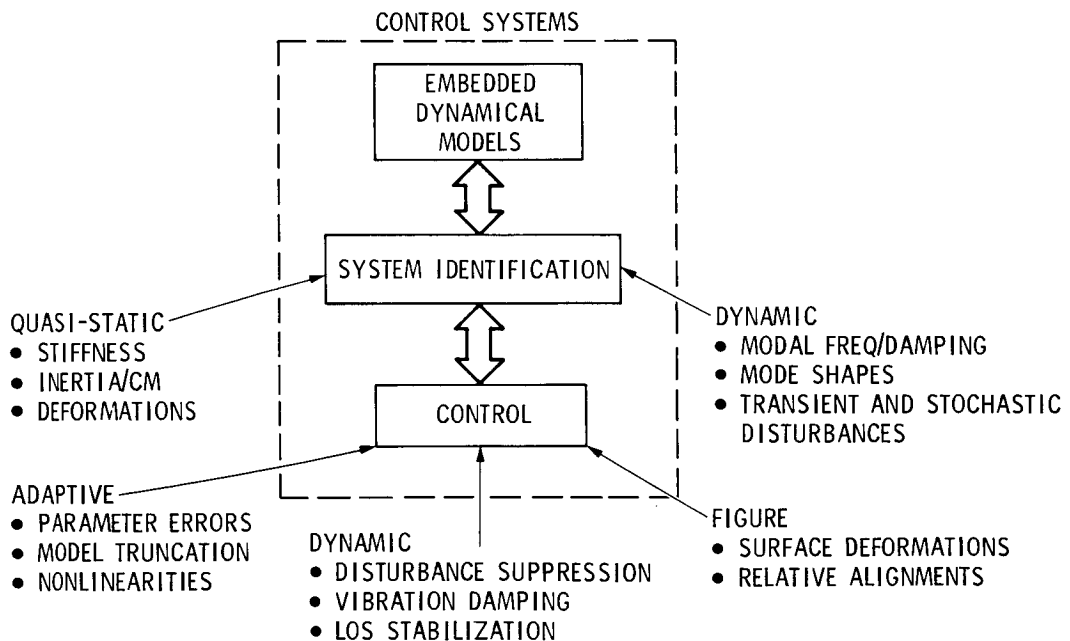# LARGE SPACE STRUCTURES ACTIVE CONTROL

High performance control systems for flexible structures which provide adequate robustness require synthesis techniques that incorporate the interdependencies between performance objectives and model fidelity. Such levels of fidelity are not possible to achieve via ground testing alone. This is due to the fact that differences in ground and space environments can significantly change the measured parameters. In addition, the time-varying nature of the space environment requires real-time "tracking" of key structural parameters.

An on-orbit ID function can provide the real-time knowledge of plant characteristics which greatly influence control performance, such as flex-body parameters, self-generated disturbances, shape distortions, actuation and sensing dynamics, etc. This information is then available for updating the controller plant model, and may serve as the data base from which a control function can make adjustments to autonomously tune the system performance and stability margins.[1]

In this discussion, the focus will be on those identification and modeling aspects primarily associated with large space structure dynamical control.

CONTROL SYSTEMS

EMBEDDED
DYNAMICAL
MODELS

SYSTEM IDENTIFICATION

CONTROL

QUASI-STATIC
• STIFFNESS
• INERTIA/CM
• DEFORMATIONS

DYNAMIC
• MODAL FREQ/DAMPING
• MODE SHAPES
• TRANSIENT AND STOCHASTIC
  DISTURBANCES

ADAPTIVE
• PARAMETER ERRORS
• MODEL TRUNCATION
• NONLINEARITIES

DYNAMIC
• DISTURBANCE SUPPRESSION
• VIBRATION DAMPING
• LOS STABILIZATION

FIGURE
• SURFACE DEFORMATIONS
• RELATIVE ALIGNMENTS

GENERAL FLEXIBLE STRUCTURE CONTROL METHODOLOGY

In general, the high frequency dynamics of LSS will not be well known and the order of the dynamics will be too large to design an effective wideband control system. New methods are required to control the low frequency modes without exciting the higher frequency dynamics inherent in the structure and to constrain the control gains from spill-over into the higher modes causing instabilities or performance loss. This area is a major thrust in the extension of modern control theory and the emerging cross-discipline technology of active structural control covers a wide range of interrelated design and system functions.

As depicted below, the general structure control methodology is to phase stabilize modes lying within the control bandwidth (in-band modes) and to gain stabilize structurally damped modes lying outside the control bandwidth. Such active control methods require very precise knowledge of the locations of the in-band modes in order to allow correct phase stabilization (such sensitivities are even more pronounced when actuators and sensors are non-colocated). Because such precise knowledge of system dynamics is not possible via ground testing alone, on-orbit system identification is required.


(PRECISE KNOWLEDGE OF IN-BAND MODES
NEEDED FOR PHASE STABILIZATION)
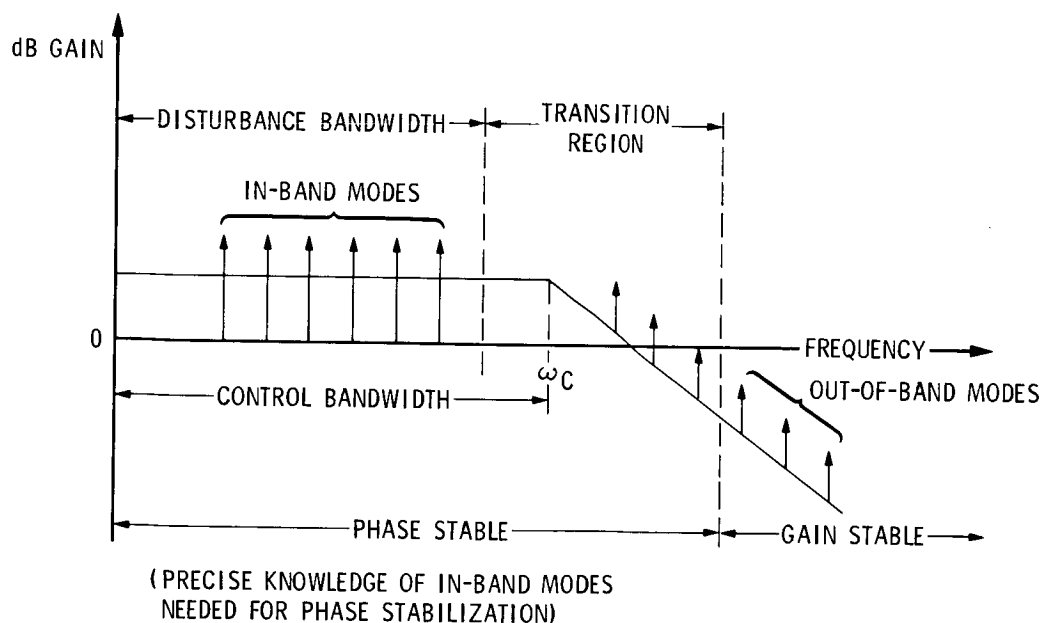
DISTRIBUTED PARAMETER MODELING, APPROXIMATION AND CONTROL

Control design for distributed parameter systems introduces a number of complexities that are either not present or relatively innocuous in the design process for lumped systems. A most fundamental issue is selecting an appropriate reduced order model so that system performance objectives can be met. As is well known, a poor selection can severely degrade performance and in some cases yield closed loop instabilities. Under reasonable hypotheses on the finite dimensional approximation schemes, the distributed parameter LQG design approach utilizing a functional gain convergence criterion achieves a correct match between model order and desired performance[2]. In addition, LQG also has the desireable property that new physical objectives are easily incorporated into the design process through the state-cost functional.

We have successfully applied this distributed parameter LQG design methodology to large-scale simulations of control systems for flexible struc-tures. The chart below contains time history plots of controller performance based on this approach. Because a functional gain convergence criterion is used, these controllers are very near optimal for the full distributed parameter system.
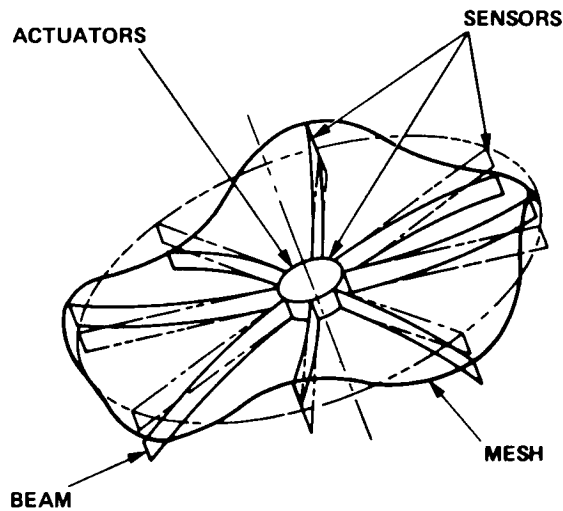

DISTRIBUTED PARAMETER ANTENNA POINTING
AND VIBRATION CONTROL SYSTEM
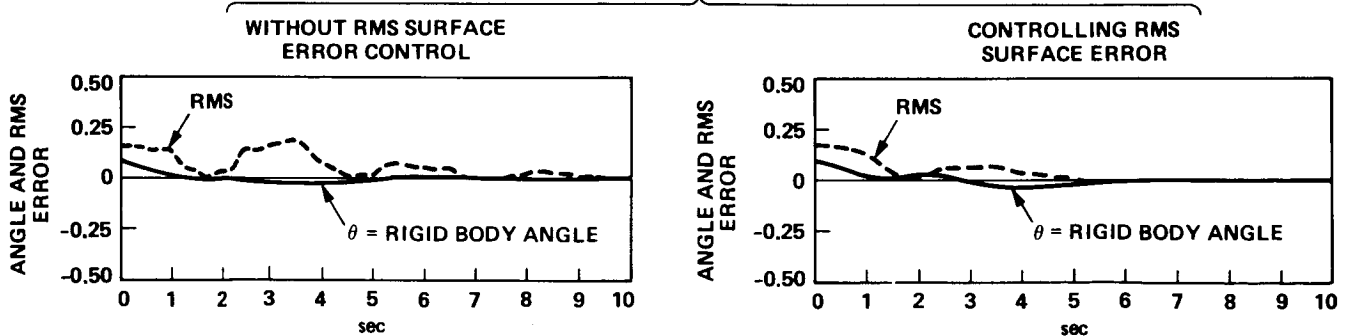
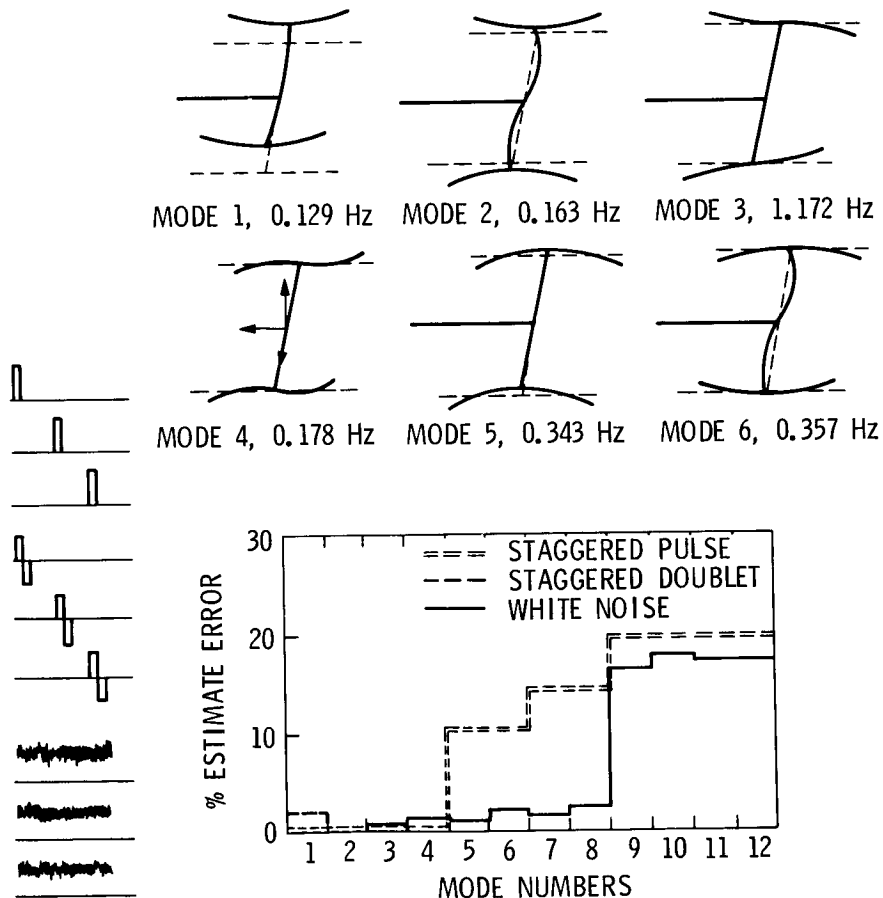# ON-ORBIT SYSTEM DYNAMICS IDENTIFICATION METHODOLOGY

The need for developing a system identification (ID) on-orbit methodology is driven by practical considerations. The post-launch changes in a physical system's characteristics must first be identified before the mission operations proceed with confidence; structural dynamics identification is essential for accomplishing active vibration control of large structures; and system characterization in space is required to verify the accuracy and adequacy of ground-based models for predicting and modifying in-flight performance.

The technical challenges involved in performing on-orbit identification are significant. As opposed to ground testing which involves elaborate test beds with virtually unlimited sensing, excitation, and computational resource, the on-orbit situation is constrained to only a few sensors, operationally viable excitations, and restricted computational resource.[3] The diagram below illustrates the integrated systems approach for on-orbit dynamics identification. The methodology involves a multi-stage identification process starting with robust nonparametric survey methods, and progressing to more refined parameter determination algorithms.
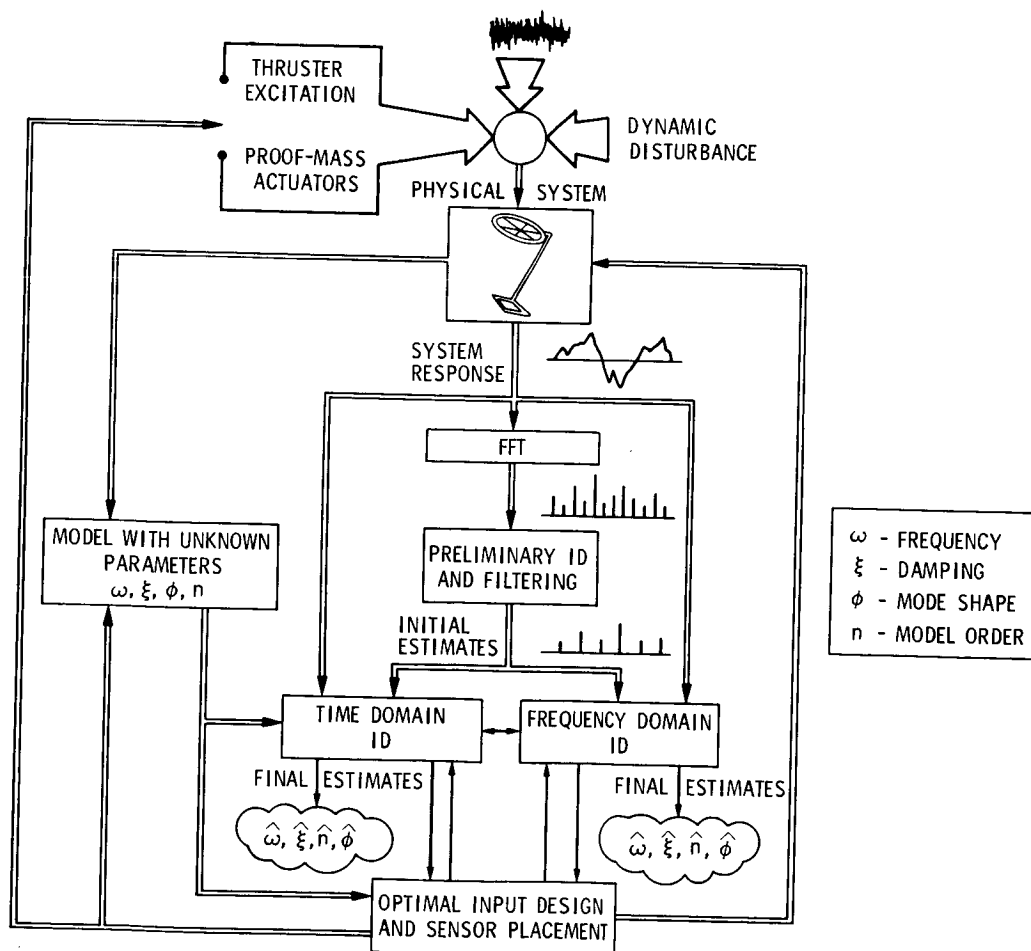
# IDENTIFICATION EXPERIMENT CONSTRAINED INPUT DESIGN

On-orbit identification of modal frequencies of a 15 degree-of-freedom Power Tower model of the Space Station was considered using maximum likelihood estimation. Low frequency modes can successfully be identified by the proper application of multi-directional thruster inputs in the form of force and torques in orthogonal spaces. Higher frequency modes, however, are insufficiently excited to permit accurate estimation due to thruster power and bandwidth limitations. Among the inputs considered, it is concluded that staggered pulse sequences are superior for obtaining a more accurate estimate of the unknown parameters. When staggered thruster pulses are used the identification process may tolerate an initial parameter estimate error of up to 50% of the nominal values for the lower frequency modes. Further research is needed for the identification of modal dampings.[4,5,6]

MODE 1, 0.129 Hz   MODE 2, 0.163 Hz   MODE 3, 1.172 Hz

MODE 4, 0.178 Hz   MODE 5, 0.343 Hz   MODE 6, 0.357 Hz

% ESTIMATE ERROR vs MODE NUMBERS

=== STAGGERED PULSE
--- STAGGERED DOUBLET
— WHITE NOISE

ROBUSTNESS ENHANCEMENT OF LQG CONTROLLERS

Our initial approach to control design utilizes infinite dimensional LQG theory to design compensators that are robust with respect to errors introduced by model truncation. A second error source that requires accommodation are those errors introduced by parameter error. At the present time two approaches have been developed and validated to improve the robustness characteristics of LQG compensators with respect to parameter error. The first approach synthesizes structured uncertainty and loop transfer recovery techniques to achieve a systematic process for making trades between performance and robustness[7]. In terms of synthesis, the method involves adjusting the weighting matrices in both the regulator and estimator portions of the LQG design problem in a way that reflects the structure and magnitude of the modeling uncertainties. This uncertainty information could be obtained from the covariance analysis provided by an on-line identification process. An alternative approach that has also been developed consists of a sensitivity optimization of the eigenvalues of the closed-loop system[8]. A nominal LQG compensator is used to initialize the nonlinear programming problem associated with the optimization. Constraints in the form of stability margins are imposed in the optimization to insure adequate trades between performance and robustness. On the models to which these methods have been applied, both approaches have yielded substantial improvement in robustness over standard LQG controllers.

The chart below illustrates the overall design methodology, and how the sensitivity optimization method can increase observer bandwidth in an LQG compensator and simultaneously increase its robustness properties.
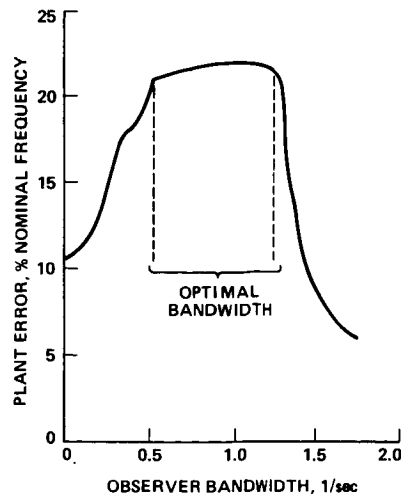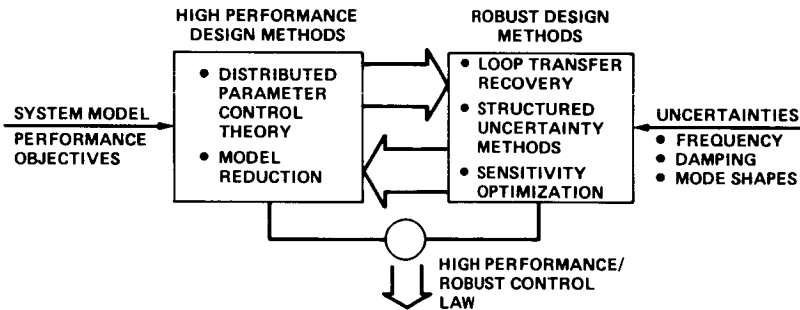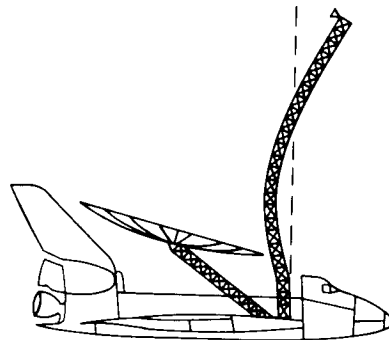
IDENTIFICATION AND CONTROL FLIGHT EXPERIMENTS

A natural progression of technology development, from analysis and simulation through laboratory physical test beds to full scale flight experiments, is basic to major CSI research initiatives. The COFS program and the ATSE (Antenna Technology Shuttle Experiment) provide the means to space test and enable application readiness of advanced identification and control technologies.

The objectives of the ATSE in identification and control have the underlying theme of an integrated system capability to support robust precision stabilization/control of the MSAT (2nd generation 20-meter dish). This can be further described by the following criteria which include operational constraints, system design limitations, in-situ performance maintenance, and synergistic use of identification/control techniques:
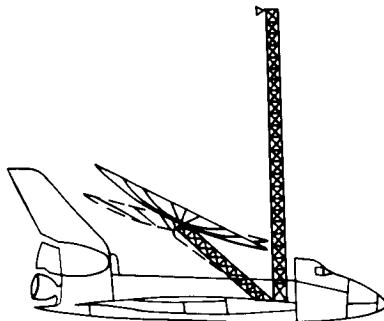
a) Integration of identification with active structure control for LOS stabilization
b) Identification in operational mission time
c) Design for flight system hardware limitations
d) Input design for controlled excitation[9,10]
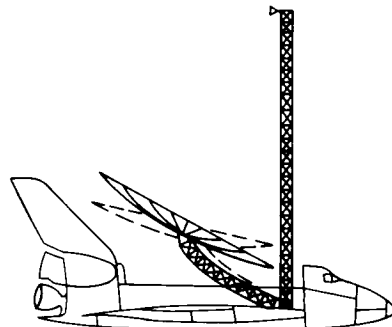e) Unify frequency and time domain techniques for in-flight support
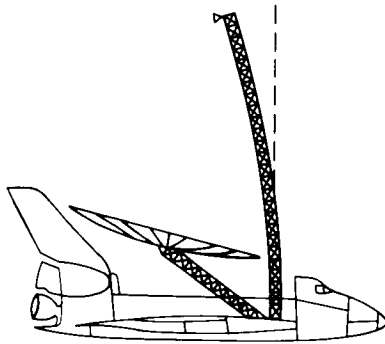
FIRST FEED-BOOM MODE (1.01 Hz)   SECOND FEED-BOOM MODE (6.60 Hz)
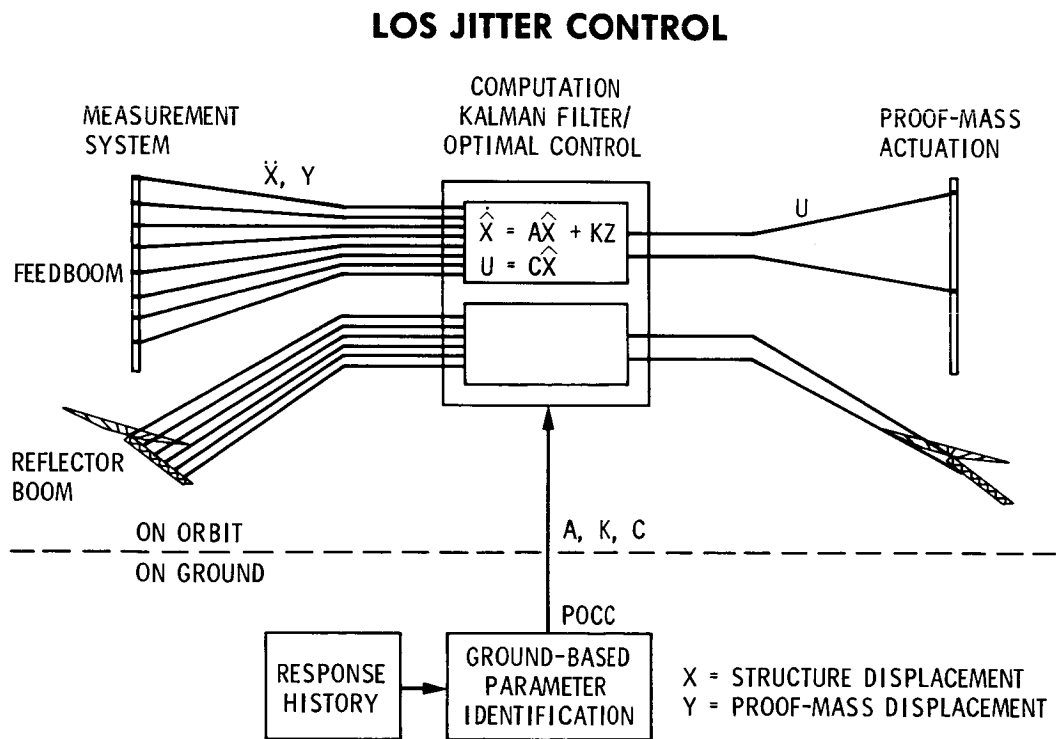
FIRST REFLECTOR-BOOM MODE (2.26 Hz)   SECOND REFLECTOR-BOOM MODE (9.52 Hz)
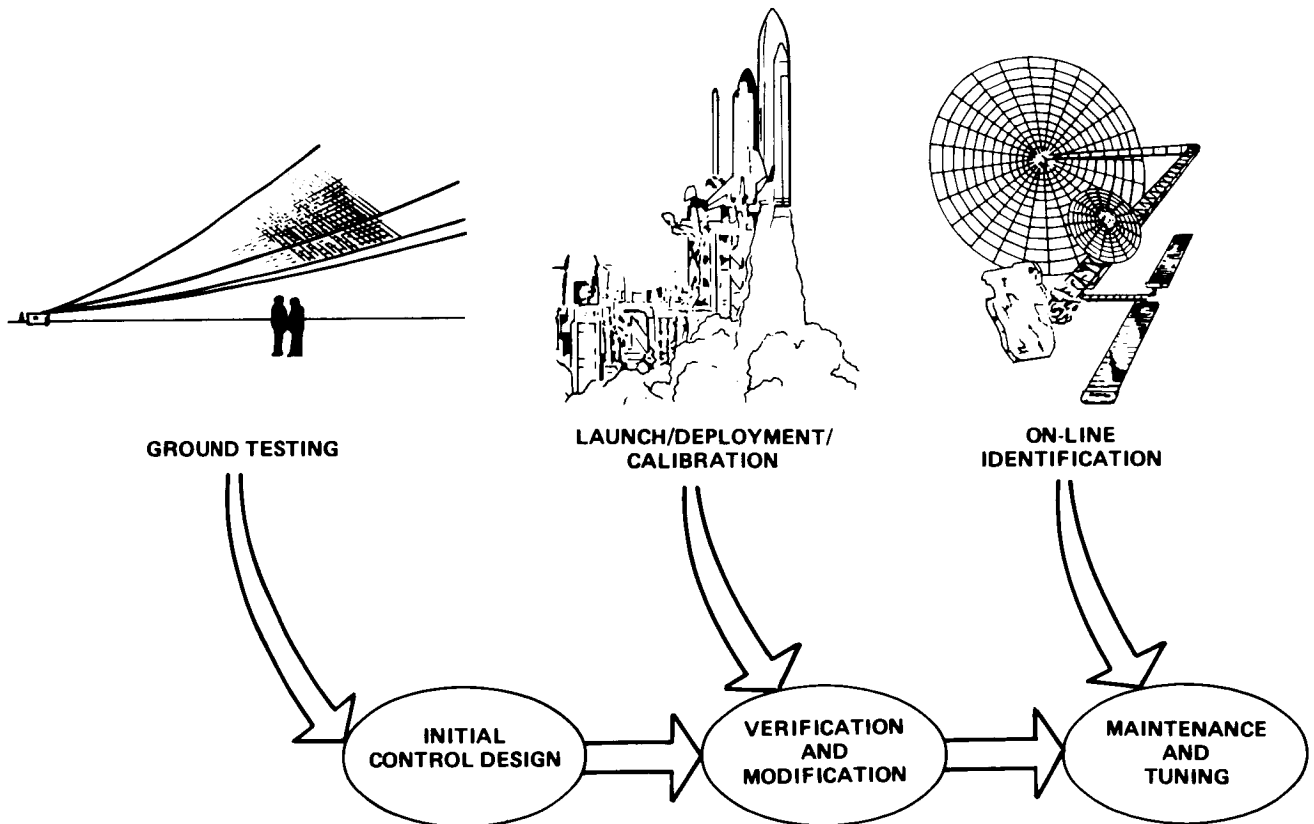
POINTING JITTER CONTROL EXPERIMENT

The objective of this experiment is to control the dynamic motions of both feed boom and reflector boom in order to maintain precision pointing of the feed to dish line-of-sight. Distributed accelerometer signals are processed onboard by selected algorithm options to actively control boom dynamics via proof-mass actuators located at midspan and tip of each boom. Parameter updates from identification processing at the payload operations control center (POCC) are used to tune the controller-embedded reduced order plant models. Both regulation and tracking control policies are to be evaluated in a sequence of sub-experiments.

LOS JITTER CONTROL

MEASUREMENT SYSTEM

COMPUTATION KALMAN FILTER/ OPTIMAL CONTROL

PROOF-MASS ACTUATION

$\ddot{X}, Y$

$\hat{\dot{X}} = A\hat{X} + KZ$

$U = C\hat{X}$

U

FEEDBOOM

REFLECTOR BOOM

ON ORBIT

A, K, C

ON GROUND

POCC

RESPONSE HISTORY

GROUND-BASED PARAMETER IDENTIFICATION

X = STRUCTURE DISPLACEMENT
Y = PROOF-MASS DISPLACEMENT

SUMMARY

We have presented the major components of a design and operational flight strategy for flexible structure control systems. In this strategy an initial distributed parameter control design is developed and implemented from available ground test data and on-orbit identification using sophisticated modeling and synthesis techniques. The reliability of this high performance controller is directly linked to the accuracy of the parameters on which the design is based. Because uncertainties inevitably grow without system monitoring, maintaining the control system requires an active on-line system identification function to supply parameter updates and covariance information. Control laws can then be modified to improve performance when the error envelopes are decreased. In terms of system safety and stability the covariance information is of equal importance as the parameter values themselves. If the on-line system ID function detects an increase in parameter error covariances, then corresponding adjustments must be made in the control laws to increase robustness. In one scenario for example, if the error covariances exceed some threshold, an autonomous calibration sequence could be initiated to restore the error envelope to an acceptable level.

GROUND TESTING   LAUNCH/DEPLOYMENT/   ON-LINE
                        CALIBRATION   IDENTIFICATION

INITIAL CONTROL DESIGN → VERIFICATION AND MODIFICATION → MAINTENANCE AND TUNING

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