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SIMULATION OF SHUTTLE FLIGHT CONTROL SYSTEM STRUCTURAL INTERATION WITH RMS DEPLOYED PAYLOADS

By

Joe Turnball
C. S. Draper Laboratories
Cambridge, MA

ABSTRACT

In support of NASA/JSC, the C. S. Draper Laboratory (CSDL) has implemented a simulation of the system made up of the Orbiter, Remote Manipulator System (RMS), and payload grappled by the RMS. CSDL has used the simulation to study the stability of this overall system when its attitude is under control of the Orbiter's On-orbit Flight Control System (FCS). CSDL has also used the simulation to study the dynamics of the system when the RMS and its associated command software are in active control of the relative Orbiter to payload position and orientation.

The simulation models all of the following elements:

- RMS boom bending (represented by two cubic bending models)
- RMS boom Torsion
- RMS joint gearbox compliance (represented by a non-linear wind-up model)
- Flexibility at the RMS to Orbiter interface
- Flexibility at the RMS to payload interface
- Joint motor dynamics
- Joint servo-loop dynamics
- RMS on-board computer command logic
- Data transfer delays between the RMS sensor and the RMS on-board computer and between the RMS on-board computer and RMS joint servos
- On-orbit flight control nonlinear control logic
- Reaction Control System (both Primary and Vernier) jet forces and moments.

The Draper RMS Simulation (DRS) has close to a decade of development effort behind it. During that time, it has been used to analyze a wide range of RMS questions. Payload weights have run from zero (i.e., an unloaded arm) to weights in excess of the original design limit of the arm (65,000 lbs.). Types of interactions studied have ranged from interactions between failure detection algorithms in the RMS command software and high frequency motor transients to interactions between the On-orbit FCS and the

fundamental bending mode of the composite system with a 20,000 to 20,000 lb payload (.0.05 to 0.2 hz).

For all its complexity the DRS is reasonably economical. A run simulating one minute of real time costs on the order of $10 when run as a low priority over night batch job. Nevertheless, increases in economy can be of benefit for flight control/structural interaction studies which will involve increasing numbers of simulations with longer and longer simulation durations. Consequently, an effort has been under way for the last several years at CSDL on a so called Limited Singing and Dancing (LSAD) simulation that would sacrifice high frequency motor dynamics but retain good representation of bending modes pertinent to the interaction of the On-orbit FCS with the Orbiter/RMS/Payload structural system. LSAD shows approximately a ten-fold increase in economy as compared to similar DRS simulations

Simulation of Shuttle Flight Control System Interaction with RMS Deployed Payloads

A Presentation by Joseph Turnbull to the

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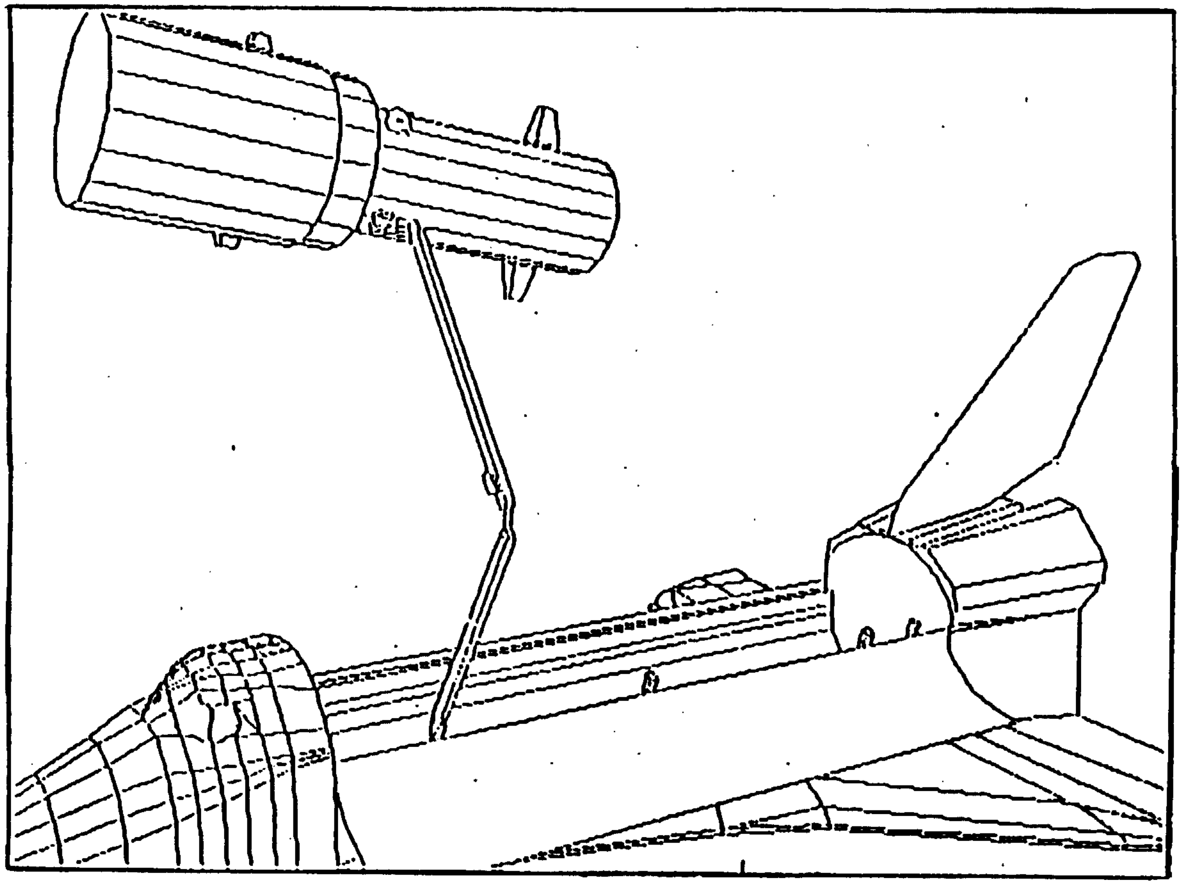
Orbiter / RMS / Payload



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The Draper RMS Simulation (DRS)

Modeled in the DRS are:

- Transverse bending in the long booms

  Two cubic modes each in–plane and cross axis

- Torsion in the long booms

  Modeled as a torsional spring

- RMS to Orbiter stiffness

  Lumped with this are the flexibilities of the short links between the shoulder pitch joint and the Orbiter

- RMS to payload interface stiffness

  Lumped with this are the flexibilities of the short links between the wrist pitch joint and the payload

- Orbiter and payload as rigid bodies

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DRS Model Elements (cont)

- RMS joint non–linear gearbox compliance
- Joint servo and motor dynamics
- Data transfer delays between the RMS sensors and the on–board computer and between the RMS on–board computer and the RMS joint servos
- RMS on–board computer command logic
- On–orbit flight control non–linear control logic
- Reaction Control System (both Primary and Vernier) jet forces and moments

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Fundamental DRS Equation of Motion

$$\ddot{x} = A^{-1}\left[u - Kx\right]$$

where:

x is the state vector (dimension 25)

A is the "inertia" matrix

K is the "stiffness" matrix

u is the "torque" vector (a function, in part, of the servo loop)

Equation is integrated using a first order predictor/corrector scheme with a 1 ms integration step size.

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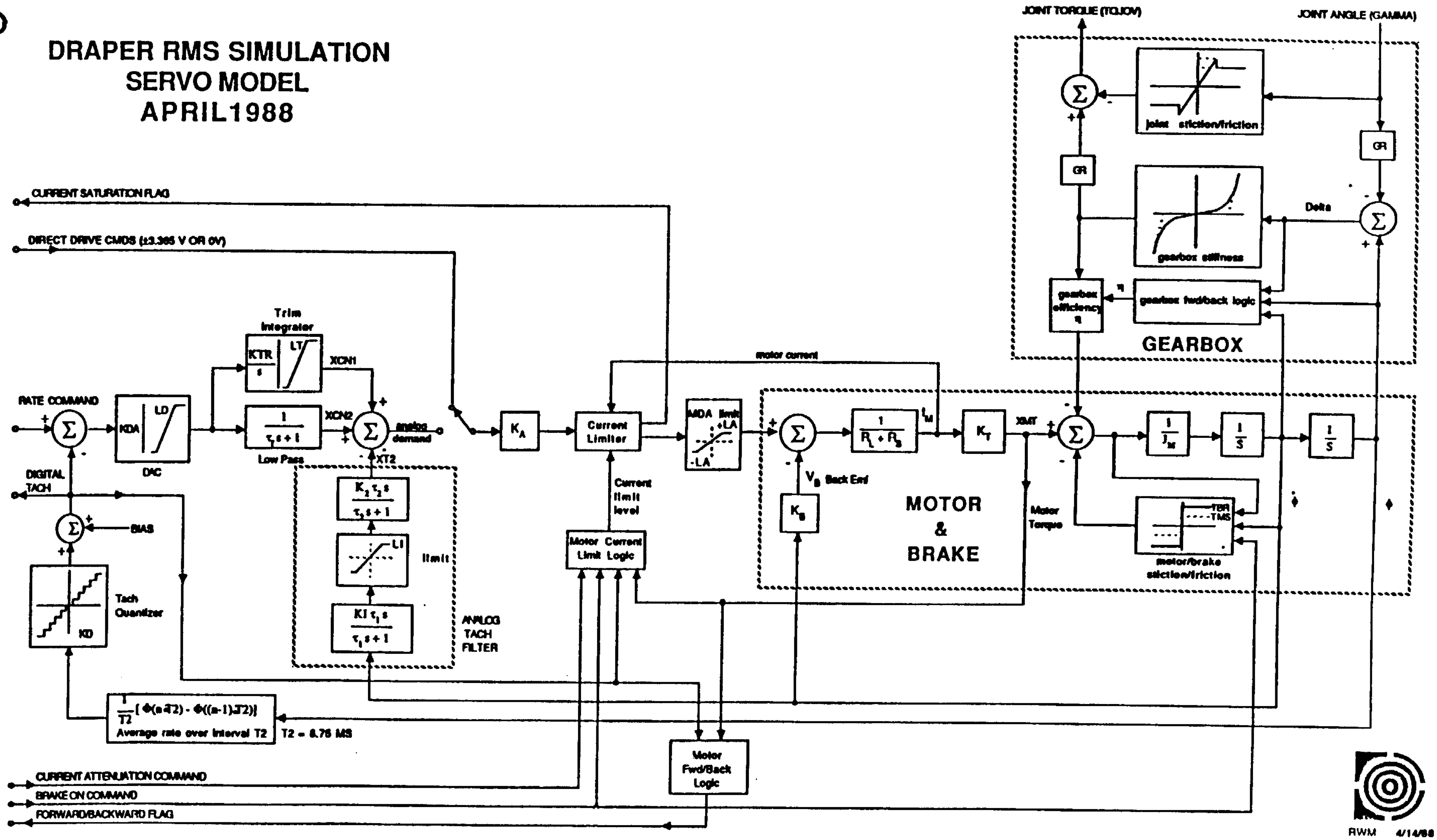
DRAPER RMS SIMULATION
SERVO MODEL
APRIL1988



DRS Verification

- Extensive simulation to flight comparison has been done.
- Model changes and parameter adjustments have been made to produce an excellent sim to flight agreement.
- Attention has been paid to both the low frequency bending and high frequency transients.

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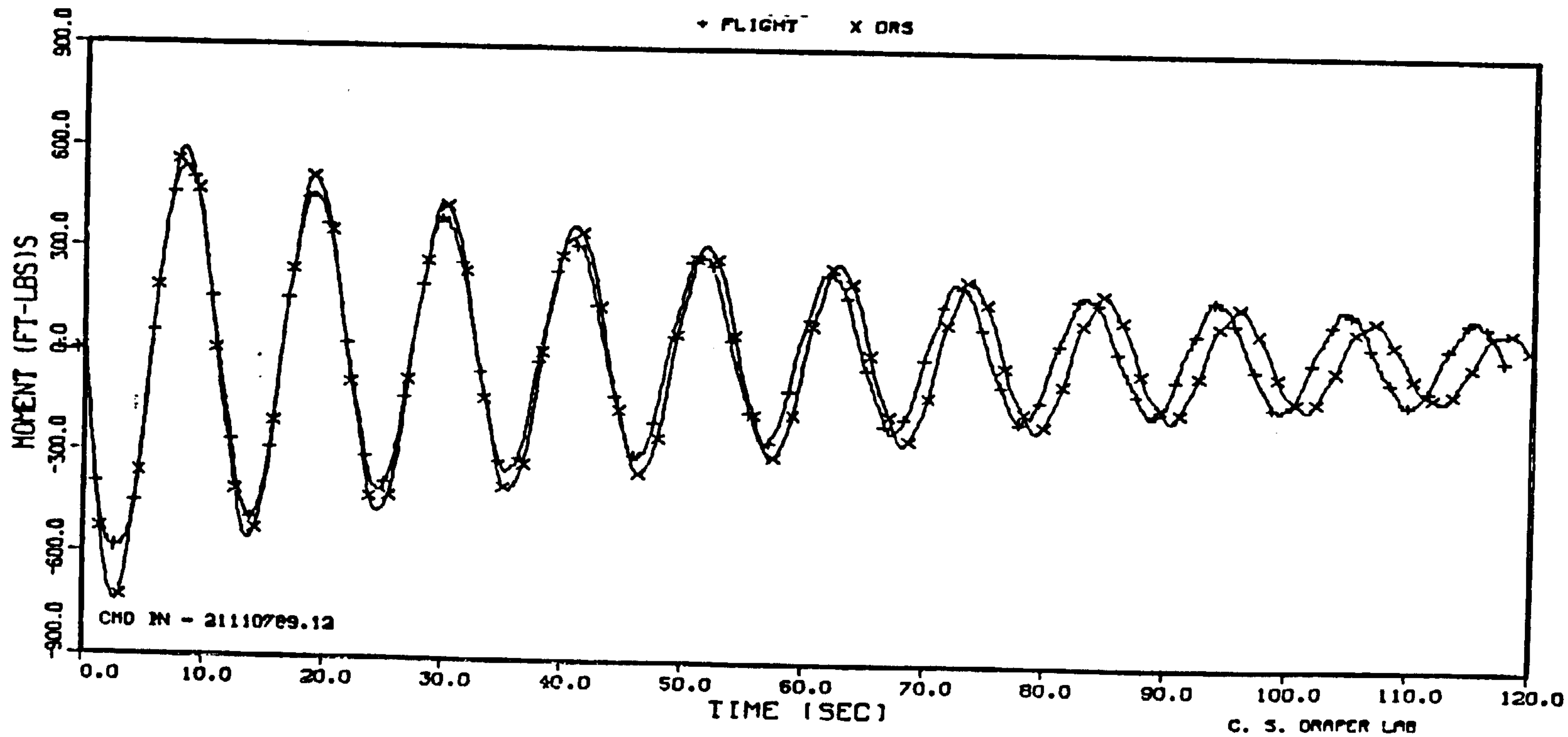
Simulation to Flight Overplot
Cross-axis Bending Excited by PRCS Jet Firing
8000 lb PFTA Grappled by RMS



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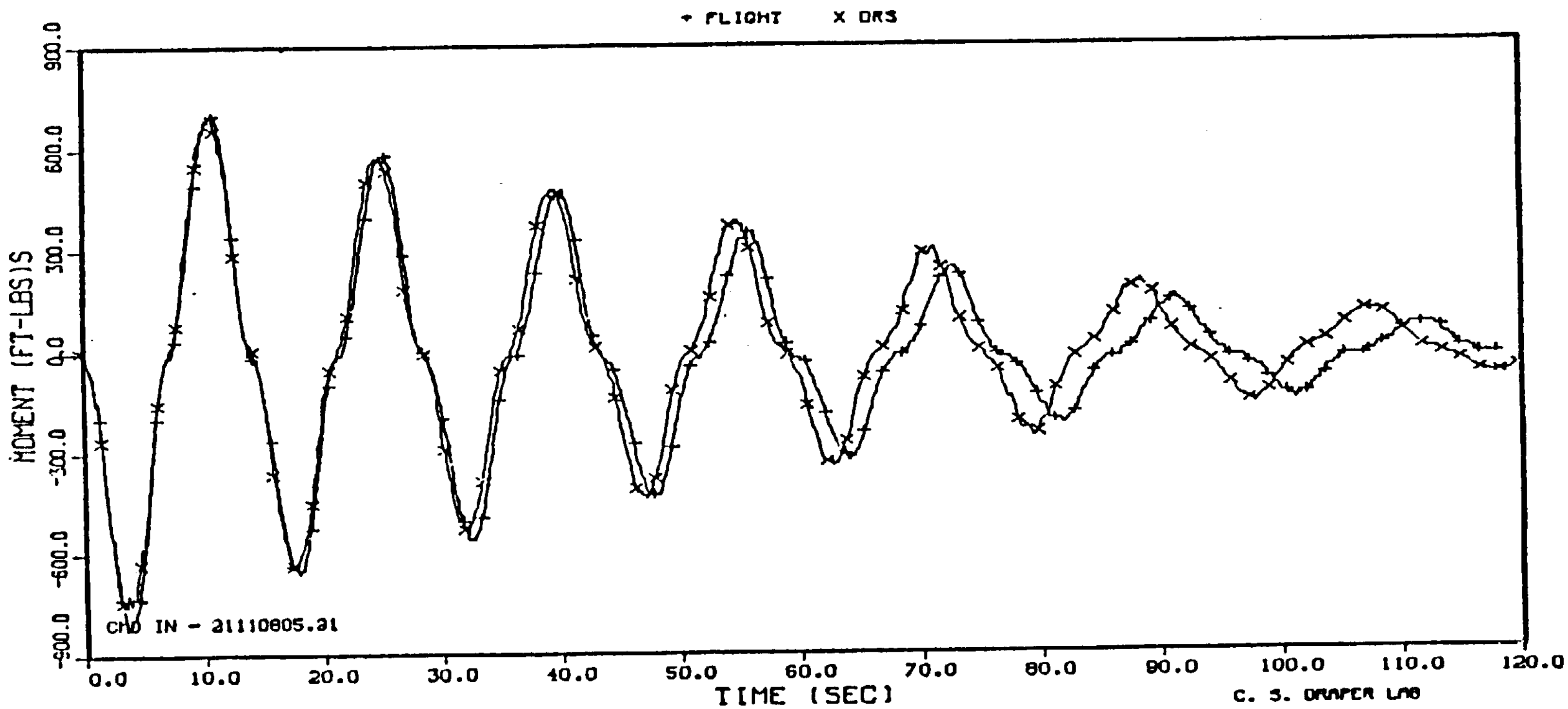
Simulation to Flight Overplot

In-plane Bending Excited by PRCS Jet Firing

8000 lb PFTA Grappled by RMS



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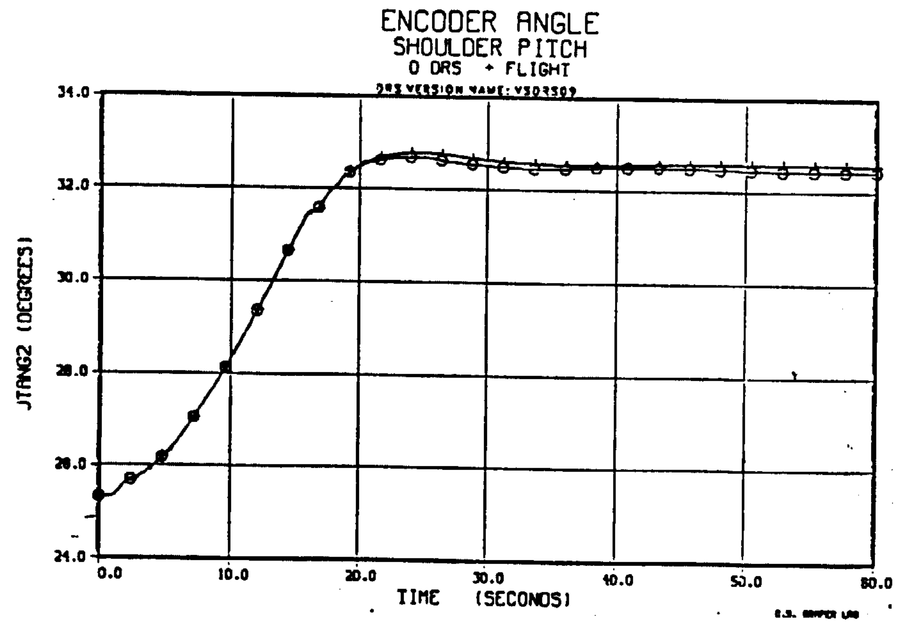
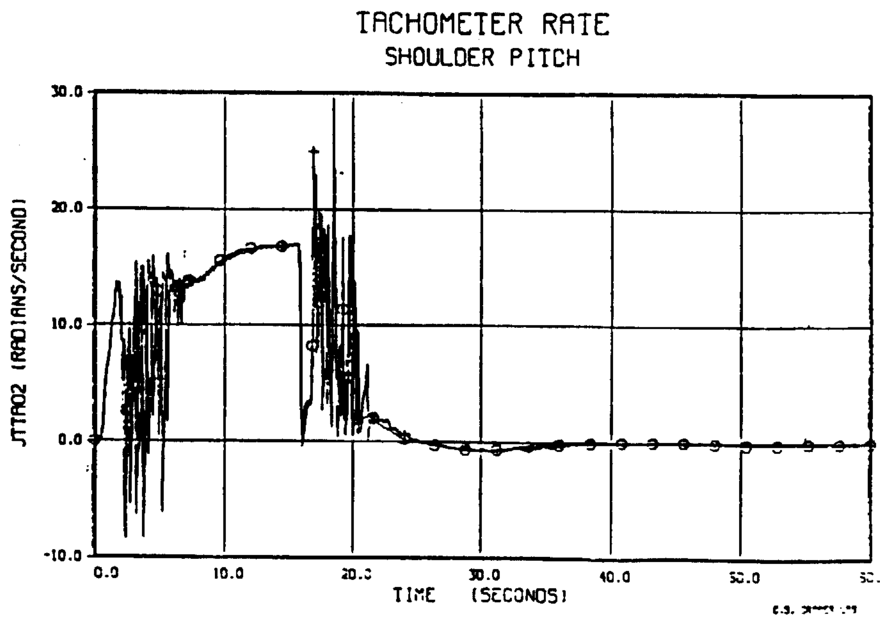
Simulation to Flight Overplot Joint Angle & Motor Rate for Shoulder Pitch Single Mode Drive 8000 lb PFTA Grappled by RMS





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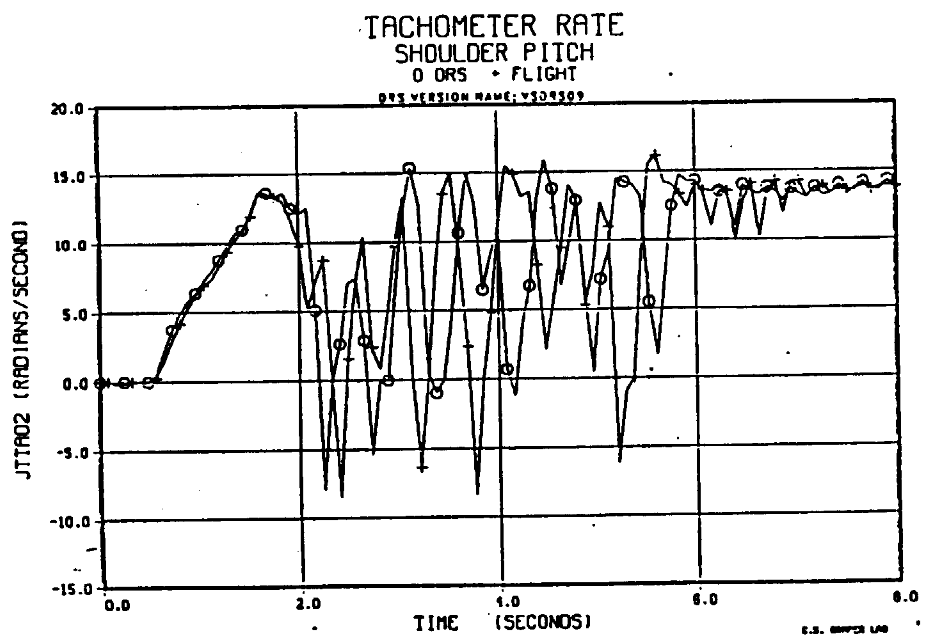
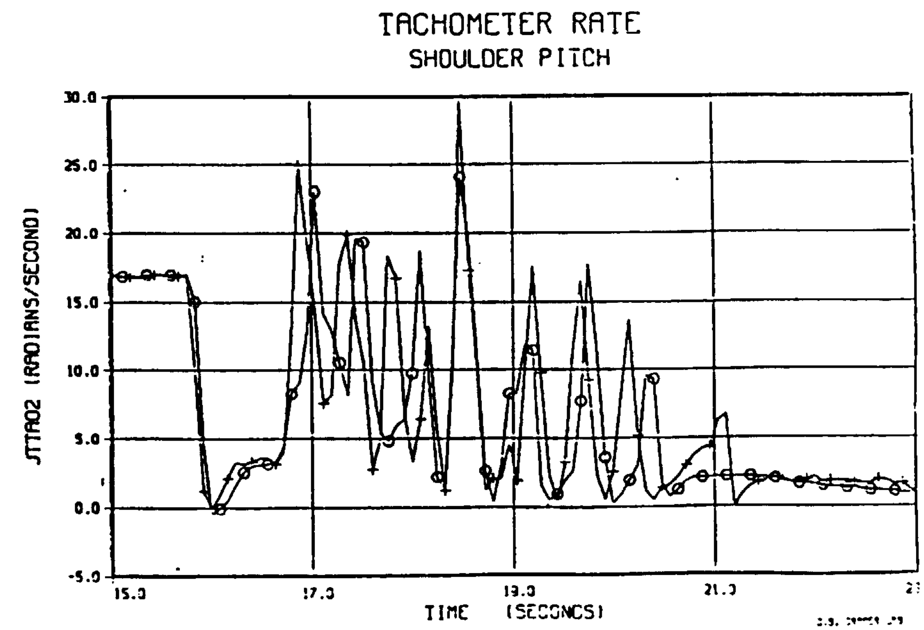
Simulation to Flight Overplot
Motor Rate Start and Stop Transients for
Shoulder Pitch Single Mode Drive
8000 lb PFTA Grappled by RMS





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Simulation Applications of the DRS

- Arm dynamics and performance analyses
  - Arm motion and loads during arm maneuvers
  - Payload tip off rates at payload release
  - Payload and arm motion during capture
  - Interaxis coupling during six joint coordinated motion
  - Post–flight estimation of joint brake effectiveness
  - Evaluation of on–board algorithm for detecting and arresting joint runaway malfunctions

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Simulation Applications of the DRS (cont)

- FCS interaction
  - Stability analyses – Self sustaining limit cycles are possible because of the relative values of FCS bandwidth, phase lag and fundamental bending frequency
  - Estimation of accelerations at the arm to payload interface due to PRCS jet activity

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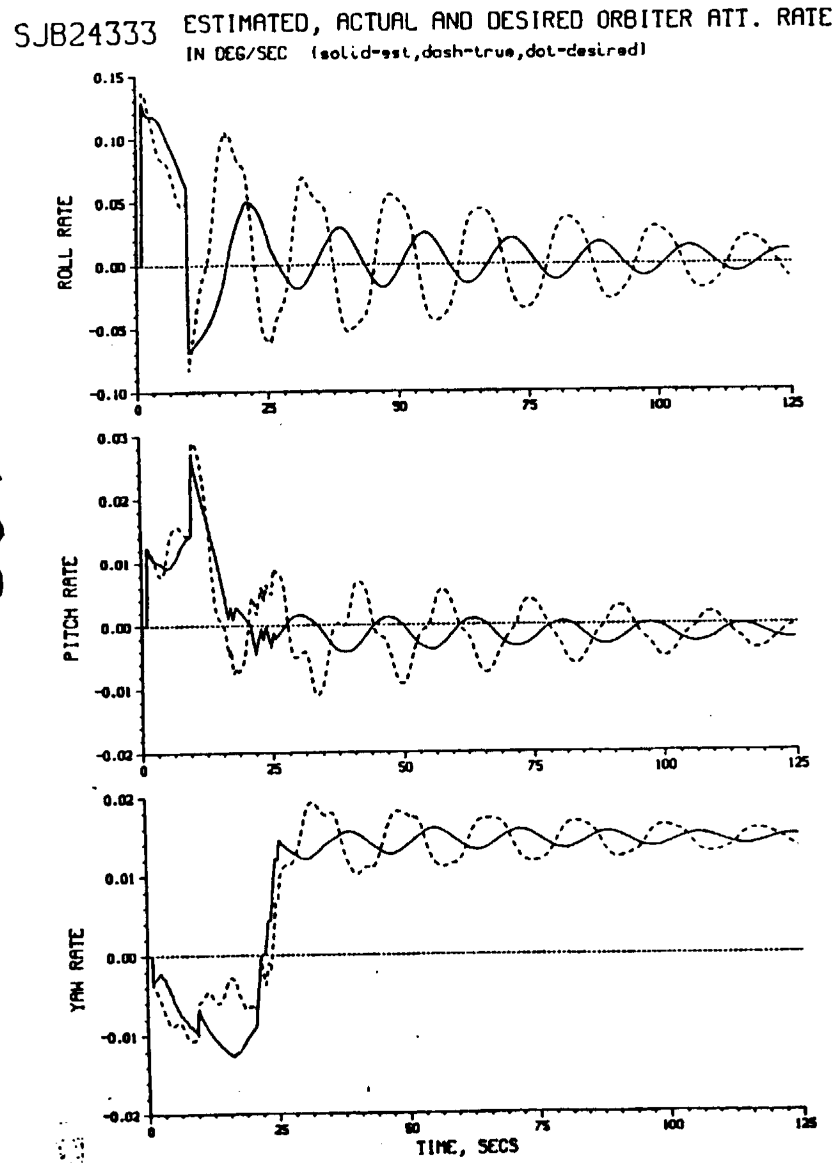
FCS Stability Analyses

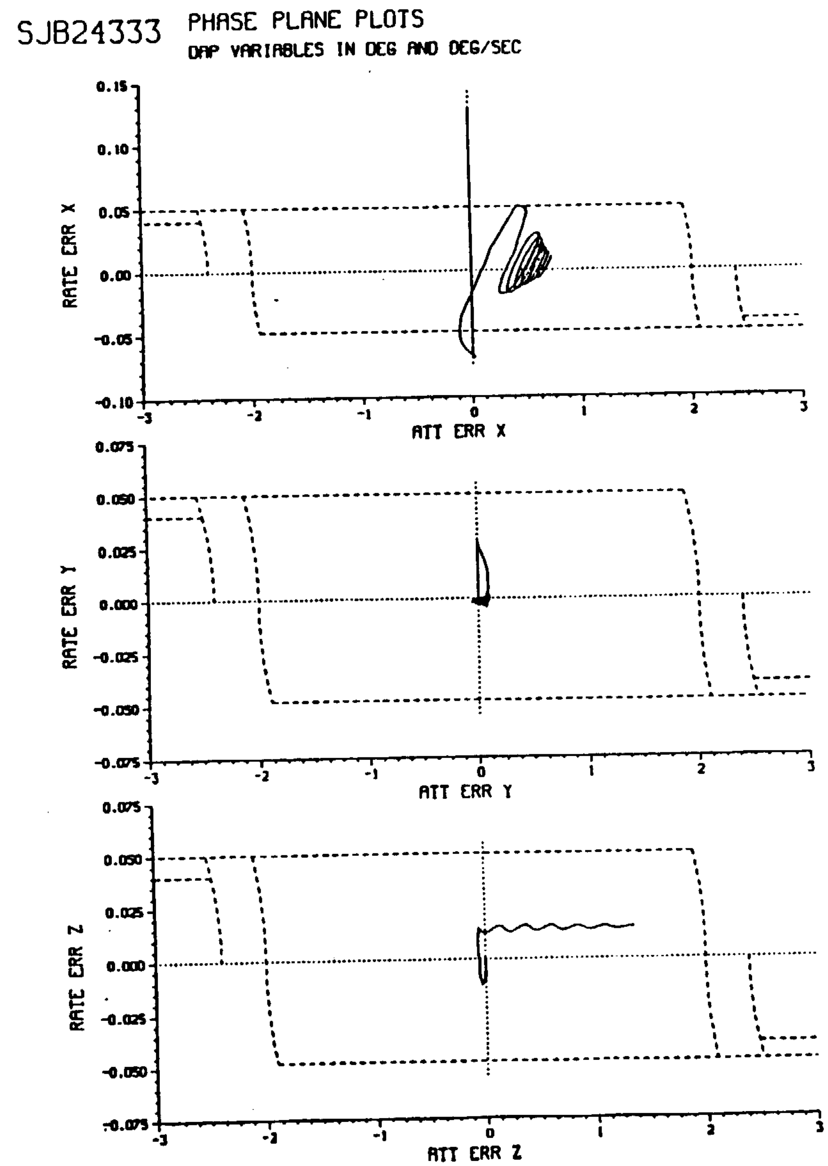
- Stability is dependent on payload position and attitude relative to the Orbiter

- For a candidate position and attitude:

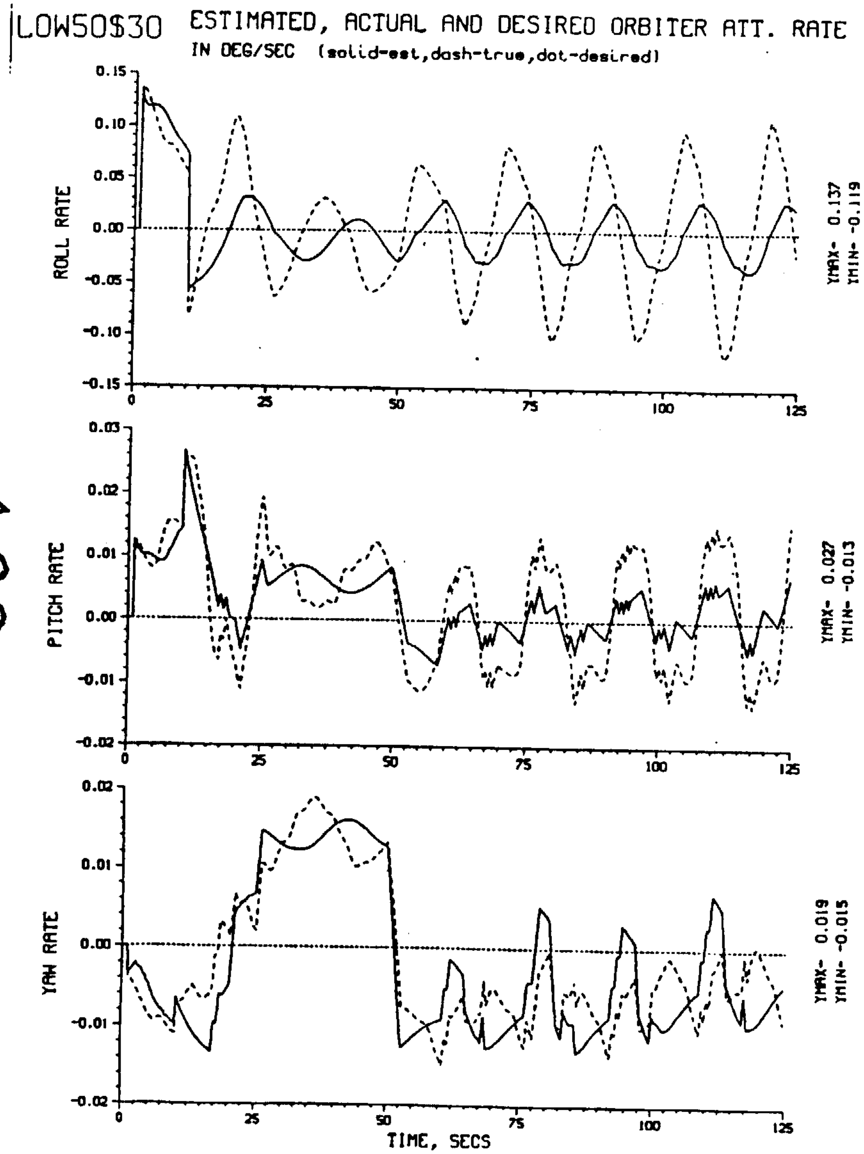
  - Apply open—loop PRCS pulses to excite the funamental flex modes of the system and then activate the FCS closed loop attitude hold, or
  - Simulate three axis attitude maneuvers,
  - Observe whether a self—sustained limit cycle results.

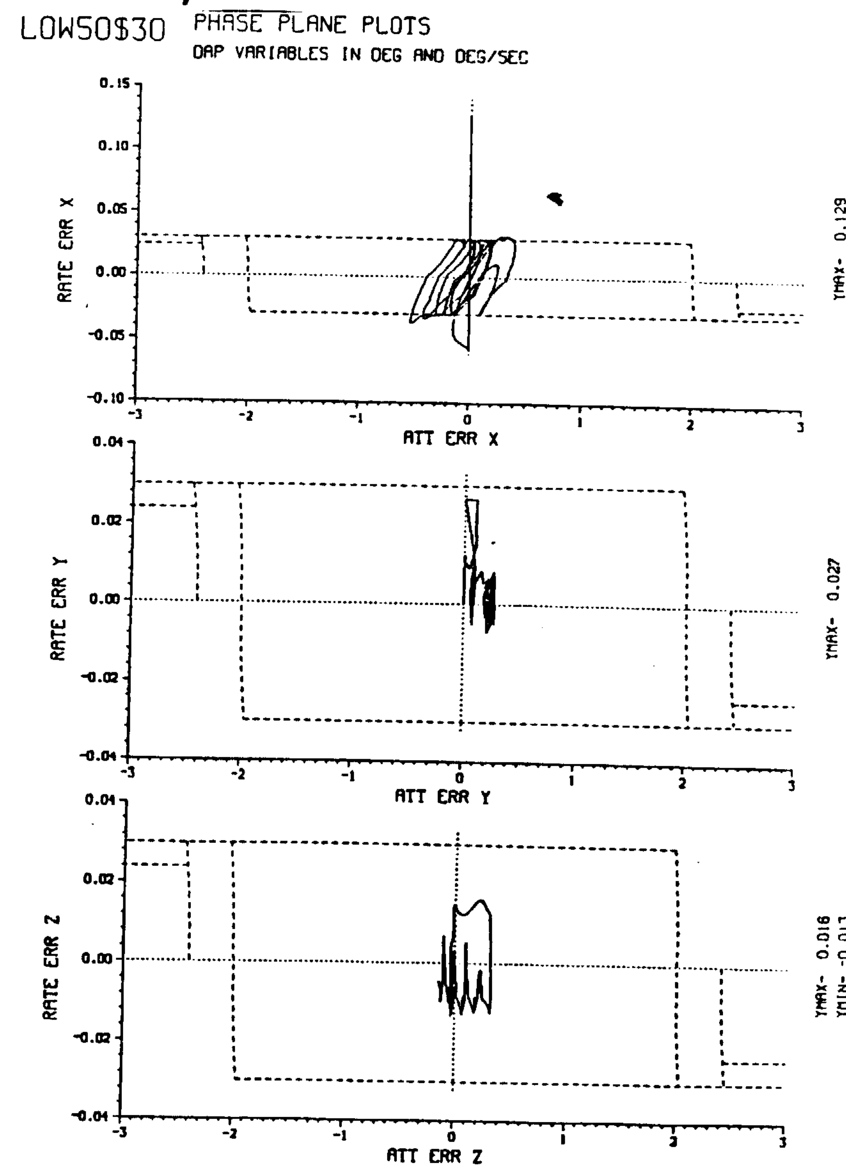
Example of a FCS Interaction Test with No Self-sustained Limit Cycle





Example of a FCS Interaction Test with A Self-sustained Limit Cycle





Cost of Running the DRS

- Simulation of one minute of FCS/RMS interaction costs about $15 when run at low priority over night.
- Normal priority for faster turn around is a factor of six more costly.
- For all its fidelity and capability, the DRS is reasonably efficient and economical.
- Nevertheless, the possible need to run hundreds of FCS interaction cases to map out stability regions was the motivation to develop an even more efficient simulation tailored to the needs of FCS interaction studies.

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Draper's LSAD Simulation

- All flexibility between the orbiter and the payload is lumped into six relative degrees of freedom. The arm is assumed to be massless. LSAD state vector has dimension six.
- A simplified algorithm is used to model the response of the joint servos. This algorithm can operate at an 80 ms time step as opposed to the 1ms DRS time step.
- Fidelity in the low frequency modes has been retained.
- Features have been added:
  - Ability to submit sets of position and attitude variation cases in a single batch,
  - Ability to start a simulation with the arm in an excited state.
- Cost of an LSAD run is about a factor of 10 less than the cost of a DRS run.

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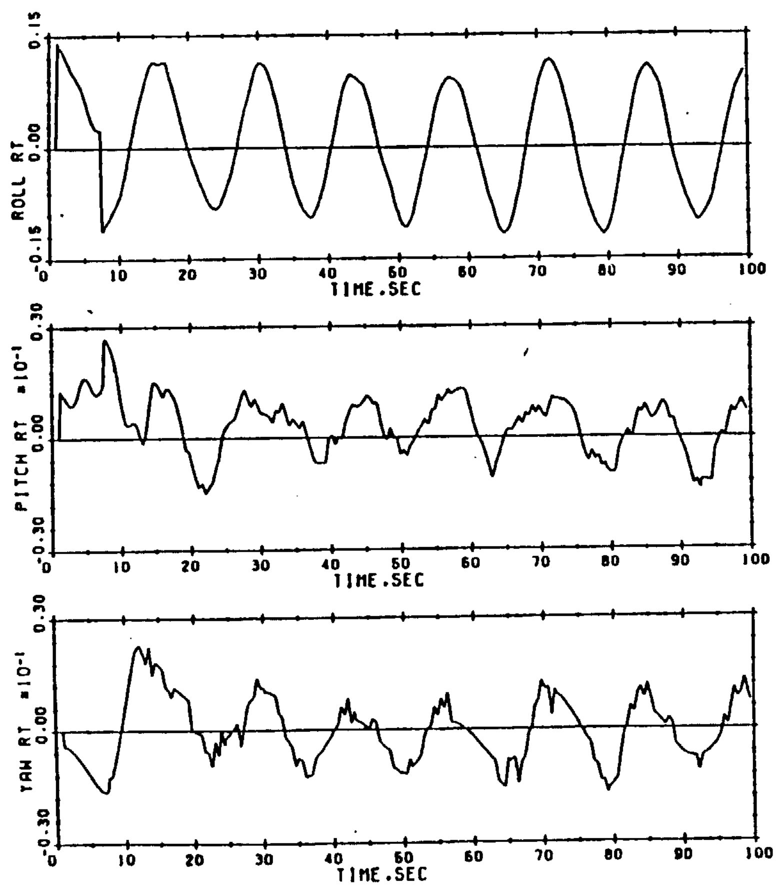
DRS to LSAD Comparison of Orbiter Rates During an FCS Stability Test

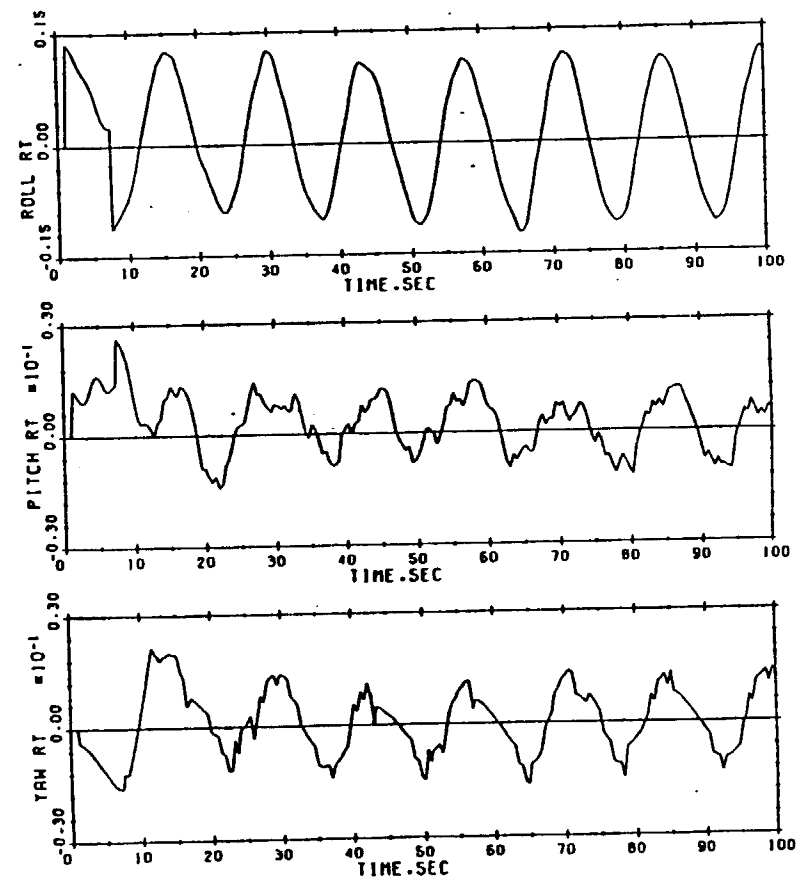
DRS STABILITY TEST

32K PL. B20S01. BRAKES ON



LSAD STABILITY TEST. RCS EXCITATION

32K PL.BRKS.B20S01 DB: 2.000. RL: 0.010. ORB/JET/ARM PLOT



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Draper Lab Contacts:

- RMS general – Joe Turnbull (617) 258–2292
- DRS – Rick Metzinger (617) 258–2912
- LSAD – Tim Barrows (617) 258–2427
- FCS Interaction – Darryl Sargent (617) 258–2296

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