Design and Integration of a Large Capacity/General Purpose 6-DOF Servo-Hydraulic Excitation System

Presented by:

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Introduction

• Through the simultaneous application of vibration in three translational and three rotational DOF, 6-DOF excitation provides the most realistic laboratory simulation of transportation and operational vibration environments.

• The Army’s Redstone Technical Test Center (RTC) identified the need to develop a large capacity general purpose 6-DOF excitation system for payloads up to 5000 lbs and footprint up to 8 ft wide and 12 ft long.

• This presentation provides a summary of the preliminary design, detailed design, fabrication and integration of the RTC system.
Phase I
Scope of Work
6-DOF System

Key Design Targets

• Basic Table Dimension: 8 ft x 8 ft
  – Table Extensions: 4 ft x 2.25 ft (accommodates 12.5’x4’ payloads)
  – Ability to mount on the table top or from the table bottom.

• Multiple Reference Criteria \((\text{simultaneous translational motion})\):
  – Mil-Std-810G Composite Wheeled Vehicle (5000 lb payload).
  – MLRS/M270A1 NBROR (5000 lb Payload)
  – Various Rotorcraft SOR.

• Dynamic Stroke: 3 in DA.

• Rotational Motion: ± 6 Degrees.
Conceptual View
Phase II
Model System Design
System Design

- Over constrained 6-DOF system
  - More actuators than DOF
  - 5 vertical servo-actuators
  - 4 horizontal servo-actuators
- Actuator and bearing design relieves necessary DOF
- Over constrained allows for application of more complex control techniques
Vertical Actuator Design

• 5 servo hydraulic actuators
• Dual spherical couplings
• Dual servo valve pairs
  – V-50 Pilot
  – V-750 Slave
• 15 in² piston area
• 3,000-4,500 psi operating pressure
• 15,000-22,500 lbf-RMS random force
• 3” DA dynamic stroke, 4” DA static stroke
Horizontal Actuators

- Opposing preloaded actuator pairs
- 4 servo hydraulic actuators
- 4 preload only actuators
- Self aligning pad bearings
- Dual servo valve pairs

- 20 in\(^2\) piston area – dynamic actuator
- 3,000-4,500 psi operating pressure
- 20,000-30,000 lbf-RMS random force
- 3” DA dynamic stroke, 4” DA static stroke
System Cross-Section

- (4) Horizontal dynamic actuators
  - Control X, Y, Rz
- (4) Horizontal preload actuators
- (5) Vertical dynamic actuators
  - Control Z, Rx, Ry
Finite Element Analysis

Table Modes

- The target for the first constrained table mode was $f_n > 200$ Hz
Finite Element Analysis

Local Modes

- Local Panel Deformation Example
Valve Selection

- Velocity and flow performance are primarily associated with the oil pressure, oil column resonance and the roll-off frequency associated with the valves employed to port oil to the actuator.
- Design goal: increase oil column stiffness and maximize flow over required bandwidth.
- Estimating performance of a highly loaded actuator and servo valve is a complex task.
  - Team has developed a proprietary hydraulic simulation program to model instantaneous flow.
  - Provides a method to optimize valve selection to a desired ASD.
Valve Selection

- Below is the Predicted Flow into the Vertical Actuator Required for the Mil-Std-810G TWT specification for a 2000 lb Payload.
- Simulation results indicated dual V-50 Pilot/V-750 Slave combinations would be required.
- The simulations provided high confidence in meeting the design objectives.
Phase III.1
Factory Acceptance Test
Factory Acceptance Test

• A series of Factory Acceptance Tests (FAT) were integrated into the build contract to ensure basic performance objectives were met.

• MIL-STD-810G Composite Two Wheeled Trailer Profile (TWT), MIL-STD-810G Composite Wheeled Vehicle Profile (CWV), and the MLRS M270A1 profiles were used as reference criteria for the actuator/valve trials.
  – The test mass associated with the FAT rigs did not exactly match anticipated tactical weight distribution.
  – Minor modification were made to the reference criteria based on effective mass estimates.

• In addition to actuator and valve performance, the software developed to control the table (TCON) was demonstrated during the FAT trials.
FAT Test Rigs

Horizontal FAT Rig

Vertical FAT Rig
Vertical FAT Results

- Tested each actuator to system design levels
- Minor modifications to ASD profiles to account for FAT rigs
- Verified actuator and bearing performance
Table Control (TCON)

State Diagram:
The LED indicators are used to display:
System State, Actual.

- Initialize
- HPS Interlock
- E-Step 1
- E-Step 2
- E-Step 3
- E-Step 4
- E-Step 5
- E-Step 6

- Verify Load
- HCM Interlock
- E-Step 1
- E-Step 2
- E-Step 3
- E-Step 4
- E-Step 5
- E-Step 6

- Pilot Flow Open
- Main Flow Close
- Warm Up

- Pilot Flow Close
- Main Flow Open
- Warm Up
- Operate

- System State, Called

This is the state being called for by the TCON Host Application.
Phase III.2
Facility Preparation Phase
Reactions Mass Enhancements

**Problem**

- The 140 kip loads from each preload actuator result in large shear and tensile forces at the interface to the reaction mass.
- A cold joint at the base of the reaction mass wall was inadequate to handle the loads.

**Solution**

- An array of 24ea high strength tension rods were installed through the 8’ deep wall into the 8’ thick thick foundation.
- 200 kip pre-tension applied to each anchor to preload the cold joint.
Reaction Mass Enhancements

**Problem**

- Under the worst case load conditions, negative pressures on the cold joint indicate cracking of the cold joint.

**Solution**

- Adding the pre-tensioned anchor rods maintains positive pressure over the entire surface of the cold joint under the worst case loading.
Hydraulic Power Supplies
Phase IV
System Integration and On-Site Acceptance Testing
Installed System
Mapping to an Instrumented Origin

- It is advantageous to place one of the reference tri-axial translational accelerometers at the user defined origin.
- This allows the data acquisition team to conduct an acceleration transformation per

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\{a\}_{\text{Meas}} = T_{a}\{c\}_{\text{Motion}}
\]

and then perform a direct comparison between the measured translational data at the origin and the associated mapped motion DOF.
Instrumentation Layout
CWV-Rectangular Control

X-DOF

Extremal (blue) and Average (black) Plots for the X-DOF
CWV-Rectangular Control

Y-DOF

Extremal (blue) and Average (black) Plots for the Y-DOF
CWV-Rectangular Control

Z-DOF

Extremal (blue) and Average (black) Plots for the Z-DOF
CWV - Kinematic Transform Control

X-DOF

Input Xform (Black), Limits (Green) and Extremal (Magenta) for the X-DOF
CWV - Kinematic Transform Control

Y-DOF

Input Xform (Black), Limits (Green) and Extremal (Magenta) for the Y-DOF

$G^2/\text{Hz}$ versus $\text{Freq (Hz)}$
CWV - Kinematic Transform Control

Z-DOF

Input Xform (Black), Limits (Green) and Extremal (Magenta) for the Z-DOF

$G^2/\text{Hz}$ vs. Frequency (Hz)
Conclusions

• Large high force systems require considerable design consideration.
• The subject 6-DOF system met the objectives set out in the original SOW.
• As expected, the system did not exhibit rigid body motion over the entire 500 Hz operational bandwidth.
• Optimal control configurations are expected to be payload specific.
• Rectangular and Kinematic Transform Control combined with various Limit strategies have been demonstrated as viable options.
Thanks for Your Attention!

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