Hydraulic Actuation and Shaking tables
Constraint for high dynamic testing application

• Stiffness of actuator is roughly proportional to cylinder area.

\[ K_h = \frac{\beta \cdot A^2}{V_0} \]

• Stiffness, Mass, piston stroke determine natural frequency \( \omega_n \)

\[ \omega_n = \sqrt{\frac{\beta}{M} \left( \frac{A_a^2}{V_a} + \frac{A_b^2}{V_b} \right)} \]

• Natural frequency determines the system's maximum controlled acceleration rate
• The system's natural frequency should be three to four times higher than the motion frequency.
• Increase the system natural frequency means increase the cylinder Area and finally the flow rate required.
• Normally higher nominal flow servovalve has worse dynamic behaviour
Categories of hydraulic actuators

Low friction seal actuators (Structural fatigue test)

Hydrodynamic Actuators (Dynamic test)
optimal solution for dynamic test at low frequency

Hydrostatic Actuators (Acceleration, Vibration, Shock test)
optimal solution when high side loads are present, allow high frequency tests.

• Bearing technology (hydrostatic or hydrodynamic): eliminates breakaway (stick-slip) friction that can plague cylinders in low-speed conditions or in motion reversal, improving accuracy, repeatability, resolution.
• Cushioned cylinders: fluid lamination at end stroke avoids shock or hammering against the cylinder head.
• Single piece machined body provide highest stiffness, long fatigue life, easy maintenance.
Customized Pseudo- dynamic product Range

<table>
<thead>
<tr>
<th>Force (kN)</th>
<th>Bore dia (mm)</th>
<th>Rod dia (mm)</th>
<th>Operating Stroke (mm)</th>
<th>Cushion each side (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>110</td>
<td>80</td>
<td>500</td>
<td>20</td>
</tr>
<tr>
<td>250</td>
<td>160</td>
<td>100</td>
<td>500</td>
<td>20</td>
</tr>
<tr>
<td>500</td>
<td>220</td>
<td>140</td>
<td>500/1000</td>
<td>20</td>
</tr>
<tr>
<td>1000</td>
<td>300</td>
<td>160</td>
<td>500</td>
<td>20</td>
</tr>
</tbody>
</table>

Main characteristics:

- Hydrostatic bearings
- Integrated manifold with shut off valve to prevent uncontrolled piston movement
- Different installation mountings
Typical MOOG Hydrostatic actuators

L085-719 hydrostatic actuator 1000 kN

L085-760 hydrostatic actuator 500 kN and 250 kN

L085-803 hydrostatic actuator 125 kN
Standard Hydrostatic Actuator

High Side loaded double rod actuator
- Used in applications such as shakers where a high side load rules out the use of a conventional actuator
- 100 million cycle fatigue rated
Design Tools – Normograph
Hydrostatic Actuator

• **Design Inputs**
  • Nominal Test Item Unsprung Weight
  • Actuator Weight
  • Test Item Sprung Weight
  • Choice of Mobil DTE 24 or 25 hydraulic oil
  • Actuator Area
  • Actuator stroke
  • Actuator valve flow (1000 psi drop)
  • Actuator target Running parameters
    • Stroke pk-to-pk
    • Run Frequency

• **Design outputs**
  • Actuator Target Running Parameters
    • Peak Flow
    • Average Flow
    • Velocity
    • Acceleration
    • Normograph of velocity vs displacement vs acceleration
  • Natural Frequency
Design Tools - Stiffness
Hydrostatic Actuator

- **Design Inputs**
  - Oil operating temperature
  - Choice of Mobil DTE 24 or 25 hydraulic oil
  - Actuator stroke length
  - Actuator stroke position
  - All pertinent actuator part dimensions & material properties
  - Oil passage way lengths & diameters for extra oil volume calculation.
  - Piston and load mass
  - All mathcad units (inputs, outputs and graphs) change from english to metric with a few key strokes.

- **Design outputs**
  - Actuator extend & retract static stiffness
  - Actuator natural frequency (without dynamic servo valve influence)
Design Tools - Bearing
Hydrostatic Actuator

• **Design Inputs**
  • System & return pressure
  • Pressure & return line lengths & number of bends
  • Bearing geometry (see picture)
  • Maximum piston eccentricity
  • Choice of Mobil DTE 24 or 25 hydraulic oil
  • Nominal oil operating temperature
  • Piston rod diameter & radial clearance

• **Design Outputs**
  • Graph of bearing flow and side load capacity vs. feed orifice diameter at the specified oil temperature and max piston eccentricity.
  • Based on the graphs below, refine hydrostatic bearing geometry and / or choose feed orifice diameter to get desired performance.
  • With the feed orifice diameter chosen, bearing oil temperatures are calculated.
  • Then output graphs of the following are plotted:
    • Bearing flow, Side load capacity, Recess pressures, Reynolds number, and Pressure drops in the line lengths, bends, and orifices versus oil temperature and piston eccentricity
    • Bearing stiffness versus temperature.
  • All mathcad units (inputs, outputs, and graphs) change from english to metric with a few key strokes.
Design Tools – Snubber/Cushion Hydrostatic Actuator

- **Design Inputs**
  - Nominal oil operating temperature
  - Choice of Mobil DTE 24 or 25 hydraulic oil
  - System & return pressure
  - Pressure, Return, Extend, Retract, and Snubbing line lengths & number of bends
  - Servo valve slot sizing
  - Snubbing orifice diameter
  - Piston rod and cylinder bore diameter
  - Extend or Retract direction
  - Load mass
  - Initial actuator position and velocity
  - Actuator metal stiffness (from stiffness calculations)
  - All mathcad units (inputs, outputs and graphs) change from english to metric with a few key strokes.

- **Types of analysis**
  - Mass with initial snubbed impact velocity, no driving pressure
  - Actuator / mass free fall, no driving pressure
  - Actuator / mass falling and intentionally driven into snubbed with system (or reduced) pressure.

- **Design Outputs**
  - Graphs of actuator Position, Velocity, Accel / Decel, Flow, Extend & Retract pressures, Snubbing pressure, Individual pressure drops (to assess orifice authority), and Snubbing Circuit fluid velocity Versus Time.
  - Stress level in cylinder due to pressure spike
  - Stress level in tie rods (or end cap bolts) due to impact velocity & moving mass
New 8-Pocket Hydrostatic Bearing Geometry

- Manifold Return Line
- Manifold Pressure Line
- Extend Port
- Extend Snubbing Circuit
- Xylan 1620 PTFE-Epoxy coated piston head & gland
- Actuator Piston (Rod split to show hydrostatic bearing recesses)
- Bearing Oil Flow
- Displacement sensor Body
- Bearing Recess Orifice
- 8 Recesses of the Hydrostatic Bearing
- Scraper Seal
- Tailstock
Pedestal base actuator typical layout
## Product Range - Hydrostatic Actuator

<table>
<thead>
<tr>
<th>Force Rating</th>
<th>Rod Diameter</th>
<th>Cyl Bore</th>
<th>Piston Area</th>
<th>Cushion Stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>kip</td>
<td>ln.</td>
<td>mm</td>
<td>sq.in.</td>
<td>ln.</td>
</tr>
<tr>
<td>6.6</td>
<td>3.15</td>
<td>80.0</td>
<td>2.51</td>
<td>1.0</td>
</tr>
<tr>
<td>8.5</td>
<td>3.15</td>
<td>80.0</td>
<td>3.20</td>
<td>1.0</td>
</tr>
<tr>
<td>11</td>
<td>3.15</td>
<td>80.0</td>
<td>4.14</td>
<td>1.0</td>
</tr>
<tr>
<td>22</td>
<td>3.94</td>
<td>100.0</td>
<td>8.40</td>
<td>1.0</td>
</tr>
<tr>
<td>35</td>
<td>3.94</td>
<td>100.0</td>
<td>13.42</td>
<td>1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Force Rating</th>
<th>Rod Diameter</th>
<th>Cyl Bore</th>
<th>Piston Area</th>
<th>Cushion Stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>kN</td>
<td>ln.</td>
<td>mm</td>
<td>sq.cm</td>
<td>mm</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>38</td>
<td>38</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>160</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Force</th>
<th>Stroke Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke Length</td>
<td>mm</td>
</tr>
<tr>
<td>ln.</td>
<td></td>
</tr>
<tr>
<td>6.2 kip (28 kN) to 35 kip (160kN)</td>
<td>6 152</td>
</tr>
<tr>
<td></td>
<td>8 204</td>
</tr>
<tr>
<td></td>
<td>10 254</td>
</tr>
<tr>
<td></td>
<td>12 306</td>
</tr>
</tbody>
</table>
Building Blocks – Hydrostatic Actuator

Building Block Approach results:
- Flexibility to meet customer needs
- Maximum amount of configurations
- Less part numbers and drawings

Key for configurations:
- Joints and Bases
- Servo valves
- Accumulators
- Manifolds
Typical Pseudo dynamic application
Test Rig for Hydrodynamic Actuator

Test bench with two opposed actuators for dynamic performance evaluation.

Maximum force: up to 600kN
Shaking tables

Moog Seismic Table (3x3mt) with 2 DOF. Easy and compact the table incorporates the hydraulic servoactuators for both X and Y axis.

Seismic Table Moog with hydrostatic bearing in order to avoid friction and guarantee high linearity acceleration signals.

<table>
<thead>
<tr>
<th>Dimension:</th>
<th>3x3 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max acc.</td>
<td>1g</td>
</tr>
<tr>
<td>Max payload</td>
<td>20 ton (each table)</td>
</tr>
<tr>
<td>Max frequency</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>
In every table are mounted:

- n° 2 servo actuators of 700 kN
- Double symmetrical road
- Working stroke: ± 250 mms
- Stall load at operative pressure 700 kN
- Dynamic load 525 kN
- Hydrostatic bearing:
  - 2 hydrostatic pads on both roads, hydrodynamic pad on the piston.
- Operational pressure: 28 MPa
- Testing pressure 42 MPa
- Hydraulic brakes
- 2 Servovalves D792 1000L/min each
High frequency 6DOF Shaking tables

<table>
<thead>
<tr>
<th>Specification</th>
<th>Specification Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Payload</td>
<td>600 kg (1,322 lb)</td>
</tr>
<tr>
<td>Table Mass</td>
<td>742 kg (1,635 lb)</td>
</tr>
<tr>
<td>Total Payload (combined)</td>
<td>1342 kg (2,950 lb)</td>
</tr>
<tr>
<td>Table Size (LxW)</td>
<td>2300 x 2000 mm (7.5 x 6.6 ft)</td>
</tr>
<tr>
<td>Table Mounting Pattern</td>
<td>200 x 200 mm (8 x 8 in)</td>
</tr>
<tr>
<td>Table Mounting Hole Size</td>
<td>M16</td>
</tr>
<tr>
<td>Actuator Peak Force</td>
<td>53 kN (12 kip)</td>
</tr>
<tr>
<td>Degree of Freedom</td>
<td>6 DOF Stewart Hexapod</td>
</tr>
<tr>
<td>Frequency</td>
<td>150 Hz</td>
</tr>
</tbody>
</table>

**Acceleration**

- (Z) Heave (Vertical): +109/-89.5 m/sec² (+11.1/-9.93 g)
- (Y) Lateral: ±63.7 m/sec² (6.49 g)
- (X) Longitudinal: ±80.5 m/sec² (8.21 g)
- Roll: ±4175 deg/sec² (72.87 rad/sec²)
- Pitch: +4210/-5130 deg/sec² (73.48/-89.54 rad/sec²)
- Yaw: ±8900 deg/sec² (155.33 rad/sec²)
High frequency 6DOF Shaking tables
Electric motors and electromechanical actuation
Motors Offering Overview

CORE
- FAS G400
- FAS J
  - Cooling: natural, fan, liquid
  - Sizes: 3, 4, 6, 6, 7

SPECIAL
- FAS G49x
- Explosion Proof
- FAS G48x
- Gearbox Motors

OTHER
- FAS T, F, W

LEGACY
- FAS K
- FAS N
- FAS Y
Brushless motor Torque range

- W-Series
- F-Series
- T-Series
- J-Series Liquid Cooled
- J-Series Fan Cooled
- J-Series Natural Cooling
- G400 Series

Continuous Torque (Nm) Log Scale
Dynamic Performance Comparison

FAS J: Highest dynamics, consistent performance over all power levels

Moog proprietary and/or confidential data
The new FAS J motor accelerates twice as fast as our already very dynamic FAS W motors.
MOOG Screws

Ball screws

• ISO 3408 classes 3-5-7 (*)
• Ø from 13 to 100mm
• Pitch from 4 to 50mm
• Length up to 3600mm
• Load capacity:
  Dynamic up to 400kN
  Static up to 900kN
• Acceleration 10-12 m/s²
• Single or multistart

Planetary roller screws

• Ø from 16 to 90mm
• Pitch from 2 to 36mm
• Length up to 1800mm
• Load capacity:
  Dynamic up to 670kN
  Static up to 1400kN
• Acceleration up to 40m/s²
• Starts N° 5

(*) ISO defines key geometric features and tolerances of ball screws
Example of MOOG EMA maxforce

<table>
<thead>
<tr>
<th>type</th>
<th>Stroke (mm)</th>
<th>Continuous Force (kN)</th>
<th>Lead (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series 4</td>
<td>From 100 to 2000</td>
<td>From 2 to 20</td>
<td>5, 10, 20</td>
</tr>
<tr>
<td>Series 5</td>
<td>From 150 to 2500</td>
<td>From 4 to 50</td>
<td>5, 10, 20</td>
</tr>
<tr>
<td>Series 6</td>
<td>from 150 to 2500</td>
<td>From 7 to 100</td>
<td>5, 10, 20</td>
</tr>
</tbody>
</table>

Higher continuous force (up to 350kN) on request
MCG Linear motor family

3 FORCE RANGES – 2 Motor Diameters = 4 and 5 Inch

<table>
<thead>
<tr>
<th>Motor Combination</th>
<th>Force (lbs)</th>
<th>Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4020-2 / 5020-2</td>
<td>375</td>
<td>1668</td>
</tr>
<tr>
<td>4020-4 / 5020-4</td>
<td>750</td>
<td>3335</td>
</tr>
<tr>
<td>4020-6 / 5020-6</td>
<td>1125</td>
<td>5003</td>
</tr>
</tbody>
</table>

5 Inch Diameter Motors Offer Increased Continuous Force

1 pound force = 4.44822162 newtons

Moog proprietary and/or confidential data
Component development
Further investigation and development

• Use advanced simulation techniques to optimize the system design

• Use of advanced control techniques to improve the fidelity of the response of the actuator

• Improved the stiffness of the overall actuation system adopting combined EH and EM actuation
Thank for your attention

Questions?