Lecture 7

Coming week’s lab:
- Lab 14: Integrative lab (part 2)
- Lab 15: Intro. Electro-hydraulic Control Setups (2 sessions)
  - 4th floor Shepherd (room # TBD)

Guest lecturer next week (10/30/15):
- Dr. Denis Harvey, MTS

Today:
- Your feedback
- Pump (motor) theory
- Hydro-static transmission and Hydraulic Hybrids
- Electro-hydraulics overview
Piston Pump - flow ripples

- Each cylinder has a pumping cycle
- Total flow = flow of each cylinder
- More cylinders, less ripple
- Frequency:
  - Even # cylinders \( n \times \text{rpm} \)
  - Odd # cylinders \((2n)\times \text{rpm}\)
- Can be problematic for manual operator (ergonomic issue)
- Noise

Displacement = # Cylinders \times\ Stroke \times\ Bore Area
# of Pistons Effect on Flow Ripples

Matlab code: flow_ripple.m
Pumping theory

- Create a partial vacuum (i.e. reduced pressure)
- Atmospheric / tank pressure forces fluid into pump
  - usually tank check valve opens
  - outlet check valve closes
- Power stroke expels fluid to outlet
  - outlet check valve opens
  - tank check valve closes
- **Power demand** for prime mover (ideal calculation)
  - (piston pump) Power = Force*velocity = Pressure*area*piston speed
    = Pressure * Flow rate
- If power required > power available => Pumps **stall** or decrease speed
Hydraulic Motor / Actuator

- Hydraulic motors / actuators are basically pumps run in reverse
- Input = hydraulic power
- Output = mechanical power

For motor:
- Frequency (rpm) = \( Q \, \text{gallons per min} / D \, \text{gallons} \) * efficiency
- Torque (lb-in) = Pressure (psi) * \( D \, \text{inch}^3 \) * efficiency

- Efficiency about 90%
- Note: units
Models for Pumps and Motors

- Ideal case (SI units):
  
  Flow: \[ Q \left[ \frac{m^3}{sec} \right] = \frac{D[m^3]}{2\pi} \omega \left[ \frac{rad}{sec} \right] \]

  Torque: \[ T[Nm] = \frac{D[m^3]}{2\pi} \Delta P \ [Pa] \]

- Hydraulic power =
  \[ \Delta P \times Q = \left( T[Nm] \frac{2\pi}{D[m^3]} \right) \times \left( \frac{D[m^3]}{2\pi} \omega \left[ \frac{rad}{sec} \right] \right) \]
  
  \[ = T[Nm] \times \omega \left[ \frac{rad}{sec} \right] \]
  
  \[ = \text{mechanical power} \]
Non-ideal Pump/Motor Efficiencies

- Ideal torque = torque required/generated for the ideal pump/motor
- Ideal flow = flow generated/required for the ideal pump/motor
- Torque loss (friction)
- Flow loss (leakage)
- Signs different for pumping and motoring mode

(Reverse if motor case !! )
Pumping Theory – Efficiency

\[
Q = x\omega D \left[ 1 - \frac{C_s}{x} \left( \frac{p}{\mu \omega} \right) - \left( \frac{p}{xB} \right) \left( V_r + \frac{1+x}{2} \right) \right]
\]

\[
T = xpD \left[ 1 + \frac{C_v}{x} \left( \frac{\mu \omega}{p} \right) + \frac{C_f}{x} \right]
\]

where:
- \( p \) = system pressure
- \( \mu \) = viscosity of hydraulic fluid
- \( \omega \) = rotational speed of pump/motor
- \( D \) = displacement of hydraulic unit
- \( x \) = fraction of maximum displacement
- \( B \) = Bulk modulus of hydraulic fluid
- \( C_s \) = coefficient of slip
- \( C_v \) = coefficient of viscous drag
- \( C_f \) = coefficient of coulomb (dry) friction
- \( V_r \) = volume ratio of hydraulic unit
Aeration and Cavitation
Aeration and Cavitation

• Disastrous events - cause rapid erosion

• Aeration
  • air bubbles enters pump at low pressure side (through leakage)
  • bubbles expand when absolute pressure is low (partial vacuum).
  • when fluid+air travel to high pressure side, bubbles collapse
  • micro-jets are formed which cause rapid erosion

• Cavitation
  • Dissolved air comes out of solution / Fluid evaporates (boils) in partial vacuum to form bubbles
  • bubbles expands then collapse
  • as bubbles collapse, micro-jets formed, causing rapid erosion

http://www.youtube.com/watch?v=eMDAw0TXvUo
Causes of cavitation and aeration

- For positive displacement pumps, the filling rate is determined by pump speed; \((Q\text{-demand}) = D \times \text{freq}\)

- Filling pressure = tank pressure - inlet pressure
  - \(Q\text{-actual} = f(\text{filling pressure, viscosity, orifice size, dirt})\)

- If \(Q\text{-actual} < Q\text{-demand}\), inlet pressure decreases significantly
  - This causes air to enter (via leakage) or to evaporation (cavitates)

- To prevent cavitation/aeration
  - increase tank pressure
  - low viscosity, large orifice
  - lower speed (hence lower \(Q\text{-demand}\))
Hydro-static Transmission

- A combination of a pump and a motor
  - Either pump or motor can have variable displacement

- Replaces mechanical transmission
  - By varying displacements of pump/motor, transmission ratio is changed

- Various topologies:
  - single pump / multi-motors
  - multi (pump-motor)
  - Open / closed circuit
  - Open / closed loop control

- Integrated package / split implementation
Hydrostatic Transmission
Closed Circuit Hydrostat Circuit

- Charge pump circuit (pump + shuttle valve)
- Bi-directional relief
- Closed circuit re-circulates fluid
- Open circuit systems draw and return flow to a reservoir
Hydrostat vs. Mechanical Transmission

• Advantages:
  • Infinite gear ratios - continuous variable transmission (CVT)
    • No interruption to power when shifting gear
  • High power, low inertia (relative to mechanical transmission)
  • Dynamic braking via relief valve
  • Engine does not stall
  • Compact packaging

• Disadvantage:
  • Lower energy efficiency (85% versus 92%+ for mechanical transmission)
  • Power transmission goes through both pump and motor
    • Improvement: hydro-mechanical transmission (HMT) or power-split!
  • Leaks!
Hydrostatic Transmission

- Let pump and motor displacements be $D_1$ and $D_2$, with one or both being variable.
- Let the torque (Nm) and speeds (rad/s) of the pump and motor be $(T_1, S_1)$ and $(T_2, S_2)$
- Assuming ideal pumps and motors:

\[
Q = \frac{S_1 D_1}{2\pi} = \frac{S_2 D_2}{2\pi}
\]

\[
\Delta P = 2\pi \frac{T_1}{D_1} = 2\pi \frac{T_2}{D_2}
\]

\[
\frac{S_2}{S_1} = \frac{D_1}{D_2}
\]

\[
\frac{T_2}{T_1} = \frac{D_2}{D_1}
\]

Transmission ratio Variable by varying $D_1$ or $D_2$

Infinite and negative ratios possible if pump can go over-center

Note: $Pow_{in} = S_1 T_1 = S_2 T_2 = Pow_{out}$
**Hydraulic Transformer**

- Used to change pressure in a power conservative way
- Pressure boost or buck is accompanied by proportionate flow decrease and increase
- Note: Hydrostatic transmission can be thought of as a mechanical transformer (torque boost/buck)

\[
\begin{align*}
Q_1 & \rightarrow & \Delta P_1 & \rightarrow & Q_2 \\
D_1 & \rightarrow & \Delta P_1 & \rightarrow & D_2 \\
\end{align*}
\]

Research opportunity!
How Hybrid Vehicles Save Energy?

With a secondary power source/storage, it is possible to:

- Manage engine operation
- Store/reuse braking energy
- Turn off engine
- Downsize engine for continuous power

Example vehicle on EPA-UDDS cycle:
- Baseline (10% engine efficiency): 24 mpg
- Engine management (38% efficiency): 95 mpg
- Above with regeneration: 140 mpg
Hydraulic Accumulators

- Energy Storage Device
- Oil Compresses a Pre-Charged Gas (Nitrogen)
**Why Hydraulic Hybrids?**

Why not stick with electric hybrids?
- Electric batteries / ultracaps (cost, reliability, recycling, power density)
- Electric motors & inverters (cost, power density)
- Affect overall cost, weight, and power

**Metrics**
- Fuel economy
- Cost
- Performance
Hybrid Hydraulic versus Hybrid Electric Vehicle

- Hydraulic pump/motor have significantly higher power density than electric motor/generator (16:1 by weight, 8:1 by volume)
- Hydraulic drives have much lower torque density than electric drives
- Accumulators are 10x more power dense than batteries
- Efficient power electronics are expensive

- Batteries have 2 order magnitude higher energy density than accumulators
- Current hydraulic systems tend to be noisy and leaky

- Overall tradeoff: Hydraulic hybrids can be significantly lighter and cheaper than electric hybrids if energy density limitation can be solved.
# Hydraulic Hybrids Versus Electric Hybrids

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<thead>
<tr>
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<th>Electric</th>
<th>Fluid Power</th>
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<tr>
<td><strong>Performance</strong></td>
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<tr>
<td>• acceleration</td>
<td>--</td>
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<td>• regenerative braking</td>
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<tr>
<td><strong>Component efficiency</strong></td>
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<tr>
<td><strong>Regenerative efficiency</strong></td>
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<tr>
<td><strong>Weight</strong></td>
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<td><strong>Cost</strong></td>
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<td><strong>Reliability</strong></td>
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<tr>
<td><strong>Environmental impact</strong></td>
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<td>+</td>
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<tr>
<td><strong>Energy storage</strong></td>
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<td><strong>NVH</strong></td>
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**Realize opportunities for**
- Both performance & efficiency
- Cost and reliability

**Overcome threats in**
- Inefficient components
- Low density energy storage
- Noise, vibration, harshness
**Parallel Architecture**

Example: HLA system for F150 & garbage trucks

- Regenerates braking energy
- Utilizes efficient mechanical transmission
- Does not allow full engine management

![Engine BSFC Diagram](image)

**Achievable engine op. points**
**Series Architecture**

- **Example:** Eaton/UPS (truck), Ford/EPA (Escape), Artemis (BMW-5), …
  - Regenerates braking energy
  - Allows for full engine management
  - Independent wheel torque control possible
  - All power must be transmitted through fluid power components

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![Diagram showing series architecture with components labeled for normal driving operating range at 10-15% and maximum performance at 38%.]
**Power-Split: Hydromechanical Transmission (HMT)**

- Power split between mechanical and hydraulic paths
  - Hybridized HMT – i.e. w/ regeneration
Overall efficiencies of Hybrid Architectures

- Series / HMT at peak engine efficiency (38.5%)
- Parallel at lower engine efficiency (33%)

\[
\%_{mech} = 40\%
\]

\[
\eta_{mech} = 98\%
\]
New Experimental Systems
Servo-Hydraulics

- Directional control valve
- Proportional valve
- Servo-valve
Directional Control Valve

Discrete positions only:
- either 1 or 2 (or 3)
Four Way Directional Control Valve

Figure 5.3 Three-land-four-way spool valve.
**Single Stage Proportional Valves**

- Infinite position (partially open/closed orifices)
- Solenoids **Create Spool Displacement**
- LVDT Spool Position Feedback
- Spring (sometimes) for Safety
Single Stage Proportional Valves

• **Advantages:**
  - Simple design
  - Reliable
  - Cost effective

• **Disadvantages:**
  - Poor dynamic performance (bandwidth)
  - At high flow rates and bandwidths, large stroking force is needed
  - Large (and expensive) solenoids / torque motors needed.
  - Low end market ….
Multi-stage valves

- Use hydraulic force to drive the spool ….
Electrohydraulic servo-valve

- Multi-stage valve
- Typically uses a flapper-nozzle pilot stage
- Built-in feedback via feedback wire
- Very high dynamic performance
- Bandwidth = 100-200+Hz

For a fun place to learn how a servo-valve works:
R. Dolid “Electrohydraulic Valve Coloring Book”
Servo-Valve
**Servo-Valve**

Nozzle-flapper pilot valve:
1. Electromagnetic torque motor moves flapper to left (or right)
2. Nozzle and restriction at source form two resistances in series
3. Flapper differentially opens and closes nozzle
4. Pressure increases on side with closed nozzle; decreases on side with open nozzle; creating pressure differential

Feedback spring:
1. Regulates the position of the main-stage by negative feedback on the flapper

Main stage:
1. Four-way spool valve actuated by differential pressure generated by pilot stage