Project 16ST1: AC Hydraulic Pump/Motor

Mengtang Li, Graduate Student, Vanderbilt University
Ryan Foss, Graduate Student, University of Minnesota
Prof. Kim Stelson
Prof. James Van de Ven
Prof. Eric Barth
Hydraulic Pump

Common Fixed Displacement Pump:
• Gear Pump
• Vane Pump
• Bent Axis Pump
• Axial Piston Pump
• Radial Piston Pump

Common Variable Displacement Pump:
• Swash-Plate Axial Piston Pump
• Bent Axis Pump

Goal:
• Variable Displacement
• Compactness
• Simple Structure
• High Efficiency
AFH Variable Displacement Pump

Piston 1
Piston 2
(Phase adjusting)
Combined Waveform

Piston Stroke
Basic Idea of AFH VDP

Phase Shift = 0°, Fractional Displacement = 1

![Diagram of AFH VDP](image)
Basic Idea of AFH VDP

Phase Shift = 180°, Fractional Displacement = 0

![Diagram showing phase shift and fractional displacement](image)

![Graph showing phase shift vs fractional displacement](image)

![Graph showing flow rate for phase shift = 180°](image)
Basic Idea of AFH VDP

Phase Shift = 90°, Fractional Displacement = 70.83%
AFH VDP Prototype 1

8 Discrete Phases

3CP1120

2018 CCEFP
AFH VDP Prototype 1

- Output Flow Sens.
- Pipes connecting cylinder chambers
- Sprocket-chain
- Torque Sens.
- CAT 3CP1120

Input, Output, and Cylinder Pressure Sens.
AFH VDP Model

- The model captures piston kinematics and cylinder pressure as functions of the pump’s phase shift angle.

\[
\begin{align*}
\gamma_1 &= r(1 - \cos \theta) + l - \sqrt{l^2 - r^2 \sin^2 \theta} \\
\gamma_2 &= r(1 - \cos(\theta + \varphi)) + l - \sqrt{l^2 - r^2 \sin^2(\theta + \varphi)} \\
V_{cyl,1} &= V_{tdc} + A_p \left[ r(1 - \cos \theta) + l - \sqrt{l^2 - r^2 \sin^2 \theta} \right] \\
V_{cyl,2} &= V_{tdc} + A_p \left[ r(1 - \cos(\theta + \varphi)) + l - \sqrt{l^2 - r^2 \sin^2(\theta + \varphi)} \right] \\
\dot{V}_{cyl,1} &= A_p \omega r \left[ 1 + \frac{r \cos \theta}{\sqrt{l^2 - r^2 \sin^2 \theta}} \right] \\
\dot{V}_{cyl,2} &= A_p \omega r \left[ 1 + \frac{r \cos(\theta + \varphi)}{\sqrt{l^2 - r^2 \sin^2(\theta + \varphi)}} \right] \\
\dot{p}_{cyl,i} &= \frac{\beta_{eff}}{V_{cyl,i}} (Q_{in,i} - Q_{out,i} - Q_{leak,i} - \dot{V}_{cyl,i} - Q_{con})
\end{align*}
\]
AFH VDP Model

- The model captures flows between pairs of cylinders as functions of the pump’s phase shift angle.
AFH VDP Model

- The model also captures check valve dynamics

AFH VDP Model

- The model also captures input motor torque
AFH VDP Model

• The model also considers
  1. Leakage

\[ Q_{\text{leak},i} = \frac{\pi d^2 h^3}{12\mu l_p} (P_{\text{cyl},i} - P_o) \]

2. Viscous friction

\[ F_{\text{viscous},i} = \frac{\pi d^2 l_p \mu}{h_p} \dot{v}_i \]

3. Effective bulk modulus

\[ \beta_{\text{eff}} = \beta_0 \left[ \left( \frac{P_{\text{cyl},i}}{P_o} \right)^\frac{1}{\gamma} e^{\frac{P_o - P_{\text{cyl},i}}{\beta_o}} + K \left( \frac{P_{\text{cyl},i}}{P_o} \right)^\frac{1}{\gamma} e^{\frac{P_o - P_{\text{cyl},i}}{\beta_o}} + K \right] \]
AFH VDP Model

A Dynamic Model using first principles captures
• Piston kinematics and dynamics
• Cylinder pressure
• Flows between pairs of cylinders
• Net inlet and outlet flows as functions of the pump’s phase shift angle.

The model also captures
• Hydraulic check valve dynamics
• The effective bulk modulus
• Leakage flows
• Viscous friction
• Input motor torque

Input: Downstream Pressure, Motor Speed, Phase Shift Angle
Output: Cylinder Pressure, Flowrates*, Energy*. 
AFH VDP Model Validation

(a) $\phi = 2^\circ$, 250 rpm

(b) $\phi = 2^\circ$, 250 rpm

(c) $\phi = 165^\circ$, 250 rpm

(d) $\phi = 165^\circ$, 250 rpm
AFH VDP Model Validation

- **$\phi = 2^\circ$**
  - 250 rpm
  - 1000 psi

- **$\phi = 165^\circ$**
  - 250 rpm
  - 1000 psi
AFH VDP Model Validation

Results start to deviate from model due to large dead volume.

Large dead volume, viscous losses and friction in chain and seals.
Phase Shift 1 – Differential Gear

- One *wide hollow* shaft (to drive one cam) and one *narrow long* shaft (to drive the other cam).
- The differential gear set can be placed at one side of a radial piston pump, thus reducing the distance between two parallel pumping units and shortening the connecting pipe size.
- The whole size of this phase shift mechanism can be small. For illustration purpose, it is larger here.
Phase Shift 2 – Pin in Slot

Cam 1        Cam 2

* Credits go to Caroline for her great work.
Phase Shift 3 – Toyota Phaser

In Phase

Out of Phase
Thank You!
Question?

Mengtang Li
Mengtang.li@Vanderbilt.edu
Ryan Foss
fossx231@umn.edu