Design and Modeling of Fluid Power Systems

ME 597/ABE 591 - Lecture 13

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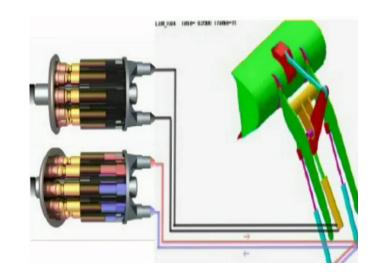MAHA Fluid Power Research Center
Purdue University

- Design and modeling of electrohydraulic pump control system

- Displacement controlled linear actuator

- Displacement controlled rotary actuator
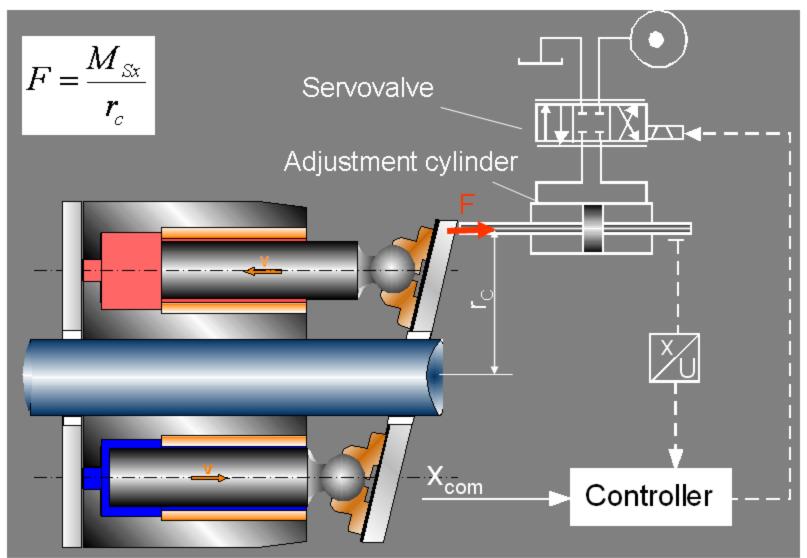
- Secundary controlled actuator

Swash plate control system

Electrohydraulic swash plate control system

$$F = \frac{M_{Sx}}{r_c}$$

Servovalve

Adjustment cylinder

F

r_c

v

v

$\frac{X}{U}$

X_{com}

Controller

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Swash plate moment M_{Sx}

$$M_{Sx} = \frac{R}{\cos^2 \beta} \cdot \sum_{i=1}^{z} F_{AKi} \cos \varphi_i$$
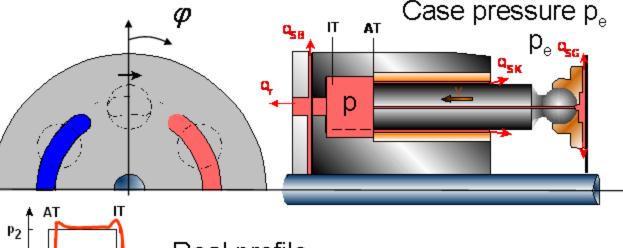
$$Q_S = f(\Delta p, n, V_i, \mu)$$

f(p_i) instantaneous cylinder pressure

$$F_{AK} = F_{DK} + F_{aK} + F_{TK}$$

$$\frac{dp}{d\varphi} = -\frac{K}{\omega} \left(\frac{v_K \cdot A_K - Q_r - Q_{SK} - Q_{SB} - Q_{SG}}{V_0 - s_K \cdot A_K} \right)$$

$$F_{DK} = A_K \cdot (p - p_e)$$

Case pressure p_e

$$M_{Sx} = f(\Delta p, n, V_i, \mu)$$

Real profile

$$d\varphi = \omega \cdot dt$$

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Swash plate moment M_{Sx}

$$M_{Sx} = \frac{R}{\cos^2 \beta} \cdot \sum_{i=1}^{z} F_{AKi} \cdot \cos \varphi_i$$
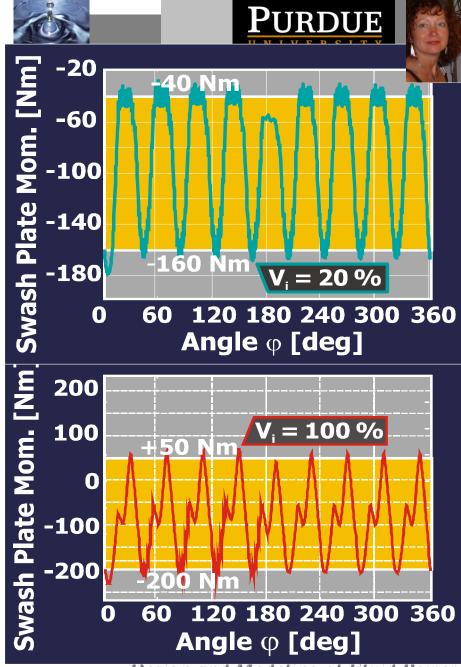

$V_i = 20 \%$

$V_i = 100 \%$

$\Delta p = 300$ bar
$n = 2000$ rpm

$$M_{Sx} = f \left(\Delta p, n, V_i, \mu \right)$$

-40 Nm

-160 Nm

$V_i = 20 \%$

+50 Nm

$V_i = 100 \%$

-200 Nm

5
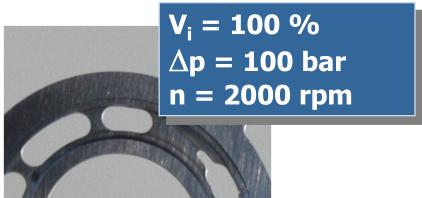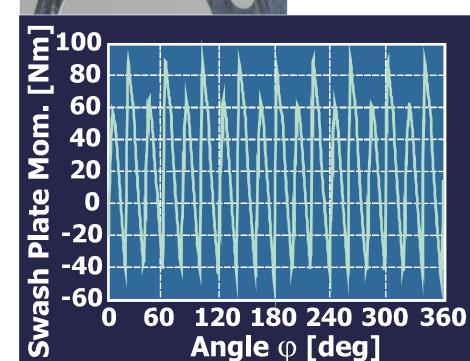
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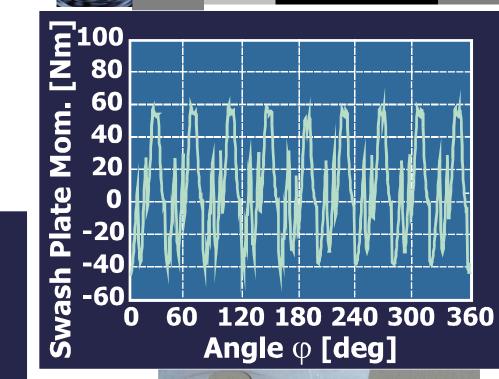
Influence of the Valve Plate Design

$V_i = 100\ \%$
$\Delta p = 100\ \text{bar}$
$n = 2000\ \text{rpm}$

$$M_{Sx} = f\left(\varphi\right)$$
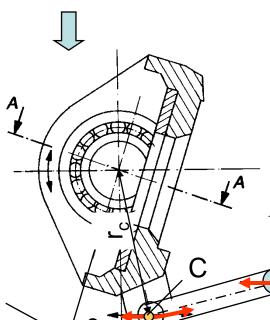
$$H = 2 \cdot x_{\max} = 2 \cdot r_c \cdot \tan \beta_{\max} \quad (2)$$
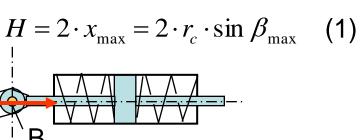
Connecting rod less

or

Connecting rod joint

Sliding motion

$$H = 2 \cdot x_{\max} = 2 \cdot r_c \cdot \sin \beta_{\max} \quad (1)$$

C

B

ß

r_c

Swash Plate Bearing Design Examples

$$F_S = \sqrt{F_{Sy}^2 + F_{Sz}^2} = F_N = \sum_{i=1}^{z} F_{NSi}$$

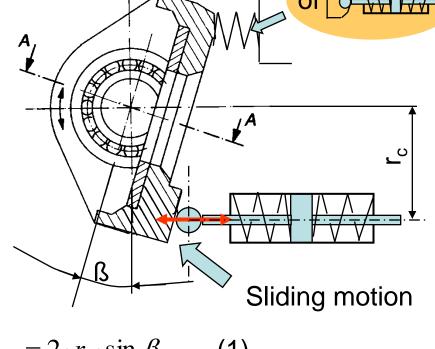$$M_{Sy} = -\sum_{i=1}^{z} F_{Szi} \cdot x_{Si} = -R \cdot \sum_{i=1}^{z} F_{AKi} \cdot \sin \varphi_i$$

$$M_{Sz} = -R \cdot \left(\sum_{i=1}^{z} F_{TSi} + \tan \beta \cdot \sum_{i=1}^{z} F_{AKi} \cdot \sin \varphi_i \right)$$

must be carried by swash plate bearing

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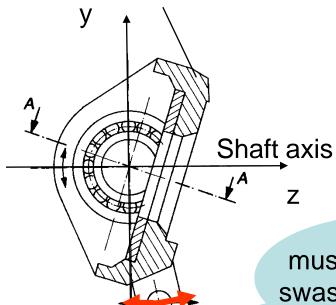
Swash Plate Bearing – Design Examples

In case of variable displacement pumps very often radial bearings are used

Swash plate

y

A

Shaft axis

z

A - A

x

Swash plate

Shaft axis

z
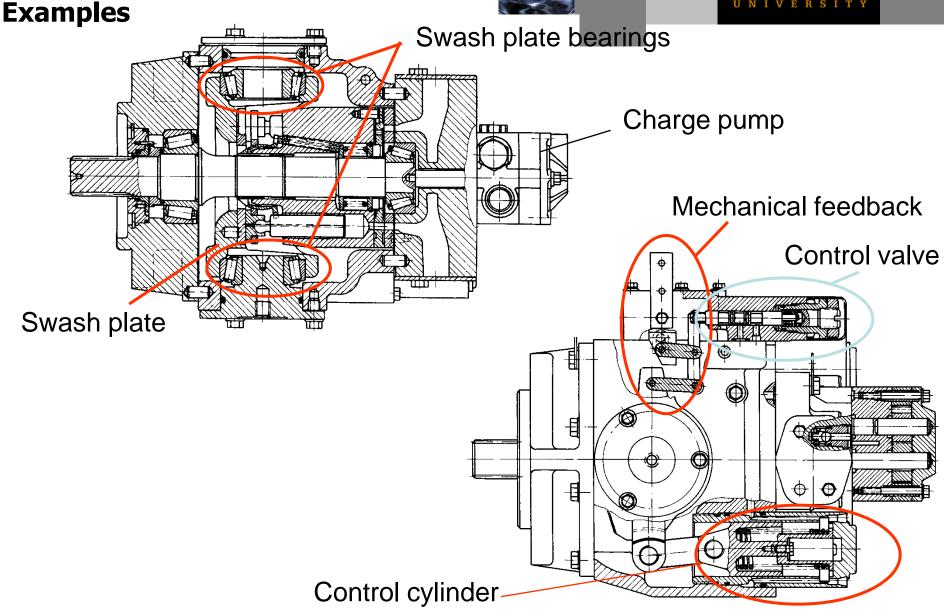
must be carried by swash plate bearing

$$F_S = \sqrt{F_{Sy}^2 + F_{Sz}^2}$$

$$M_{Sz} = -R \cdot \left(\sum_{i=1}^{z} F_{TSi} + \tan \beta \cdot \sum_{i=1}^{z} F_{AKi} \cdot \sin \varphi_i \right)$$

$$M_{Sy} = -\sum_{i=1}^{z} F_{Szi} \cdot x_{Si} = -R \cdot \sum_{i=1}^{z} F_{AKi} \cdot \sin \varphi_i$$

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Swash Plate Bearing – Design Examples

Swash plate bearings

Charge pump

Swash plate

Mechanical feedback

Control valve

Control cylinder

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Design of swash plate control system

Swash plate control cylinder $\quad H = 2 \cdot x_{max} = 2 \cdot r_c \cdot \tan \beta_{max}$

m... moveable mass

$$m \cdot \frac{d^2 x}{dt^2} + d \cdot \frac{dx}{dt} + F + c \cdot x = A(p_A - p_B)$$

$$F = \frac{M_{Sx}}{r_c}$$

d... coefficient of viscous friction
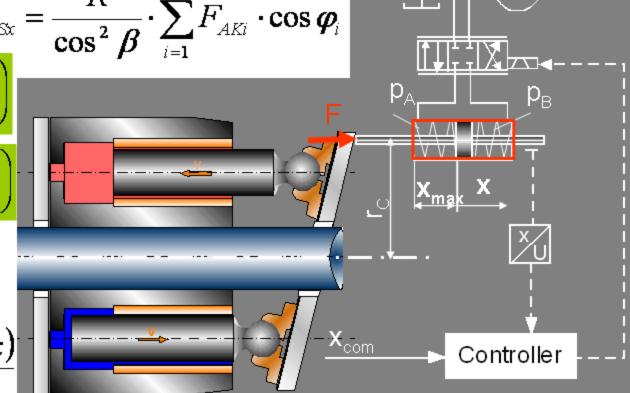
c... spring constant

$$M_{Sx} = \frac{R}{\cos^2 \beta} \cdot \sum_{i=1}^{z} F_{AKi} \cdot \cos \varphi_i$$

$$\frac{dp_A}{dt} = \frac{1}{C_{HA}} \left(Q_A - Q_{Si} - A \cdot \frac{dx}{dt} \right)$$

$$\frac{dp_B}{dt} = \frac{1}{C_{HB}} \left(-Q_B + Q_{Si} + A \cdot \frac{dx}{dt} \right)$$

$$C_{HA} = \frac{V_{deadA} + A \cdot (x_{max} + x)}{K}$$

$$C_{HB} = \frac{V_{deadB} + A \cdot (x_{max} - x)}{K}$$

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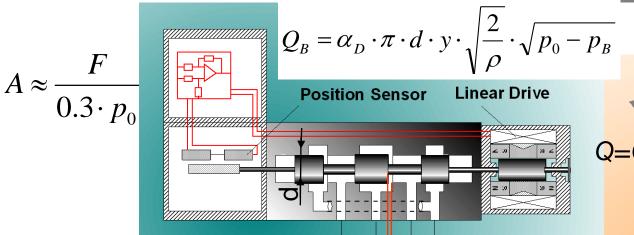
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Design of swash plate control system

Selection of control valve

$$Q_B = \alpha_D \cdot \pi \cdot d \cdot y \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{p_0 - p_B}$$

$p_{nomSV} = 70 \, bar$

$p_L = p_A - p_B$

$$A \approx \frac{F}{0.3 \cdot p_0}$$

Position Sensor   **Linear Drive**

$Q = Q_A = Q_B$ 1   2

A p_0 B

y

Valve size:

$$Q_{nom} = B \cdot y_{max} \sqrt{\frac{p_{nom}}{2}}$$

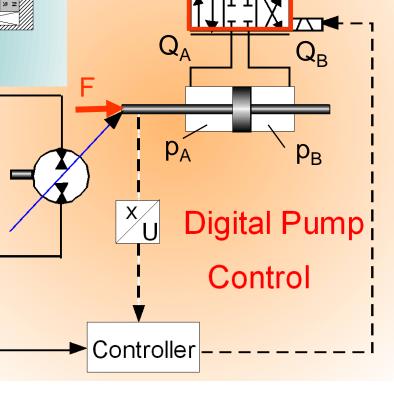$$B = \alpha_D \cdot \pi \cdot d \cdot \sqrt{\frac{2}{\rho}}$$

Q_A Q_B

F

p_A p_B

Required flow rate:

$$Q = A \cdot \dot{x}_{max}$$

$$\dot{x}_{max} = \frac{2 \cdot x_{max}}{t_{min}}$$

x / U

Digital Pump Control

$$Q_{nom} = Q \cdot \sqrt{\frac{p_{nom}}{p_0 - p_L}}$$

x_{com} → Controller

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Design of swash plate control system

Main design requirements:

- Low power

- High bandwidth

- Min time t_{min} for ß=0 to ß=ß$_{max}$ (20 ms up to 200 ms)
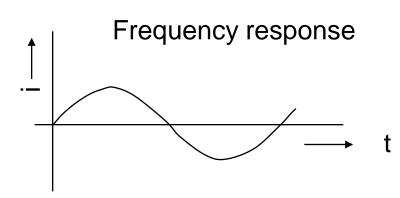
$$Q_{nom} = Q \cdot \sqrt{\frac{p_{nom}}{p_0 - p_L}}$$

Maximal flow rate

$$x = \hat{x} \cdot \sin(\omega \cdot t)$$

$$\dot{x} = \hat{x} \cdot \omega \cdot \cos(\omega \cdot t)$$

$$\ddot{x} = -\hat{x} \cdot \omega^2 \cdot \sin(\omega \cdot t)$$

Frequency response

Servovalve input current

$$i(t) = \hat{i} \cdot \sin(\omega \cdot t)$$

Pressure required to realized necessary acceleration

$$A \cdot p_{\ddot{x}} = m \cdot \ddot{x}$$

$$p_{\ddot{x}} = \frac{m}{A} \cdot \hat{x} \cdot \omega^2 \cdot \sin(\omega \cdot t)$$

Pressure required for velocity

$$A \cdot \dot{x} = Q_{nom} \cdot \sqrt{\frac{p_{\dot{x}}}{p_{nom}}}$$

$$p_{\dot{x}} = \frac{p_{nom}}{Q_{nom}^2} \cdot (\hat{x} \cdot \omega \cdot \cos(\omega \cdot t))^2 \cdot A^2$$

Maximal value

$$\frac{dp_{dyn}}{dt} = 0$$

$$\frac{dp_{dyn}}{dt} = \frac{p_{nom}}{Q_{nom}^2} \cdot \hat{x}^2 \cdot \omega^3 \cdot 2 \cdot \cos(\omega \cdot t) \sin(\omega \cdot t) A^2 + \frac{m}{A} \cdot \hat{x} \cdot \omega^3 \cdot \cos(\omega \cdot t) = 0$$

Maximal value $\Longrightarrow$

$$\sin(\omega \cdot t) = \frac{m \cdot Q_{nom}^2}{2 \cdot p_{nom} \cdot \hat{x} \cdot A^3}$$

Q_{nom}

Design of swash plate control system

Swash plate moment M_{Sx}
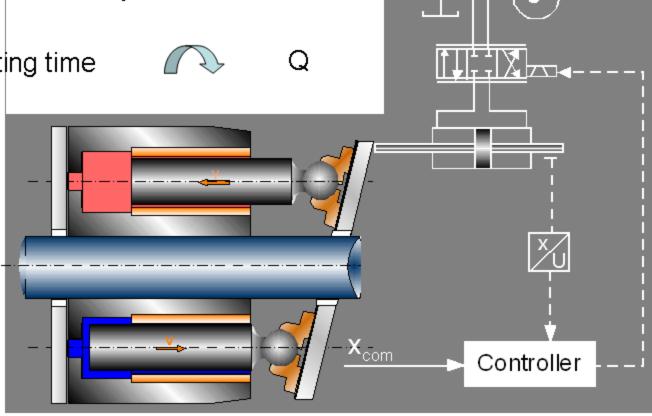
Supply pressure p_0

$$F = \frac{M_{Sx}}{r_c}$$

Effective piston area of control cylinder

Response time, adjusting time Q

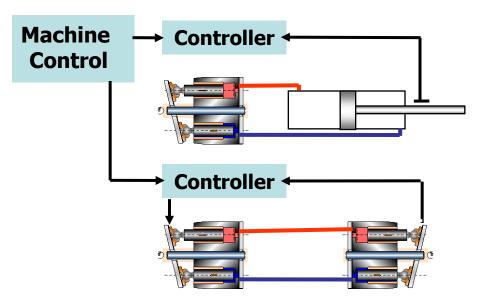Servovalve or proportional valve size
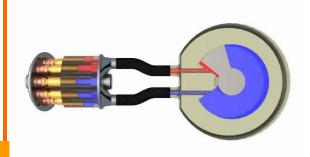
Swash plate controller

x_{com}

Controller

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Displacement controlled actuator

Advanced Energy Saving Actuator Technology

Machine Control → **Controller** ←

Controller ←

Mobile Robots

Successfully tested on laboratory test rig

New Valveless Rotary Actuator

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Displacement controlled actuator

- **Advanced Energy Saving Actuator Technology**
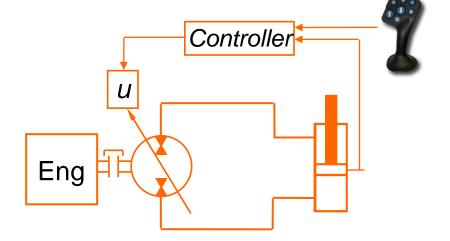
Pump control instead valve control

What are the advantages ?

Better Utilization of Primary Energy

Energy Recovery

Easier to Control

System Simplification

Less weight & space

New Linear Actuator

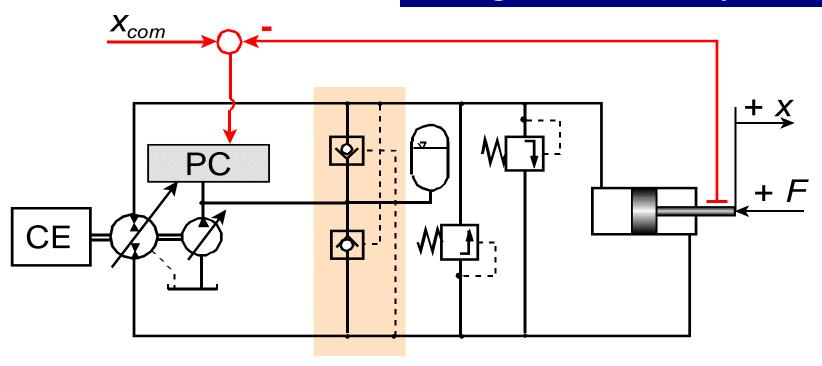*Controller*

u

Eng

Less fuel consumption

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Displacement Controlled Linear Actuator

Using a Differential Cylinder

X_{com}

-

PC

CE

+ x

+ F
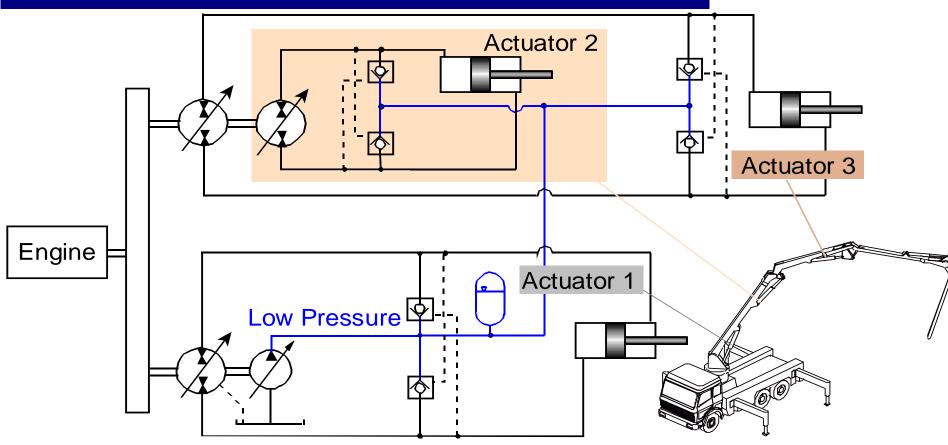
New linear actuator with single road cylinder
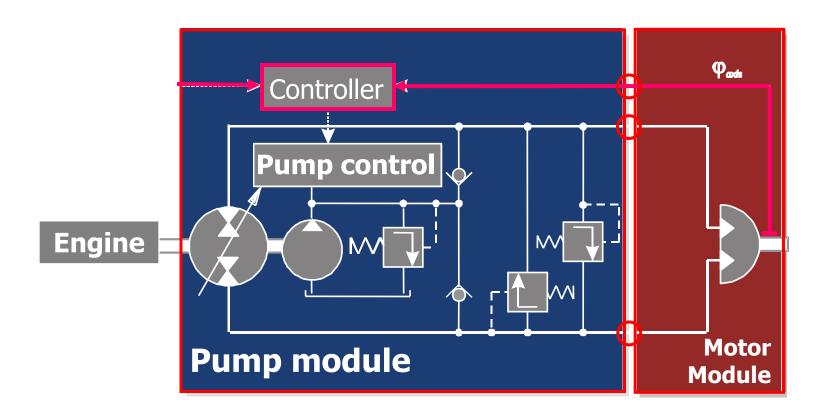
Joint Low Pressure Net for Connected Actuators

Actuator 2

Actuator 3

Engine

Actuator 1

Low Pressure

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Displacement controlled rotary actuator

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Possible applications?

Steering System

Stabilizer – roll control

Vehicle Suspension System – active damping control

Power Split Drive Technology using Hydrostatic Transmission

Cabriolet Roof Actuation and others
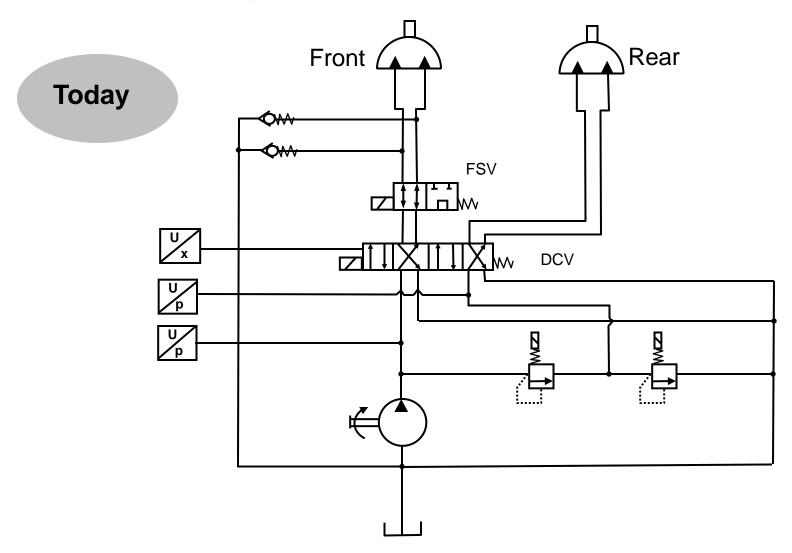
➡️ **Systems with linear or rotary actuator movement**

Active roll stabilization

Valve controlled system

Today

Front   Rear

FSV

U/x

U/p

U/p

DCV

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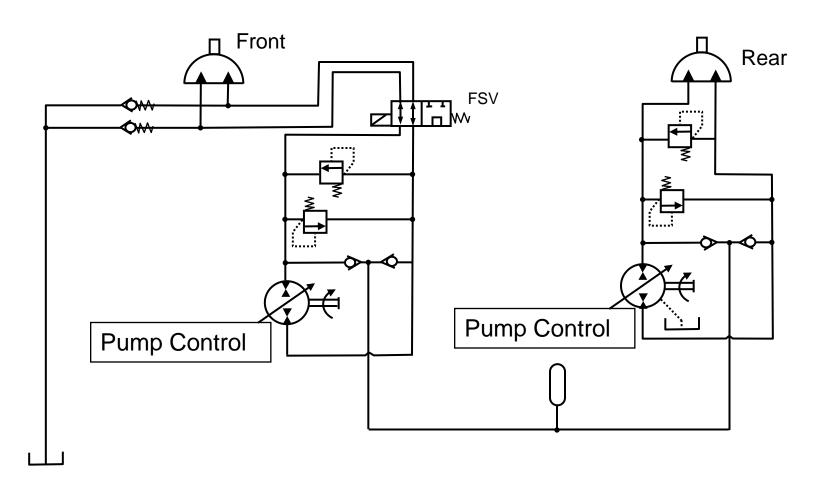
Active roll stabilization

Alternative Solution

Front

Rear

FSV

Pump Control

Pump Control
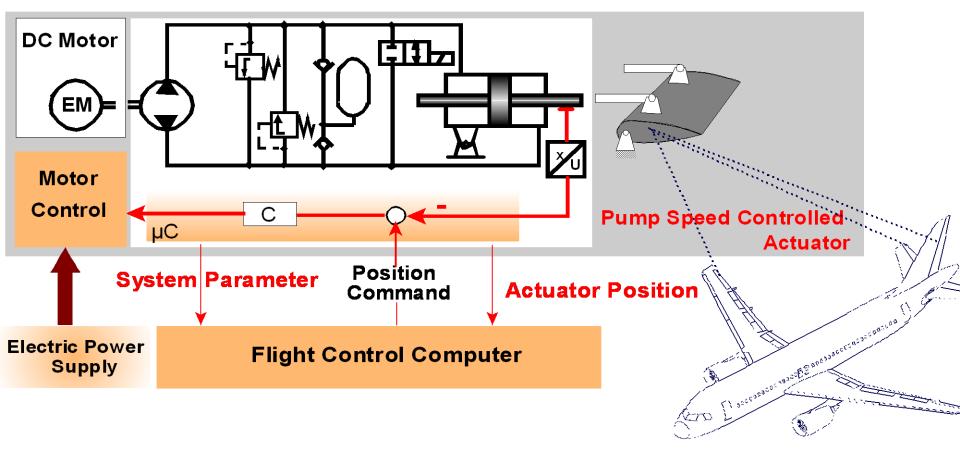
➡ **Fuel savings by valveless actuator technology**

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EHA with fixed displacement pump

Examples - Primary Flight Control

DC Motor

EM

Motor Control

µC

C

-

Pump Speed Controlled Actuator

System Parameter

Position Command

Actuator Position

Electric Power Supply

Flight Control Computer

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Examples - Primary Flight Control

Electric Power Supply

Flight Control Computer

System Parameter **Position Command** **Actuator Position**

µC   C   –   **Displacement Controlled Actuator**

U / x

EM

AC Motor
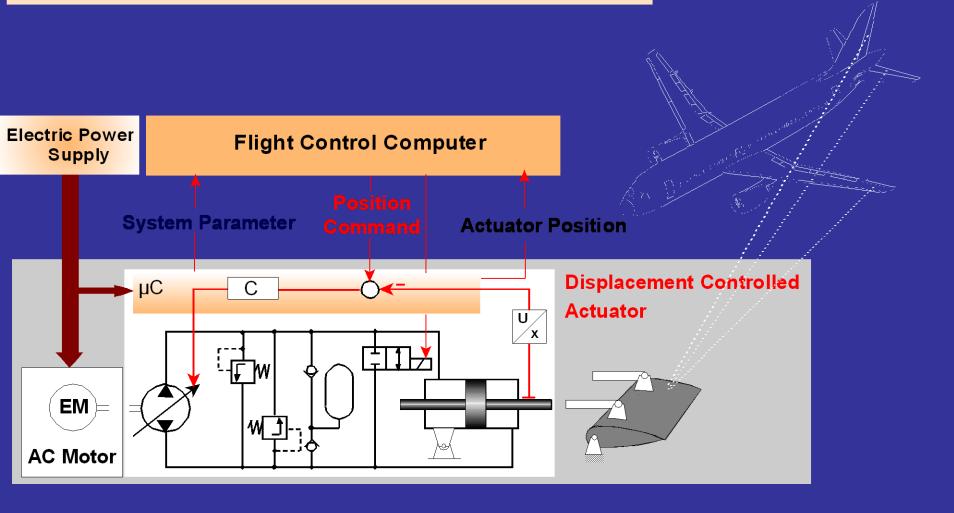
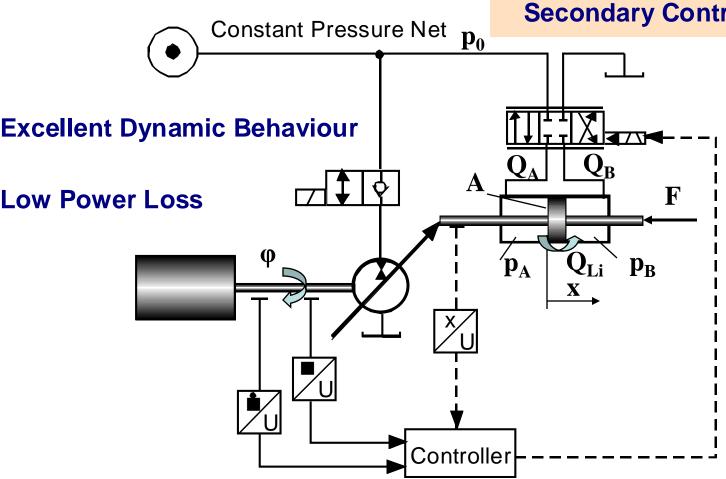# Secondary controlled actuator

Requires constant pressure supply

$$M_{Sx} = \frac{R}{\cos^2 \beta} \cdot \sum_{i=1}^{z} F_{AKi} \cdot \cos \varphi_i$$

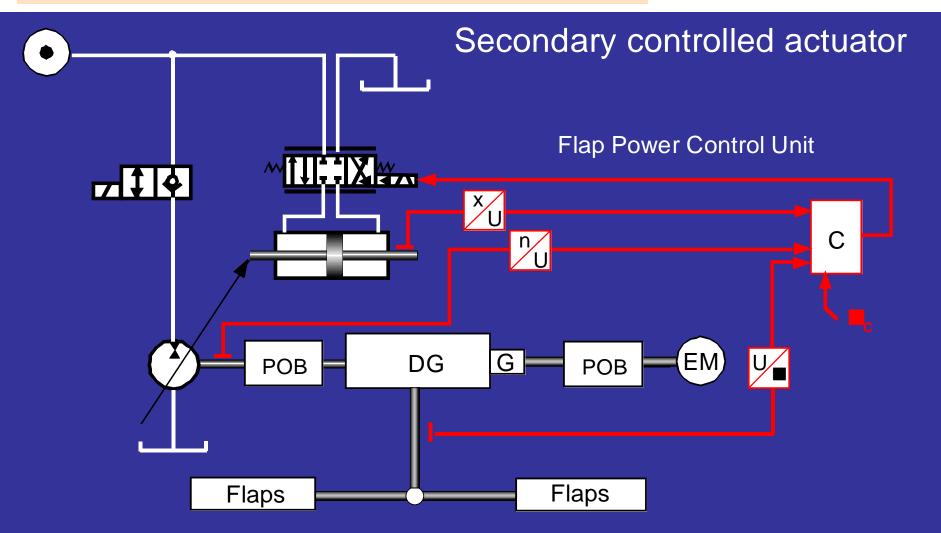**Displacement Controlled Rotary Drive**

Secondary Controlled Drive

Constant Pressure Net p_0

Excellent Dynamic Behaviour

$$F = \frac{M_{Sx}}{r_c}$$

Low Power Loss

Q_A Q_B

A

F

φ

p_A Q_{Li} p_B

x

X/U

■/U

▲/U

Controller
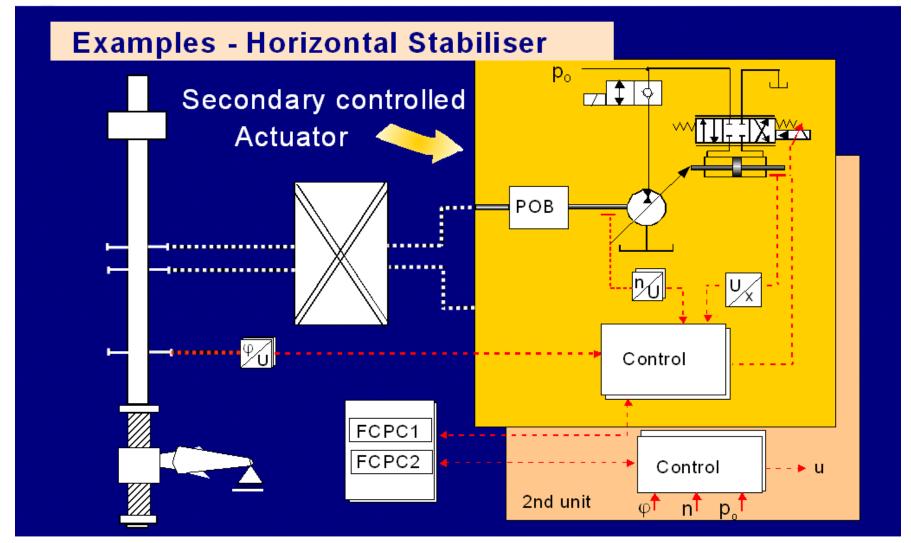
Examples - High Lift System

Secondary controlled actuator

Flap Power Control Unit

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Secondary controlled actuator

Examples - Horizontal Stabiliser

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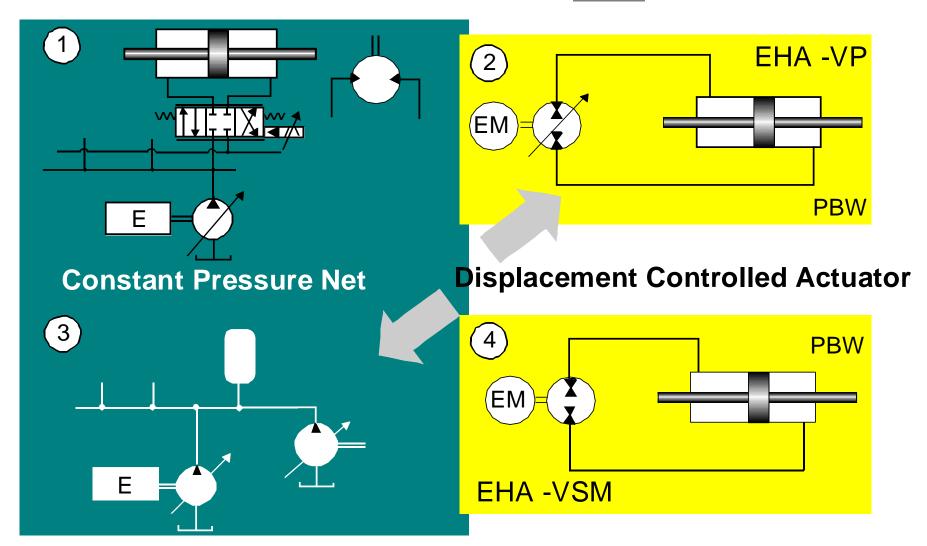
Hydraulic actuator principles

Constant Pressure Net

Displacement Controlled Actuator

EHA -VP

PBW

EHA -VSM

PBW

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Classification & Main System Properties

Valve Controlled Actuator

1

Proportional valve

Servovalve

LS- valve

- Energy Dissipation
- High Bandwith
- Central Pressure Supply
- ~~Energy Recover~~

Displacement Controlled Actuator

2

Pump Control

Secondary Control

- ~~Central Pressure Supply~~
- Energy Recover
- High Bandwith
- Central Pressure Supply

Speed Controlled Actuator

3

Electric Motor Control

- ~~Central Pressure Supply~~
- Energy Recover

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