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Valve-based compensation for controllability improvement of the energy-saving electrohydraulic flow matching system

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Introduction

- Current mobile machinery
  - High energy consumption
  - Low energy efficiency
  - Poor adaptability under different load conditions
- Regulations and standards

  « …exhaust pollutants … of non-road mobile machinery (IV)»
- Demand of mobile hydraulics
  - High efficiency
  - Good controllability
  - High safety performance

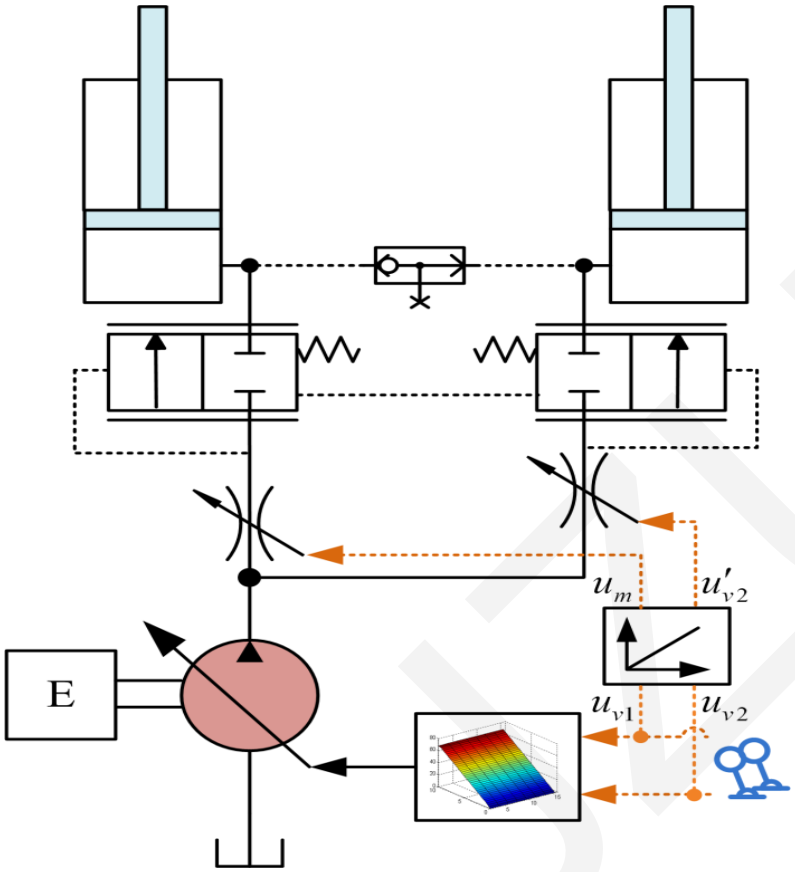






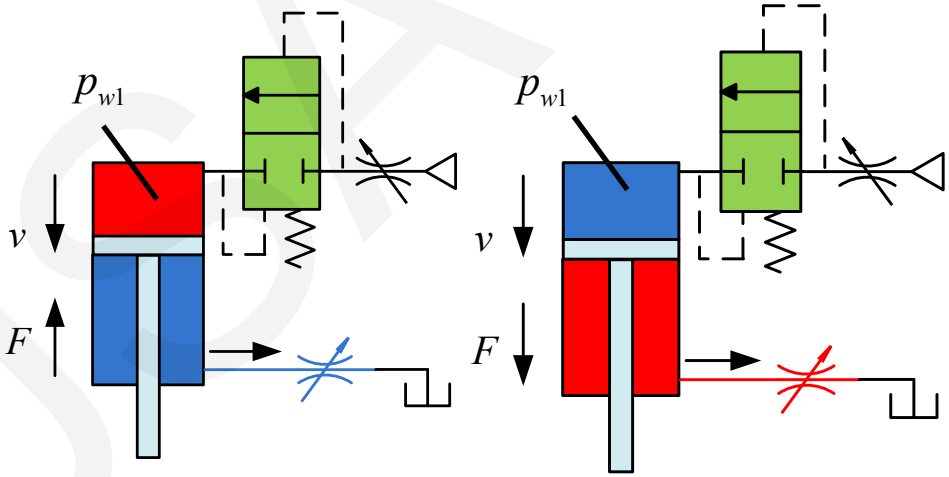

Problem statement

●Energy saving with EFM control



$$q_{v1} = C_{d1} f_1(u_{vm}) \sqrt{\frac{2\Delta p_c}{\rho}} \qquad q_{v2} = C_{d2} f_2(u_{v2}) \sqrt{\frac{2\Delta p_c}{\rho}}$$

●Problem statement



Resistive loads Overrunning loads

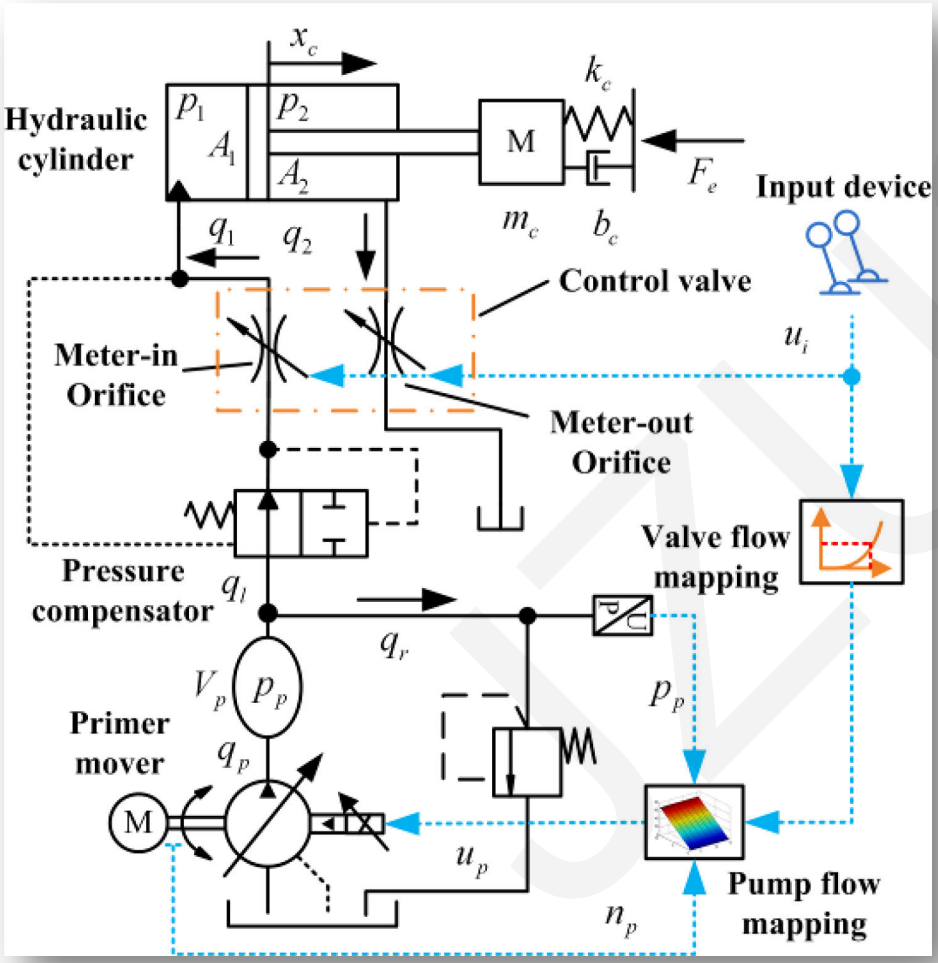
●In overrunning loads, the velocity control performance is deformed.

●How to identify load condition?

●How to control the valve opening to minimize its pressure loss ?

System modeling

- **System layout based on electrohydraulic flow matching**



- **Mathematical model**

$$p_p(s)=\frac{\beta_e}{V_p s}\left[q_p(s)-q_l(s)\right]$$

$$q_2(s)=k_q x_v(s)+k_{pq}p_2(s)$$

$$(m_c s+b_c+\frac{k_c}{s})v_c(s)=A_1 p_1(s)-A_2 p_2(s)-F_e(s)$$

$$q_l(s)=q_1(s)=A_1 v_c(s)+\frac{V_1}{\beta_e}sp_1(s)$$

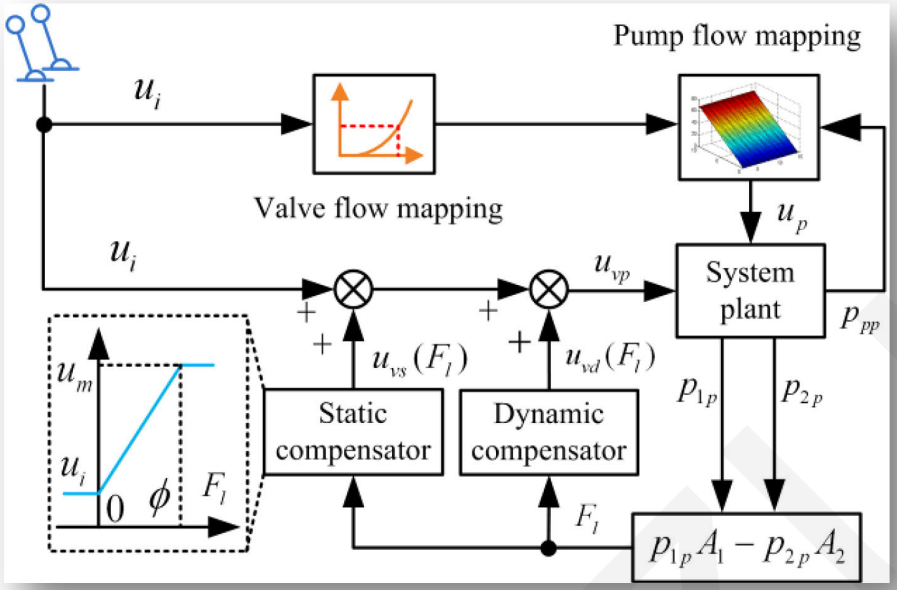
$$q_2(s)=A_2 v_c(s)-\frac{V_2}{\beta_e}sp_2(s)$$

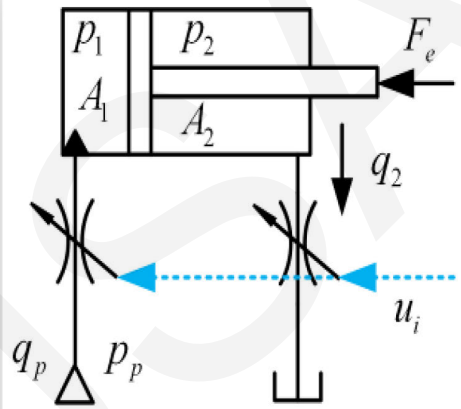
- **System velocity**

$$v_c(s)=\frac{B(s)}{A(s)}q_p(s)+\frac{C(s)}{A(s)}x_v(s)+\frac{D(s)}{A(s)}F_e(s)$$

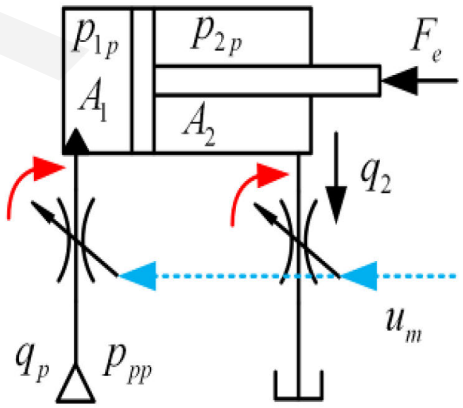
Valve-based compensation method

- **Compensator design**





(a) System by the traditional controller



(b) System by the proposed controller

Valve signal: $u_{vp} = u_i + u_{vs}(F_l) + u_{vd}(F_l)$

$$u_{vs}(F_l) = \begin{cases} u_m - u_i, F_l > \phi \\ \dfrac{F_l}{\phi}(u_m - u_i), 0 \le F_l \le \phi \\ 0, F_l < 0 \end{cases}$$

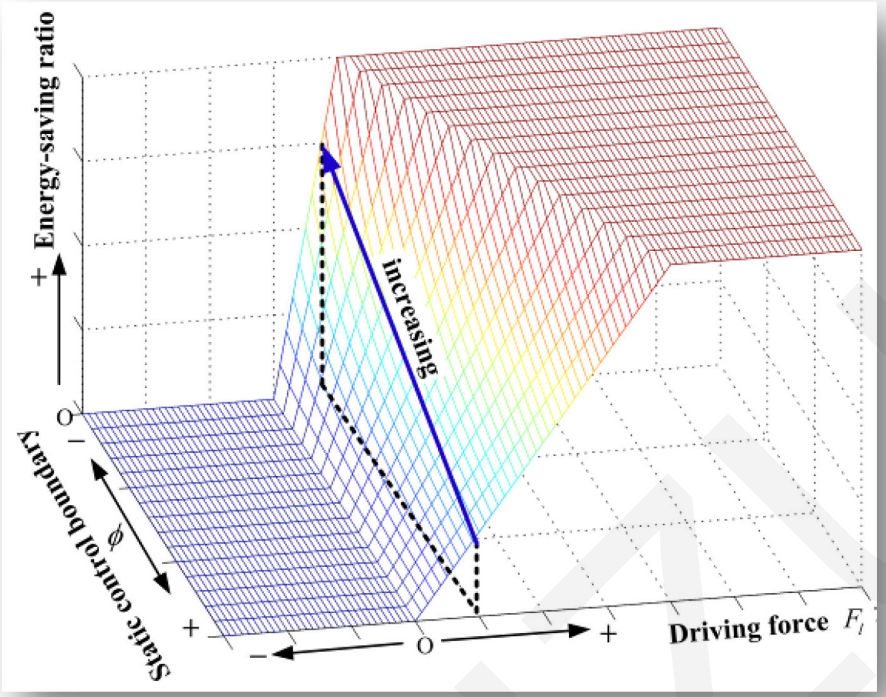
Static compensator

$$u_{vd}(F_l) = \begin{cases} k_{vd}\left[\dot{p}_{1p}(t)A_1 - \dot{p}_{2p}(t)A_2\right], 0 \le F_l \le \phi \\ 0, F_l > \phi \text{ or } F_l < 0 \end{cases}$$

Dynamic compensator

Valve-based compensation method

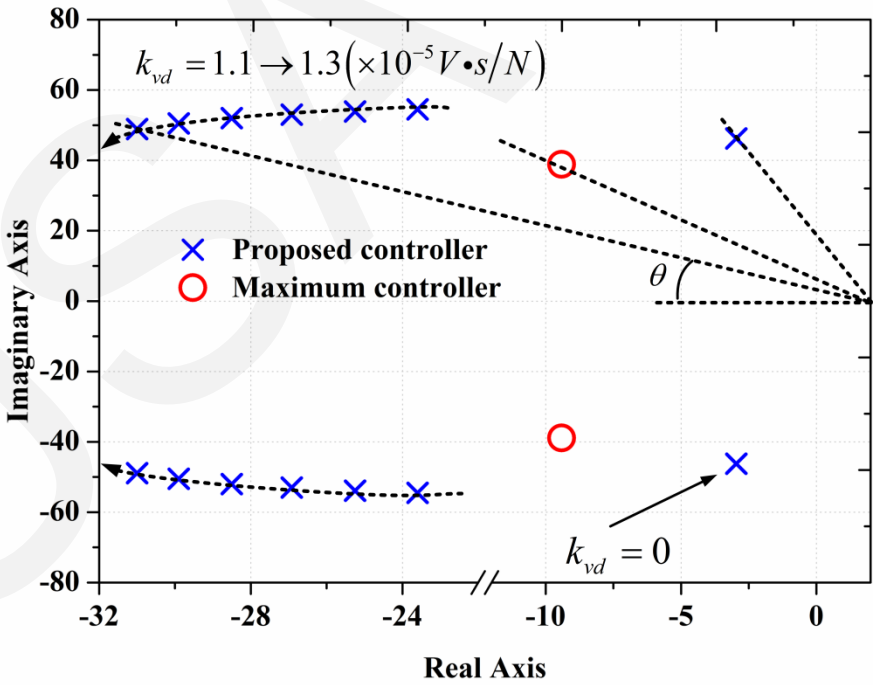
●Efficiency comparison



- **Efficiency improvement**

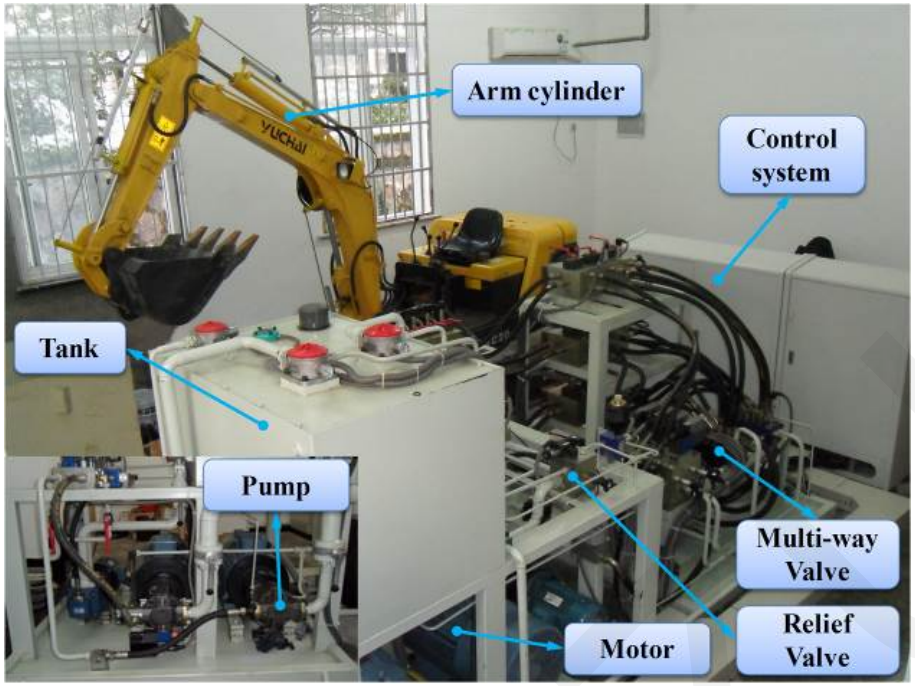
$$\eta_e = \frac{\Delta p_p}{p_p} = \frac{(A_1^3 + A_2^3)\left[A^2(x_{vp}) - A^2(x_v)\right]\Delta p_m}{A_1^3 A^2(x_{vp}) p_p}$$

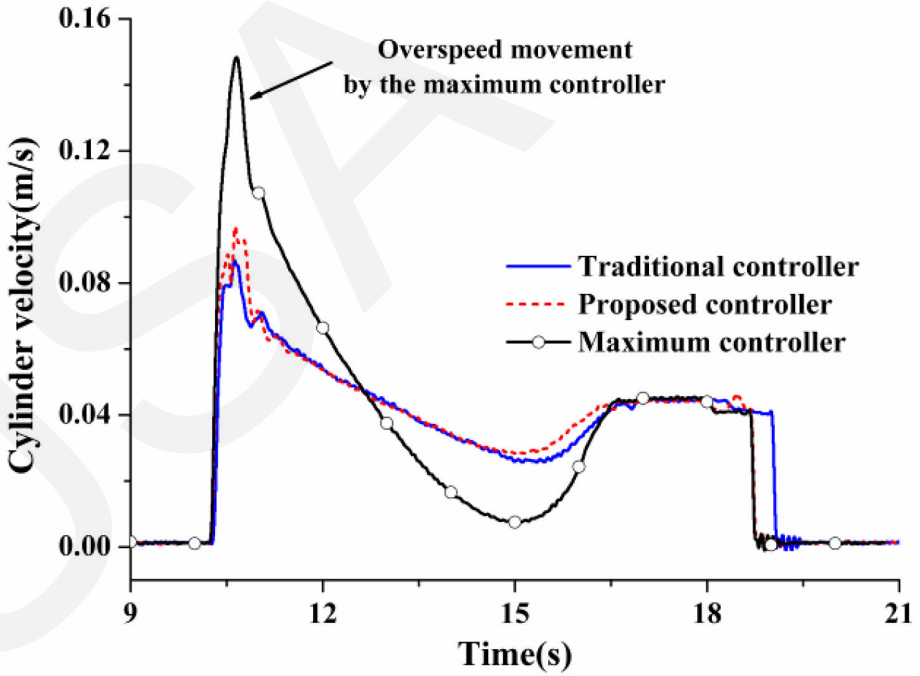
●Analysis of stability and dynamic



- **The system stability is proofed by the Routh-Hurwitz criteria.**
- **The dynamic behavior is improved through the pole placement method.**

Experimental tests





- The energy efficiency is improved by 3.2~6.8% by the proposed controller.
- Although the proposed controller obtains a smaller efficiency improvement than the maximum controller, its velocity is more consistent with that of the traditional controller.
- The dynamic behavior is improved through the pole placement method.

Conclusion and future work

- **Conclusion**
  - **A valve-based compensation method is proposed to reduce the pressure drop over the control valve and ensure the controllability, consisting of a static compensator and a dynamic compensator.**
  - **The test results indicated that the energy efficiency were reduced by with the proposed controller, while the controllability was consistent with that of the traditional controller.**
- **Future work**
  - **Future work will be focused on testing the effectiveness of the proposed controller in actual digging cycles.**
- **Additional information can be found in:**

Cheng M, Zhang J, Ding R. Pump-based compensation for dynamic improvement of the electrohydraulic flow matching system. IEEE Transactions on Industrial Electronics, 2016, DOI: 10.1109/TIE.2016. 2633478.