1st International Electronic Conference on Actuator Technology: Materials, Devices and Applications (IeCAT 2020)

A Generalized Control Model and Its Digital Algorithm for Aerospace Electrohydraulic Actuators

--and Actuators for Chinese Long March Launch Vehicles

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Self Introduction

Self Introduction

Mr. Zhao Shou.Jun : Born in 1972. Graduated in 1997 with a Master degree in Fluid Transmission and Control, SiChuan University (located in Chengdu, Sichuan Prov., the hometown of PANDA), China.

Has been working on the Actuators and Components for the Thrust Vector Control for launch vehicles.

Currently is the director of a research team on actuators to gimbal Chinese non-toxic-non-pollution launcher engines.

Beijing Inst. Of Precision Mechatronics and Controls: Beijing, China.

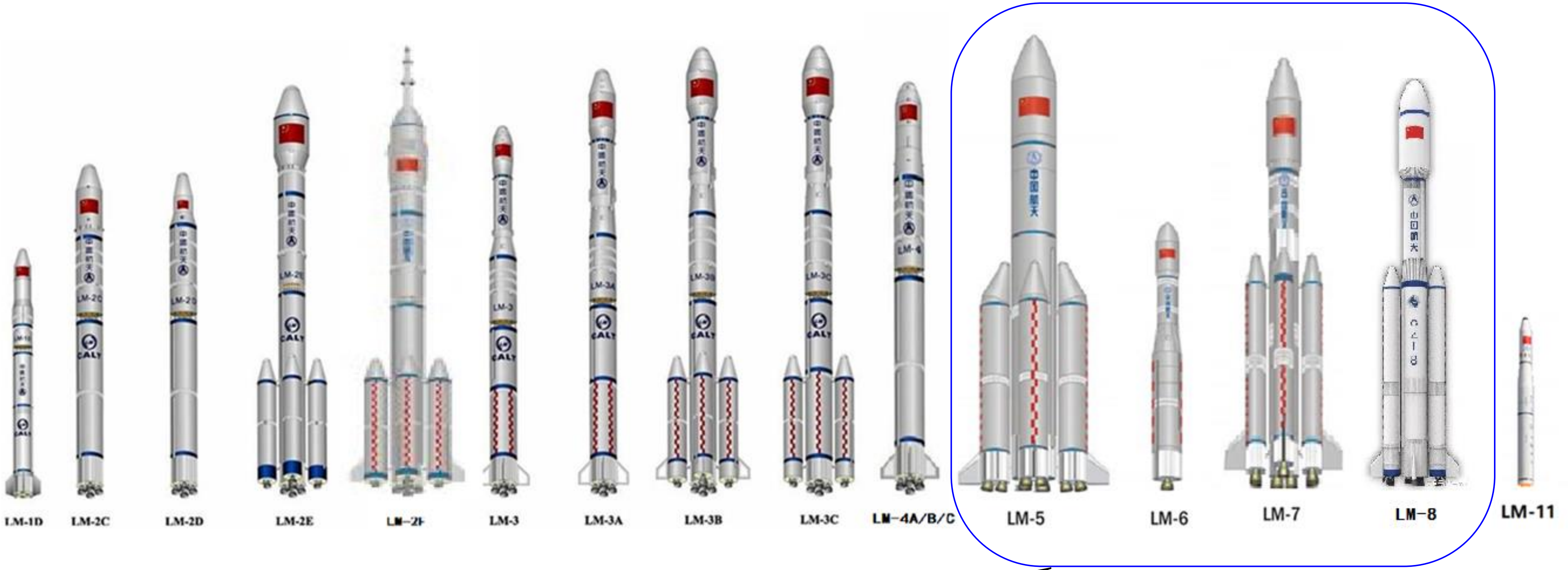
The principle institute to do researches on Actuators for launch vehicles in China.

Has developed a majority of actuators for Chinese Long March launch vehicles.

The upper management body is China Aerospace Science and Technology Corporation (CASC).

Chinese Launch Vehicles

Long March Family



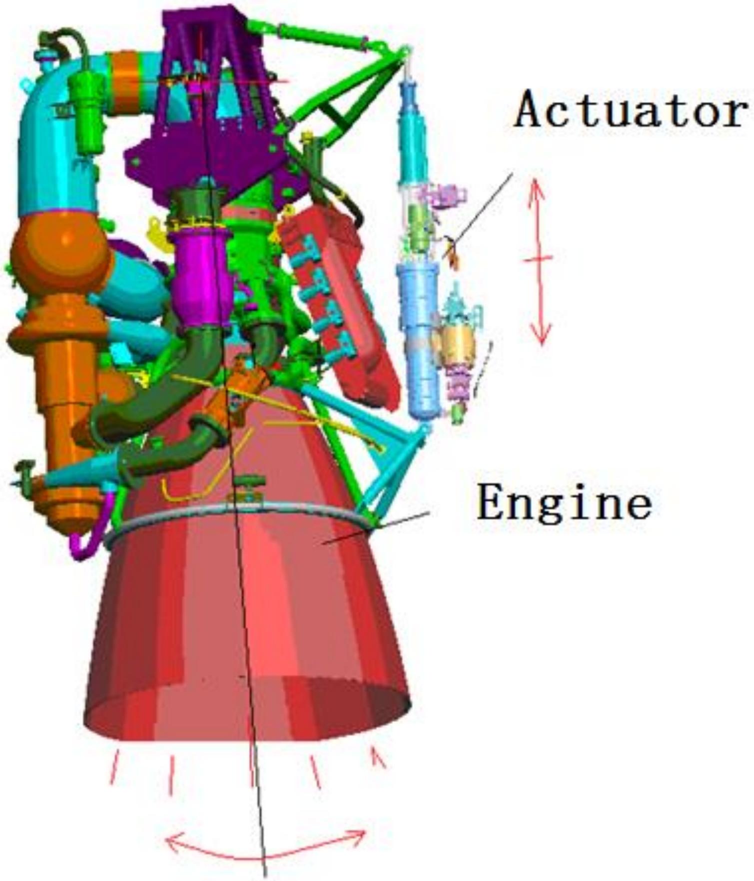
Using Non-toxic-non-pollution Engines

High thrust Chinese Launcher Engines

1200kN Liquid-Oxygen-Kerosene Engine

500kN Liquid-Hydrogen-Liquid-Oxygen Engine

An Actuator to gimbal an Engine

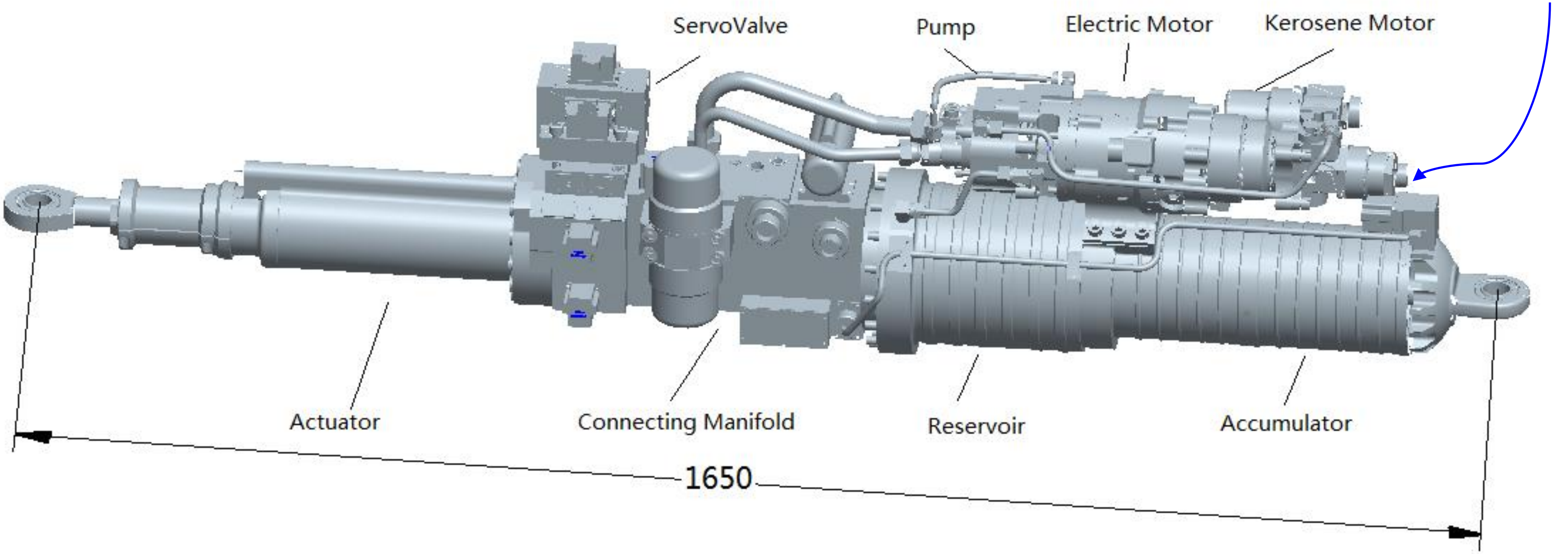


Chinese Actuators for Launchers

The Actuator to gimbal a 1200kN Liquid-Oxygen-Kerosene Engine

Zhao Shoujun. Zhao Yingxin. Zhang Xiaosha. The TVC Systems for a Chinese Liquid Oxygen and Kerosene Launch Vehicle, IAC-13-C4,P,27.p1, 64th International Astronautical Congress (IAC), Beijing, China, 25-29 Oct. 2013

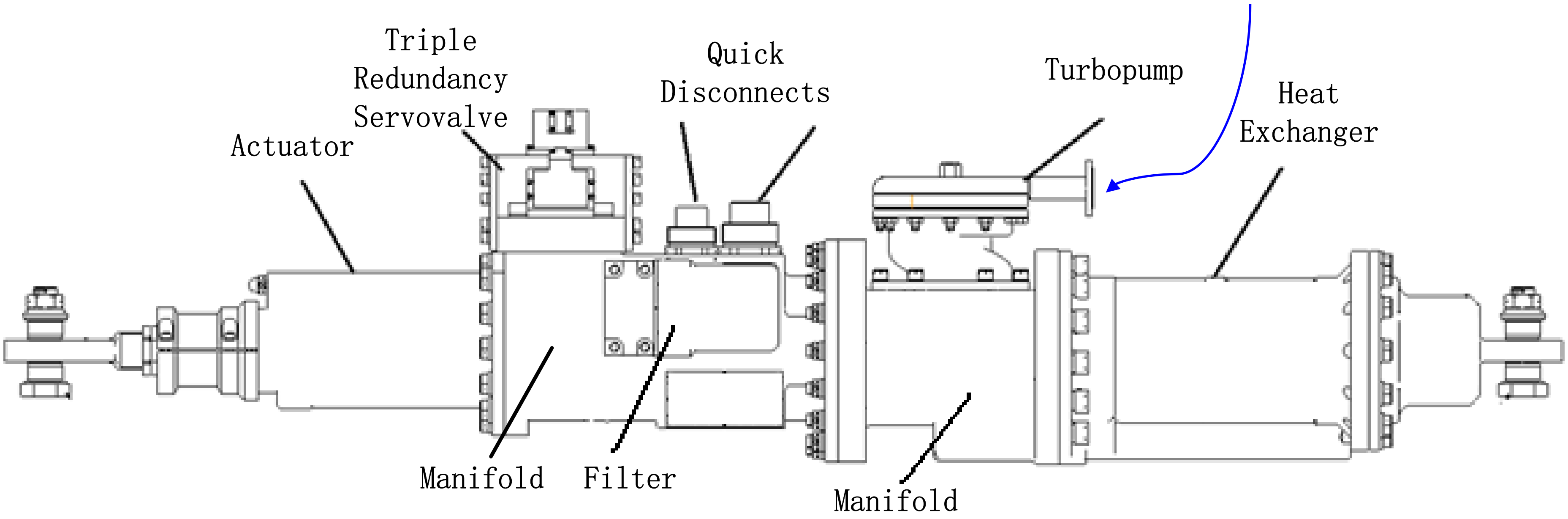
Kerosene



draws high pressure kerosene from the engine to drive a motor-pump assembly to produce the hydraulic power

The Actuator to gimbal a 500kN Liquid-Hydrogen-Liquid-Oxygen Engine

Guanghui Jing. Xiaosha Zhang. Guangshang Zeng. Shoujun Zhao. Chuanwei Yin. A Hydrogen-Turbopump-Powered Thrust Vector Control Servo System for High Thrust LH2/LOX Rocket Engines, IAC-17-D2.5.10, 68th International Astronautical Congress (IAC), Adelaide, Australia, 25-29 Sept. 2017



draws high pressure hydrogen gas from the engine to drive a turbo-pump to produce the hydraulic power

Features

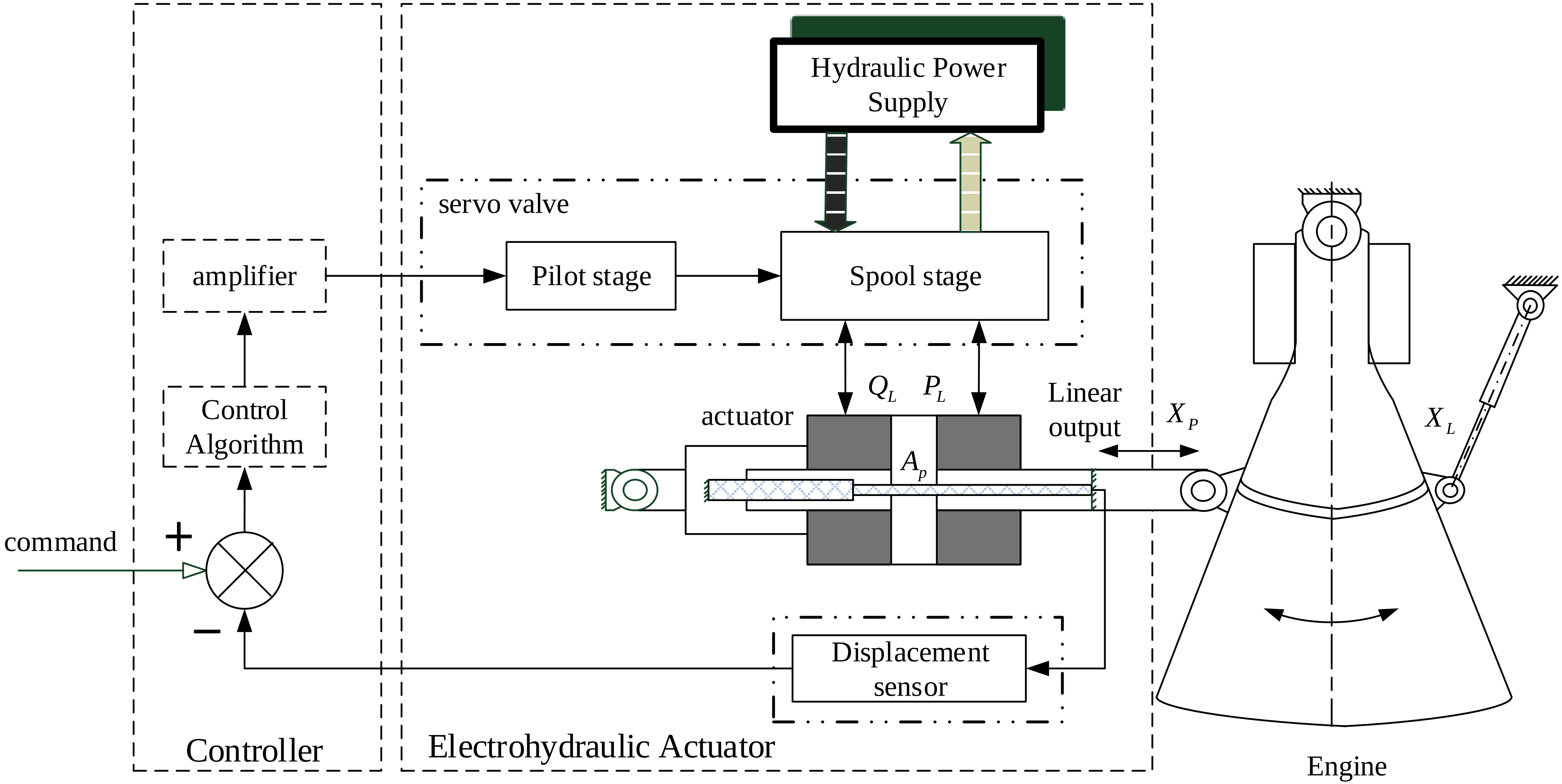
1.Monolithic structure to comprise all hydraulic power elements and hydraulic control elements

2.Triple Redundancy Servo-valves, triple piston displacement sensors, triple controllers

3.Digital control to suppress the resonance, without using traditional Dynamic Pressure Feedback

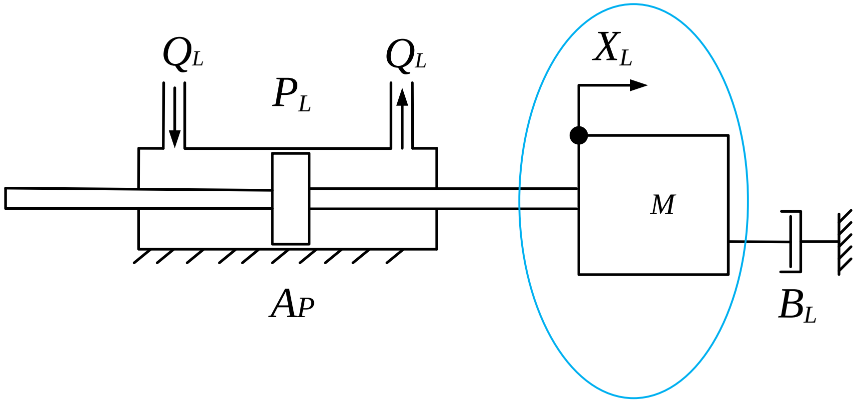
The System Model and Control Algorithm

The Actuation system



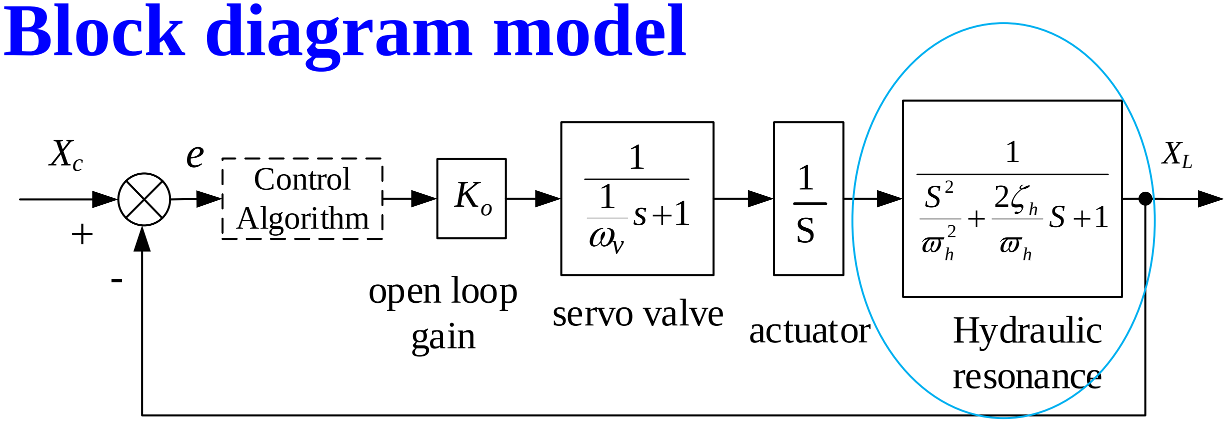
Models in most publications

Physical Model



In most used models, the piston rod is directly attached to the equivalent driven mass.

Block diagram model

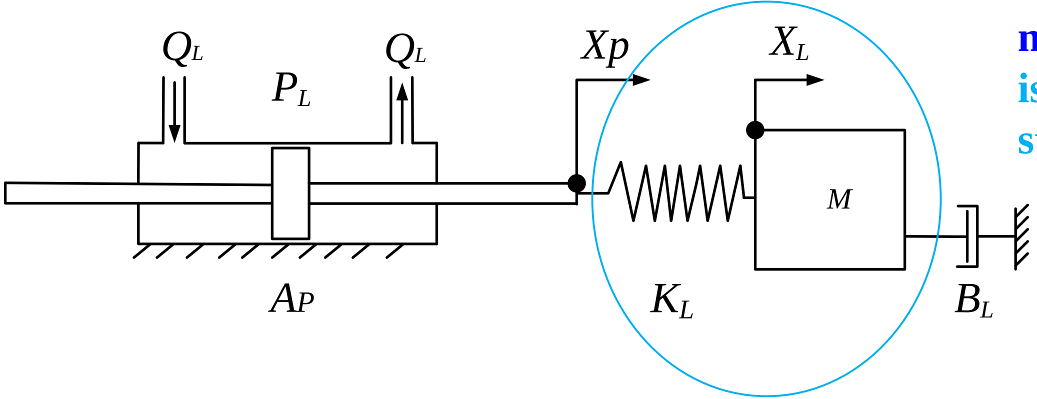


So, the hydraulic natural frequency ω_h dominates

The model may applies to some applications, but not to fast moving actuators, i.e., aerospace actuators.

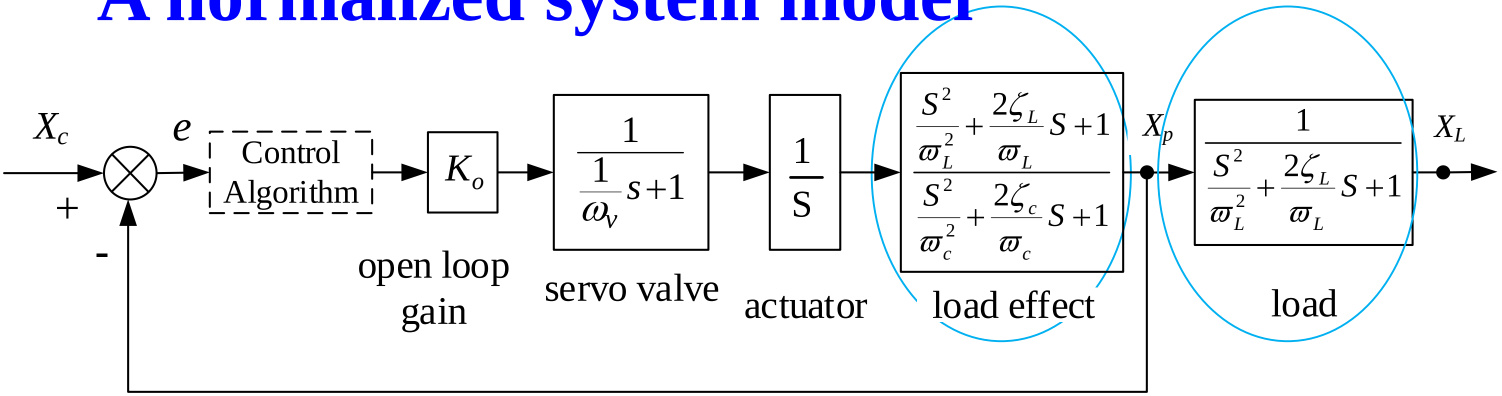
A normalized system model for fast acting aerospace actuation system

One-mass-one-spring Model



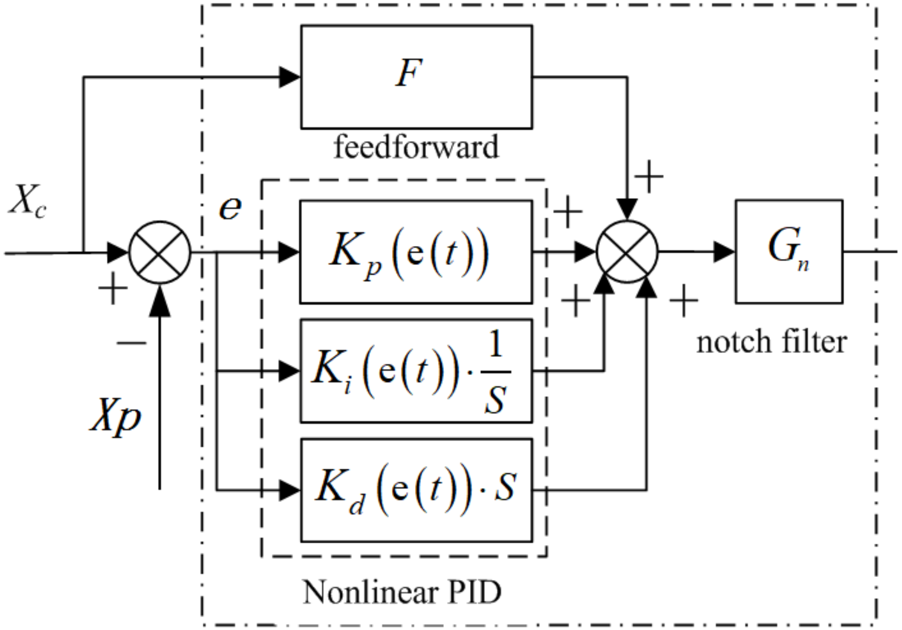
In highly dynamic aerospace applications, a one-mass-one-spring model has to be used. **To note, there is not a real spring, but modelling the internal stiffness of the engine body.**

A normalized system model



The load structural natural frequency ω_L dominates.

A combined control algorithm



Notch Filter to cancel out the resonance poles

$$G_n = \frac{\frac{1}{\omega_{n1}^2}S^2 + \frac{2\xi_{n1}}{\omega_{n1}}S + 1}{\frac{1}{\omega_{n2}^2}S^2 + \frac{2\xi_{n2}}{\omega_{n2}}S + 1}$$

High proportional gain near null to overcome non-linear phenomenon of servo-valve

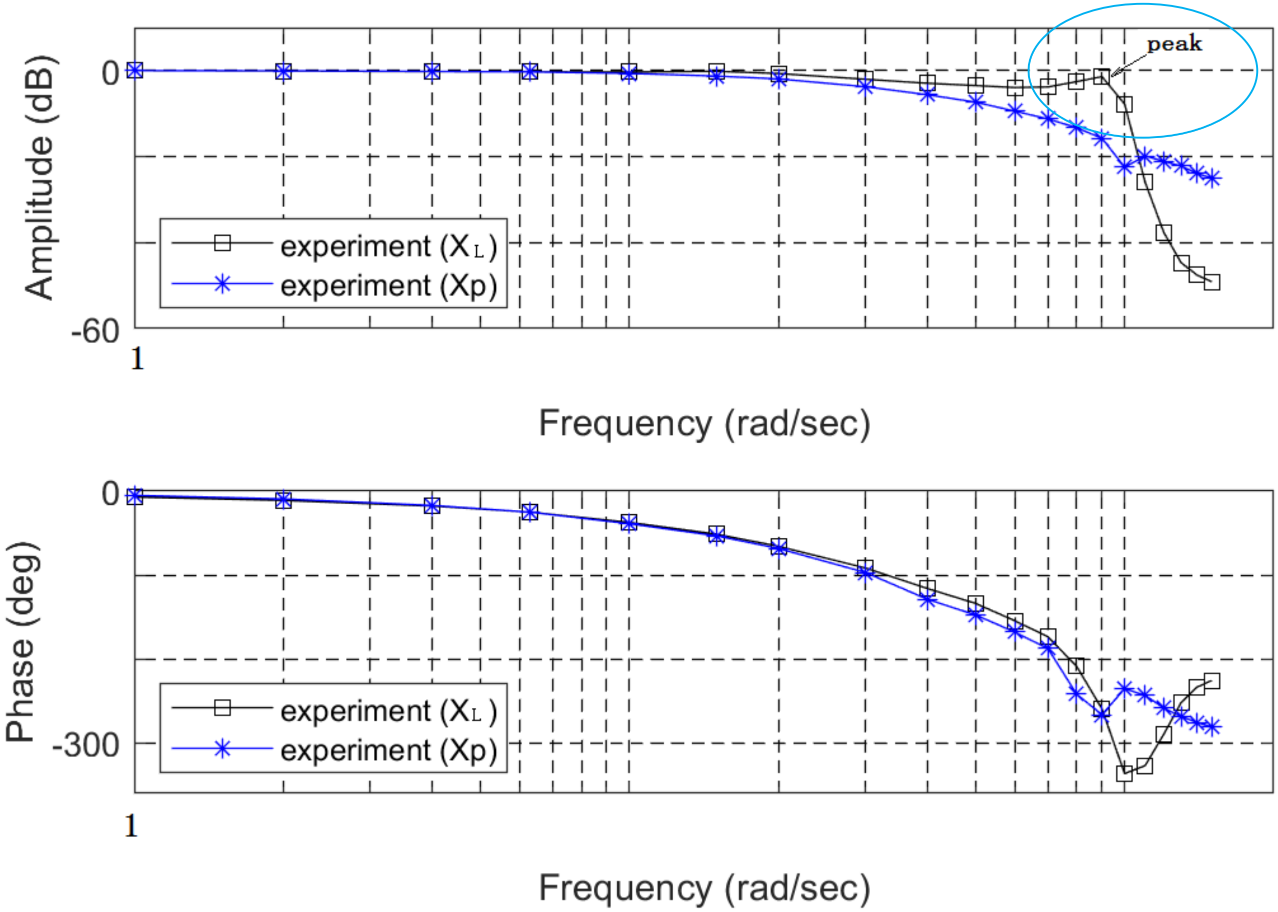
$$K_P(e(t)) = \begin{cases} f_K \cdot K_P \quad (f_K > 1) & |e(t)| \le e_n \\ K_P & |e(t)| > e_n \end{cases}$$

Feedforward to increase the tracking precision

$$F = K_f \cdot S \cdot X_c$$

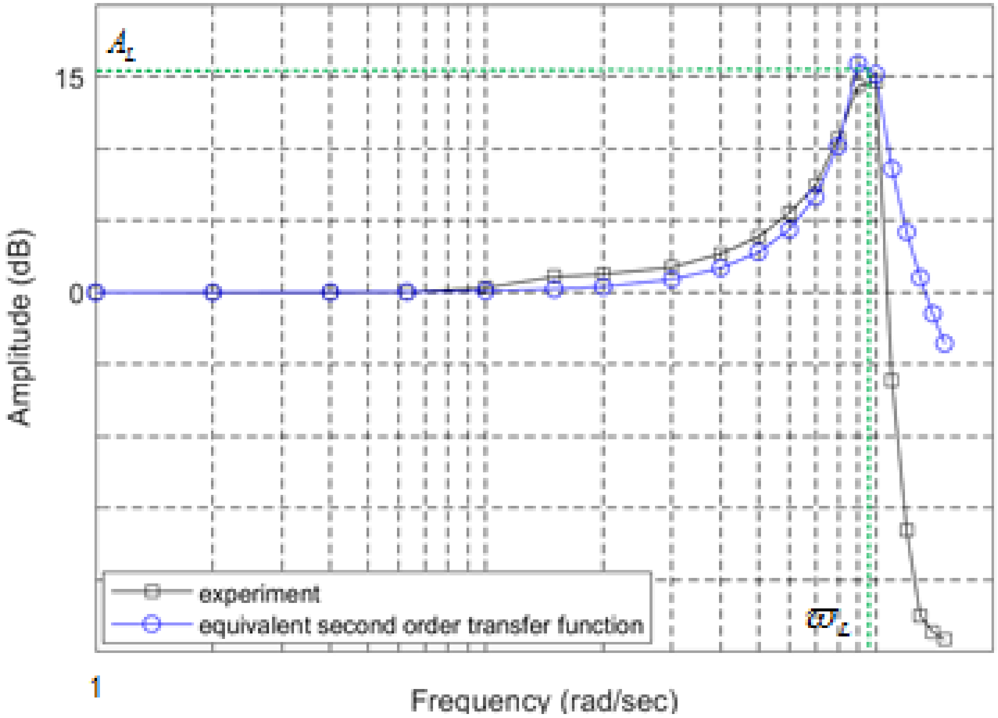
Simulation and Experiments

A uncompensated system dynamics for a LHLO engine actuation system



Without compensation, only with a small open loop gain, the system has a tendency to vibrate

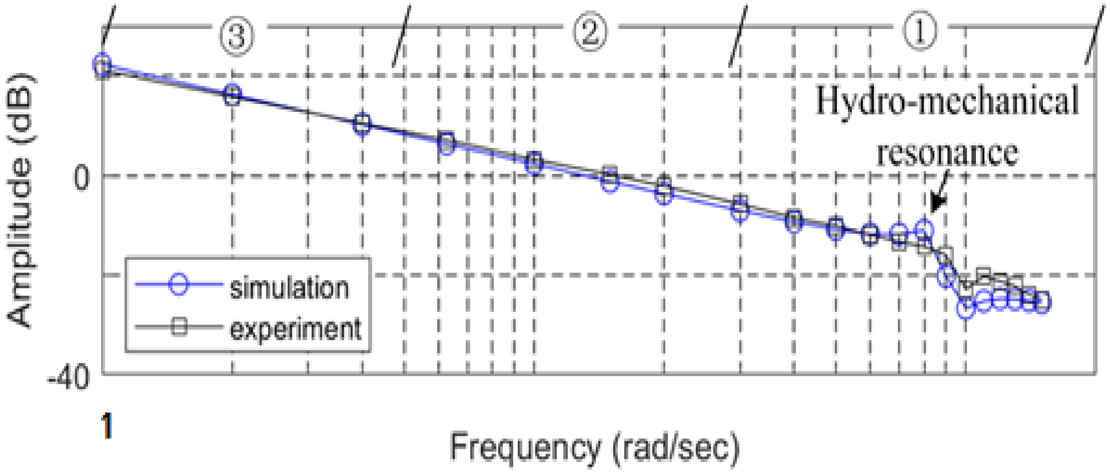
The derived structural resonance



$$G_L = \frac{X_L}{X_p} = \frac{1}{\frac{1}{\omega_L^2} S^2 + \frac{2\xi_L}{\omega_L} S + 1}$$

The engine's structural resonance nature can be obtained by subtracting the former dynamics of X_p at the piston point directly from the that of X_L at the load output, which can be simulated as a standard second-order transfer function

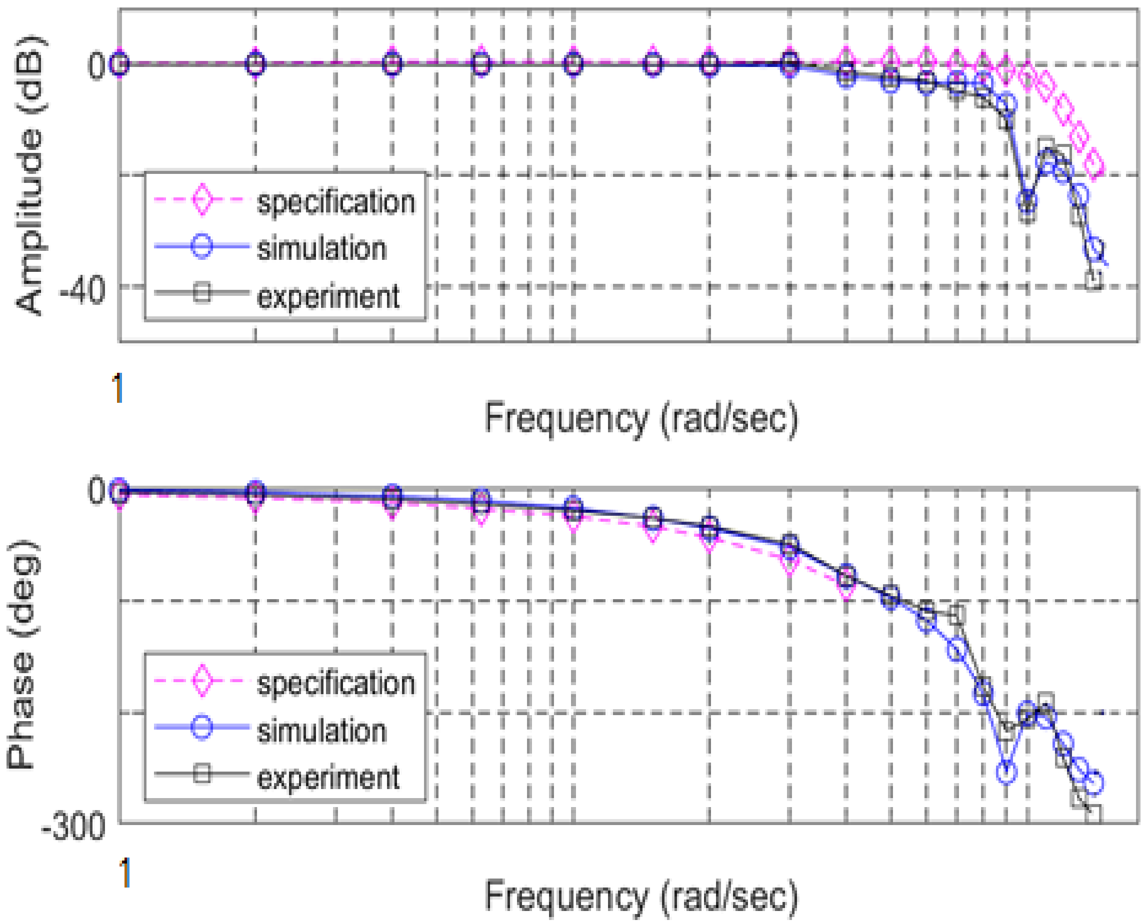
The hydro-mechanical resonance inside the closed piston position loop



The hydro-mechanical resonance peak in the amplitude curve is the bottle neck to increase the stability margin, while the composite natural frequency ω_c is limited by the structural natural frequency ω_L.

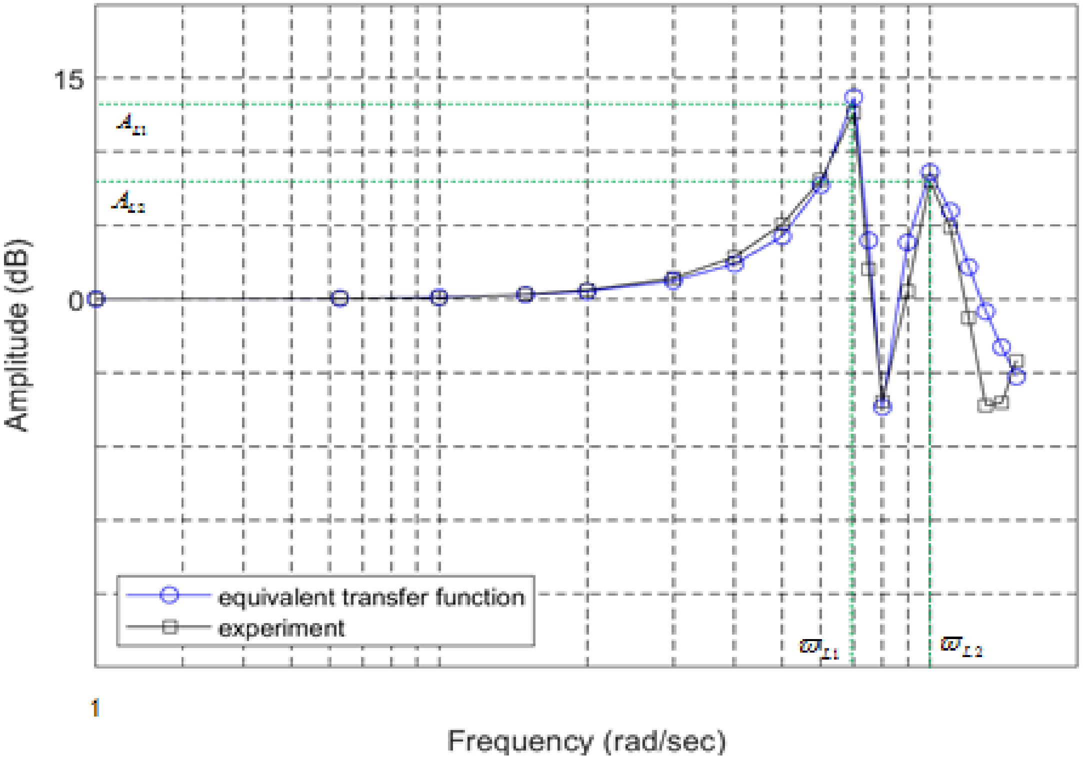
In the high frequency region ①， the notch filter play the main role.
In the intermediate frequency region ② , a higher gain and the feedforward compensation act.
In the low frequency region ③ , the nonlinear PID upgrades the response.

The final output dynamics of the compensated electro-hydraulic actuation system

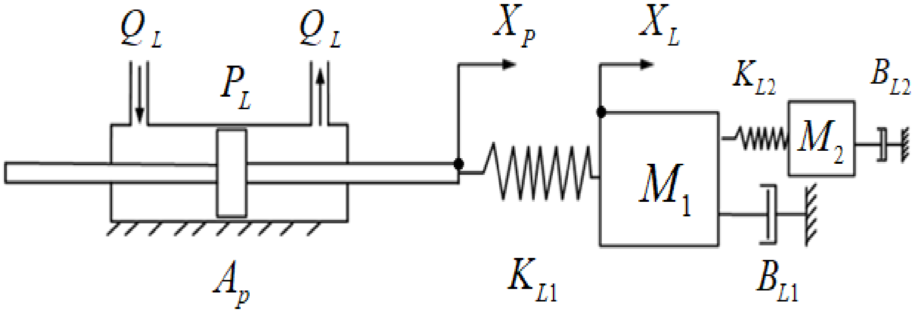


With the combined control algorithm, the open loop gain can be increased to 25 rad/s, and a satisfactory performance was obtained.

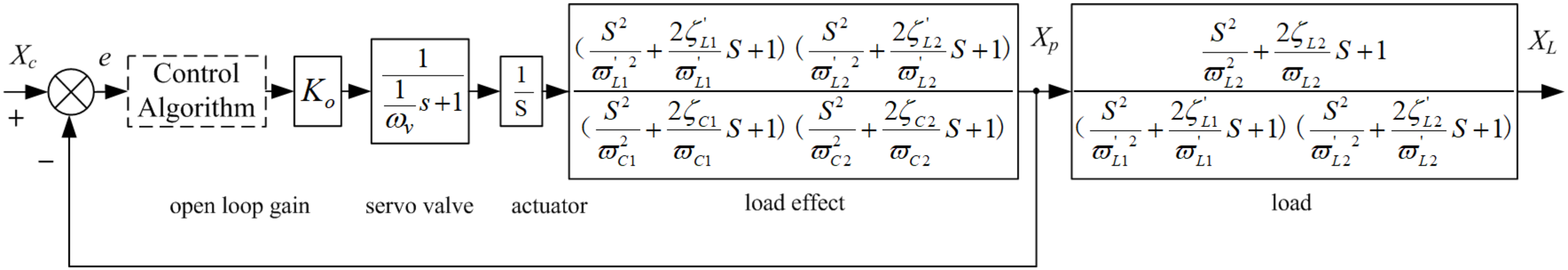
The more complicated structural dynamics of a liquid-oxygen-kerosene launcher engine



Having 2 resonance, meaning more complicated mass distribution. A two-mass-two-spring model is constructed.



Modified Model and control algorithm



$$G_n=\frac{\frac{1}{\omega_{n1}^2}S^2+\frac{2\xi_{n1}}{\omega_{n1}}S+1}{\frac{1}{\omega_{n2}^2}S^2+\frac{2\xi_{n2}}{\omega_{n2}}S+1}\cdot\frac{\frac{1}{\omega_{n3}^2}S^2+\frac{2\xi_{n3}}{\omega_{n3}}S+1}{\frac{1}{\omega_{n4}^2}S^2+\frac{2\xi_{n4}}{\omega_{n4}}S+1}$$

Two rather than one notch filters were used to deal with the two resonance frequencies.

Conclusion

Key Point

It is demonstrated that, in a highly dynamic aerospace electro-hydraulic actuation system, the load structural resonance, rather than the hydraulic resonance as often stated in other applications, is the dominating constraint and should be treated in the foremost place in the design.

Thank you very much for your attention!