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Multi-objective optimization design of a 30 kW Electro-hydrostatic Actuator

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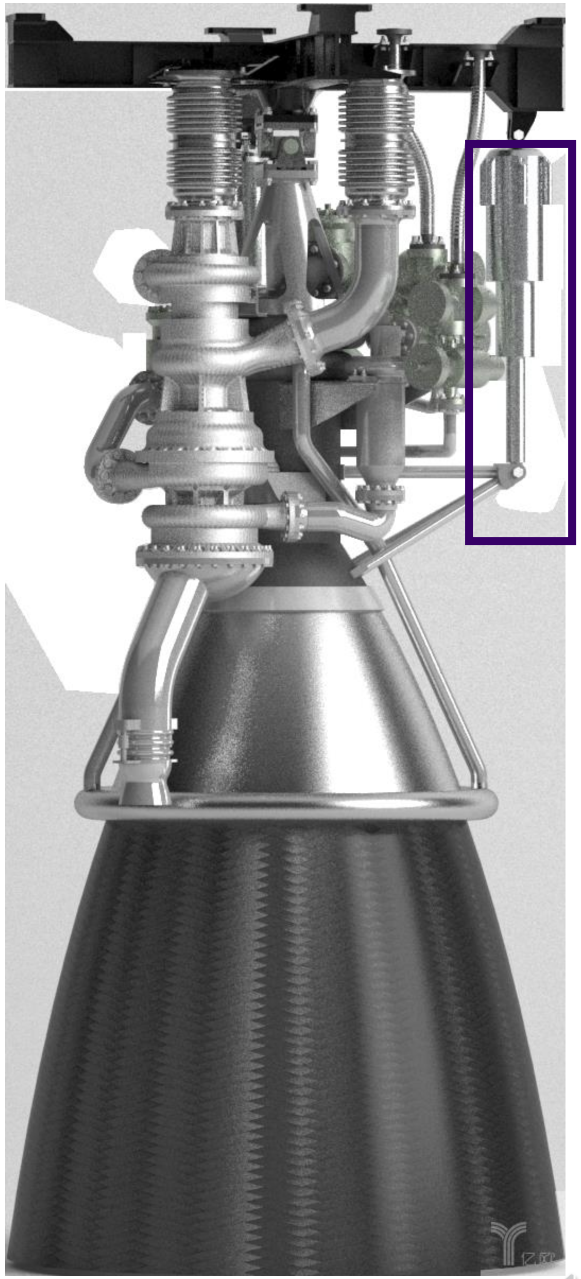
Contents

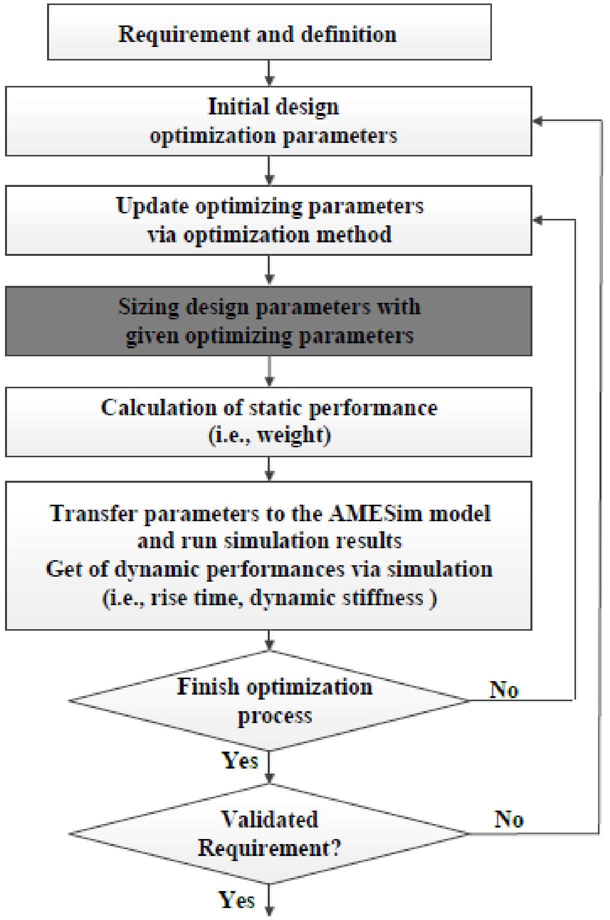
Introduction —— Background

- Hydraulic actuation is the priority of heavy machinery and vehicles.
- Electro-hydrostatic actuator (EHA) is replacing conventional hydraulic actuators due to its combination of advantages of both electric and hydraulic actuation.
- The high power EHA is more challenging to meet all the requirements, especially the dynamic performance.
- Multi-objective optimization is a beneficial method to alleviate this issue.

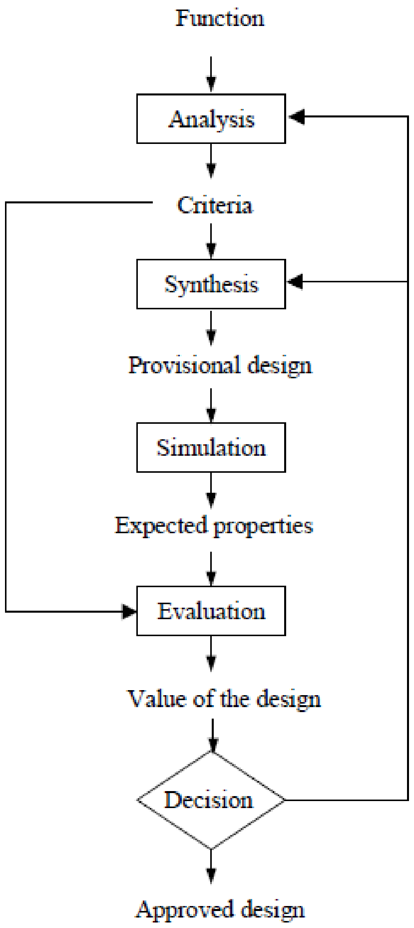


Source: https://legacy.iyiou.com/p/120966.html

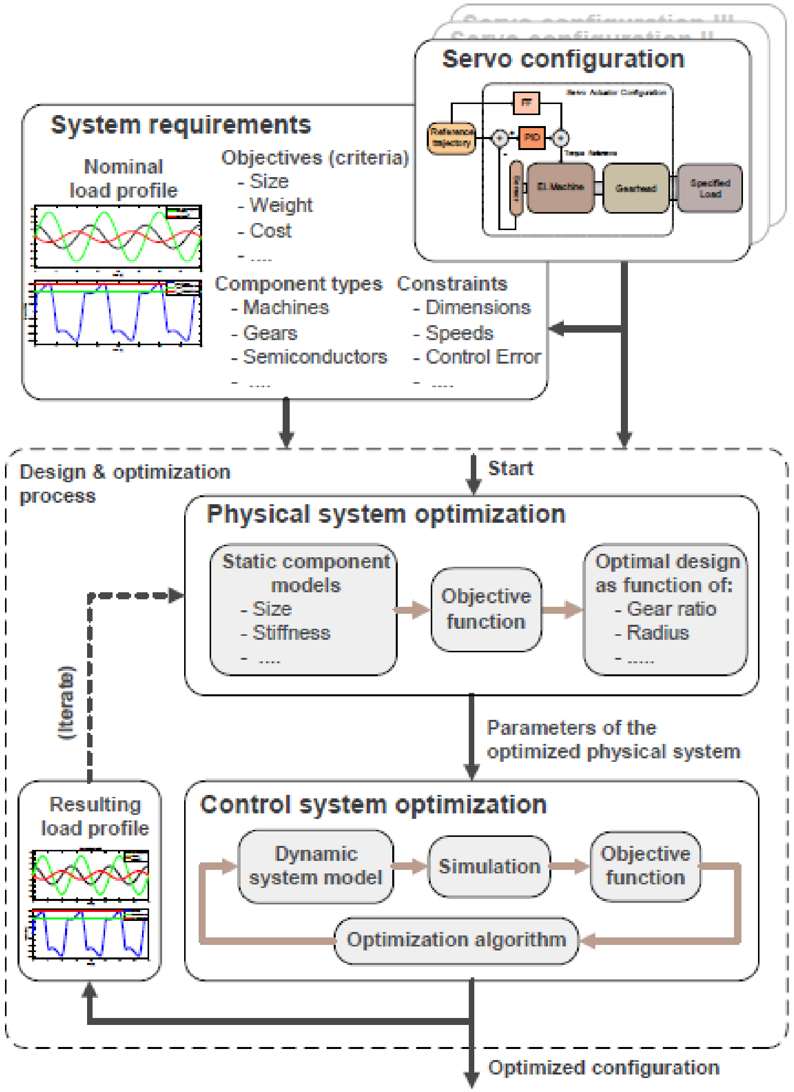
Introduction —— State-of-the-art



Source: Xue L. et. al. A simulation-based multi-objective optimization design method for pump-driven electro-hydrostatic actuators



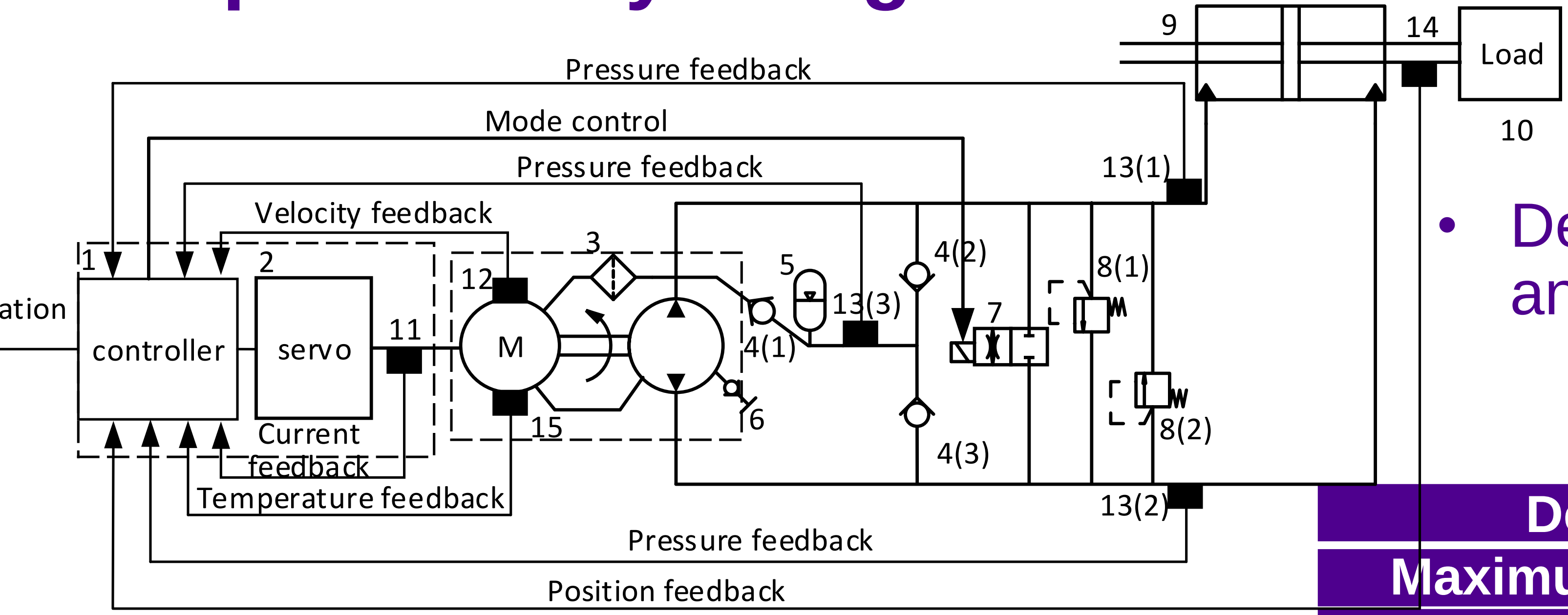
Source: Andersson, J. Multiobjective optimization in engineering design: applications to fluid power systems.



Source: Roos, F. Towards a methodology for integrated design of mechatronic servo.

- The multi-objective optimization preliminary design considering all the requirements is to be developed, especially considering the dynamic performance.

The preliminary design task



- Determine the component types and the lumped parameters

Description	Value	Unit
Maximum output force	100,000	N
Rated output force	200,000	N
Maximum output velocity	150	mm/s
Rated output velocity	100	mm/s
Stroke	±55	mm
Position control bandwidth	8	Hz
Control accuracy	±0.1	mm
Maximum mass	115	kg
Static stiffness	9*10^7	N/m
Ambient temperature	-40~80	℃

- Predict performance with limited information,
- Multi-disciplinary evaluation models,
- Maximum the performance with the available resources,
- High calculation efficiency

The preliminary design task

$$\min f(x) = \begin{bmatrix} f_1(x_1, x_2, \dots, x_n) \\ f_2(x_1, x_2, \dots, x_n) \\ \dots \\ f_m(x_1, x_2, \dots, x_n) \end{bmatrix}$$

$$x \in \Omega \qquad \text{s.t. } g(x) \le 0$$

- Major parameters as variables
- Other parameters generated automatically
- (x_1, x_2, x_3) = motor rated torque T_m (Nm), the pump displacement D_p (mL/rev), and the piston diameter of the cylinder d_{pis} (m)

Competitive performance as objectives →

- Weight
- Efficiency
- Bandwidth

Bounded performance as constraints →

- Force
- Velocity
- Accuracy
- Stroke
- Stiffness

Note: thermal management is considered upon the optimization design results

Evaluation models —— Weight

$$m_{\mathrm{EHA}} = m_{\mathrm{m}} + m_{\mathrm{p}} + m_{\mathrm{c}} + m_{\mathrm{b}}$$

- Scaling law for pump and motor

$$m_{\mathrm{p}} = 0.2717 D_{\mathrm{p}}^{1.308} + 0.7186$$

$$m_{\mathrm{m}} = 0.1397 T_{\mathrm{m}}^{1.308} + 2.051$$

$$J_{\mathrm{m}} = 0.0003666 T_{\mathrm{m}}^{0.576}$$

$$J_{\mathrm{p}} = 0.0008218 T D_{\mathrm{p}}^{0.2366}$$

- Analytical model for cylinder

$$m_{\mathrm{c}} = m_{\mathrm{pis}} + m_{\mathrm{shell}} + m_{\mathrm{bottom}}$$

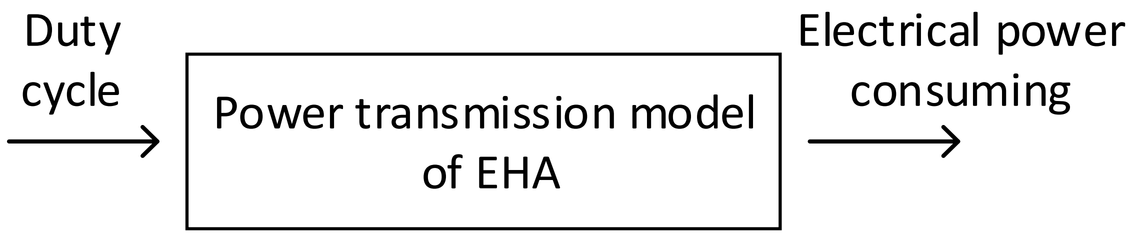
$$m_{\mathrm{pis}} = \frac{\pi}{4}\left(d_{\mathrm{pis}} + \delta_{\mathrm{pis}}\right)^2 \left(s + l_{\mathrm{pis}} + l_{\mathrm{top}}\right)\rho - \frac{\pi}{4} d_{\mathrm{pis}}^2 (s + l_{\mathrm{pis}})\rho + \frac{\pi}{4} d_{\mathrm{shell}}^2 l_{\mathrm{pis}} \rho$$

$$m_{\mathrm{shell}} = \frac{\pi}{4}(d_{\mathrm{shell}} + \delta_{\mathrm{shell}})^2 \left(s + l_{\mathrm{pis}} + l_{\mathrm{top}}\right)\rho - \frac{\pi}{4} d_{\mathrm{shell}}^2 \left(s + l_{\mathrm{pis}}\right)\rho$$

$$m_{\mathrm{bottom}} = h \frac{\pi}{4}\left(d_{\mathrm{shell}} + \delta_{\mathrm{shell}}\right)^2 \rho$$

Evaluation models —— Efficiency

Transferred as the energy consumption under the specified duty cycle



- A low calculation cost backward model

$$\frac{dw(k)}{dt} = \begin{cases} \frac{\omega(k)}{h}, when\ k = 1 \\ \frac{\omega(k) - \omega(k-1)}{h}, when\ k > 1 \end{cases}$$

Cylinder

$$Q_{cy}(k) = Av(k) + C_c \Delta P(k)$$

$$\Delta P(k) = \frac{F(k) + Bv(k)}{A}$$

Pump

$$Q_{pump}(k) = Q_{cy}(k) + C_p \Delta P(k)$$

$$\omega(k) = \frac{Q_{pump}}{D_p}$$

$$T(k) = J\frac{d\omega(k)}{dt} + k_{fric}\omega(k) + \Delta P(k)\frac{D_p}{2\pi}$$

Motor

$$I_m(k) = \frac{T(k)}{K_t} \qquad U_m(k) = L\frac{dI_m(k)}{dt} + K_e w(k) + I_m(k)R$$

$$\frac{dI_m(k)}{dt} = \begin{cases} \frac{I_m(k)}{h}, when\ k = 1 \\ \frac{I_m(k) - I_m(k-1)}{h}, when\ k > 1 \end{cases}$$

Evaluation models —— Bandwidth

open-loop transfer function of EHA

$$G_0(s) = D_p G_{pp}(s) G_{cp}(s) s^{-1}$$

$$G_{pp}(s) = \frac{K_t}{LJs^2 + (K_f L + RJ)s + RK_f + KtKe}$$

$$G_{cp}(s) = \frac{A^{-1}}{\frac{Vm}{EA^2}s^2 + \left(\frac{C_{st}m}{A^2} + \frac{VB}{EA^2}\right)s + \frac{C_{st}B}{A^2} + 1}$$

Applying power limitation

$$\omega_c < \min\left(\frac{\pi D_p}{30Ax_m} n_N, \frac{1}{2\pi}\sqrt{\frac{T_{maxD_p A}}{x_m(A^2 J + D_p^2 m)}}\right)$$

Applying PID based cascade controller

$$G_{os}(s) = G_{cx} K_{os} / s$$

$$K_{os} = \frac{AD_p}{BC_{st} + A^2}$$

$$X(s) = \frac{K_{px}K_{os}s + K_{os}K_{ix}}{s^2 + K_{px}K_{os}s + K_{os}K_{ix}} X_d(s)$$

$$\frac{X(s)}{X_d(s)} = \frac{2\omega_c s + \omega_c^2}{s^2 + 2\omega_c s + \omega_c^2}$$

$$K_{px} = 2\omega_c / K_{os}, K_{ix} = \omega_c^2 / K_{os}$$

Applying stability limitation

$$G_0(s) = \left(K_{px} + \frac{K_{ix}}{s}\right) D_p G_{cp}(s) s^{-1}$$

Evaluation models —— Constraints

After the motor rated torque T_{m}, the pump displacement D_{p}, and the piston diameter of the cylinder d_{pis} are assigned

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Generating other parameters

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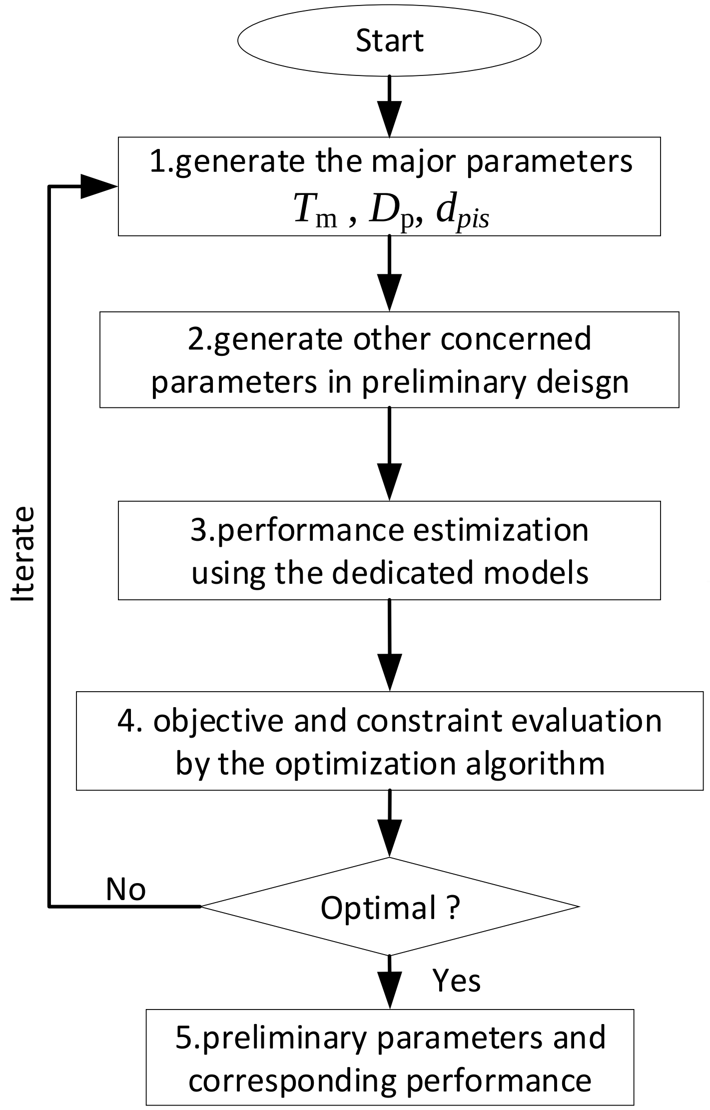
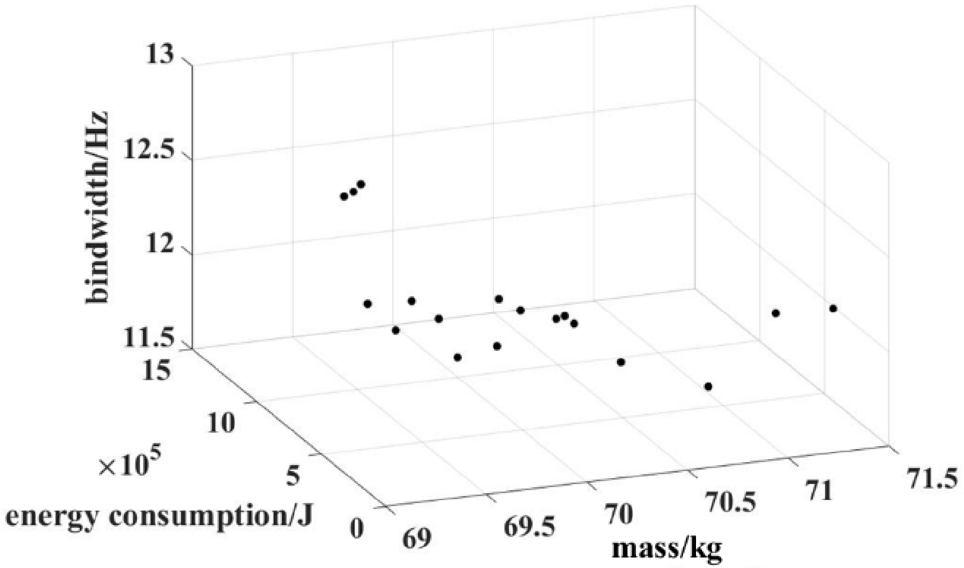
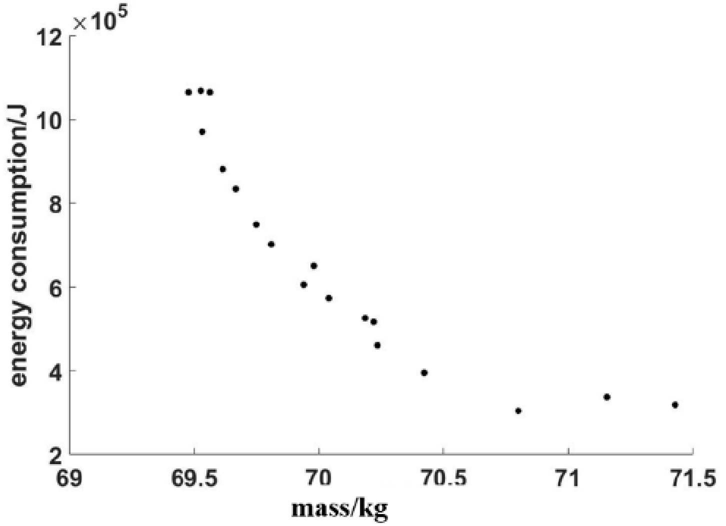
- Calculate force and velocity based on energy conversion formula
- Calculate static stiffness based on bulk modulus formula
- Calculate control accuracy based on the following control model

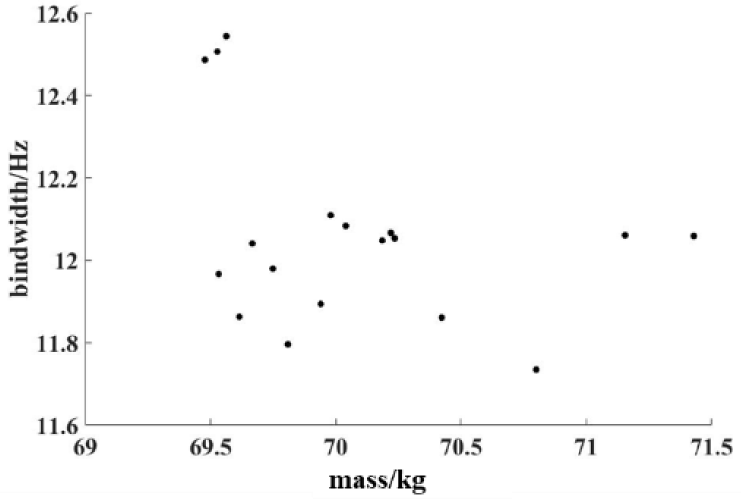
$$\frac{X(s)}{X_{\mathrm{d}}(s)} = \frac{2\omega_{\mathrm{c}} s + \omega_{\mathrm{c}}^2}{s^2 + 2\omega_{\mathrm{c}} s + \omega_{\mathrm{c}}^2}$$

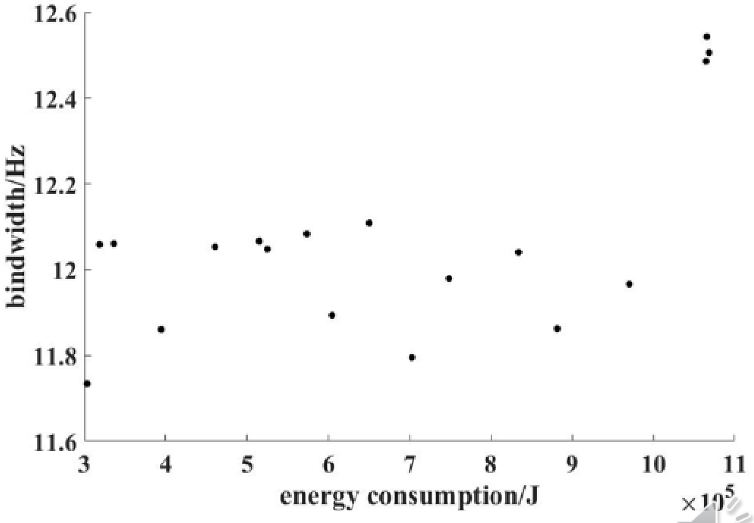
Optimization design implementation











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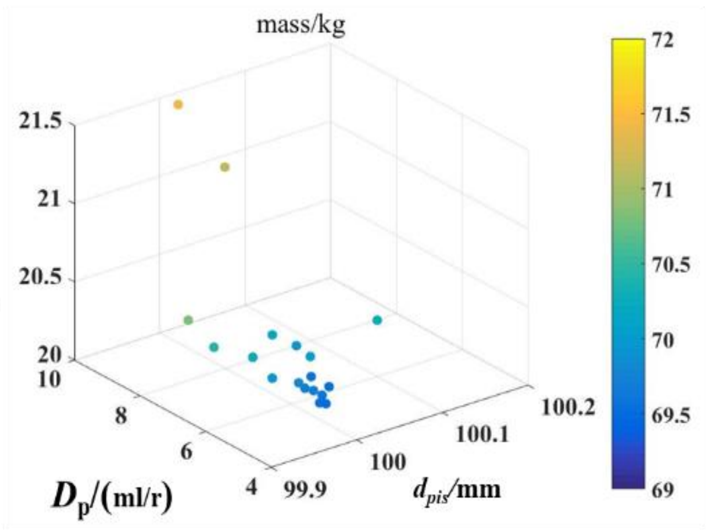
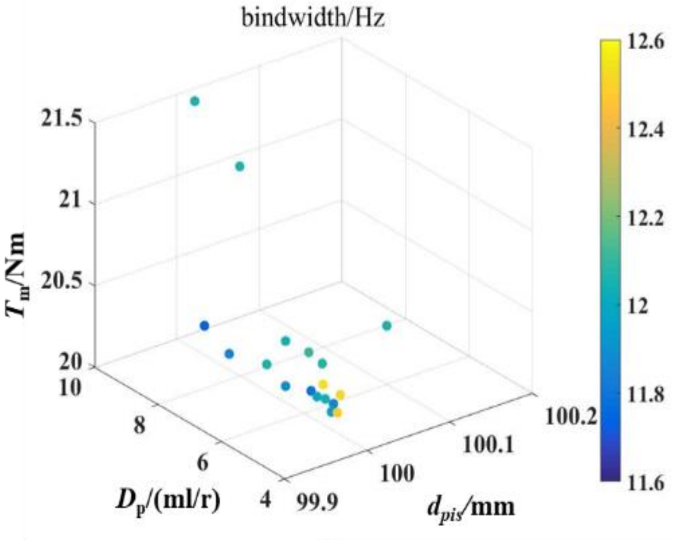
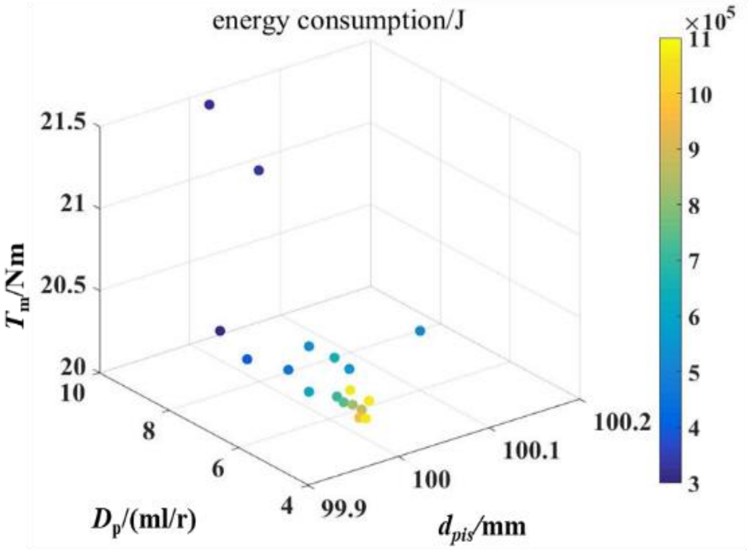
Optimization design implementation







- (T_m=21 Nm, D_p=9.5 mL/rev, d_{pis}=100 mm)
- (m_{EHA}=71.155 kg, ω_b=12 Hz, E=337 kJ)
- T_m ↑ m_{EHA} ↑ ω_b ↑ E ↓
- D_p ↑ m_{EHA} ↑ ω_b ↓ E ↑
- d_{pis} ↑ m_{EHA} ↑ ω_b ↑ E ↓

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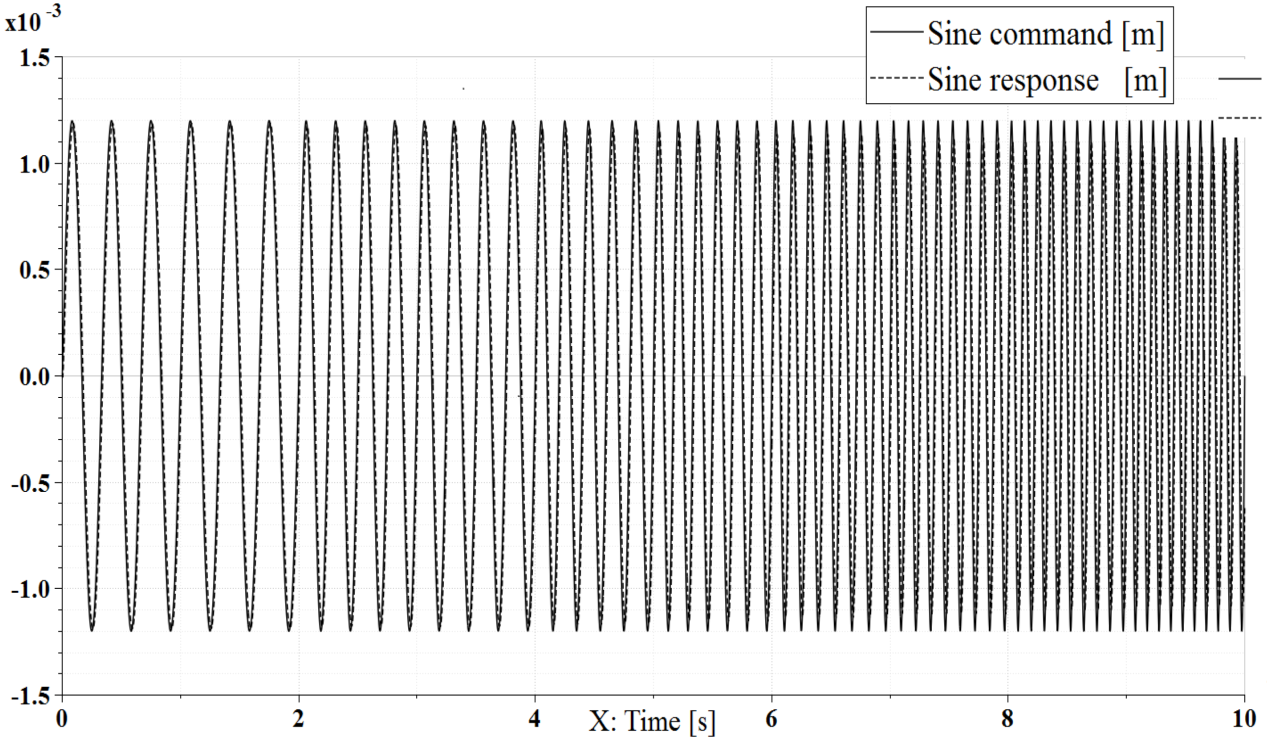
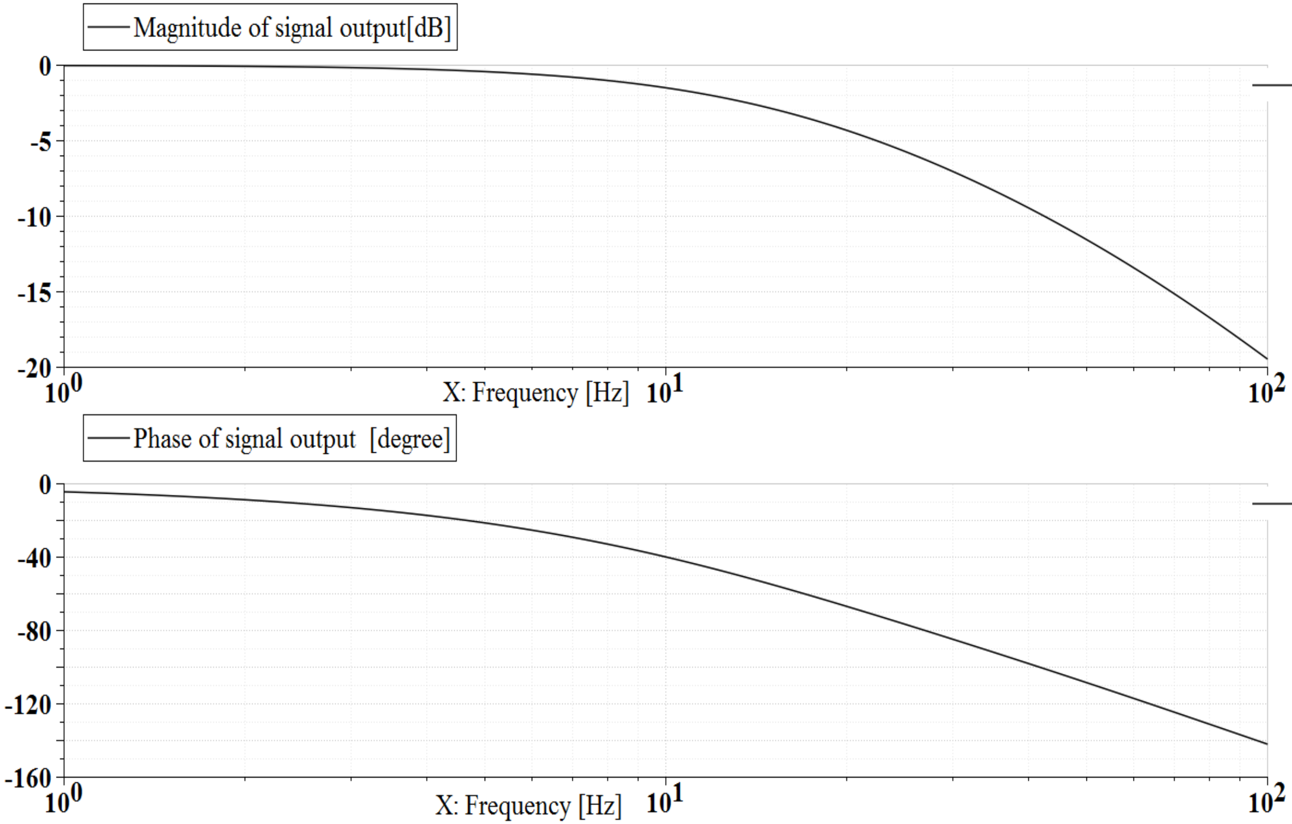
Simulation analysis

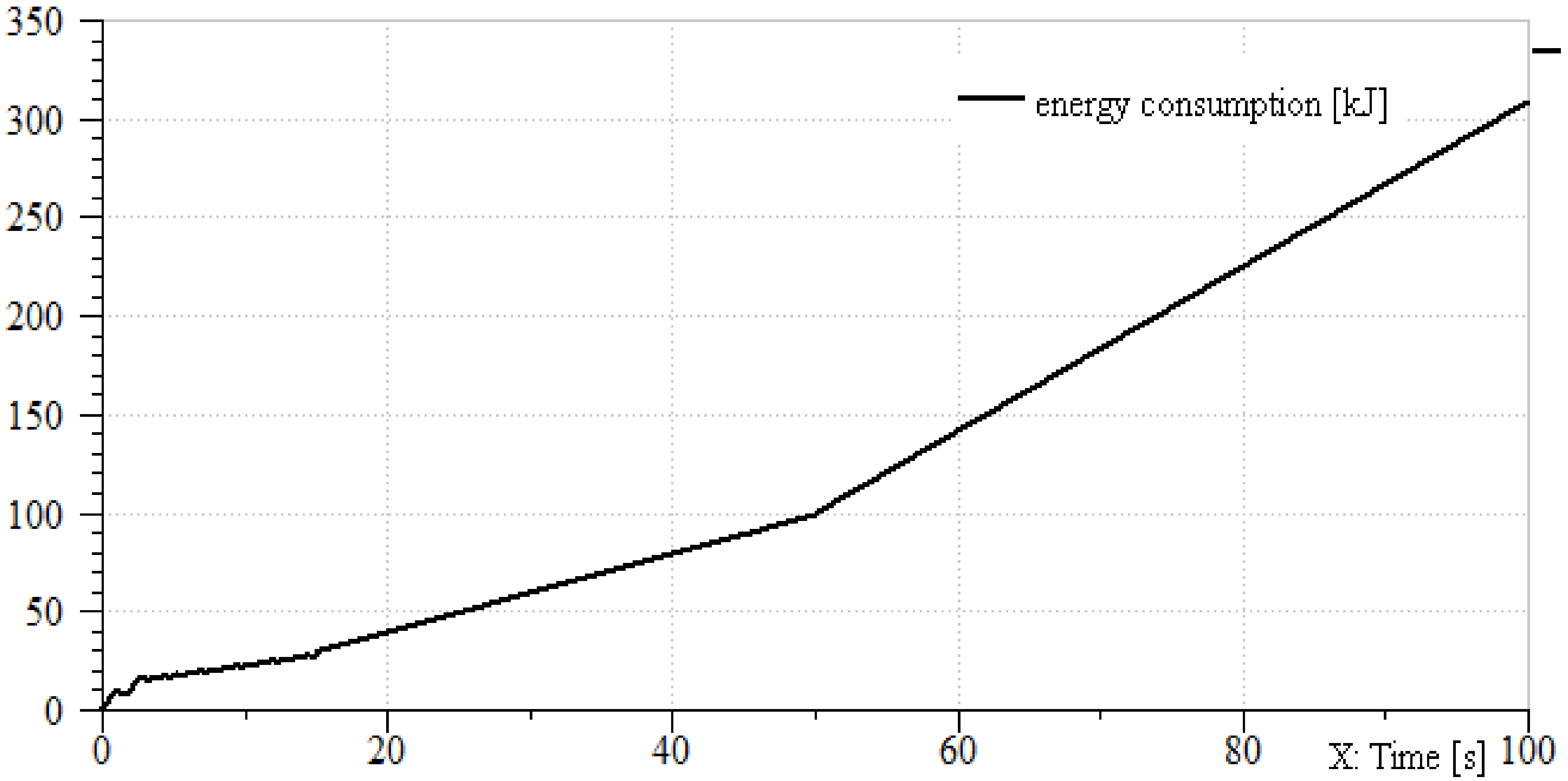
Simulate the design solution with AMESim model





Dynamic performance

Simulation analysis



Power consumption (8.6% error)

Conclusion

- EHA preliminary design task can be transferred into a multi-objective optimization problem to maximum the performance of the available resources;
- Parameter generation tools and dedicated models were proposed to implement the objective and constraint evaluation;
- A 30 kW EHA achieved more than 10 Hz bandwidth with under 72 kg weight, the efficiency was also optimized;
- The performance envelope and the in-depth understanding were realized.
- The optimization results were verified with an EHA AMESim model.

Thanks for your attention! ***Q&A?***