ACTIVE VIBRATION ISOLATION OF MACHINE TOOLS USING AN ELECTRO-HYDRAULIC ACTUATOR

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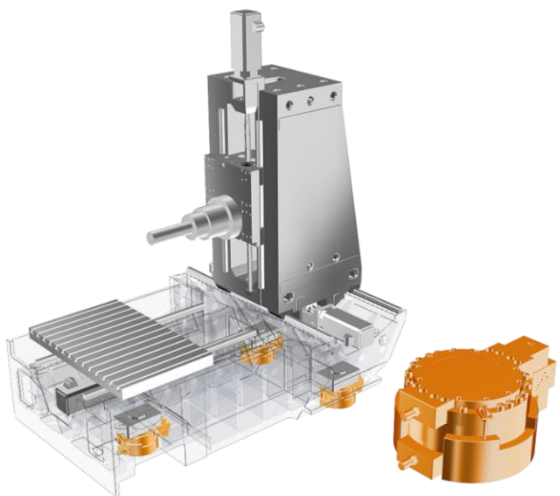

VMPT2015

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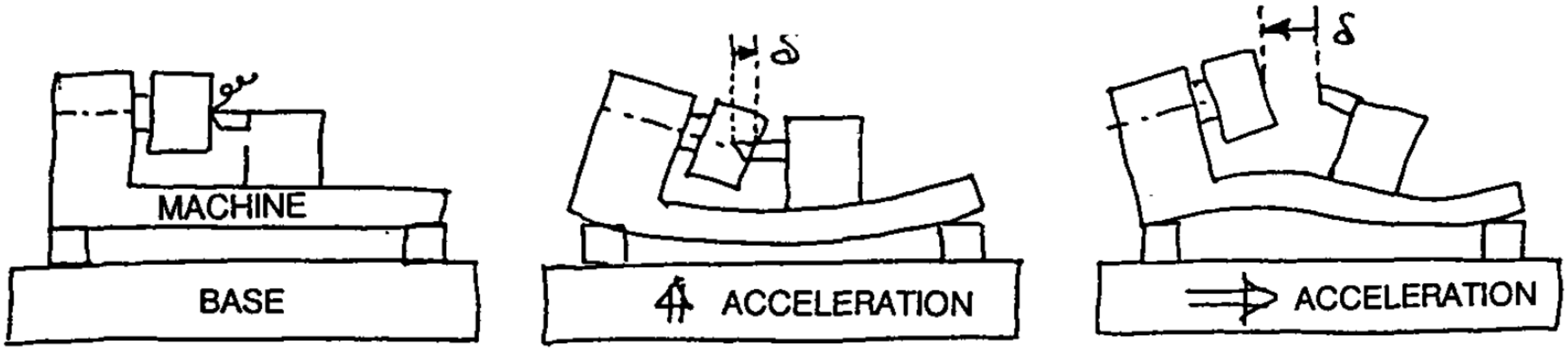
Ground vibrations influencing machine accuracy

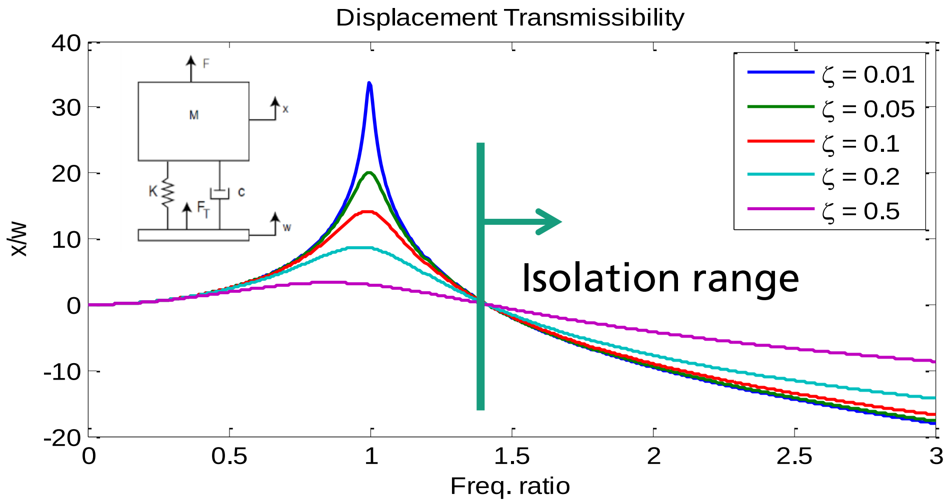


DeBra (1992)

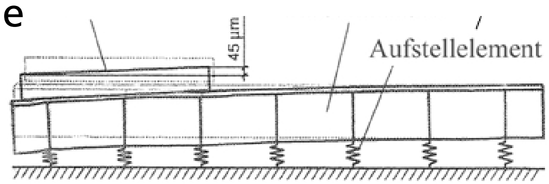
- Ground vibrations distort the machine and results in loss of machining accuracy
- Insulating the machine from its production environment is difficult
- Hence, necessary to isolate machine from disturbances to maintain accuracy

Vibration isolation: passive and/or active?

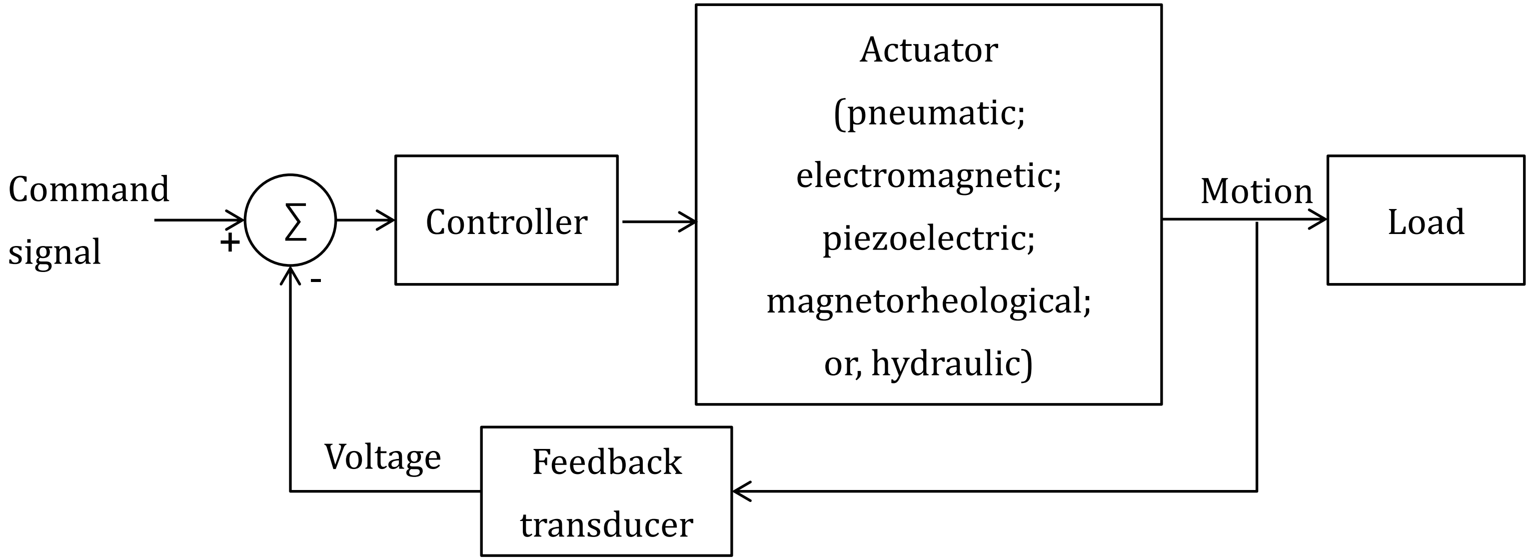
Passive isolators: High damping and relatively low support stiffness



- Passive isolators offer simple and effective isolation solutions
- Dynamic instabilities like rocking due to the low support stiffness
- Difficult to design when ground vibrates with unpredictable waveform that has broadband spectrum



Active isolators and objectives of this work



Actuating principles

- Pneumatic → Unable to support high loads
- Electromagnetic → Low strokes
- Magnetorheological → Suffers from hysteresis
- Piezoelectric → Small deflection capacities

Hydraulic actuators

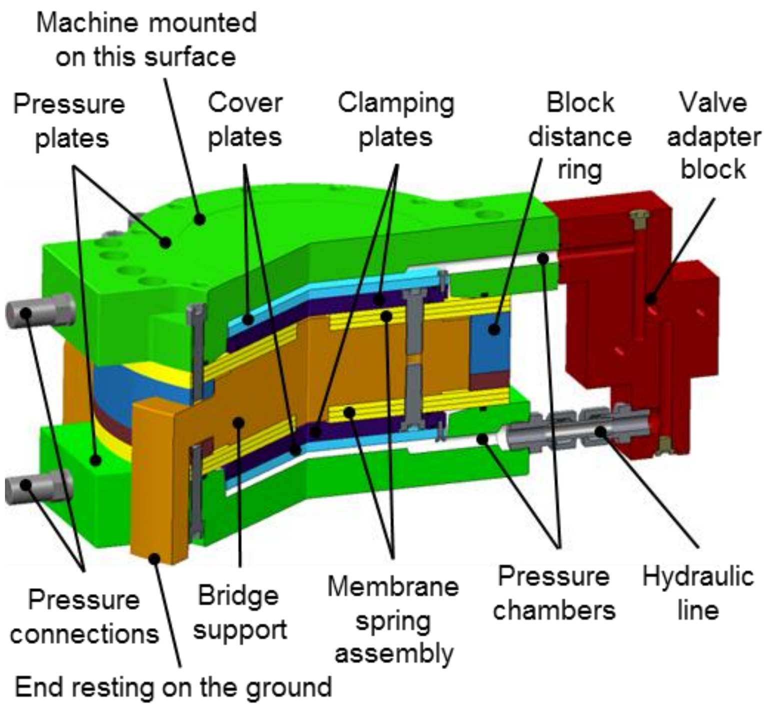
- ✓ High static stiffness
- ✓ No hysteresis
- ✓ Large deflection

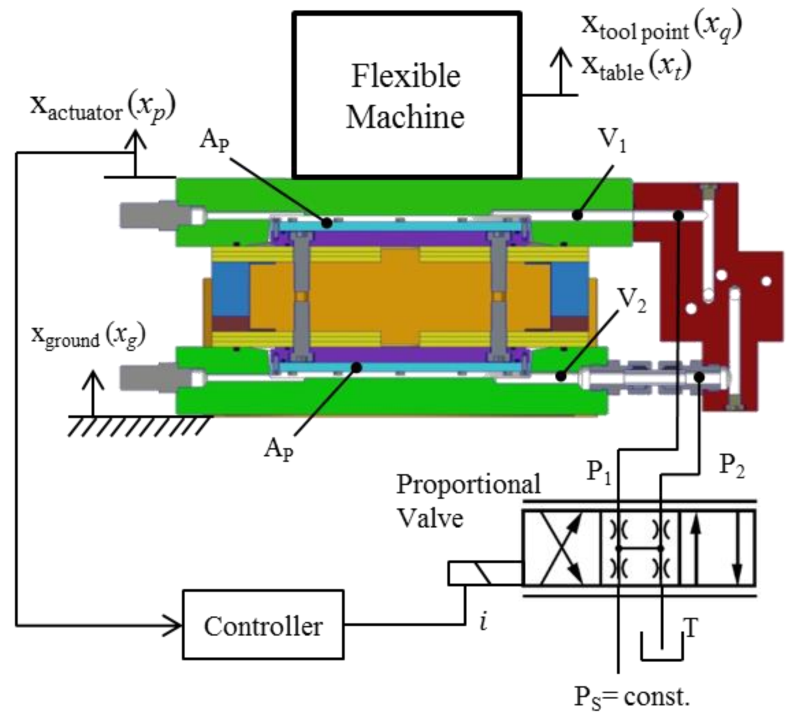
Structure

- Introduction and Motivation
- Electro-hydraulic active isolator
  - Actuator working principle and dynamics
  - Experimental characterization
- Active isolation of machine tools
  - Transmissibility of a flexible machine
- Conclusions and outlook

Proposed electro-hydraulic isolation system @ IWU

Working principle: displacement compensation





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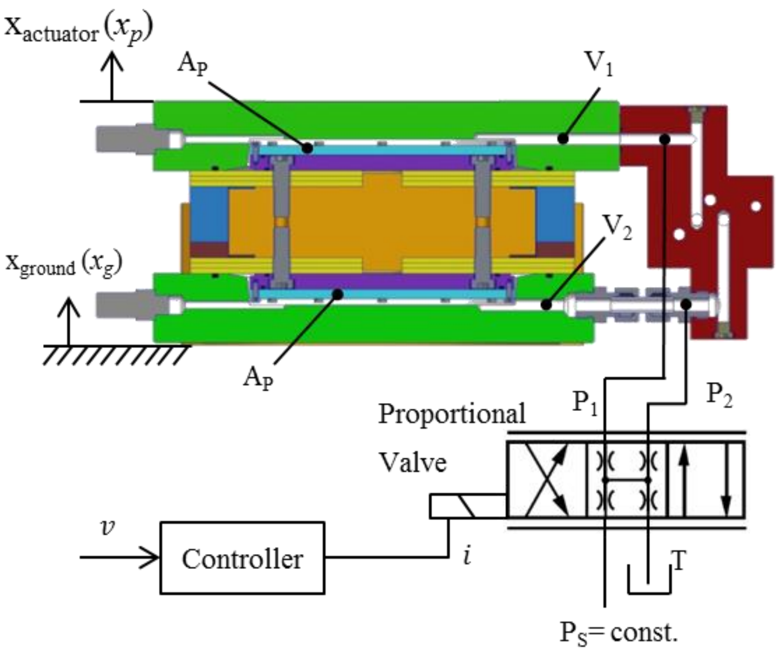
Actuator dynamics (without load and disturbance)



$$\boxed{G_{EHA} = \frac{x_p}{v} = G_{valve} G_{act}}$$

Valve dynamics:

$$G_{valve} = \frac{x_v}{v}(s) = K_v \left[\frac{1}{1 + \left(\frac{2\zeta}{\omega_{n_v}}\right) s + \left(\frac{s}{\omega_{n_v}}\right)^2} \right]$$

Hydraulic and Piston dynamics:

$$Q_L = K_Q x_v - K_C P_L; \qquad Q_L = A_p s x_p + \frac{V_t}{4\beta} s P_L$$

$$\begin{pmatrix} V_t = V_1 + V_2 = 2V_0; \\ P_L = P_1 - P_2 \end{pmatrix}$$

$$F_p = P_L A_p = M s^2 x_p + C s x_p + K_L x_p + F_L$$

$$G_{act} = \frac{x_p}{x_v} = \frac{K_Q / A_p}{\left(s + \frac{K_C K_L}{A_p^{\,2}}\right)\left(\frac{s^2}{\omega_h^{\,2}} + \frac{2\delta_h}{\omega_h} + 1\right)}$$

Hyd. stiffness and damping

$$\omega_h = \sqrt{\frac{4\beta A_p^{\,2}}{V_t M}} \qquad \delta_h = \frac{K_C}{A_p}\sqrt{\frac{\beta M}{V_t}}$$

Meritt (1967);
Jelali & Kroll (2003)

Unknown parameter identification

$$\boxed{G_{EHA} = \frac{x_p}{v} = G_{valve} G_{act}}$$

$$G_{valve} = \frac{x_v}{v}(s) = K_v \left[\frac{1}{1 + \left(\frac{2\zeta}{\omega_{n_v}}\right) s + \left(\frac{s}{\omega_{n_v}}\right)^2} \right]$$

$$G_{act} = \frac{x_p}{x_v} = \frac{K_Q / A_p}{\left(s + \frac{K_C K_L}{A_p{}^2}\right)\left(\frac{s^2}{\omega_h{}^2} + \frac{2\delta_h}{\omega_h} + 1\right)}$$

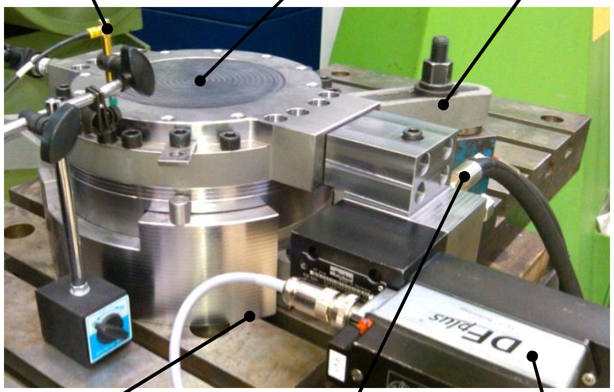
System identification:

$$x_d \subset \{K_L; C; \omega_{n_v}; \zeta; K_Q; K_C\}$$

$$\min f_{objs}(x_d) = \sum_{i=1}^{n_p} r_i^2 \text{ such that } lb \le x_d \le ub$$

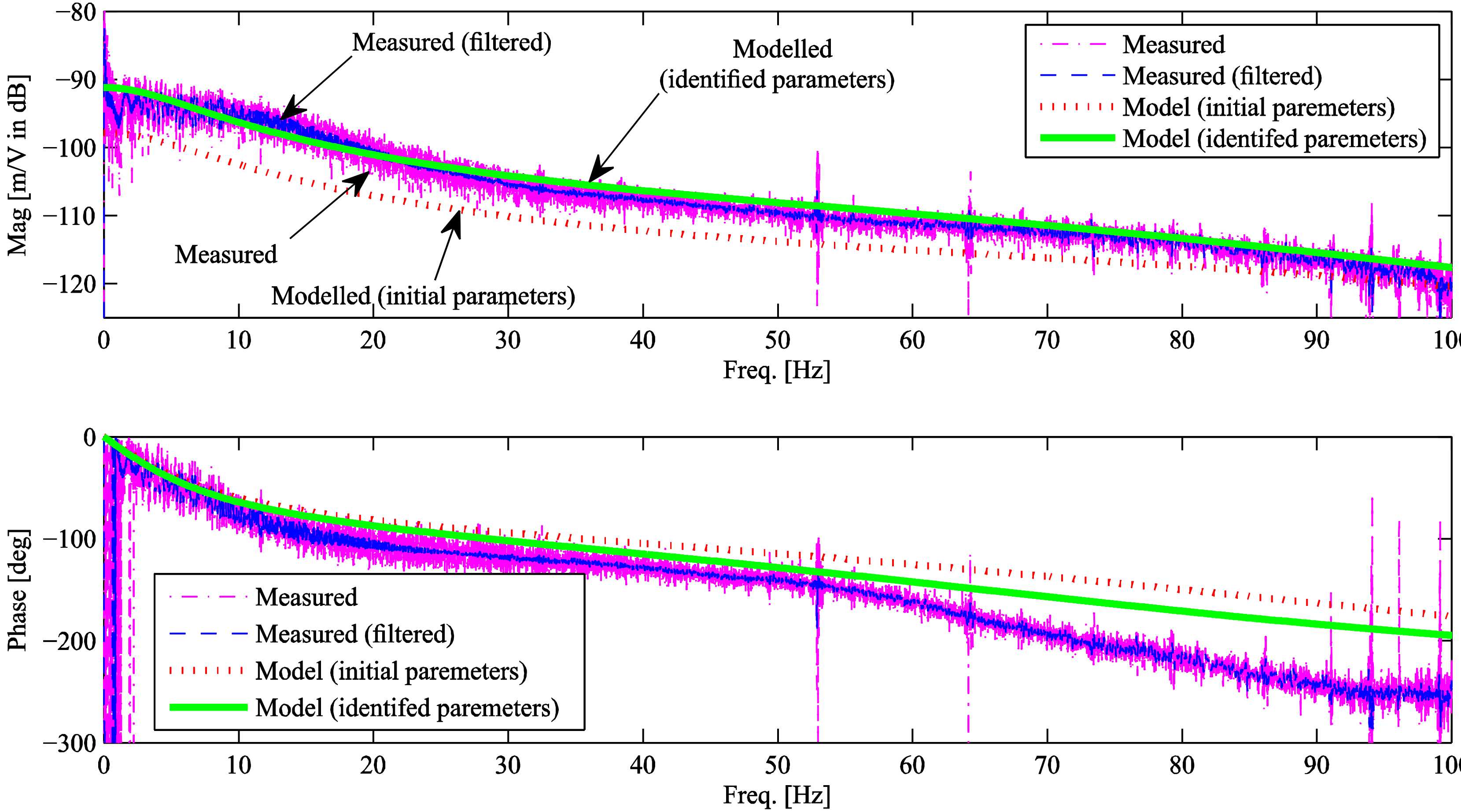
$$r_i = G_{EHA_{measured}} - G_{EHA}(x_d)$$

Jelali & Kroll (2003)

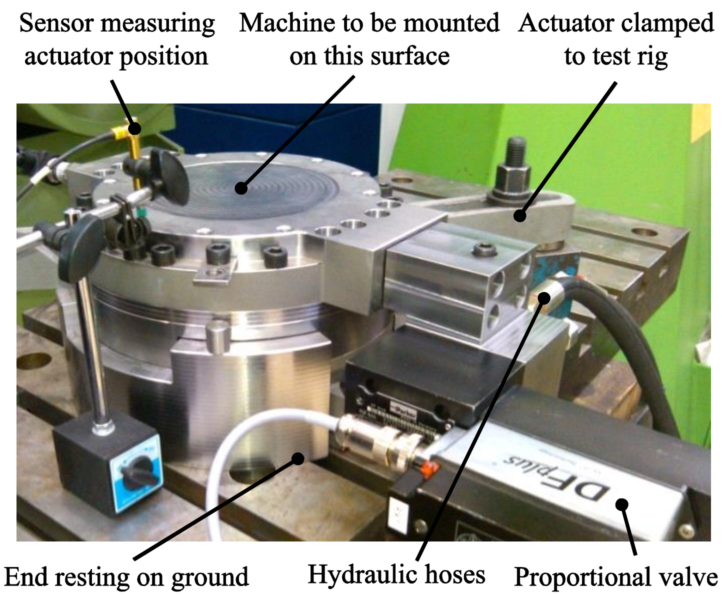


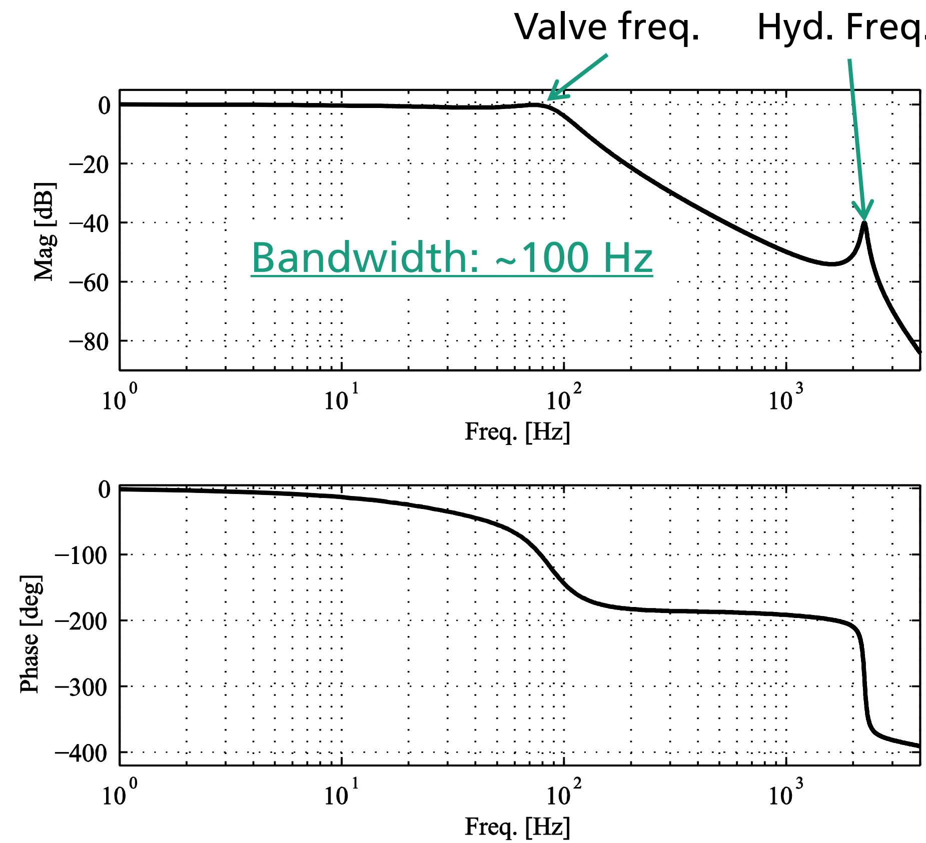
Variable	Intial value	Identified value
Viscous coefficient, C [Ns/m]	3900	1951
Actuator static stiffness, K_L [N/m]	6.8×10^8	6.8×10^8
Flow gain coefficient, K_Q $[m^3/s/mA]$	9.74×10^{-6}	9.74×10^{-6}
Flow pressure coefficient, K_C $[m^3/s/Pa]$	7.15×10^{-11}	6.6×10^{-11}
Valve Natural frequency, ω_{n_v} [rad/s]	628	524
Damping ratio, ζ	0.48	0.65

Experimental characterization



Closed-loop dynamics of the actuator (without machine and external disturbance)





Structure

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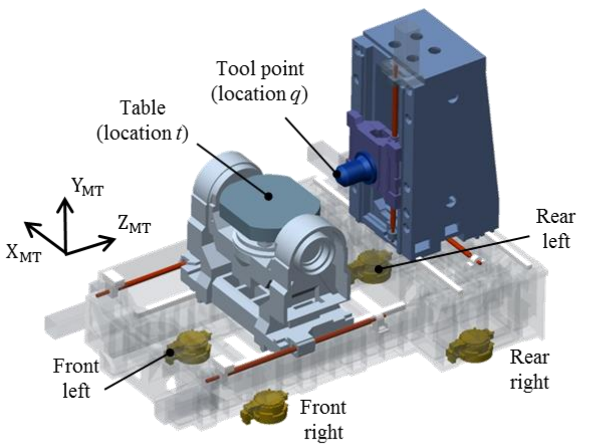
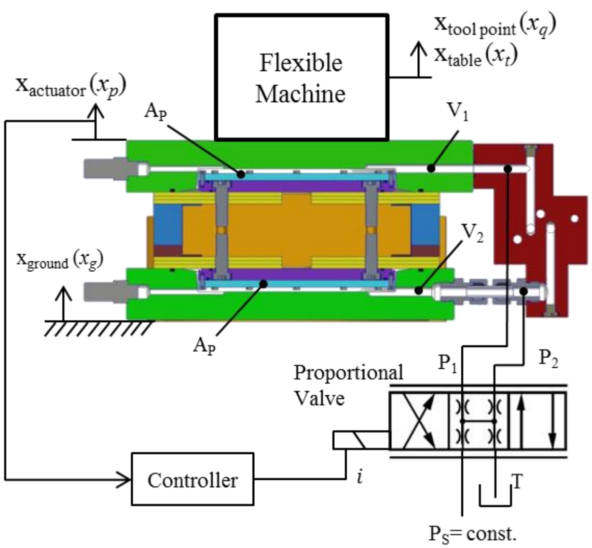
Active isolation of machine tools





Transmissibility between ground and table:

$$TR_{tg} = \frac{x_t}{x_g} = \frac{x_p}{x_g} \times \boxed{\frac{x_t}{x_p}}; \qquad p = 1 \dots 4$$

Transmissibility between ground and actuator

Transmissibility between actuator and table

Transmissibility between ground and tool point:

$$TR_{qg} = \frac{x_q}{x_g} = \frac{x_p}{x_g} \times \boxed{\frac{x_q}{x_p}}; \qquad p = 1 \dots 4$$

Transmissibility between ground and actuator

Transmissibility between actuator and tool point

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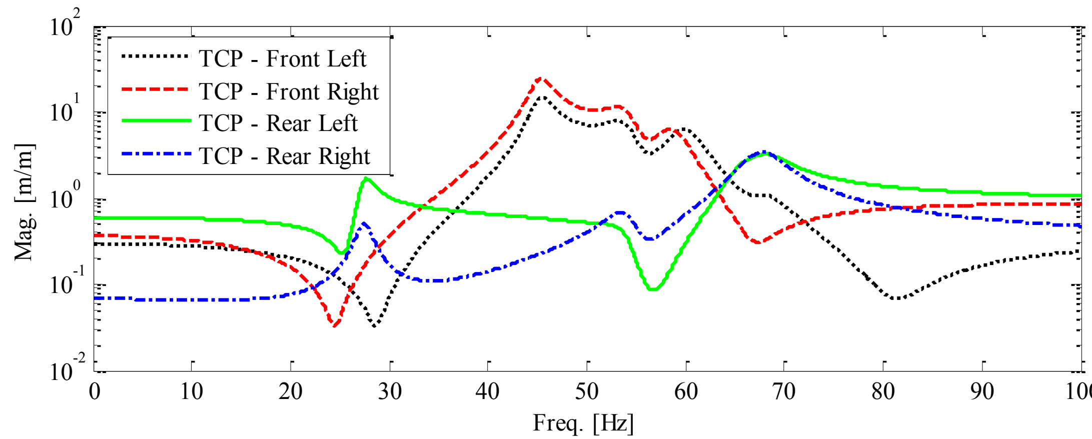
Transmissibility betn actuator and table/tool point

TR betn actuator and tool point:

$$TR_{qp}(\omega) = \frac{x_q(\omega)}{x_p(\omega)} = \frac{x_q(\omega)/F_p(\omega)}{x_p(\omega)/F_p(\omega)}$$

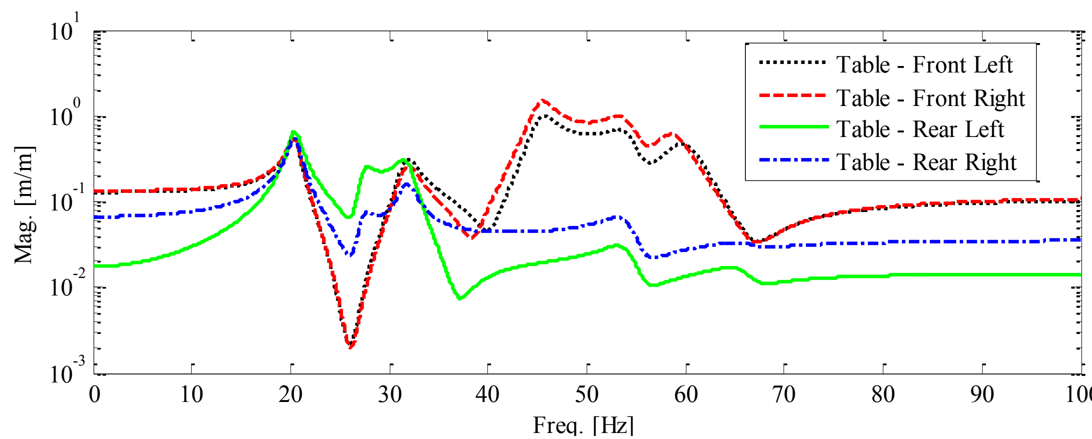
$$= \frac{H_{qp}(\omega)}{H_{pp}(\omega)}; \quad p = 1 \dots 4$$



TR betn actuator and table:

$$TR_{tp}(\omega) = \frac{x_t(\omega)}{x_p(\omega)} = \frac{x_t(\omega)/F_p(\omega)}{x_p(\omega)/F_p(\omega)}$$

$$= \frac{H_{tp}(\omega)}{H_{pp}(\omega)}; \quad p = 1 \dots 4$$



wherein:

$$H_{ij}(\omega) = \sum_{r}^{N_m} \frac{\Phi_{i_r}\Phi_{j_r}}{-\omega^2 + i_m 2\zeta_r \omega \omega_{n_r} + \omega_{n_r}^2}$$

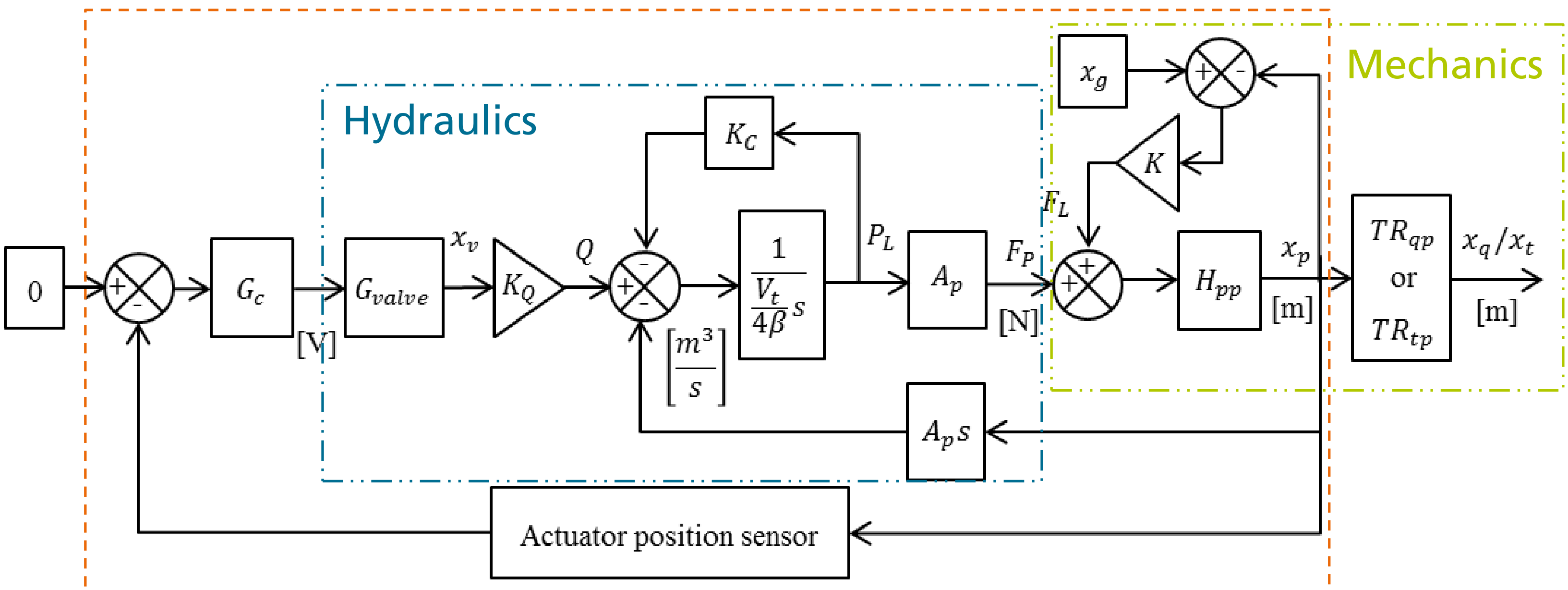
Controlled transmissibility

<u>TR between ground and table:</u>

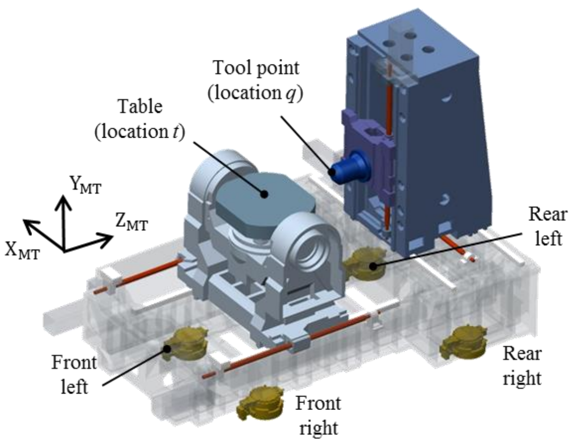
$$TR_{tg} = \frac{x_t}{x_g} = \boxed{\frac{x_p}{x_g}} \times \frac{x_t}{x_p}; \qquad p = 1 \dots 4$$

<u>TR between ground and tool point:</u>

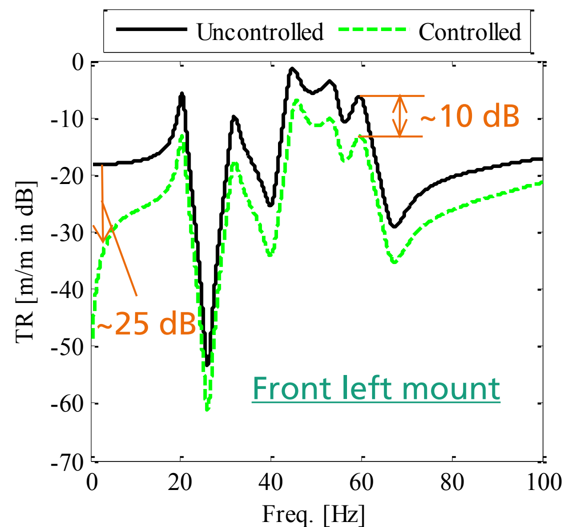
$$TR_{qg} = \frac{x_q}{x_g} = \boxed{\frac{x_p}{x_g}} \times \frac{x_q}{x_p}; \qquad p = 1 \dots 4$$

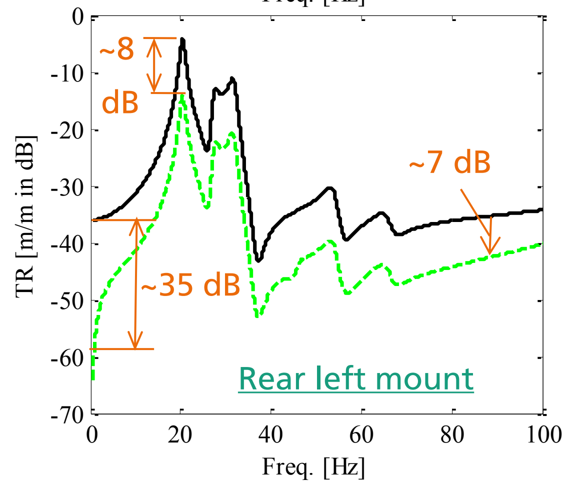


Controlled transmissibility

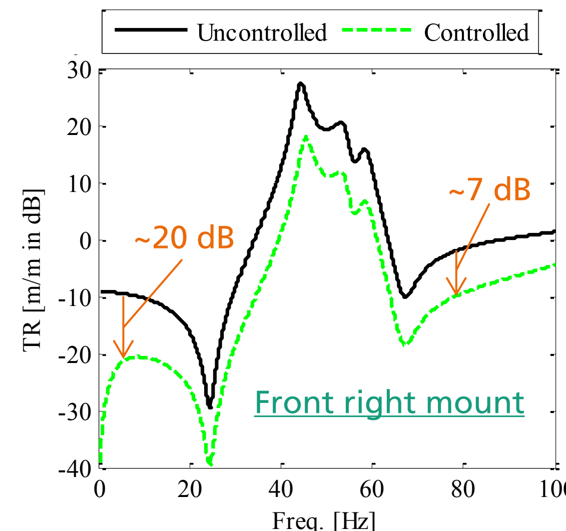


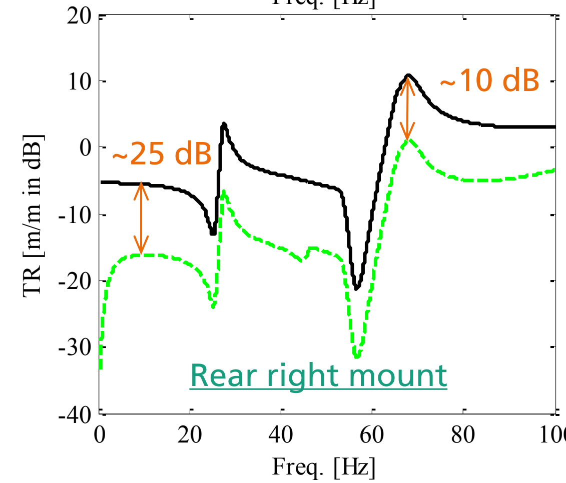
TR between ground and table





TR between ground and tool point



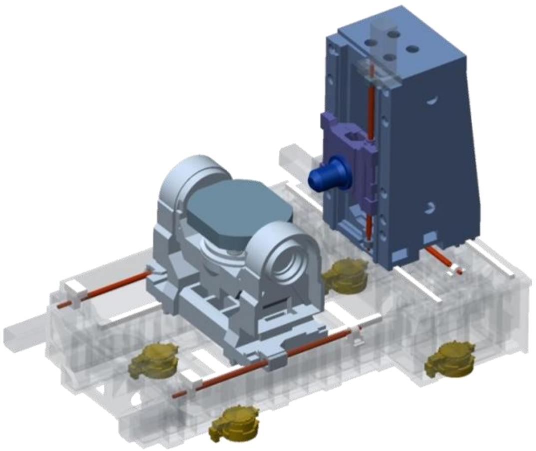


Summary

- ✓ Designed and developed a novel electro-hydraulic isolator
- ✓ Actuator has a high static stiffness to support large inertial loads
- ✓ Controlled closed-loop transmissibility shows actuator:
  - Has a high bandwidth (~100 Hz)
  - Can attenuate ground motion transmitted to the tool/table up to 35 dB

Future work

- ➢ Further experimental characterization of actuator
- ➢ Investigate advanced control strategies



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Thank you for your attention!

Questions?

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