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Book of Abstracts

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Loop-Shaping for Narrow-Band Active Damping Control

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1 Research Contribution

Lightly damped structural resonances limit the performance of high-precision mechatronic systems and flexible structures. Conventional active damping schemes, such as positive and negative position feedback, provide moderate damping at the targeted mode, but often suffer from spillover at low and high frequencies, especially in systems with closely spaced modes or high noise sensitivity. This work presents a generalized higher-order band-pass active damping framework that enhances modal selectivity and stability for narrow-band damping. A non-minimum-phase filter is incorporated to compensate for delay-induced phase degradation, while a tunable damping coefficient increases the design flexibility. Simulation studies on identified collocated and non-collocated systems demonstrate that the proposed controller achieves sharp resonance suppression, improved noise attenuation, and reduced spillover compared with conventional active damping schemes.

2 Loop Shaping via Band-Pass Controller

For an active damping controller $C_d(s)$ that is implemented within a negative feedback loop, the open-loop transfer function $\mathcal{L}(s)$ is defined as $\mathcal{L}(s) = G(s)C_d(s)$. The closed-loop transfer function $\mathcal{PS}_{xd}(s)$, which maps the input disturbance d to the performance output x, is given by:

$$\mathcal{PS}_{xd}(s) = \frac{G(s)}{1 + G(s)C_d(s)} = G(s)\left(\mathcal{S}_{xn}(s) + 1\right). \quad (1)$$

To achieve the desired closed-loop resonance peak attenuation at the system's natural frequency ω_n of $\mathcal{PS}_{xd}(s)$ and suppression of noise propagation to the performance output in $\mathcal{S}_{xn}(s)$, the open-loop transfer function $\mathcal{L}(s)$ must satisfy the following gain conditions:

$$\begin{array}{ll|ll} |\mathcal{L}(s)| \gg 1 & |\mathcal{PS}_{xd}(s)| \ll |G(s)| & \text{at } \omega \approx \omega_n, \\ |\mathcal{L}(s)| \ll 1 & |\mathcal{S}_{xn}(s)| \approx 0 & \forall\, \omega \neq \omega_n. \end{array} \quad (2)$$

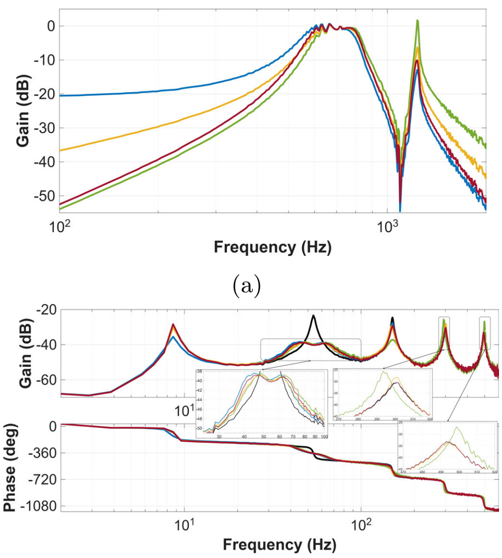
These conditions correspond to an idealized triangular loop-gain profile, where the gain exceeds unity within a finite frequency band. This is rendered by a generalized delay-compensated band-pass damping controller, expressed as:

$$C_d(s) = \underbrace{g(n)\left(\frac{s}{(s+\omega_c)^2}\right)^n \cdot h(m)(s+\omega_c)^m}_{\text{Band-Pass Damping Controller}} \cdot \underbrace{\sigma\left(\frac{s-\omega_d}{s+\omega_d}\right)}_{\text{NMP Filter}}, \quad (3)$$

where ω_c and ω_d represent the corner frequency of band-pass and NMP filter respectively, with $g(n) = M(2\omega_c)^n$ and $h(m) = 2^{-m/2}\omega_c^{-m}$ ensure a fixed maximum gain $M > 0$ for any combination of slope orders (n, m).

3 Illustrative Case Studies

The band-pass controller is designed to provide narrow-band damping at the targeted mode while minimizing low- and high-frequency spillover and noise amplification. Performance is compared with benchmark Positive Position Feedback (PPF) and Negative Position Feedback (NPF) controllers.



(b)

Figure 1: Simulated frequency response of (a) collocated nanopositioning system $G(s)$ (—) and closed-loop response $|\mathcal{S}_{xn}(s)|$, and (b) non-collocated flexural beam $G(s)$ (—) and closed-loop response $\mathcal{PS}_{xd}(s)$, obtained via implementing active damping controller $C_d(s)$ as PPF controller (—), NPF controller (—), proposed band-pass controller with $n = 1$ (—), and with $n = 2$ (—).