Vibration Suppression Design for Virtual Compliance Control in Bilateral Teleoperation

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Introduction

Problem statement

Application of one degree of freedom inertia-spring-damper system for **vibration suppression** in a bilateral control system.

System compliance for different input frequency controlled by the value of virtual elements (based on the cut-off frequencies and stiffness of the virtual spring).

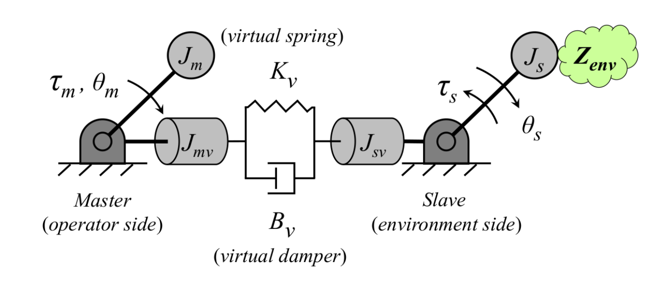
Motivation

1. **Stability** of the closed loop system irrespective to the behaviour of the human and the environment

2. **Transparency** of the teleoperation task: same forces and displacements on the two sides of the system

System Modeling

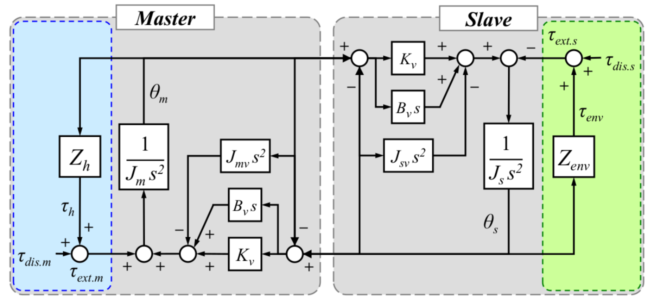
Inertia-Spring-Damper System



Position error based torque reflection to the operator at the master side.

- Real inertias: J_m, J_s
- Virtual inertias: J_{mv}, J_{sv}
- Virtual damper and spring: B_v, K_v

Bilateral Control Scheme



Dynamics equations in frequency domain:

$$(J_m + J_{mv})s^2\theta_m + (B_v s + K_v)(\theta_m - \theta_s) = \tau_m$$
$$(J_s + J_{sv})s^2\theta_s + (B_v s + K_v)(\theta_s - \theta_m) = -\tau_s$$

System Analysis

Bilateral Controller

External torques as action and reaction torque of human and environment impedance, Z_h and Z_{env}:

$$J_m s^2\theta_m = \tau_m - (B_v s + K_v)(\theta_m - \theta_s) - J_{mv} s^2\theta_m$$
$$J_s s^2\theta_s = -\tau_s - (B_v s + K_v)(\theta_s - \theta_m) - J_{sv} s^2\theta_s$$

System represented by 2×2 hybrid matrix as:

$$\begin{bmatrix} \tau_m \\ \theta_s \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \theta_m \\ -\tau_s \end{bmatrix}$$

Bilateral Controller

Hybrid parameters H_{ij}:

$$
\begin{aligned}
H_{11} &= \frac{1}{Z_s}[Z_m Z_s - (B_v s + K_v)^2] \\
H_{12} &= -\frac{1}{Z_s}[B_v s + K_v] \\
H_{21} &= \frac{1}{Z_s}[B_v s + K_v] \\
H_{22} &= \frac{1}{Z_s}
\end{aligned}
$$

where:

$$
\begin{aligned}
Z_m &= (J_m + J_{mv})s^2 + B_v s + K_v \\
Z_s &= (J_s + J_{sv})s^2 + B_v s + K_v
\end{aligned}
$$

Bilateral Controller

Condition of transparency: Trasmitted impedance Z_t transferred to the operator should be equal to environment impedance Z_{env}:

$$\frac{\tau_m}{\theta_m} = Z_t = Z_{env} = \frac{\tau_s}{\theta_s}$$

Relationship between Z_t and Z_{env}:

$$Z_t = \left(\frac{-H_{12}H_{21}}{1 + H_{22}Z_{env}}\right)Z_{env} + H_{11}$$

Hybrid parameters for the perfect transparency condition, derived as:

$$\begin{bmatrix} \tau_m \\ \theta_s \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \theta_m \\ -\tau_s \end{bmatrix}$$

Vibration Suppression Design

Parameters Selection and Design

Assume system disturbed by environment vibration noise.

Inspect H_{22} for the relationship of position response θ^{res} and external torque input τ_{ext}:

$$\frac{\theta_s}{\tau_{ext}} = \frac{1}{(J_s + J_{sv})s^2 + B_v s + K_v}$$

Virtual parameters J_v, B_v and K_v determined from the second-order characteristic equation:

$$s^2 + (g_1 + g_2)s + (g_1 * g_2) = 0$$

established from two poles g_1 and g_2, representing the desired cut-off frequencies of the system for disturbance suppression.

Parameters Selection and Design

Spring stiffness K_v influences the behaviour of the system.

It regulates the *compliance* of this, achieving **rigid coupling** (high spring stiffness) or **spring coupling** (low spring stiffness).

Virtual parameters B_v and J_v computed according to K_v:

$$B_v = \left(\frac{g_1 + g_2}{g_1 * g_2}\right) K_v$$

and

$$J_{sv} = \left(\frac{1}{g_1 * g_2}\right) K_v - J_s$$

Vibration Suppression Performance Analysis

Results

Simulation Setup

Simulation Scenario and Results

Simulation Scenario and Results

VIDEO

Conclusion

Summary

Thank you for your attention!