Admittance-based Haptic Interface Performance Evaluation and Associated Challenges

THE UNIVERSITY of WISCONSIN MADISON

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Admittance-based Haptic Interface Performance Evaluation and Associated Challenges

Device Types

Impedance-based Devices

- Generally **backdrivable**

- Operated open-loop
- Generally no explicit closed loop control

Admittance-based Devices

- Generally **non-backdrivable**

- Requires a task-space force/torque sensor
- Requires closed-loop controller

Phantom

Omega

• • •

VISHARD

• • •

HapticMaster

Impedance-based ⟷ ***Admittance-based***

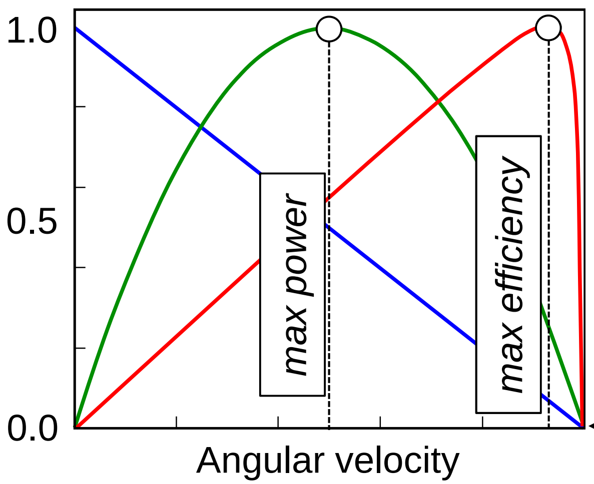
Natural rendering: *low inertia, low stiffness* ⟷ *high inertia, high stiffness*

Output force / power: *low* ⟷ *high*

Design complexity: *low* ⟷ *high*

Effect of Actuation Characteristics

Haptic device actuation **dominant** → EM actuators



Overview: [Hollerbach et al 1992]

- low torque density
- maximum power / efficiency at high velocity

ω_{NL} ~ 1k – 10k RPM

Commonly paired with gear reduction

- increases output torque
  - ➡ *for high torque applications*
- deceases output velocity
  - ➡ *operate closer to P_{max}*

but ...

Amplifies motor dynamics

- as seen at output
  - ➡ *motor inertia x N^2*
  - ➡ *motor friction* — *coulomb x N*; *viscous x N^2*

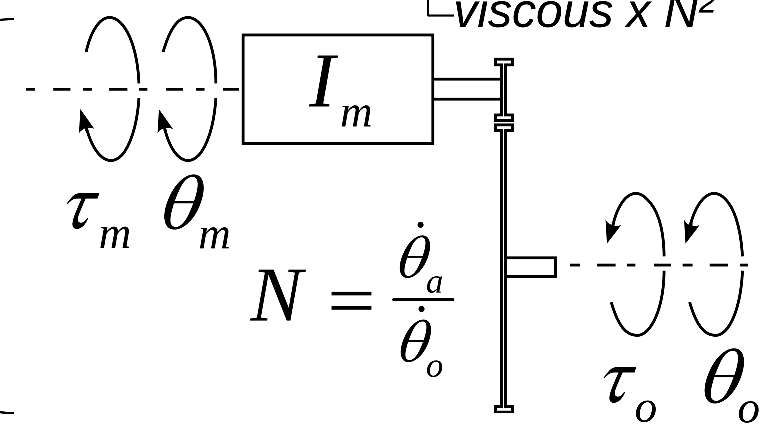
Actuation characteristics
constrain
Device characteristics

torque amplification

$$\tau_o = N \tau_m$$

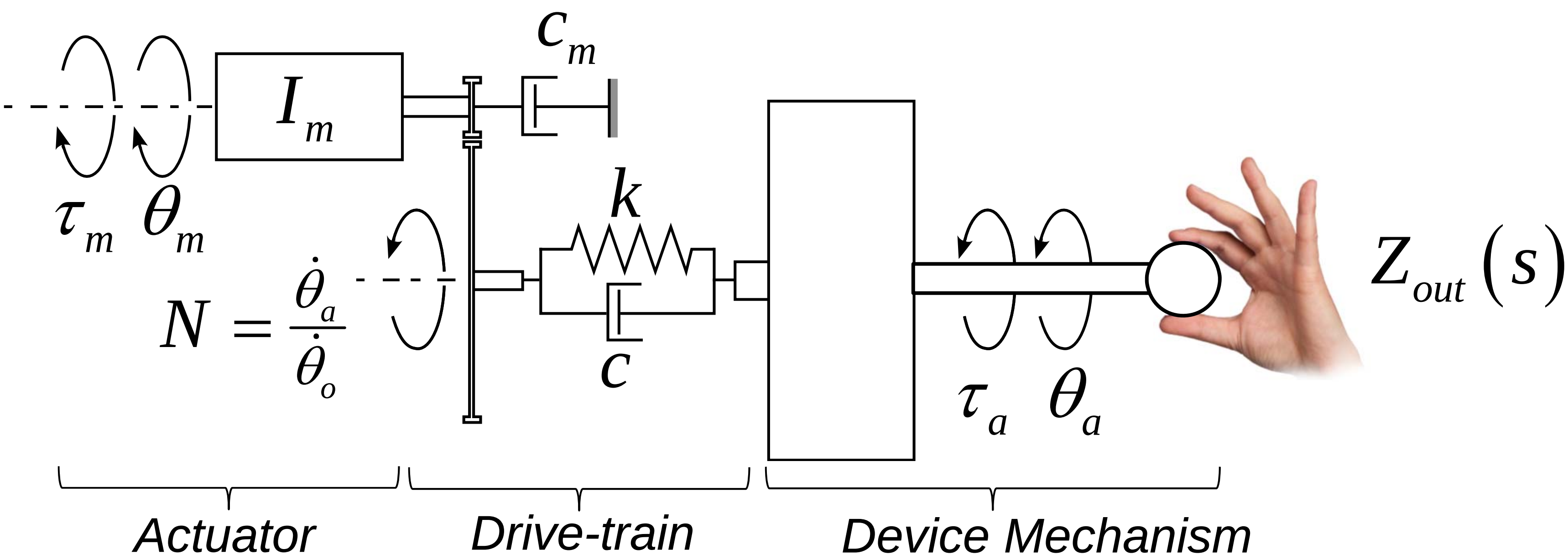
reflected inertia:

$$I_o = N^2 I_m$$



$$N = \frac{\dot{\theta}_a}{\dot{\theta}_o}$$

Simplified Device Model:

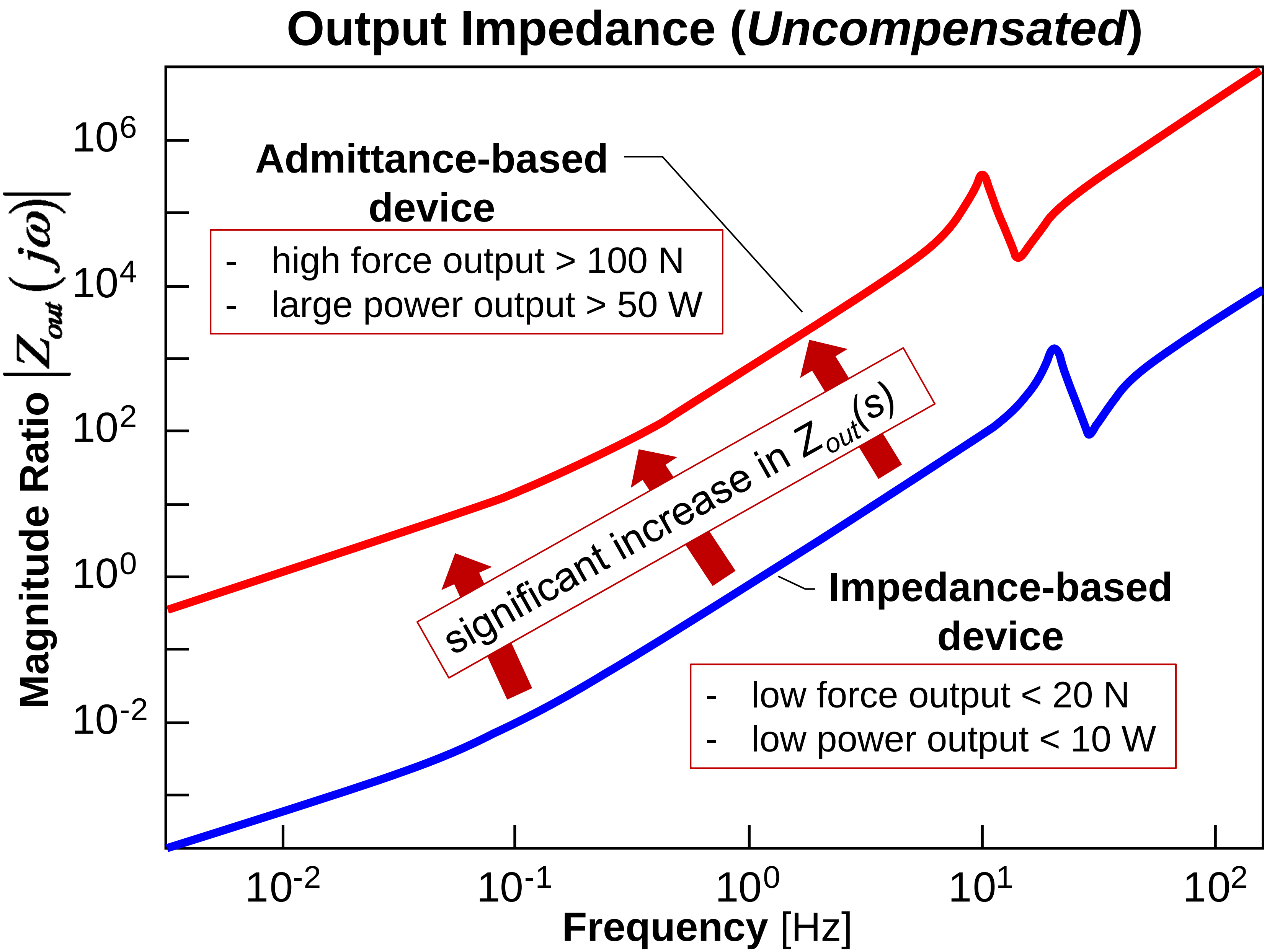


Output Impedance:

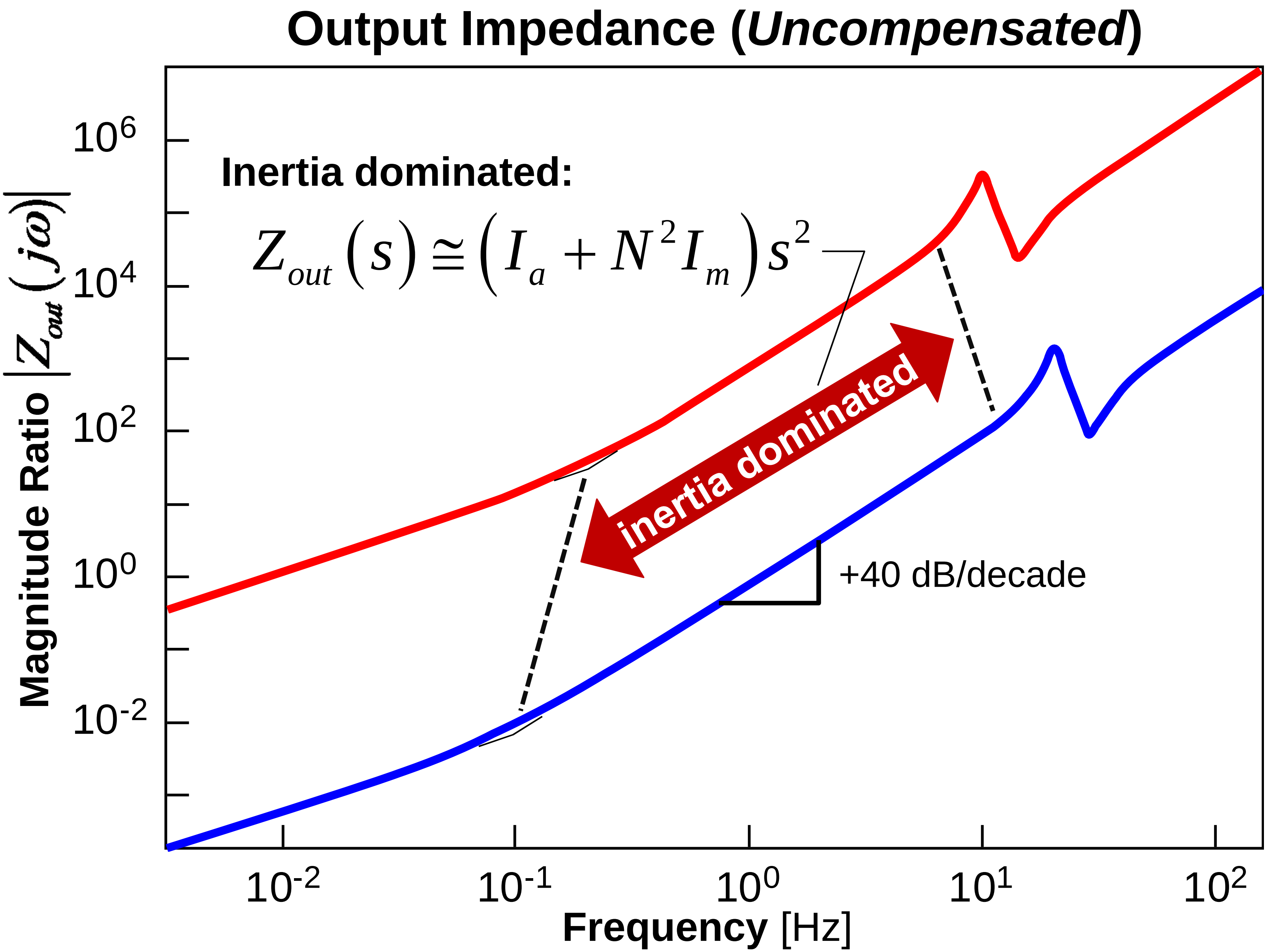
$$Z_{out}(s) = \frac{\tau_a(s)}{\theta(s)}$$

alternative definition from standard $\frac{\tau_a(s)}{\omega(s)}$

Device Output Impedance



Device Output Impedance



Device Output Impedance

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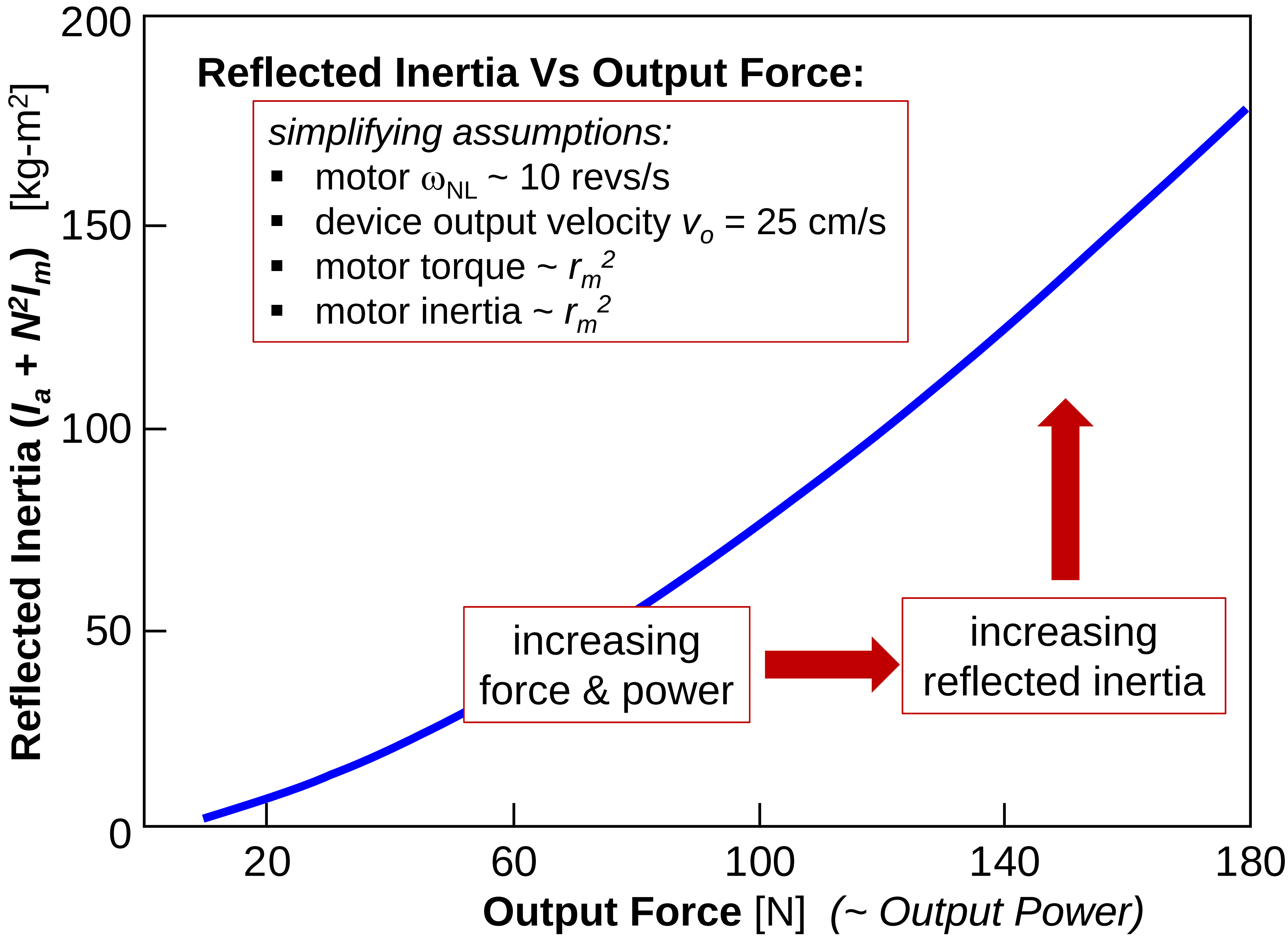
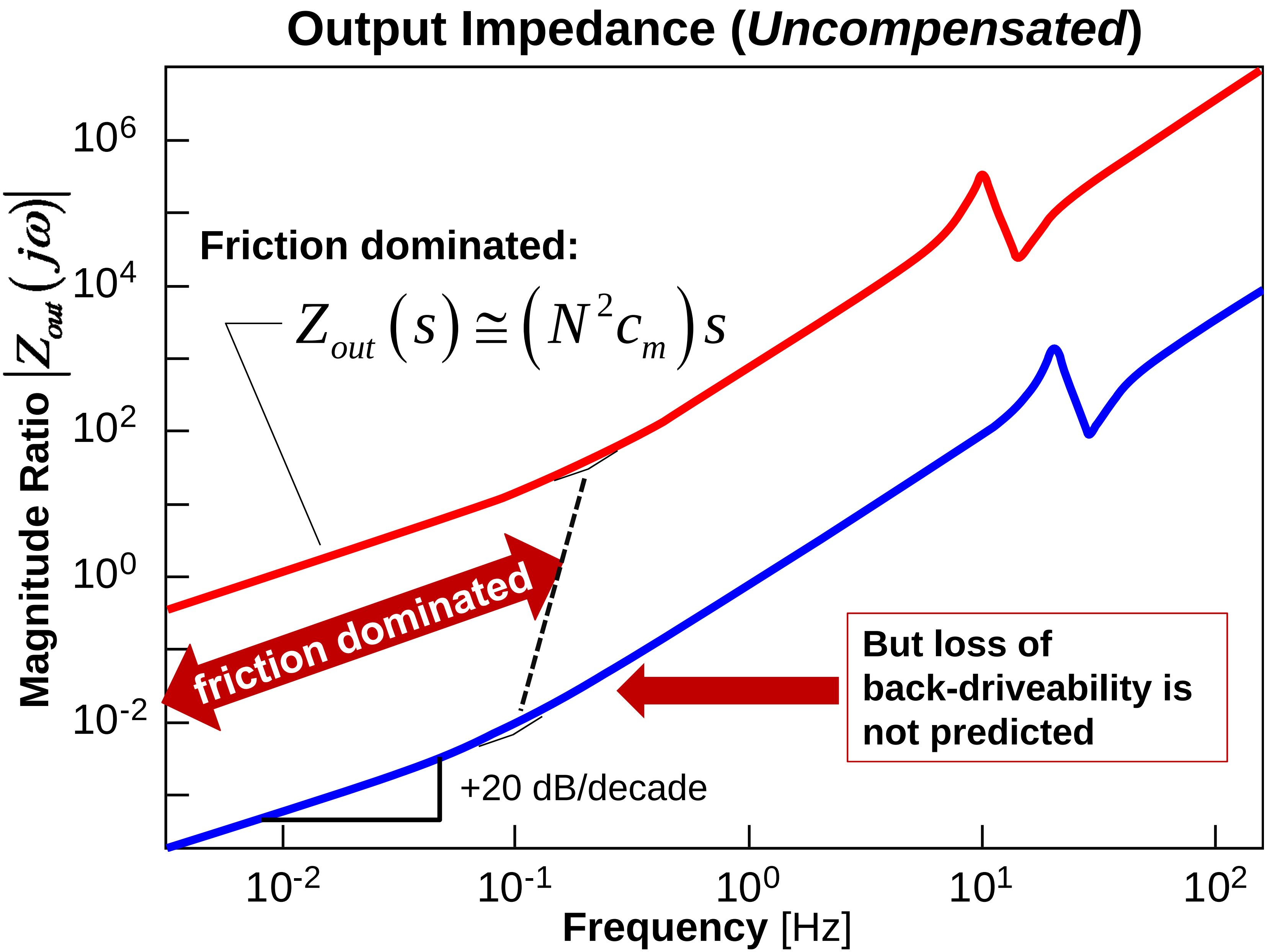
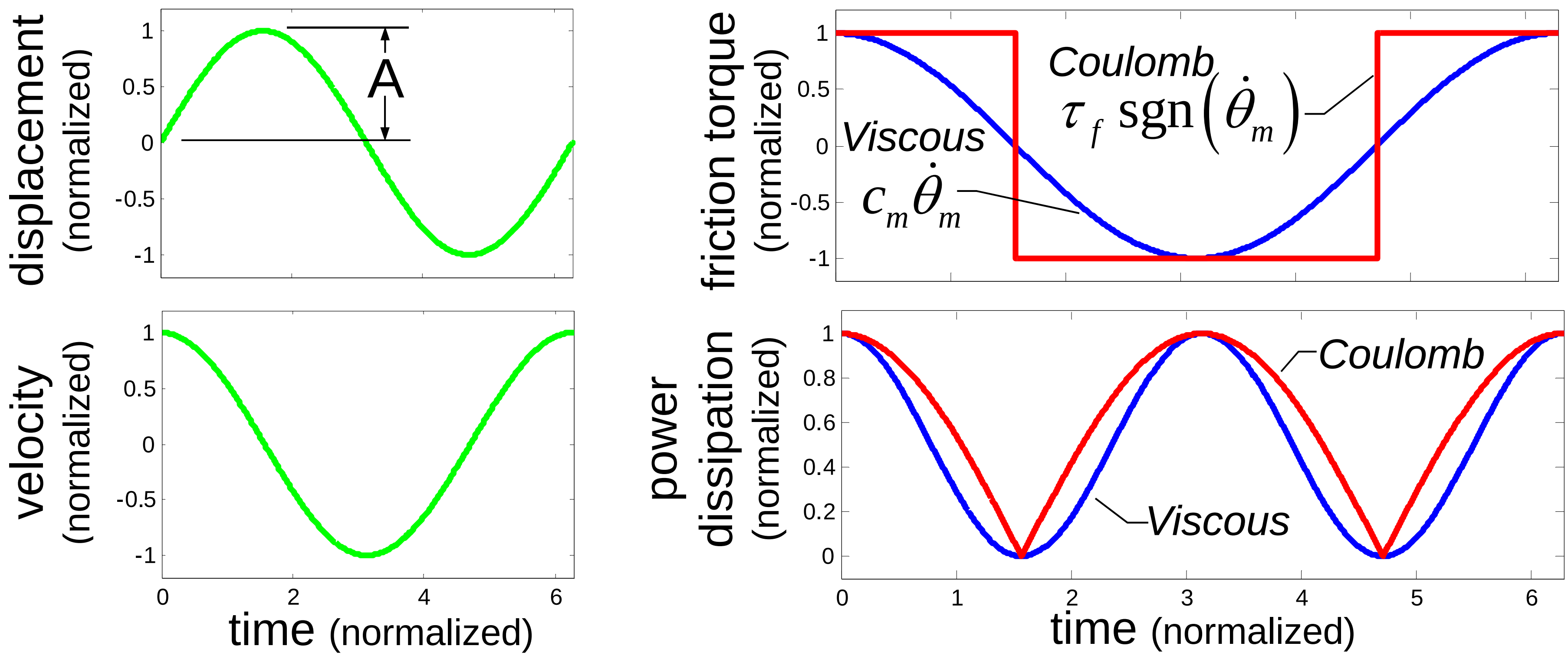


Device Output Impedance



Equivalent Viscous-Coulomb Friction

Coulomb Friction ⇨ Equivalent Viscous Friction Model

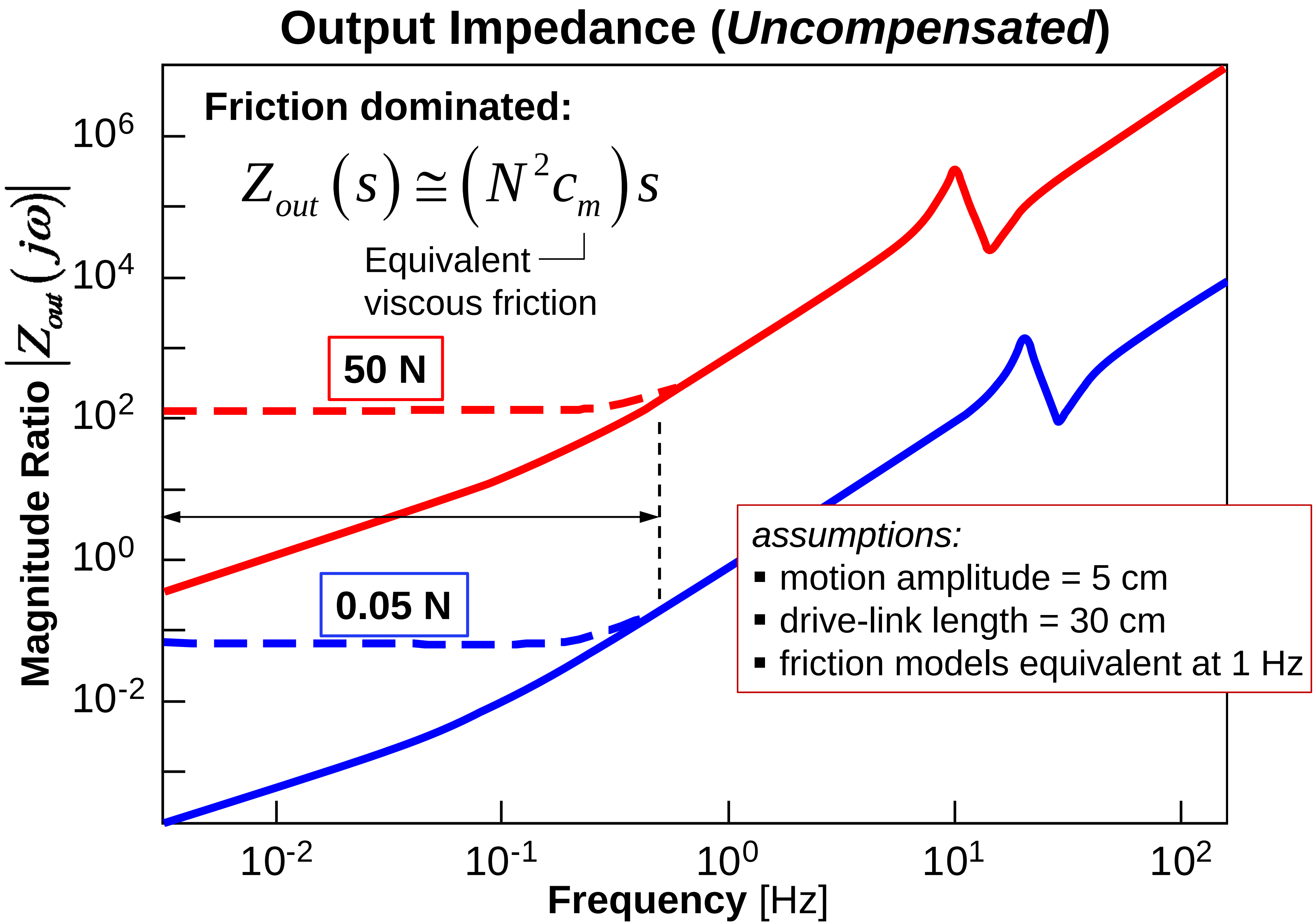


Equate work done over 1-cycle

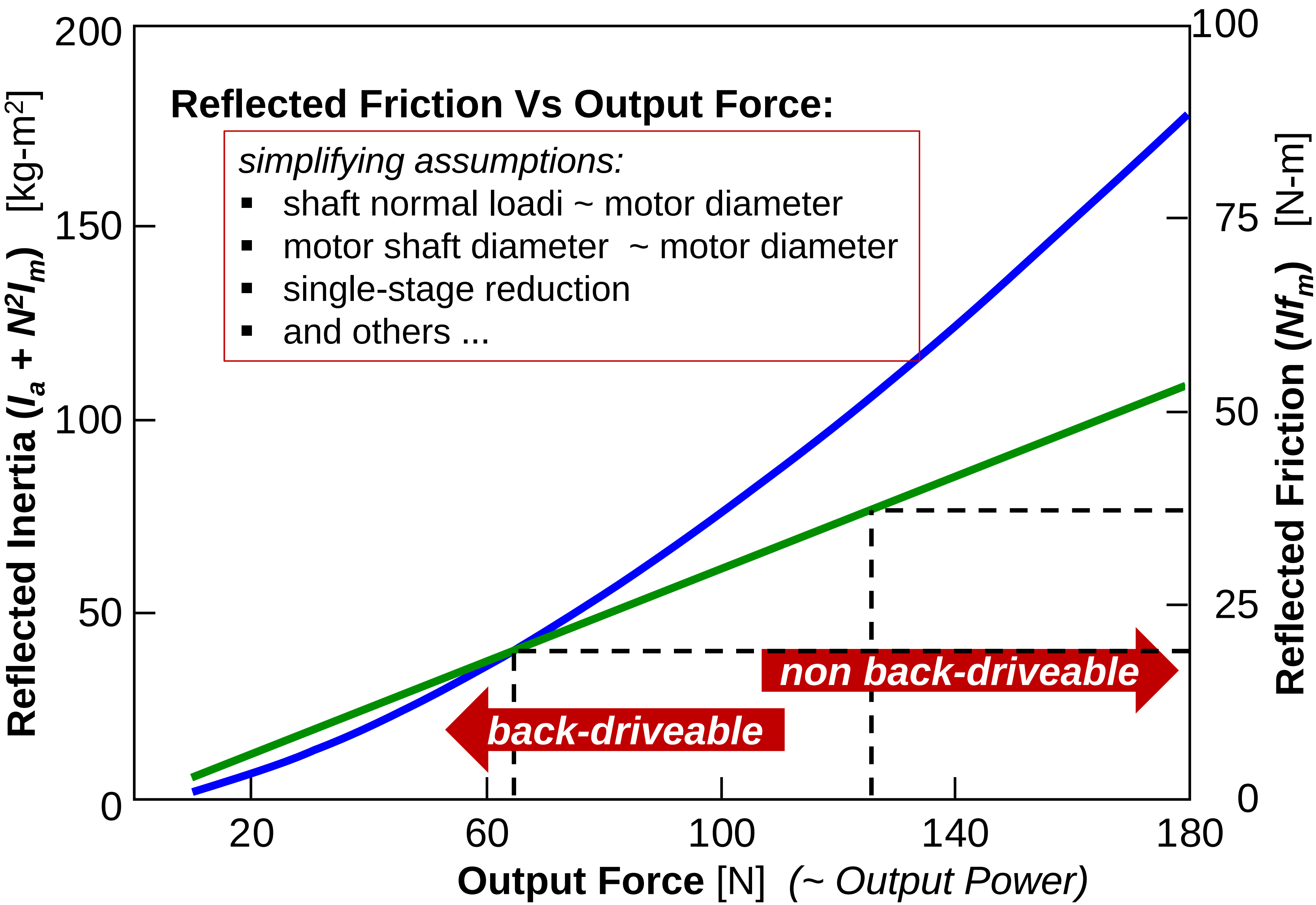
$$W = \int_0^T P\,dt \quad \begin{cases} \textit{Viscous:} \quad W = \pi A^2 \omega c_m \\ \textit{Coulomb:} \quad W = 4A\tau_f \end{cases} \Rightarrow c_m = \frac{4\tau_f}{\pi A \omega}$$

Equivalent viscous friction

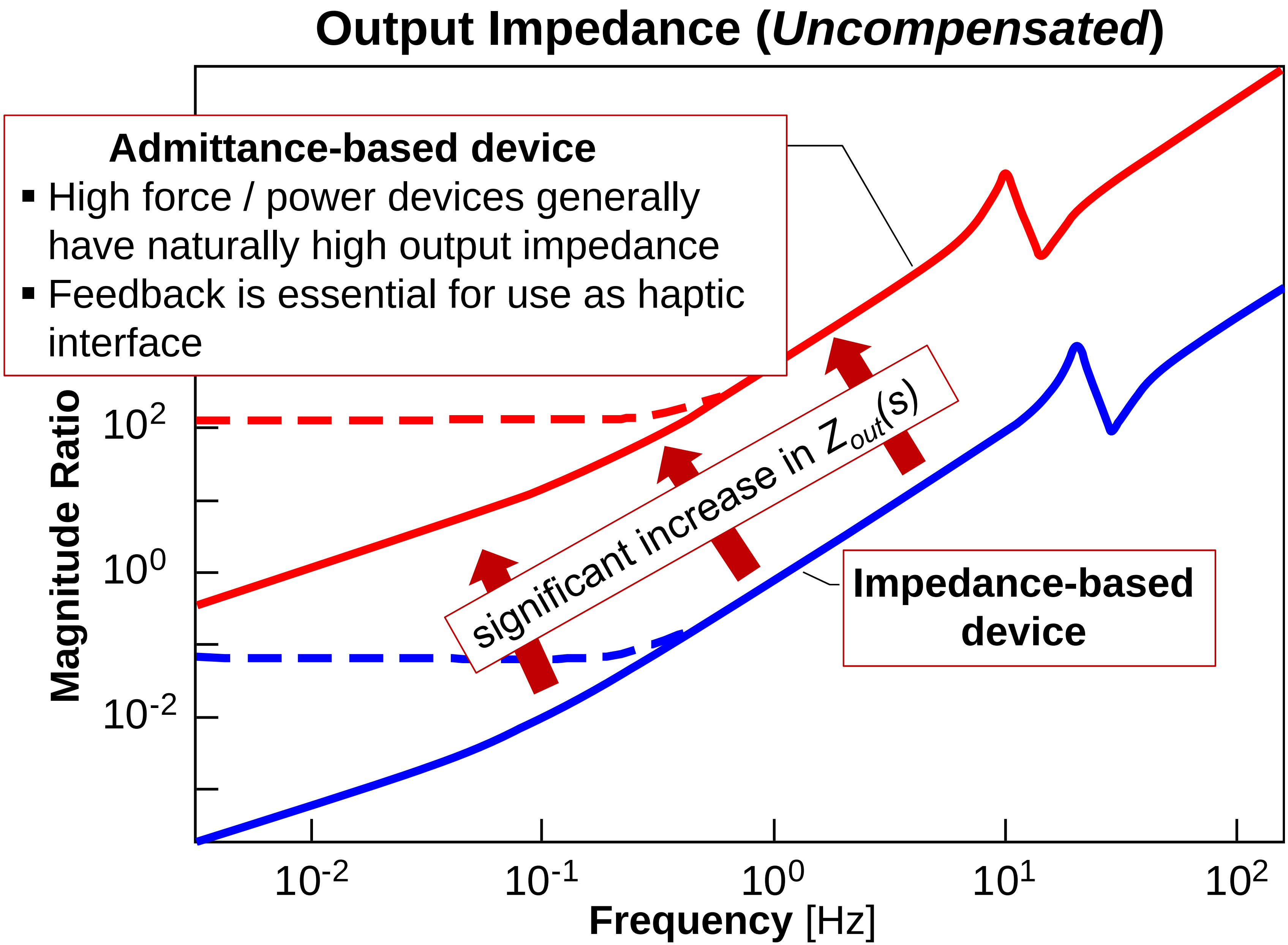
Device Output Impedance



Device Output Impedance



Device Output Impedance

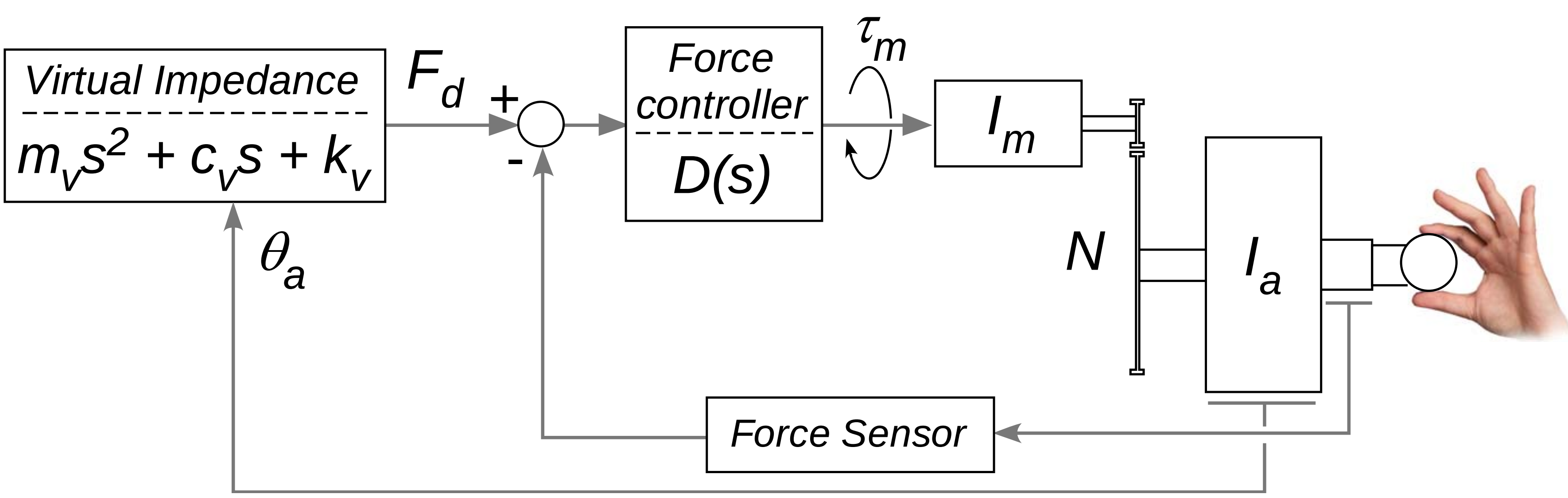


Control Approach

Admittance-based systems require feedback

- feedback is required to overcome device characteristics:
  - non-backdriveable
  - high reflected inertia
- Numerous control strategies have been adopted
  - explicit force control – virtual impedance

example control architecture – explicit force control



Control Approach

Admittance-based systems require feedback

- feedback is required to overcome device characteristics:
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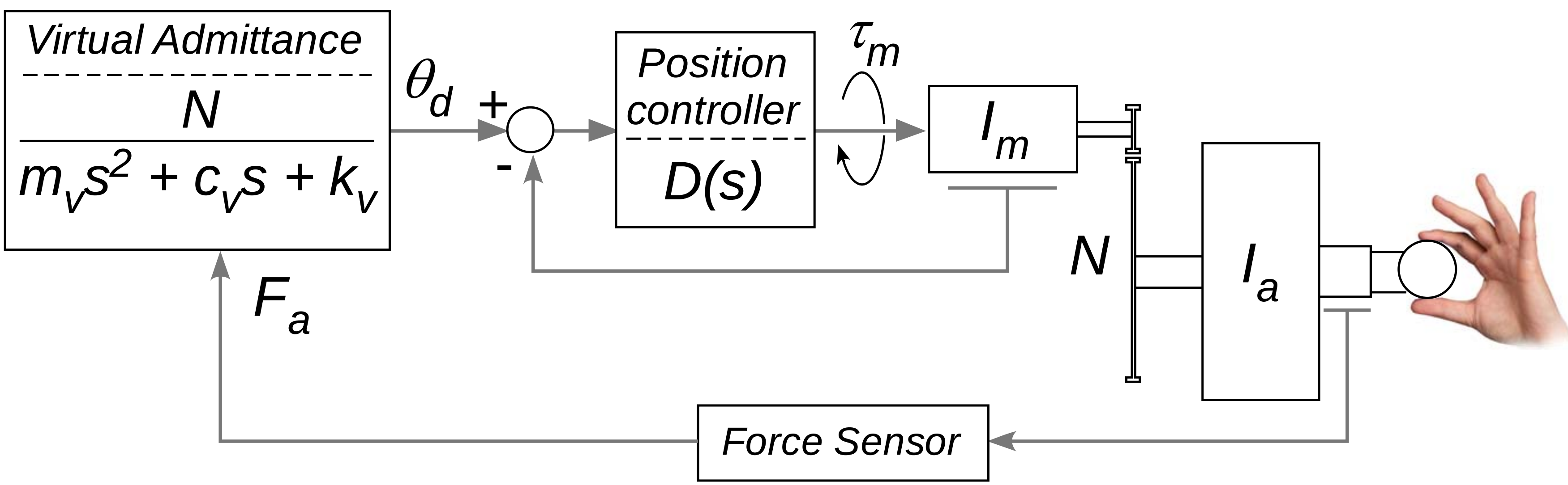
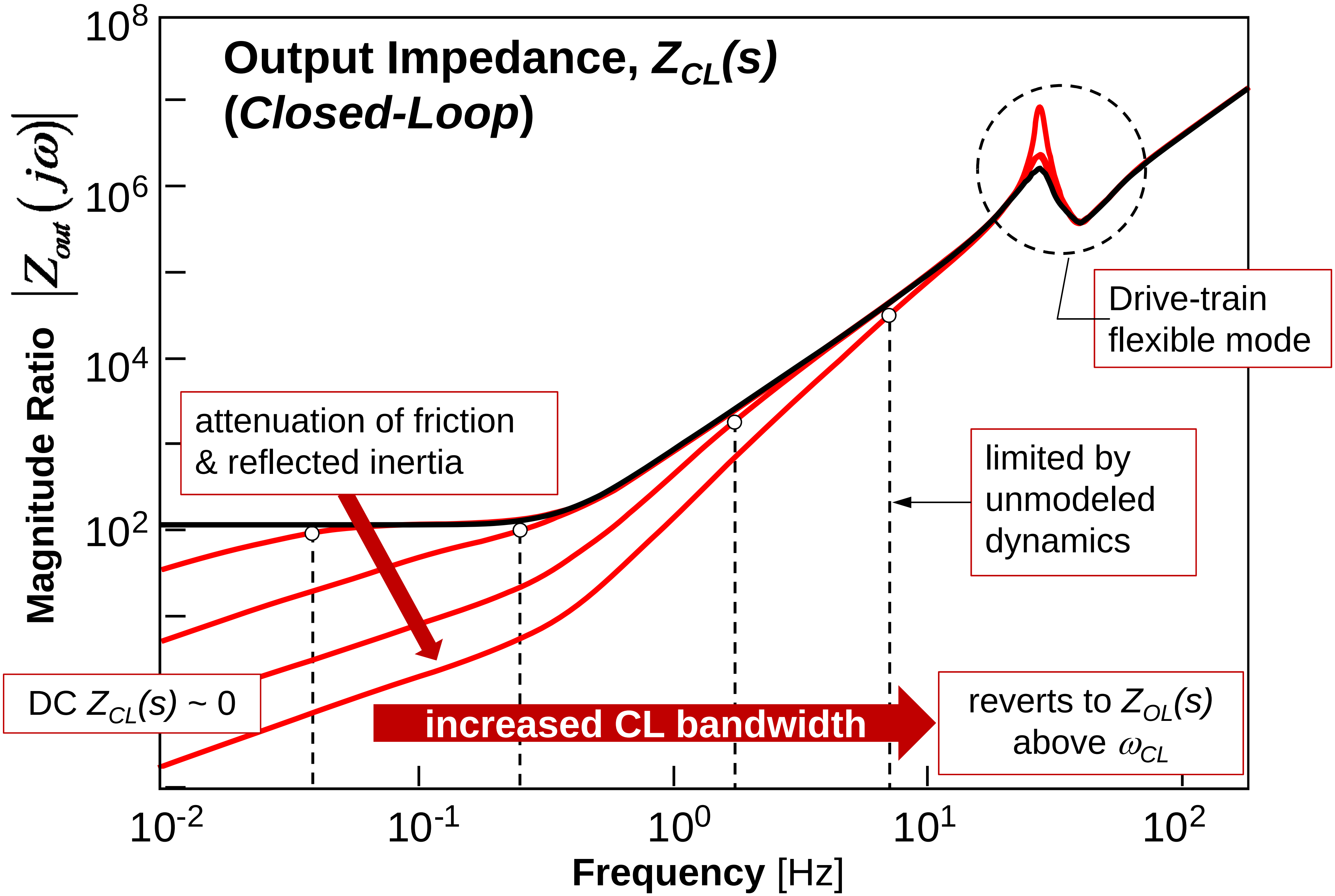
  - high reflected inertia
- Numerous control strategies have been adopted
  - explicit force control – virtual impedance
  - inner position loop – virtual admittance

example control architecture – inner position loop



Closed-Loop Output Impedance



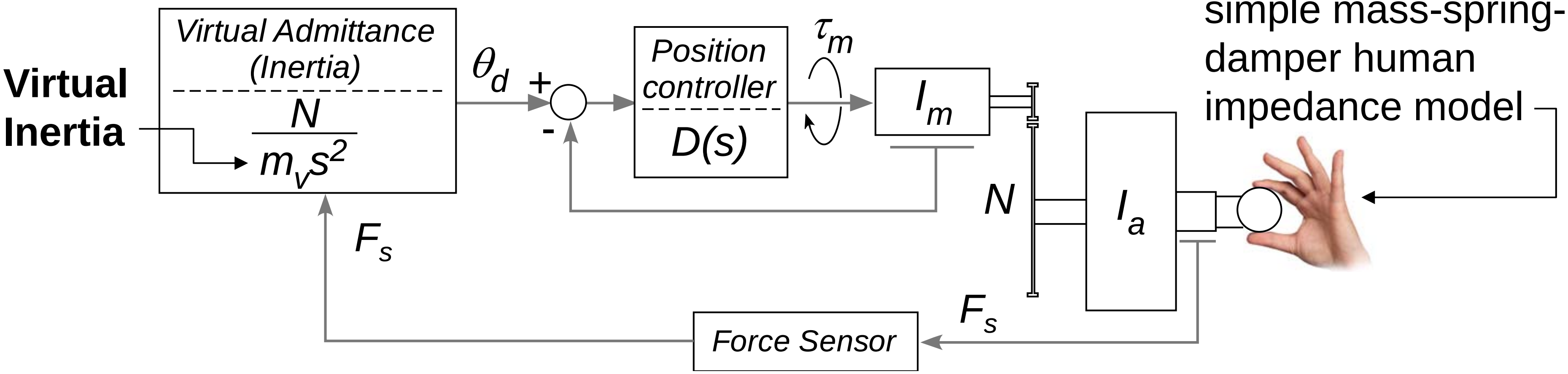
Rendering Challenge: Low Inertia

- *Low frequency transparency* can approach *zero*
  - Only limited by sensor and controller limitations
  - Quantification of transparency at DC may not be well defined

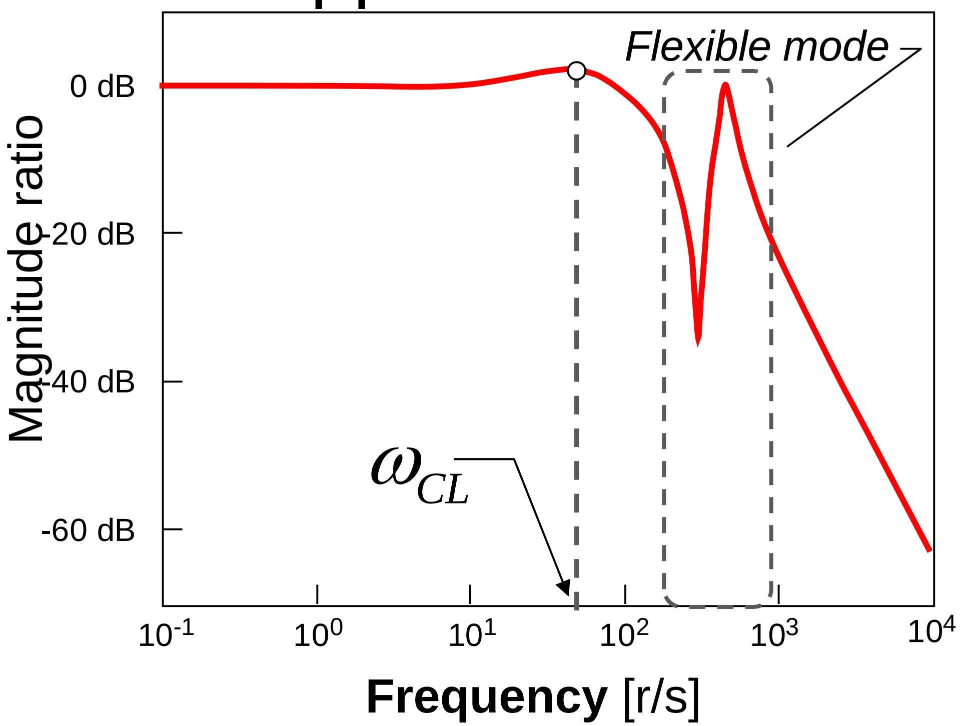
- BUT ... rendering *low inertia* is *hard* for admittance devices ... why?

Rendering Challenge: Low Inertia

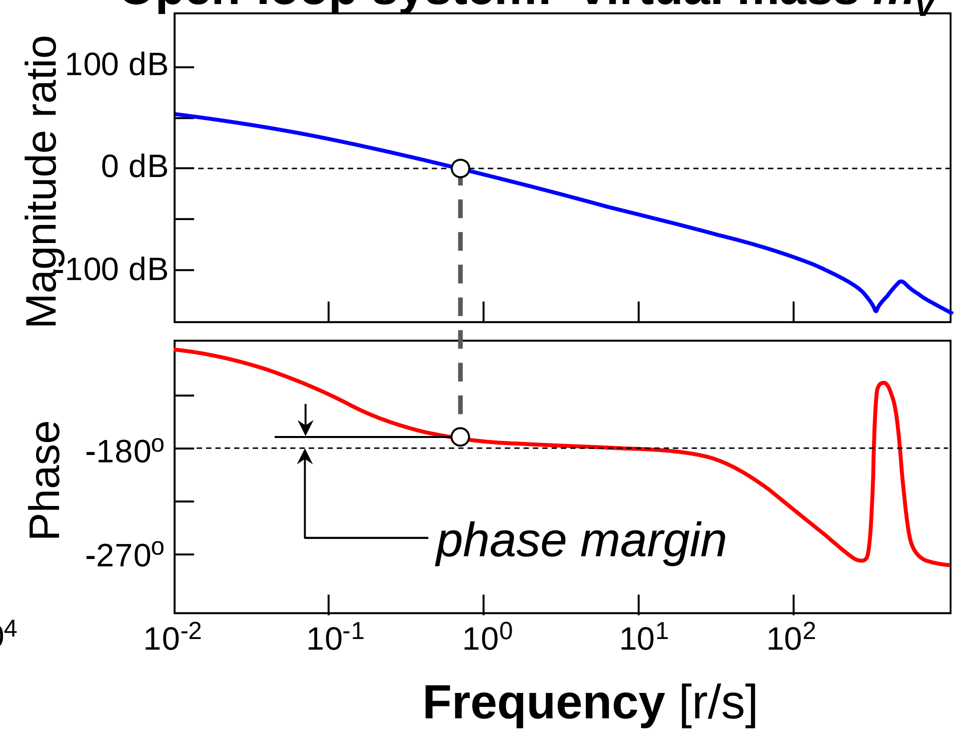
Simplified system model:



Closed-loop position control:

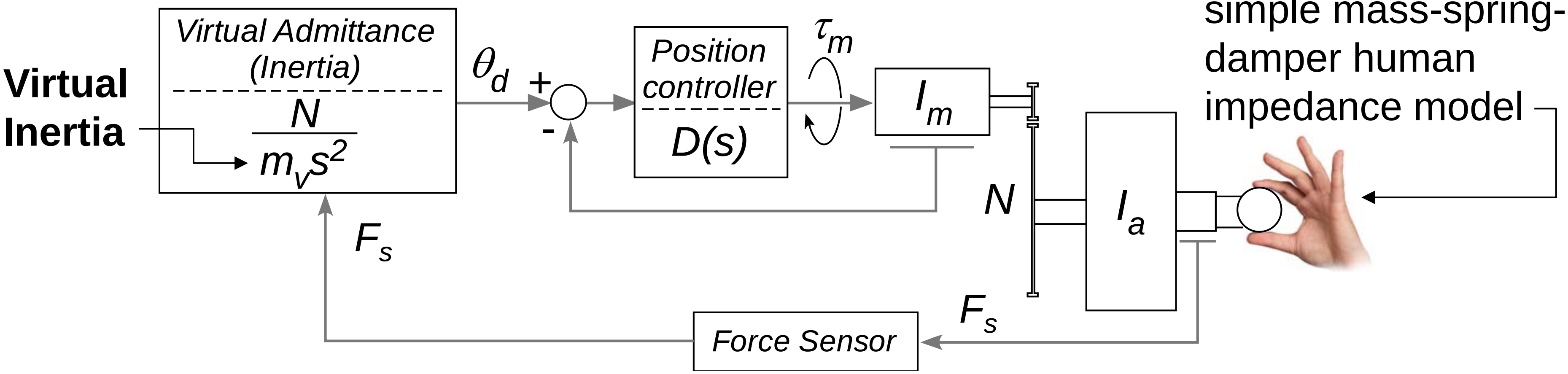


Open-loop system: virtual mass m_v

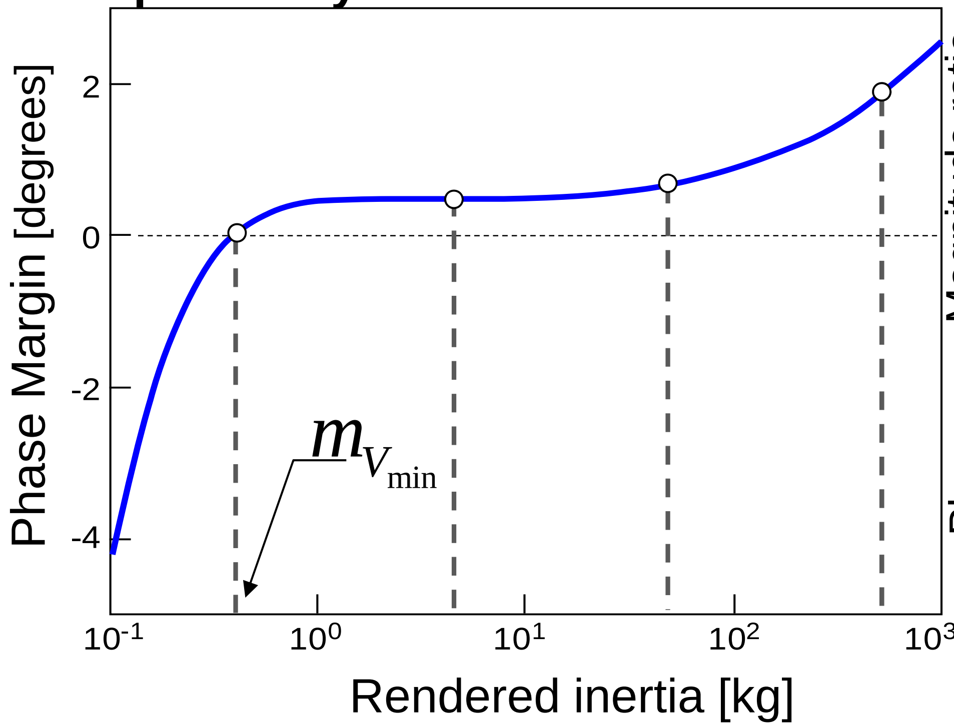


Rendering Challenge: Low Inertia

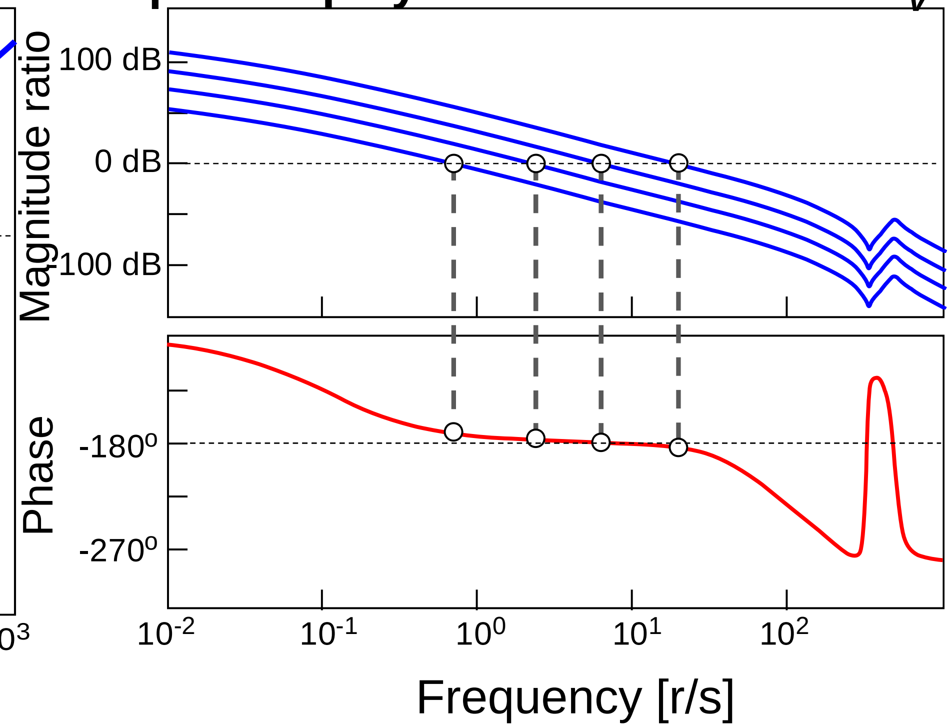
Simplified system model:



Loop stability vs Rendered Inertia

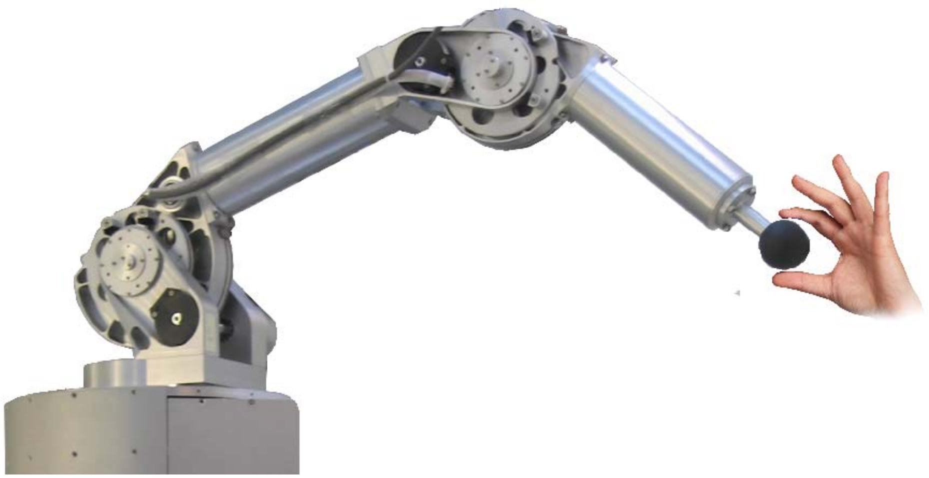


Open-loop system: virtual mass m_v



Evaluation using human subjects

Device-user evaluation of rendering limits:



Evaluate range of stable virtual impedance via direct user-device interaction

$$Z_{des}(s) = ms^2 + cs + k$$

Advantages:

- Direct determination of rendering limits / stability bounds – including minimum inertia (for admittance systems)
- end-to-end system evaluation

Disadvantages:

- Subjective evaluation of stability limits
- Human subject variability and grasp variability
- Difficult to measure robustness

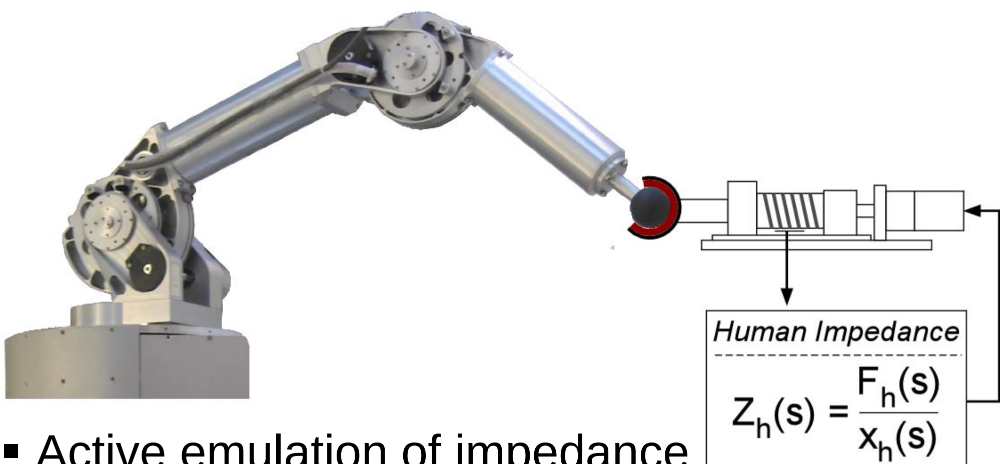
Emulated human-impedance

Device-Impedance model evaluation of rendering limits:

Passive impedance emulation

[Hayward-Astley 1996]
[Ellis, R. E., et al 1996]

Active impedance emulation



- Active emulation of impedance
- e.g. Series Elastic Actuation (SEA) or its derivatives

Evaluate range of stable virtual impedance using emulation of human impedance

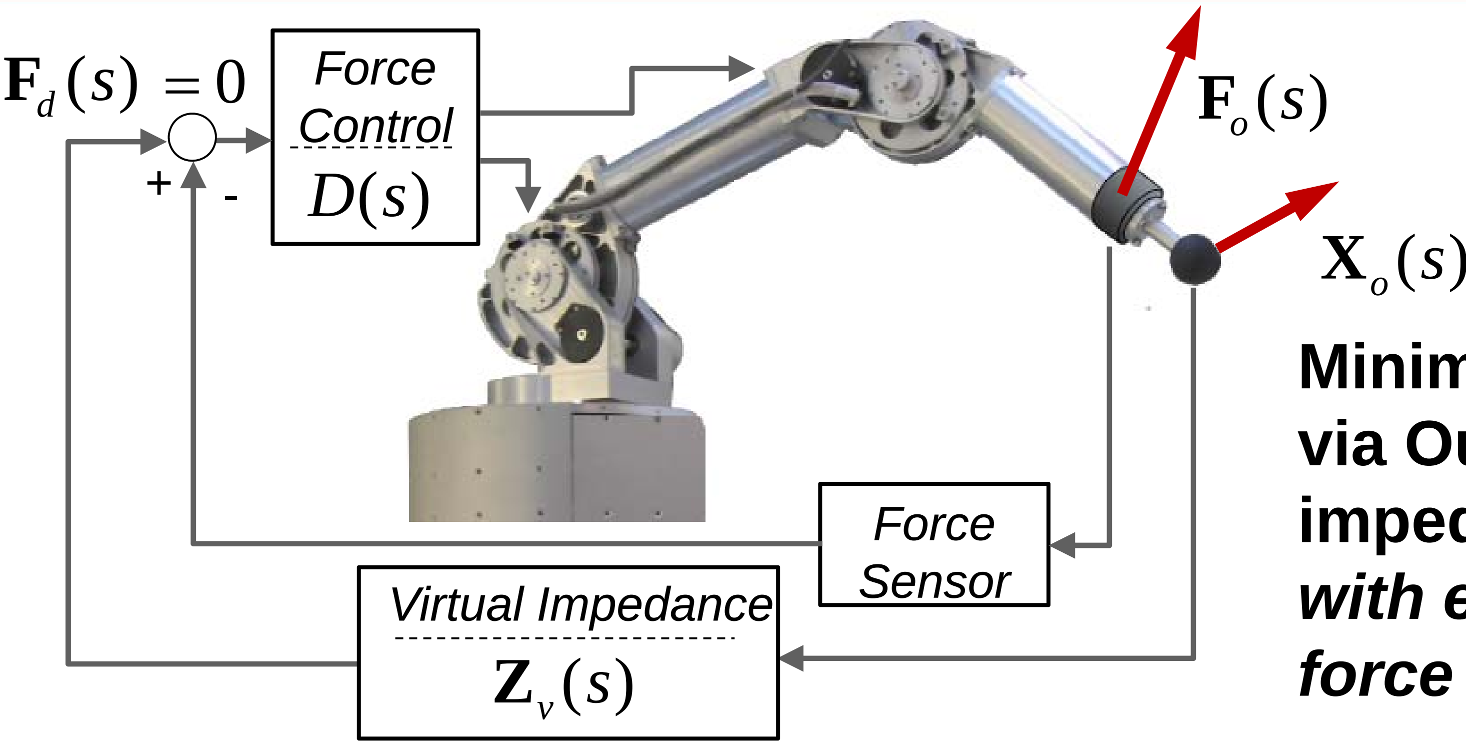
Advantages:

- good repeatability
- Allows evaluation of robustness

Disadvantages:

- no commonly accepted human impedance model
- complexity of hardware setup
- difficulty evaluating complete device workspace

Measurement of Output Impedance



Minimum inertia via Output impedance – ***with explicit force control***

$$\mathbf{F}_o(s) = \mathbf{T}_{f/d}(s)\mathbf{F}_d(s) + \mathbf{T}_{f/x}(s)\mathbf{X}_o(s)$$

set desired force, $F_d = 0$

$$\mathbf{F}_o(s) = \underbrace{\mathbf{T}_{f/x}(s)}_{\text{output impedance}}\mathbf{X}_o(s)$$

Generally simplify to 1 DOF (ignore coupling)

$$\frac{F_o(s)}{X_o(s)} = \overbrace{T_{f/x}(s)}^{\text{output impedance}} = Z_o(s)$$

← determine transparency and I_{min} from $Z_o(s)$

Measurement of Output Impedance

Output impedance Measurement – systems *with explicit force control*

$$Z_o(s) = \frac{F_o(s)}{X_o(s)}$$

Measurement options:

Position input ➡ Force measurement
Force input ➡ Position measurement

<u>Position</u> input:

- Typical method for impedance based device
- Use of high impedance position/velocity source
- Challenging for admittance-based devices
  - Not useable above ω_{CL} of haptic device controller
  - Can reduced position controller gains for testing [Ueberle, Buss 2002]

<u>Force</u> input:

- Well suited to admittance-based devices
- Force sources are challenging to implement
  - Ideal source has zero output impedance
  - Source dynamics can distort and destabilize system

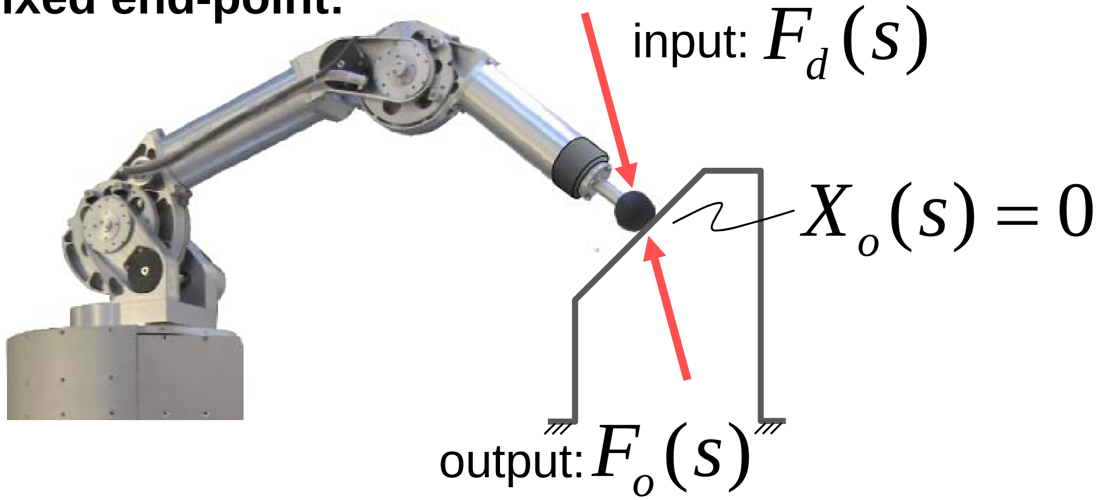
Measurement of Output Impedance

Indirect measurement of output impedance – *with explicit force control*

[Chapius 2009]

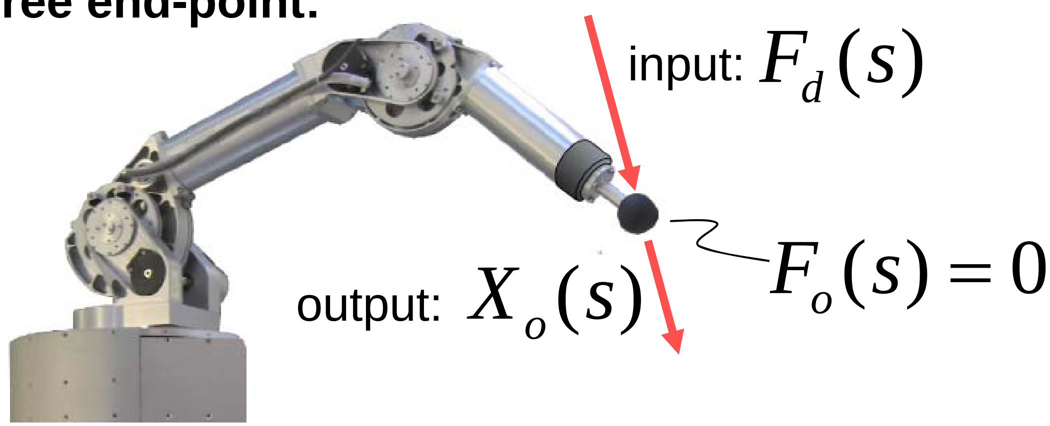
$$F_o(s) = T_{f/d}(s)F_d(s) + \underbrace{T_{f/x}(s)}_{\text{output impedance}}X_o(s)$$

Fixed end-point:



$$\left.\frac{F_o(s)}{F_d(s)}\right|_{X_o=0} = T_{f/d}(s)$$

Free end-point:



$$\left.\frac{X_o(s)}{F_d(s)}\right|_{F_o=0} = -\frac{T_{f/d}(s)}{T_{f/x}(s)}$$

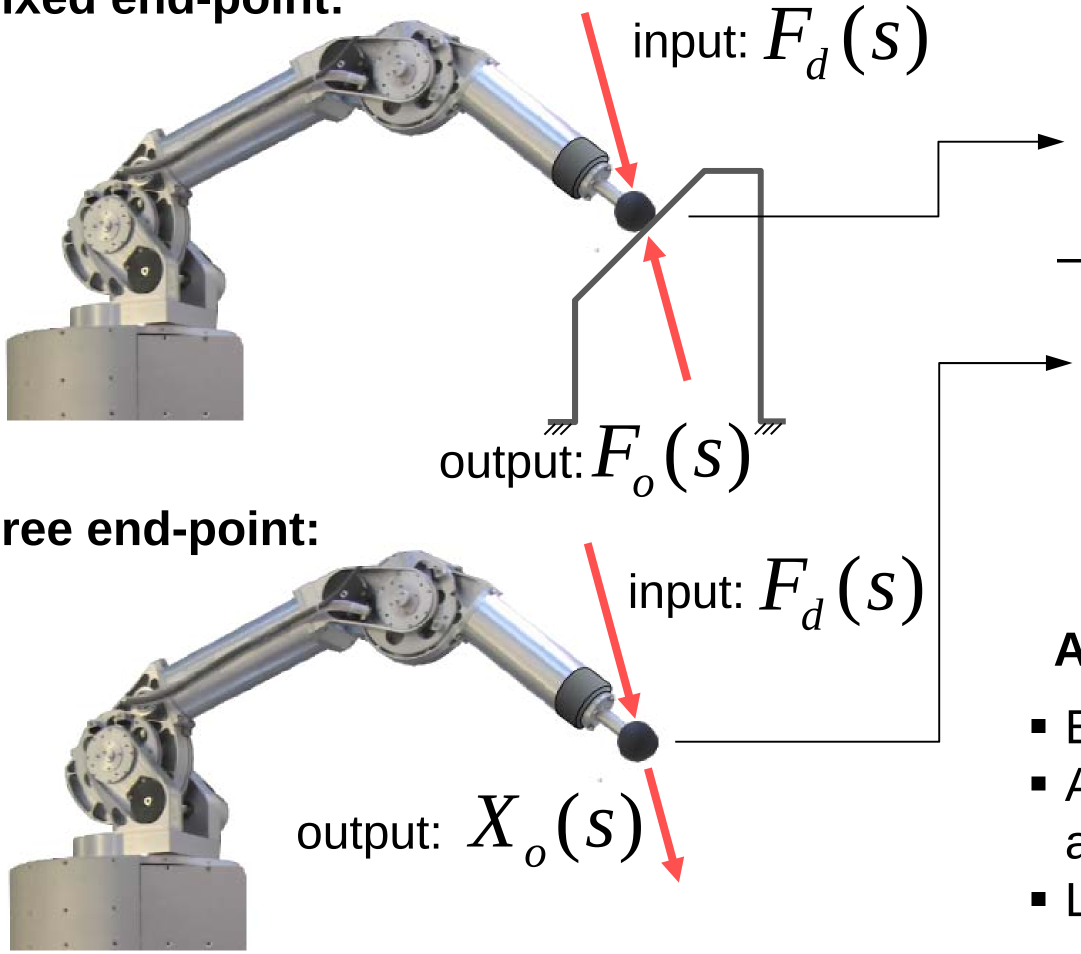
Measurement of Output Impedance

Indirect measurement of output impedance –
with explicit force control

$$F_o(s) = T_{f/d}(s)F_d(s) + \underbrace{T_{f/x}(s)}_{\text{output impedance}}X_o(s)$$

Fixed end-point:

Free end-point:



$$-\frac{\left.\frac{F_o(s)}{F_d(s)}\right|_{X_o=0}}{\left.\frac{X_o(s)}{F_d(s)}\right|_{F_o=0}} = T_{f/x}(s)$$

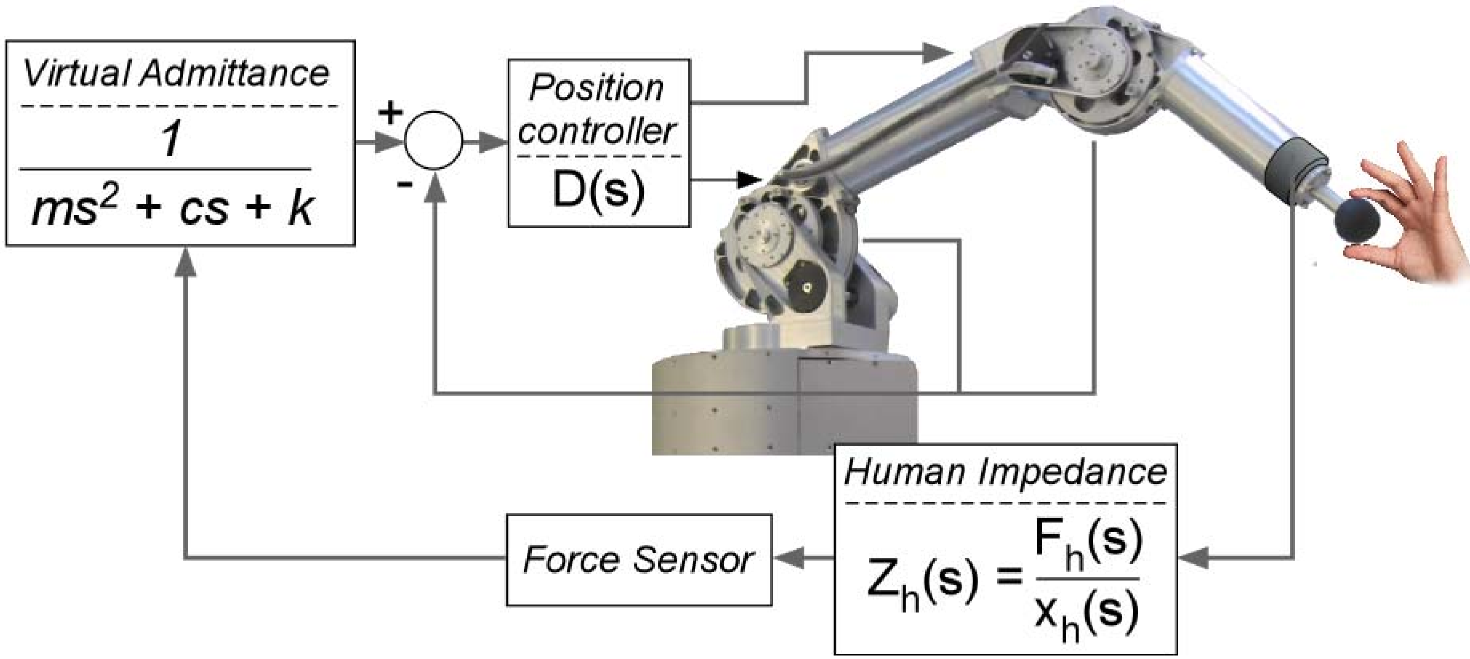
can also measure acceleration
[Samur et al 2011]

Advantages / Disadvantages:

- Experimental evaluation of Z_{out}
- Additional simplification through acceleration measurements
- Limited to force controlled systems

Evaluation of Rendering Limits

Systems without explicit force control:

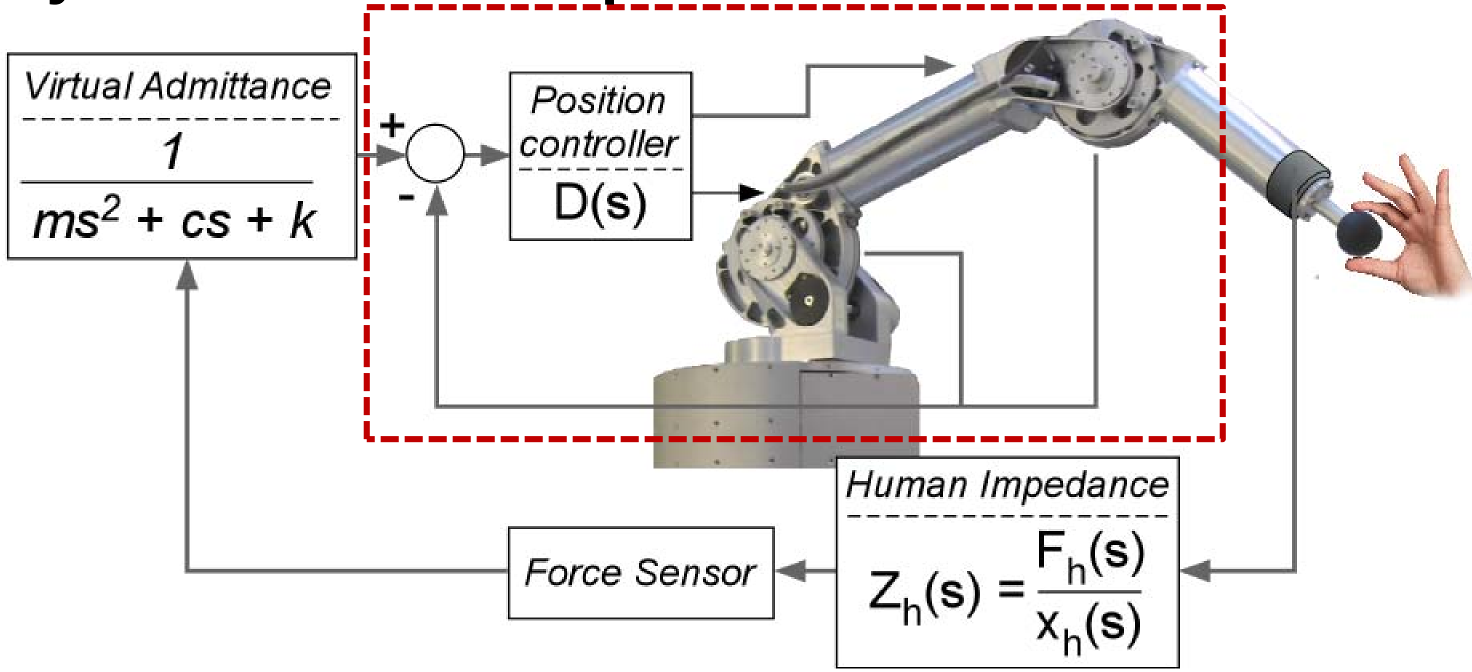


Partition system and evaluate via modeling & experiment

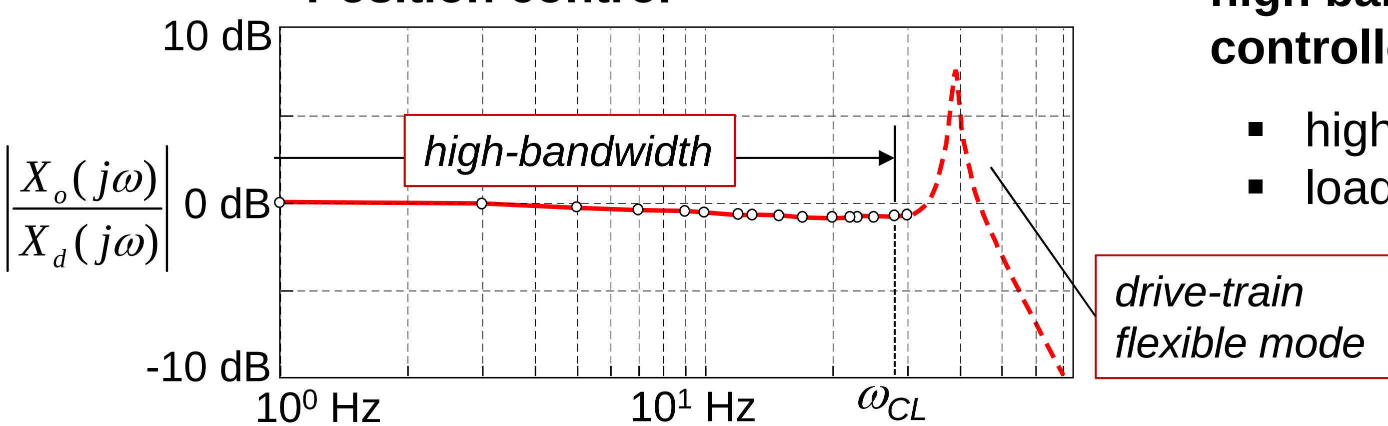
- Position controlled device
- Human-impedance
- Virtual impedance (or admittance)

Evaluation of Rendering Limits

Systems without explicit force control:



Position control

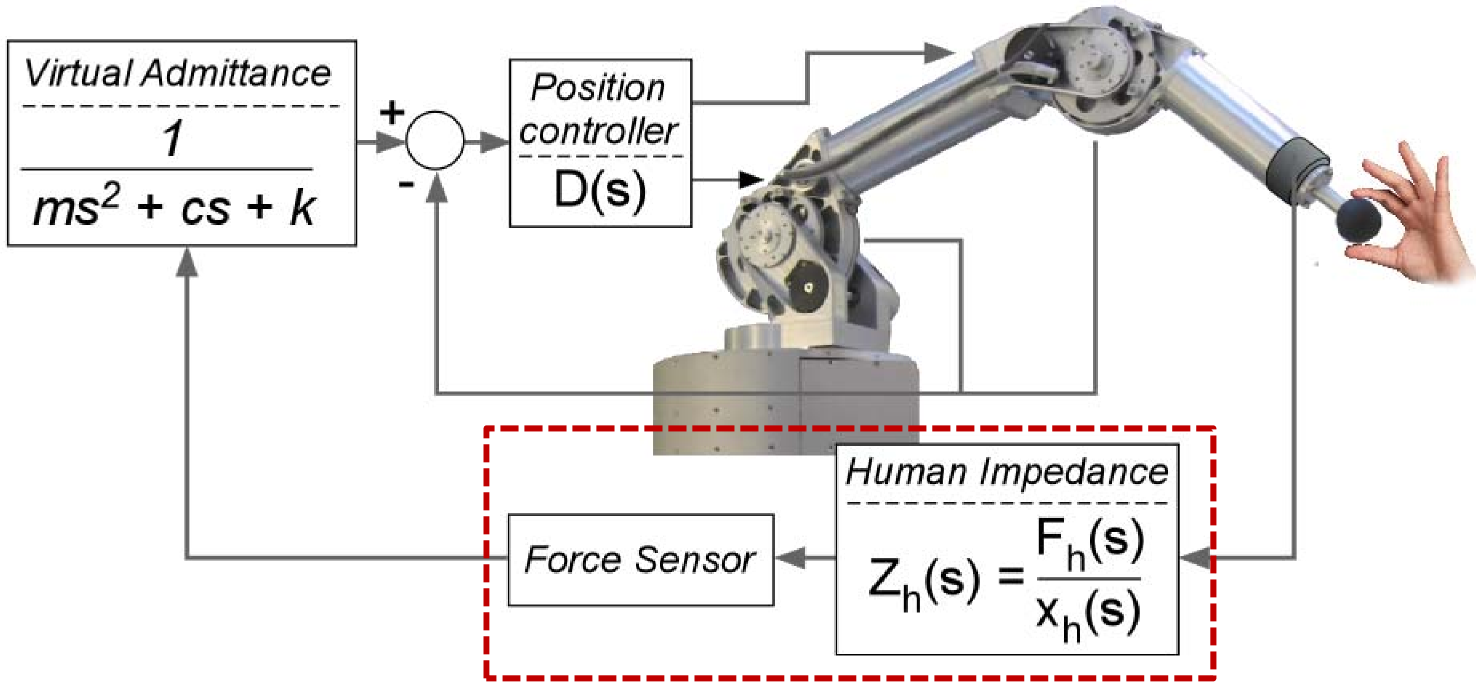


high bandwidth position controller

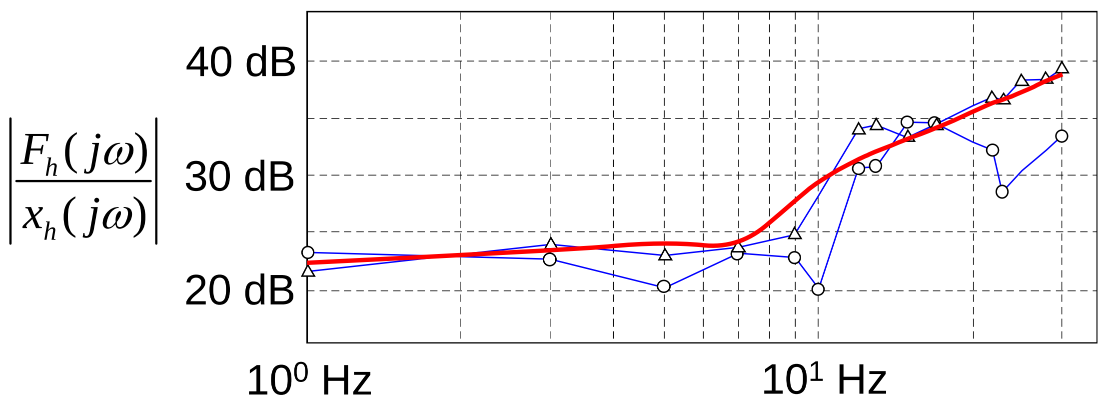
- high output impedance
- loading effects negligible

Evaluation of Rendering Limits

Systems without explicit force control:



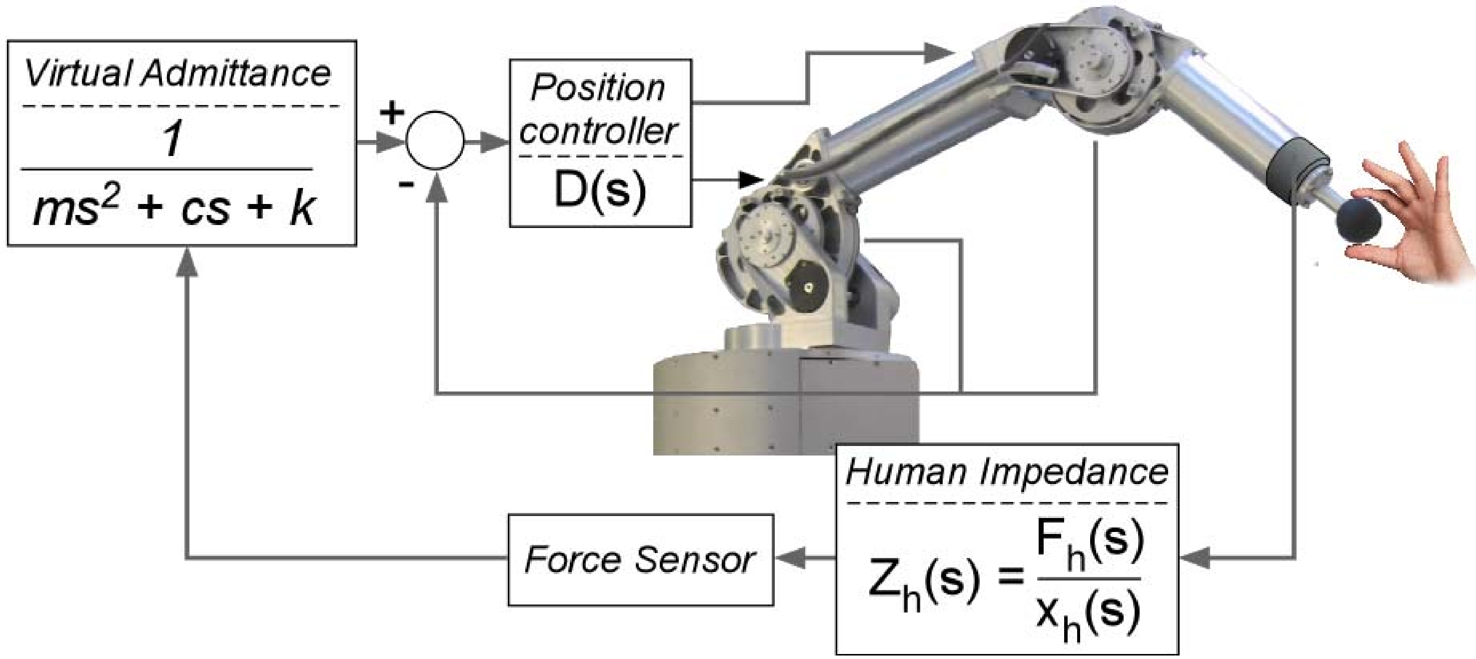
Human Impedance model [Speich 2005]



- mass-spring damper model of human impedance
- experimentally-fit model parameters
- but – very difficult to identify suitable model / parameters

Evaluation of Rendering Limits

Systems without explicit force control:



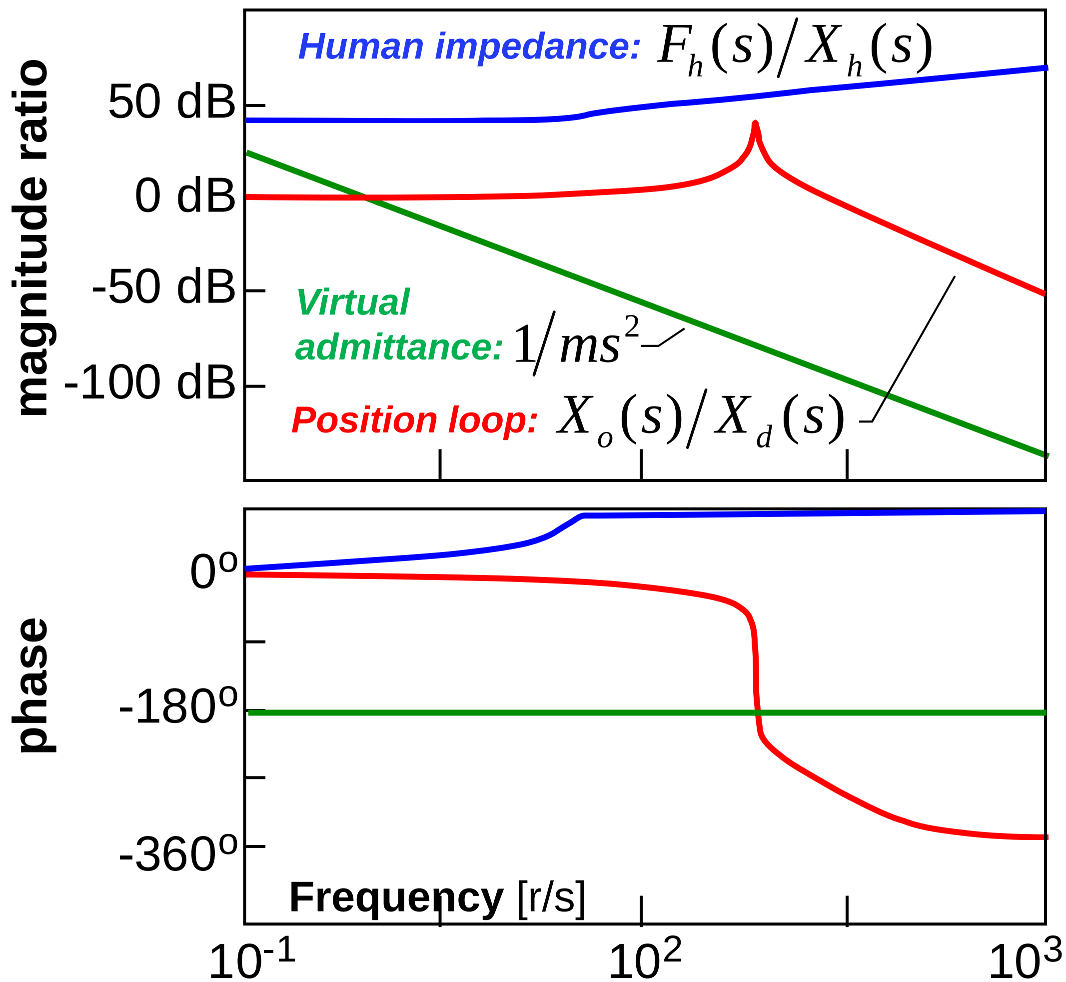
Partition system and evaluate via modeling & experiment

- Position controlled device
- Human-impedance
- Virtual impedance (or admittance)

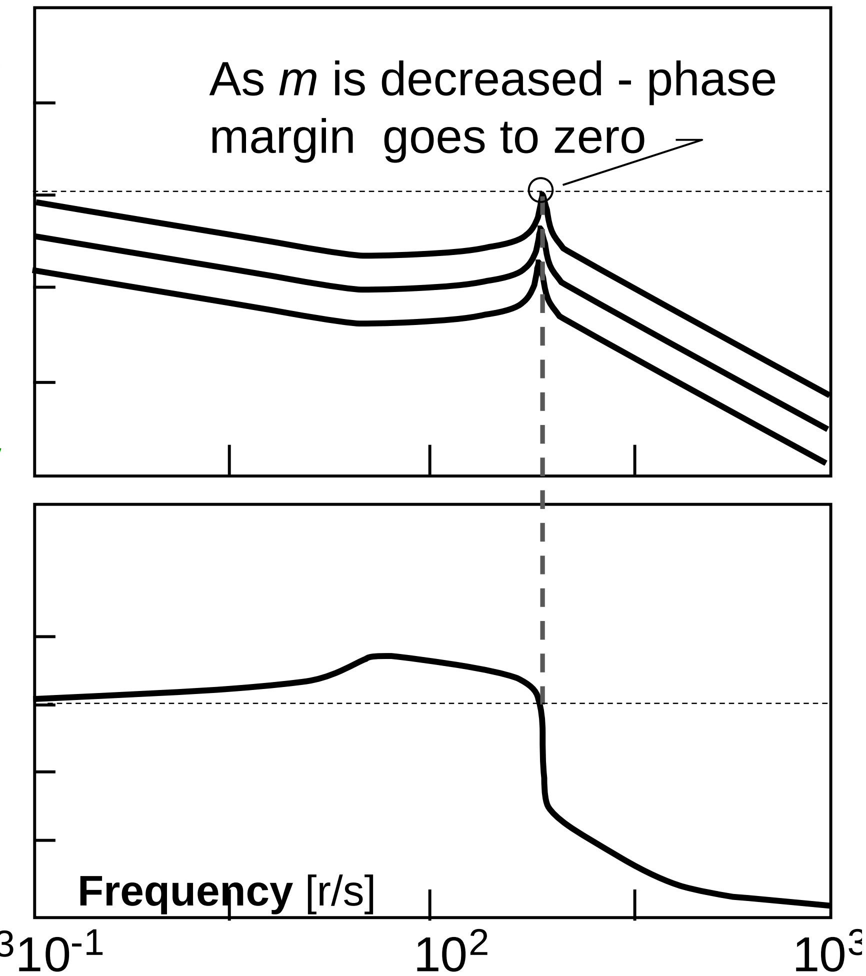
➡ **Evaluate stable virtual admittances (e.g. stability margins)**

Evaluation of Rendering Limits

Measured / Modeled System Components:



Full system – open loop response



Advantages / Disadvantages:

- stability margins to estimate range of stable virtual impedances
- Relies on human impedance model

Summary

- Admittance-based devices are fundamentally different than impedance-based devices
  - High open-loop output impedance
    - Characteristics are unavoidable
  - Rendering capabilities are different (opposite) than impedance-based devices
    - Low inertia is difficult
- Evaluation of rendering capability is challenging
  - High output impedance limits techniques
  - Various techniques used / suggested … but more work is required

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