Performance Measurements for Haptic Actuators

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Why is it hard to make haptic systems?

- The human hand is pretty amazing and…
- Actuators are nonlinear
  - Friction
  - Saturation
- Force density is a challenge
  - peak forces
  - peak pressure
  - delivery of power
- Dynamic range is a challenge
  - Min vs. Max forces
- Inertia is always in the way
- Energy density is hard to achieve in portable devices
  - battery life
- Feedback algorithms & sensors vary in effectiveness

Passive System Measurements

- Quasi-static
  - Peak Force (transient)
  - Peak Force (continuous)
  - Force resolution
  - Position resolution
  - Position Range
- Dynamic
  - Unpowered impedance (captures mass, friction, viscous drag)
  - Peak Acceleration (Open loop, driven)

- Easy to measure, predict from specs

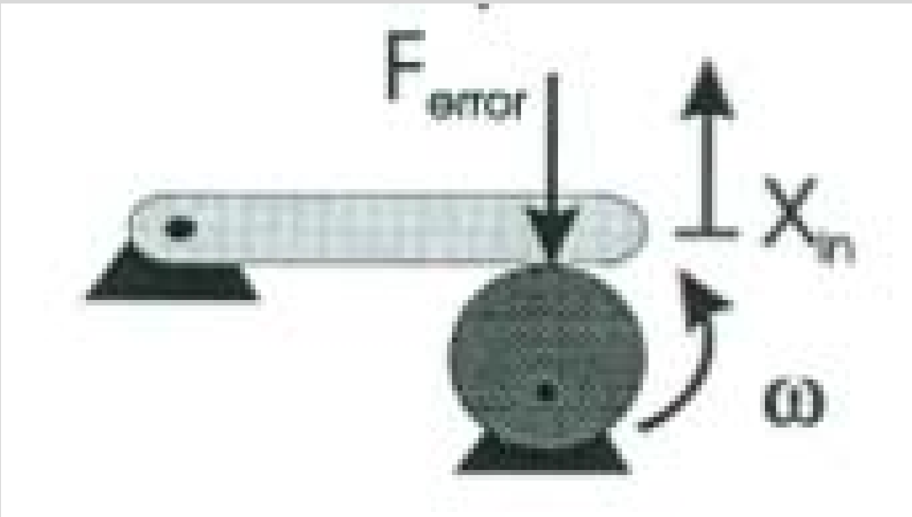
Controlled System Measurements

- Quasi-static
  - Force Precision
  - Position Precision
  - Dynamic Range
- Dynamic *(The performance we usually care about)*
  - Position Bandwidth
  - Force bandwidth
  - Impedance
  - Force Fidelity

Example

- 1 DOF link
  - Torque Saturation
  - Friction
  - Quantization of torque and position
  - Finite control bandwidth

- Frequency measurements
  - Must evaluate at multiple input magnitudes
  - Roughly based on a describing function model



Position Bandwidth

$$H(\omega) = \left. \frac{X(\omega)}{X_{des}(\omega)} \right|_{F_e = 0}$$

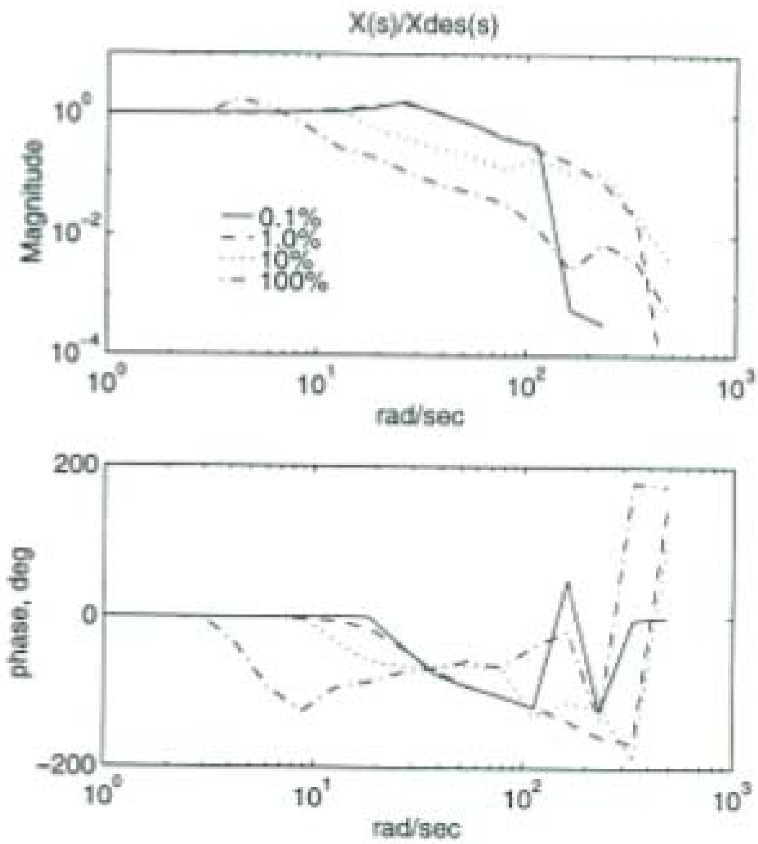
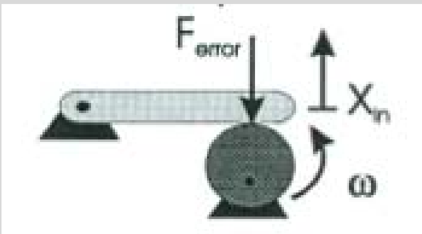
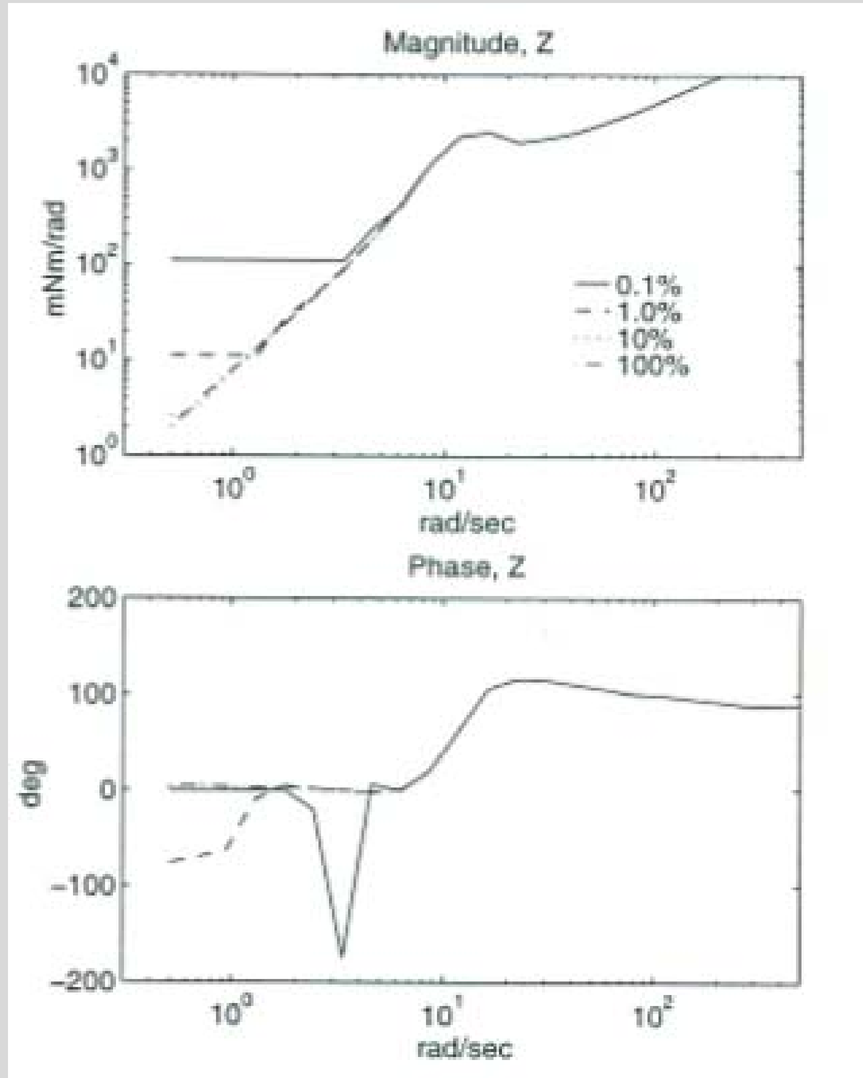


Figure 3: Position Bandwidth of example actuator using an impedance controller at 0.1%, 1%, 10%, and 100% of displacement range.

Unpowered Impedance

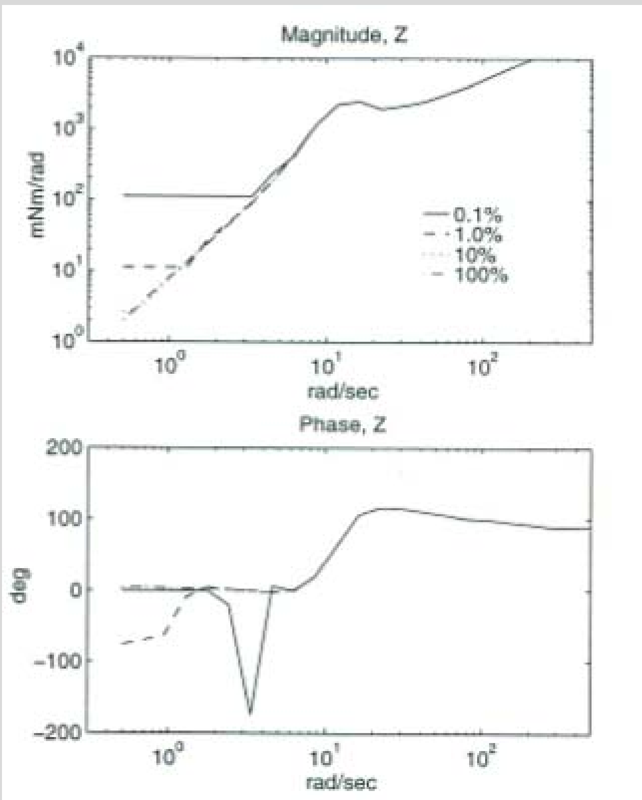


$$Z(\omega)=\left.\frac{F_{error}(\omega)}{X_{in}(\omega)}\right|_{F_{des}=const}$$



Impedance

$$Z(\omega) = \left. \frac{F_{error}(\omega)}{X_{in}(\omega)} \right|_{F_{des}=const}$$



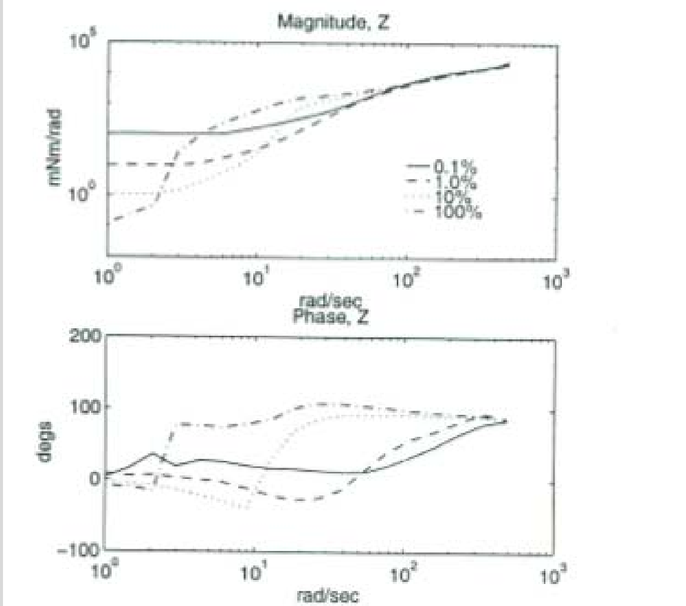
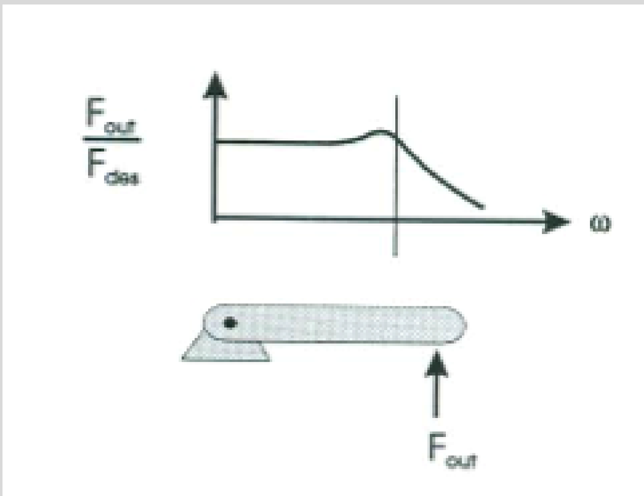


Figure 6: Impedance (Backdrivability), $Z(\omega)$, for example actuator at 0.1%, 1%, 10%, and 100% of displacement range. Impedance bandwidth may defined as the frequency where the force error begins to increase with frequency.

Force Bandwidth



$$H(\omega)=\left.\frac{F_e(\omega)}{F_{des}(\omega)}\right|_{X_e=0}$$

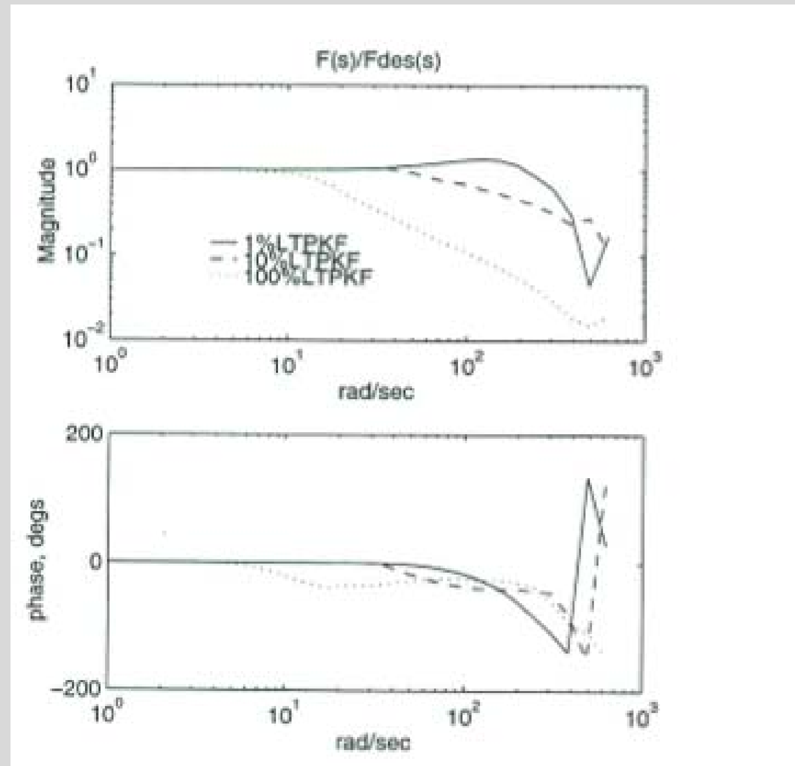


Figure 5: Force Bandwidth at 1%, 10%, and 100% of LΣ

Force Fidelity

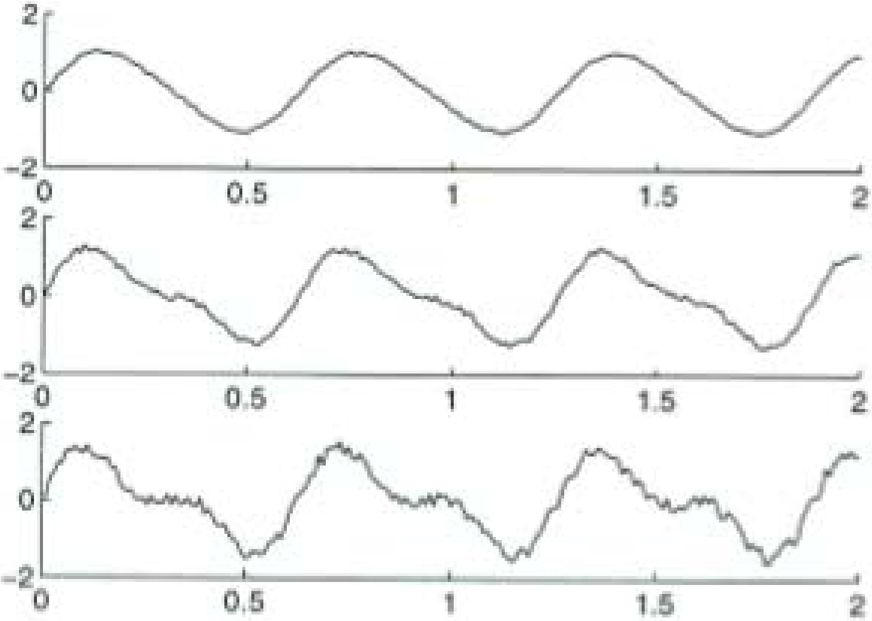


Figure 7: Force Fidelity Example - These three graphs show examples of force vs. time. The values of Force Fidelity for these graphs are 0.99, 0.86, and 0.74. Distortion is 1%, 14%, and 26% respectively.

Force Fidelity

$$\text{Force Fidelity} = \frac{T^T R A}{T^T T}$$

where

$T = \text{sampled signal}$

$$R = \begin{bmatrix} \sin(\omega t) & \cos(\omega t) \end{bmatrix}$$

$$A = \begin{bmatrix} C_1 & C_2 \end{bmatrix}^T = \left(R^T R\right)^{-1} R^T T$$

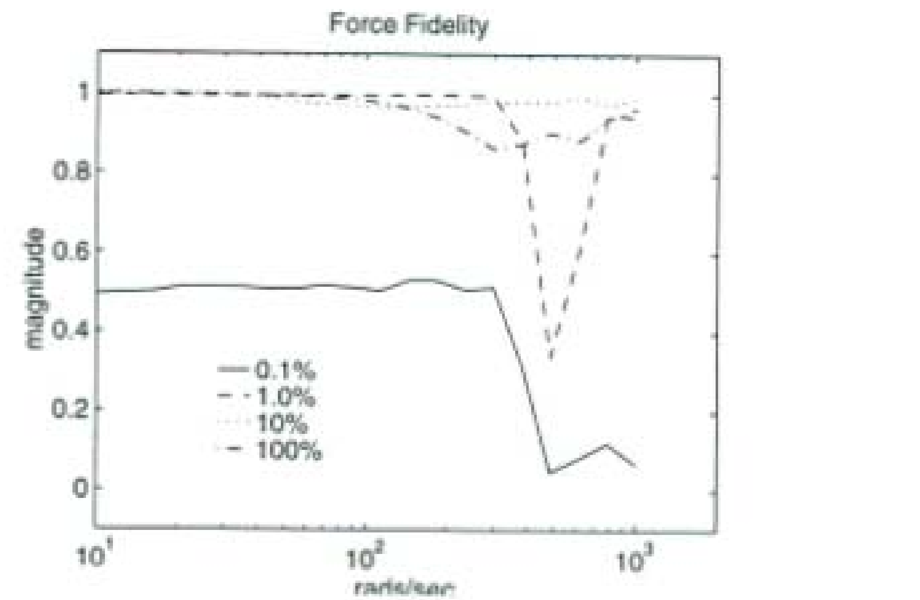


Figure 8: Force Fidelity at 0.1%, 1%, 10%, and 100% LTPKF for example actuator ($F_{des} = 0$). Note that friction makes force fidelity very low for small forces (0.1% LTPKF)