Admittance-adaptive Model-based Cancellation of Biodynamic Feedthrough

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Accelerations

Involuntary control inputs
What is biodynamic feedthrough?

**Biodynamic feedthrough (BDFT)**
the transfer of accelerations through the human body during the execution of a manual control task, causing involuntary forces being applied to the control device which may result in involuntary control device deflections.
What is biodynamic feedthrough mitigation?

Admittance-adaptive mitigation
Neuromuscular adaptation

Force-position relation depends on:
- Limb weight
- Muscle co-contraction
- Reflexive activity
- Control task
- …
BDFT depends on admittance

Asymptote modeling

• Dynamics can be approximated by simple functions: base functions

• By tuning the asymptotic behavior of the base functions the measured dynamics can be approximated

• A possible base function

\[ H_B(s, \omega_n, \zeta, \gamma) = \left(1 + \frac{2\zeta}{\omega_n} s + s^2 / \omega_n^2\right)^\gamma \]

  - order
  - damping
  - natural frequency

• If the order is -1:

\[ H_B = \frac{1}{1 + \frac{2\zeta}{\omega_n} s + \frac{1}{\omega_n^2} s^2} = \frac{\omega_n^2}{\omega_n^2 + 2\zeta \omega_n s + s^2} \]

Asymptote modeling

- By tuning the parameters the asymptotes can be adapted
- When multiplying two or more base functions the new dynamics are governed by the sum of the base functions’ asymptotes

Asymptote modeling in action

\[ H_{\text{mod}} = K H_{B1} H_{B2} H_{B3} H_{B4} H_{B5} \]

<table>
<thead>
<tr>
<th>( f_n ) (nat freq)</th>
<th>( \zeta ) (damp)</th>
<th>( \nu ) (order)</th>
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Asymptote modeling

- Benefits of asymptote modeling
  - Systematic construction of model structure
  - Create complex model from elementary elements
  - Parameters retain their mathematical interpretation

- Parameters determined by minimizing difference between measured dynamics and model

Experiment description

• Goal: proof-of-concept for admittance-adaptive model-based BDFT cancellation approach

• Experiment loosely based on a rotorcraft application

• Task: fly through virtual tunnel: highway-in-the-sky (HITS)

• Neuromuscular adaptation: ‘stiff’ (PT) and ‘relaxed’ (RT)
Experiment conditions

- **HITS Tunnel (TUN)**
  - Straight tunnel (STR)
  - Curved tunnel (CUR)

- **Task (TSK)**
  - Position task (PT): “stiff”
  - Relax task (RT): “relax”

- **Identification measurements**

- **Condition (COND)**
  - Static (STA): motion OFF (no BDFT)
  - Motion (MOT): motion ON, cancellation OFF
  - Cancellation (CAN): motion ON, cancellation ON
Experiment description: metrics

- Cancellation percentage: indication for quality of cancellation

\[ P_{can} = \left( 1 - \frac{RMS(\theta_{can}^{M_{dist}}(t))}{RMS(\theta_{cd}^{M_{dist}}(t))} \right) \cdot 100\% \]

- Average heading error: indication of control performance

\[ \mu_{\psi_e} = \frac{1}{N} \sum_{k=1}^{N} |\psi_{tar}(k) - \psi_{cur}(k)| \]

- RMS of steering speed: indication of control effort

\[ E_{\dot{\theta}_{res}} = RMS(\dot{\theta}_{cd}^{res}(t)) \]
Hypotheses

• **BDFT hypothesis**: due to BDFT performance decreases and effort increase in MOT w.r.t. STA condition

\[
\text{STA}_{\text{error}} < \text{MOT}_{\text{error}} \quad \& \quad \text{STA}_{\text{effort}} < \text{MOT}_{\text{effort}}
\]

• **Cancellation hypothesis**: due to cancellation performance increase and effort decrease in CAN w.r.t. MOT condition

\[
\text{CAN}_{\text{error}} < \text{MOT}_{\text{error}} \quad \& \quad \text{CAN}_{\text{effort}} < \text{MOT}_{\text{effort}}
\]
Results: cancellation metric

PT – CAN

RT – CAN
Results: performance (tracking error)
Results: effort (steering speed)
Conclusions

• Hypotheses confirmed
  – BDFT hypothesis:
    \[ \text{STA}_{\text{error}} < \text{MOT}_{\text{error}} \quad \& \quad \text{STA}_{\text{effort}} < \text{MOT}_{\text{effort}} \]
  – Cancellation hypothesis:
    \[ \text{CAN}_{\text{error}} < \text{MOT}_{\text{error}} \quad \& \quad \text{CAN}_{\text{effort}} < \text{MOT}_{\text{effort}} \]

• This demonstrates the effectiveness of the proposed mitigation method

• Future challenge: obtain a reliable online estimate of the neuromuscular admittance