Biodynamic feedthrough: Current Status and Open Issues

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What is biodynamic feedthrough?
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[Diagram showing a feedback control system with labels for human operator, control device, and vehicle, with inputs and outputs for voluntary and involuntary forces and inputs.]

Goal state $y_{goal}$ leads to error $y_{err}$.

Voluntary forces $F_{app}$ affect the human operator.

Vehicle state $y_{cur}$ influences the control loop.

Vehicle accelerations $M_{dist}$ are output.

BDFL loop and control inputs $\theta_{CD}$ connect vehicle and control device.
CURRENT STATUS AND OPEN ISSUES
Measuring biodynamic feedthrough

[Graphs and charts depicting various measurements and data analysis]

[Reference citations: 
- Horn 1818
- Purkinje 1820
- Allen et al. 1973
- Griffin 1981
- Smith et al. 1996
- Gillespie et al. 2006
- Venrooij 2014]
Measuring biodynamic feedthrough

Observation:

— Identification techniques are typically time-invariant

Problem:

— Requires carefully designed experimental conditions
— BDFT knowledge based on conditions that are unlike real-world situations

What can be done:

— Focus research efforts on time-variant identification
Modeling biodynamic feedthrough

Physical model

Black box model

Fig 7: Generalized Bio-Pilot Model

[Jex et al. 1978]

[Mayo 1989]

[Griffin 2001]
Modeling biodynamic feedthrough

Observations:
- Many different BDFT models exist in literature
- Community has shown preference for practical models

Problem:
- Many models fall short in either usability or fidelity
- No model seems particularly well established or accepted

What can be done:
- Revisit existing models, identify strengths and weaknesses
- Work towards practical models, tailored to intended purpose and user group
Mitigating biodynamic feedthrough

- Torle 1965
- Schubert et al. 1970
- Velger et al. 1988
- Sirouspour et al. 2003
- Gillespie et al. 2006
- Venrooij et al. 2012
- Humphreys et al. 2014
- Venrooij et al. 2014
- Pavel et al. 2015
Mitigating biodynamic feedthrough

Observations:
- Many mitigation methods developed and demonstrated
- Probably the most common/effective mitigation technique are corrective control actions (CCAs) by human operators

Problem:
- CCAs are poorly understood
- CCAs can mask a vehicle’s proneness to BDFT
- Often wrongly considered ‘free’ BDFT mitigation

What can be done:
- Focus research efforts on understanding the abilities and limitations of CCAs
TIME-VARIANT IDENTIFICATION OF BDFT
Time-invariant (TI) identification

![Diagram of human operator, control device, and vehicle with feedback loops and equations.]

\[ H^{TI}_{B2FCL}(\omega_m) = \frac{S_{m,f}(\omega_m)}{S_{m,m}(\omega_m)} \]

[Venrooij et al. 2014]
**Time-variant (TV) identification**

- Regularized Recursive Least Squares (RegRLS)
- Developed for estimating neuromuscular dynamics

\[ M_{dist} \xrightarrow{\text{BDFT}} F_{app} \]

Impulse response: \( h(t, \tau) \)

Time-variant (TV) identification

\[ F_{app}(t) = \Delta t \sum_{\tau=-\infty}^{\infty} h(t, \tau) M_{dist}(\tau) \]

- If causality and finite length is assumed

\[ F_{app}(t) = \Delta t \sum_{\tau=t-N}^{t} h(t, \tau) M_{dist}(\tau) \]

\[ F_{app}(t) = \Delta t \mathbf{M}_{dist}^T(t) \mathbf{h}(t) \]

\[ \mathbf{M}_{dist}(t) = \begin{bmatrix} M_{dist}(t) \\ \vdots \\ M_{dist}(t-N) \end{bmatrix} \quad \mathbf{h}(t) = \begin{bmatrix} h(t, t) \\ \vdots \\ h(t, t-N) \end{bmatrix} \]
Time-variant (TV) identification

- Minimize: \[ \hat{h}(t) = \min_h V(h, t) \]

- Where: \[ V(h, t) = V_\varepsilon(h, t) + V_{reg}(h) \]

\[ V_\varepsilon(t) = \sum_{\tau=1}^{t} \lambda^{t-\tau} \left( F_{app}(\tau) - \tilde{F}_{app}(\tau, h) \right)^2 \]

\[ V_{reg} = (h - h_{reg})^T \Pi_{reg} (h - h_{reg}) \]

With:
\[ h_{reg} = 0 \]
\[ \Pi_{reg} = 10^{-9} I \]
Experiment with time-varying BDFT
BDFT varies with tunnel section
Results: time-invariant vs. time-variant
Results: PT to RT
Results: RT to PT
Results: logarithmic squared error

\[ E(\omega_m, t) = \left| \log \left( \frac{H_{B2FCL}^{TV}(\omega_m, t)}{H_{B2FCL}^{TI}(\omega_m)} \right) \right|^2 \]
Conclusions

• Three open issues were identified:
  – Developing time-variant identification methods
  – Establishing a BDFT model
  – Understanding corrective control actions

• Time-variant identification method evaluated
  – Successfully captures dynamics
  – Quickly adapt to step-like change in BDFT dynamics