The Human Controller
Frequency-Domain Analyses

- **Neuromuscular control**
  - Control of limbs
- **McRuer's Cross-over model**
  - Control of systems
  - Response of visual, vestibular and NMS feedback to driving or flying

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- BioMechanical Engineering, Delft University of Technology, The Netherlands

So far…

1. **About Perception**
   1. All seven senses: physiology
   2. Measuring limits of perception
   3. Sensory Integration & Illusions

2. **About Cognition**
   1. The Brain: physiology
   2. About feed-forward and feedback
   3. Skill, Rule, Knowledge based Behaviour

3. **About Action**
   1. The Neuromuscular System: Physiology, Adaptabilty

4. **About Design and Evaluation**
   1. Metrics vs Models

Learning Goals

After this class you will be able to:

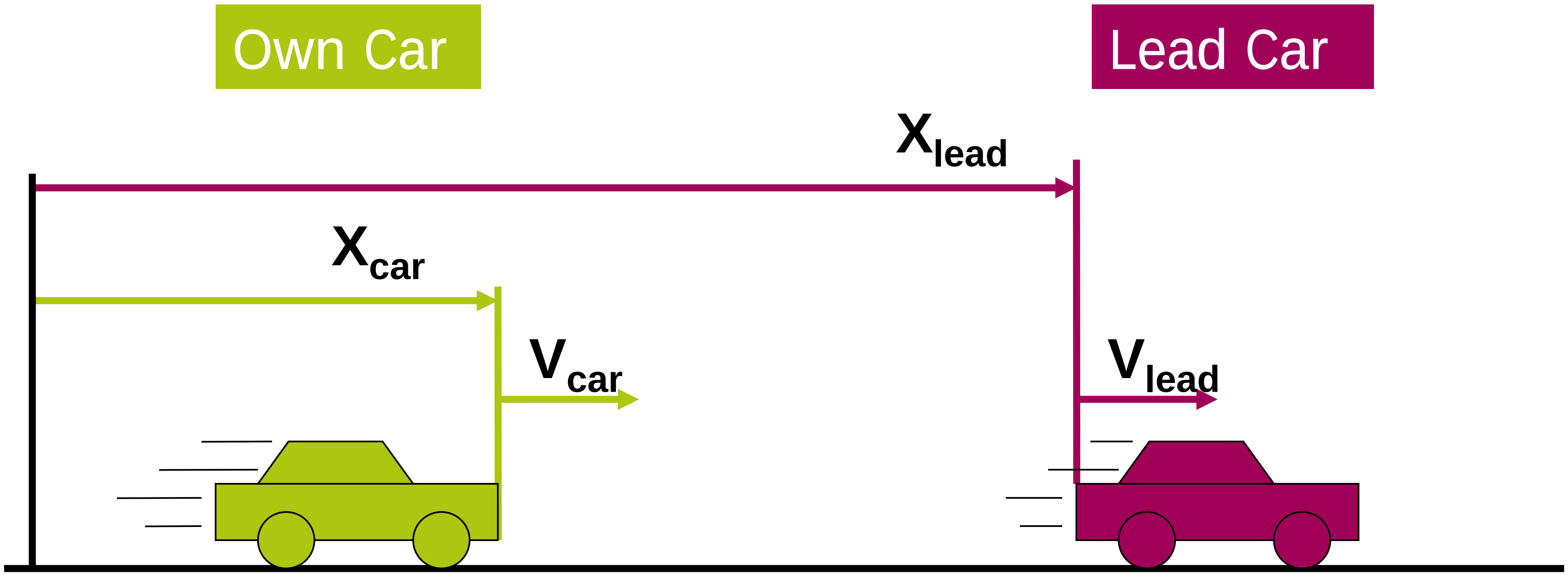
Reproduce:
- McRuer's crossover model and parameter sensitivity

Apply:
- Frequency Domain Analysis to analyze Human Control
  1. The basics: mass-spring-damper systems
  2. FRFs and models of neuromuscular systems
  3. FRFs and McRuer cross-over models

Critically Reflect on
- Applicability of frequency domain analyses
- Applicability of McRuer's Crossover model

Why bother Modeling?

Measuring and Modeling Performance



$X_{rel} = X_{lead} - X_{car}$
$V_{rel} = V_{lead} - V_{car}$

Separation States

$THW = Xrel / Vcar$
$TTC = X_{rel} / -V_{rel}$

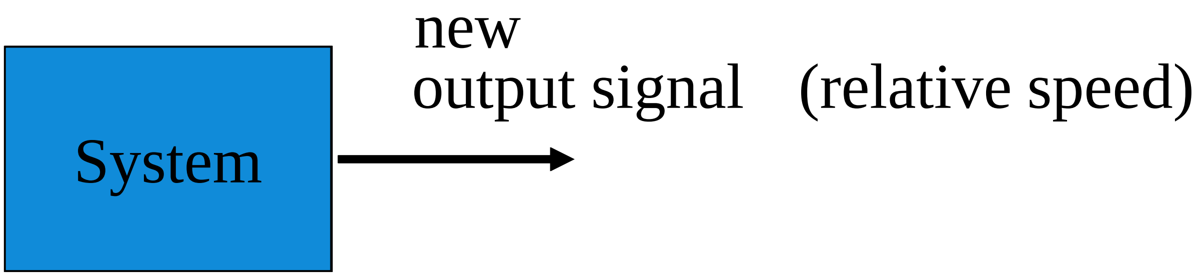
Coventional System Optimization

Measure the impact of a new system by determining

- Statistical analysis (mean, std, CDF) of a dynamic signal
- Change in performance metric for different systems (tunings)

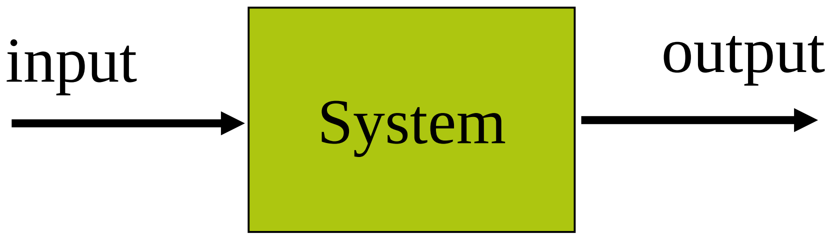
Shortcomings

- Time consuming
- Descriptive, but not predictive (hard to generalize)
- Many ways to achieve the same performance metric, unclear what situations cause change in the metrics, or interaction between them



Better way: use modeling!

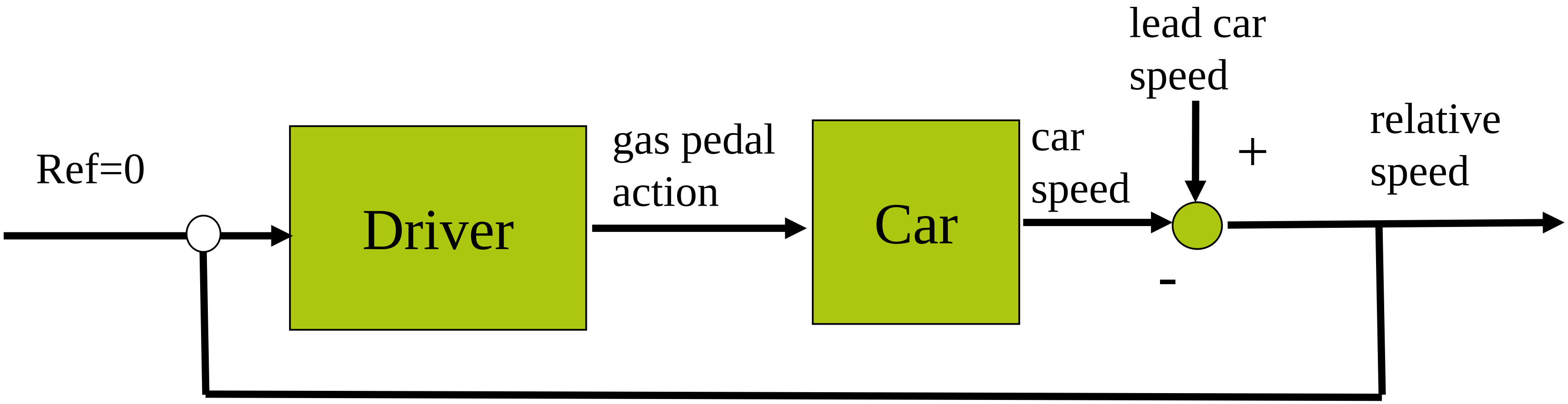
Use System Identification Techniques to determine (causal and dynamic) relationships between input and output



$$\text{System} = \frac{\text{output}}{\text{input}}$$

Cybernetic Modeling!

Cybernetics: describing a human in control engineering terms : control gains, time delays, noise



Cybernetic Modeling!

Advantages of this evaluation method:

- Quantitative -> objective
- More information -> better understanding
- Gives Predictive Models

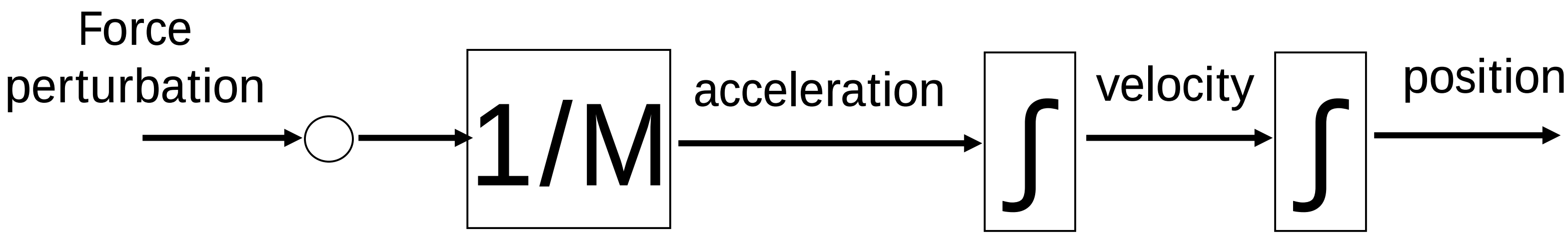
Needed

- Understanding of Control Engineering
  - Bode plots
  - Fourier Analysis

Basics of Frequency Domain Identification

Measuring a Mass-Spring-Damper System

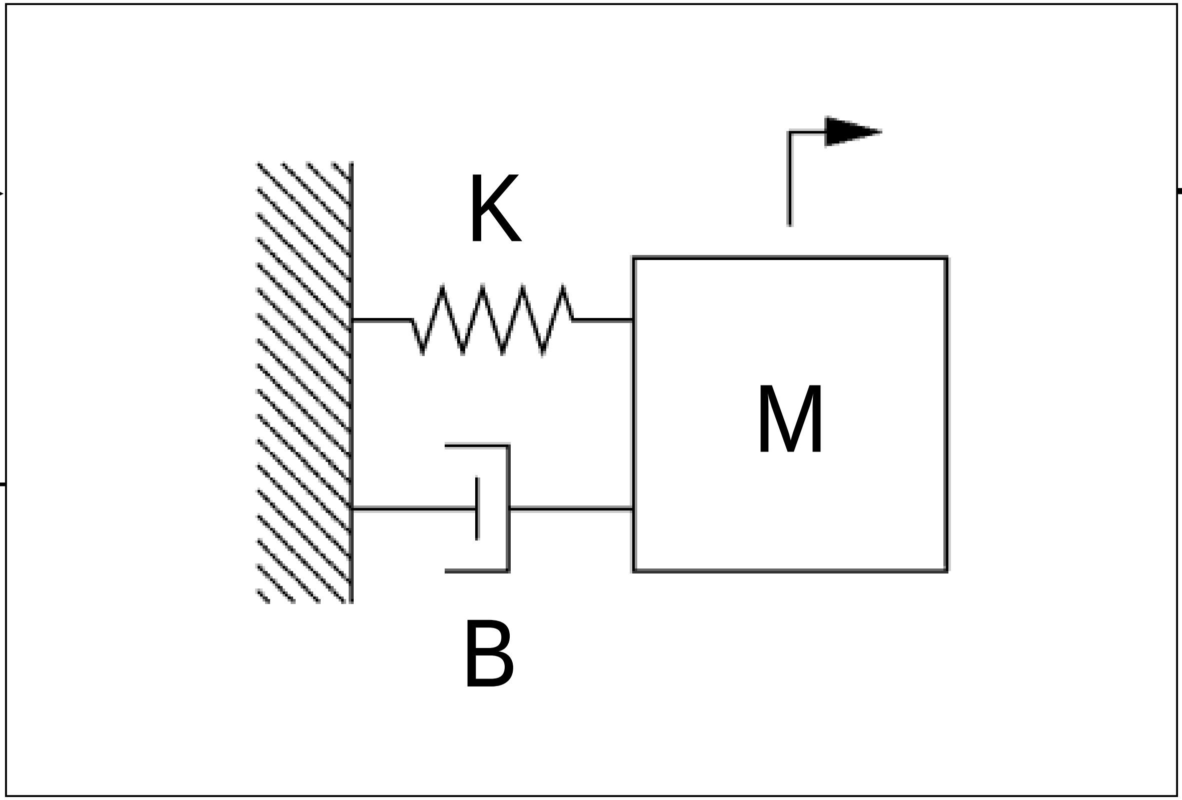
$$F = M\ddot{X}$$ (newton's law)



Measuring a Mass-Spring-Damper System

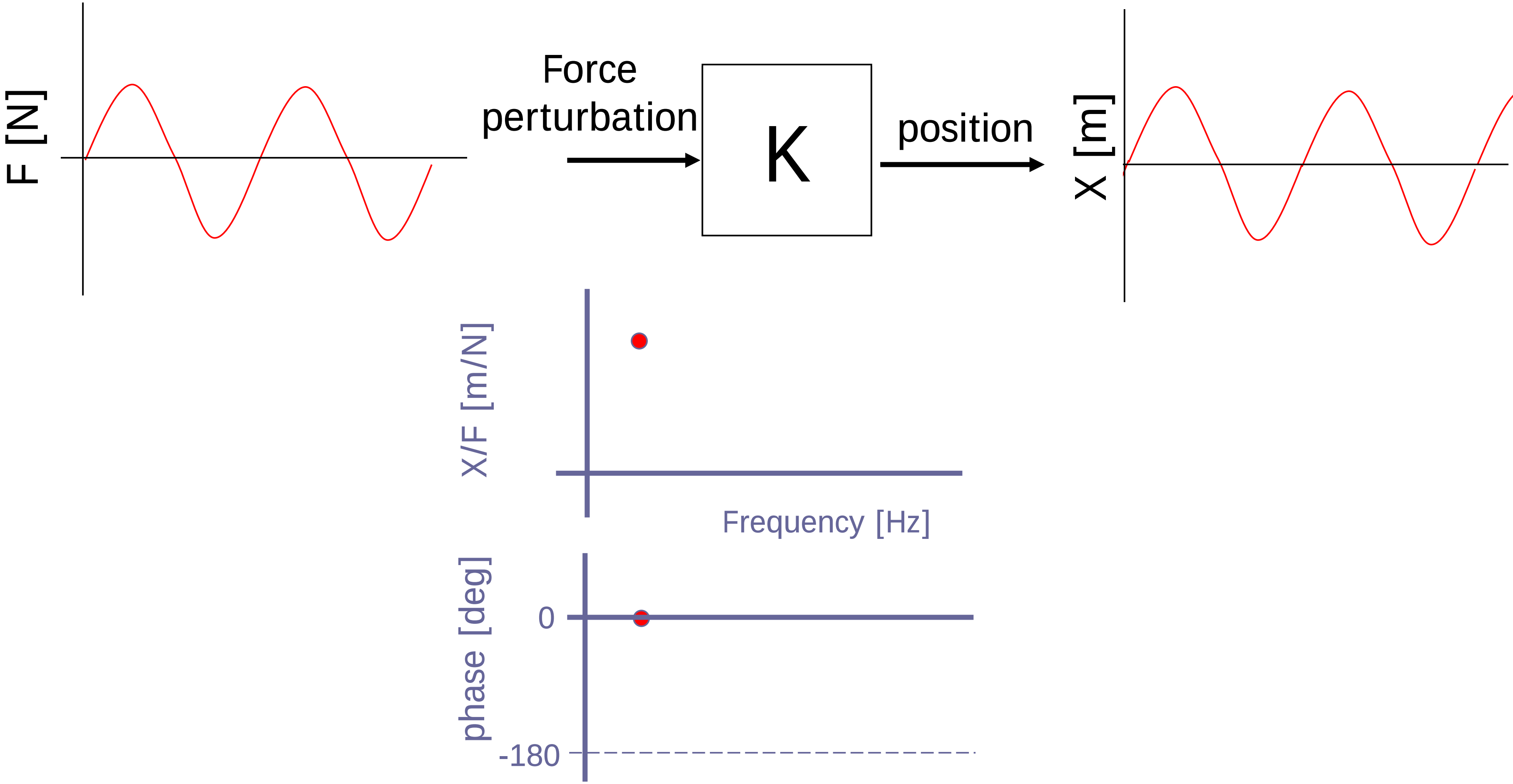
$$F = M\ddot{X} + B\dot{X} + KX$$

Force perturbation

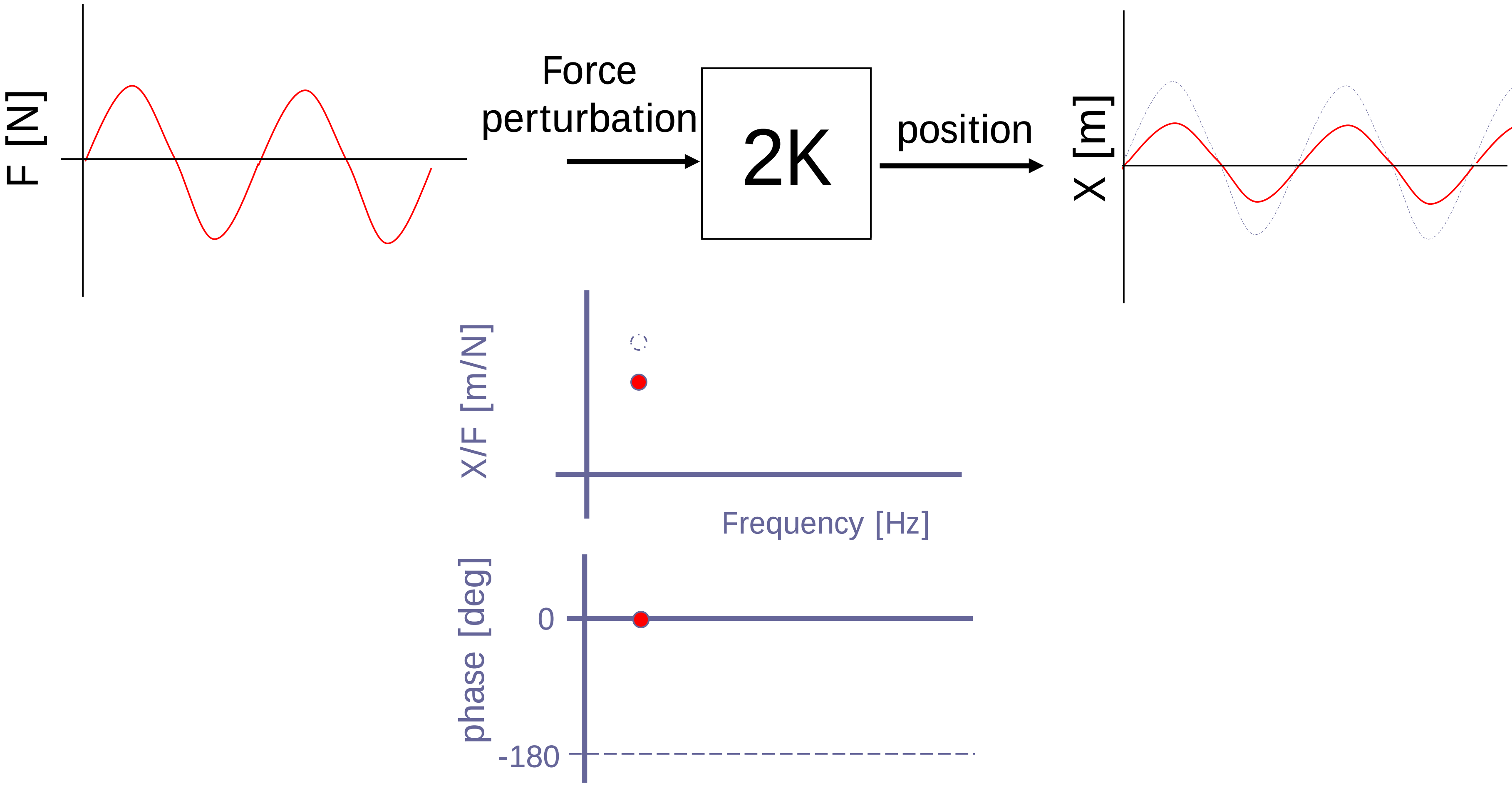


position

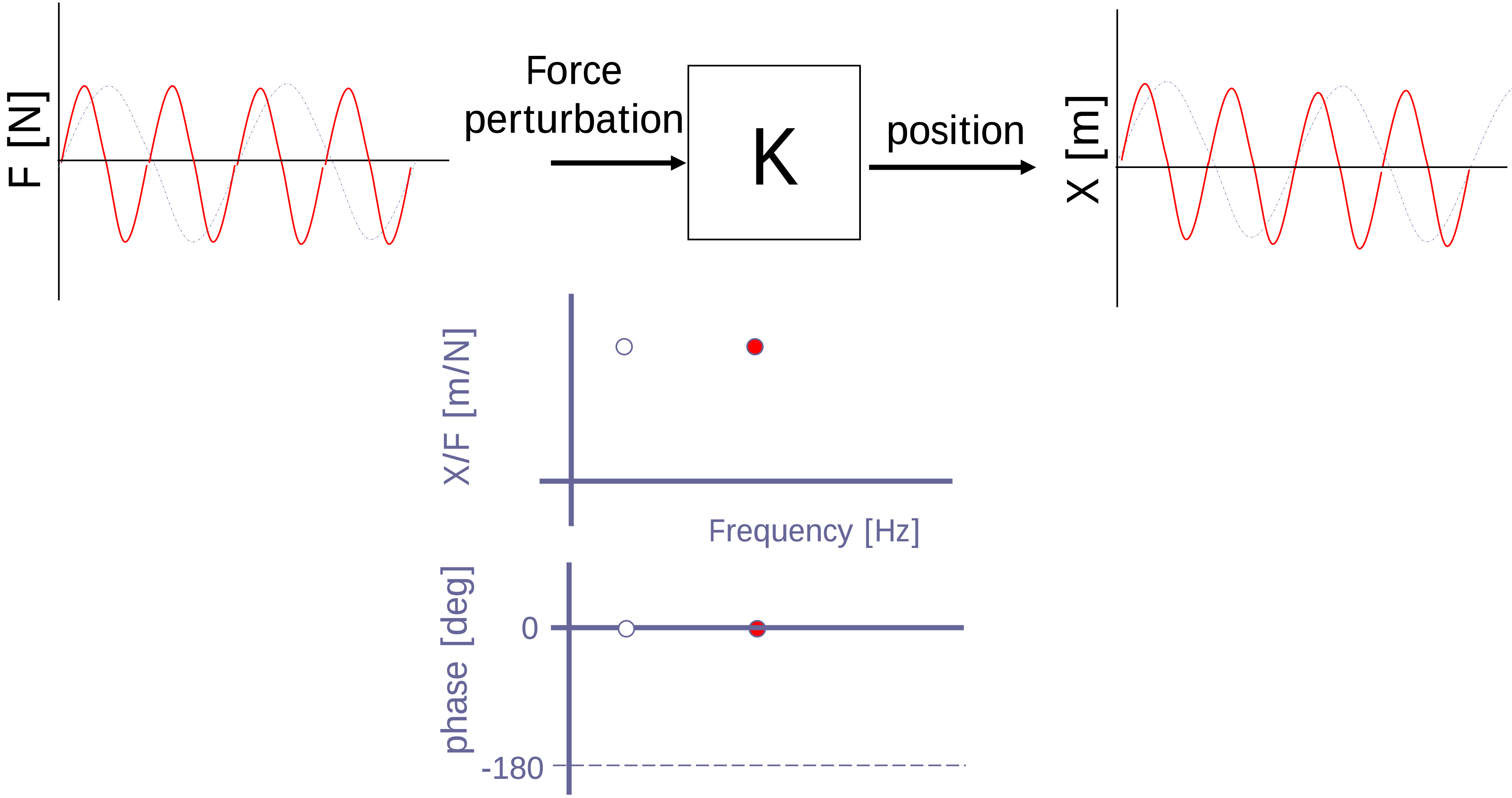
Measuring a Mass-Spring-Damper System



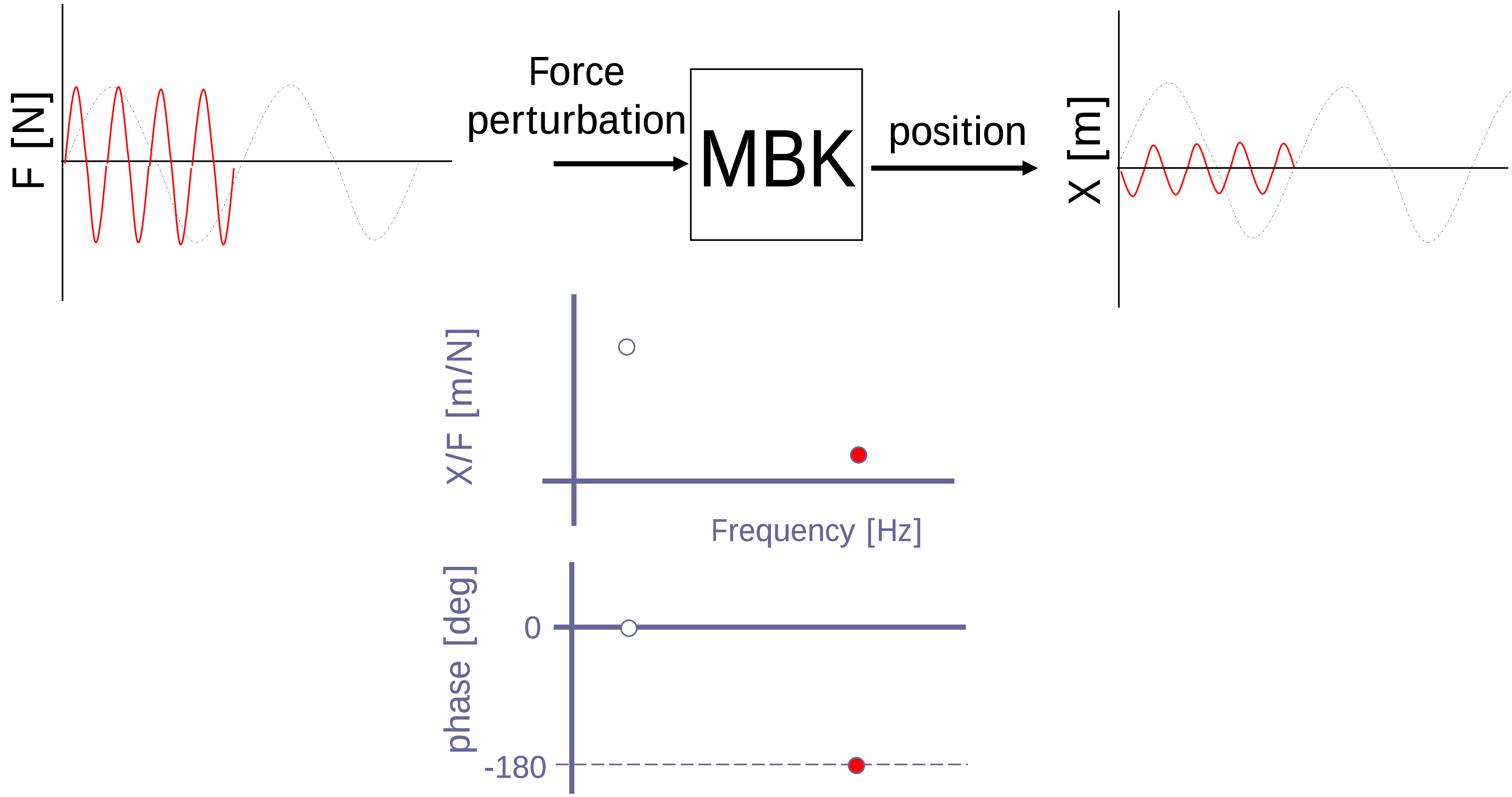
Measuring a Mass-Spring-Damper System



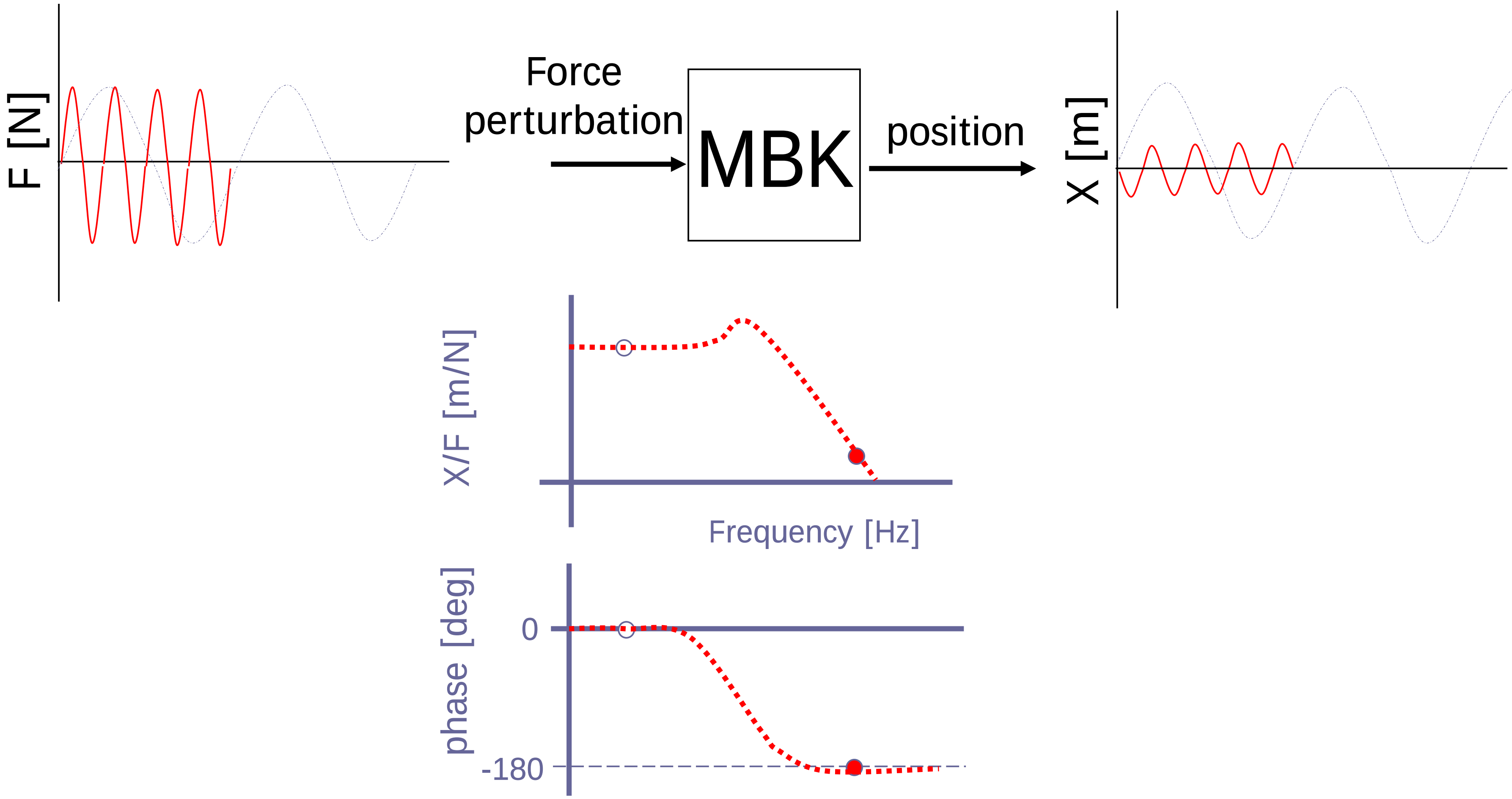
Measuring a Mass-Spring-Damper System



Measuring a Mass-Spring-Damper System



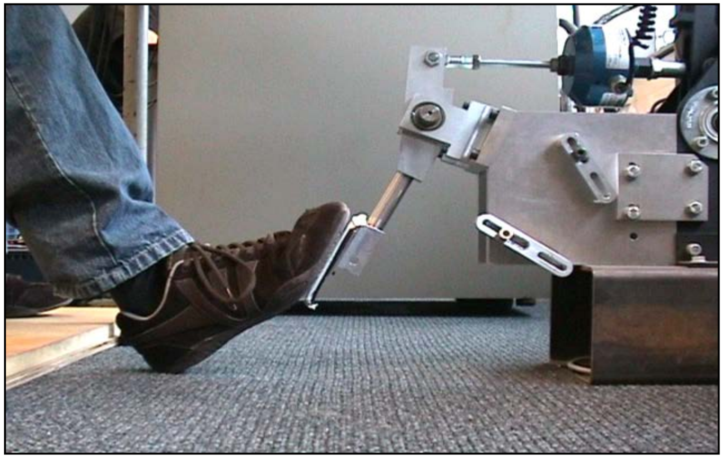
Measuring a Mass-Spring-Damper System

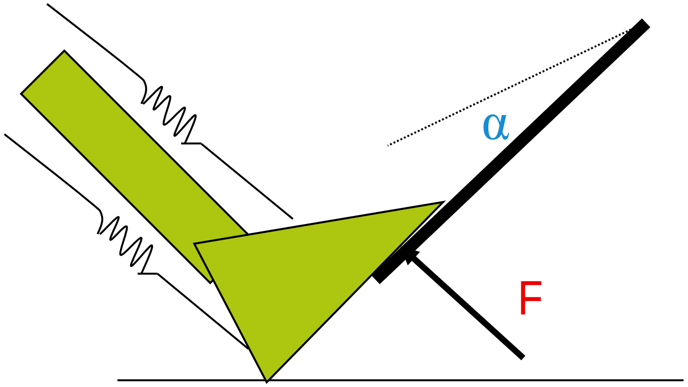


Frequency Domain Identification – applied to NMS control

Measuring the Neuromuscular System

1. Impose Force Perturbation
2. Task Instruction
3. Measure Signals
   - Pedal Force
   - Pedal Displacement
   - Force Perturbation
4. Estimate Admittance





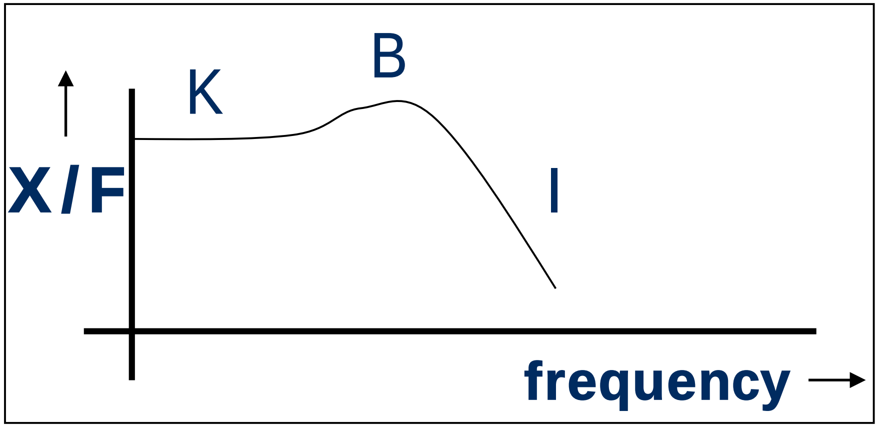
Measuring the Neuromuscular System

Admittance:

can be estimated as frequency response function

input force/torque
output position/rotation

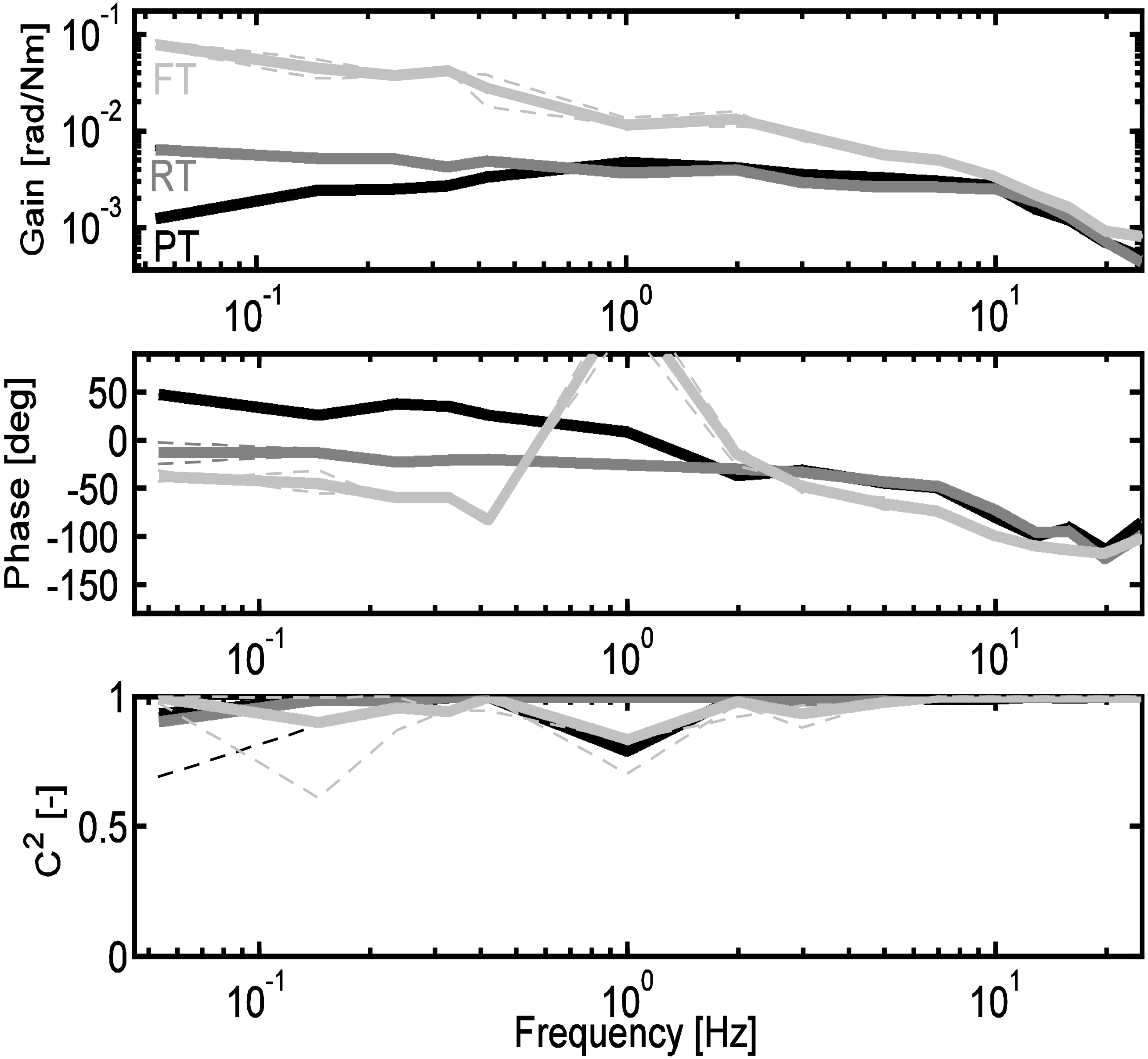
captures **causal** dynamic response of a human to interaction forces with the environment



Roughly resembles 2nd order system

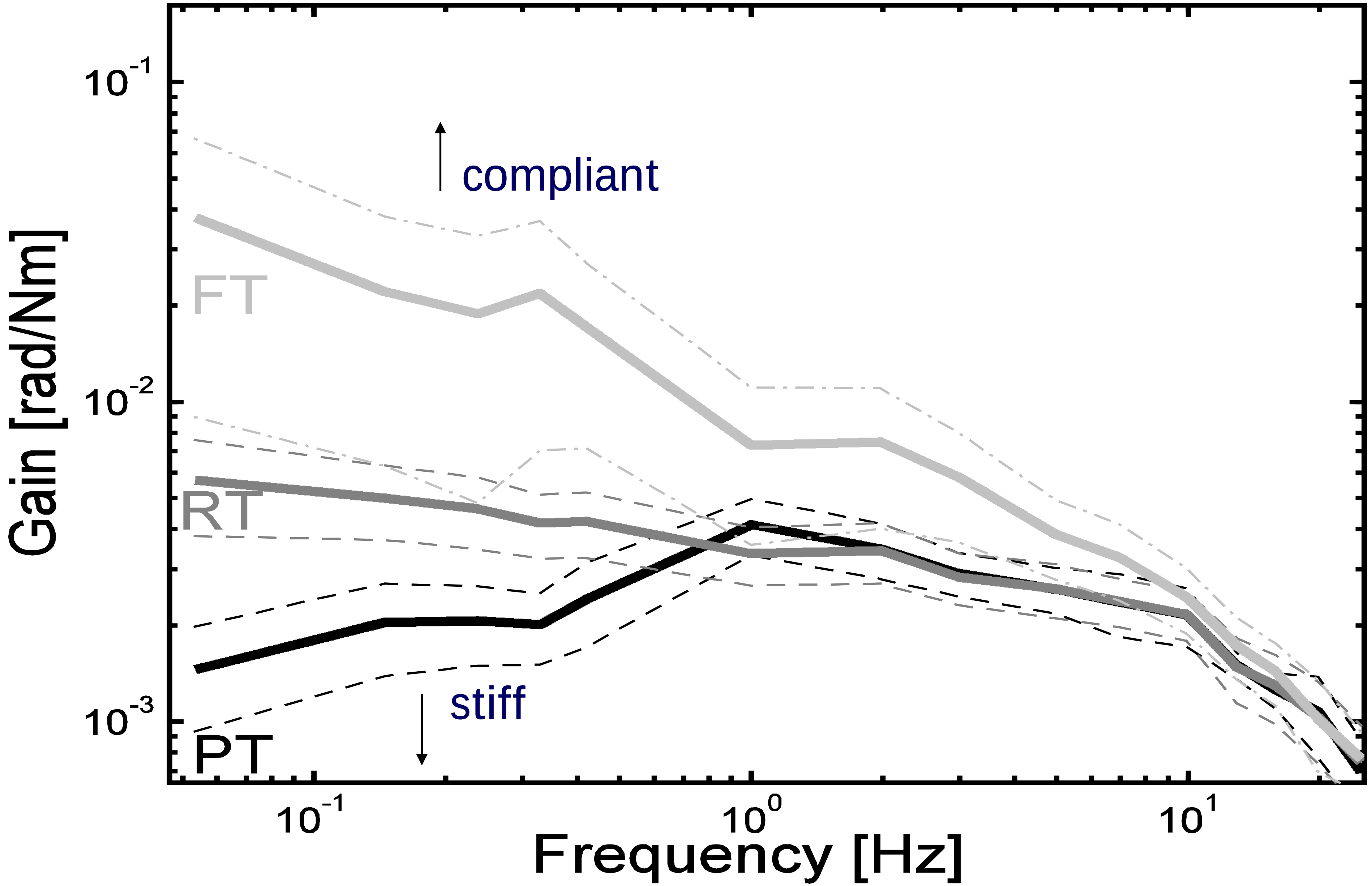
Highly adaptive!

Measuring the Neuromuscular System



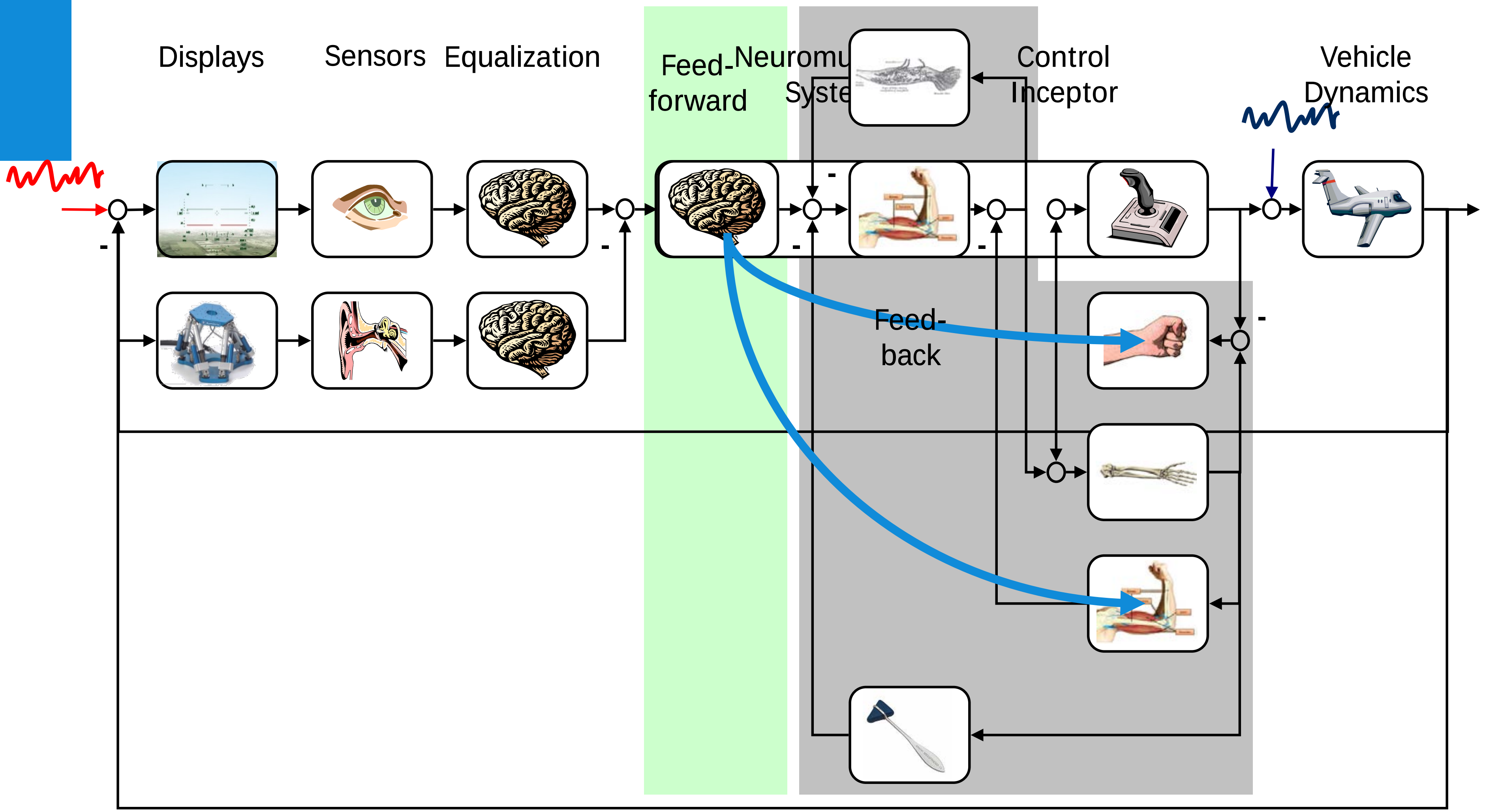
FT: Force Task
RT: Relax Task
PT: Position Task

Measuring the Neuromuscular System (10 subjects)

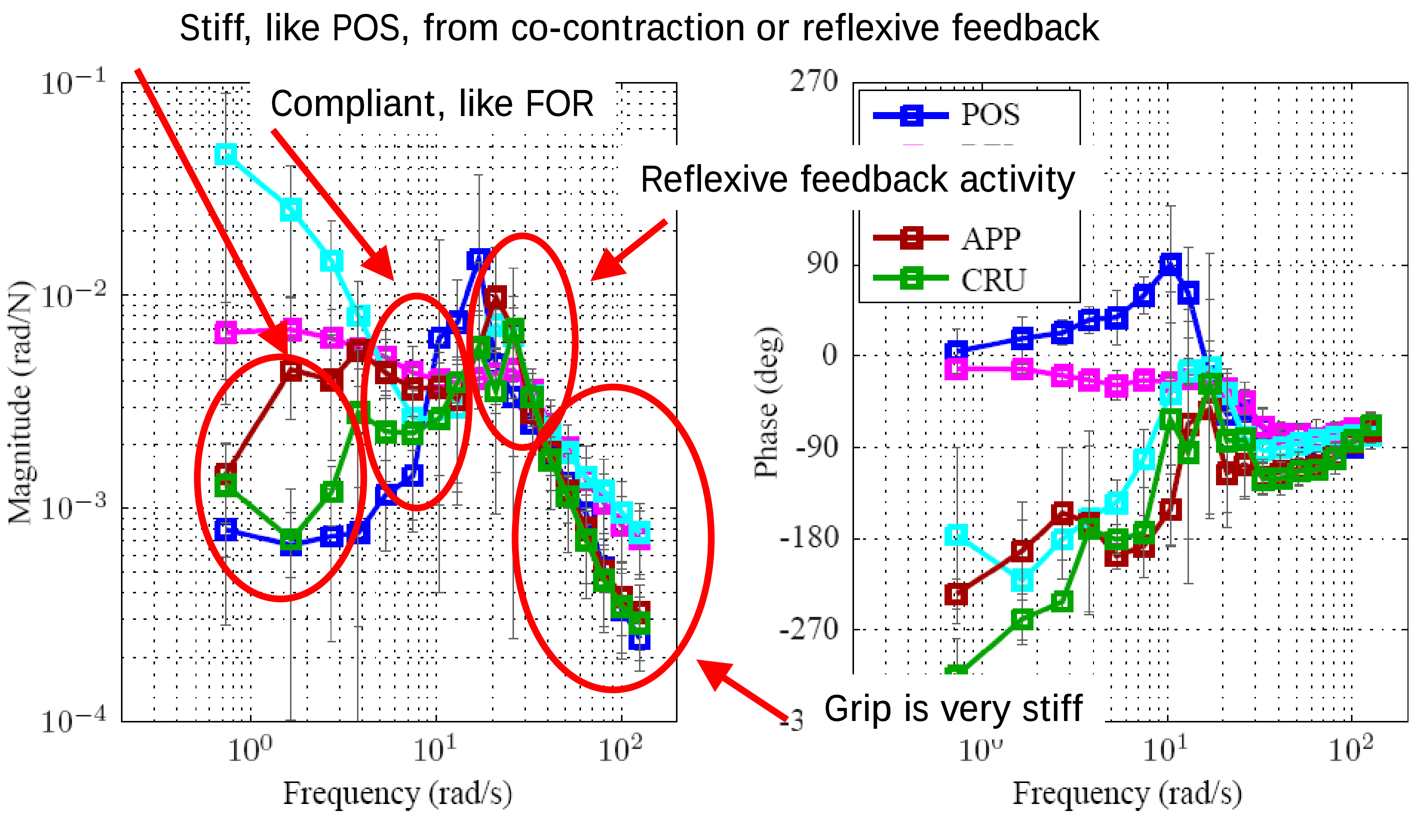


The Role of the Neuromuscular System in visual / vestibular control loops

Neuromuscular System during Pitch Control



Neuromuscular System during Pitch Control

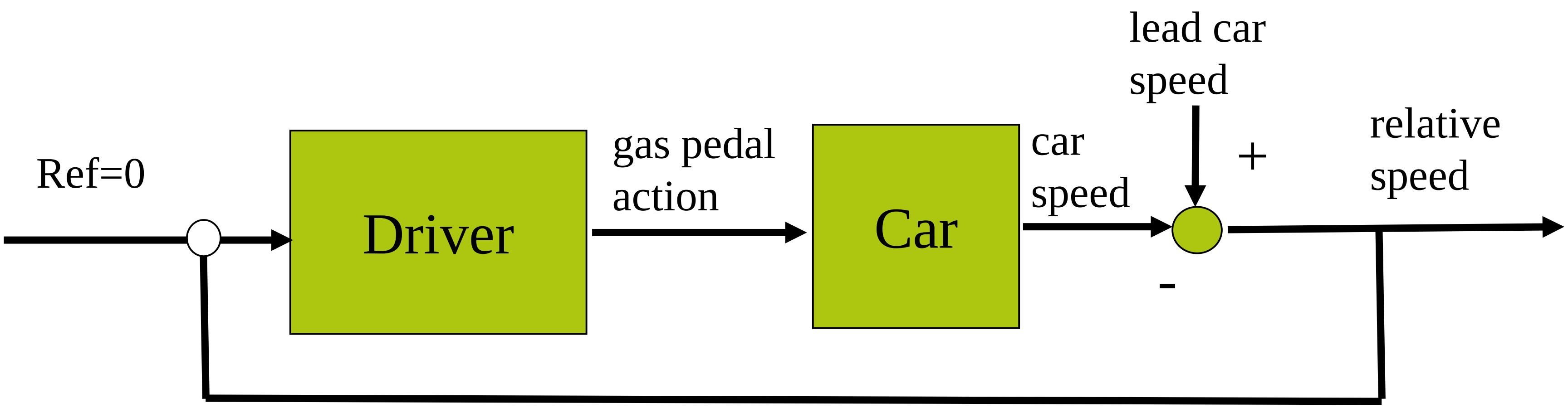


Interested in more information about measuring and modeling the NMS?

Follow:
Human Movement Control A/B

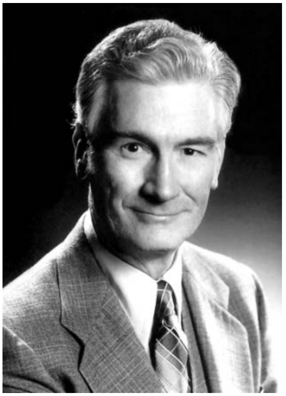
Play around with:
NMC Lab – a graphical user interface (GUI) to study the Delft Neuromuscular Model

Read:
-Schouten et al. (2008)
-Mugge & Abbink et al. (2011)
-Abbink et al. (2012)



The Cross-Over Model

Background & Theory



D. T. McRuer and H. R. Jex, “A review of quasi-linear pilot models”, IEEE Trans. Hum. Fact. 8, 231–249 (1967)

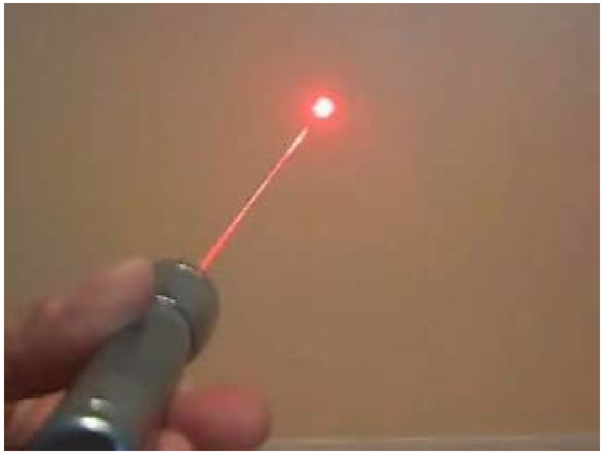
Order of Control

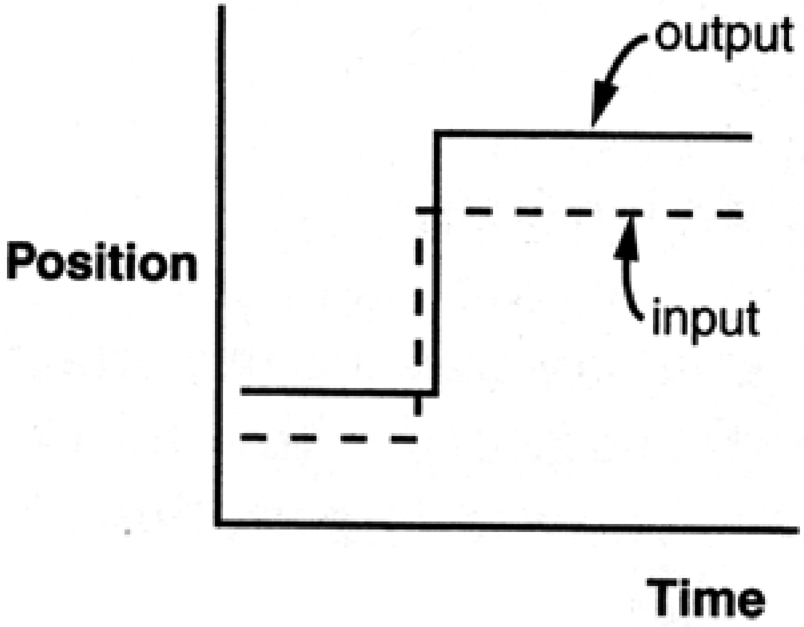
- Order of control denotes the number of integrations between the human's control movement and the output of the system being controlled.

- Highest derivative in the differential equation

Zero-order system

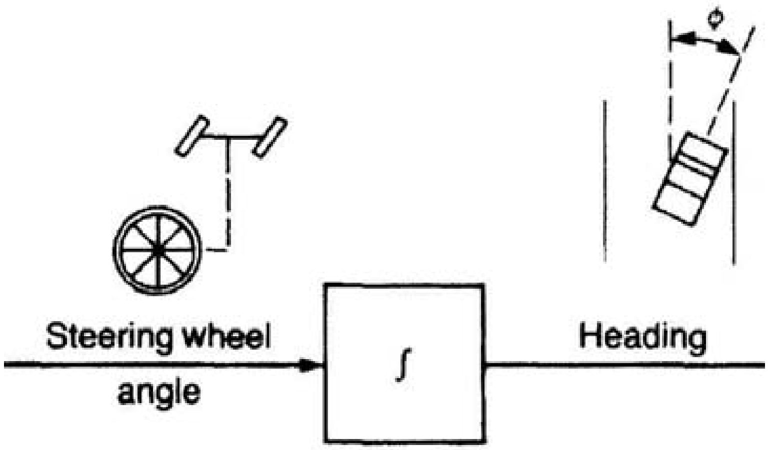
- Also called position control – pure gain

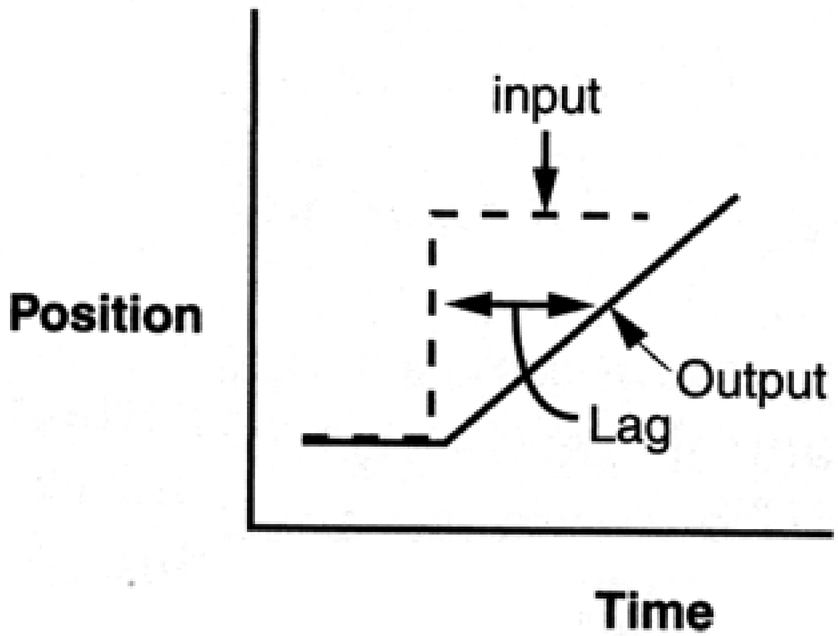




First-order system

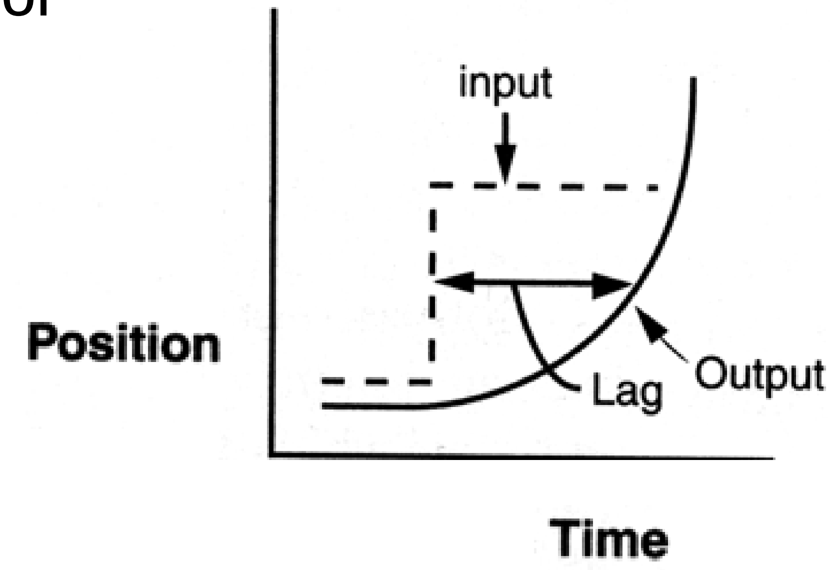
- Also velocity control – integrator

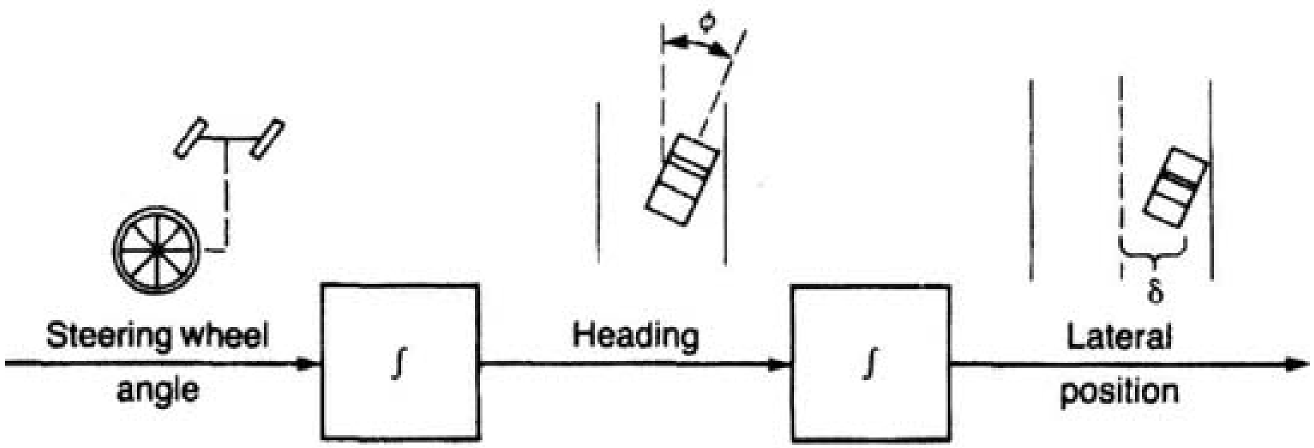




Second - order system

- Also called acceleration control





Crossover Model (McRuer)

Humans can adapt their control behaviour to steer position, velocity or acceleration (using prediction or memory), within limits:

$$K_{vis} \frac{1 + sT_{lead}}{1 + sT_{lag}} e^{-s\tau_{vis}}$$

Humans prefer the closed-loop controlled system to behave like a "first-order system"

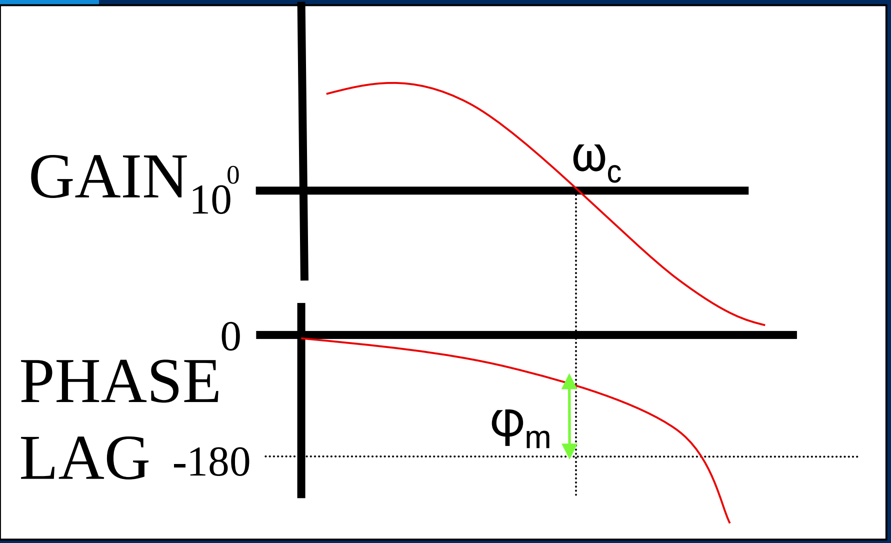
The adapted 'cross-over model': $H_{driver} H_{car} = \frac{\omega_c}{j\omega} e^{-j\omega\tau_e}$ (near ω_c)

Once adapted to the dynamics, humans can

- increase gain (ω_c)
- decrease time delay

Thereby influencing the properties of the total closed-loop system

Cross-over Theory



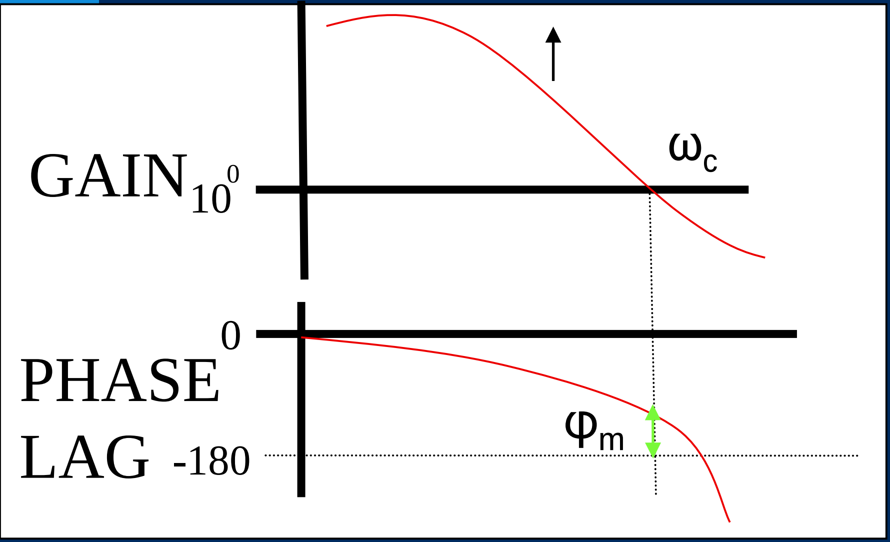
The cross-over model: $$H_{driver}H_{car} = \frac{\omega_c}{j\omega}e^{-j\omega\tau_e}$$ near ω_c

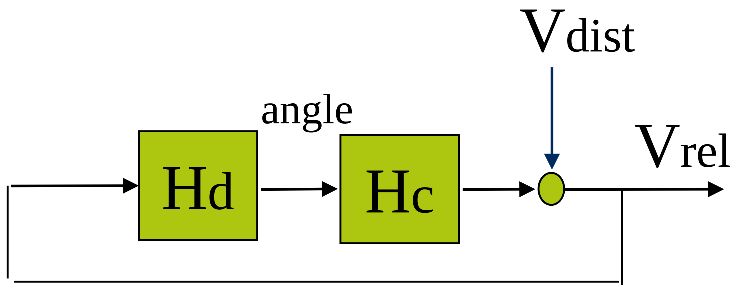
Properties of the Open-Loop system

Crossover Frequency ω_c — Measure of effort

Phase Margin φ_m — Measure of stability (safety)

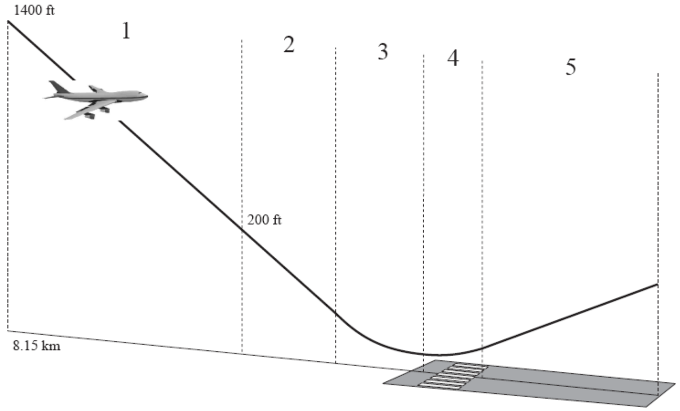
Cross-over Theory





$$\sigma^2 V_{rel} = \left| \frac{1}{1 + H_d H_c} \right| \sigma^2 V_{dist}$$

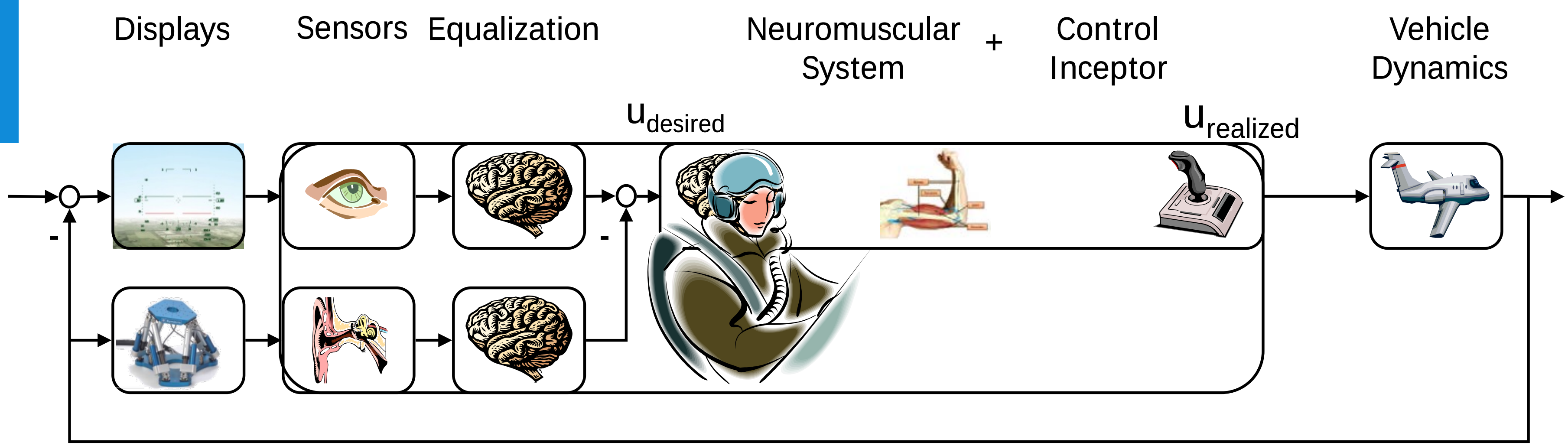
Important for stability: "open-loop function"



Cross-Over Model & Neuromuscular System

How do visual, vestibular and NMS feedback combine?

McRuer's Lumped Neuromuscular System



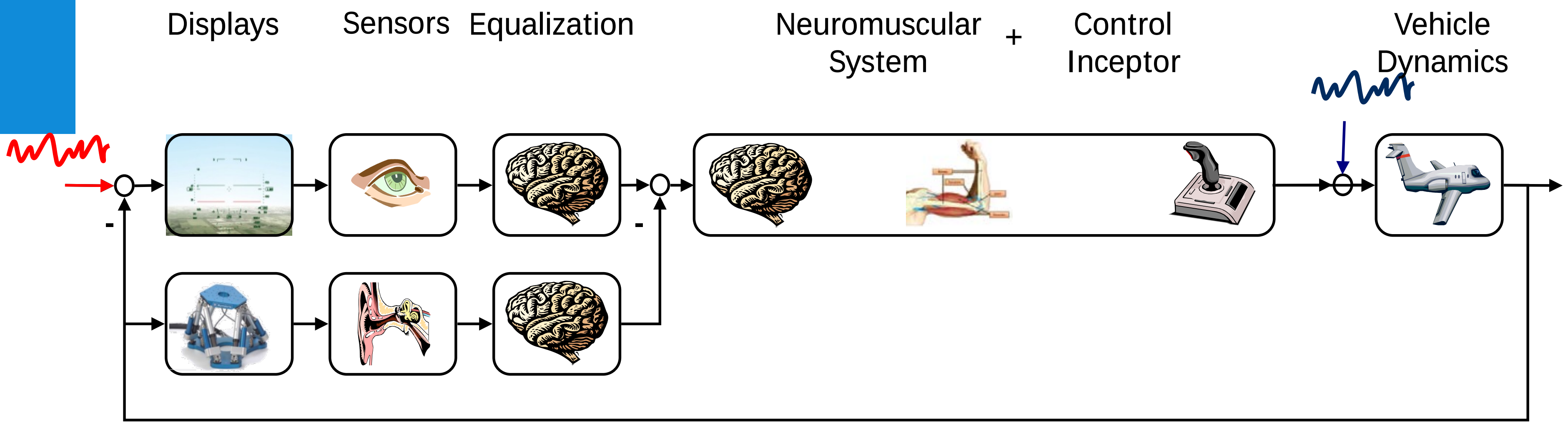
The neuromuscular system is usually considered as a limitation, and can be seen as a controller-actuator system between $u_{desired}$ and $u_{realized}$

The neuromuscular system can be modeled as a first or second-order low-pass filter: **Lumped neuromuscular system**.

$$H_{lumped} = \frac{\omega_{nm}^2}{\omega_{nm}^2 + 2\zeta_{nm}\omega_{nm}s + s^2}$$

The lumped neuromuscular system *model parameters* can be obtained from the *identified* visual and vestibular frequency response functions.

The Lumped Neuromuscular System

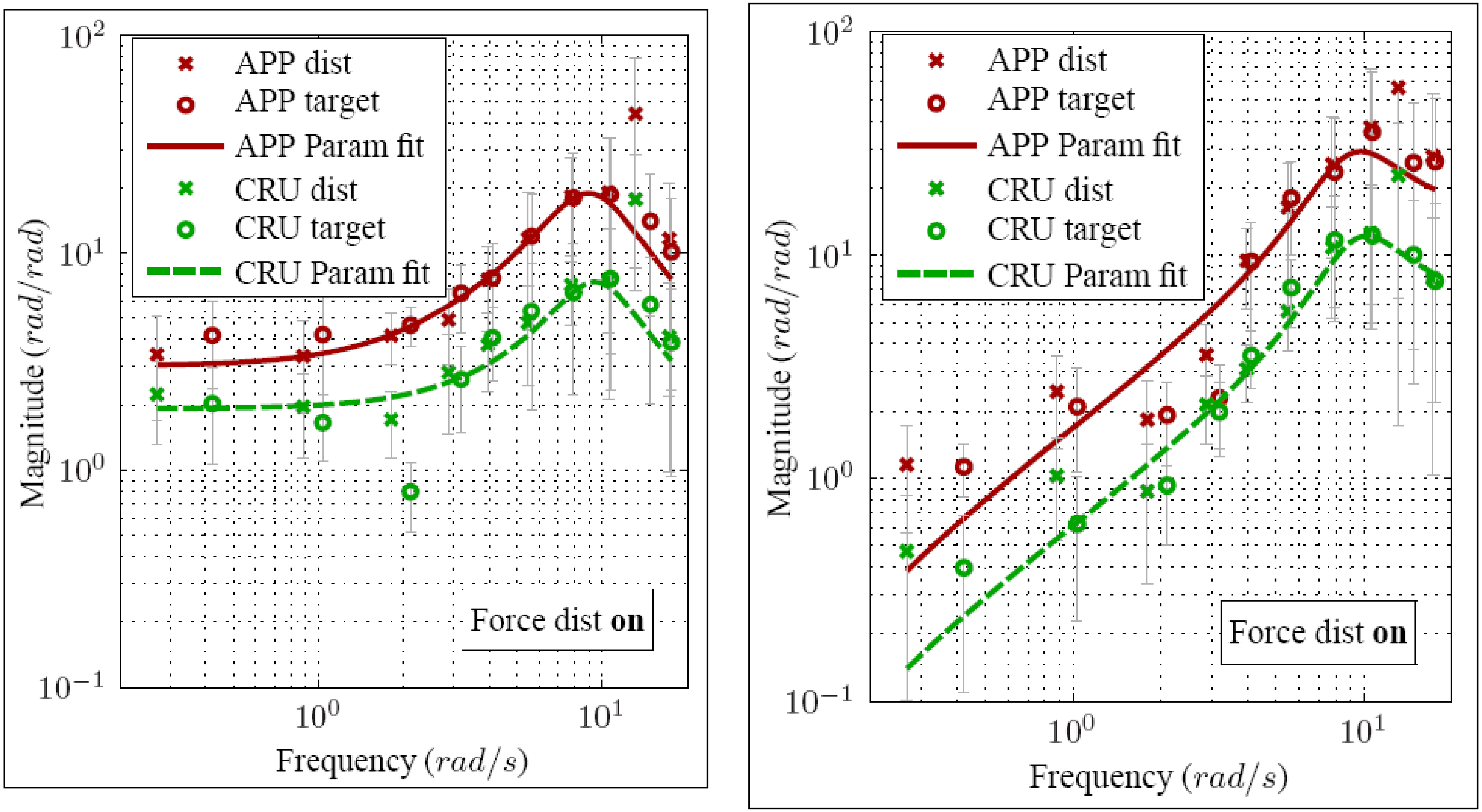


Two forcing functions are needed to identify the contributions of the visual and vestibular systems separately:

- A forcing function provides a pitch attitude command signal on the PFD.
- A second forcing function perturbs the elevator of the aircraft.

$$K_{vis}\frac{1+sT_{lead}}{1+sT_{lag}}e^{-s\tau_{vis}} \qquad K_{vest}\,e^{-s\tau_{vest}} \qquad \frac{\omega_{nm}^2}{\omega_{nm}^2+2\zeta_{nm}\omega_{nm}s+s^2}$$

Visual and Vestibular Responses to perturbations

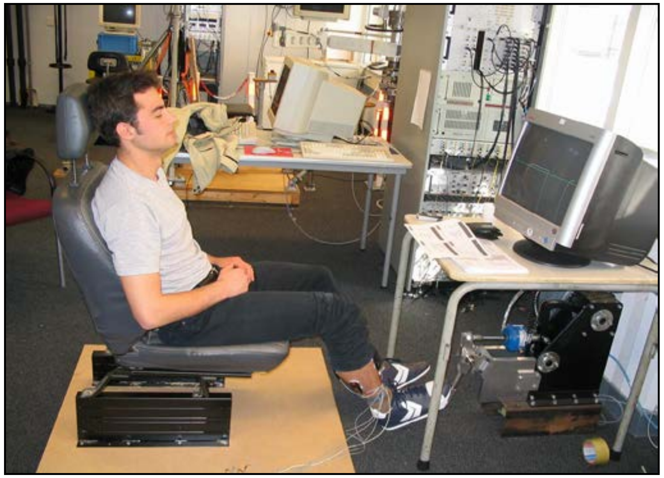


Cross-Over Model & Neuromuscular System

How do visual and NMS feedback contribute to car-following behaviour in case of haptic gas pedal feedback?

Evaluation – Car Following with Haptic Driver Support System (DSS)

Goal: Experimentally Investigate impact of haptic DSS on car following AND neuromuscular control behaviour



Experimental Facilities

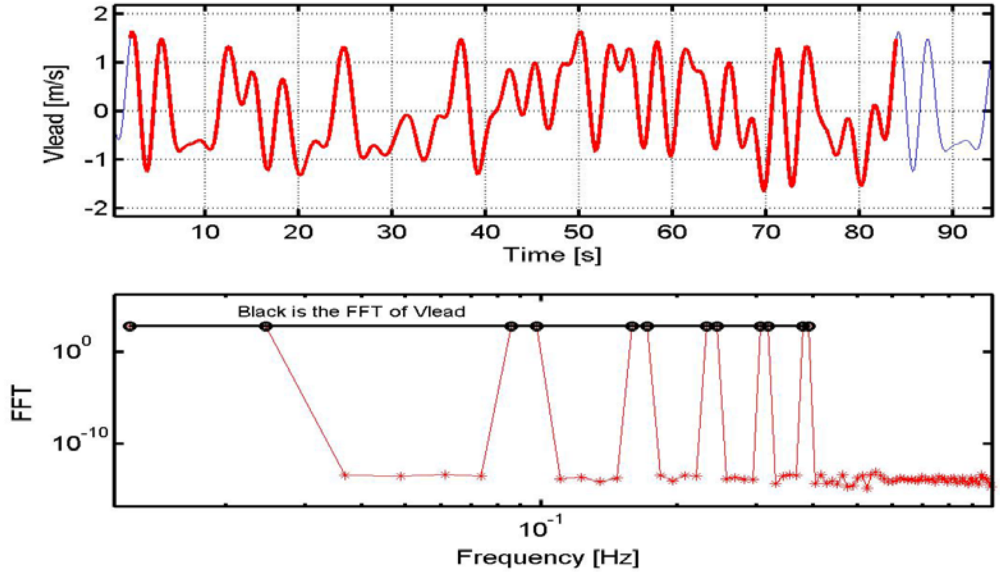
1. Simplified Simulator (ME), capable of admittance measurements
2. Realistic Fixed Base Driving Simulator (AE) for checking

Subjects:
5 male, 5 female subjects

Experimental Conditions:

- **V** (drive with visual feedback)
- **VH** (drive with visual and haptic feedback)
- **H** (drive with haptic feedback only)

Task Instruction & Perturbation

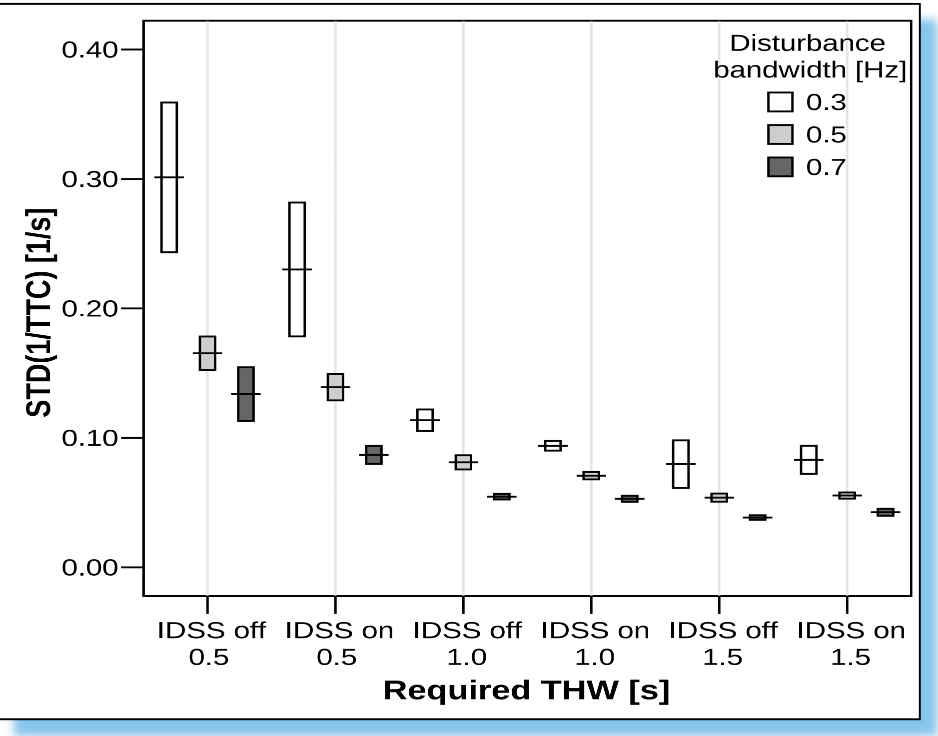


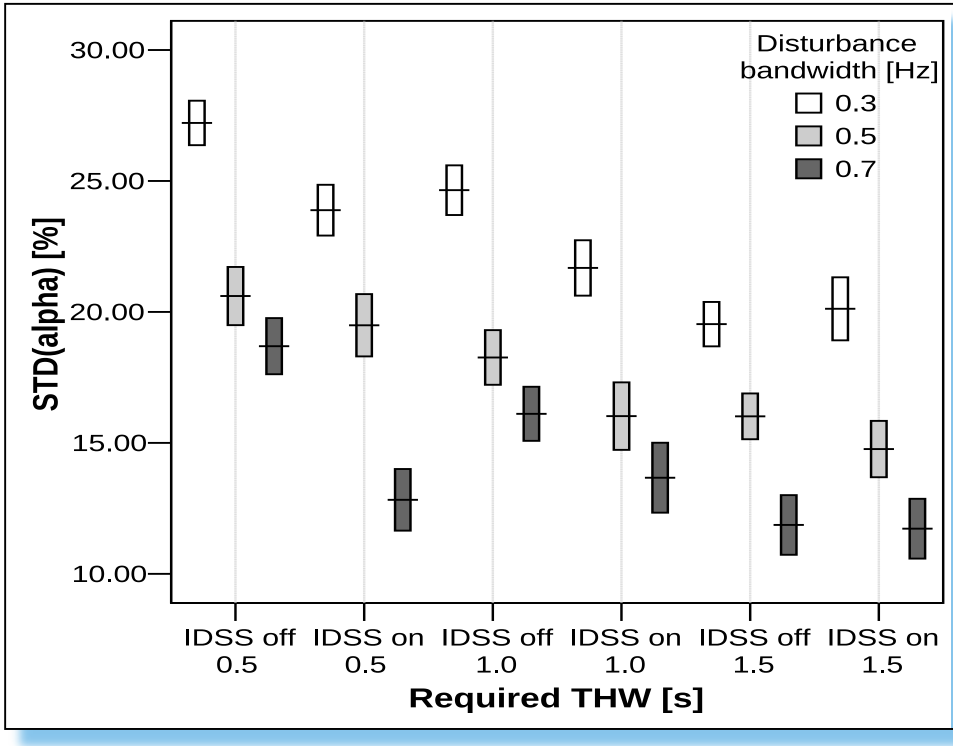
Car-following experiment

Experimental results: classical metrics

Performance (std 1/TTC)
- IDSS increased performance

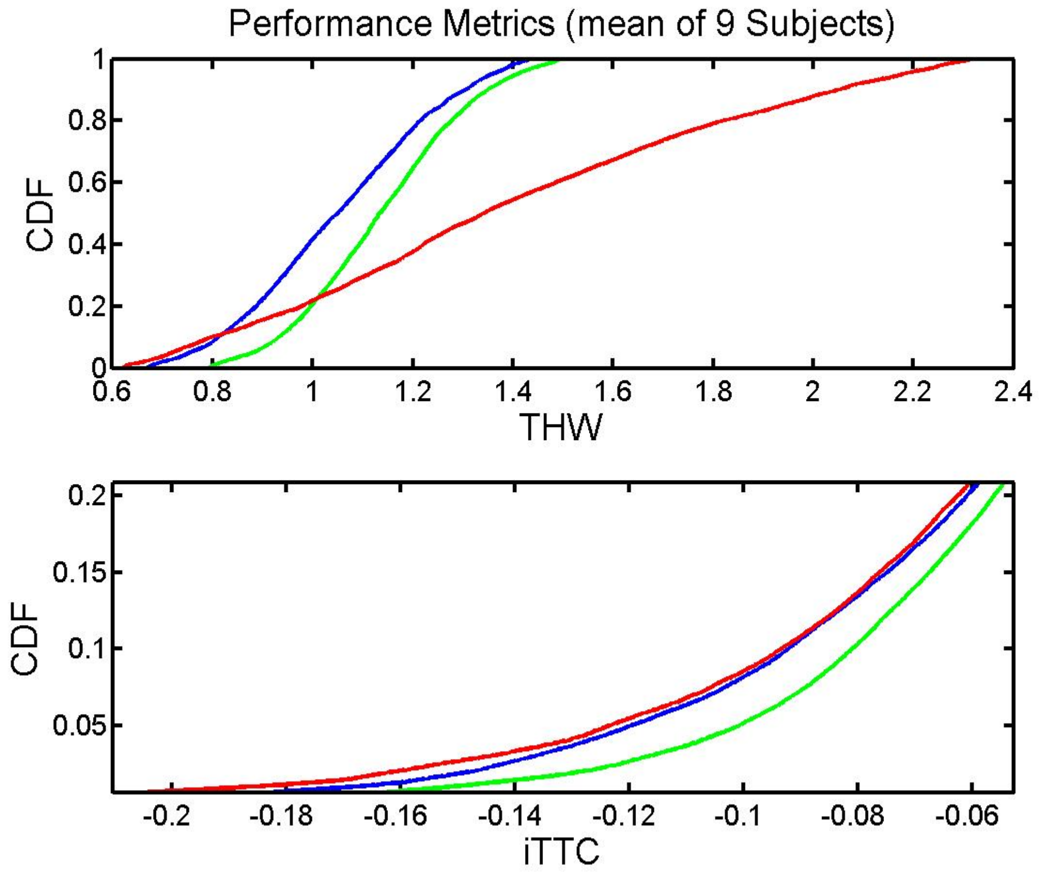
Effort (std Pedal Depression)
- IDSS decreased effort





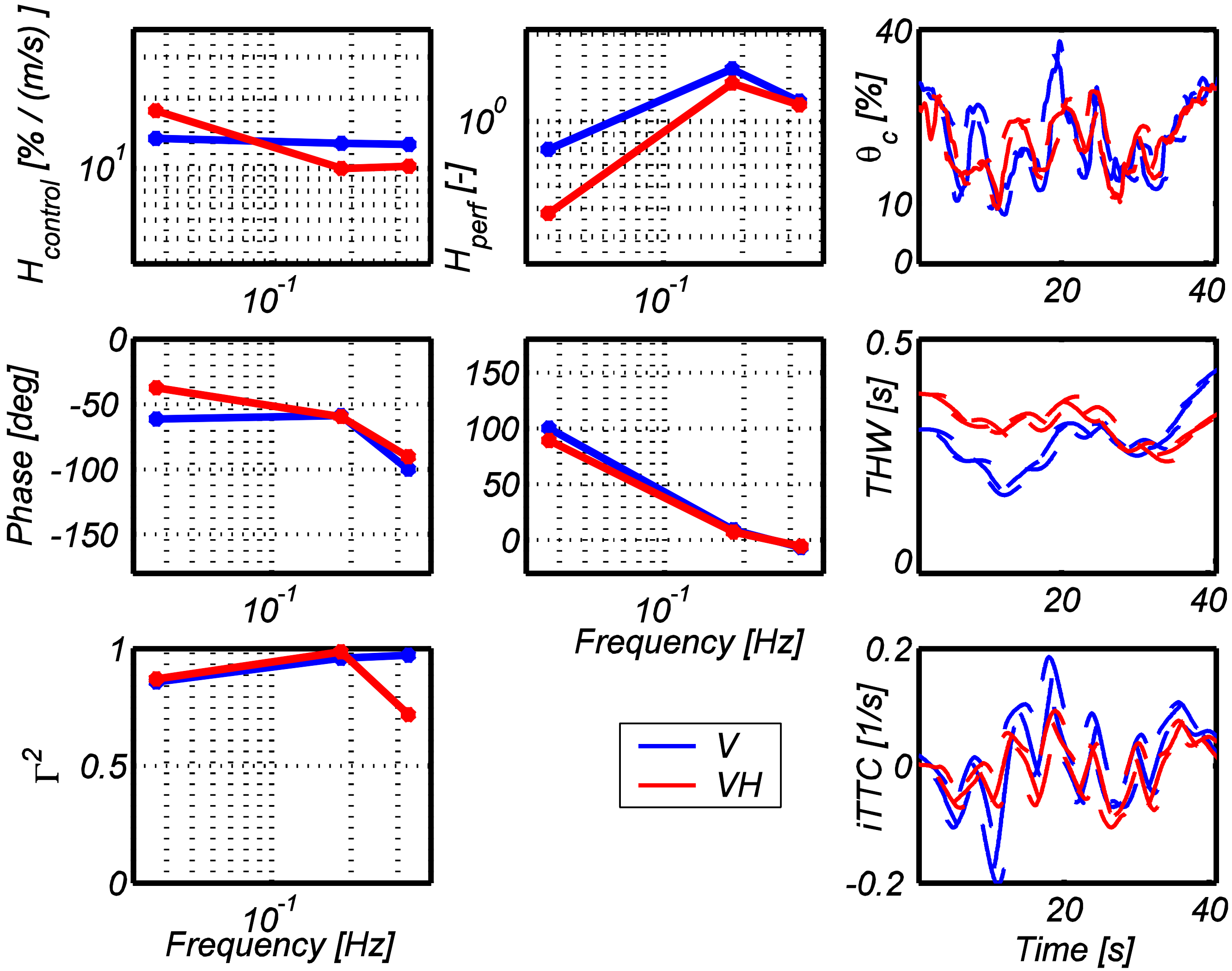
Car-following experiment

Experimental results: classical metrics (for THW=1, Bandwidth = 0.5)



Car-following experiment

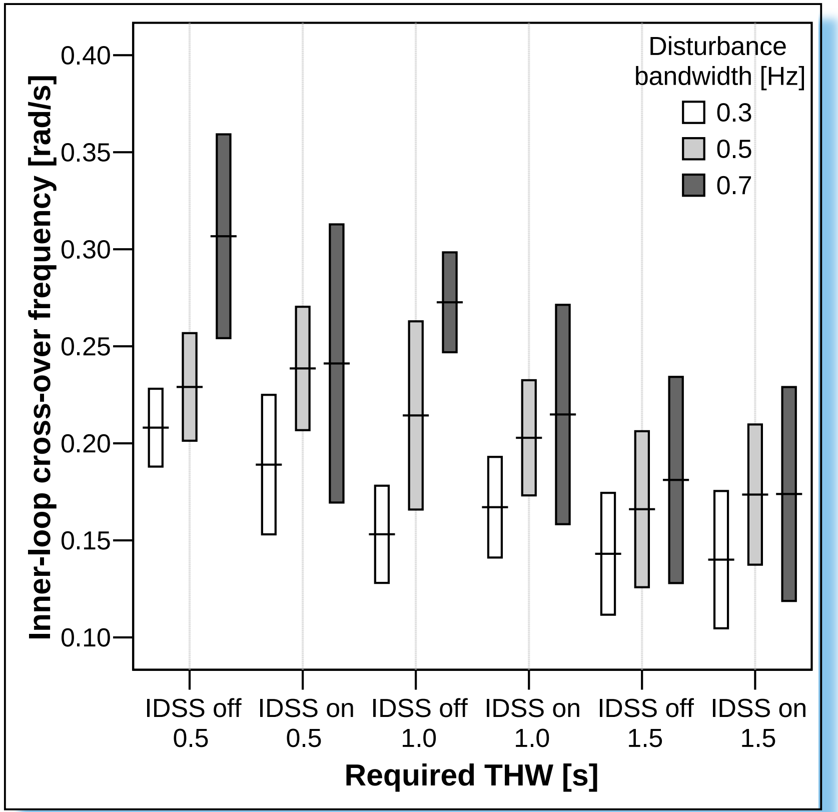
Experimental results: frequency domain and time domain



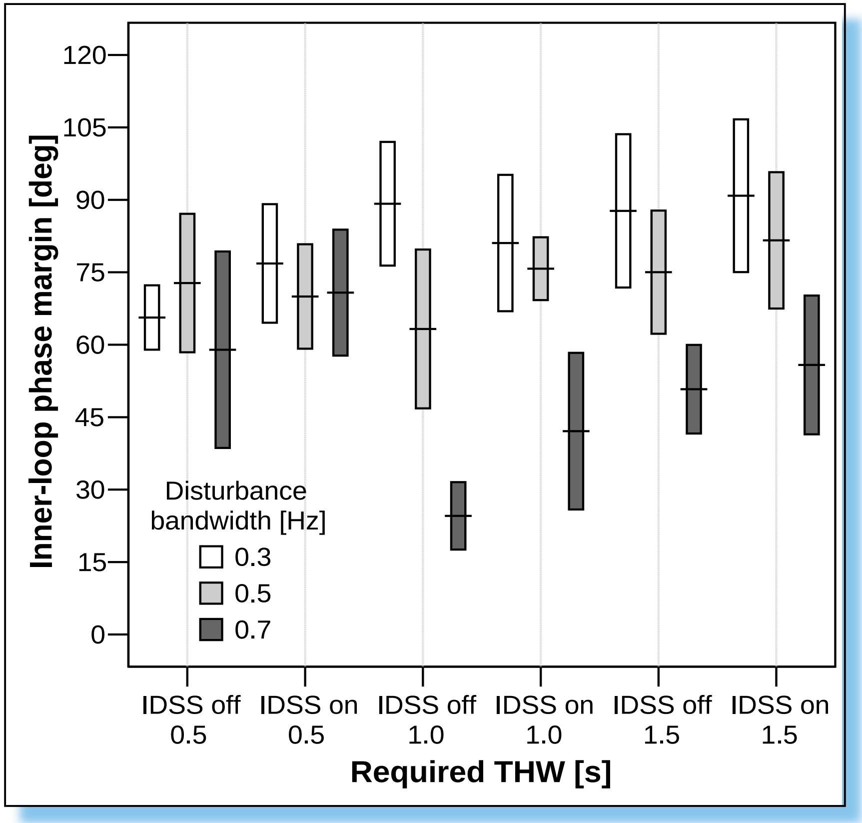
Car-following experiment

identification results: Cybernetic Results

Control Effort (crossover freq)



Performance (phase margin)



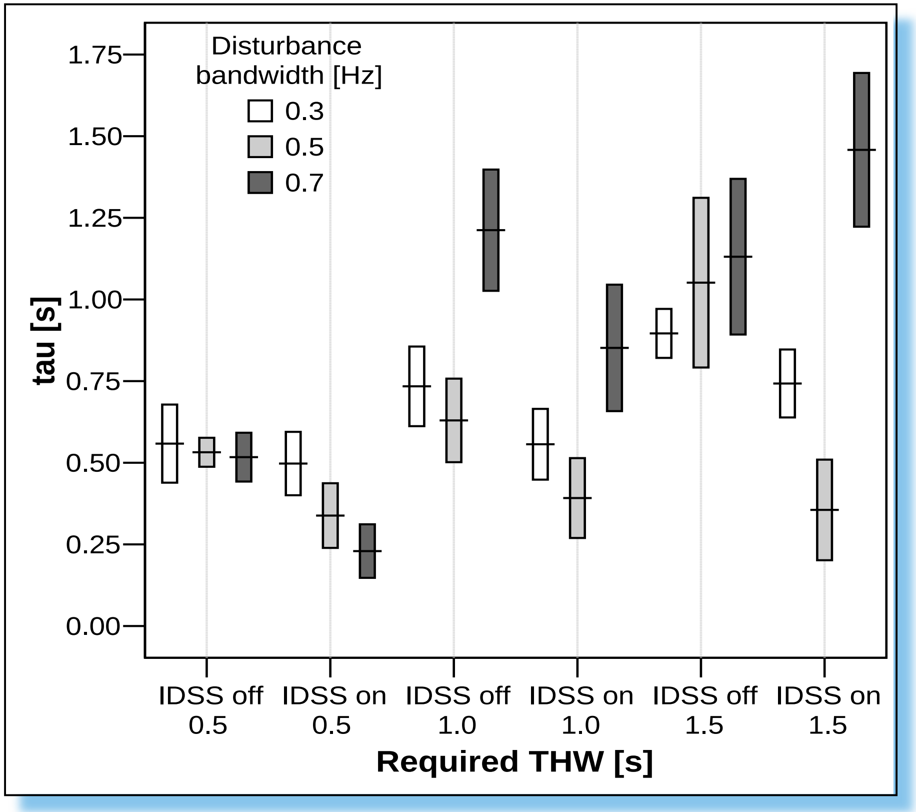
Car-following experiment

identification results: Cybernetic Results

Modeled Time delay decreases with haptic gas pedal feedback

- More time available

But what is the cause?



Haptic Gas Pedal Evaluation – Exp.

Beneficial changes in Car-Following Behaviour:

Performance (deviations in Xrel, THW, Vrel, iTTC)

- Similar or slightly better

Control Effort (deviations in pedal position, muscle activity)

- Decrease

Driving with only haptic (H) feedback possible

How? Look at changes in Neuromuscular Control Behaviour

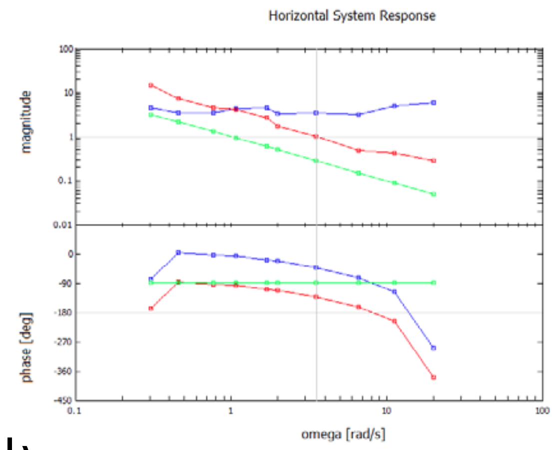
Admittance

Modeling

Next Class – ‘Computerzaal B’ (TBM)

Study Human Control Behaviour with MMS - Lab

- Group Enroll (available now)
- Download from BlackBoard (available tomorrow)



Do experiment

- Test several conditions on yourself
  - 1st order, 2nd order system, 3rd order system (normal)
  - 1st order, 2nd order system, 3rd order system (with predictor)
- Save each of the data files and two plots
  - (time-domain, frequency domain)
- Report in a short presentations
  - Report results in time domain and frequency domain
  - Discuss results in terms of McRuer Cross-over modelding
  - Discuss inter- and intra-subject variability