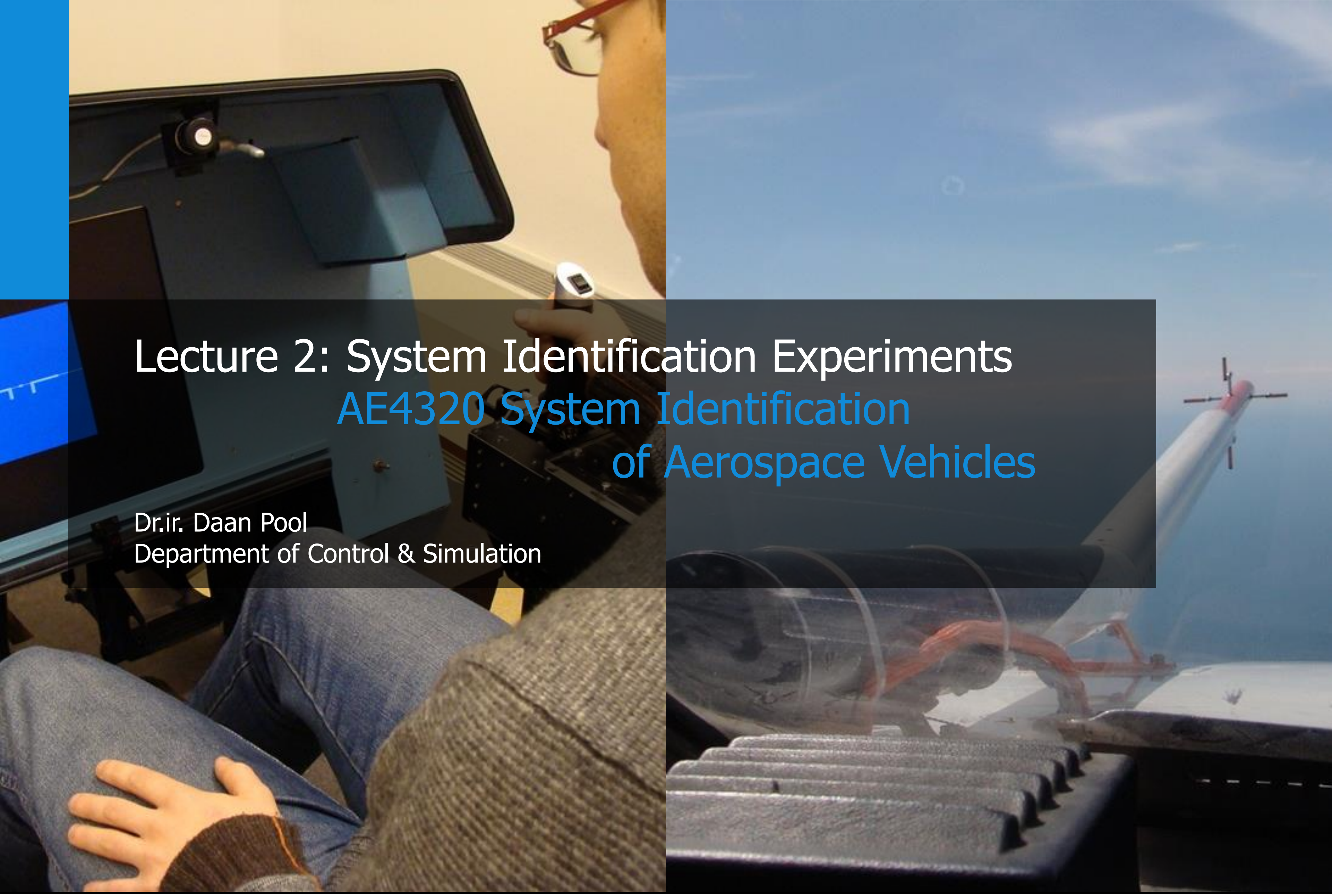


Lecture 2: System Identification Experiments

AE4320 System Identification of Aerospace Vehicles

Dr.ir. Daan Pool
Department of Control & Simulation

TU Delft
Delft University of Technology

Course Outline

- **Lecture 1: (dr.ir. Coen de Visser)**
  - Course goals and objectives
  - Introduction to System Identification
- **Lecture 2,3: (dr.ir. Daan Pool)**
  - System Identification Experiments
- **Lecture 4,5,6: (dr.ir. Daan Pool)**
  - Kalman filters
  - State estimation & Sensor Fusion
- **Lecture 7,8: (dr.ir. Coen de Visser)**
  - Model structure selection
  - Model parameter estimation

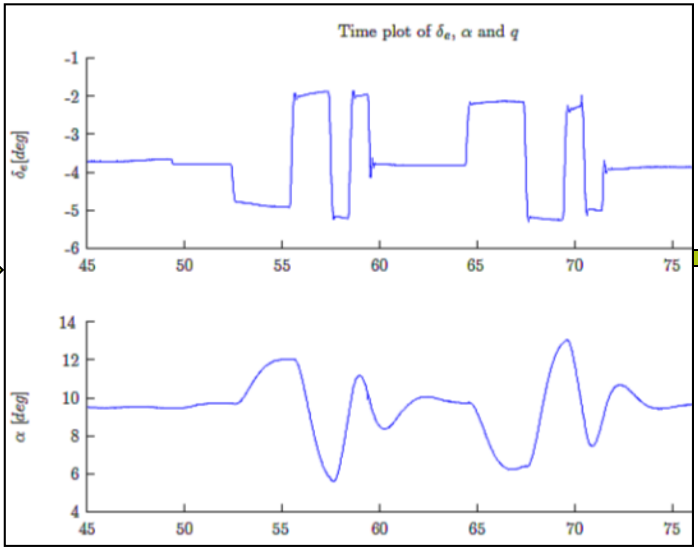
Course Outline

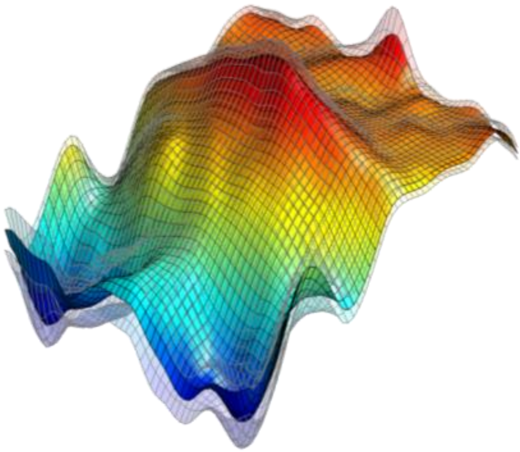
- **Lecture 9: (dr.ir. Coen de Visser)**
  - Advanced identification approach: Neural networks
- **Lecture 10,11: (dr.ir. Coen de Visser)**
  - Advanced identification approach: Multivariate B-Splines
- **Lecture 12: (dr.ir. Coen de Visser)**
  - Model validation, course conclusion

Goals of this Lecture

Questions that will be answered during this lecture:

1. *How are the <u>model objectives</u> related to the experiment that is performed to collect the data for system identification?*
2. *How do we design <u>inputs</u> for a system identification experiment?*
3. *How do we <u>conduct</u> a system identification experiment?*
4. *What do we <u>measure</u> and how do we measure it?*





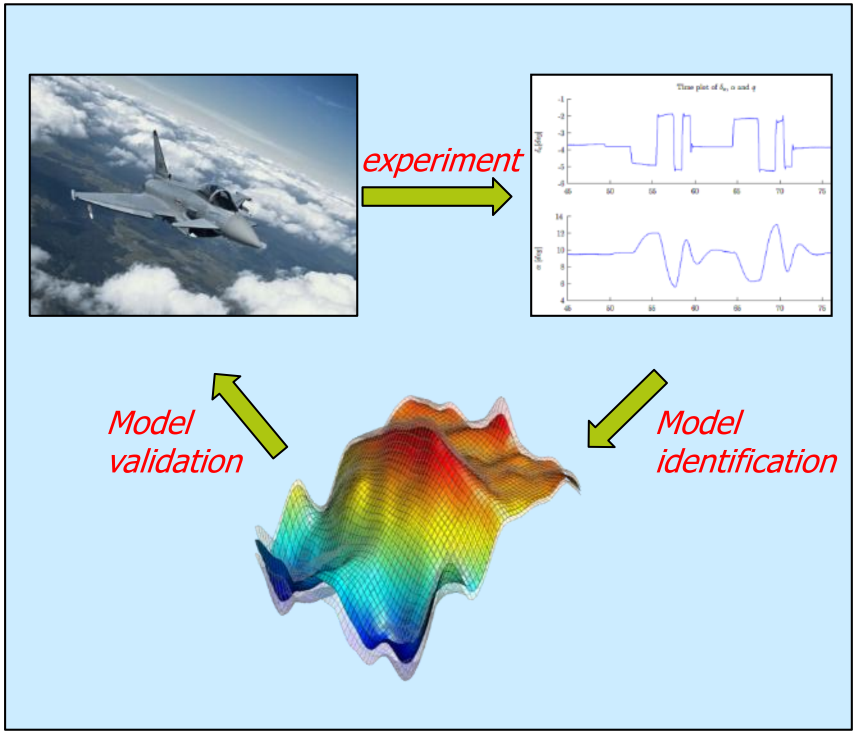
SysID High Level Overview

Where we are now in the System Identification Cycle:

Experiment phase
- Plant analysis
- Experiment design and execution
- Data logging and pre-processing

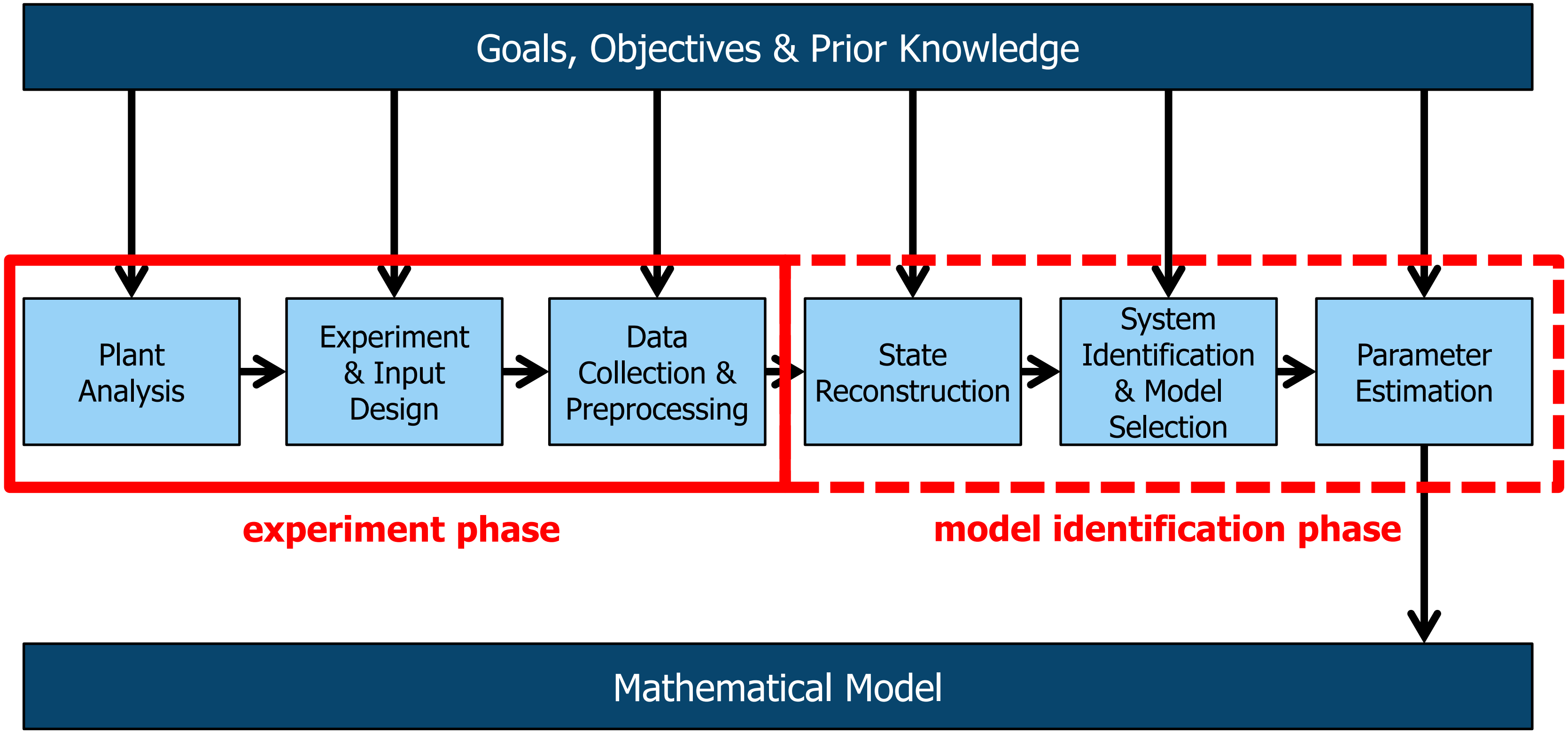
Model identification phase
- State estimation
- Model structure definition
- Parameter estimation

Model validation phase
- Model validation



Especially true for system identification experiments!

The System Identification Problem



System Identification Experiments


Lennart Ljung

"*When confronted with a physical system whose dynamics is to be identified, there are a number of questions to be answered.*"

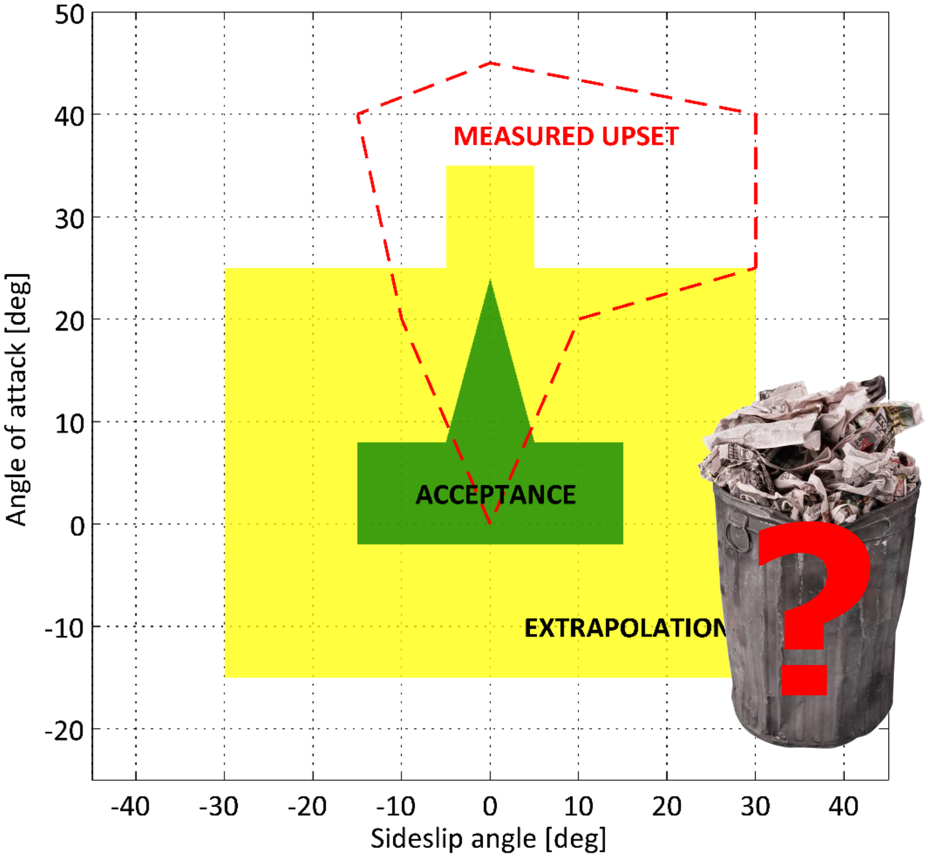
L. Ljung, *System Identification: Theory for the User*, Prentice-Hall, 1999

1. Which signals are to be considered as **outputs** and which are to be considered as **inputs**? (*system definition*)
2. Which signals should be manipulated (inputs) so as to **"excite" the system** during the experiment? (*system excitation/input design*)
3. **Where and what** to measure? (*measurement definition*)
4. **When** to measure? (*experiment design*)

The answers to these questions are highly application-dependent and to a large extent determine the final model validity!

Example of Final Model Validity

- Aircraft model application: simulator-based upset training (e.g., stall and "unusual attitudes")
- Good models for upset scenarios do not exist:
  - Dangerous maneuvers
  - Complex nonlinear and stochastic dynamics
  - Very expensive flight tests!
- Problem: experiment phase!



Modified after: Advani, Schroeder & Burks, *What Really Can Be Done in Simulation to Improve Upset Training?*, Proceedings of the AIAA Modeling and Simulation Technologies Conference, 2010.

System Identification at C&S

- **<u>Case 1:</u> Pilot control behavior identification**
  - Understanding the human controller
  - Quantification of control behavior
  - Prediction of human-machine system performance

- **<u>Case 2:</u> Aircraft dynamics identification**
  - Verification of new aircraft designs
  - Advanced control systems
  - Flight simulation mathematical models

Lecture Structure

- Case 1: Pilot Control Dynamics Identification (*today*)
- Case 2: Aircraft Dynamics Identification (*next lecture*)
- General System Identification Experiment Considerations (*next lecture*)

Case 1:
Pilot Control Dynamics Identification

Background

Goals and Objectives

Goals/objectives of pilot control dynamics identification and modeling:

- **<u>Understand</u>** human behavior, e.g.:
  - Limitations
  - Cognitive processing
  - Sensory dynamics
  - Human performance!
  - Adaptation

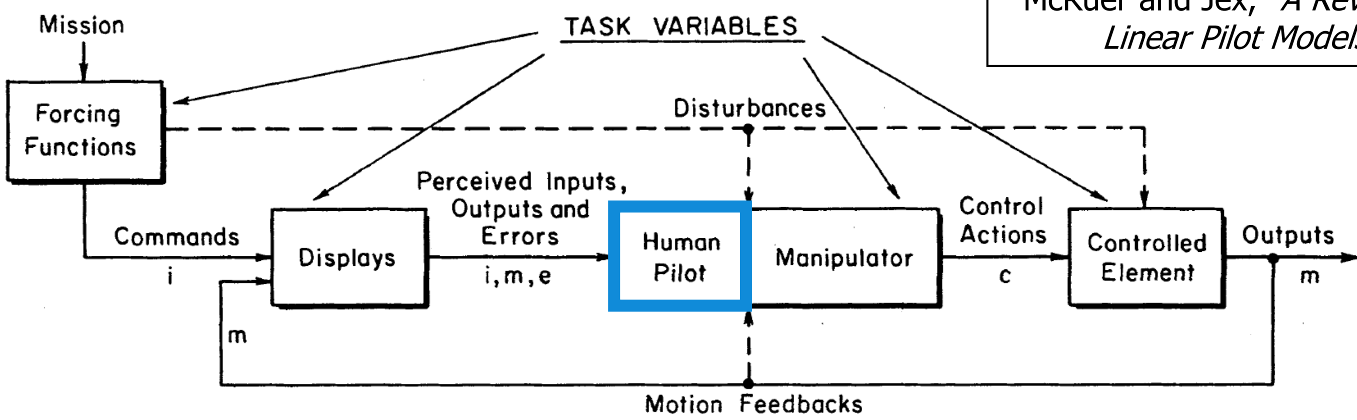
- **<u>Quantify</u>** human behavior, e.g.:
  - System evaluation (compare behavior)
  - System simulation (predict behavior)

*<u>There is no **one model** that can describe all pilot control behavior!</u>*

Prior Knowledge

Factors that affect pilot dynamics

McRuer and Jex, "*A Review of Quasi-Linear Pilot Models*", 1967



ENVIRONMENTAL VARIABLES:	OPERATOR-CENTERED VARIABLES:	PROCEDURAL VARIABLES:
In-Flight vs. Fixed-Base	Motivation	Instructions
Vibration	Stress	Practice
G-Level	Workload	Experimental Design
Temperature	Training	Order of Presentation
Atmospheric Conditions	Fatigue	Etc.
Etc.	Etc.	

Pilots' control dynamics during manual control are <u>highly adaptive</u> and dependent on a myriad of factors!

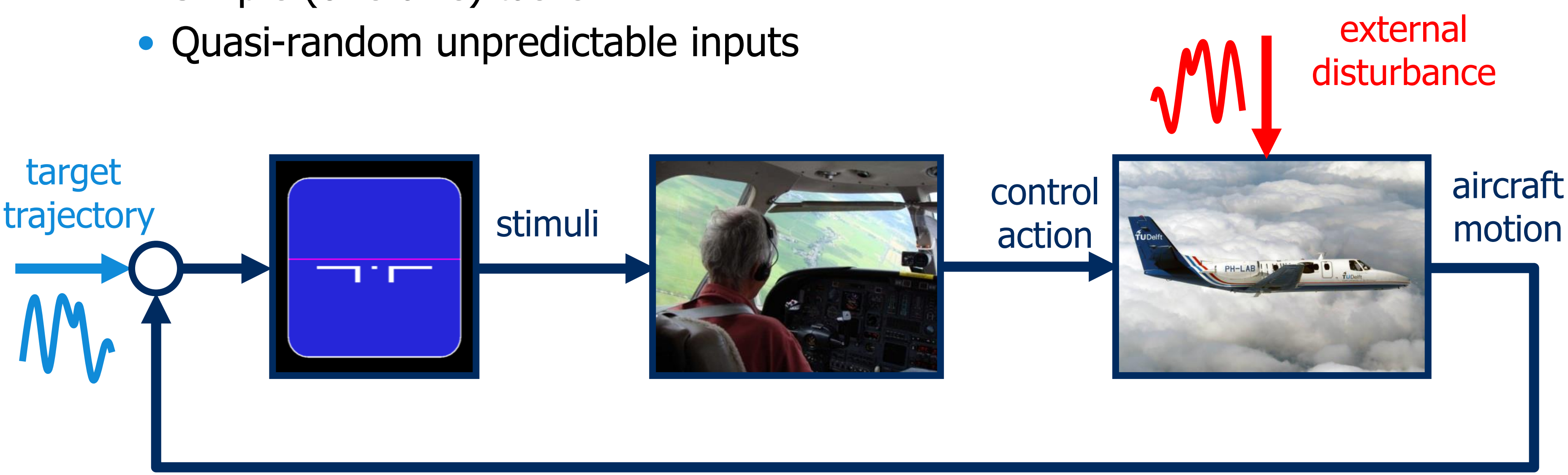
Prior Knowledge
Tracking Tasks

Pilot control behavior is adaptive, nonlinear, nonstationary, etc…

…and therefore extremely difficult to model and identify!

However, in **tracking tasks** it's sufficiently linear for system identification:

- Simple (one-axis) tasks
- Quasi-random unpredictable inputs



Prior Knowledge

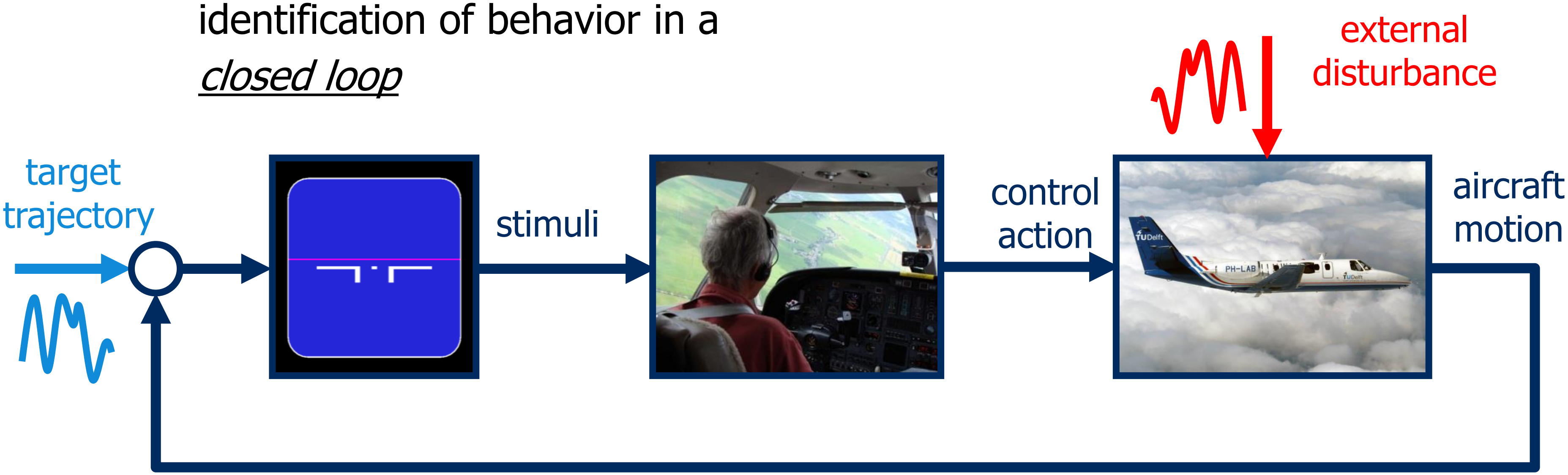
Forcing Functions

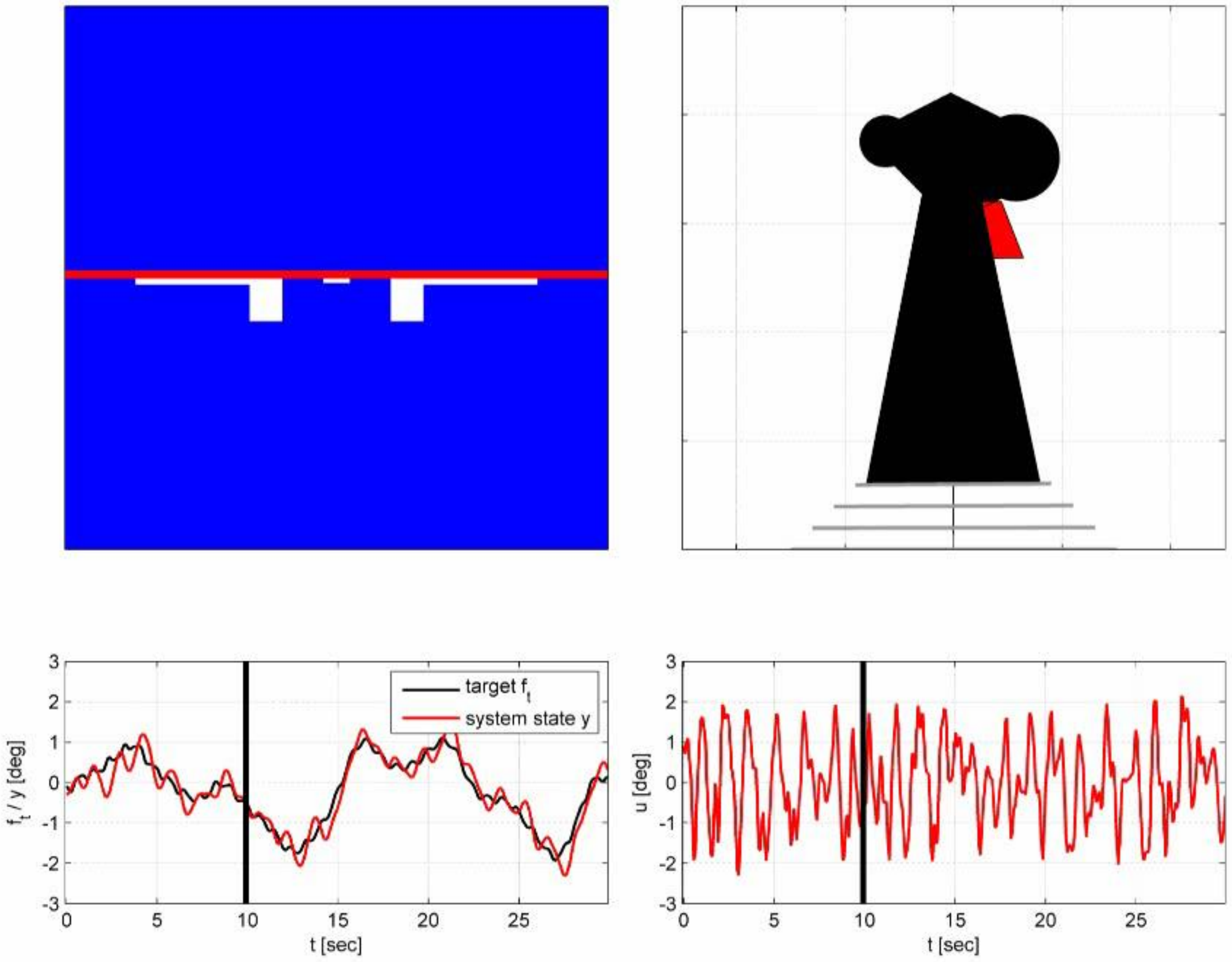
Forcing functions have <u>two important functions</u>:

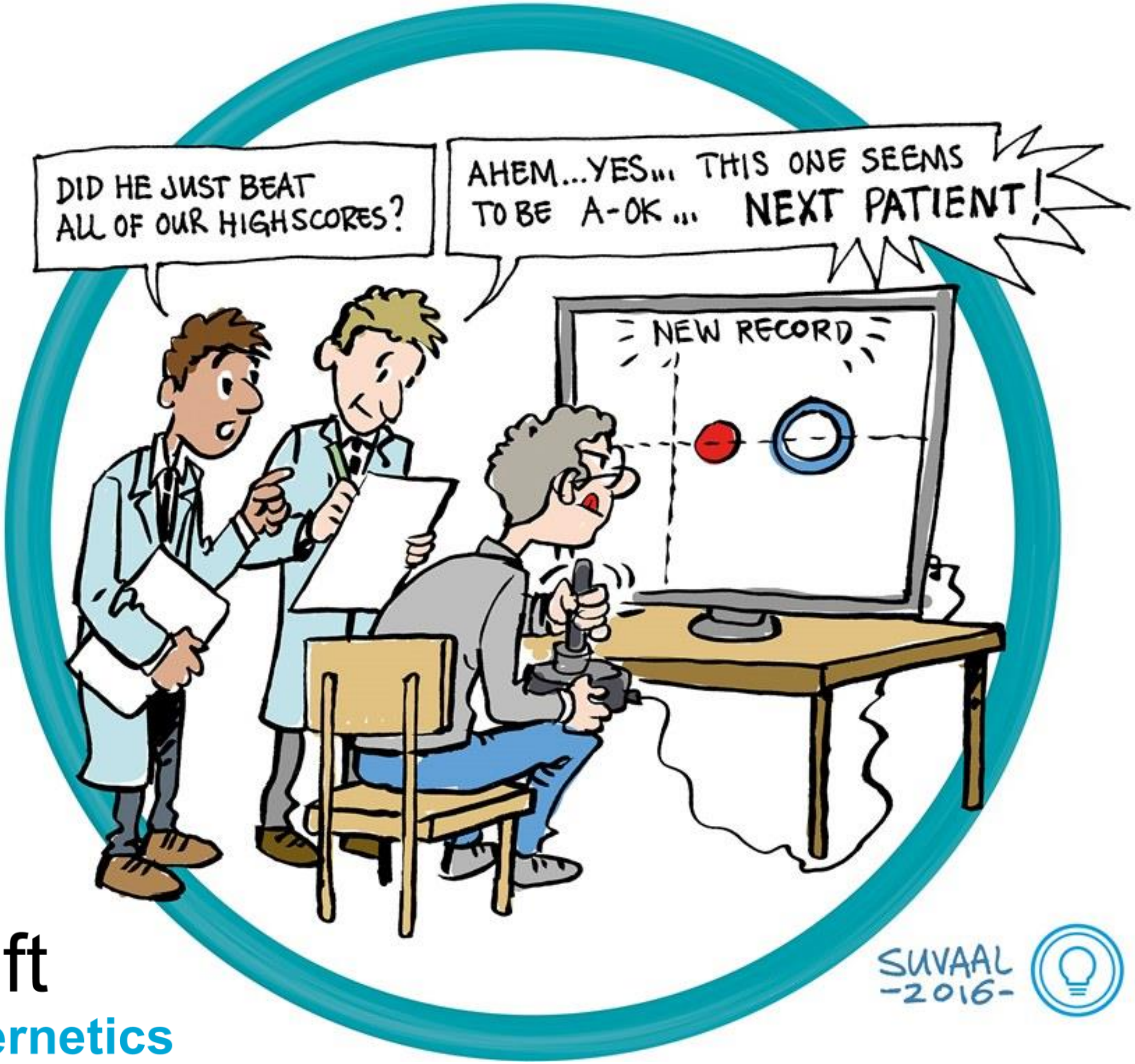
1. **Task definition**: induce the right kind of behavior
2. **Identification**: facilitate the identification of behavior in a <u>*closed loop*</u>

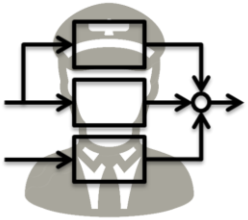
Typically applied forcing functions:

- Target (reference)
- Disturbance (turbulence)
- …




target f_t
system state y
f_t / y [deg]
t [sec]
u [deg]
t [sec]



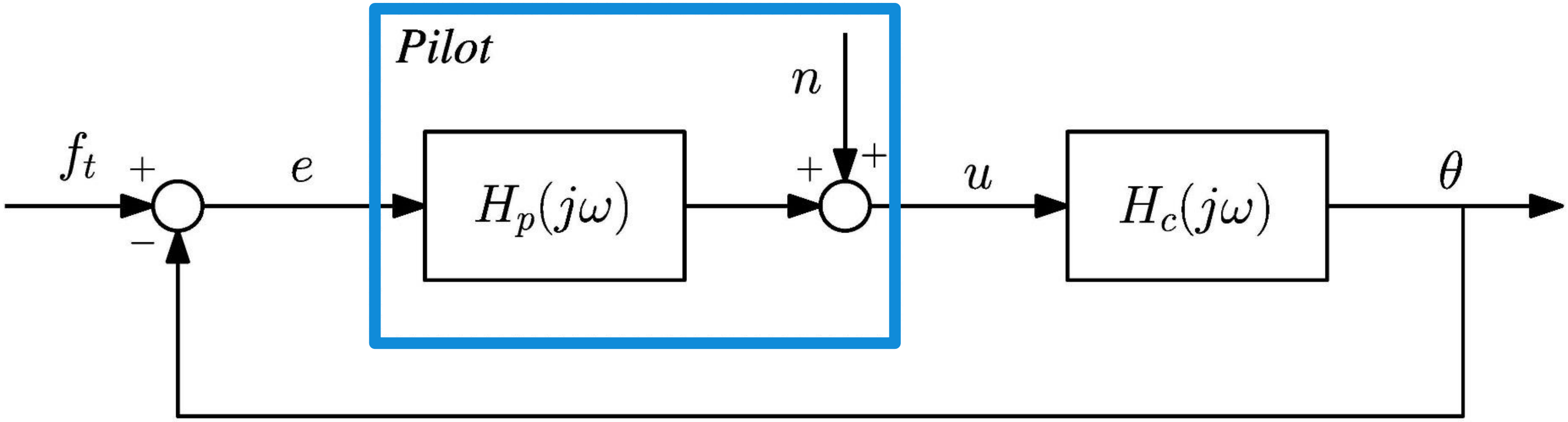


Delft
Cybernetics

http://cs.lr.tudelft.nl/cybernetics/

Prior Knowledge

Identification of Pilot Dynamics (1)

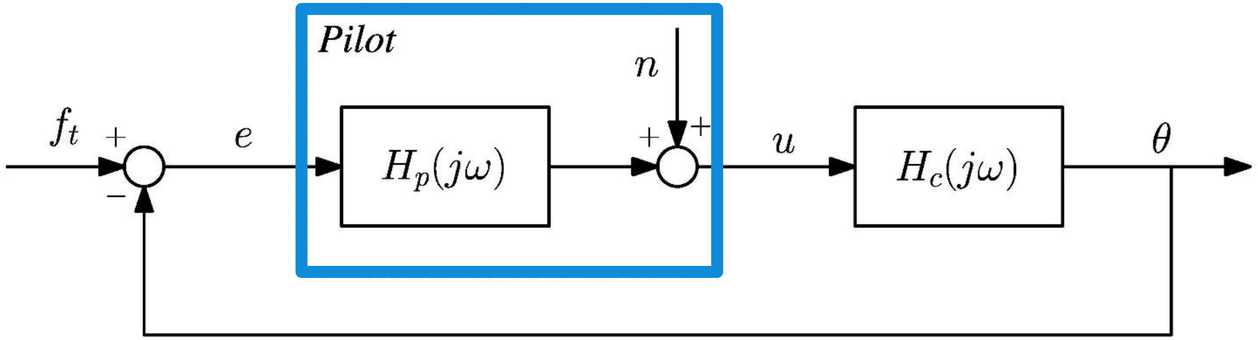


- The system we want to identify is in a **closed-loop**!
- Pilot control dynamics consist of **two parts**:
  - Correlated with forcing functions (linear)
  - Not correlated with forcing functions (nonlinear, instationary, e.g. remnant)
- **Solution**: the *instrumental variable method* and *multisine forcing function signals*

Prior Knowledge

Identification of Pilot Dynamics (2)

- From block diagram: $U(j\omega;\xi) = H_p(j\omega)E(j\omega;\xi) + N(j\omega;\xi)$
- Solving for $H_p(j\omega)$: $$H_p(j\omega) = \frac{U(j\omega;\xi)}{E(j\omega;\xi)} - \frac{N(j\omega;\xi)}{E(j\omega;\xi)}$$
- Instrumental variable approach: $$\hat{H}_p(j\omega_f) = \boxed{\frac{S_{u,f_t}(j\omega_f;\xi)}{S_{e,f_t}(j\omega_f;\xi)}}$$

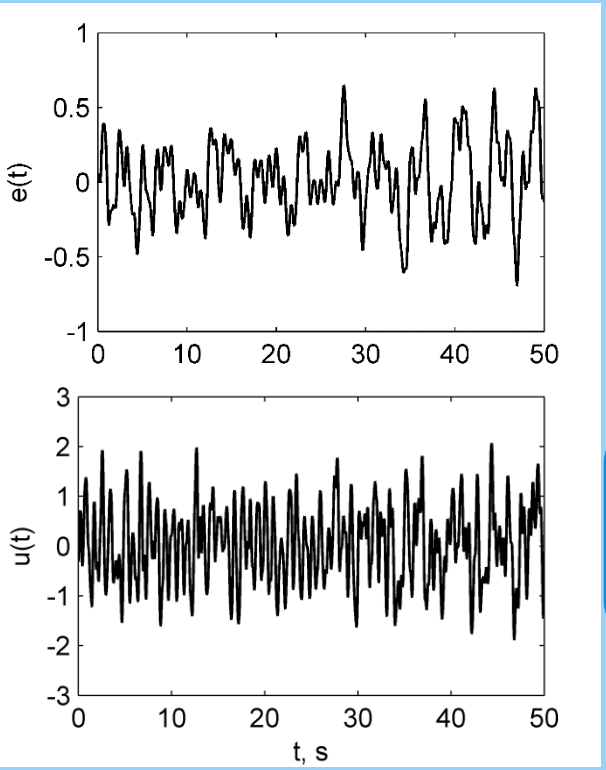


Use *cross power spectral densities* to isolate the response correlated with the forcing function(s)!

Prior Knowledge

Identification of Pilot Dynamics (3)

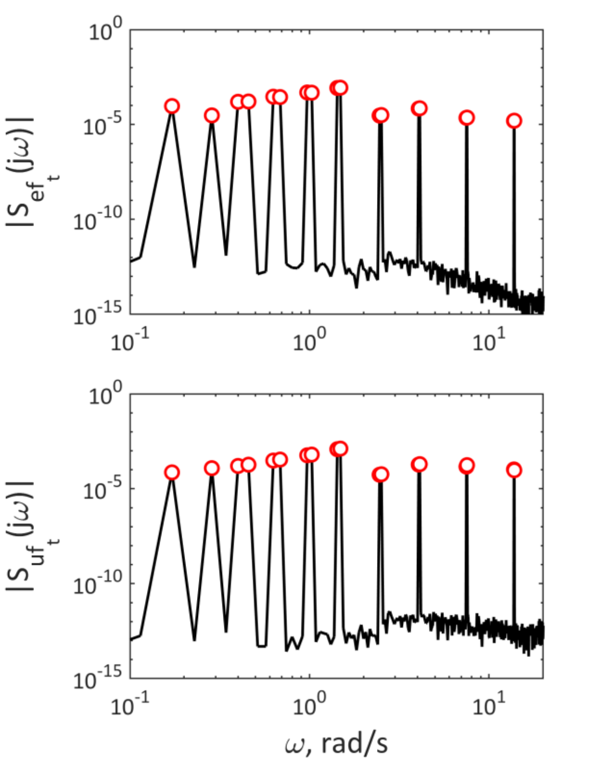
1: Measured time traces



Discrete Fourier Transform

$$S_{e,f_t} = \frac{1}{N} E\ F_t^* dt$$

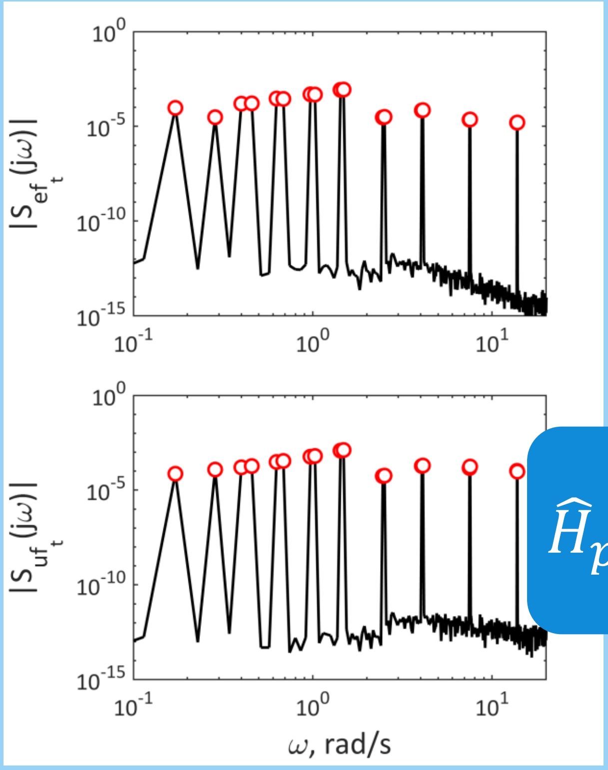
2: Spectra of time traces



Prior Knowledge

Identification of Pilot Dynamics (4)

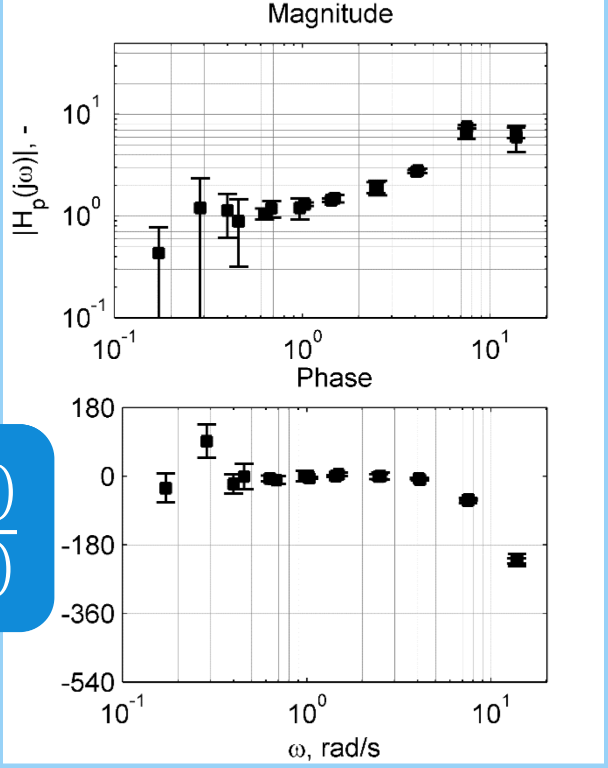
2: Spectra of time traces



Instrumental Variable Method

$$\hat{H}_p(j\omega_f) = \frac{S_{u,f_t}(j\omega_f)}{S_{e,f_t}(j\omega_f)}$$

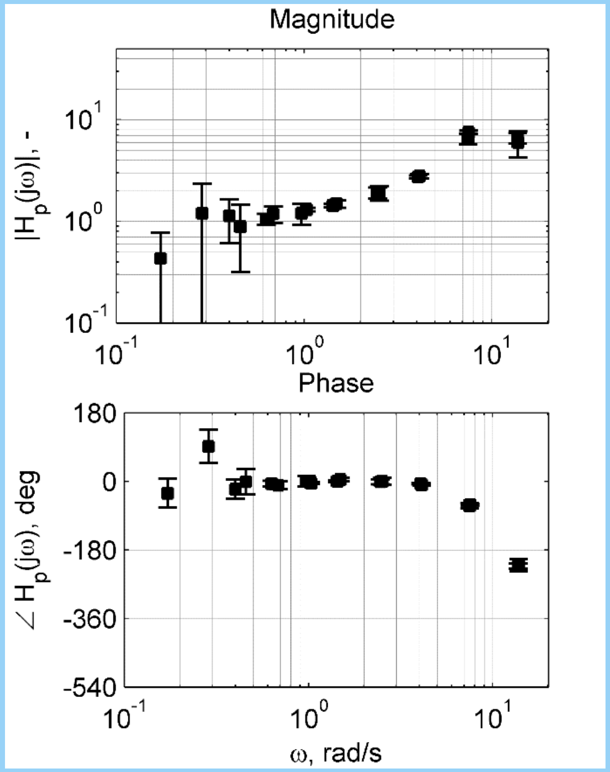
3: Estimated FRF



Prior Knowledge

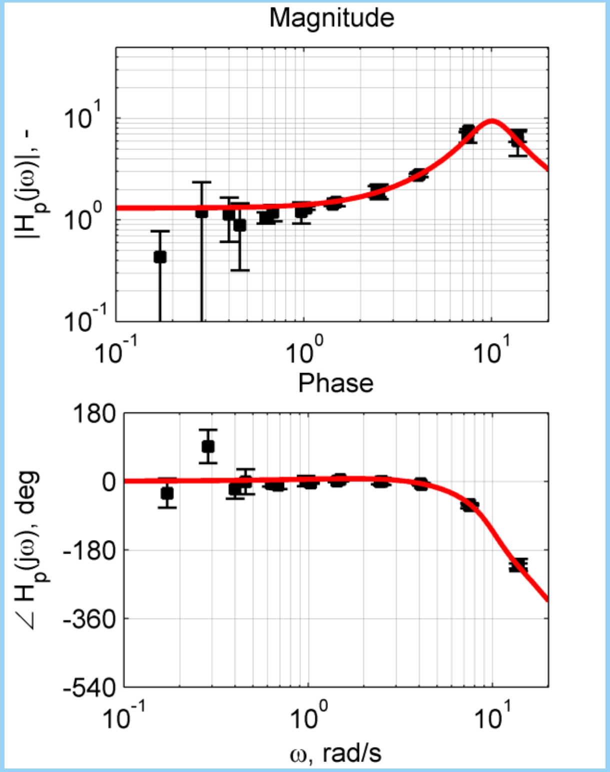
Identification of Pilot Dynamics (5)

3: Estimated FRF



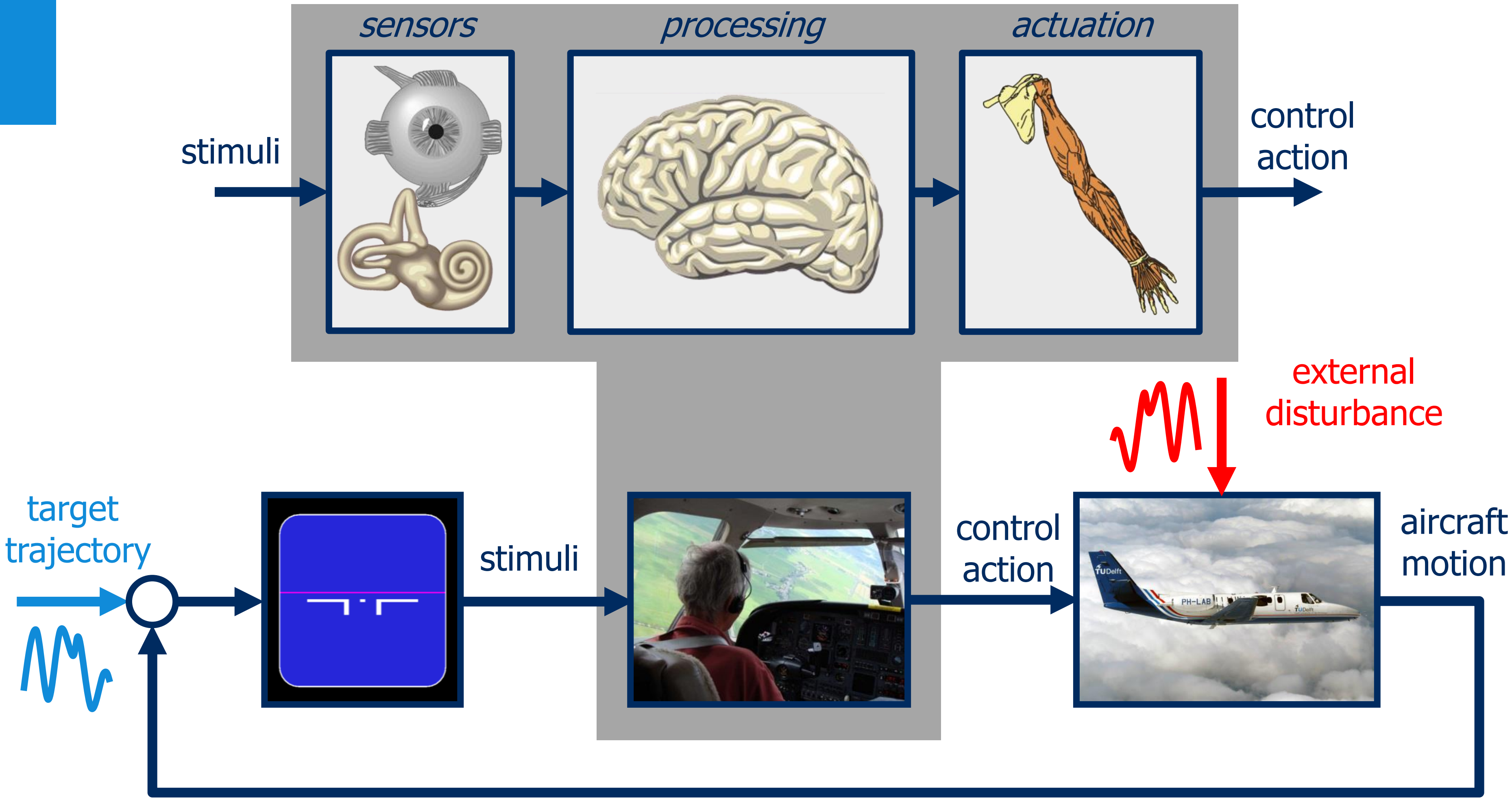
Model Selection & Parameter Estimation

4: Estimated Model



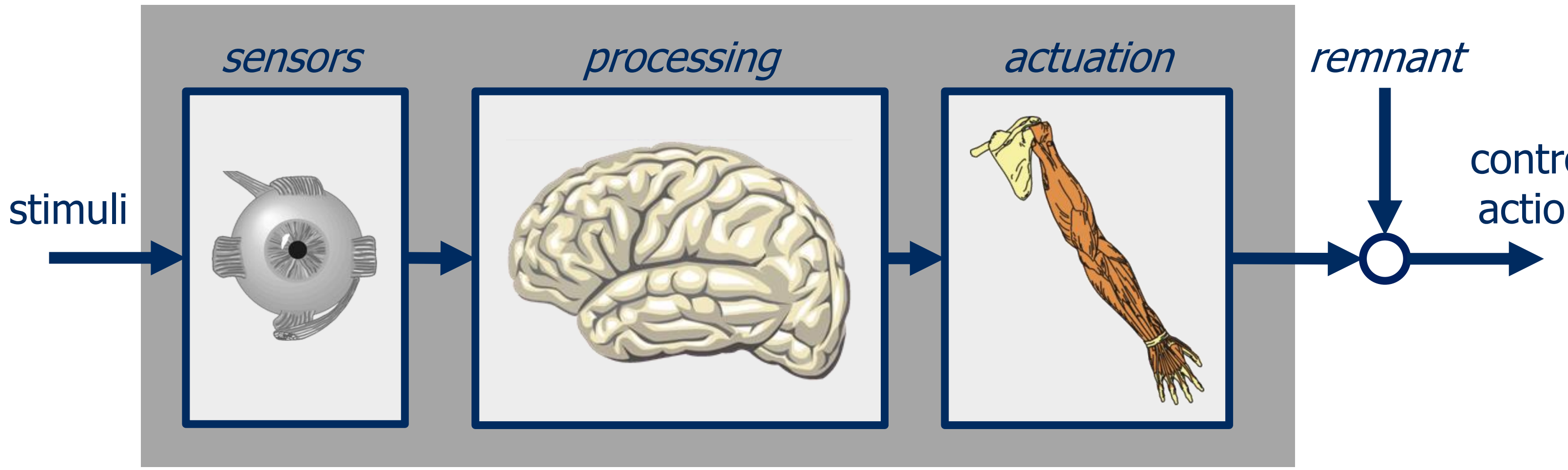
Prior Knowledge

Sensors, Processing, and Actuation



Prior Knowledge

Quasi-Linear Models of Pilot Dynamics

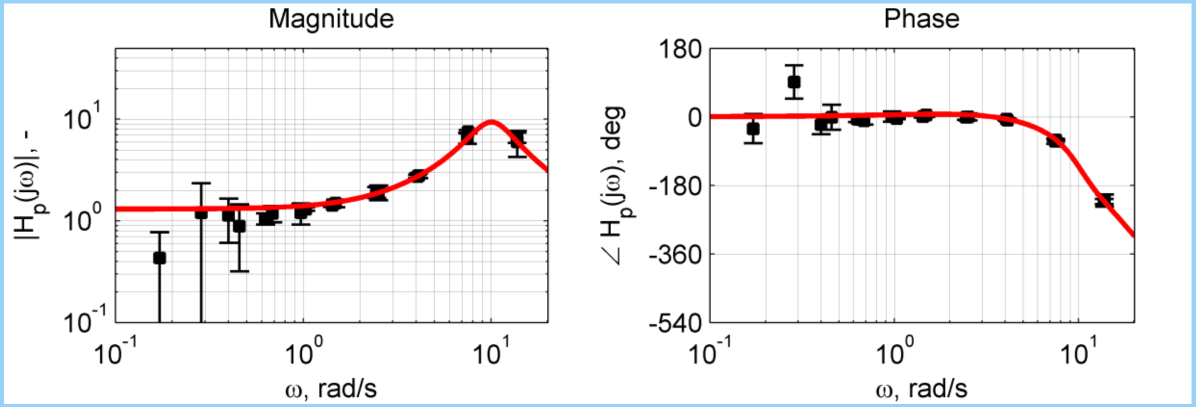


$$H_p(j\omega) = \underbrace{1}_{\textit{sensors}} \times \underbrace{K_p \frac{T_L j\omega + 1}{T_I j\omega + 1} e^{-j\omega\tau_p}}_{\textit{processing}} \times \underbrace{\frac{\omega_{nm}^2}{(j\omega)^2 + 2\xi_{nm}\omega_{nm} j\omega + \omega_{nm}^2}}_{\textit{actuation}}$$

Prior Knowledge

Quasi-Linear Models of Pilot Dynamics

4: Estimated Model



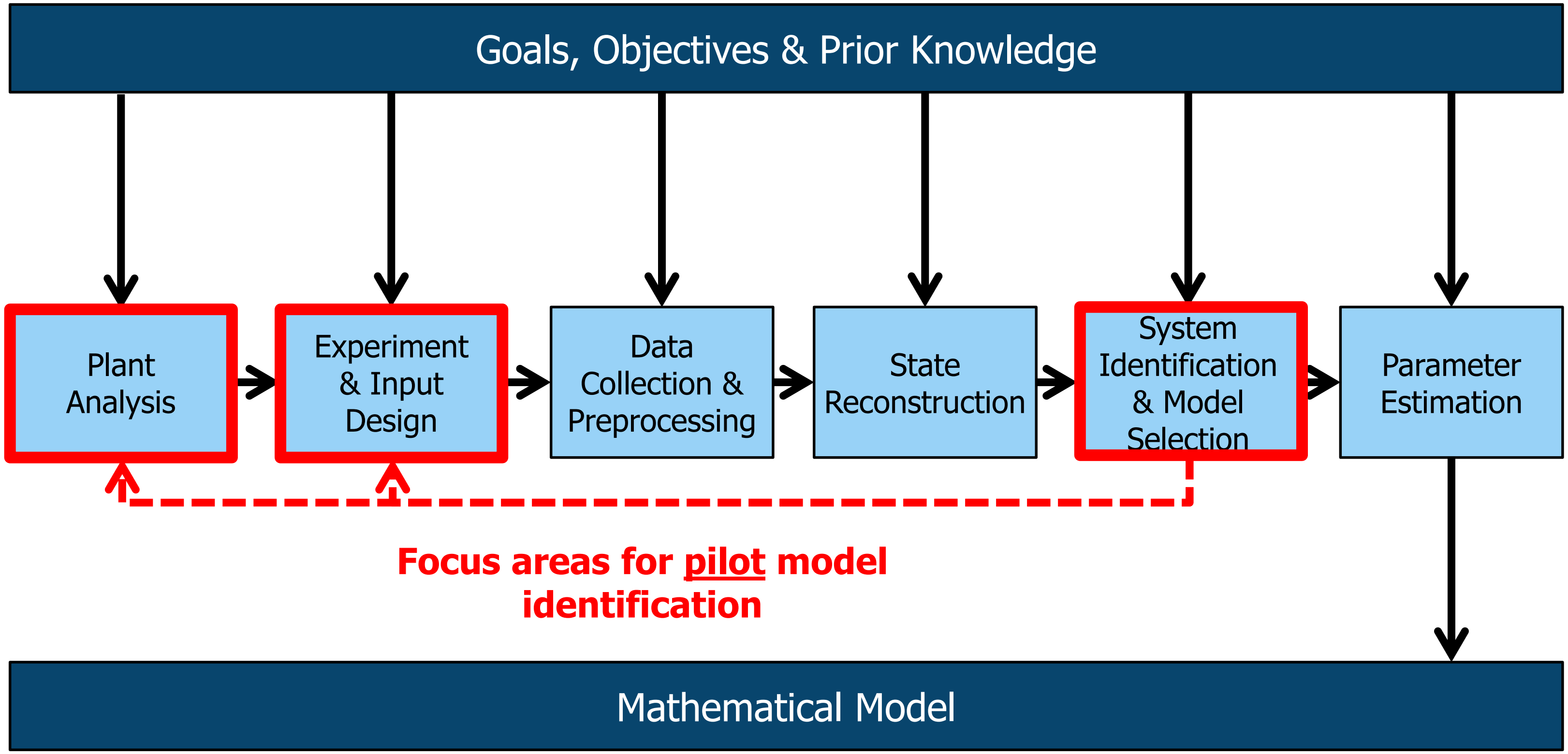
$$K_p = 1.3087$$
$$T_L = 0.3728\ s$$
$$T_I = 0.0\ s$$
$$\tau_p = 0.2054\ s$$
$$\omega_{nm} = 10.0961\ rad/s$$
$$\xi_{nm} = 0.2716$$

$$H_p(j\omega) = K_p \frac{T_L j\omega + 1}{T_I j\omega + 1} e^{-j\omega\tau_p} \frac{\omega_{nm}^2}{(j\omega)^2 + 2\xi_{nm}\omega_{nm} j\omega + \omega_{nm}^2}$$

Using such very simple quasi-linear models we can quantify pilots' control dynamics and typically explain between 70-95% of our measured signals!

The System Identification Problem

Pilot Control Dynamics Identification



Ljung's Questions


Lennart Ljung

1. Which signals are to be considered as **outputs** and which are to be considered as **inputs**? (*system definition*)

- ***Plant analysis***: *a first principles analysis of task and pilots' in- and outputs.*

2. Which signals should be manipulated (inputs) so as to **"excite" the system** during the experiment? (*system excitation/input design*)

- *Inputs that excite all relevant dynamics of the pilot, and induce the desired kind of behavior.*

3. **Where and what** to measure? (*measurement definition*)

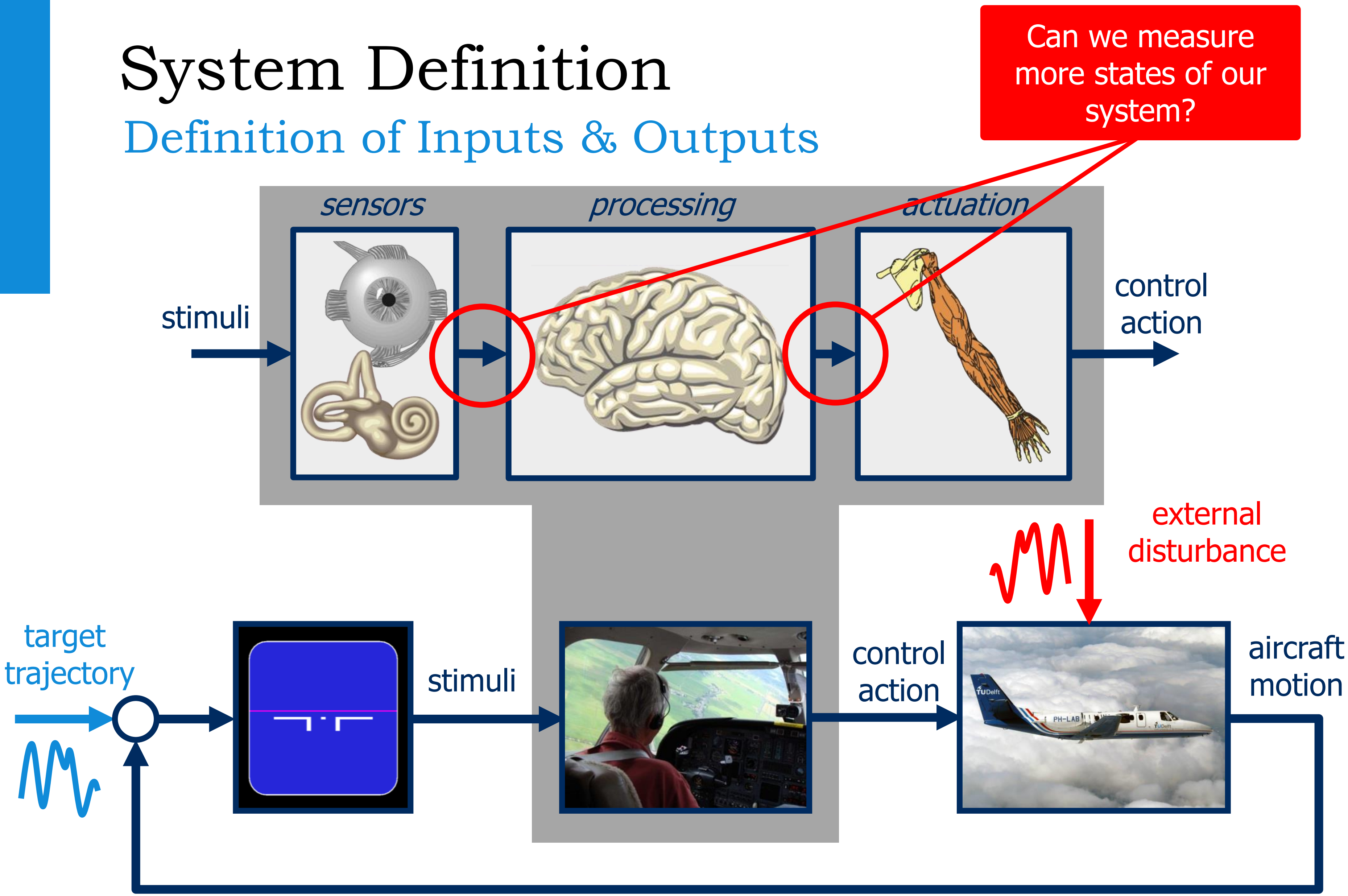
- *We need reliable and synchronized measurements of pilot in- and outputs.*

4. **When** to measure? (*experiment design*)

- ***Human subject experiment****, so we need a well thought-through experiment and a number of repeated measurements!*

System Definition

Definition of Inputs & Outputs

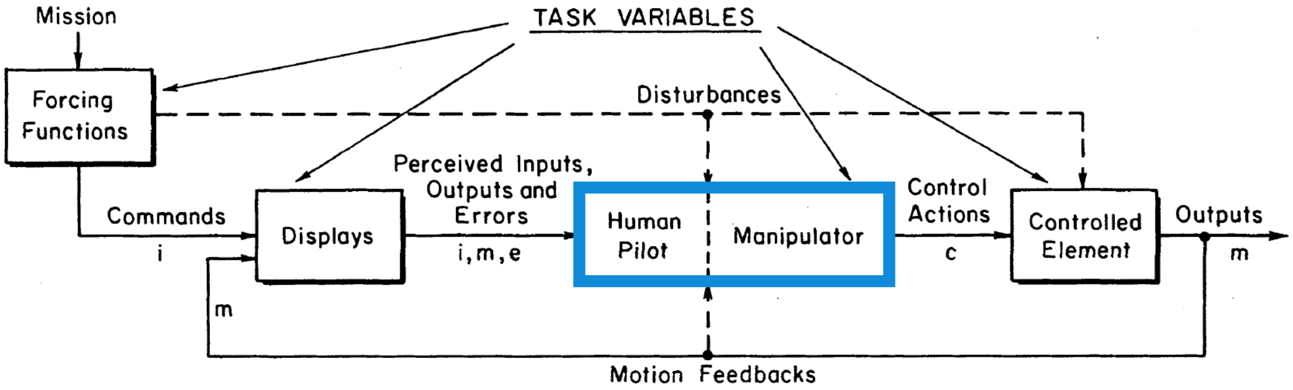


System Definition

Fun Fact

- Output of "pilot system" is the control action

- *<u>What about the manipulator (stick or steering wheel) dynamics?</u>*



System Definition

Plant Analysis

stimuli

control action

Processing ("equalization"):

- Highly task-dependent
  - Controlled system dynamics
  - Forcing function signals
- Highly pilot-dependent

$$H_p(j\omega) = K_p \frac{T_L j\omega + 1}{T_I j\omega + 1} e^{-j\omega\tau_p} \frac{\omega_{nm}^2}{(j\omega)^2 + 2\xi_{nm}\omega_{nm} j\omega + \omega_{nm}^2}$$

Time delay:

- Always there (pilot limitation)
- τ_p between 0.1 and 0.4 s

Neuromuscular dynamics:

- Always there (pilot limitation)
- ω_{nm} between 7 and 20 rad/s
- ξ_{nm} between 0.1 and 0.5

System Definition

Pilot Control Dynamics Identification

Our system definition: "Pilot"

Inputs/Outputs:

- Input(s): perceived stimuli
- Output(s): control action

Main system characteristics:

- Nonlinear, but considered quasi-linear for tracking tasks with quasi-random input signals
- No additional measurements of system states possible!
- Highly adaptable, and thus unknown, dynamics
- Not a true stationary system: remnant!

Input Design

Forcing Function Signals

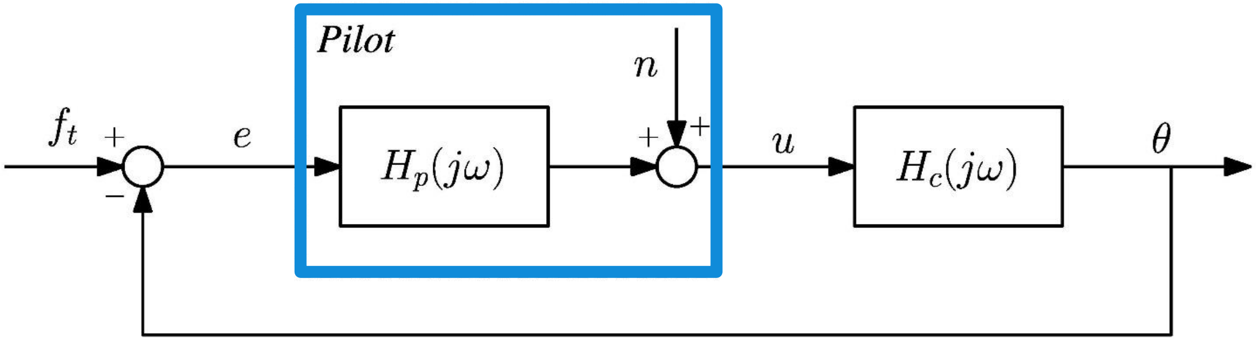

Werner Heisenberg

"Science no longer is in the position of observer of nature, but rather recognizes itself as part of the interplay between man and nature. The scientific method [...] changes and transforms its object: the procedure can no longer keep its distance from the object."

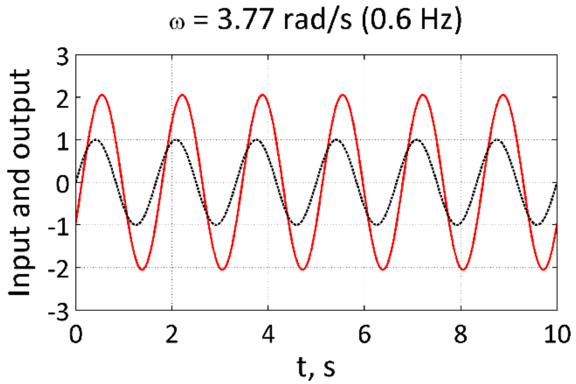
Werner Heisenberg, "*The Representation of Nature in Contemporary Physics*", 1958

This is especially true for the design of forcing function signals:

- The characteristics of the applied forcing functions change the dynamics of the system we want to identify (the pilot)
- So, input design becomes crucially important to your results!



Input Design
Multisine Signals



- Used **VERY OFTEN** for measuring a system's stationary (homogeneous) response: sinusoidal inputs
- Using single-sine inputs is not convenient, especially if you want to know your system's dynamics over a wide frequency range
- Solution: multi-sine input signals: $f(t) = \sum_{k=1}^{N_f} A_f[k] \sin(\omega_f[k] t + \phi_f[k])$
- Completely deterministic, but still random appearing!
- Select sinusoid frequencies, amplitudes, and phases for proper excitation/induced behavior

Input Design

$$f(t) = \sum_{k=1}^{N_f} A_f[k] \sin(\boxed{\omega_f[k]} t + \phi_f[k])$$

Multisine Signals: Frequencies (1)

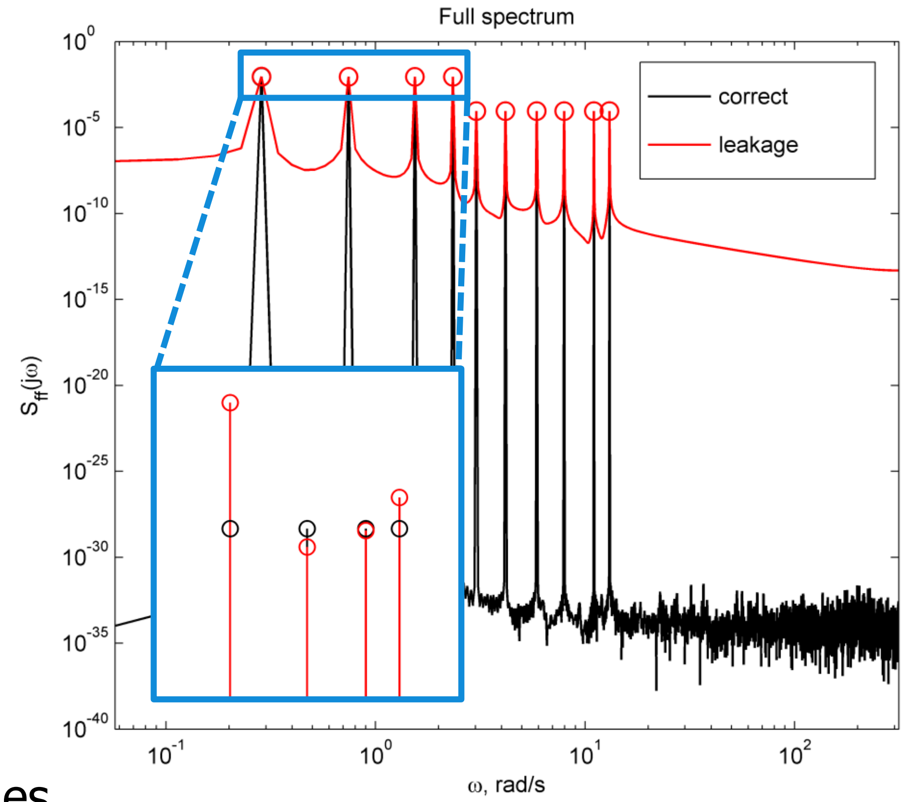
- Measurement length: T_m
- Measurement base frequency:

$$\omega_m = \frac{2\pi}{T_m}$$

- Sinusoid frequencies:

$$\omega_f[k] = n_f[k]\omega_m$$

- **Leakage** occurs when, e.g.:
  - Too many/too few data points
  - Rounded-off sinusoid frequencies



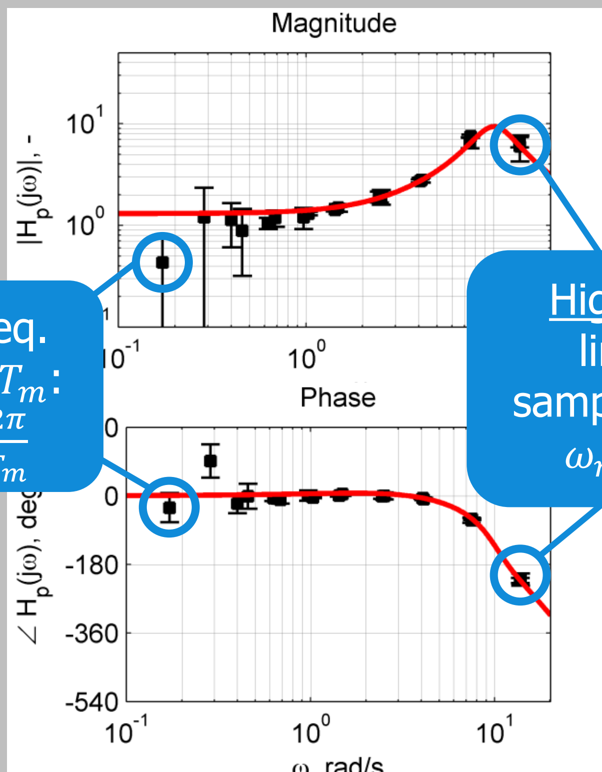
- Leakage causes bias in identification results!

Input Design

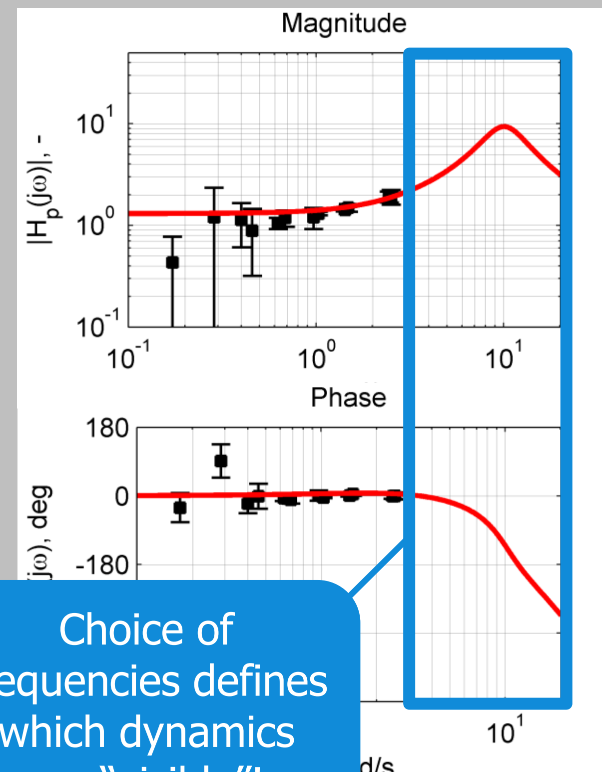
Multisine Signals: Frequencies (2)

$$f(t) = \sum_{k=1}^{N_f} A_f[k] \sin(\boxed{\omega_f[k]}\, t + \phi_f[k])$$

Frequency range: 0.1-15 rad/s



*Frequency range: 0.1-**3** rad/s*



<u>Lowest</u> freq. limited by T_m:

$$\omega_{min} = \frac{2\pi}{T_m}$$

<u>Highest</u> freq. limited by sampling rate f_s:

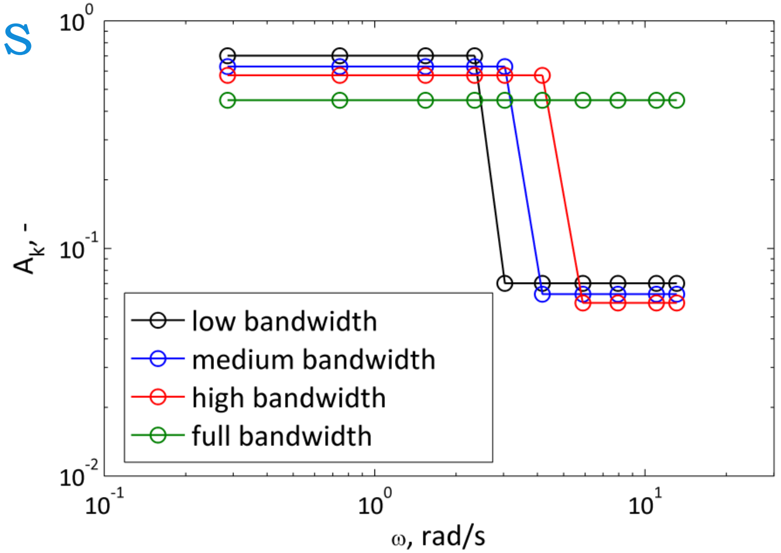
$$\omega_{max} = \pi f_s$$

Choice of frequencies defines which dynamics are “visible”!

Input Design

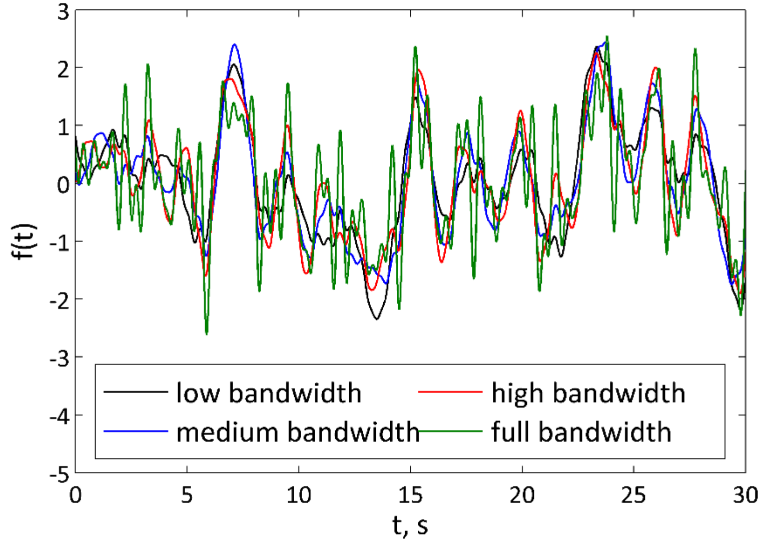
Multisine Signals: Amplitudes

$$f(t) = \sum_{k=1}^{N_f} \boxed{A_f[k]} \sin(\omega_f[k]t + \phi_f[k])$$



Signal amplitudes:

- Visibility of signal components
- Realism of task
- Signal-to-noise ratio in data!



Signal amplitude distribution:

- Bandwidth: frequency until where the signal has high power
- Realism of task
- High bandwidth = difficult signal!

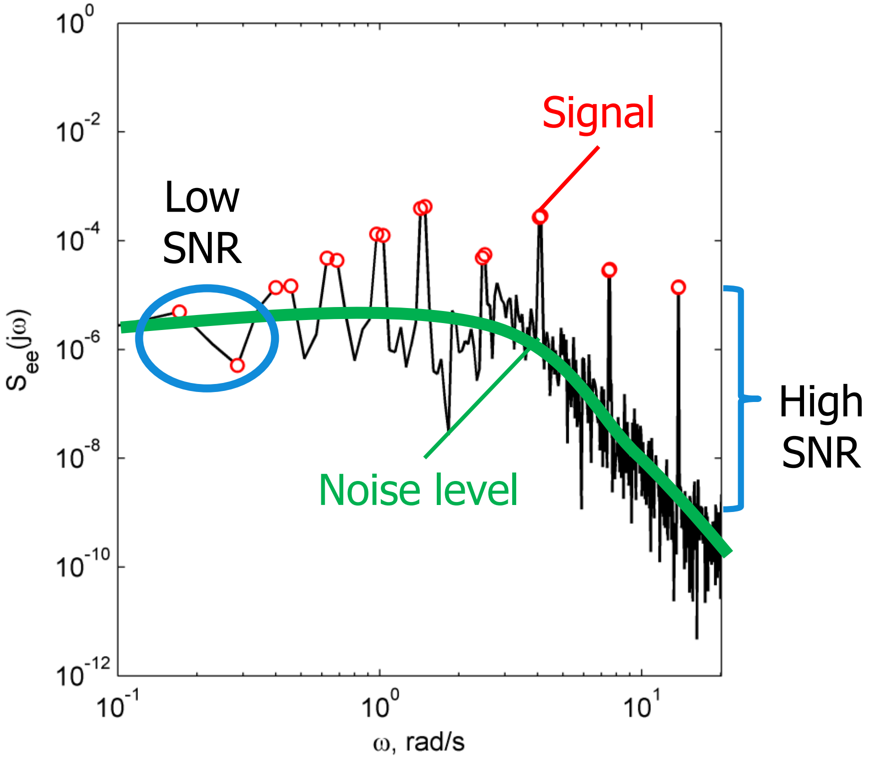
Choices in signal amplitudes will affect the measured behavior!

Input Design

Multisine Signals: Amplitudes

$$f(t) = \sum_{k=1}^{N_f} \boxed{A_f[k]} \sin(\omega_f[k]t + \phi_f[k])$$

- Signal-to-noise ratio (SNR)
- We want <u>high SNRs</u>, as then our instrumental variable method is accurate
- SNR can (to some extent) be controlled by:
  - Overall signal amplitude
  - Shape of amplitude distribution



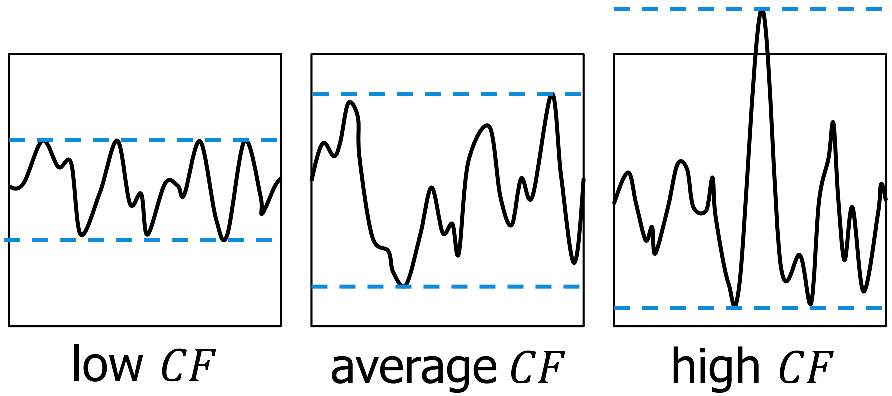
Input Design

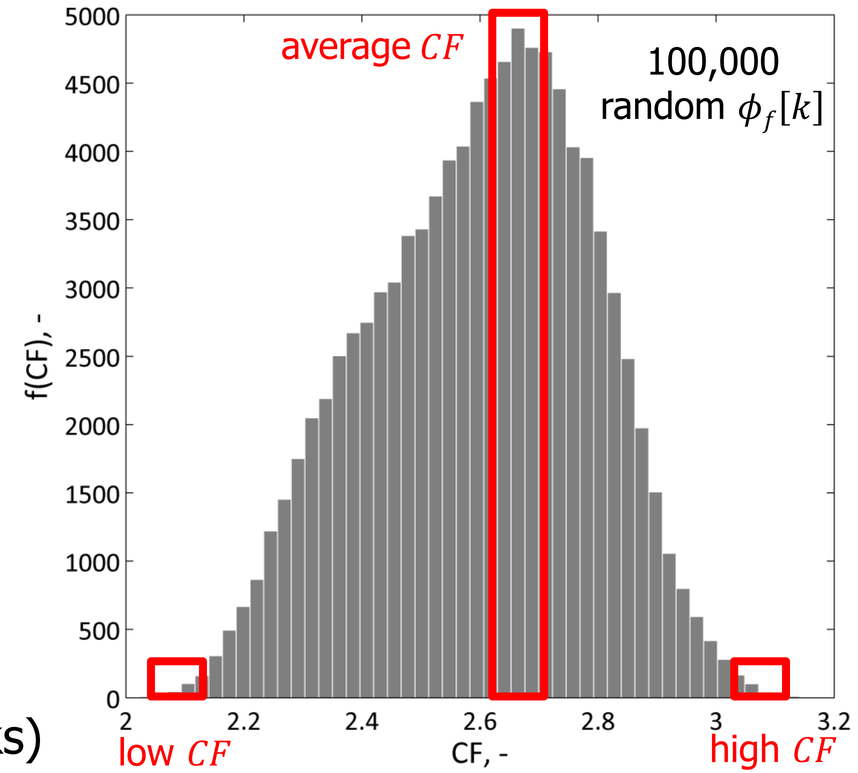
Multisine Signals: Phases

$$f(t) = \sum_{k=1}^{N_f} A_f[k] \sin(\omega_f[k]t + \boxed{\phi_f[k]})$$

$$CF(f(t)) = \frac{max(f(t))}{rms(f(t))}$$

- Sinusoid phases define appearance of the signal, e.g. crest factor CF

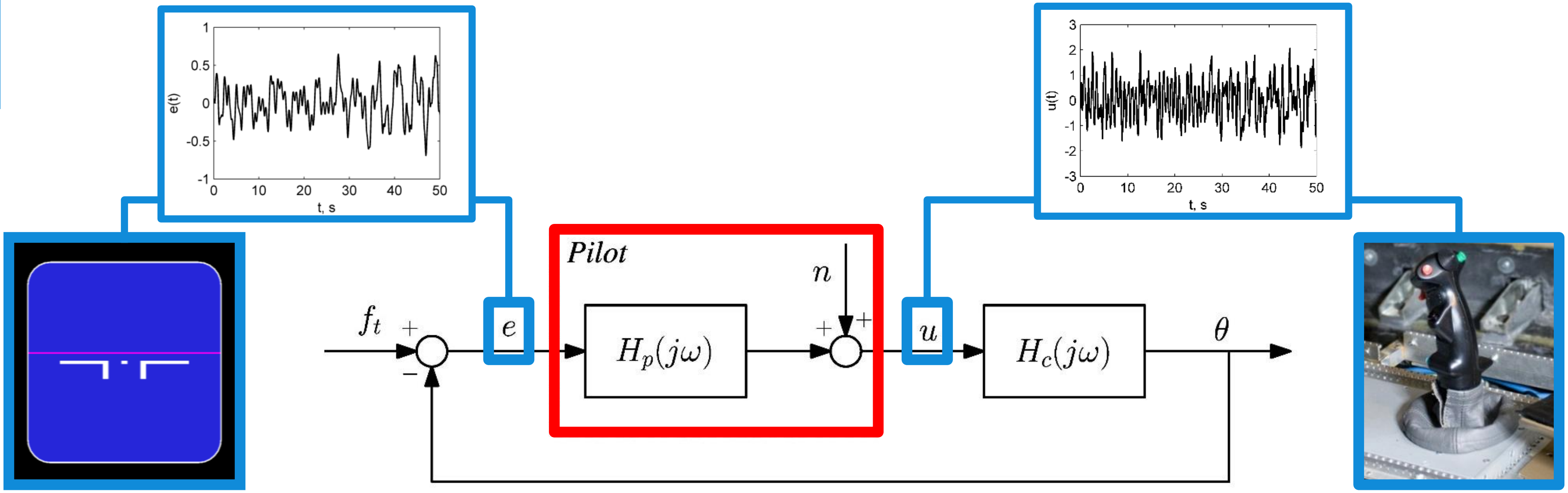




- Aim at average crest factor:
  - Not predictable
  - Stationary behavior (no big peaks)

Measurement Definition

Measured Signals



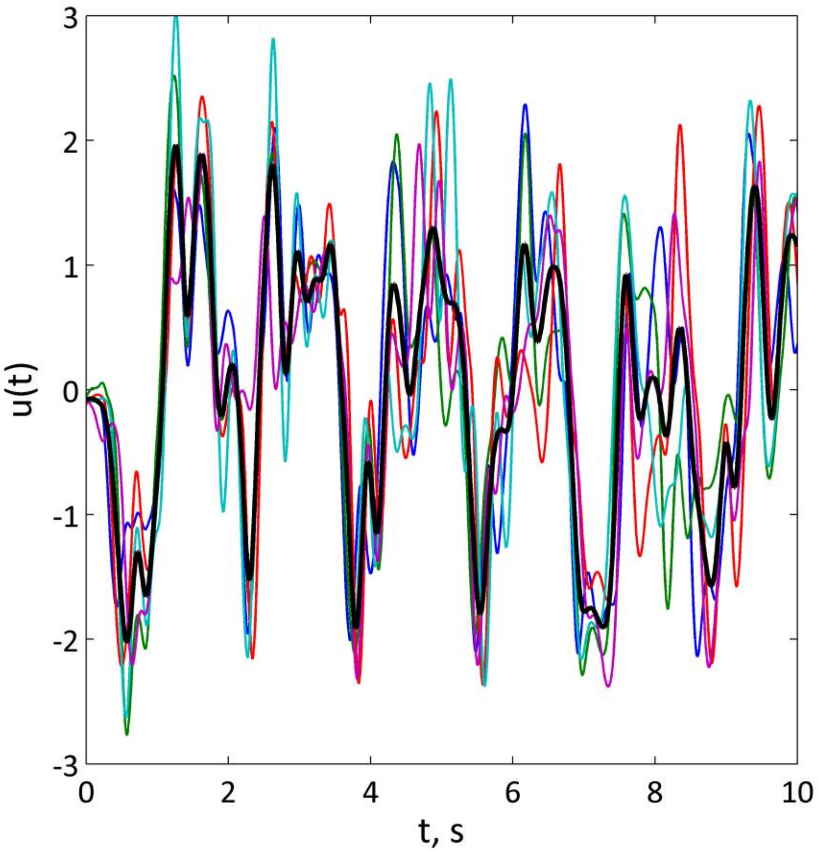
- Typical measurement settings:
  - 100 s
  - 100 Hz

  } 10,000 data points per measurement
- Crucial: <u>delays and lags</u> of input/output measurements!

Measurement Definition

Repetitions and Averaging

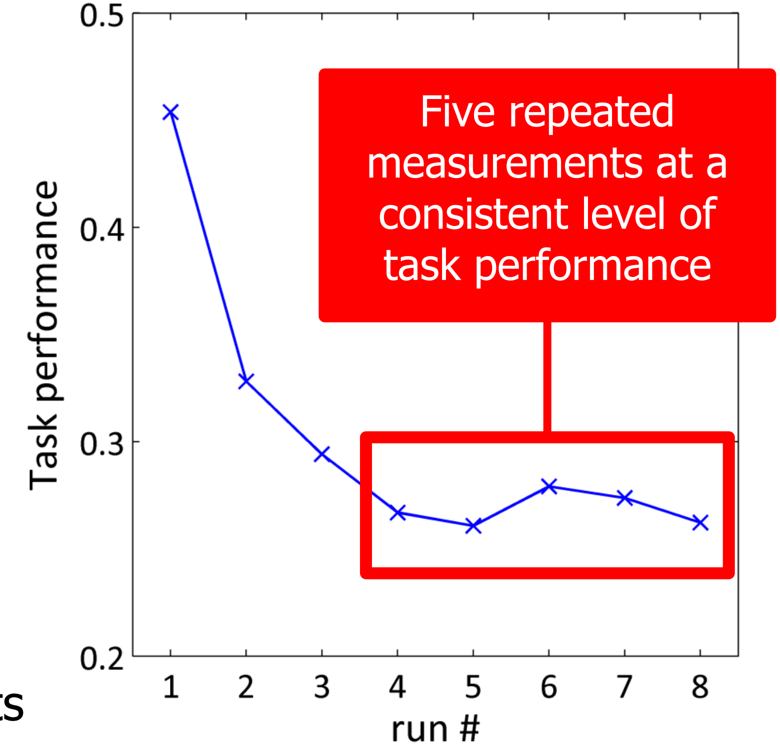
- Reduce effects of remnant: collect multiple measurements
- Allows for checking the linearity of the pilot's control behavior
- Averaging of:
  - Time traces (time domain)
  - FRFs (frequency domain)



Measurement Definition

Training and Measurement Phases

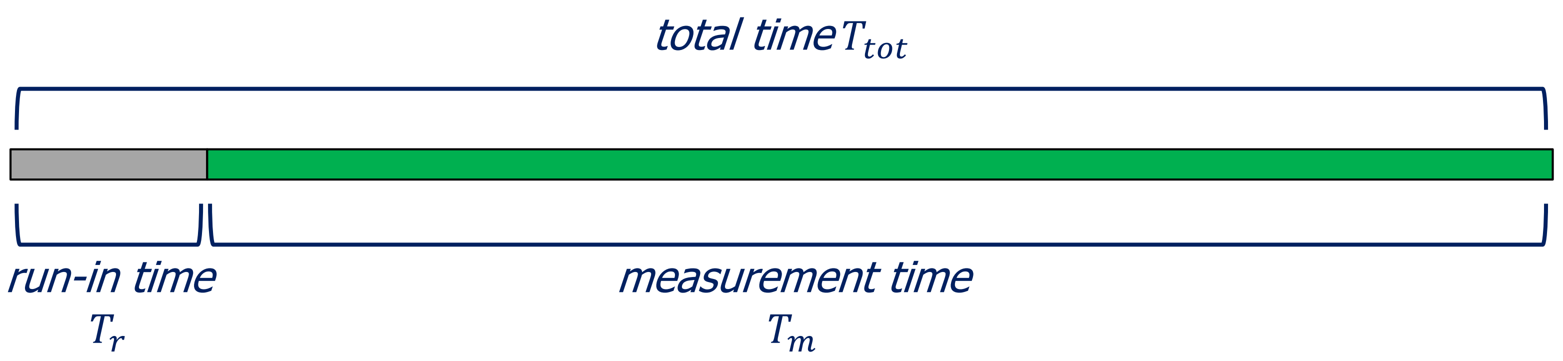
- Pilots need **<u>time</u>** to:
  - Familiarize themselves with a new control task
  - Find their “optimal” control dynamics and performance
- We need a **<u>training phase</u>** in which we train pilots to an asymptotic level of task performance
- Continue measuring until we have our desired number of repeated measurements
- Watch for fatigue/boredom!



Measurement Definition

Measurement Window

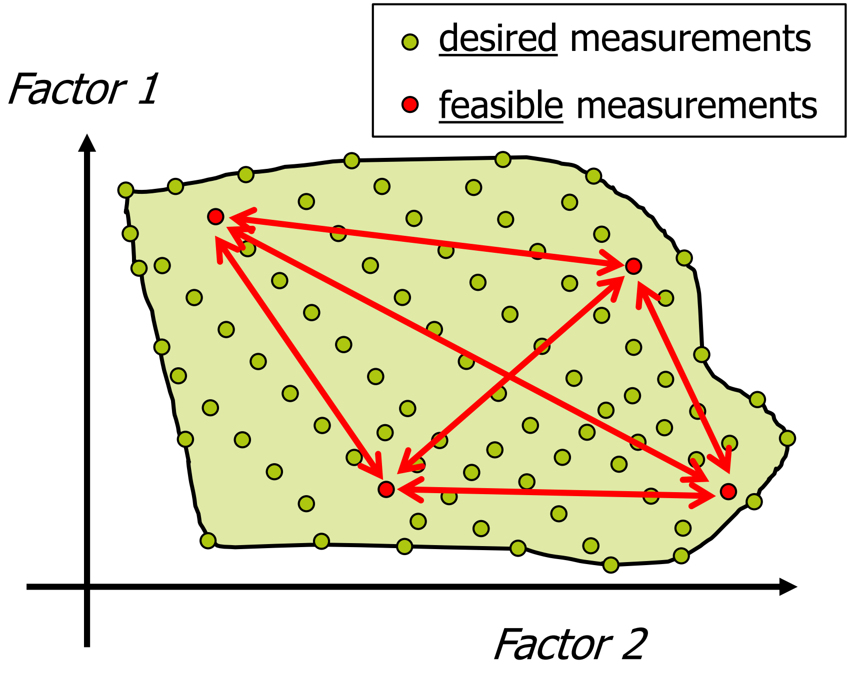
- We design our multisine signals to be periodic over a certain measurement window T_m
- We want a measurement of the pilot's control dynamics <u>in a stationary state</u> over this measurement window
- When starting a measurement run: transients in the pilot's response!
- So, we add a certain **<u>run-in time</u>** T_r to our measurement (~10 s)
- The run-in time data is discarded and not used for any analysis



Experiment Design

Conditions and Testing

- Typically we want to know pilots' adaptation to multiple factors
- Limited number of test points feasible, so <u>limited model validity</u>!
- Pilots are not machines, so we need to take care of <u>order effects</u>!
  - Training (*continued*)
  - Fatigue
  - Boredom
- <u>Balanced</u> experiment designs!



subject	session I					session II				
1	NM5	NM4	M2	M5	NM2	NM1	NM3	M3	M4	M1
2	NM4	M5	NM5	NM1	M2	M3	NM2	M1	NM3	M4
3	M5	NM1	NM4	M3	NM5	M1	M2	M4	NM2	NM3
4	NM1	M3	M5	M1	NM4	M4	NM5	NM3	M2	NM2
5	M3	M1	NM1	M4	M5	NM3	NM4	NM2	NM5	M2
6	M1	M4	M3	NM3	NM1	NM2	M5	M2	NM4	NM5
7	M4	NM3	M1	NM2	M3	M2	NM1	NM5	M5	NM4
8	NM3	NM2	M4	M2	M1	NM5	M3	NM4	NM1	M5
9	NM2	M2	NM3	NM5	M4	NM4	M1	M5	M3	NM1
10	M2	NM5	NM2	NM4	NM3	M5	M4	NM1	M1	M3

Experiment Design

Planning and Execution

- Typical experiment:
  - 8 conditions
  - 8+ subjects
  - 10+ repeated runs
- A lot of data sets are recorded, and not all are useful!
- Be organized:
  - Experiment logbook
  - Logging software

Run table 5 of 10

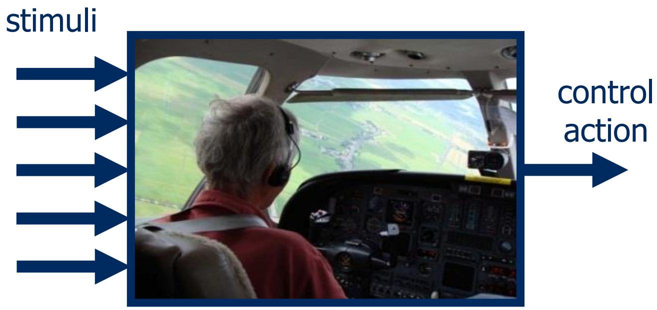
Date:	25-03-2013
Start time:	11:46
End time:	12:10

	Run #	Dynamics	Motion	Comments
	55	CarYawLat	OFF	
	56	CarYawLat	OFF	
	57	CarYawLat	OFF	"had het idee dat ik voor geen meter ging..."
	59	CarYawLat	OFF	
	60	CarYawLat	OFF	
X	61	CarYawLat	OFF	Lage control activity, slechte score
	62	CarYawLat	OFF	
	63	CarYawLat	OFF	
	64	CarYawLat	OFF	
	65	CarYawLat	OFF	hele lage score en stuuractiviteit
	66	CarYawLat	OFF	
	[illegible]	CarYawLat	OFF	
		CarYawLat	OFF	

grote stap in control activity, onhandig ☺

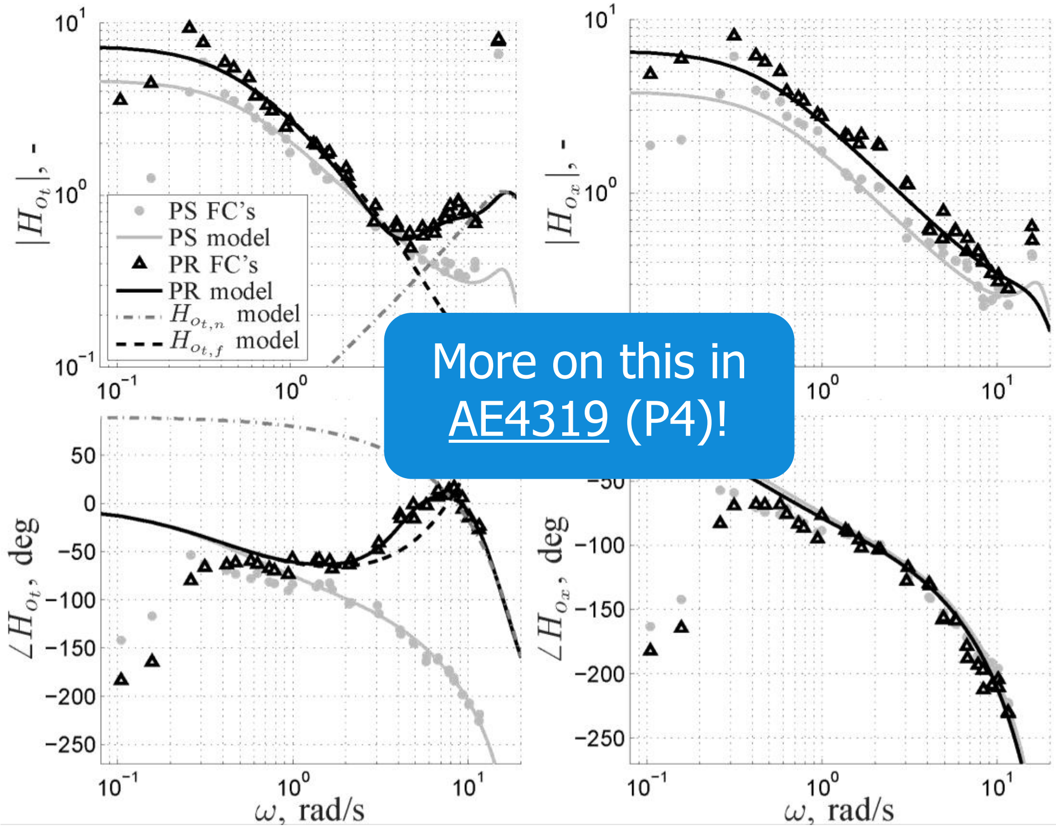
Current Trends

More "Realistic" Control Tasks



- More inputs to the pilot:
  - Pursuit displays
  - Preview
  - Outside visual scene
  - Motion feedback
  - Multiple axes

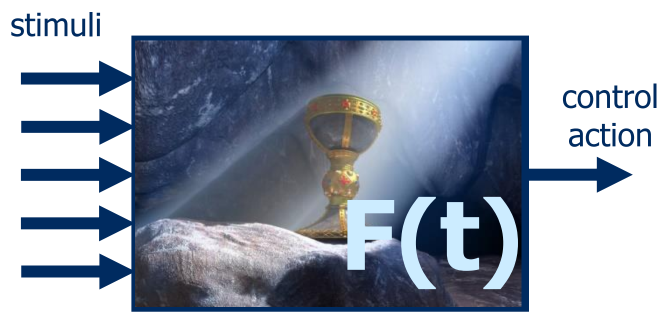
- More "realistic" tasks/inputs
  - Ramp tracking
  - Decrab
  - Helicopter sidestep

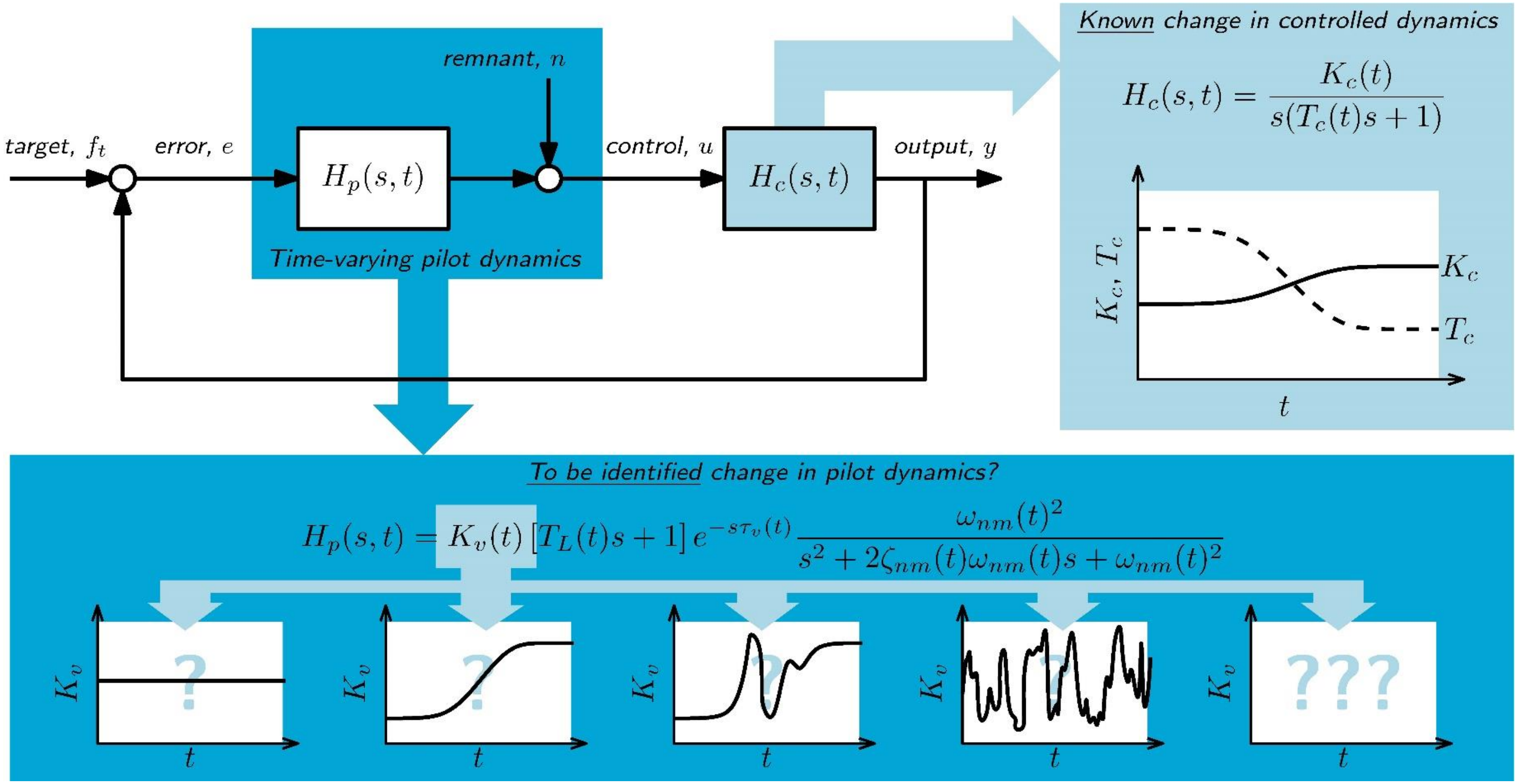


More on this in AE4319 (P4)!

Current Trends

Time-Varying Pilot Identification





*Methods currently tested (**MSc. projects!**):* Recursive LS, Kalman Filters, LPV models

Summary

Pilot Control Dynamics Identification

- ✓ For simple tasks: quasi-linear models
- ✓ Pilot dynamics are not known beforehand, so we need "black box" identification inputs (multisines)
- ✓ Excitation signals also directly affect the dynamics of the system we are identifying
- ✓ Repeated measurements to remove as much "nonlinear" control contributions as possible
- ✓ Take care of order effects in experiment design

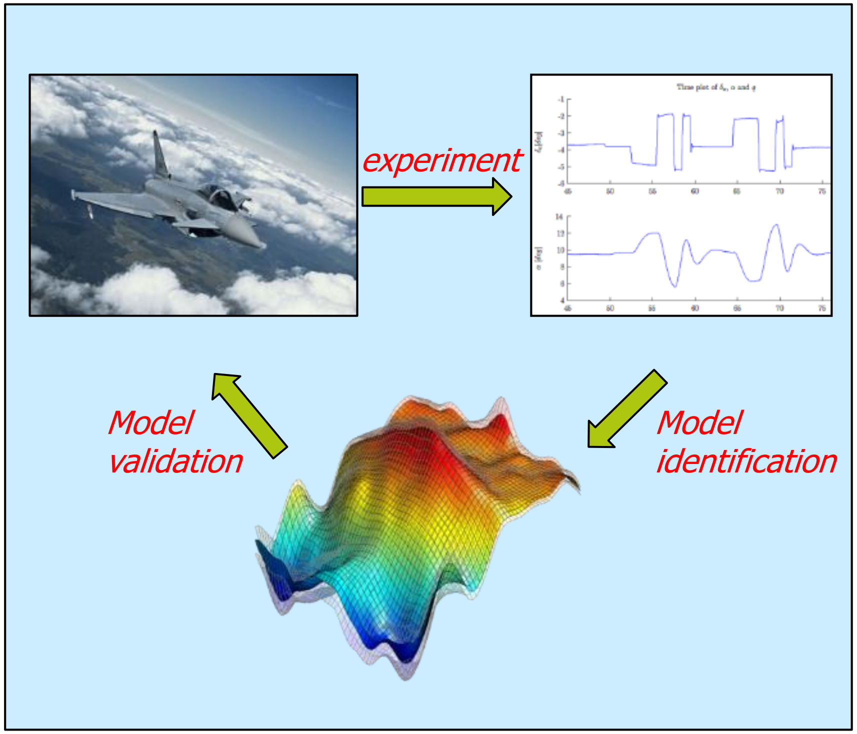
SysID High Level Overview

Where we are now in the System Identification Cycle:

Experiment phase
- Plant analysis
- Experiment design and execution
- Data logging and pre-processing

Model identification phase
- State estimation
- Model structure definition
- Parameter estimation

Model validation phase
- Model validation



Lecture Structure

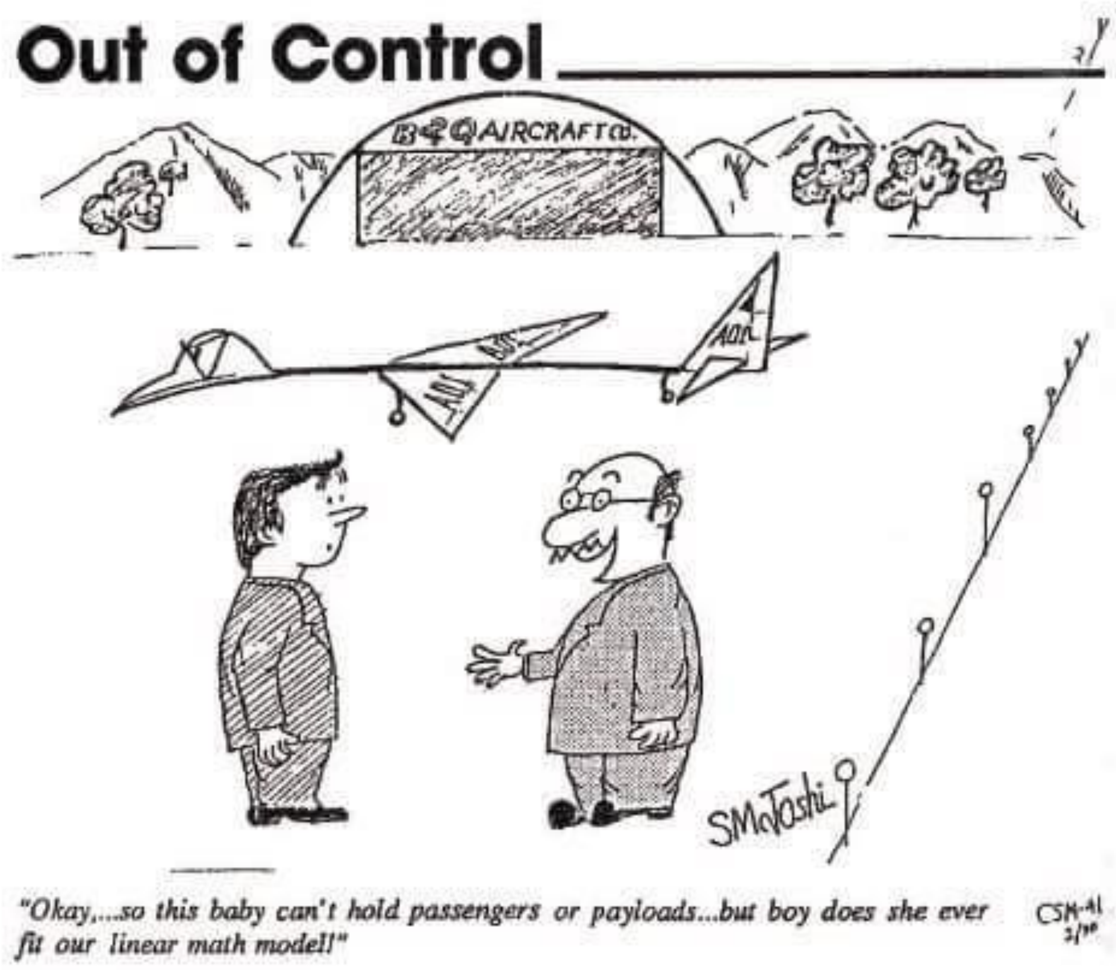
- Case 1: Pilot Control Dynamics Identification (*previous lecture*)

- Case 2: Aircraft Dynamics Identification (*today*)

- General System Identification Experiment Considerations (*today*)

Case 2:
Aircraft Dynamics Identification

Background


Out of Control
B&Q AIRCRAFT CO.
"Okay,...so this baby can't hold passengers or payloads...but boy does she ever fit our linear math model!"

Background

Flight Test Experiments

Everybody still does it…

Boeing 787: 7 aircraft, 3000 flight test hours

Lockheed-Martin F-22A: 9 aircraft, 7600 flight test hours

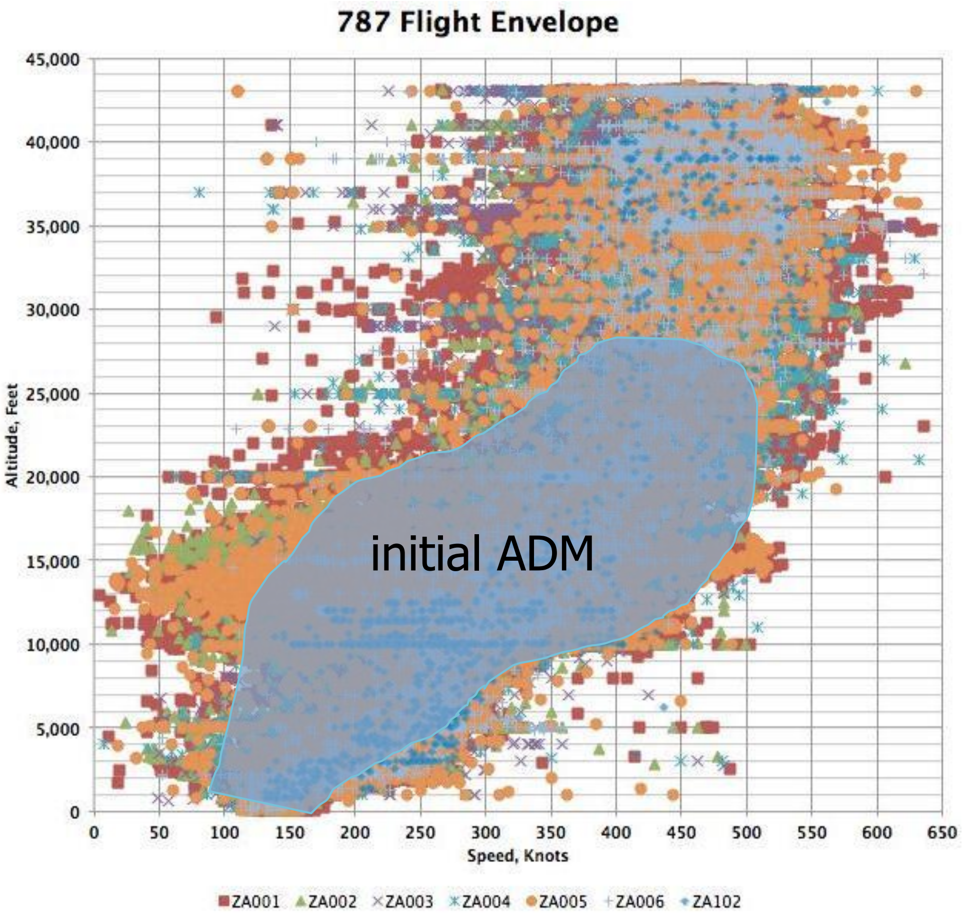
Background

Flight Test Experiments

Everybody still does it…

…because:

1. Validating an **initial** aerodynamic model
2. Expanding the initial flight envelope
3. Some aerodynamic parameters cannot be obtained from CFD or wind tunnel data (e.g., *damping coefficients*)



Source: www.airinformatics.com

Ljung's Questions


Lennart Ljung

1. Which signals are to be considered as **outputs** and which are to be considered as **inputs**? (*system definition*)

- ***Plant analysis***: *a first principles analysis of the aircraft dynamics.*

2. Which signals should be manipulated (inputs) so as to **"excite" the system** during the experiment? (*system excitation/input design*)

- *Inputs that excite all relevant dynamics (eigenmodes) of the aircraft need to be included in the identification data set.*

3. **Where and what** to measure? (*measurement definition*)

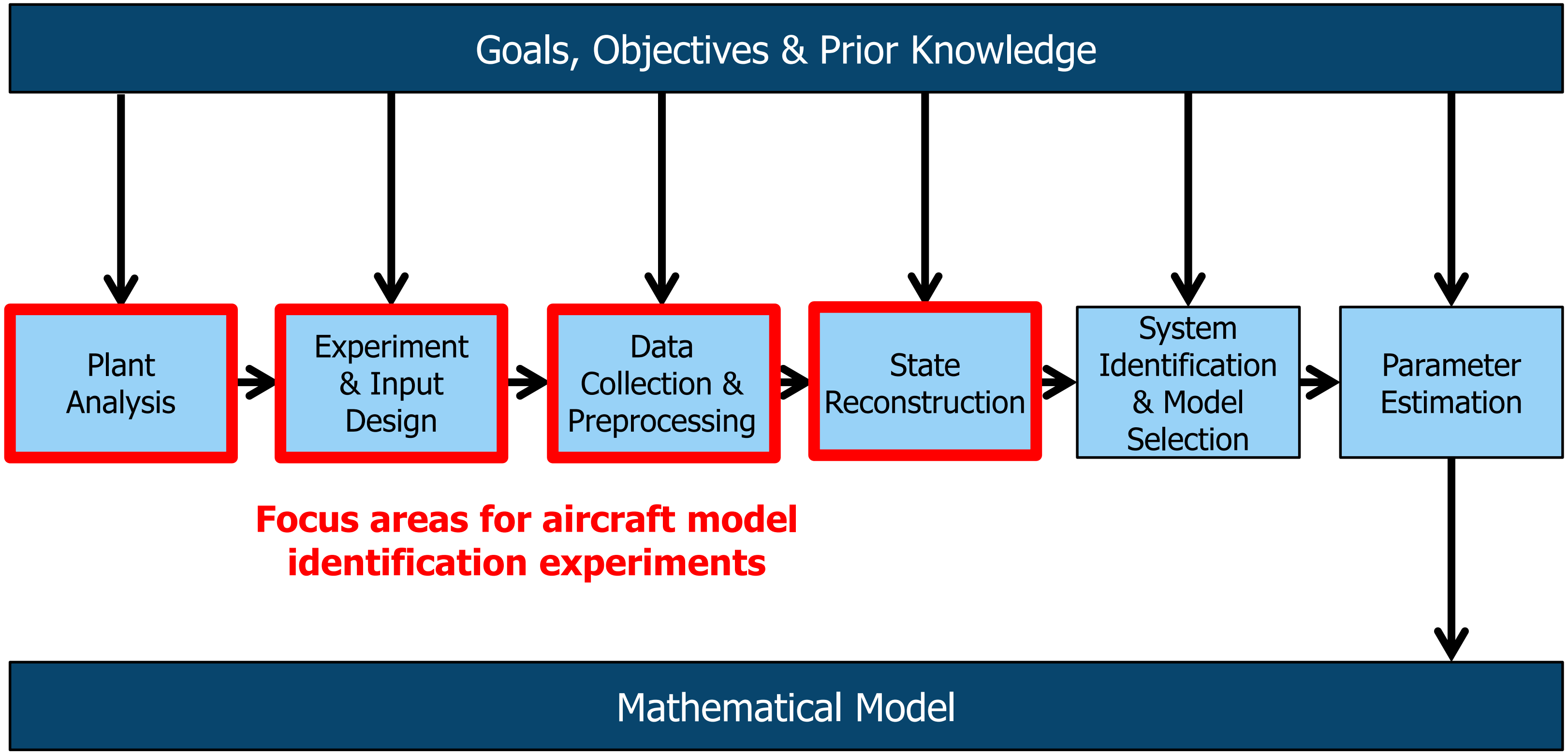
- *Depending on our system definition. We need a carefully setup and extensive Flight Test Instrumentation System (FTIS): sensors, actuators, data logging.*

4. **When** to measure? (*experiment design*)

- *Which part of the flight envelope do we want our model to cover?*

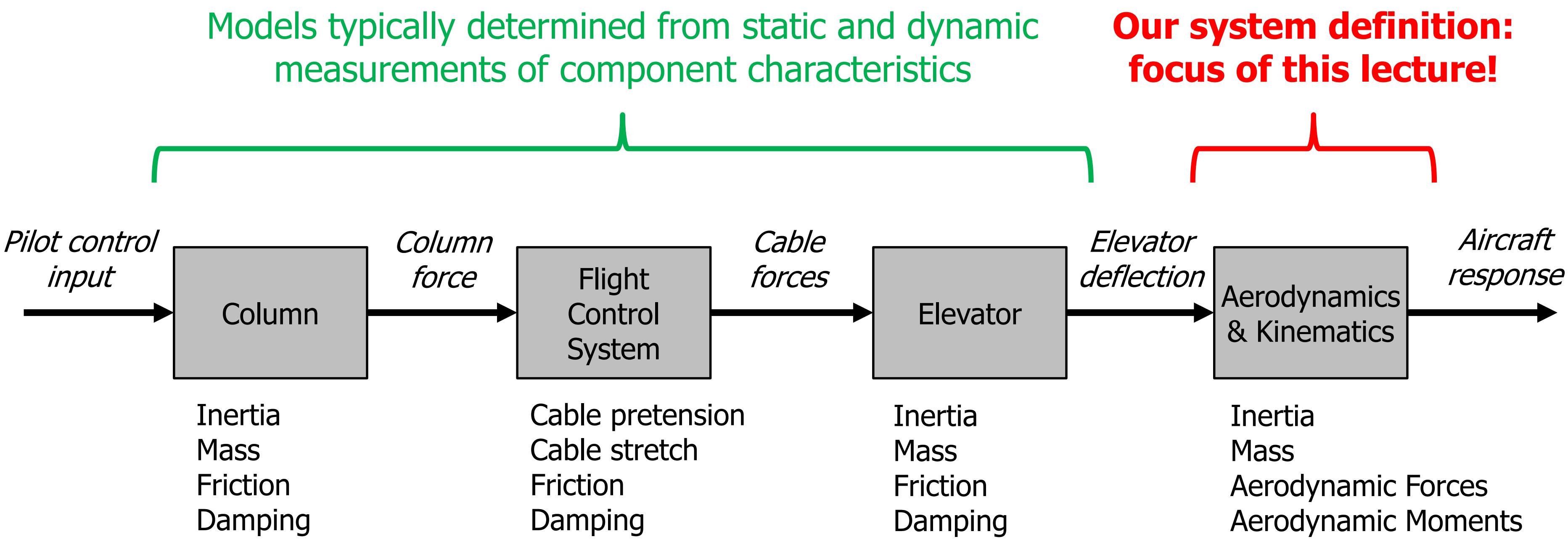
The System Identification Problem

Aircraft Model Identification



System Definition

Focus on Aerodynamic Model of the Aircraft

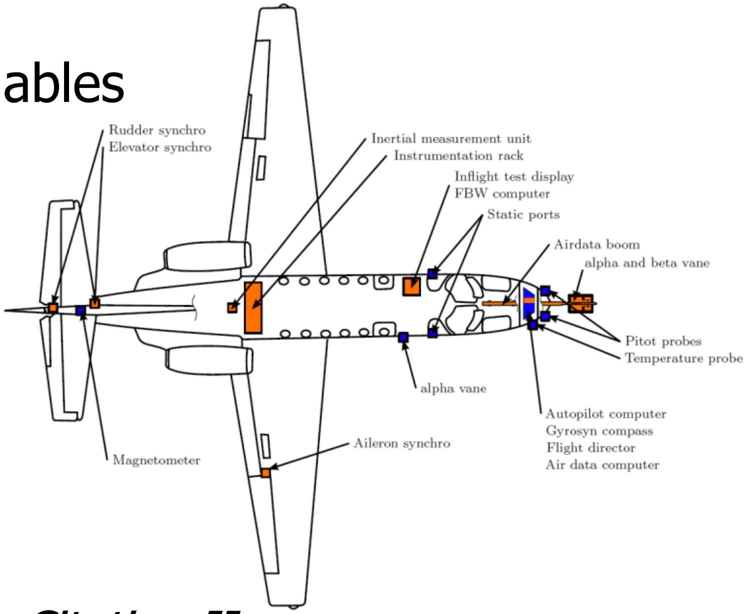


System Definition

Plant Analysis

Plant analysis is necessary for:

- Definition of initial aircraft model structure based on (linearized) equations of motion (EOM).
- Definition of initial model dimensions
- Creation of list of to-be-measured variables
- Design of flight test inputs



Example: Flight test design for the Cessna Citation II

System Definition

Plant Analysis from EOM

- Start with general aircraft nonlinear EOM.
- What are we going to measure **before** flight testing?
- What are we going to measure **during** flight testing?

$$m\begin{bmatrix} \dot{u}+qw-rv \\ \dot{v}+ru-pw \\ \dot{w}+pv-qu \end{bmatrix} = mg\begin{bmatrix} -\sin\theta \\ \sin\varphi\cos\theta \\ \cos\varphi\cos\theta \end{bmatrix} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$\begin{bmatrix} J_{xx}\dot{p}+\left(J_{zz}-J_{yy}\right)qr-J_{xz}\left(pq+\dot{r}\right) \\ J_{yy}\dot{q}+\left(J_{xx}-J_{zz}\right)pr+\left(p^2-r^2\right) \\ J_{zz}\dot{r}+\left(J_{yy}-J_{xx}\right)pq+\left(qr-\dot{p}\right) \end{bmatrix} = \begin{bmatrix} L \\ M \\ N \end{bmatrix}$$

System Definition

Plant Analysis from EOM

- Assume initial longitudinal aircraft model structure based on (linearized) equations of motion (EOM):

$$\begin{bmatrix} C_{X_u} - 2\mu_c \frac{\bar{c}}{V}\frac{d}{dt} & C_{X_\alpha} & C_{Z_0} & 0 \\ C_{Z_u} & C_{Z_\alpha} + \left(C_{Z_{\dot{\alpha}}} - 2\mu_c\right)\frac{\bar{c}}{V}\frac{d}{dt} & C_{X_0} & -\left(C_{Z_q} + 2\mu_c\right) \\ 0 & 0 & -\frac{\bar{c}}{V}\frac{d}{dt} & -1 \\ C_{m_u} & C_{m_\alpha} + C_{m_{\dot{\alpha}}}\frac{\bar{c}}{V}\frac{d}{dt} & 0 & C_{m_q} - 2\mu_c K_Y^2 \frac{\bar{c}}{V}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} \bar{u} \\ \alpha \\ \theta \\ \bar{q} \end{bmatrix} = \begin{bmatrix} -C_{X_{\delta e}} & -C_{X_{\delta t}} \\ -C_{Z_{\delta e}} & -C_{Z_{\delta t}} \\ 0 & 0 \\ -C_{m_{\delta e}} & -C_{m_{\delta t}} \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix}$$

System Definition

Plant Analysis from EOM

- What are we going to measure **before** flight testing?
- What are we going to measure **during** flight testing?

$$\begin{bmatrix} C_{X_u} - 2\mu_c \frac{\bar{c}}{V}\frac{d}{dt} & C_{X_\alpha} & C_{Z_0} & 0 \\ C_{Z_u} & C_{Z_\alpha} + \left(C_{Z_{\dot{\alpha}}} - 2\mu_c\right)\frac{\bar{c}}{V}\frac{d}{dt} & C_{X_0} & -\left(C_{Z_q} + 2\mu_c\right) \\ 0 & 0 & -\frac{\bar{c}}{V}\frac{d}{dt} & -1 \\ C_{m_u} & C_{m_\alpha} + C_{m_{\dot{\alpha}}}\frac{\bar{c}}{V}\frac{d}{dt} & 0 & C_{m_q} - 2\mu_c K_Y^2 \frac{\bar{c}}{V}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} \bar{u} \\ \alpha \\ \theta \\ \bar{q} \end{bmatrix} = \begin{bmatrix} -C_{X_{\delta e}} & -C_{X_{\delta t}} \\ -C_{Z_{\delta e}} & -C_{Z_{\delta t}} \\ 0 & 0 \\ -C_{m_{\delta e}} & -C_{m_{\delta t}} \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix}$$

System Definition

Plant Analysis from EOM

Longitudinal model variables:

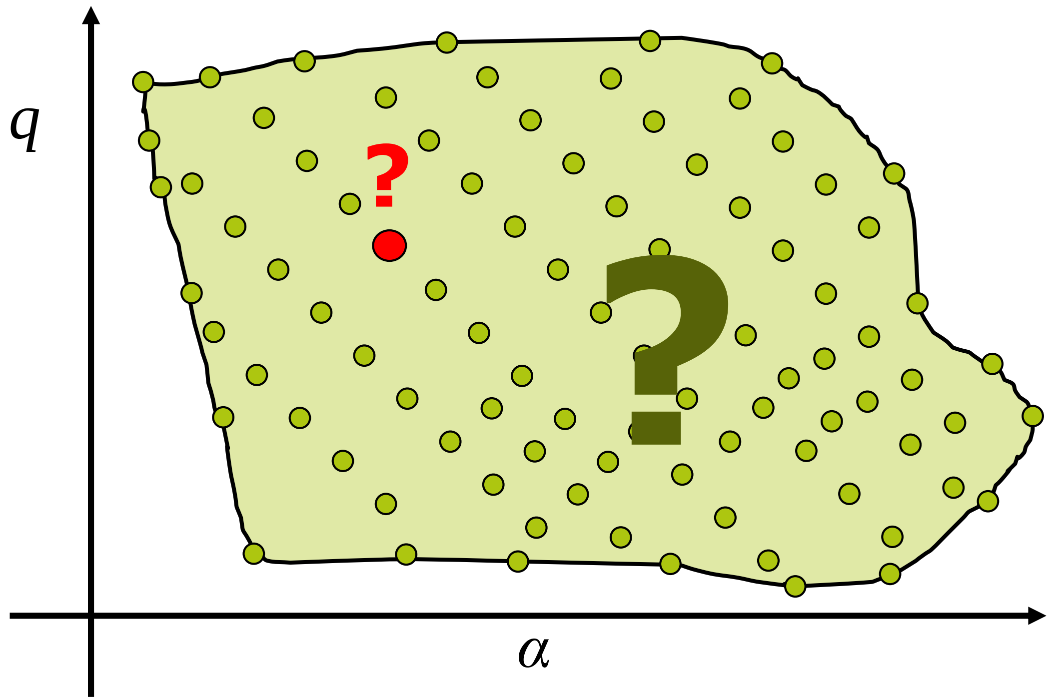
Variable	Sensor	In-flight?
u	body velocity sensor	yes
α	angle of attack sensor	yes
θ	Euler angle sensor	yes
q	pitch rate sensor	yes
m	mass sensor	yes
$\bar{c}$	chord measurement	**no**
V	airspeed sensor	yes
J_{yy}	moment of inertia sensor	yes
δ_e	elevator deflection sensor	yes
δ_t	trim tab deflection sensor	yes
S	wing surface	**no**
ρ	air density	yes

System Definition

Model Scope and Validity

What do we want to use our model for? Describe aircraft dynamics in

- a single flight condition, or
- **<u>over the complete flight envelope?</u>**



System Definition
Aircraft Model Identification

<u>Our system definition: "Aircraft"</u>

Inputs/Outputs:

- Input(s): control surfaces
- Output(s): aircraft states

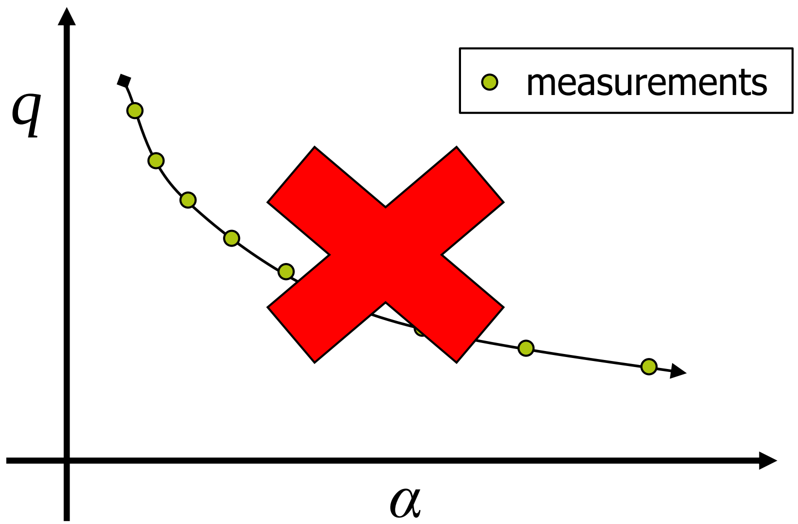
Main system characteristics:

- Limit model to aerodynamics + EOM
- One measureable input, <u>a lot of measureable outputs!</u>
- Constant dynamics (equations), parameters vary for each flight condition
- We need <u>a lot</u> of sensors and measurements!

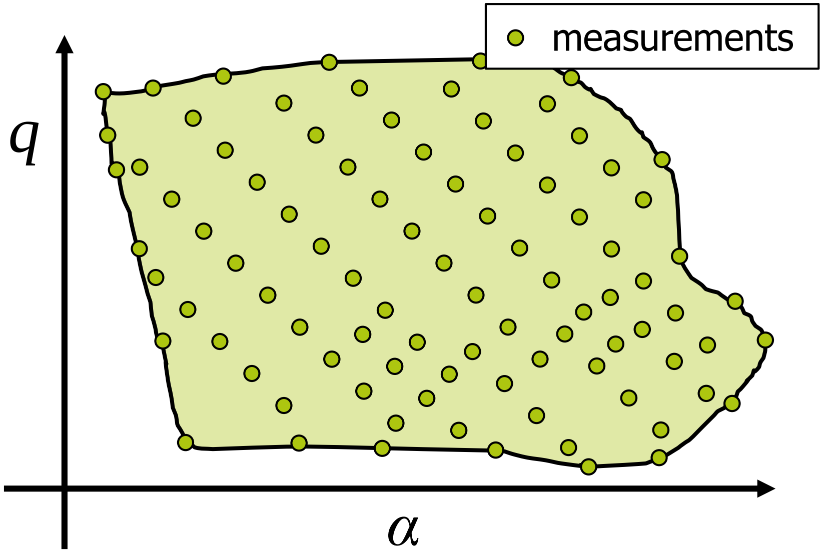
Input Design

What strategy do we use to excite the model variables?

Just “fly around” with the aircraft?

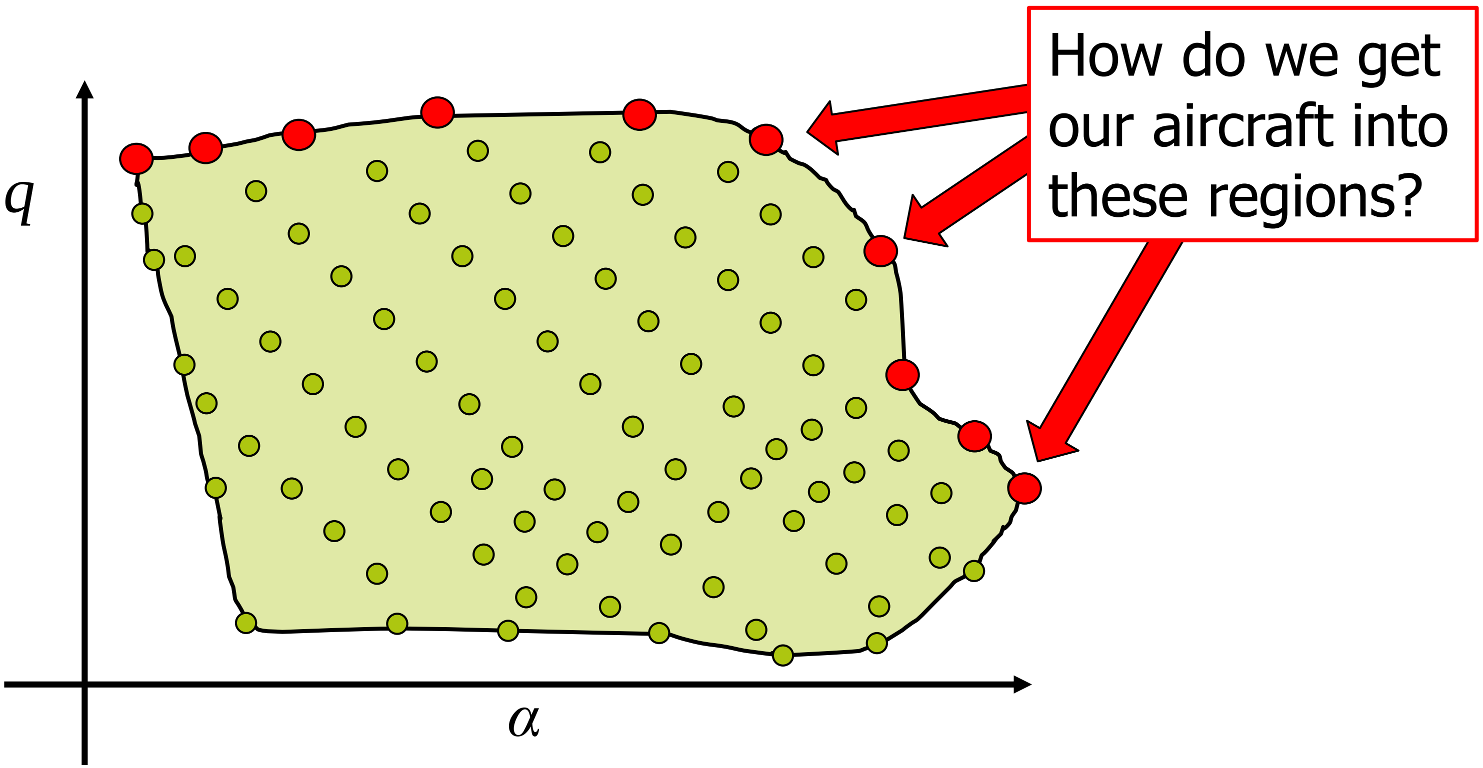


Cover a domain in state space?



Input Design

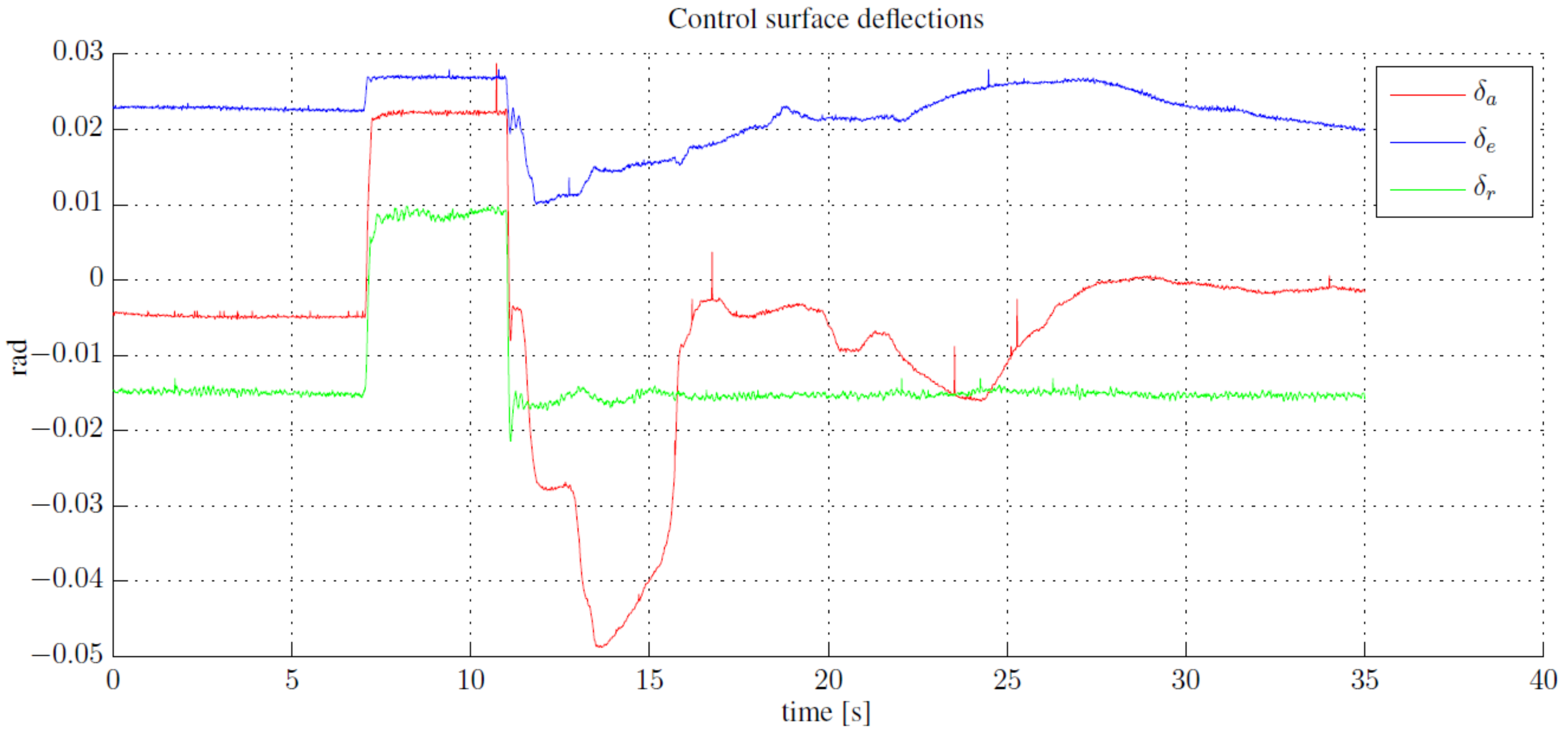
How do we cover the required flight envelope with test points?



Input Design

How do we cover the required flight envelope with test points?

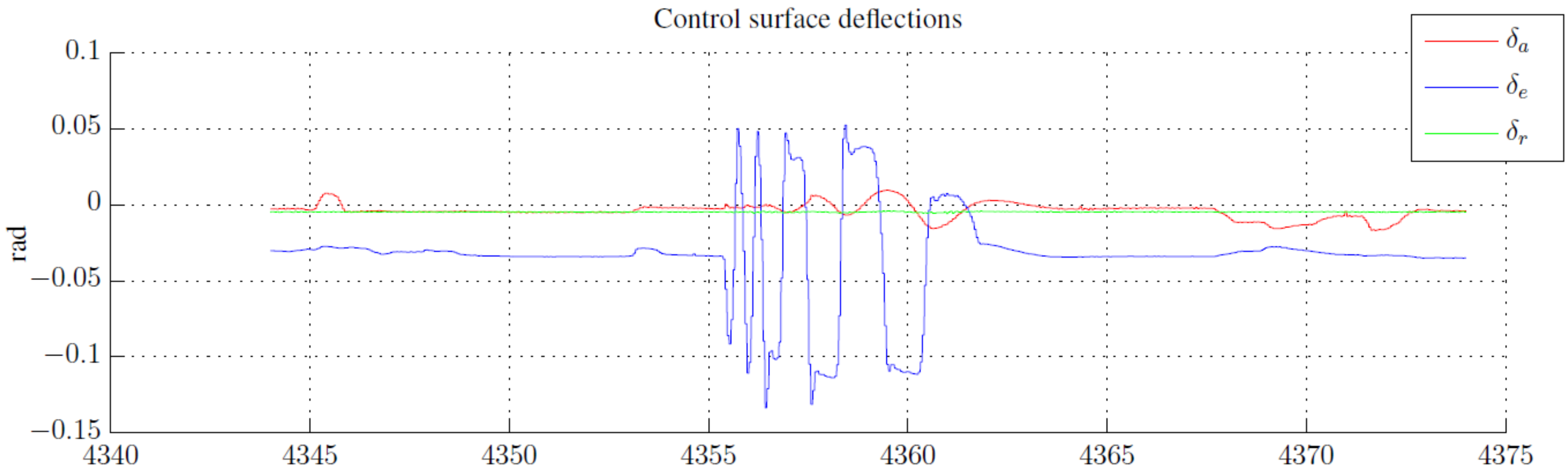
- We use special flight test maneuvers: e.g., <u>doublets</u>



Input Design

How do we cover the required flight envelope with test points?

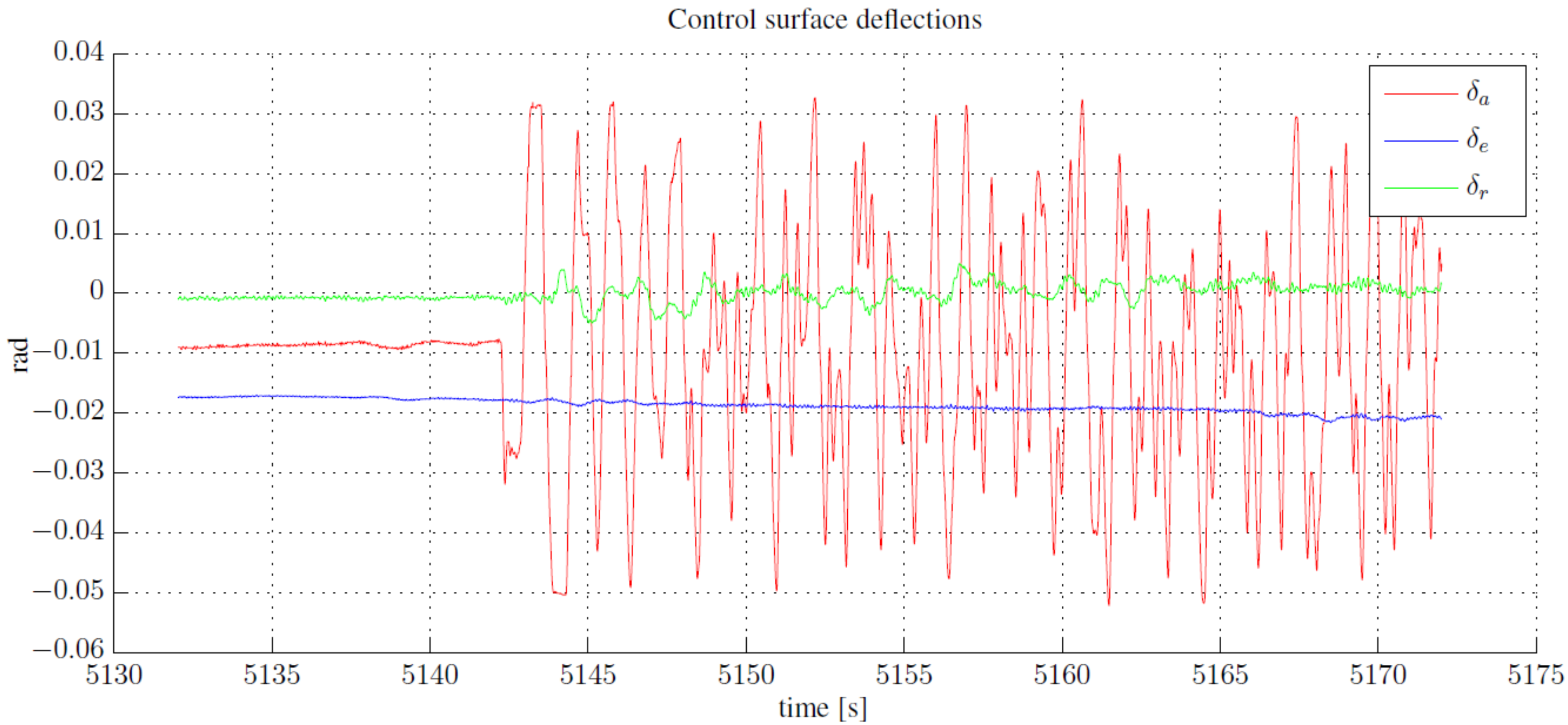
- We use special flight test maneuvers: e.g., <u>frequency sweep</u>



Input Design

How do we cover the required flight envelope with test points?

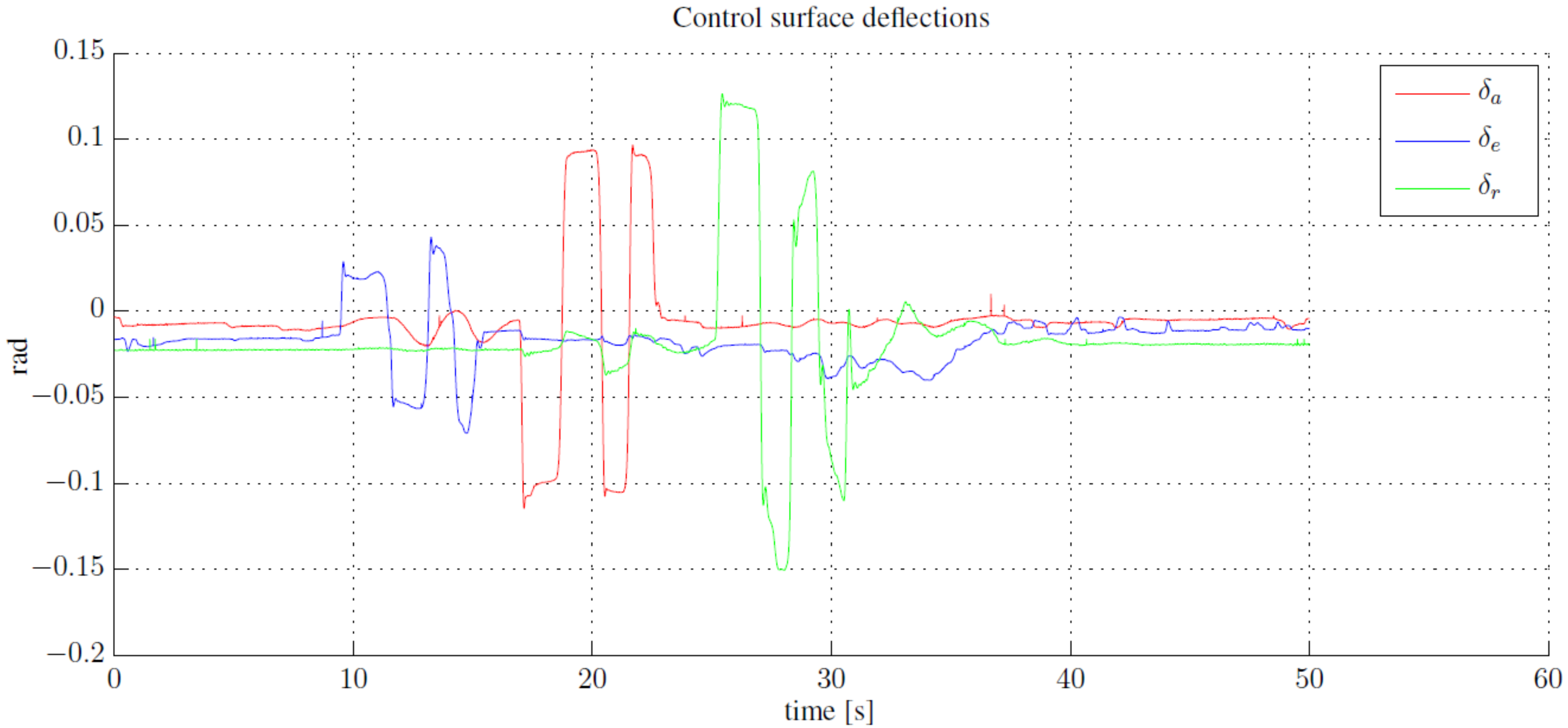
- We use special flight test maneuvers: e.g., pseudo-random noise



Input Design

How do we cover the required flight envelope with test points?

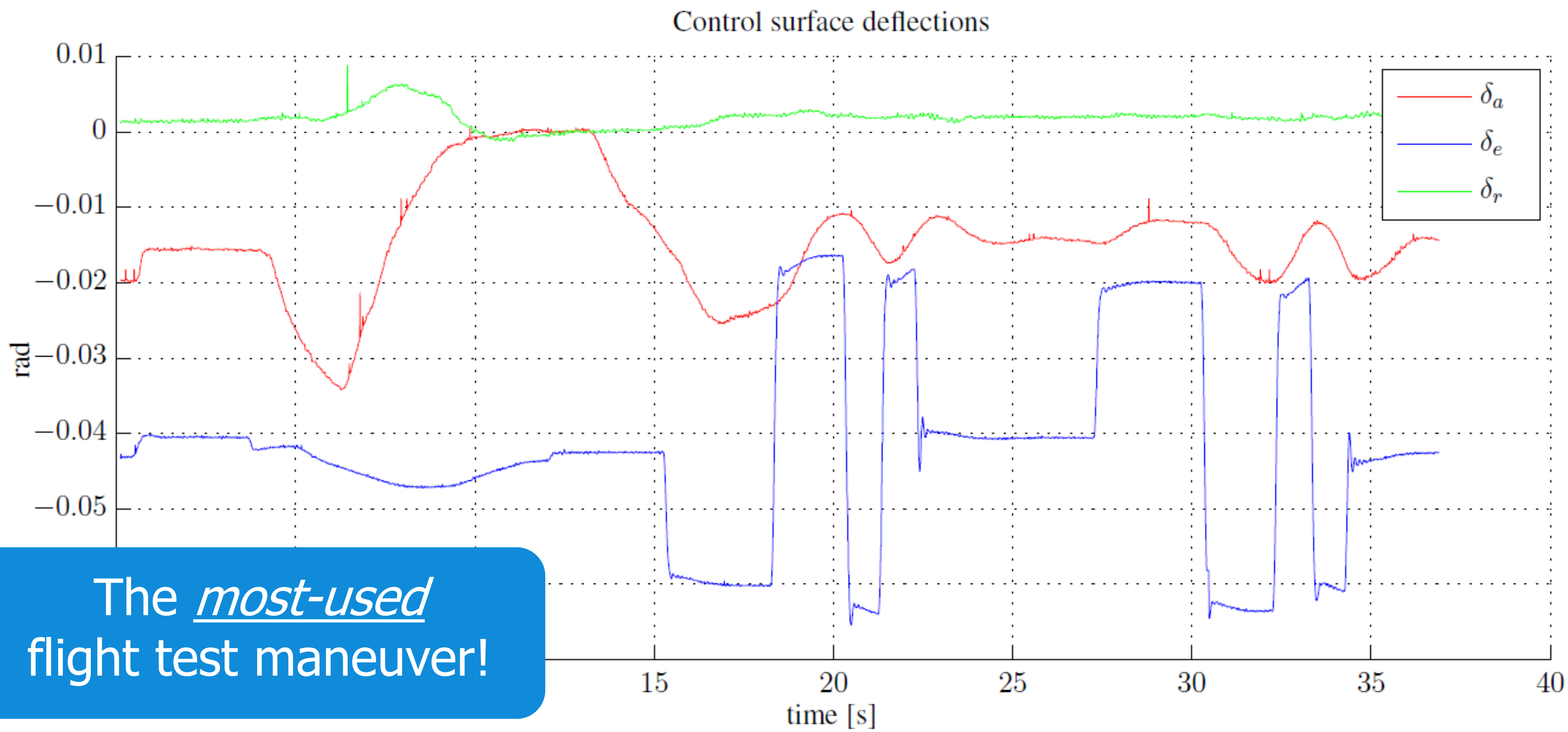
➡ We use special flight test maneuvers: e.g., <u>high-amplitude maneuvers</u>



Input Design

How do we cover the required flight envelope with test points?

- We use special flight test maneuvers: e.g., <u>3211 maneuvers</u>



The ***most-used*** flight test maneuver!

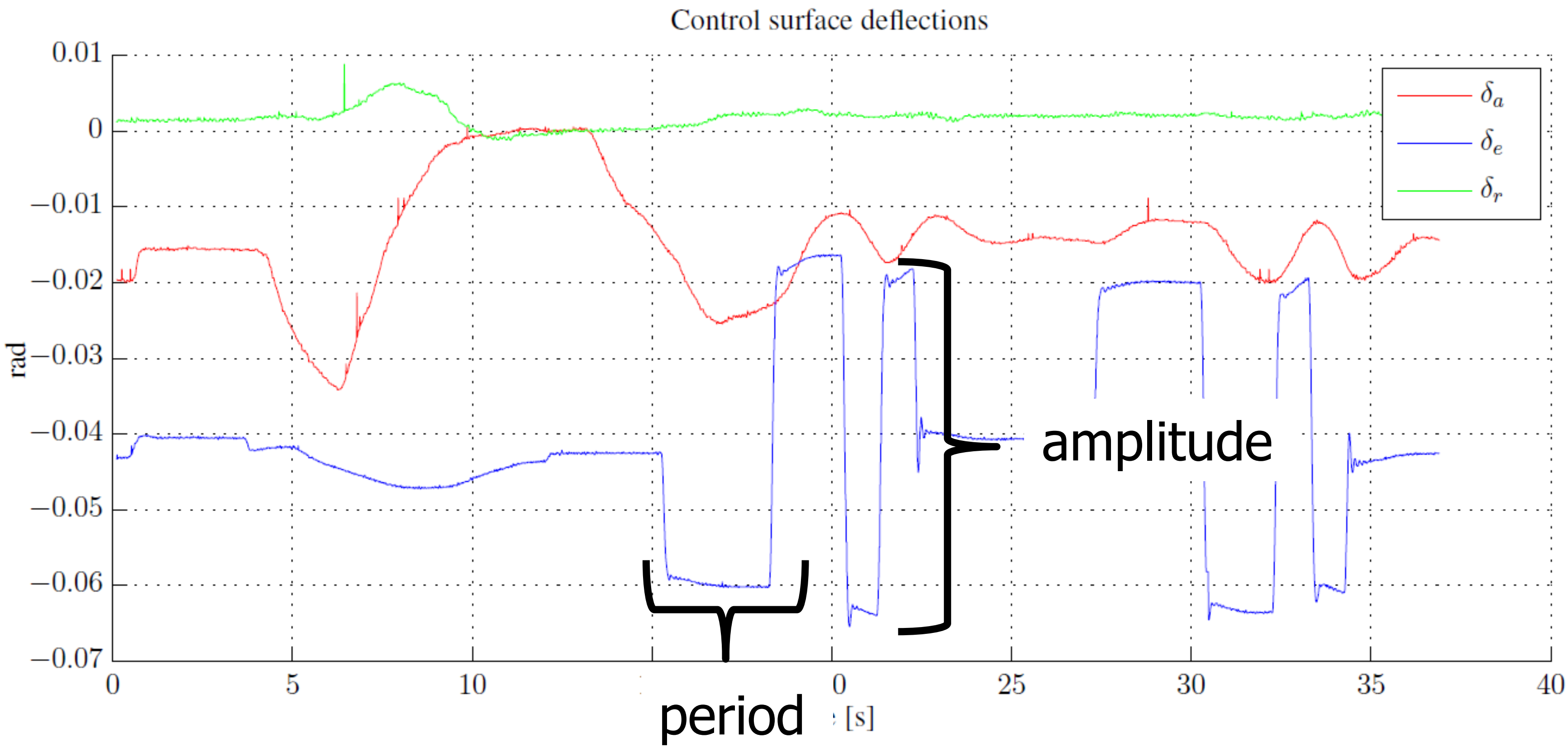
Input Design

3211 Maneuver Movie

Input Design

Example: 3211 Maneuver

How to determine the periods/amplitudes?



Input Design

Example: 3211 Maneuver

How to determine the periods/amplitudes?

- Eigenvalue analysis of initial aircraft model...

$$\begin{bmatrix} C_{X_u} - 2\mu_c \frac{\bar{c}}{V}\frac{d}{dt} & C_{X_\alpha} & C_{Z_0} & 0 \\ C_{Z_u} & C_{Z_\alpha} + \left(C_{Z_{\dot{\alpha}}} - 2\mu_c\right)\frac{\bar{c}}{V}\frac{d}{dt} & C_{X_0} & -\left(C_{Z_q} + 2\mu_c\right) \\ 0 & 0 & -\frac{\bar{c}}{V}\frac{d}{dt} & -1 \\ C_{m_u} & C_{m_\alpha} + C_{m_{\dot{\alpha}}}\frac{\bar{c}}{V}\frac{d}{dt} & 0 & C_{m_q} - 2\mu_c K_Y^2 \frac{\bar{c}}{V}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} \bar{u} \\ \alpha \\ \theta \\ \bar{q} \end{bmatrix} = \begin{bmatrix} -C_{X_{\delta e}} & -C_{X_{\delta t}} \\ -C_{Z_{\delta e}} & -C_{Z_{\delta t}} \\ 0 & 0 \\ -C_{m_{\delta e}} & -C_{m_{\delta t}} \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix}$$

Input Design

Example: 3211 Maneuver

How to determine the periods/amplitudes?

Eigenvalue analysis of initial aircraft model...

$$\begin{bmatrix} -2\mu_c \frac{\bar{c}}{V}\frac{d}{dt} & 0 & 0 & 0 \\ 0 & \left(C_{Z_{\dot{\alpha}}} - 2\mu_c\right)\frac{\bar{c}}{V}\frac{d}{dt} & 0 & 0 \\ 0 & 0 & -\frac{\bar{c}}{V}\frac{d}{dt} & 0 \\ 0 & C_{m_{\dot{\alpha}}}\frac{\bar{c}}{V}\frac{d}{dt} & 0 & -2\mu_c K_Y^2 \frac{\bar{c}}{V}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} \bar{u} \\ \alpha \\ \theta \\ \bar{q} \end{bmatrix} =$$

$$\begin{bmatrix} -C_{X_u} & -C_{X_\alpha} & -C_{Z_0} & 0 \\ -C_{Z_u} & -C_{Z_\alpha} & C_{X_0} & -\left(C_{Z_q} + 2\mu_c\right) \\ 0 & 0 & 0 & -1 \\ -C_{m_u} & -C_{m_\alpha} & 0 & -C_{m_q} \end{bmatrix} \begin{bmatrix} \bar{u} \\ \alpha \\ \theta \\ \bar{q} \end{bmatrix} + \begin{bmatrix} -C_{X_{\delta e}} & -C_{X_{\delta t}} \\ -C_{Z_{\delta e}} & -C_{Z_{\delta t}} \\ 0 & 0 \\ -C_{m_{\delta e}} & -C_{m_{\delta t}} \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix}$$

Input Design

Example: 3211 Maneuver

How to determine the periods/amplitudes?

Eigenvalue analysis of initial aircraft model...

$$P \cdot \begin{bmatrix} \dot{\bar{u}} \\ \dot{\alpha} \\ \dot{\theta} \\ \dot{\bar{q}} \end{bmatrix} = Q \cdot \begin{bmatrix} \bar{u} \\ \alpha \\ \theta \\ \bar{q} \end{bmatrix} + R \cdot \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix}$$

$$\begin{bmatrix} \dot{\bar{u}} \\ \dot{\alpha} \\ \dot{\theta} \\ \dot{\bar{q}} \end{bmatrix} = P^{-1}Q \cdot \begin{bmatrix} \bar{u} \\ \alpha \\ \theta \\ \bar{q} \end{bmatrix} + P^{-1}R \cdot \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix} = Ax + Bu$$

- Eigenvalues λ are calculated as follows: $\left| A - \lambda_c I \right| = 0$

Input Design

Example: 3211 Maneuver

How to determine the periods/amplitudes?

$$\begin{vmatrix} C_{X_u} - 2\mu_c\lambda_c & C_{X_\alpha} & C_{Z_0} & 0 \\ C_{Z_u} & C_{Z_\alpha} + \left(C_{Z_{\dot{\alpha}}} - 2\mu_c\right)\lambda_c & -C_{X_0} & C_{Z_q} + 2\mu_c \\ 0 & 0 & -\lambda_c & 1 \\ C_{m_u} & C_{m_\alpha} + C_{m_{\dot{\alpha}}}\lambda_c & 0 & C_{m_q} - 2\mu_c K_Y^2 \lambda_c \end{vmatrix} = 0$$

Short period motion is most important to pitch dynamics...

$$\Rightarrow \begin{vmatrix} C_{Z_\alpha} + \left(C_{Z_{\dot{\alpha}}} - 2\mu_c\right)\lambda_c & C_{Z_q} + 2\mu_c \\ C_{m_\alpha} + C_{m_{\dot{\alpha}}}\lambda_c & C_{m_q} - 2\mu_c K_Y^2 \lambda_c \end{vmatrix} = 0$$

Input Design

Example: 3211 Maneuver

How to determine the periods/amplitudes?

$$\begin{vmatrix} C_{Z_\alpha} + \left(-2\mu_c\right)\lambda_c & 2\mu_c \\ C_{m_\alpha} + C_{m_{\dot{\alpha}}}\lambda_c & C_{m_q} - 2\mu_c K_Y^2 \lambda_c \end{vmatrix} = 0$$

$$\gamma = 0 \rightarrow \alpha = \theta$$

$$\frac{d\bar{q}}{dt} = \frac{d^2\theta}{dt^2}$$

$$\begin{vmatrix} -2\mu_c\lambda_c & 2\mu_c \\ C_{m_\alpha} + C_{m_{\dot{\alpha}}}\lambda_c & C_{m_q} - 2\mu_c K_Y^2 \lambda_c \end{vmatrix} = 0$$

Input Design
Example: 3211 Maneuver

Exercise 2.1: Cessna Citation II maneuver design (1/3)

$$\begin{vmatrix} -2\mu_c\lambda_c & 2\mu_c \\ C_{m_\alpha} + C_{m_{\dot{\alpha}}}\lambda_c & C_{m_q} - 2\mu_c K_Y^2 \lambda_c \end{vmatrix} = 0$$

Use the following data for the Cessna Citation II

$$\mu_c = 102.7, \quad K_Y^2 = 0.98, \quad V = 80, \quad \bar{c} = 1.991$$

$$C_{m_{\dot{\alpha}}} = -3.70, \quad C_{m_\alpha} = -0.43, \quad C_{m_q} = -7.04$$

λ_c = -0.0267 +/- 0.0377j

$P = ?$

Input Design

Example: 3211 Maneuver

Exercise 2.1: Cessna Citation II maneuver design (2/3)

the 3211 must span the eigenmotion bandwidth:

$$\omega_0 = \sqrt{\xi_c^2 + \eta_c^2}\,\frac{V}{\bar{c}} = 1.8562\ \text{[rad/s]}$$

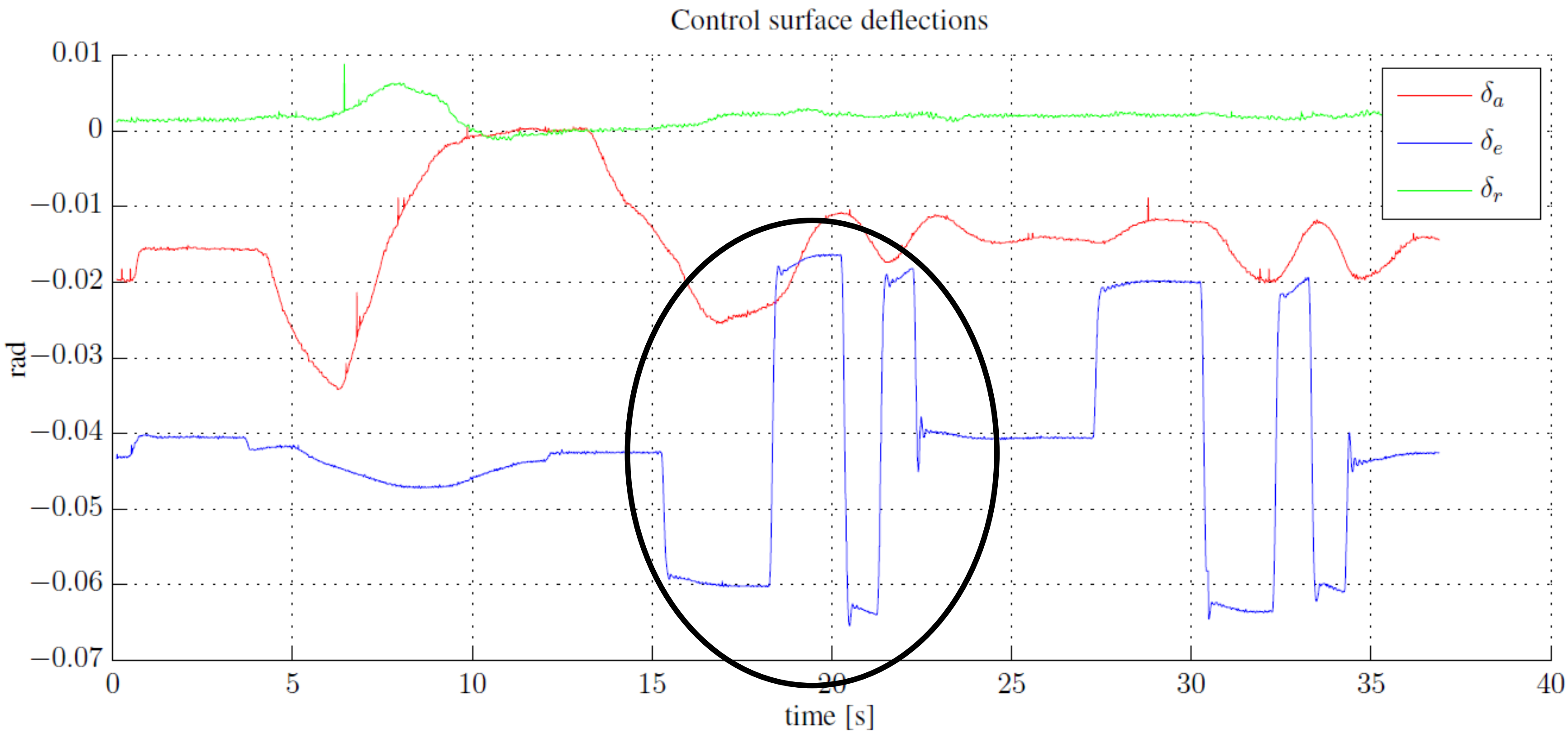
$$\omega_n = \omega_0 \sqrt{1 - \frac{\xi_c^2}{\xi_c^2 + \eta_c^2}} = 1.5148\ \text{[rad/s]}$$

$$\Rightarrow \quad P = \frac{2\pi}{\omega_n} = 4.1\,[s]$$

Input Design

Example: 3211 Maneuver

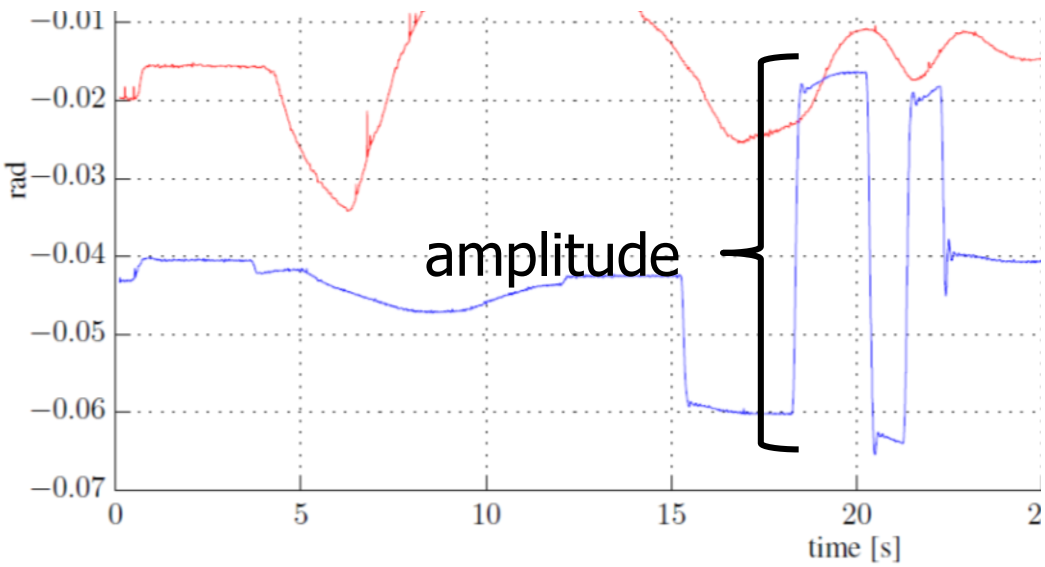
Exercise 2.1: Cessna Citation II maneuver design (3/3)



Input Design
Example: 3211 Maneuver

How about maneuver amplitude?

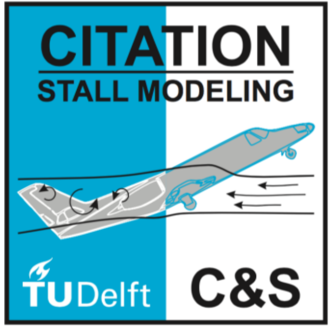
- Slowly increase, prevent aircraft from exiting the safe flight envelope...



- Use *optimal input sequences* to determine amplitudes [Mulder1986]

Input Design

Recent Example: Stall Modeling

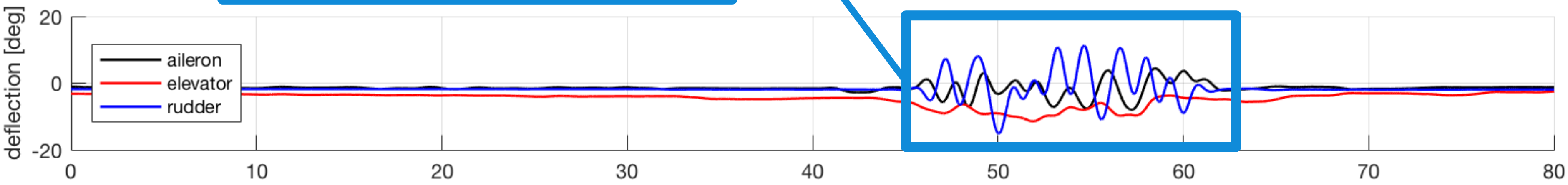


Inputs for stall identification:

<u>Uncorrelated</u> pitch/roll inputs during (short duration!) stall maneuver.

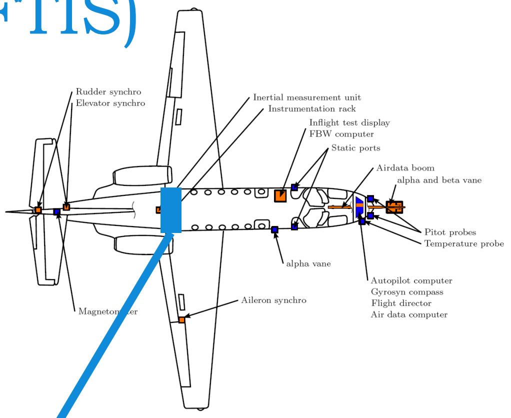
Use two pilots!

Citation flight tests (November 2016)



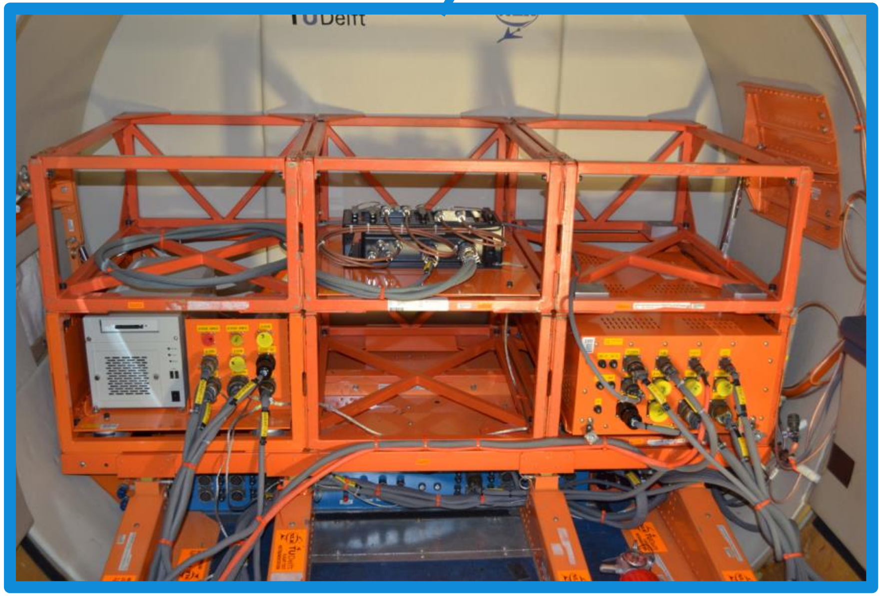
Measurement Definition

Flight Test Instrumentation System (FTIS)



<u>NEW</u> Citation FTIS consists of:

- EtherCAT data acquisition modules
- Custom logging with DUECA software
- Tablets for direct tracking of flight states!



Measurement Definition

Flight Test Instrumentation System (FTIS)

Sensor data stored by FTIS:

- AHRS

  $\phi, \theta, \psi, p, q, r, A_x, A_y, A_z$
- GPS

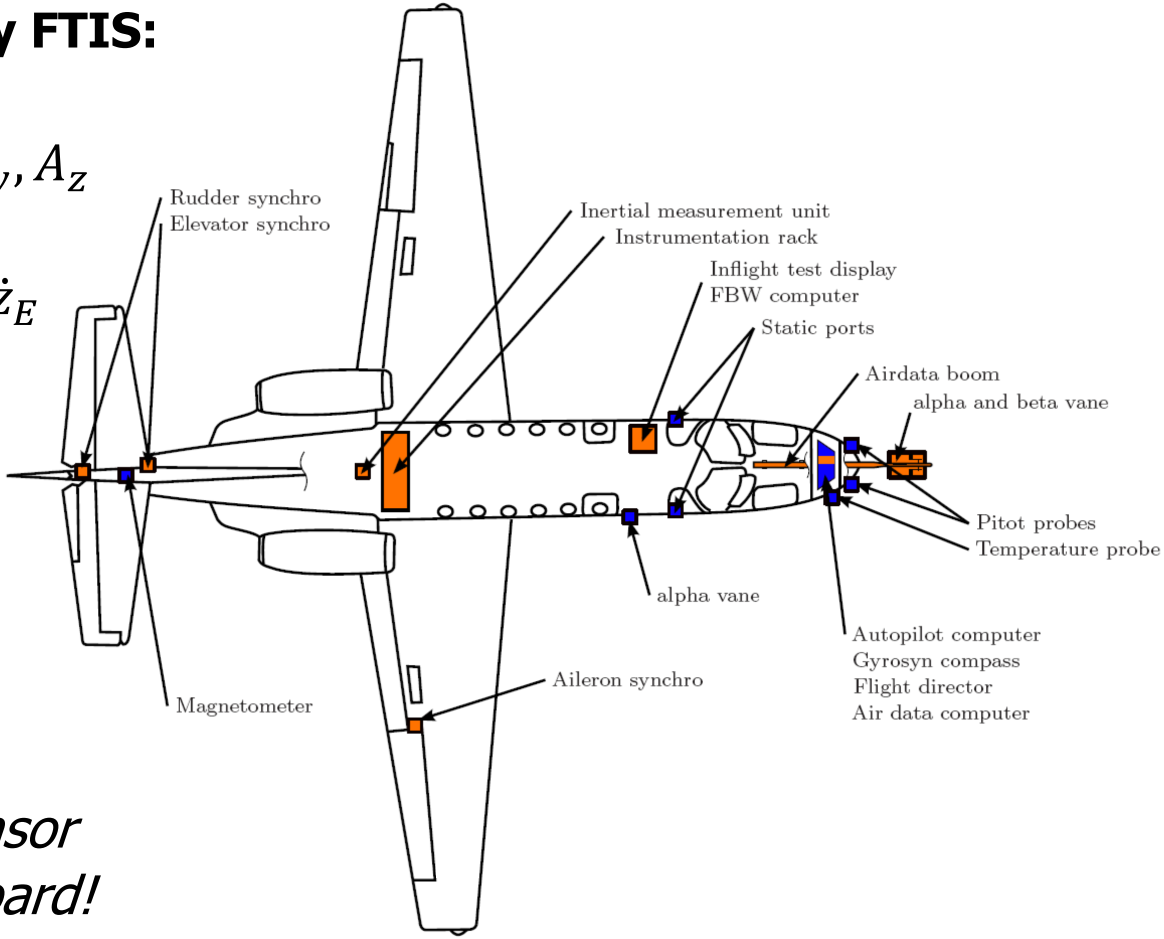
  $x_E, y_E, z_E, \dot{x}_E, \dot{y}_E, \dot{z}_E$
- DADC

  V_{TAS}, α_{vane}
- Synchro's

  $\delta_a\ \delta_e, \delta_r$
- Air data boom

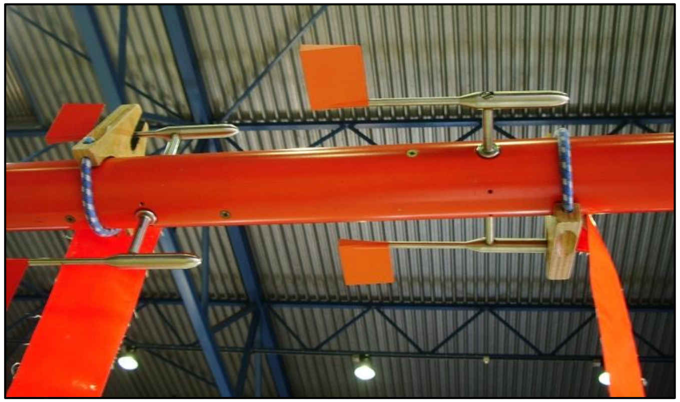
  $\alpha_{boom}, \beta_{boom}$

- *...and any other sensor you can carry on board!*



Measurement Definition

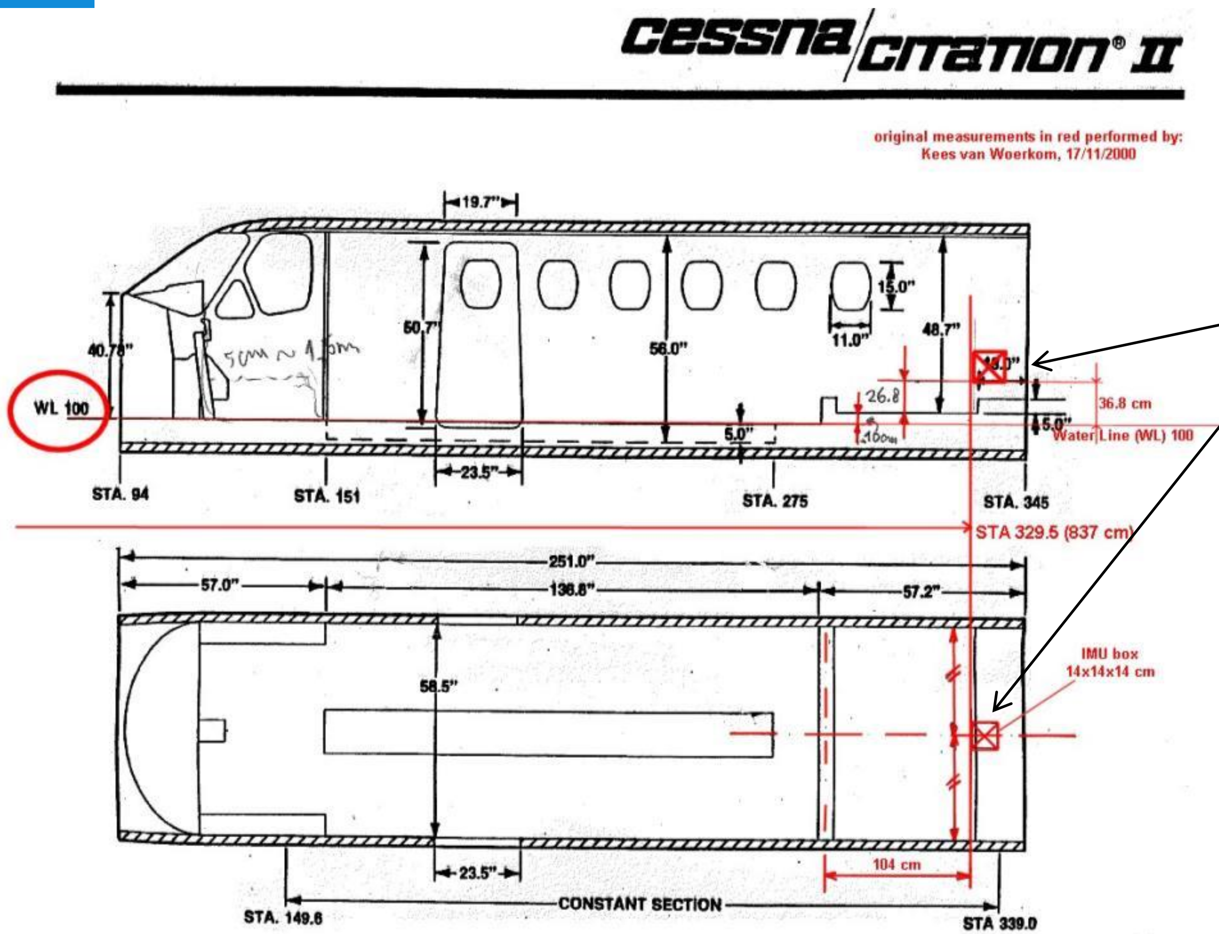
Flight Test Instrumentation System (FTIS)

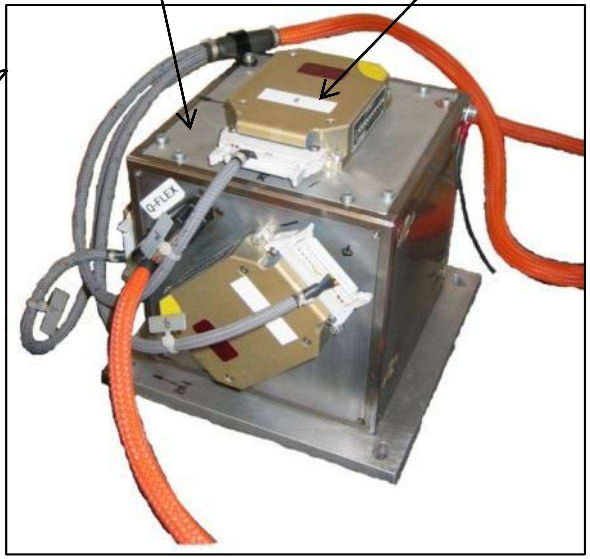


Boom with alpha (2x) and beta (2x) vanes

Measurement Definition

Flight Test Instrumentation System (FTIS)

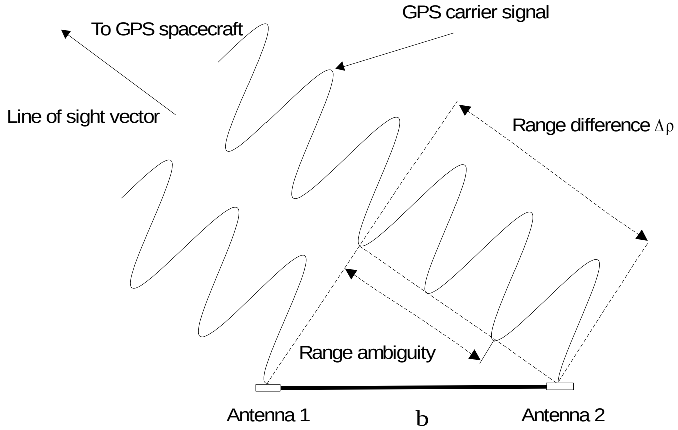


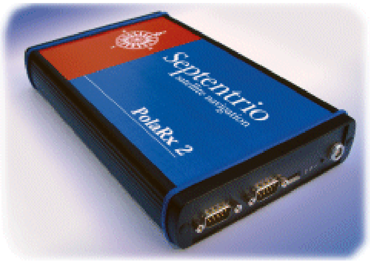


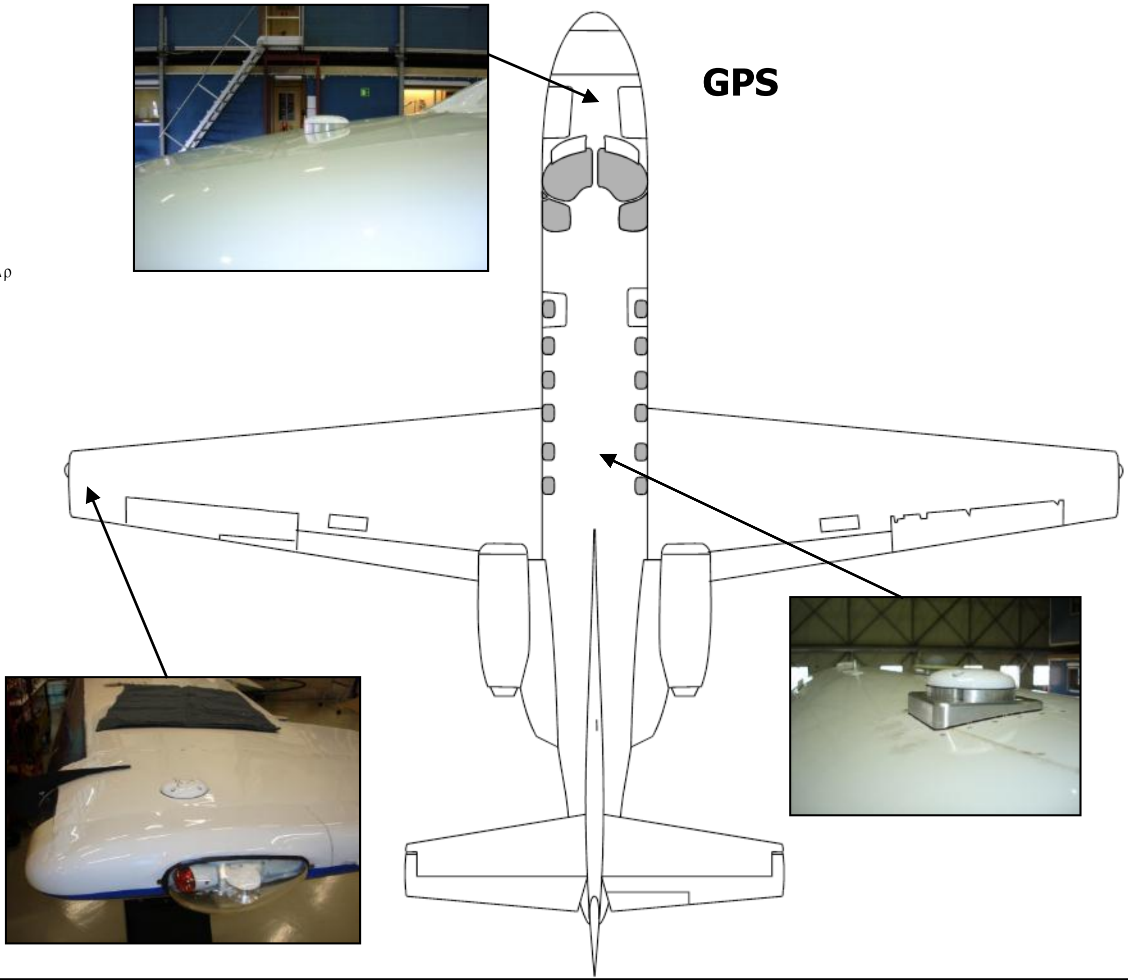
IMU: 3 Q-Flex accelerometers, 3 LITEF rate gyros

Measurement Definition

Flight Test Instrumentation System (FTIS)





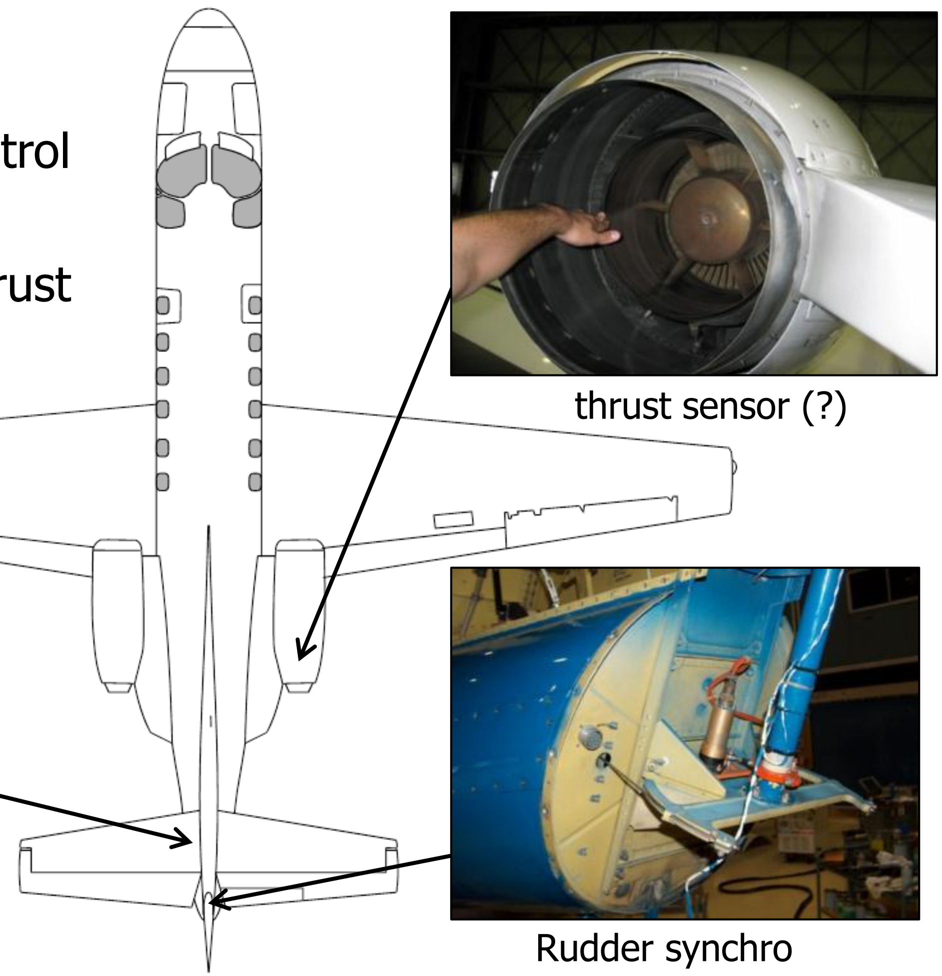


Measurement Definition

Flight Test Instrumentation System (FTIS)

Synchro's

- Used for measuring control surface deflections
- At current no engine thrust sensor!!!



Elevator synchro

Measurement Definition

Certification: A Necessary Evil…

- Keyword in aviation: **safety**
- Flight test experiments typically involve:
  - New aircraft
  - Modifications to existing aircraft
  - “Exciting” maneuvers
- Any modification to internal or external systems requires (re)certification
- Always take into account during flight test planning, because certification is very costly and time consuming!

From: www.CartoonStock.com

Measurement Definition

Measured Variables

Recall our list of required longitudinal states:

Variable	Virtual Sensor	Real sensor?
u	body velocity sensor	**no**, derive from IMU/AHRS
α	angle of attack sensor	yes, vane on boom
θ	Euler angle sensor	yes, use AHRS
q	pitch rate sensor	yes, use AHRS
m	mass sensor	**no**, use mass model
$\bar{c}$	chord measurement	measure before flight
V	airspeed sensor	yes, DADC
J_{yy}	moment of inertia sensor	**no**, use mass model
δ_e	elevator deflection sensor	yes, synchro
δ_t	trim tab deflection sensor	yes, synchro
S	wing surface	measure before flight
ρ	air density	yes, DADC

Measurement Definition

Measured Variables

Some states can not be measured directly

- States must be reconstructed by combining measurements from different sensors: **Sensor Fusion** (next lecture!).

Sensors produce noisy and sometimes biased results

- Biases must be estimated, and sensor noise must be removed in a process called **State Estimation** (next lecture!).

Sensors are subject to H/W and S/W **glitches**

- All raw flight data must be analyzed for the occurrence of sensor signal glitches and cleaned-up (end of this lecture).

Experiment Design

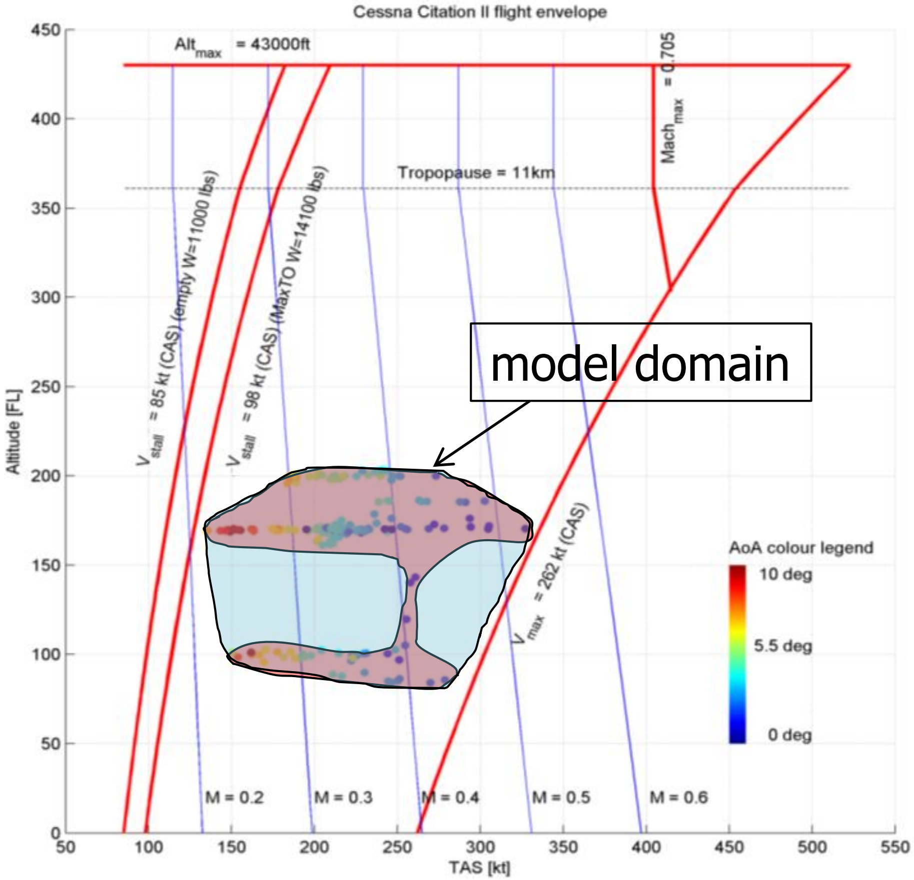
Model Validity vs. Flight Envelope

<u>Ask yourself:</u>

What is the required domain of the aerodynamic model?

Desired/required model domain determines:

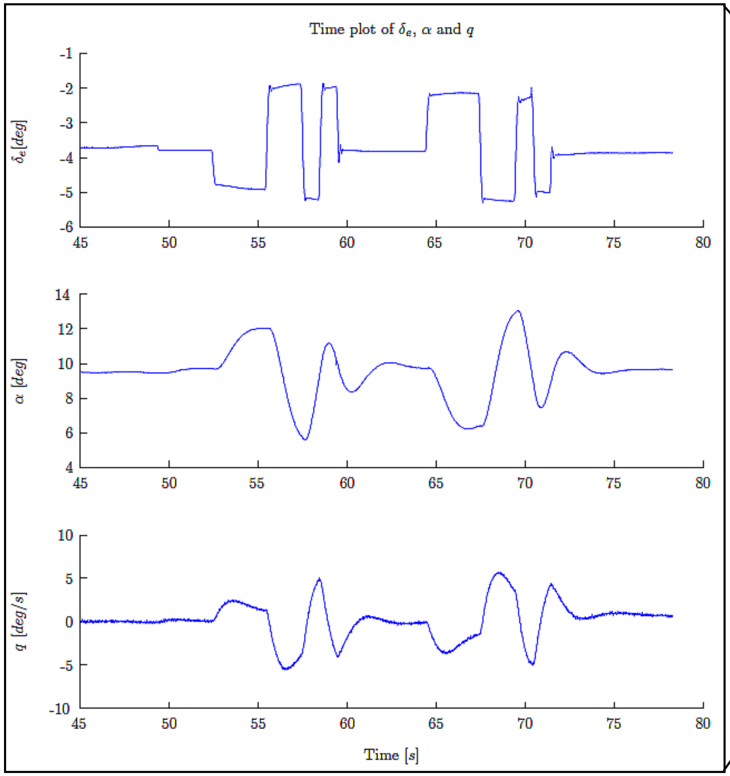
- Area of the flight envelope that must be covered by experiment.
- Density of test points.

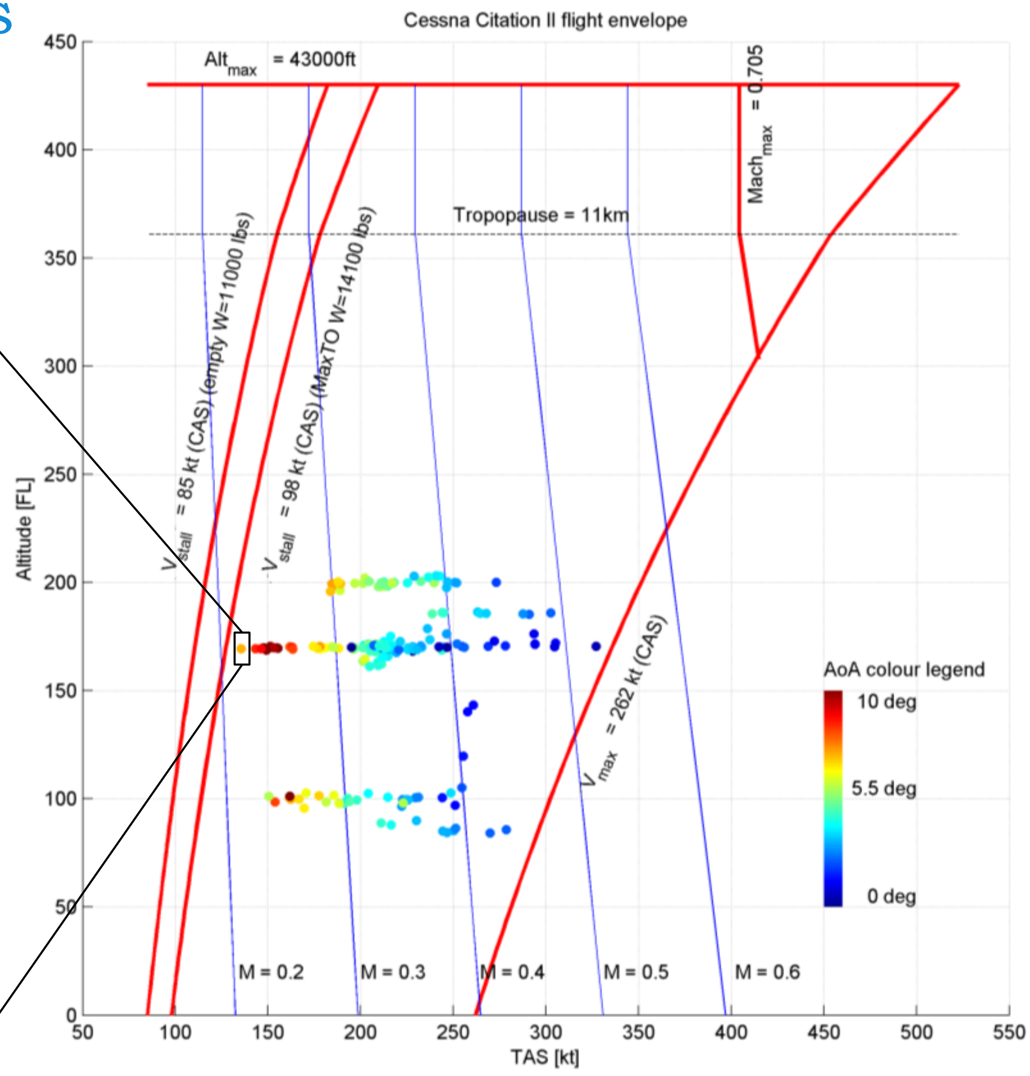


Experiment Design

Flight Test Maneuvers

For each test point, define flight test maneuvers...





Experiment Design

Flight Test Execution

For in-flight experiments, make use of "flight test cards" and logbooks:

- Clear objectives for pilots.
- Systematic execution of flight maneuvers.
- Reduces data preconditioning workload (why?).

Time: Date:

Manoeuvre	Time	Aoa	IAS	Remarks
Engine power up				
C.1 - Ground Manouvres				
C.1 - Ground Manouvres				
C.1 - Ground Manouvres				
C.1 - Ground Manouvres				
Take off and reach flight-test area				
O1 - Modelling of the nose-boom				
Start manoeuvre C.2 AoA sweep ; FL100 ; auto-pilot on, altitude hold mode on ; Vmin				
IAS = 100kt				
Increase speed to 155kt during 2 minutes				
IAS = 155kt				
Hold AoA for 1 minute				
IAS = 155kt				
Increase speed to 210kt during 2 minutes				
IAS = 210kt				
Hold AoA for 1 minute				
IAS = 210kt				
Increase speed to 260kt during 2 minutes				

Flight Plan Worksheet for Flight Coordinator

Logbook PH-LAB stall flight test February 7 2018

	#	Time	Maneuver	Altitude	Elevator	Aileron	Rudder	Comments	
DEMO	1	10:21 12 54	1 kt/s stall NO input	8940	–	–	–	film 1.	
	2	1340	"					" 2	
	3	1400	"					" 4	
DATA	4	1610	input test	9000	V	–	–	3211 pitch	+10 kts
	5	1694	input test	9 –	V	–	–	" (–)	
TUNING	6	1784	input test	9 –	–	–	V	3211 yaw	klew
	7	1810	"	–	–	–	V	" β ±5	good

Summary

Aircraft Dynamics Identification

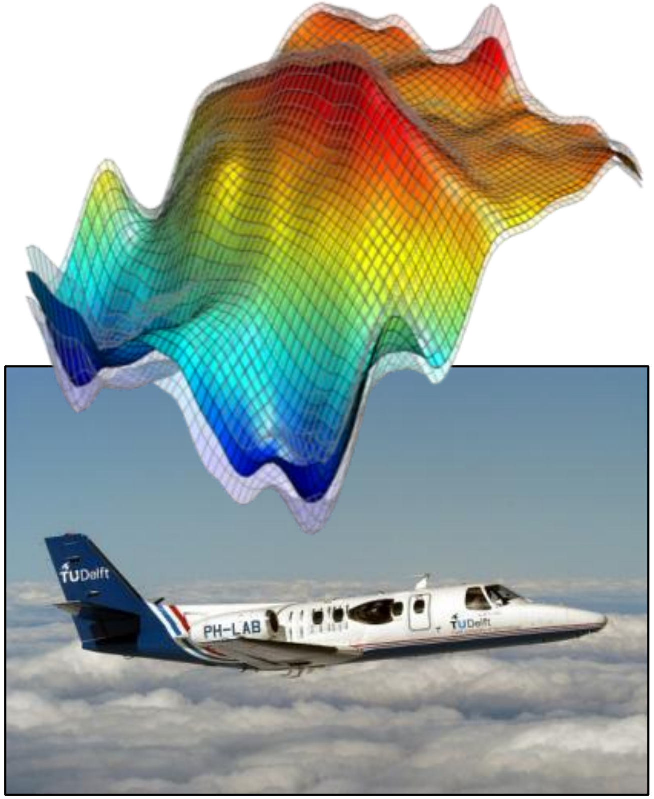
- ✓ Aerodynamic model definition:
  - ✓ Known EOM
  - ✓ Parameters that vary with flight condition

- ✓ Model identification requires inputs that excite all relevant dynamics (eigenmodes)

- ✓ Different aircraft states are measured with different types of sensors: sensor calibration and fusion

- ✓ Covered part of flight envelope defines range of model validity (and €€€)

- ✓ Flight tests are costly, so prepare and plan well!

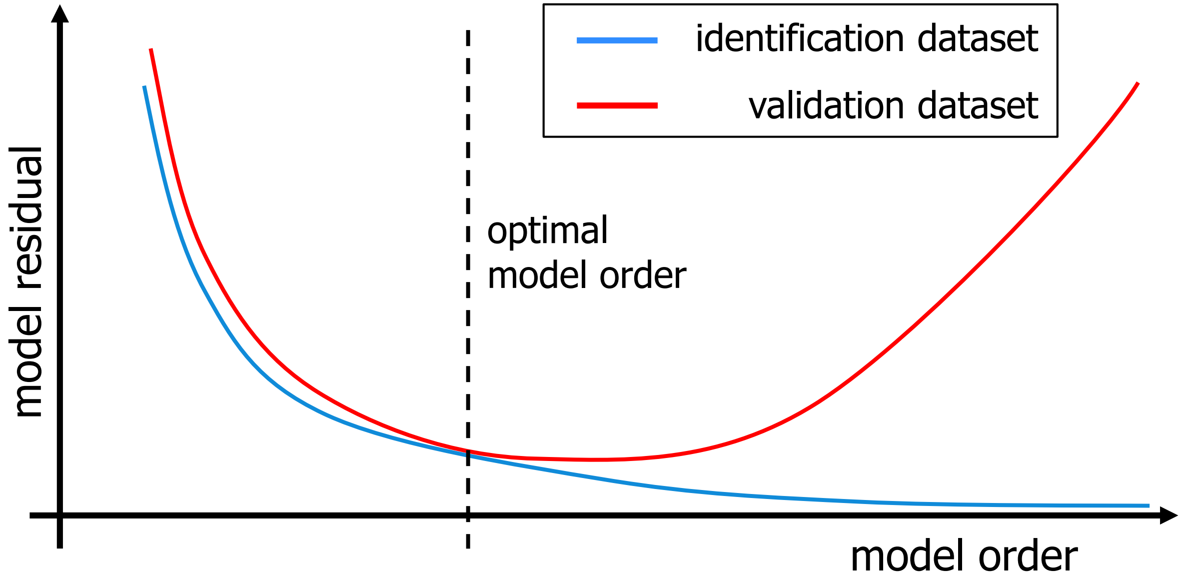


General System Identification Experiment Considerations

Identification & Validation Datasets

Data must be split into a separate identification and validation datasets:

- Identification of a model performed using the **identification dataset**.
- The identified model is then tested against the **validation dataset**.



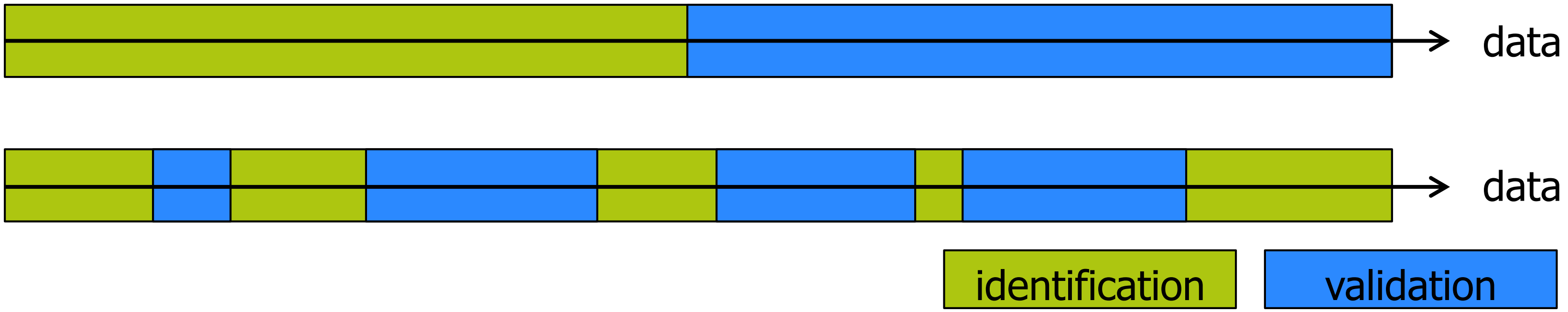
Identification & Validation Datasets

Splitting the dataset into identification and validation sets can be done in many different ways.

In general we want to have a **validation** dataset that is **as large as possible!**

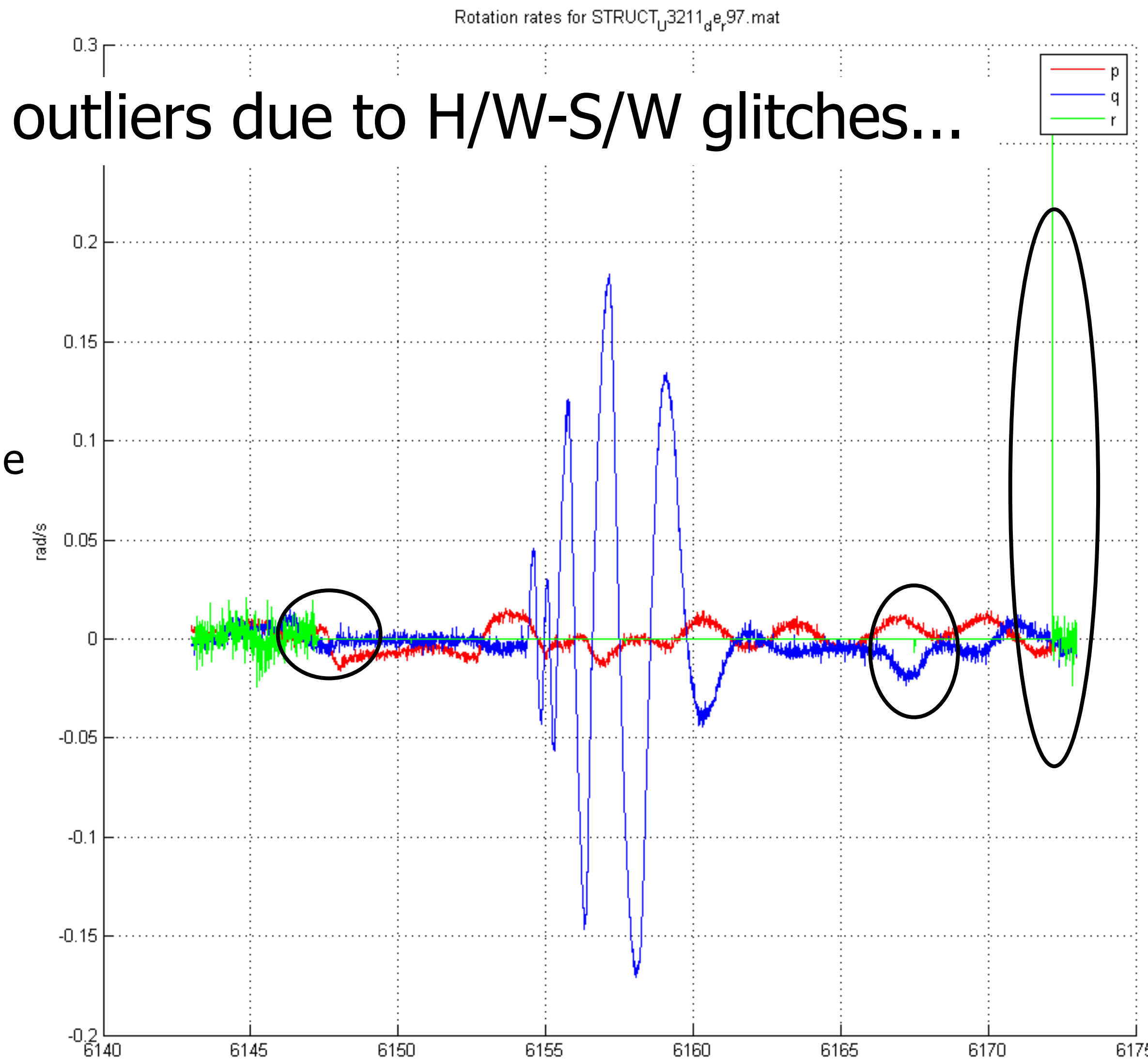
In any case, try to divide into a identification set containing at least 50% of the data, and a validation set containing 50% of the data. Make sure the validation **set contains sufficient dynamics!**

There are many different strategies for splitting the dataset:



Data Sanitation and Preconditioning

Raw data contains outliers due to H/W-S/W glitches...



Spot the glitches!

- In most cases, single outliers...
- In some cases multi-sample outliers...
- In some cases, signal loss for multiple seconds...
- What is real and what is not?

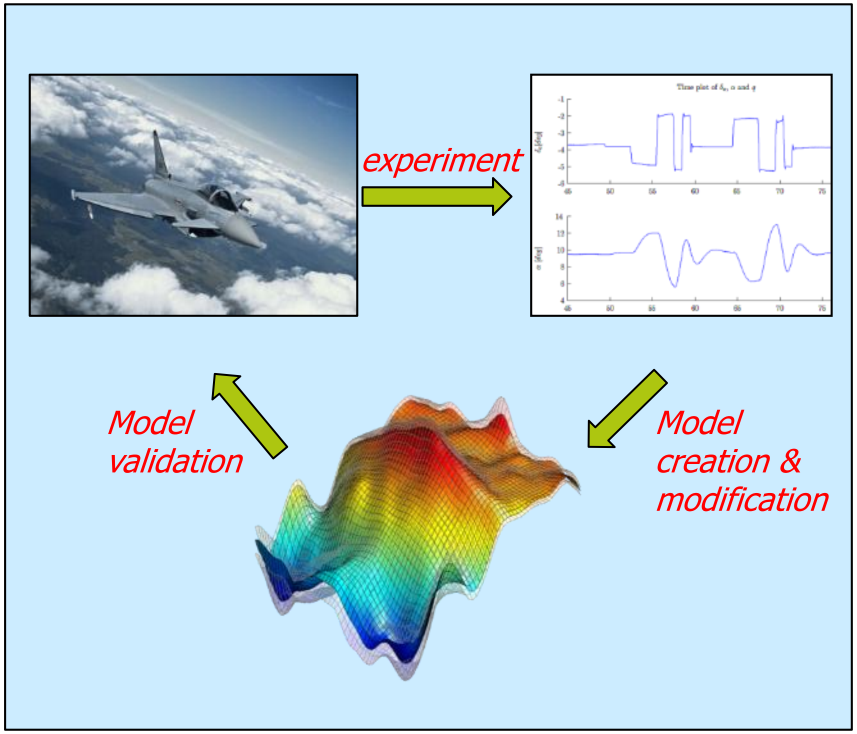
Conclusion: SysID overview

Phases of the System Identification Cycle:

Experiment phase
- Plant analysis
- Experiment design and execution
- Data logging and pre-processing

Model estimation phase
- Model structure definition
- State estimation
- Parameter estimation

Model validation phase
- Model validation



Conclusion: Goals of this Lecture

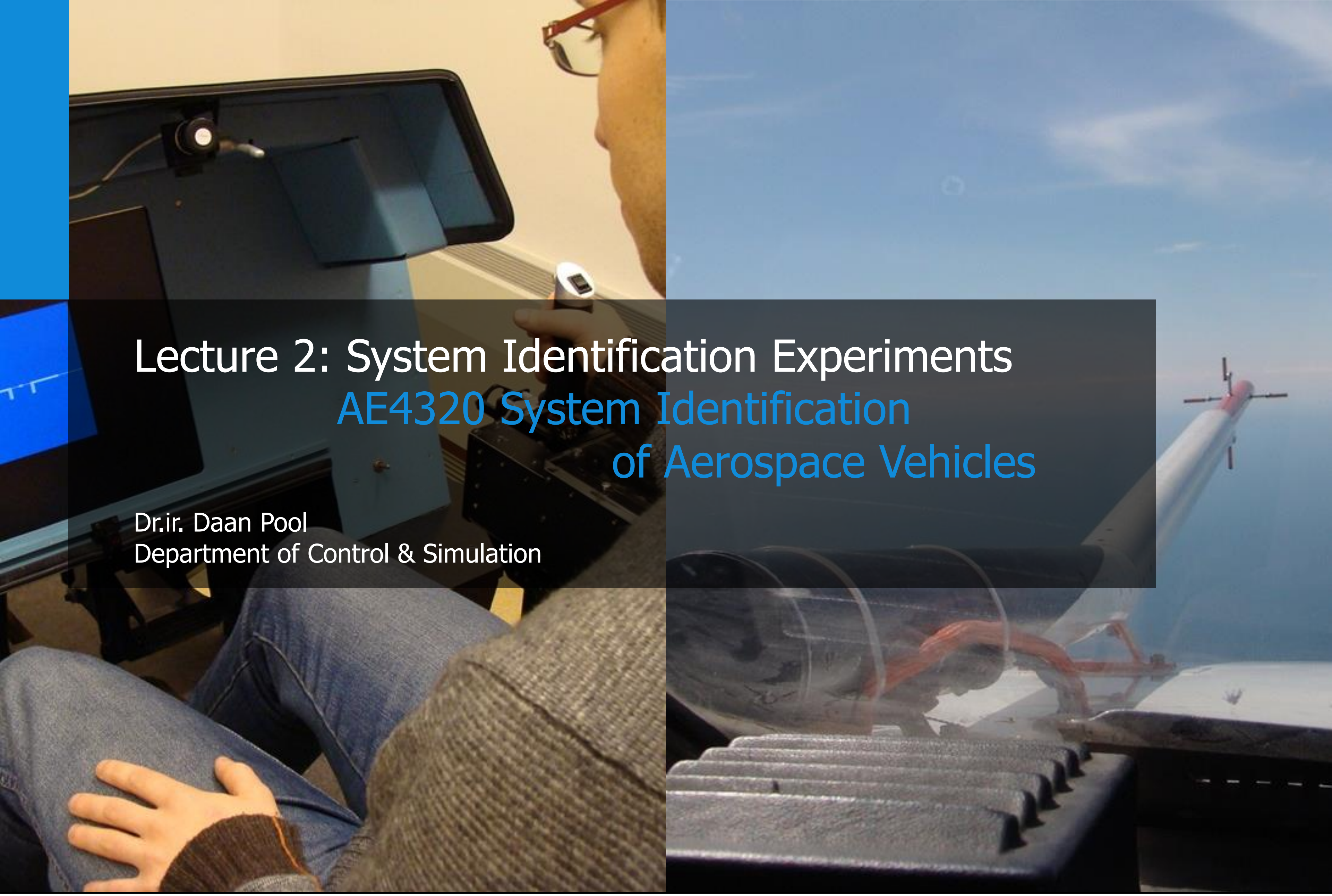
Questions that were answered during this lecture:

1. Q: How are the <u>model objectives</u> related to the experiment that is performed to collect the data for system identification?
   - A1.1: Choice of model inputs, outputs, and scope ("flight envelope") defines <u>model validity</u>.
   - A1.2: Choice of model inputs and outputs determines <u>what should be measured</u> in the experiment.
2. Q: How do we design <u>inputs</u> for a system identification experiment?
   - A2: Design input maneuvers based on <u>initial plant analysis</u>, so that all <u>relevant system dynamics are excited</u>.
3. Q: How do we <u>conduct</u> a system identification experiment?
   - A3: Select/install/calibrate/certify necessary sensors, data logging equipment, create flight test cards/logbooks, use designed inputs to collect data for <u>all measurement conditions</u>.

Conclusion: Goals of this Lecture

Questions that will be answered during this lecture:

4. Q: What do we measure and how do we measure it?
   - A4.1: We will measure all variables that were identified as model inputs and outputs during the initial plant analysis, and which can be measured directly.
   - A4.2: If these variables are directly measurable, we use specialized sensors to measure them. Variables that cannot be measured directly will be estimated in a process called *state estimation* (topic of next lectures!).
   - A4.3: To keep track of all measurements (different conditions), plan ahead: proper experiment design and logging.
   - A4.4: The raw data may have timing issues or contain sensor glitches which must be removed before system identification!



Lecture 2: System Identification Experiments

AE4320 System Identification of Aerospace Vehicles

Dr.ir. Daan Pool
Department of Control & Simulation