System Identification of Flexible Aircraft

NASA Aeroservoelasticity (ASE) Simulation Workshop

18 - 19 April 2012, National Institute of Aerospace, Hampton, VA

Deutsches Zentrum für Luft- und Raumfahrt (DLR)
German Aerospace Center - Institute of Flight Systems, Braunschweig

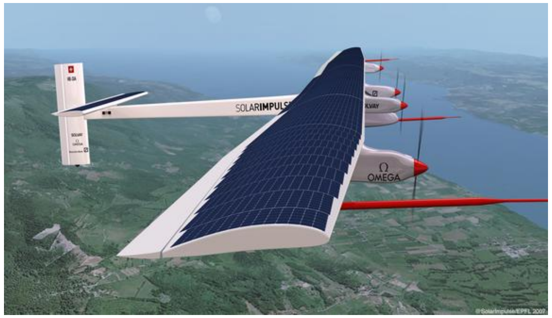
Overview

- Introduction
- Motivation
- System Identification
- Flight Test Campaign (SB10 Sailplane)
- Flight Test Instrumentation
- Flexible A/C Model for SysID
- Identification Results
- Future Research

Introduction

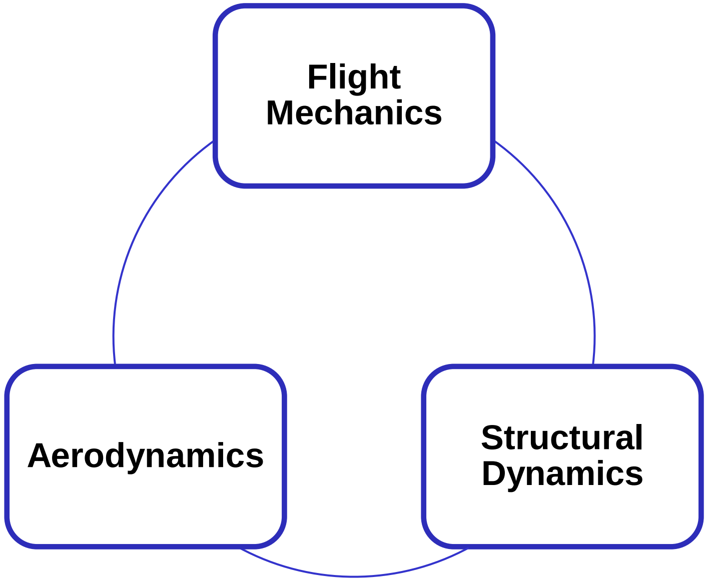
- Flexible aircraft
    - Interaction between rigid body and aeroelastic dynamics
    - Close structural and rigid body frequencies

- Use of optimized structures - weight saving
- Higher aspect ratios / thinner airfoils
- Very large transport aircraft
- Environmentally friendly aircraft



Motivation I

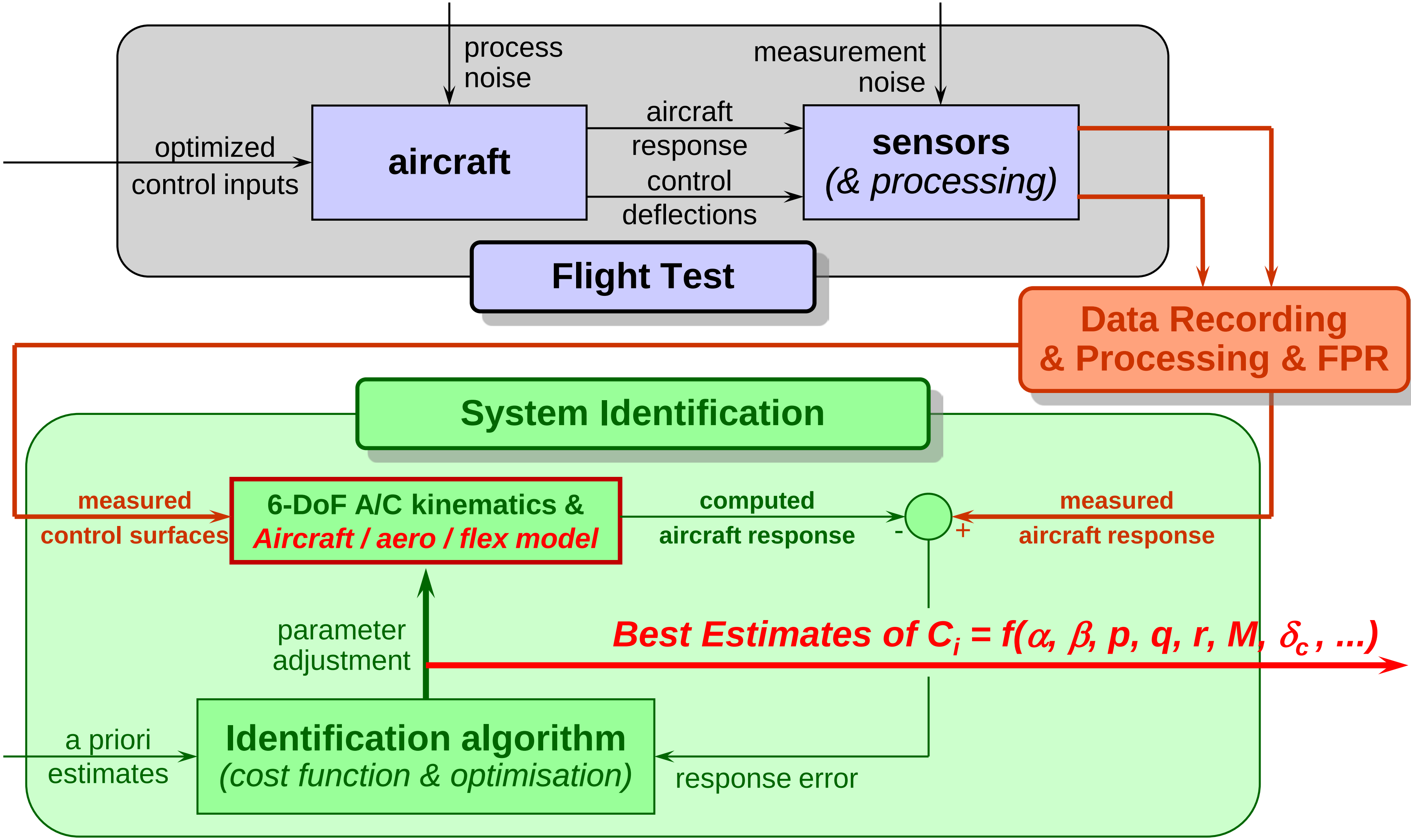
- A new modeling approach for the flight dynamics, accounting for the influence of structural deformation, has special importance:
  - Simulators for assessment of aeroelastic effects on handling qualities
  - Design of flight control laws to improve passenger comfort
  - Alleviation of structural loads during maneuvers or entering gusts



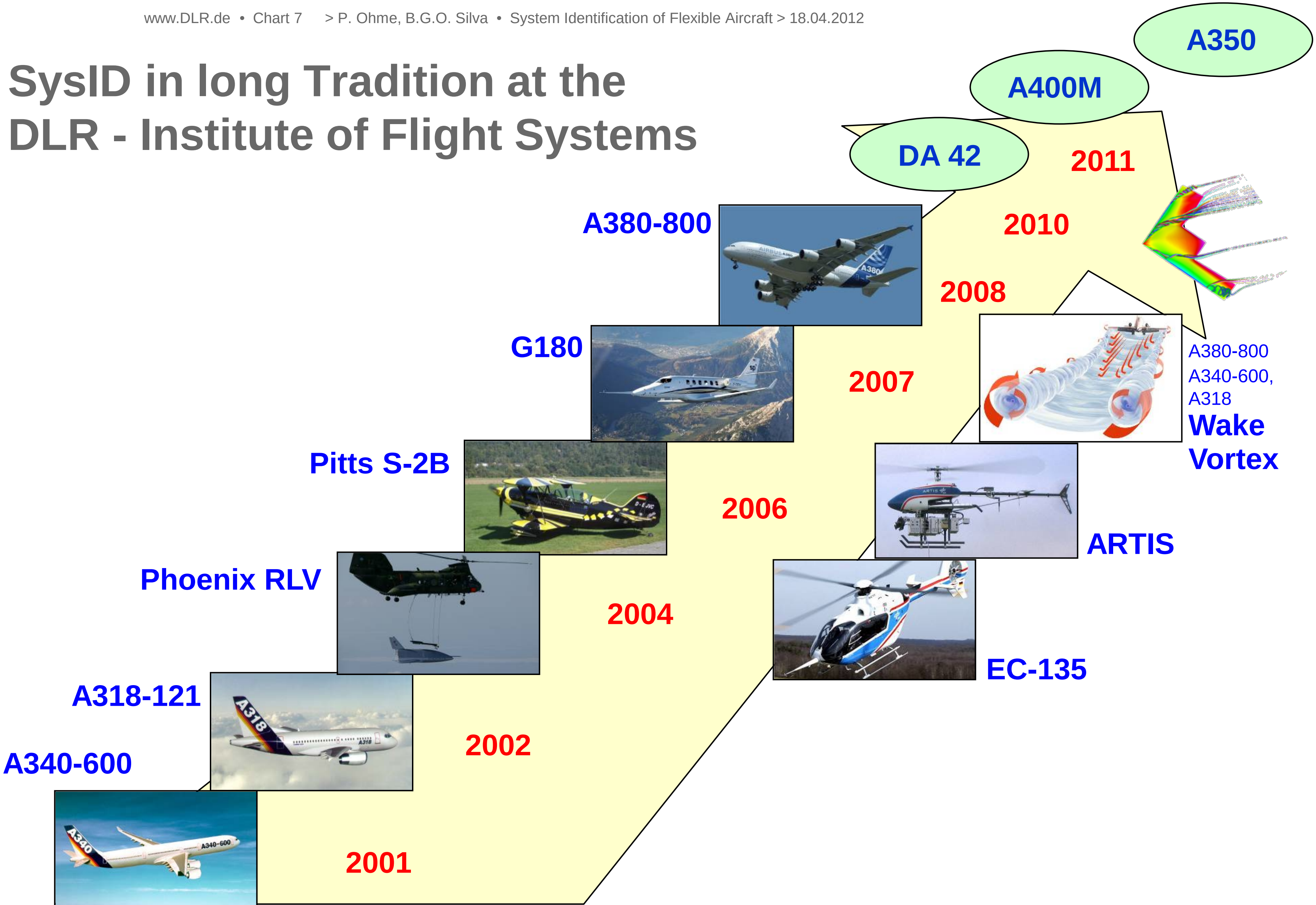
- Search for a model of flexible aircraft:
  - With affordable computational cost (for real time applications)
  - Represented in a parametric form
  - Validated from real flight data

Motivation II

- Main objectives
  - Propose an integrated model of the dynamics of the “Flexible Aircraft”, suitable for parameter estimation in time domain
  - Investigate and propose flight test techniques to enable identification of the model
  - Validate the identified model from real flight test data

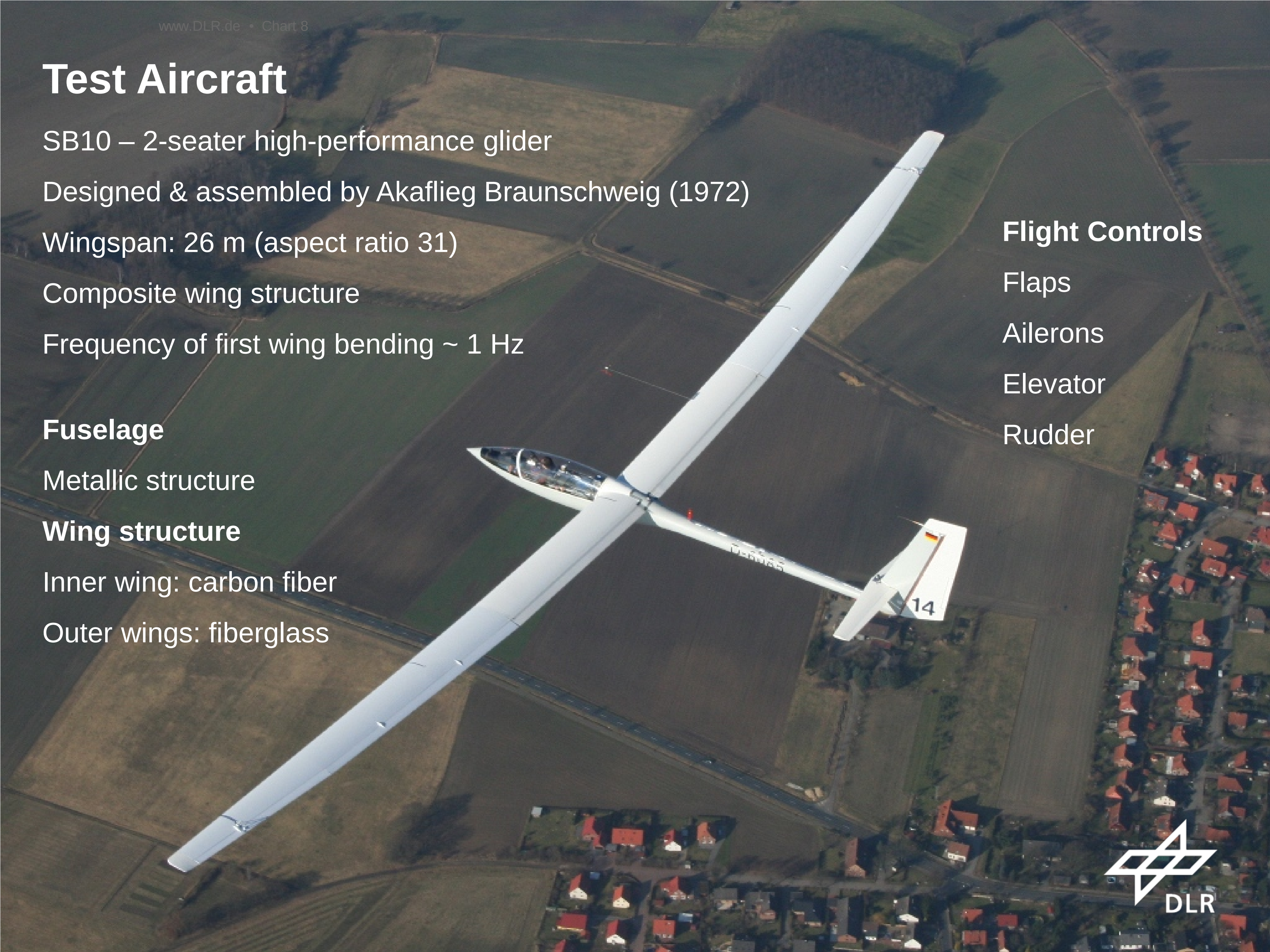

process
noise
measurement
noise
optimized
control inputs
aircraft
aircraft
response
control
deflections
sensors
(& processing)
Flight Test
Data Recording
& Processing & FPR
System Identification
measured
control surfaces
6-DoF A/C kinematics &
Aircraft / aero / flex model
computed
aircraft response
-
+
measured
aircraft response
parameter
adjustment
Best Estimates of $C_i = f(\alpha, \beta, p, q, r, M, \delta_c, ...)$
a priori
estimates
Identification algorithm
(cost function & optimisation)
response error

SysID in long Tradition at the DLR - Institute of Flight Systems



DLR

Test Aircraft



SB10 – 2-seater high-performance glider

Designed & assembled by Akaflieg Braunschweig (1972)

Wingspan: 26 m (aspect ratio 31)

Composite wing structure

Frequency of first wing bending ~ 1 Hz

Fuselage

Metallic structure

Wing structure

Inner wing: carbon fiber

Outer wings: fiberglass

Flight Controls

Flaps

Ailerons

Elevator

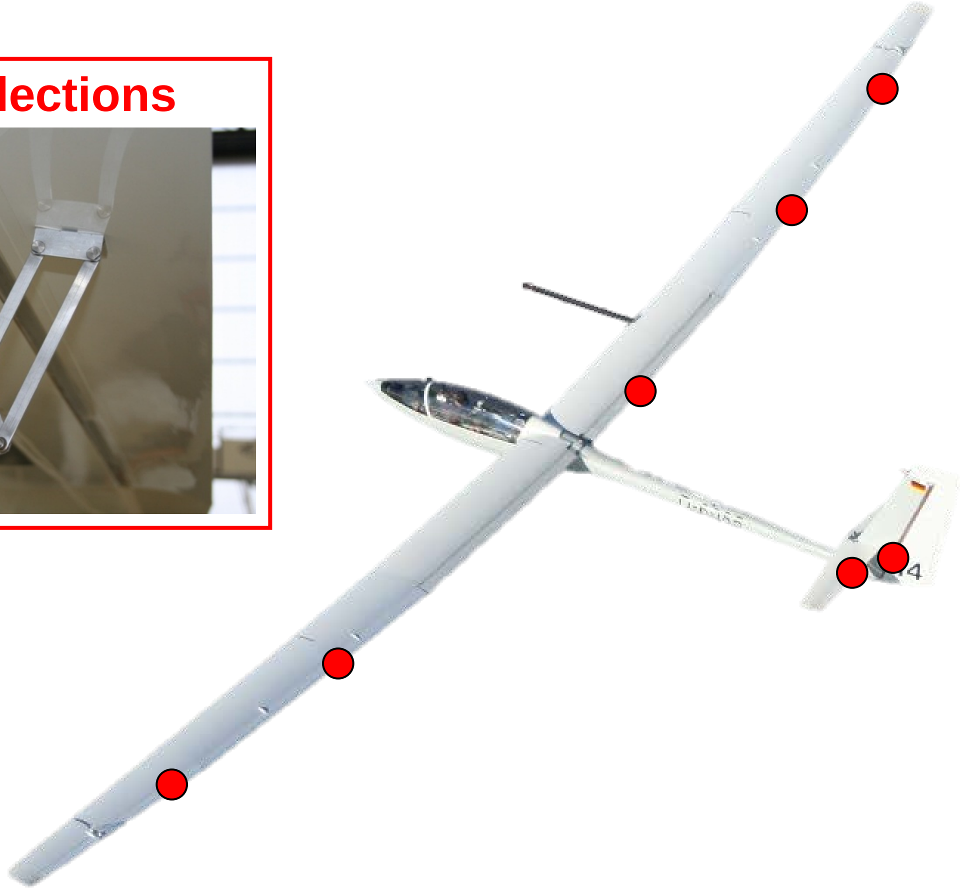
Rudder

Flight Test Campaign

- November 2010 – January 2011
- 11 flights – 11 flight hours – 72 test points
- Towed T/O and climb to 3.000 m (≈ 10.000 ft)
- 2 test IAS – 110 and 160 km/h (59 and 86 kt)
- 1 flap setting – (position "-1")

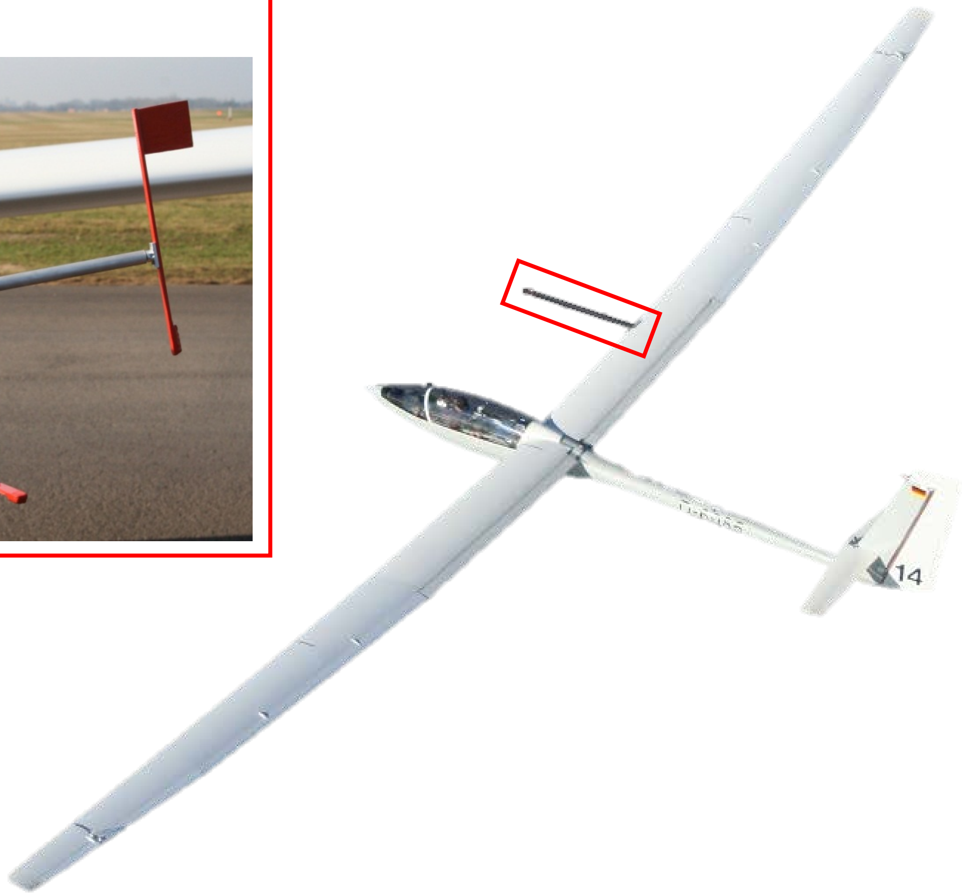
Flight Test Instrumentation

Control deflections



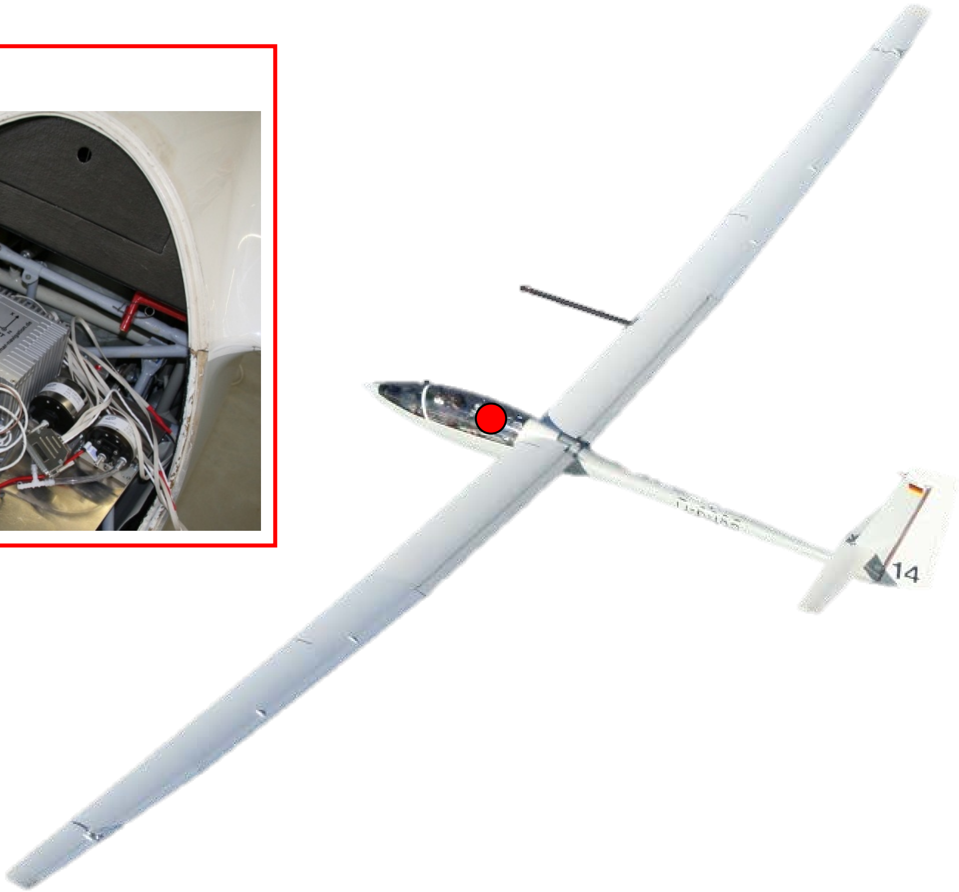
Flight Test Instrumentation

α and β



Flight Test Instrumentation

IMU



ϕ, θ, ψ

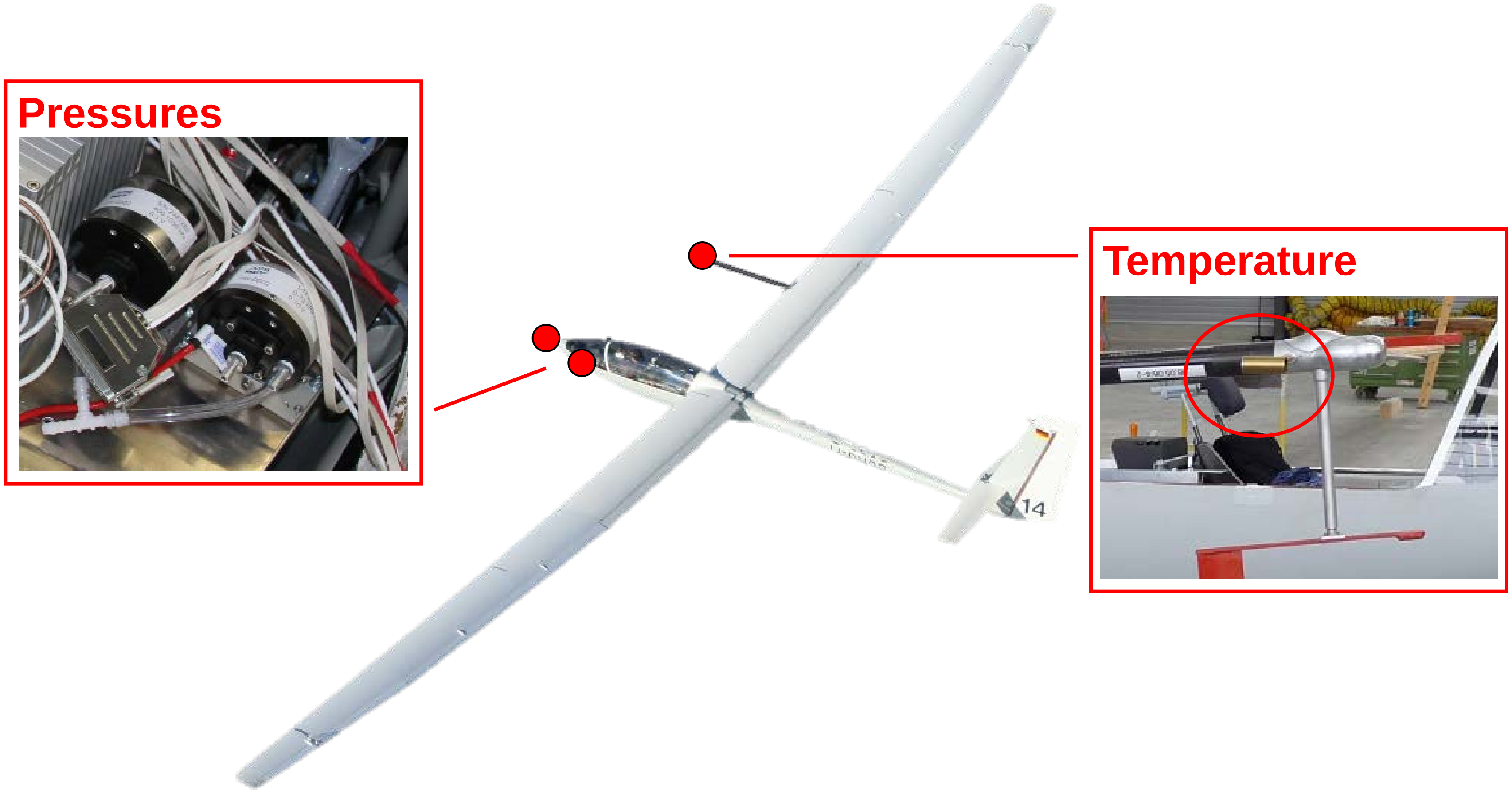
p, q, r

a_x, a_y, a_z

φ, λ, h

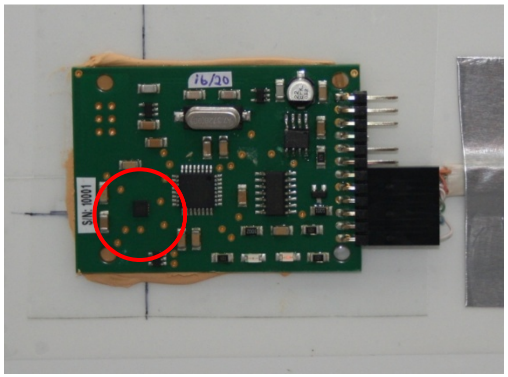
…

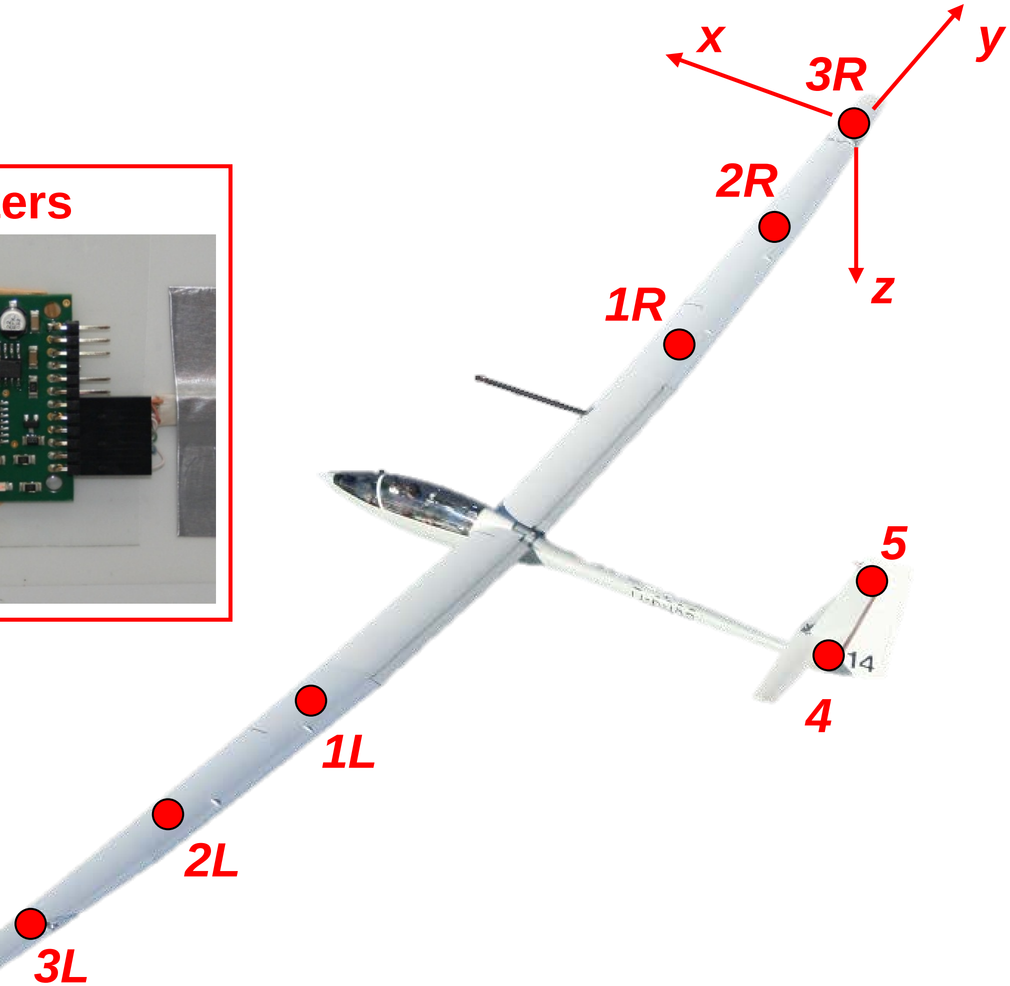
Flight Test Instrumentation



Flight Test Instrumentation

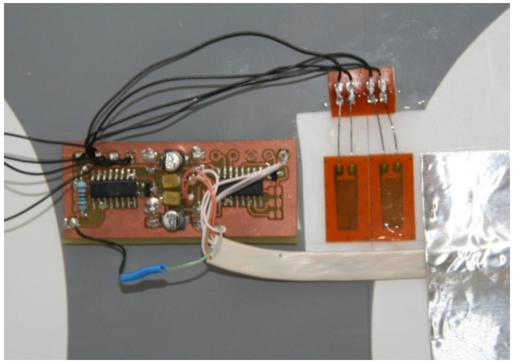
Accelerometers

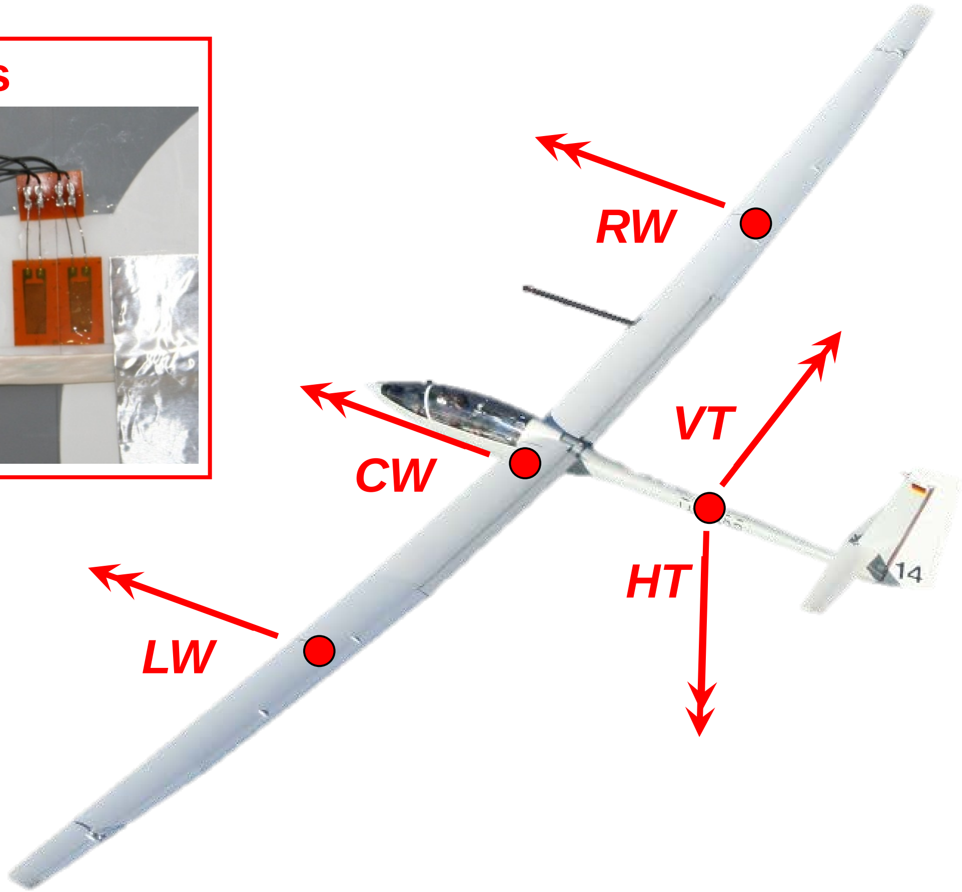




Flight Test Instrumentation

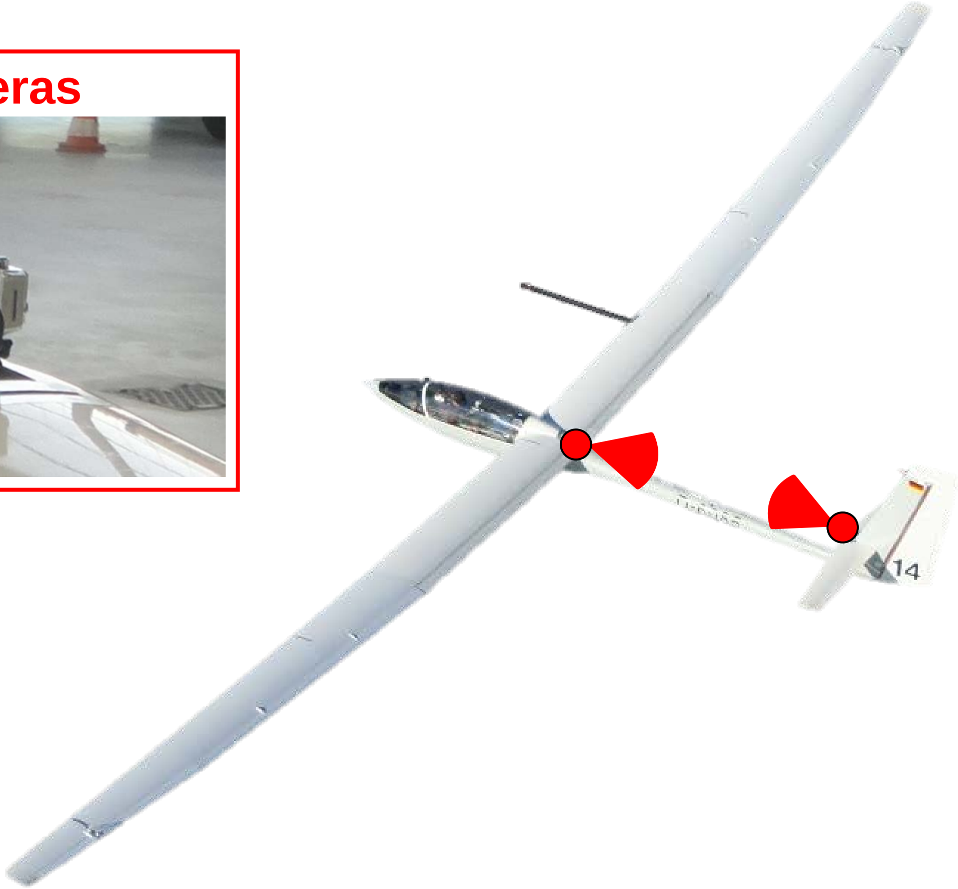
Strain gauges





Flight Test Instrumentation

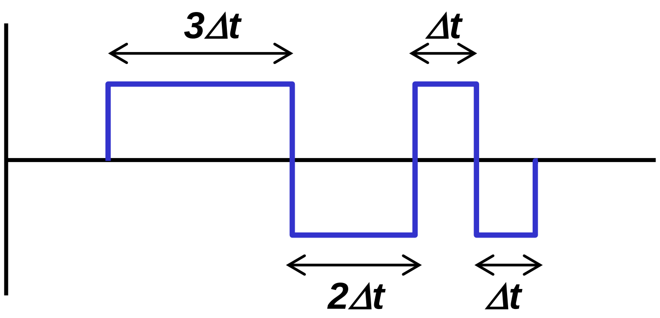
Video Cameras



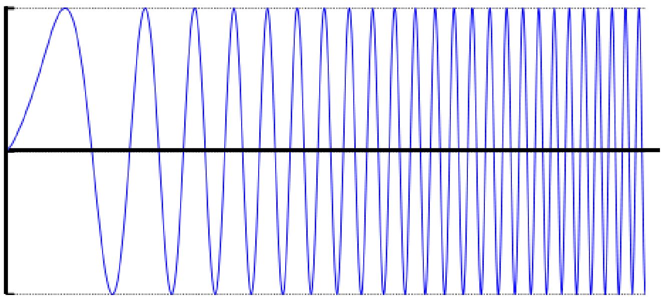
Flight Test Planning

- Maneuvers
    - Excitation of modes of interest (rigid body + aeroelastic)
    - Piloted maneuvers

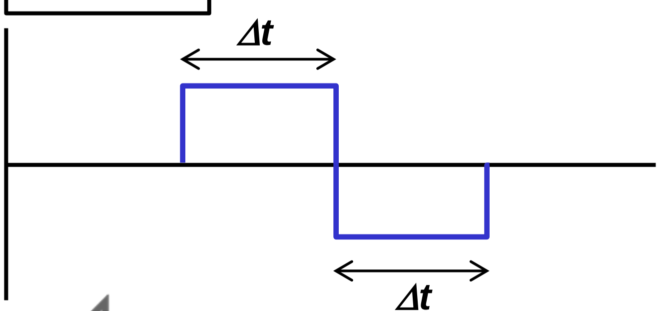
3-2-1-1



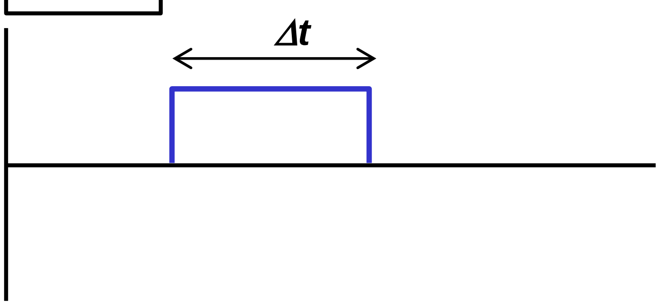
Frequency sweep



Doublet



Pulse



Maneuvers performed

Maneuver	Control Surfaces				Identification	Validation
	Elevator	Ailerons	Rudder	Flaps		
Pulse	✓				✓	✓
				✓	✓	
3-2-1-1	✓	✓	✓	✓	✓	
Doublet				✓	✓	
			✓		✓	✓
	✓				✓	✓
Frequency sweep	✓	✓	✓		✓	✓
				✓	✓	
Pushover-pullup	✓				✓	
Bank-to-bank		✓			✓	
Step response		✓	✓			✓
Spiral stability						✓


System Identification of Flexible Aircraft
D-6085
14
Flight test campaign
DLR

Flexible Model applied for Identification

- based on Waszac and Schmidt (1988)

- Structural dynamics → modal representation

$$\vec{d}_i(x,y,z,t) = \vec{\Phi}_i(x,y,z)\eta_i(t)$$

- Equations of motion (simplified for longitudinal dynamics, 1st wing bending)

Rigid

$$\dot{u} + qw + g\sin\theta = {}^{X}\!/_{m}$$

$$\dot{w} - qu - g\cos\theta = {}^{Z}\!/_{m}$$

$$\dot{q} = {}^{M_y}\!/_{I_{yy}}$$

Flexible

$$\ddot{\eta}_1 + \zeta_1\omega_1\dot{\eta}_1 + \omega_1^2\eta_1 = {}^{Q_1}\!/_{m_1}$$

Rigid | Flexible

$$X = X_R + X_F$$

$$Z = Z_R + Z_F$$

$$M_y = M_{y_R} + M_{y_F}$$

$$Q_1 = Q_{1_R} + Q_{1_F}$$

Influence elastic modes → rigid body forces / moments

Influence rigid body motion → generalized loads

Influence modal deflections → generalized loads

DLR

Flexible Model applied for Identification

- Rigid body aerodynamics
    - Stability and control derivatives approach
    - 2-point model
- Effects of flexibility
    - Quasi-static aerodynamic model

$$Z_F = \bar{q}S\left(c_{z_{\eta_1}}\eta_1 + c_{z_{\dot{\eta}_1}}\frac{\dot{\eta}_1\bar{c}}{2V}\right)$$

- Identifiability issues

$$\ddot{\eta}_1 = -\underline{\zeta_1\omega_1}\dot{\eta}_1 - \underline{\omega_1^2}\eta_1 + \underbrace{\frac{\bar{q}S\bar{c}}{m_1}\left(\underline{c_{\eta_{1_{\eta_1}}}}\eta_1 + \underline{c_{\eta_{1_{\dot{\eta}_1}}}}\frac{\dot{\eta}_1\bar{c}}{2V}\right)}_{Q_{1_F}} + \underbrace{\frac{\bar{q}S\bar{c}}{m_1}\left(c_{\eta_{1_{\delta_e}}}\delta_e + c_{\eta_{1_{\delta_f}}}\delta_f + c_{\eta_{1_\alpha}}\alpha + c_{\eta_{1_q}}\frac{q\bar{c}}{2V}\right)}_{Q_{1_R}}$$

$$\ddot{\eta}_1 = -\zeta_{1_{eq}}\omega_{1_{eq}}\dot{\eta}_1 - \omega_{1_{eq}}^2\eta_1 + \frac{\bar{q}S\bar{c}}{\underline{m_1}}\left(c_{\eta_{1_{\delta_e}}}\delta_e + c_{\eta_{1_{\delta_f}}}\delta_f + c_{\eta_{1_\alpha}}\alpha + c_{\eta_{1_q}}\frac{q\bar{c}}{2V}\right)$$

Flexible Model applied for Identification

- Effects of flexibility on measurements (Observation equations)
  - Angular rates (IMU)

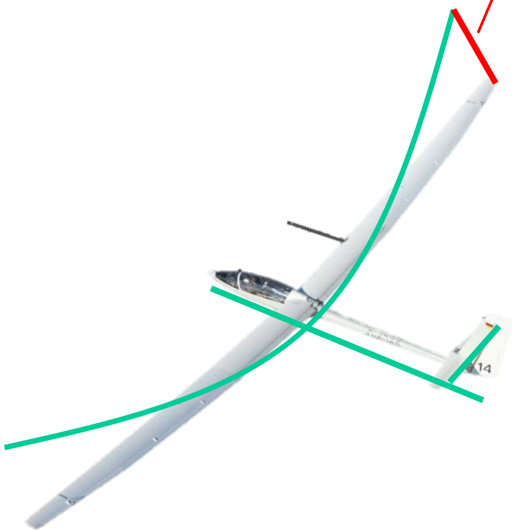
$$q_m^{IMU} = q + v_{y1}^{IMU}\,\dot{\eta}_1$$

  - Accelerometers

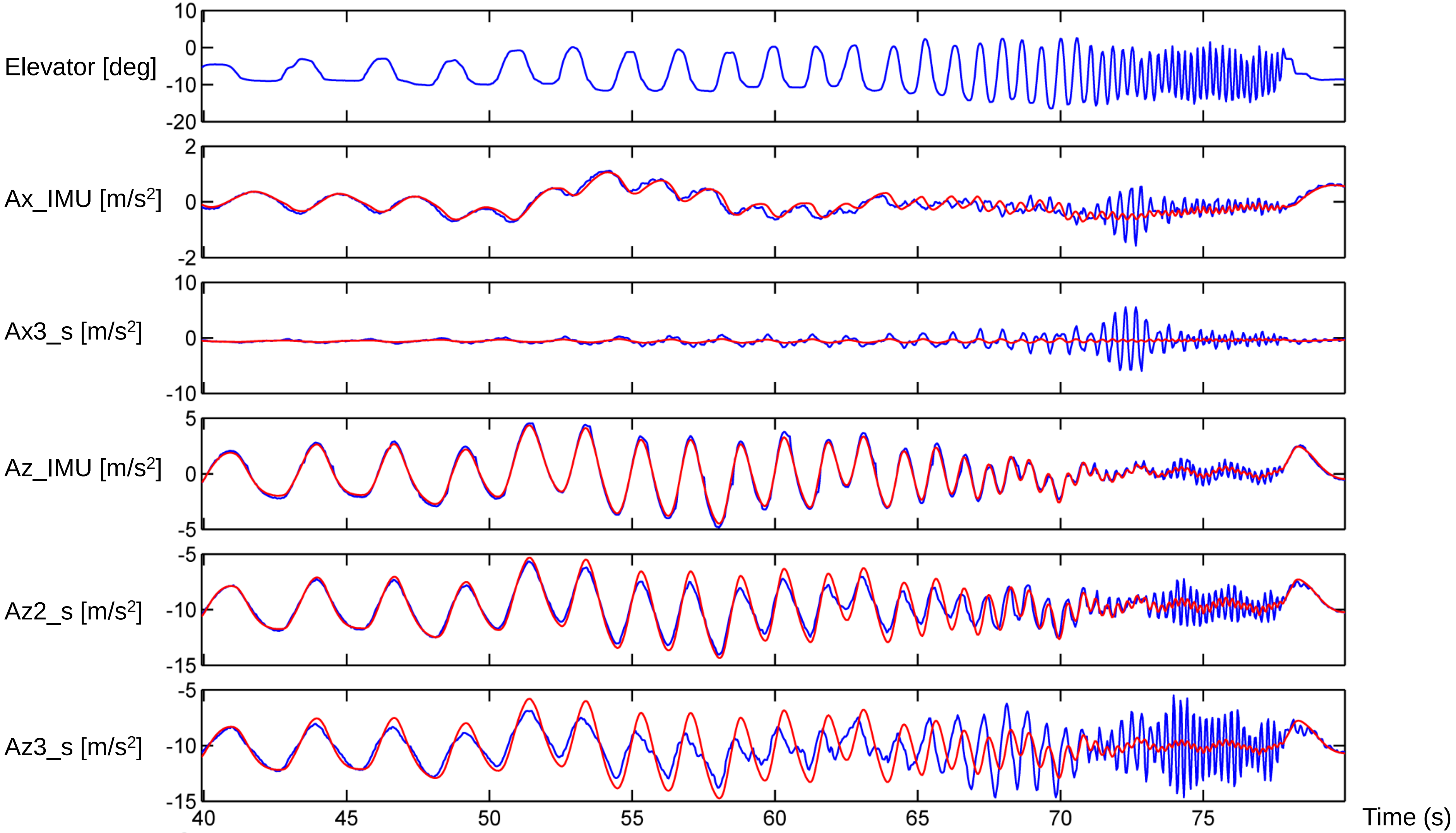
$$a_{z_k} = a_{z_{CG}} - z_k q^2 + x_k \dot{q} + \Phi_z^k \ddot{\eta}_1$$

  - Strain gauges

$$\sigma_k = \sigma_0^k + \sigma_{\eta_1}^k \eta_1$$

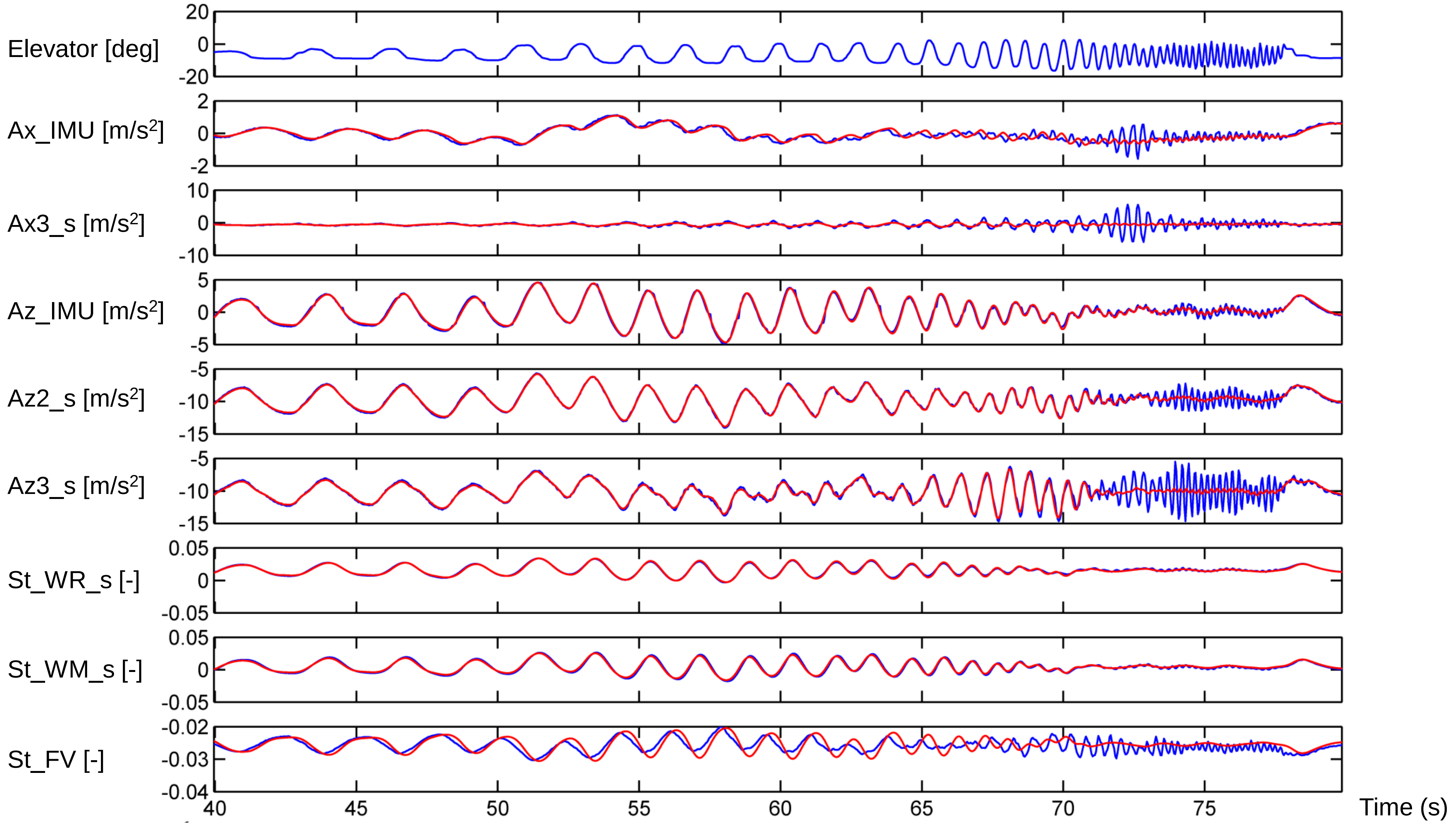


Identification Results – Elevator sweep
Rigid body (27 parameters)

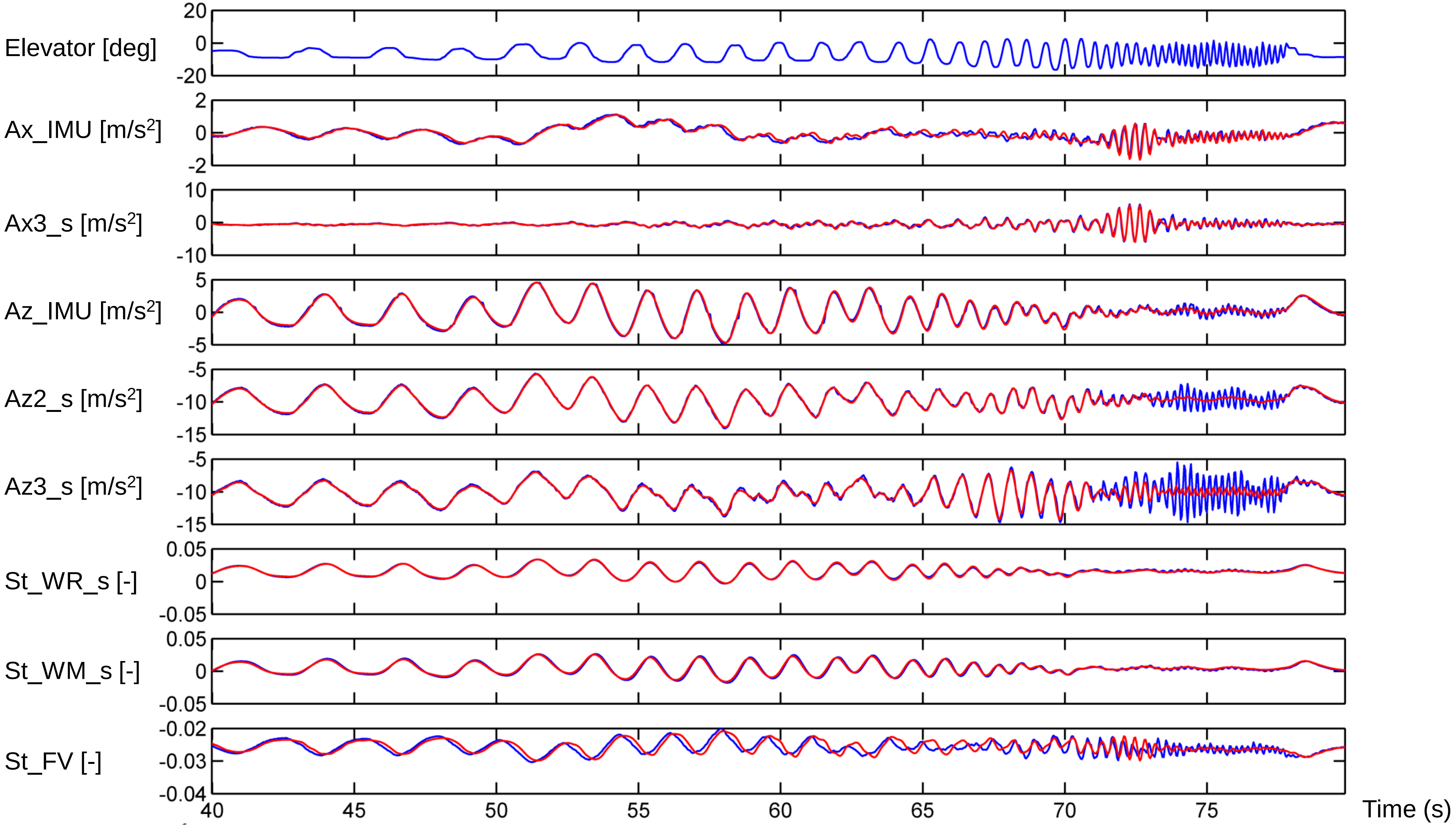


DLR

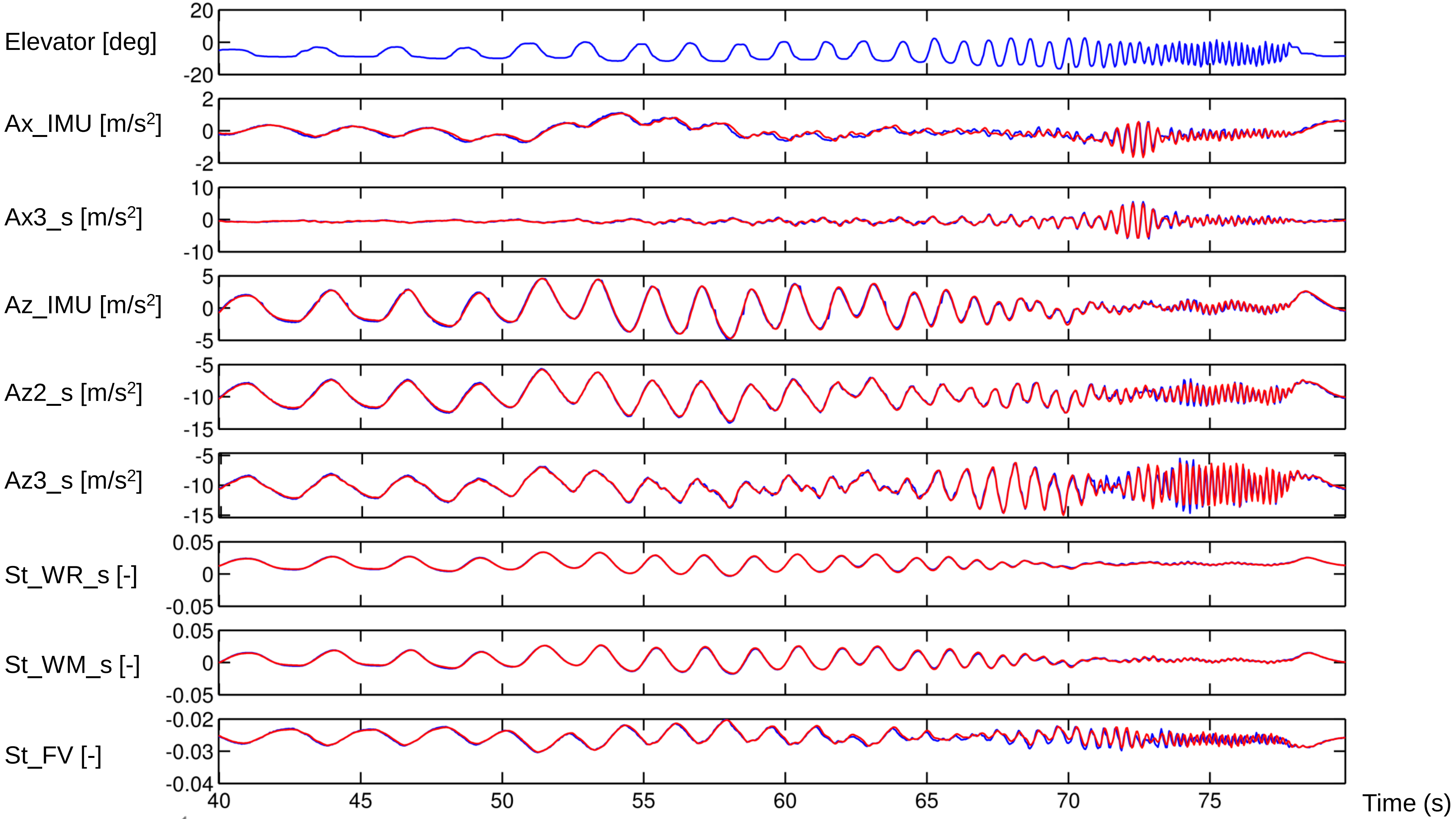
Identification Results 1 – Elevator sweep + 1st vertical wing bending, symmetric (49 parameters)



Identification Results 2 – Elevator sweep
+ 1st wing in-plane bending, symmetric (64 parameters)

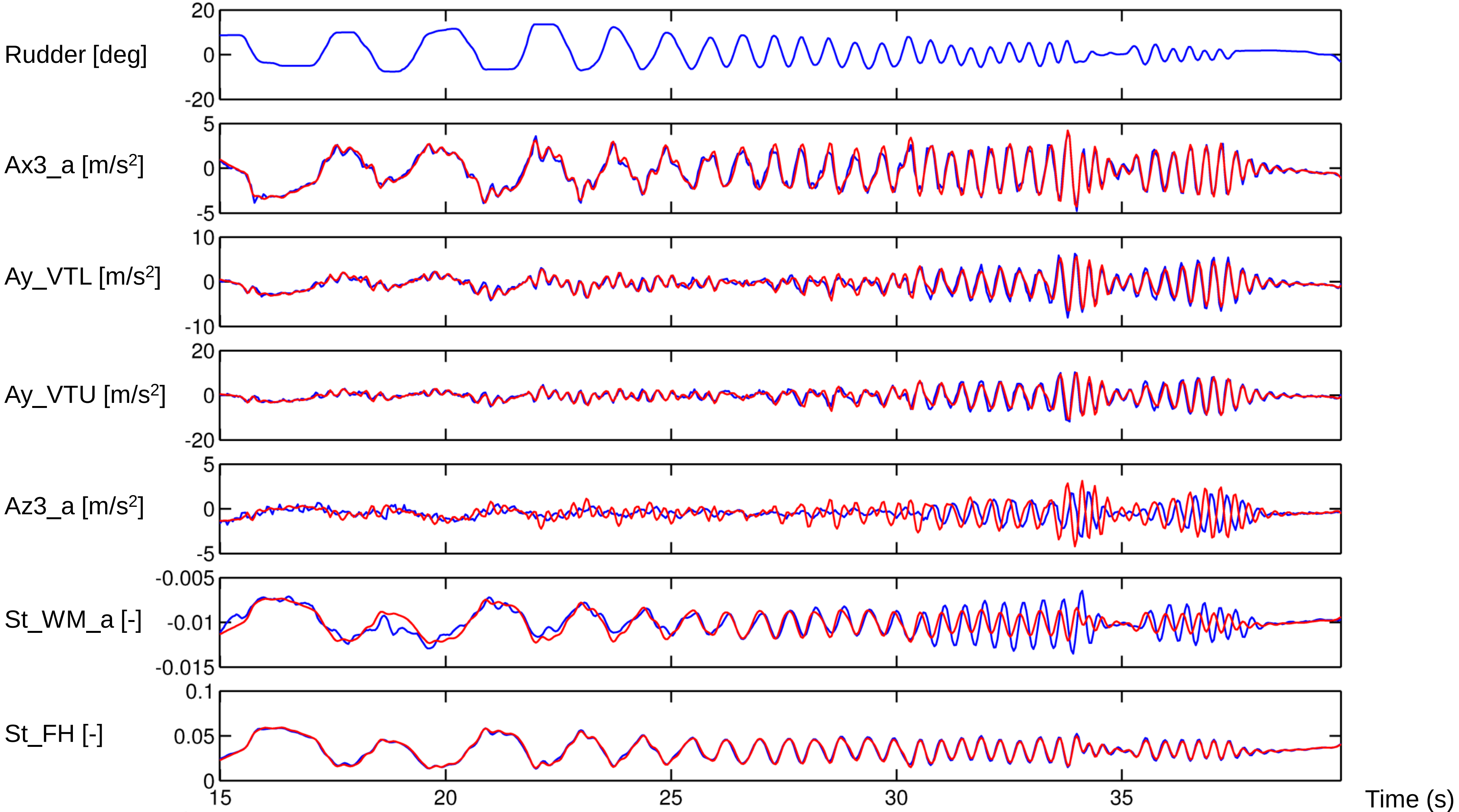


Identification Results 3 – Elevator sweep + 2nd vertical wing bending, symmetric (82 parameters)

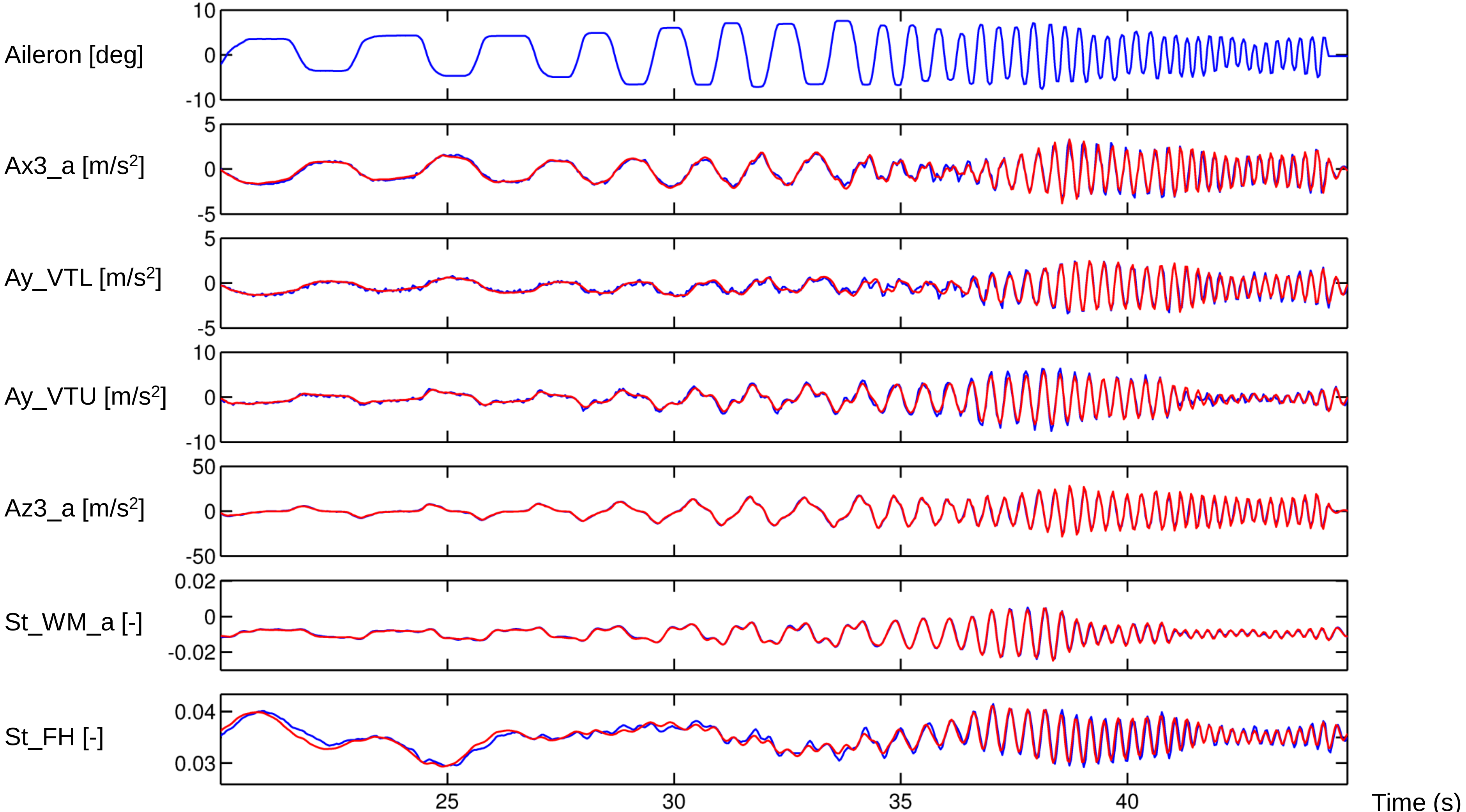


DLR

Identification Results 4 – Rudder sweep
+ 1st fuselage bending / torsion, anti-symmetric (102 parameters)



Identification Results 5 – Aileron sweep
+ 1st vertical wing bending, anti-symmetric (121 parameters)



DLR

Summary of SB10 System Identification

- **Adequate experimental setup, data acquisition & data evaluation**
  - Maneuvers & FTI provide adequate information for system identification
  - Adequate modeling approach
  - Good matching of accelerations and strains
  - Identified parameters are consistent and with low standard deviations
    → good quality estimates

- **Adopted methodology of system identification demonstrates the suitability to flexible aircraft models**

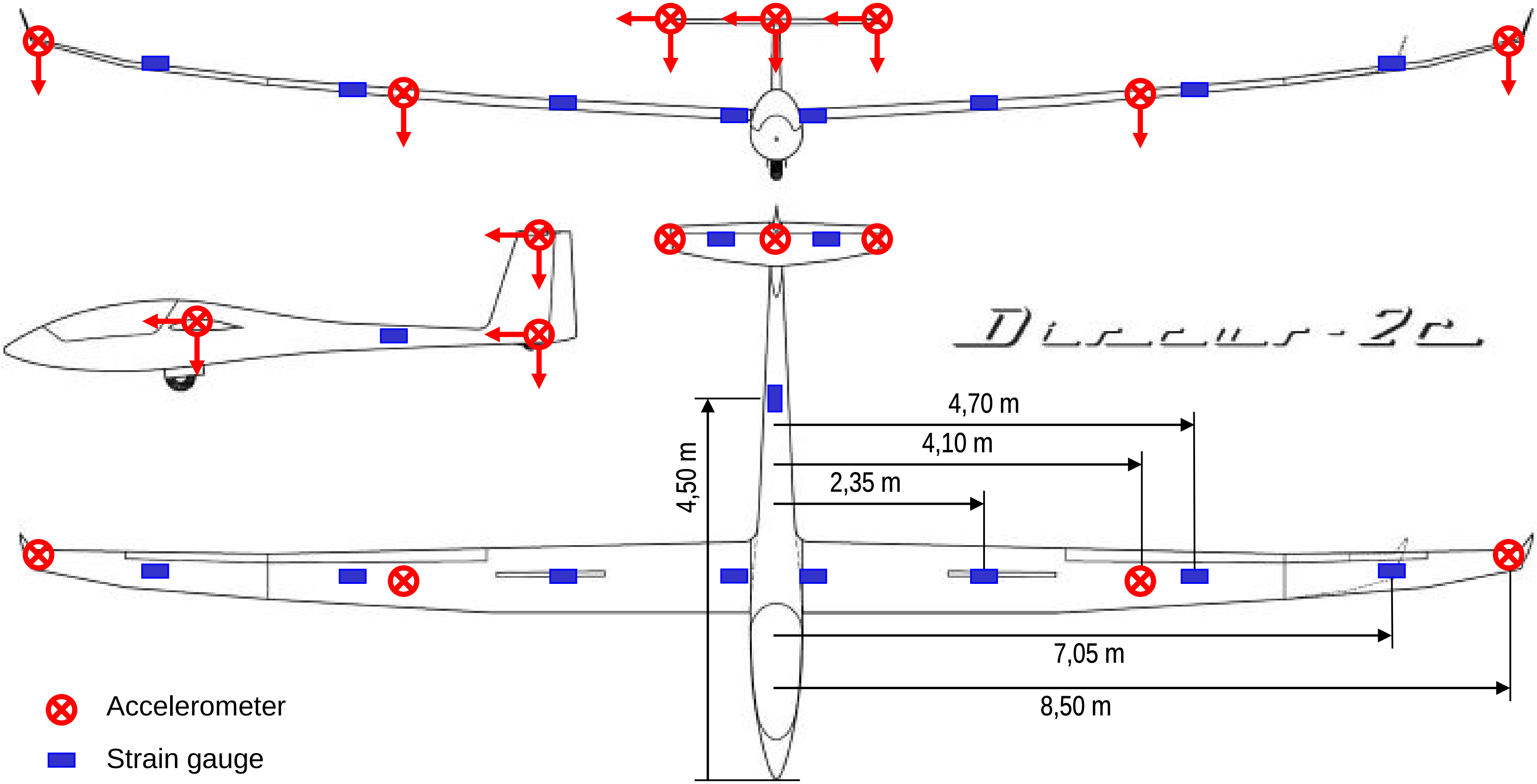
- **Future work**
  - Extension to higher symmetric modes
  - Include more lateral-directional / anti-symmetric dynamics
  - Impact of flexibility upon dynamic stability modes
  - Run the parameter estimation at different flight conditions
  - Perform a rigorous validation analysis

New Discus 2c - DLR (Schempp-Hirth Flugzeugbau)

- Wing span: 18 m (aspect ratio 28.5)
- First flight tests with full instrumentation end of 2012
- Typical measurement system: IMU, GPS, air data, Alfa, Beta, …
- Additional measurements: Accelerations, strains A/C structure

DLR

Accelerometers / Strain Gauges - Discus 2c-DLR



⇨ All sensors installed inside the aircraft structure

Additional Strain Measurements (experimental phase)

- Implementation of optical fibers with Bragg-Gratings in fuselage and right wing additional to typical strain gauges
- Measurement of bending, shear deformation and temperature

ARES (Advanced Research Simulator)

ARES (Advanced Research Simulator)

- DLR's new simulation facility for flight research is currently built up in cooperation with Technical University Braunschweig

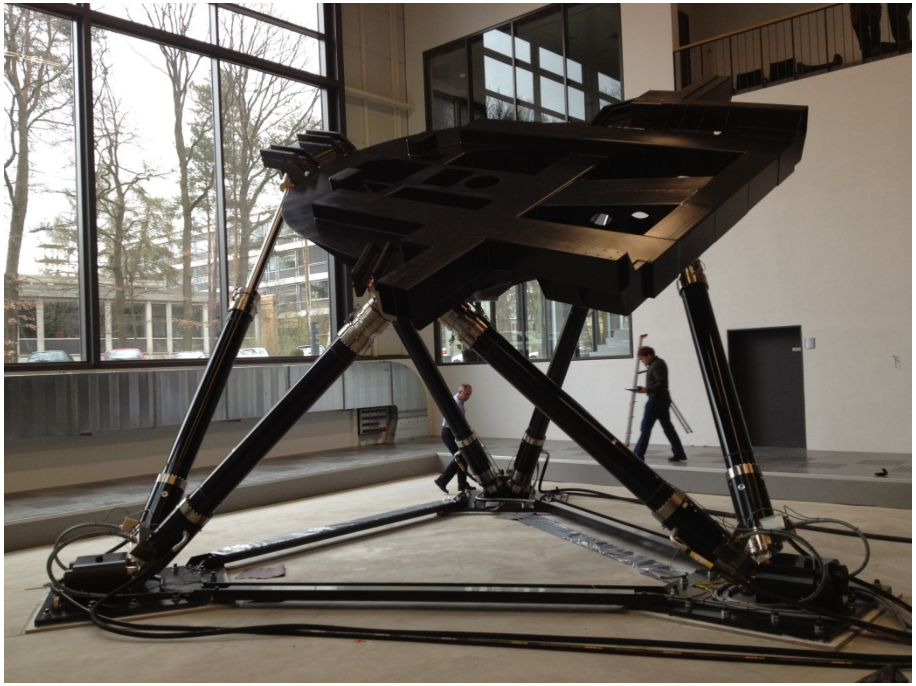
- The main research topic is the exploration of the

  dynamic interaction between a human pilot and the aircraft

- The simulation facility provides operation of interchangeable cockpits of rotorcraft (EC135) and airplanes (A320) on motion- and fixed-base platforms

- Start of operation is planned for early 2013

ARES – First Construction Phase and Test (April 2012)



ARES - Research Objectives - Airplanes

- Interaction between aircraft flexibility and pilot / flight control system
- Impact of flexibility upon aircraft handling
- Influence of flexibility on passenger comfort
- Flying qualities of new aircraft configurations, such as flying wings
- Future role of the flight crew in a team with the automatic flight control system
- Analysis of the crew's behavior in highly-automated cockpit during unexpected situations
- Wake vortex interaction, pilot assistance and automatic control systems
- Special missions of military transport aircraft

Thank you!

Any Questions?