Flight Dynamics – Tool chains and their use (on the example of Task 1.3 in CESAR)

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Flight Dynamics in Aircraft Design

- Effects:
  - „How the aircraft behaves as an aircraft“
  - Stability and Control
  - Flying Qualities / Handling Qualities

- Impacts:
  - Aircraft dimensioning
    - Empennage
    - Control Surfaces
    - Leverarms
  - Control System
  - …

- Classical Aircraft design approach:

Handbook methods for dimensioning

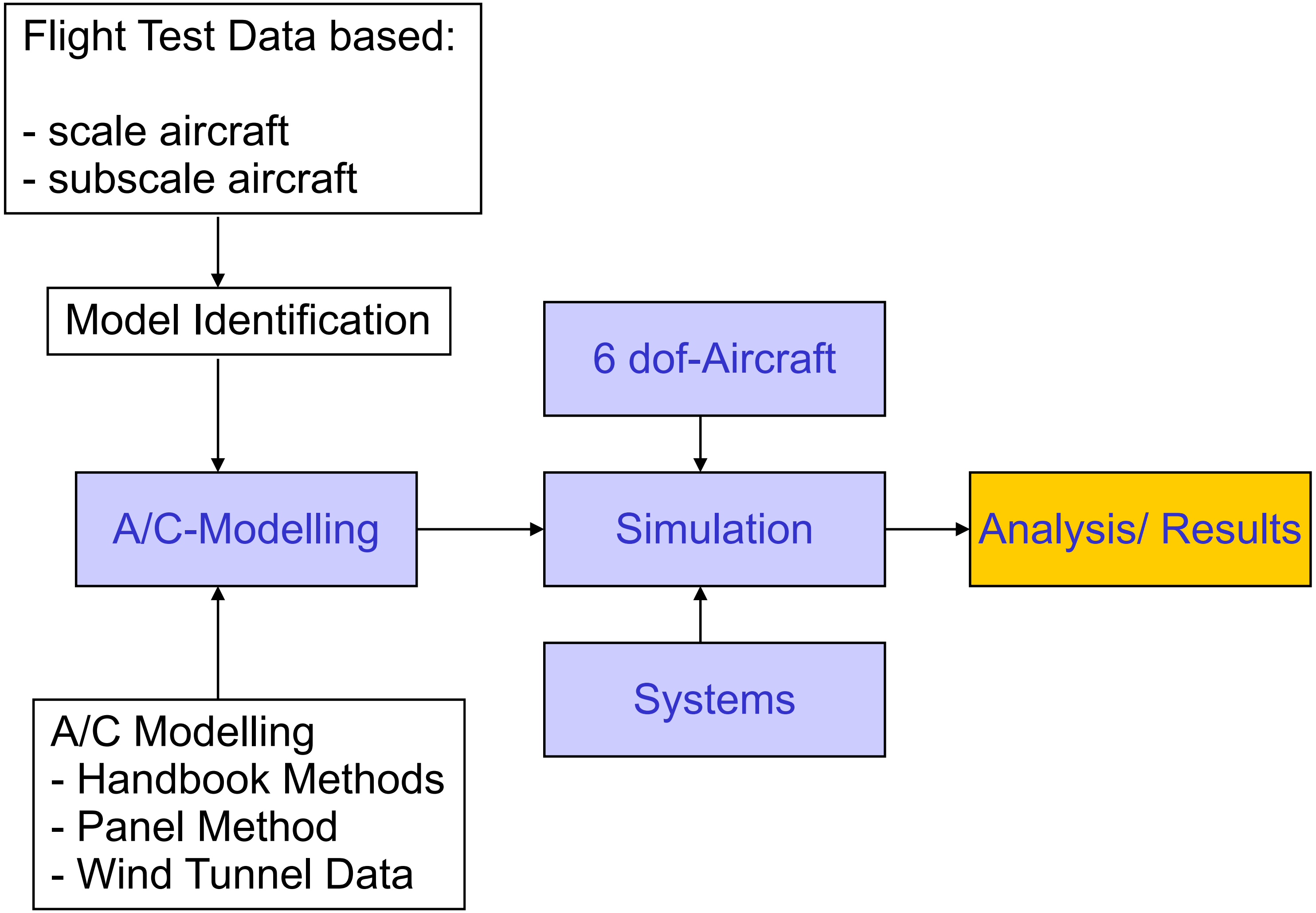
Calculations & Design

Construction & Build

Test & Evaluate

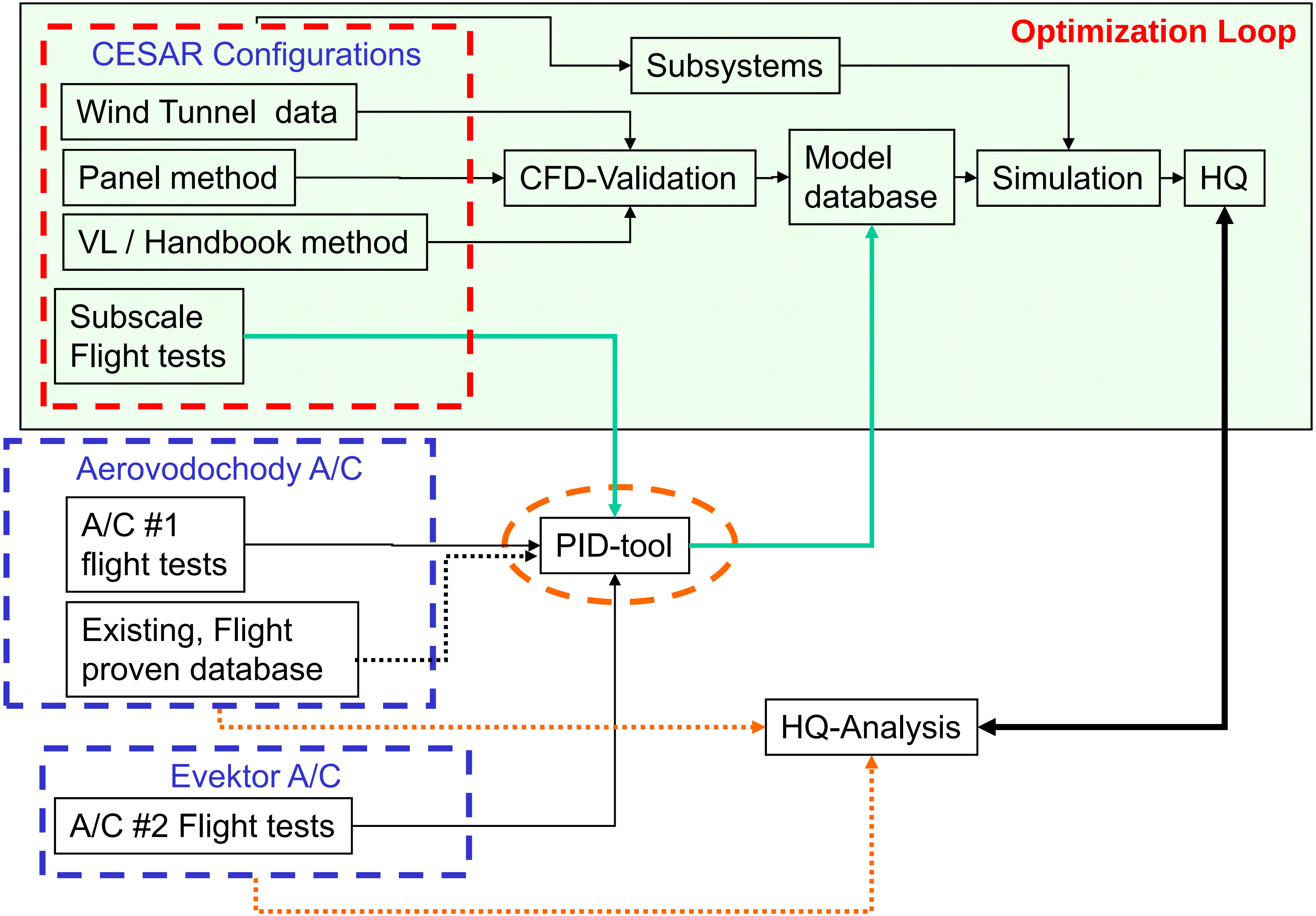
Iterate & reshape design

Rationale:


Flight Test Data based:
- scale aircraft
- subscale aircraft
Model Identification
6 dof-Aircraft
A/C-Modelling
Simulation
Analysis/ Results
Systems
A/C Modelling
- Handbook Methods
- Panel Method
- Wind Tunnel Data

Flight Dynamics – Task 1.3 Workflow

CESAR



Potential for the use of tools & design methods:

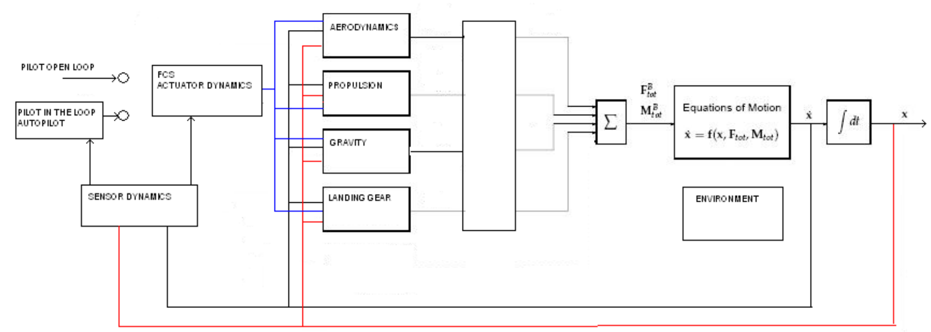
- Shift evaluation and validation forward in the development process
- Reduced live test effort
- Shorter development cycles
- Cost reduction

CESAR

Simulation, Handling Quality and Optimisation Tools

Flight Dynamics Simulation tool

- Detailed mathematical description of the aircraft kinematics and dynamics
- Generic models of typical aircraft subsystems (aerodynamic, propulsion, flight control system, actuators and sensors…)
- Implementation in a non-real-time simulation system.

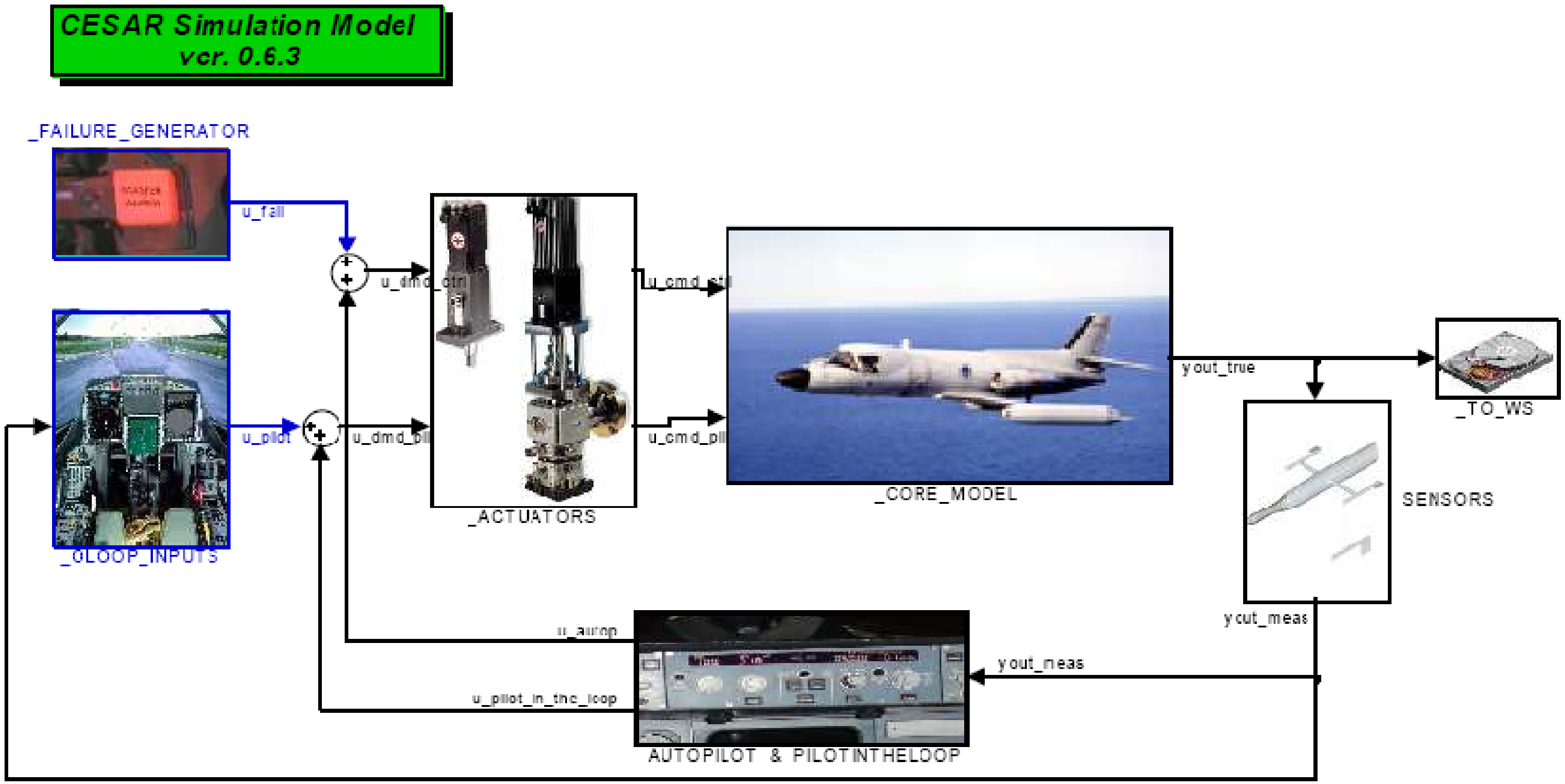


Simulation Model

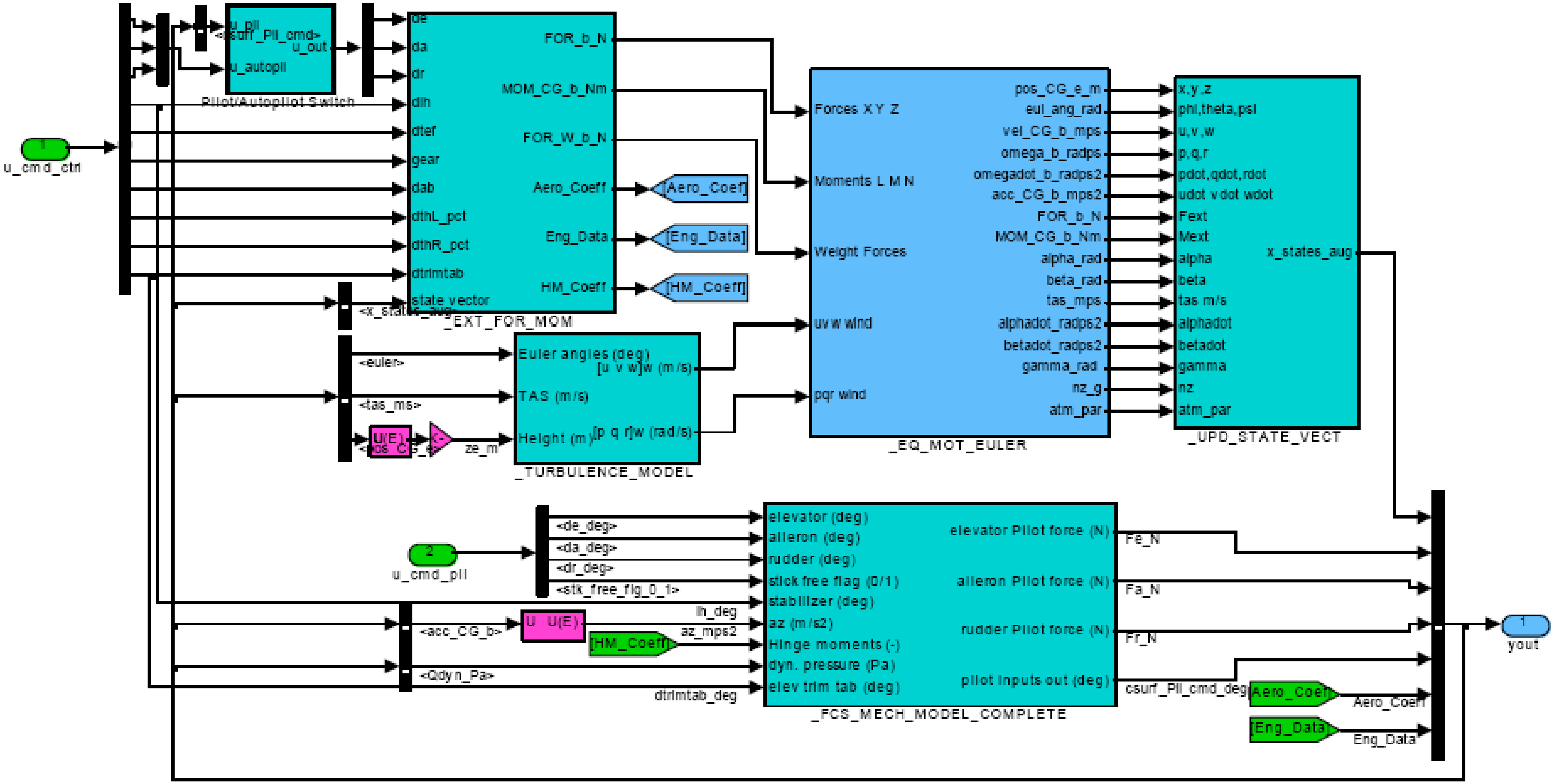
Output of the simulation process will be used for:
- Flight dynamics and handling qualities analysis
- Integrated analysis with parametric design methodologies
- Compute system responses efficiently for each design alternative

Flight Dynamics

System Simulation



Aircaft Simulation Model



Aircraft modelling

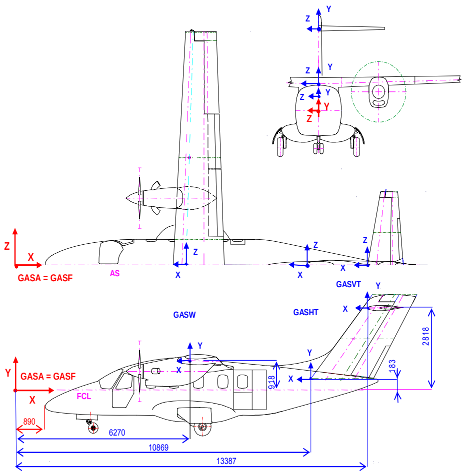
Goal:

Develop the technique for fast and simple generation of valid aerodata using

- Panel Methods (IoA)
- Handbook Methods (VZLU)
- CFD methods

During the period the aircraft Ae270 and Ev55 have been analysed

Aerovodochody Ae-270



Evektor EV-55

How to derive input for a dynamic model from flight tests?

Parameter Identification / Estimation

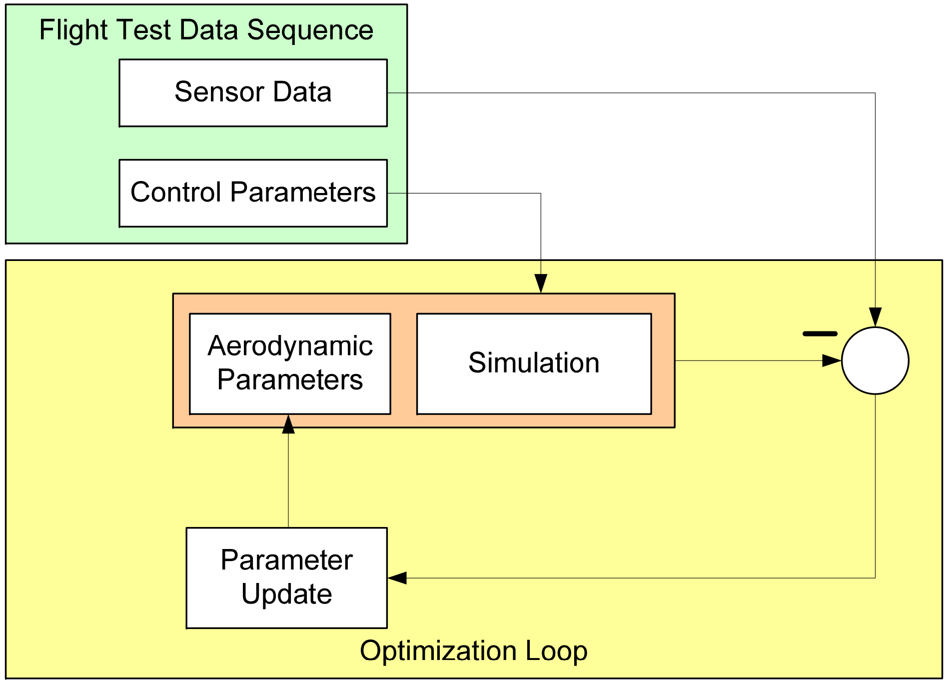
Roughly: Optimize (aerodynamic) model parameters in a way so that control inputs into a dynamic model (sim) lead to the same resulting states as they would in the measured flight test data.

Parameter identification needs to be conducted for various:

- Points in the flight envelope:
  - Airspeed
  - Altitude
- Configurations
  - Gear up/down
  - flaps

Parameter identification Tool:

– The identification process:



Flight Dynamics

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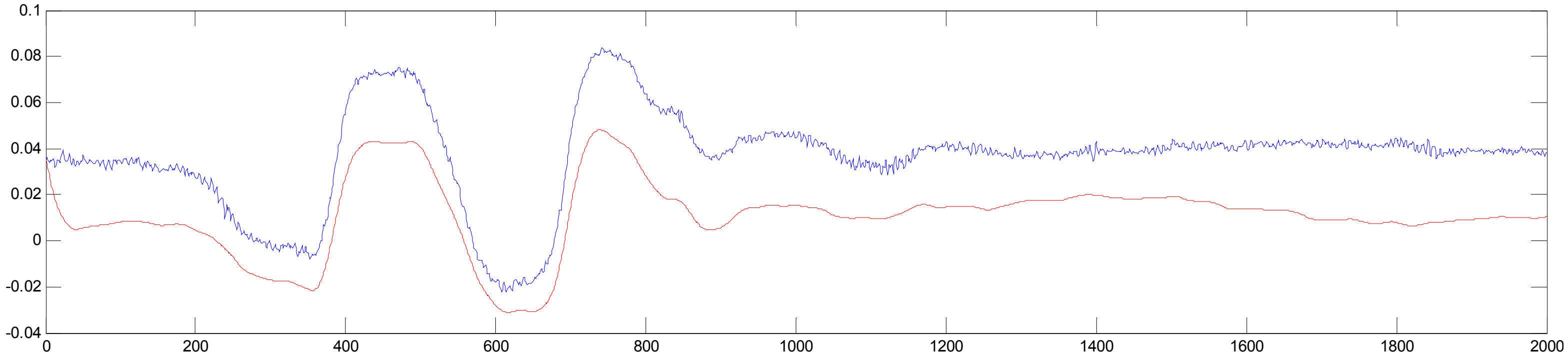
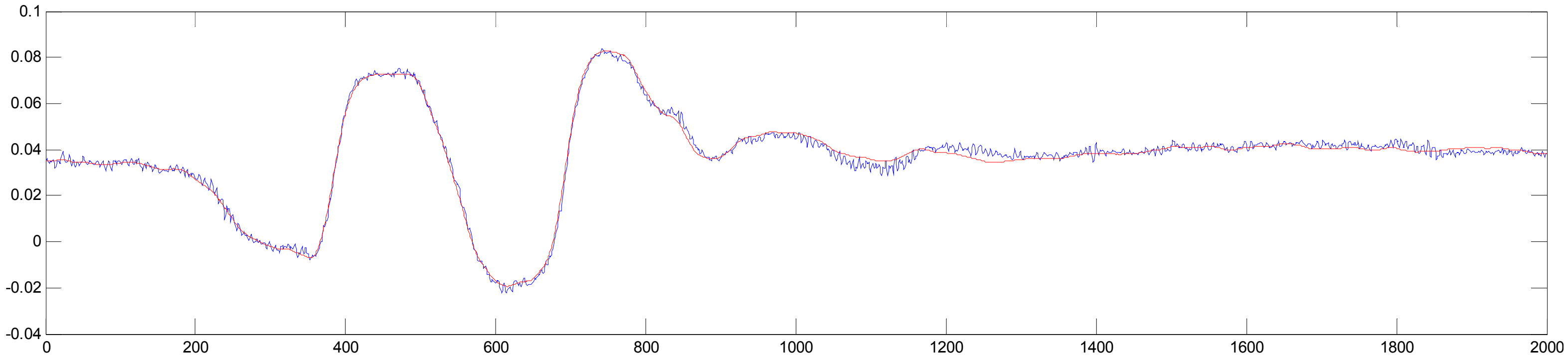
Parameter estimation:

– Fitting example: Angle of Attack

Initial Model



after 10 iterations



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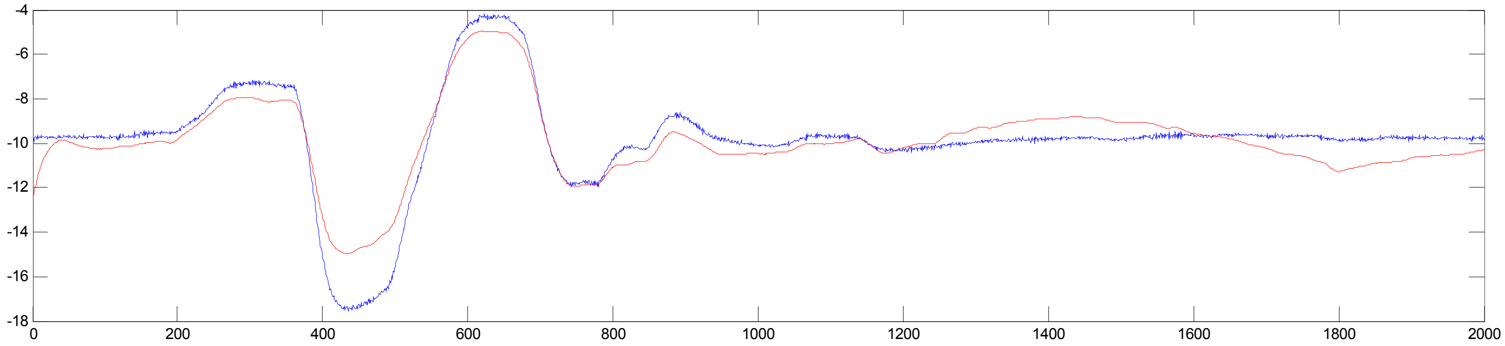
Flight Dynamics

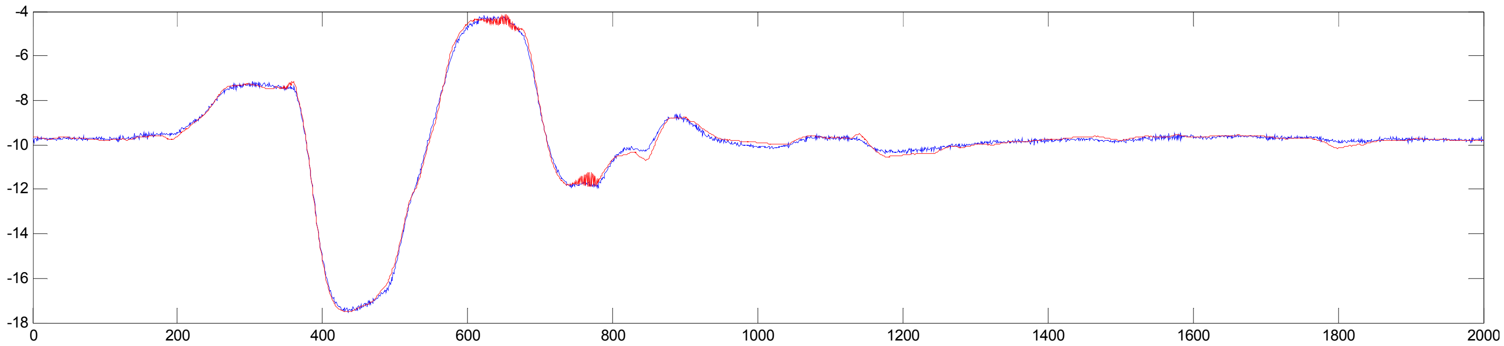
Parameter estimation:

– Fitting example: Vertical Acceleration Nz

Initial Model



after 10 iterations

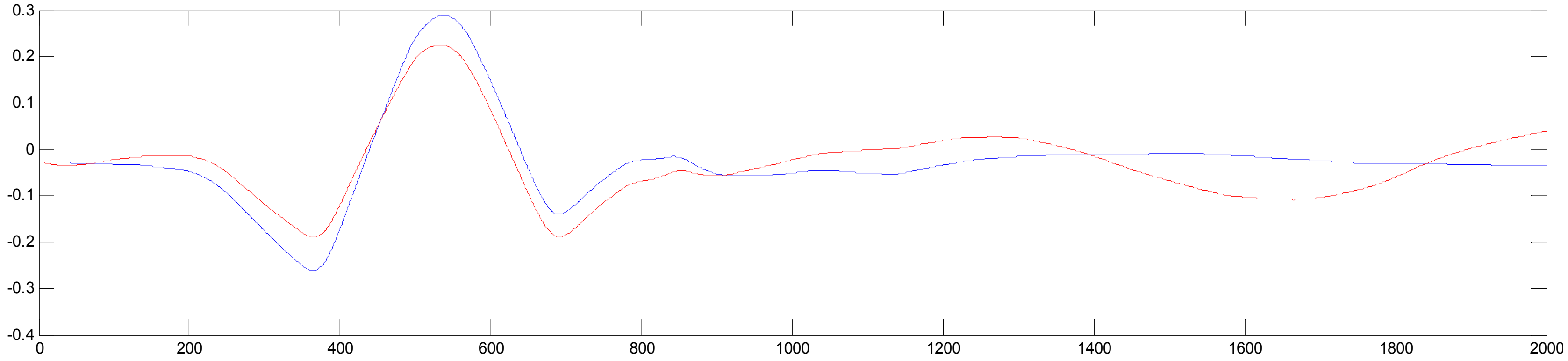


Flight Dynamics

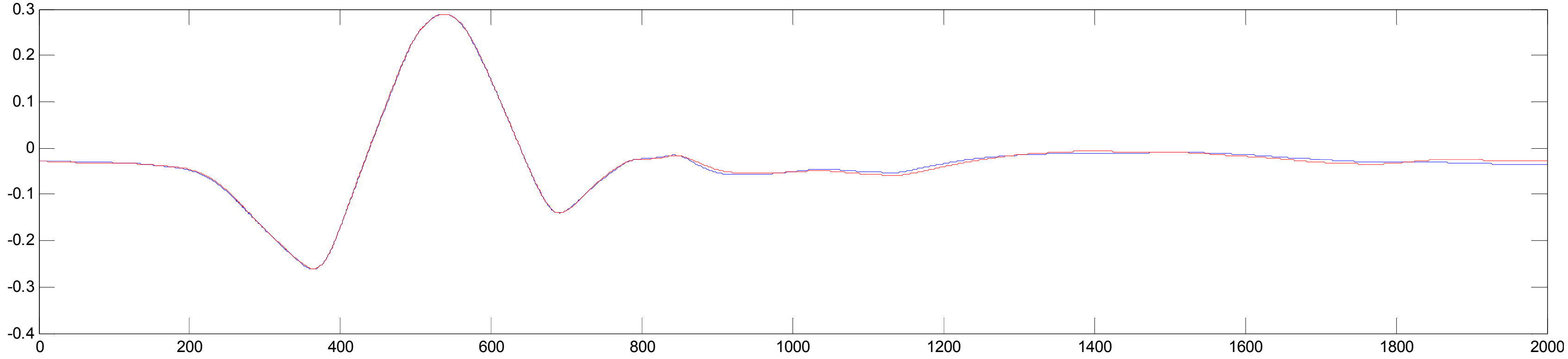
Parameter estimation:

- Fitting example: Pitch attitude Theta

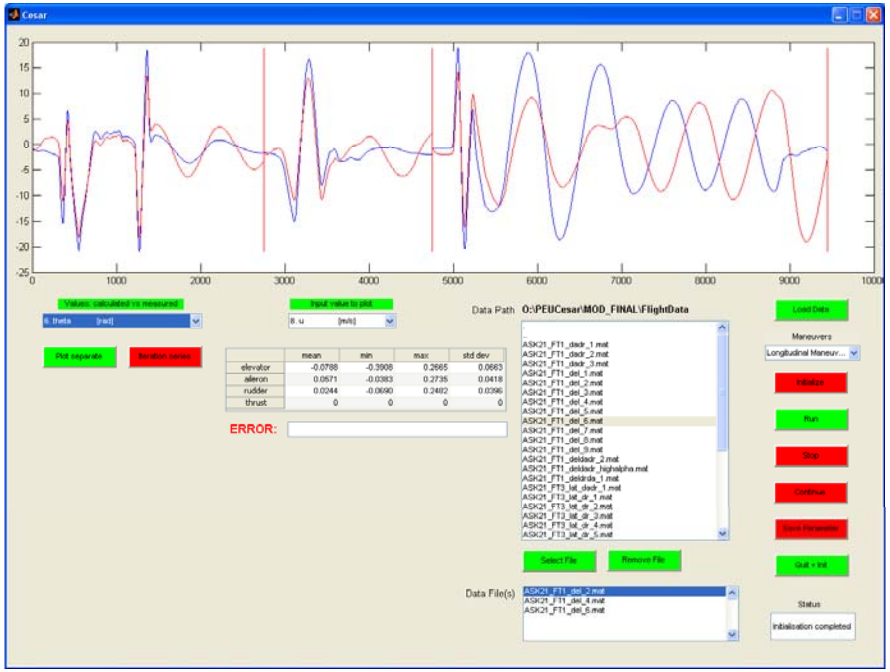
Initial Model



after 10 iterations



Parameter identification Tool-HMI



- Select flight sequences
- Select estimation axis
- Select parameters to be estimated

Results format:

Longitudinal derivatives

AERODYNAMIC PARAMETERS

	Parameter	Start Value	End Value	Std Dev	Rel Std Dev	%Diff. DATCOM
1	CD_0	0.028576	0.033059	1.967e-003	5.95	15.69
2	CD_1	0.002671	0.004181	4.579e-004	10.95	56.55
3	CD_2	0.000265	0.000050	7.585e-005	151.91	-81.13
4	CL_0	0.669803	0.602785	2.766e-002	4.59	-10.01
5	CL_1	0.105061	0.114418	3.673e-003	3.21	8.91
6	CL_2	-0.000997	-0.001080	1.909e-003	-176.78	8.28
7	CL_3	-0.000056	0.000129	7.112e-004	549.24	-332.06
8	Cm_0	-0.030970	-0.025844	5.271e-003	-20.40	-16.55
9	Cm_1	-0.019537	-0.019523	6.453e-004	-3.31	-0.07
10	Cm_2	-0.000019	0.000511	4.051e-004	79.29	-2744.32
11	Cm_3	0.000010	-0.000297	1.303e-004	-43.92	-3080.41
12	CLq_0	0.104700	0.084055	7.191e-002	85.55	-19.72
13	Cmq_0	-0.279400	-0.276349	1.167e-002	-4.22	-1.09
14	CLAoAD_0	0.018485	0.081512	9.022e-002	110.68	340.97
15	CLAoAD_1	-0.000050	-0.074075	5.904e-002	-79.70	147708.85
16	CLAoAD_2	-0.000044	0.063911	6.049e-002	94.65	-144297.91
17	CLAoAD_3	-0.000002	0.005711	3.016e-002	528.18	-279198.60
18	CLAoAD_4	0.000000	-0.019857	2.104e-002	-105.94	-28512652.42
19	CLAoAD_5	0.000000	0.005652	6.972e-003	123.36	107430211.87
20	CmAoAD_0	-0.079024	-0.106517	1.601e-002	-15.03	34.79
21	CmAoAD_1	0.000212	0.000749	1.057e-002	1411.51	252.92
22	CmAoAD_2	0.000189	-0.003343	1.142e-002	-341.69	-1865.53
23	CmAoAD_3	0.000009	0.000070	5.559e-003	7959.77	697.17
24	CmAoAD_4	-0.000000	-0.000707	3.997e-003	-565.04	239357.63
25	CmAoAD_5	-0.000000	0.000305	1.294e-003	424.21	-1361173.71
26	CL_DELOR_1	0.004713	0.008280	2.284e-003	27.58	75.69
27	CL_DELOR_3	-0.000003	0.000002	1.723e-005	1124.04	-152.20
28	Cm_DELOR_1	-0.018756	-0.020096	3.869e-004	-1.93	7.14
29	Cm_DELOR_3	0.000012	0.000006	2.964e-006	47.93	-46.93

Lateral/directional derivatives

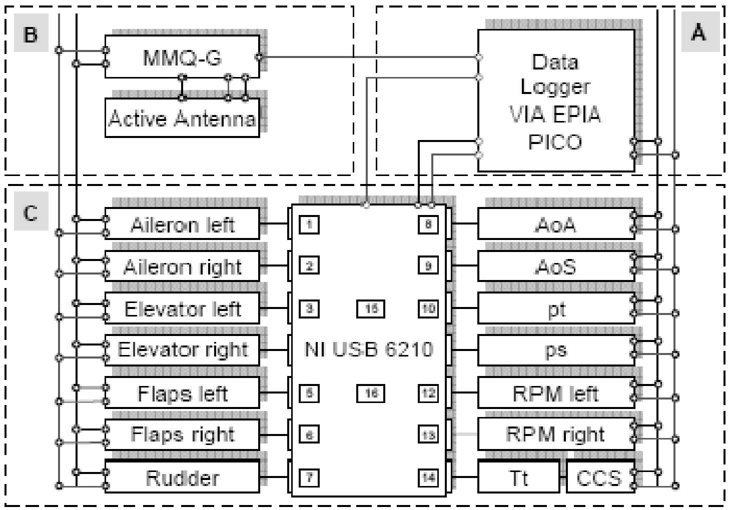
AERODYNAMIC PARAMETERS

	Parameter	Start Value	End Value	Std Dev	Rel Std Dev	%Diff. DATCOM
1	Cl_0	0.000000	-0.003439	3.158e-004	-9.18	-Inf
2	Cn_0	0.000000	-0.000480	8.952e-005	-18.67	-Inf
3	CYAoS_0	-0.005466	-0.005634	1.164e-004	-2.07	3.07
4	CnAoS_0	0.000763	0.000680	2.468e-005	3.63	-10.86
5	ClAoS_0	-0.001488	-0.001692	3.417e-004	-20.20	13.67
6	ClAoS_1	0.000038	0.000004	5.437e-005	1289.11	-88.82
7	ClAoS_2	-0.000000	-0.000005	1.679e-005	-321.85	2507.75
8	ClAoS_3	-0.000000	0.000001	2.482e-006	256.76	-8190.87
9	Clp_0	-0.009455	-0.007528	2.053e-003	-27.27	-20.38
10	Clp_1	0.000040	-0.001200	4.760e-004	-39.68	-3101.81
11	Clp_2	0.000040	-0.000293	1.299e-004	-44.26	-832.36
12	Clp_3	0.000003	-0.000009	2.056e-005	-228.86	-398.43
13	Clp_4	-0.000000	0.000002	3.441e-006	177.86	-3224.96
14	Clp_5	-0.000000	0.000000	1.729e-007	116.39	-2206.76
15	CYp_0	-0.003643	-0.001438	6.117e-004	-42.52	-60.52
16	CYp_1	-0.000225	-0.000668	2.119e-004	-31.70	197.41
17	CYp_2	0.000002	-0.000109	6.738e-005	-61.56	-4817.00
18	CYp_3	0.000000	-0.000003	6.194e-006	-223.21	-2428.24
19	Cnp_0	-0.001334	-0.001028	1.131e-004	-11.00	-22.90
20	Cnp_1	-0.000205	-0.000131	5.517e-005	-42.15	-36.04
21	Cnp_2	0.000001	-0.000019	1.608e-005	-84.26	-1671.29
22	Cnp_3	0.000000	0.000001	1.362e-006	187.19	963.62
23	Cnr_0	-0.000741	-0.000753	5.602e-005	-7.44	1.61
24	Cnr_1	-0.000038	-0.000018	2.466e-005	-138.92	-53.55
25	Cnr_2	-0.000002	-0.000001	5.838e-006	-1007.42	-69.98
26	Cnr_3	0.000000	0.000002	9.068e-007	40.03	7993.64
27	Clr_0	0.002849	0.002372	6.024e-004	25.40	-16.75
28	Clr_1	0.000364	0.000603	1.822e-004	30.23	65.41
29	Clr_2	-0.000004	0.000101	5.768e-005	57.38	-2601.36
30	Clr_3	-0.000000	0.000004	6.202e-006	160.25	-1977.27
31	Cl_DAION_1	0.001741	0.001885	4.050e-004	21.48	8.27
32	Cl_DAION_3	-0.000000	-0.000000	1.006e-006	-409.56	-33.61
33	Cn_DRUER_1	-0.000639	-0.000721	2.600e-005	-3.61	12.81
34	Cn_DRUER_3	0.000000	0.000000	2.301e-008	10.57	-16.88
35	Cl_DRUER_1	0.000060	-0.000109	9.653e-005	-88.33	-282.70
36	Cl_DRUER_3	-0.000000	0.000000	9.188e-008	31.32	-1266.47
37	CY_DRUER_1	0.002504	0.002519	1.311e-004	5.21	0.59
38	CY_DRUER_3	-0.000001	-0.000001	1.267e-007	-10.50	15.66

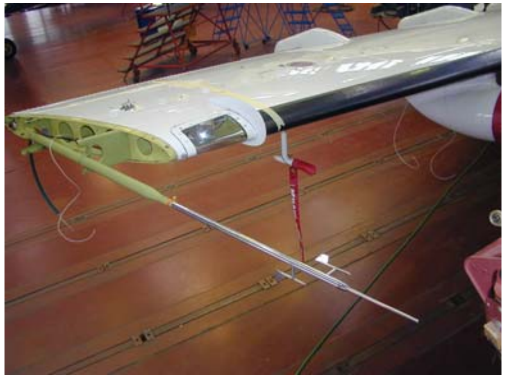
Flight Testing: Instrumentation

Design of a ‚low-cost' flight instrumentation system

- OTS Hardware
- MEMS INS/GPS
- usable in scale/subscale aircraft



Flight Testing: Instrumentation



Measured dimensions:

Latitude, Longitude, geodetic altitude WGS 84

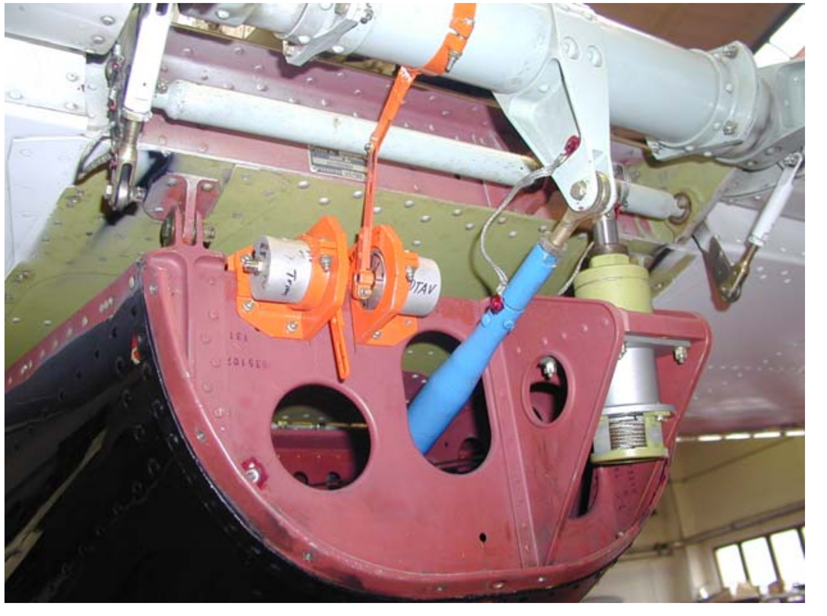
Velocities	u,v,w
Accelerations	n_x,n_y,n_z
Euler Angles	φ,ψ,θ
Angular velocities	p,q,r
Angle of attack, sideslip	α,β
Total pressure, static pressure	P_t, P_s
Total temperature	T_{tot}

Flight Testing: Instrumentation

Measured dimensions:

- Elevator command & deflection
- Aileron command & deflection
- Rudder command & deflection

- RPM left & right engine



Flight Test Instrumentation:

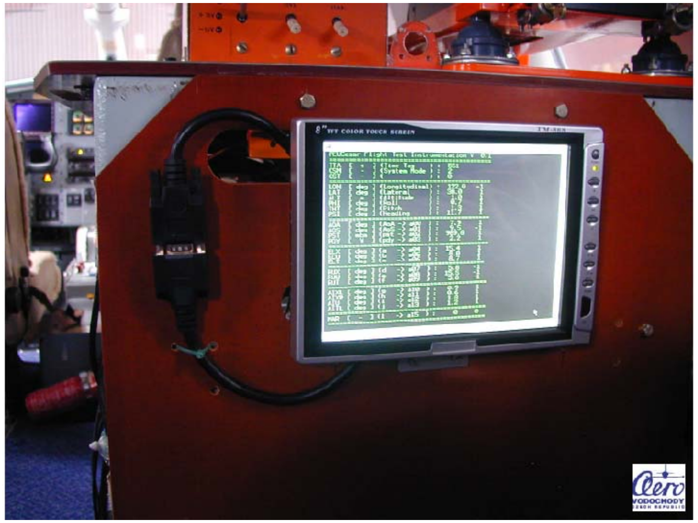
Utilized Sensors:

- Aerodynamic sensors (AoA, AoS)
- pressure sensors
- INS/GPS unit
- Pressure, temperature
- Potentiometers (Control-surface and -stick deflection)

Flight Test Instrumentation:

Recording on a standard PC device

Control and HMI:



TEST PLAN - CESAR - Ae270 s/n 0006 (OK-INA)

No. of flt	Flt design at	C.G.	Test Purpose	Number of cases in flt
1	FTI 1	N/A	**FTI evaluation**	22
2	FTI 2	N/A	**ALFA calibration + FTI evaluation**	16
3	FTI 3	N/A	**BETA calibration (fl. 0°) + FTI evaluation**	24
4	FTI 4	N/A	**BETA calibration (fl. 20°) + FTI evaluation**	16
5	FTI 5	N/A	**BETA calibration (fl. 36°) + FTI evaluation**	16
6	1	**N1** (front)	**LONGITUDINAL STATIC STABILITY**	10
7	2	N1 (front)	**LONGITUDINAL DYNAMIC STABILITY** (fugoids)	10
8	3	N1 (front)	**LONGITUDINAL DYNAMIC STABILITY** (short period)	20
9	4	**N3** (rear)	**LONGITUDINAL STATIC STABILITY**	10
10	5	N3 (rear)	**LONGITUDINAL DYNAMIC STABILITY** (fugoids)	10
11	6	N3 (rear)	**LONGITUDINAL DYNAMIC STABILITY** (short period)	20
12	7	**N2** (middle)	**LATERAL AND DIRECTIONAL STATIC STABILITY** (sideslips)	16
13	8	N2 (middle)	**LATERAL AND DIRECTIONAL STATIC STABILITY** (sideslips)	16
14	9	N2 (middle)	**LATERAL AND DIRECTIONAL DYNAMIC STABILITY** (rudder doublets)	32
15	10	N2 (middle)	**LATERAL AND DIRECTIONAL DYNAMIC STABILITY** (rudder doublets)	32

Subscale Model approach to reduce testing-cost

Check for the dynamic similarity:

Length	N
relative aircraft mass density	1
mass	N^3/σ
moment of inertia	N5/ σ
velocity	N0,5
acceleration (linear)	1
angular velocity	N-0,5
time	N0,5
reynolds number	N1,5 * υ

N : scale model / original
σ : relation of air density at altitude original / model
υ : relation of kinematic viscosity original / model
m / (ρ * F * b) : relative aircraft mass density

Subscale Model approach to reduce testing-cost

Dimensions of the sub-scale aircraft:

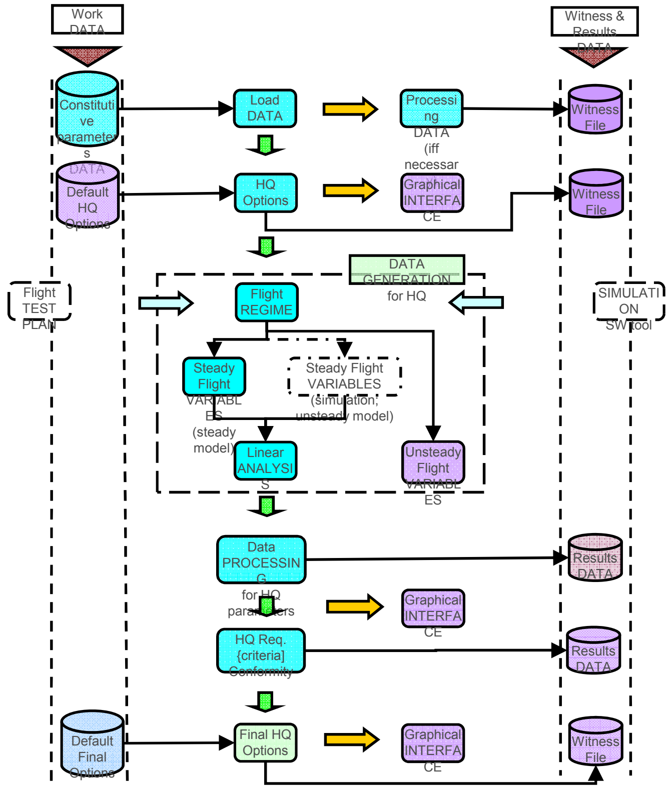
Length	2,23 [m]
Wing span	2,83 [m]
Mass	25,0 [kg]
Wing loading	316 [g/dm²]
Reynoldsnumber	896.000

Will Fly in Mid 2009 !

Handling Qualities (HQ) tool

- Includes analysis of HQ and FQ requirements as specified in CS-23.

- Utilized guidelines as specified in:
  - •MIL-F-8785C
  - •MIL-STD-1797



HQ tool architecture

Handlying Quality Analysis Tool

Considered Criteria (examples)

Phugoid	Dampening ratio / τ_P	Level 1 τ_P at least 0.4 Level 2 τ_P at least 0 Level 3 T_2 at least 55 seconds
Short period mode	Period / T_s	
"	Undamped natural frequency / ω_{nSP}	MIL- STD-F-8785C 3.2.2.1.1
"	Control anticipation parameter/ CAP= ω /(n/α)	MIL-STD-1797A APPENDIX A 4.2.1.2
"	[*Number of half time cycles]	[civilian regulations]
"	Rise time / Δt = t2 – t1	MIL-STD-1797A APPENDIX A Page 227
"	Time to double amplitude / T2 = $-0.693/\zeta_{SP}\omega_{nSP}$	MIL-STD-1797A APPENDIX A page 177, 192
"	Dampening ratio/ ζ_{sp}	See MIL- STD-F-8785C 3.2.2.1.2
"	Overshoot ratio	MIL-STD-1797A APPENDIX A page 250

Spiral mode	Valoare proprie (Minimal time to double value)	MIL- STD-F-8785C 3.3.1.3
Roll mode	Time constant τ_R	MIL- STD-F-8785C 3.3.1.2
Dutch roll	Damped period of the dutch roll / $T_d = \frac{2\pi}{\omega_d\sqrt{1-\zeta_d^2}}$	MIL-STD-1797A APPENDIX A 4.2.1.2 page 396
"	Time to double amplitude / T2 = $-0.693/\zeta_d\omega_d$	MIL-STD-1797A APPENDIX A page 412
"	Undamped natural frequency ω_d	See MIL-STD-1797A APPENDIX A 4.2.1.2 page 396
"	*Decremetnul de amortizare	[civilian regulations]
"	Modulus of the ratio off the bank angle to the sideslip angle during Dutch roll / $\lvert\phi/\beta\rvert_d$	MIL-STD-1797A APPENDIX A 4.2.1.2 page 10-13, 396
"	The argument of the ratio off roll rate to sideslip angle / arg(∠p / β)	MIL-STD-1797A APPENDIX A 4.2.1.2 page 10-13, 396
"	Dampening ratio / ζ_d	MIL-STD-1797A APPENDIX A 4.2.1.2 page 396
"	*Number of half-time cycles	Civilian regulations

CS23 requirements – constraints in optimisation problem

- Trim, Static stability
  - Static stability, Control to trim, Stick force/g
- Trim drag
  - Phugoid mode, Short period mode, Dutch roll mode, Spiral mode, Roll performance
- Flight path stability
- Dynamic stability

Optimization Framework

Utilize Tool-set and close the loop to optimize for:

- Dimensioning of control surface in the a/c design
- Control surface location
- Control Authority allocation

- Incorporation into the initial design phase of:
  – Certification requirements
  – Guidelines (MIL)

Optimization

- Global non convex optimisation
- Multicriteria
- Stochastic search methods
  - Genetic algorithms
  - Differential Evolution
- Hybridisation
  - Global stochastic methods and local search algorithms