Aerodynamic Modeling and System Identification from Flight Data – Recent Applications at DLR

by

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    - Nonlinear control surface effectiveness
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    - Stall hysteresis
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  - Database validation
  - Wake Vortex Aircraft Encounter Model
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  - UAV: Automatic Envelope Expansion through Adaptive Flight Control

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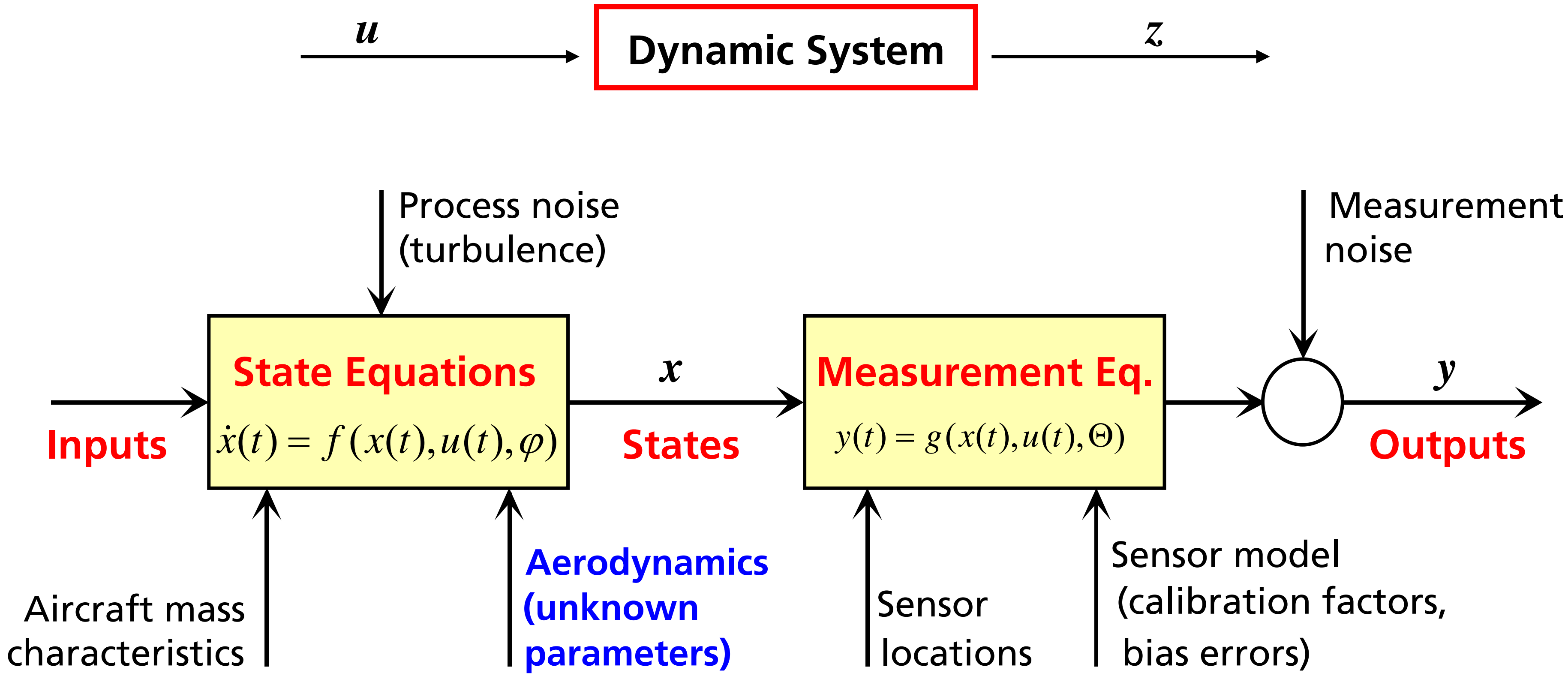
What is System Identification? (1)



u → **Dynamic System** → z

Process noise (turbulence)

Measurement noise

State Equations

$\dot{x}(t) = f(x(t), u(t), \varphi)$

Inputs

x

States

Measurement Eq.

$y(t) = g(x(t), u(t), \Theta)$

y

Outputs

Aircraft mass characteristics

Aerodynamics (unknown parameters)

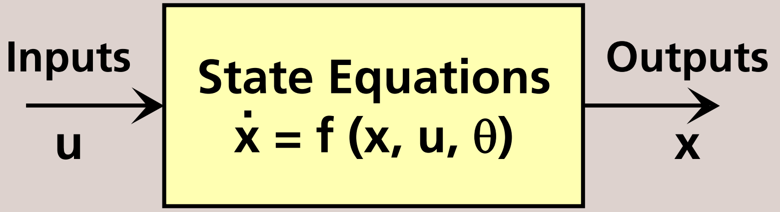
Sensor locations

Sensor model (calibration factors, bias errors)

AIM: To determine unknown model parameters Θ such that the model response y matches well with the measured system response z.

What is System Identification? (2)

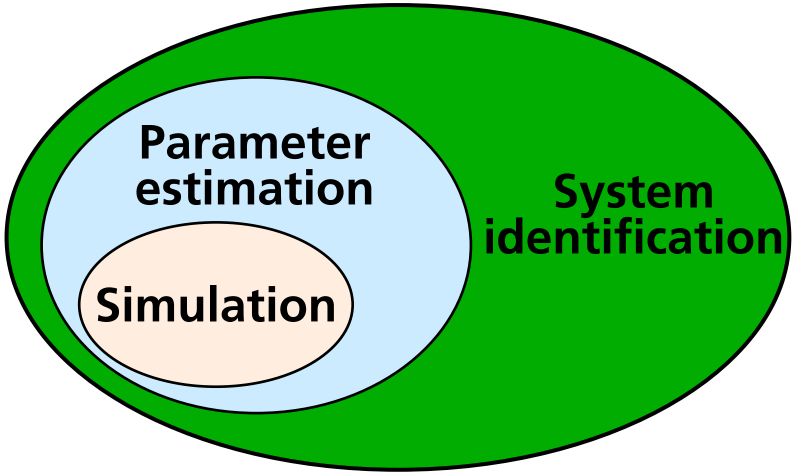
Classification

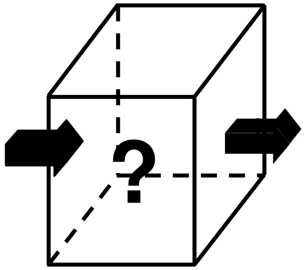


Simulation: given u and f, find x

Control: given x and f, find u

Identification: given u and x, find f





SysID: an Inverse Problem

Given the answer, what are the questions, i.e., look at the results and try to figure out what situation caused those results.

(1) System Identification

⇨ Concerned with the mathematical structure of a flight vehicle model

(2) Parameter Estimation

⇨ Quantifying of parameters for a selected flight vehicle model

Is the commonly used terminology PID appropriate?

Why System Identification?

- **Need and quest to better understand the system**
  - Cause-effect relationship purported to underlie the physical phenomenon

- **Mathematical models required for:**
  - Investigation of system performance and characteristics
  - Aerodynamic databases valid over operational envelope for flight simulators
  - High-fidelity / high-bandwidth models for in-flight simulators
  - Flight control law design
  - Analysis of handling qualities compliance

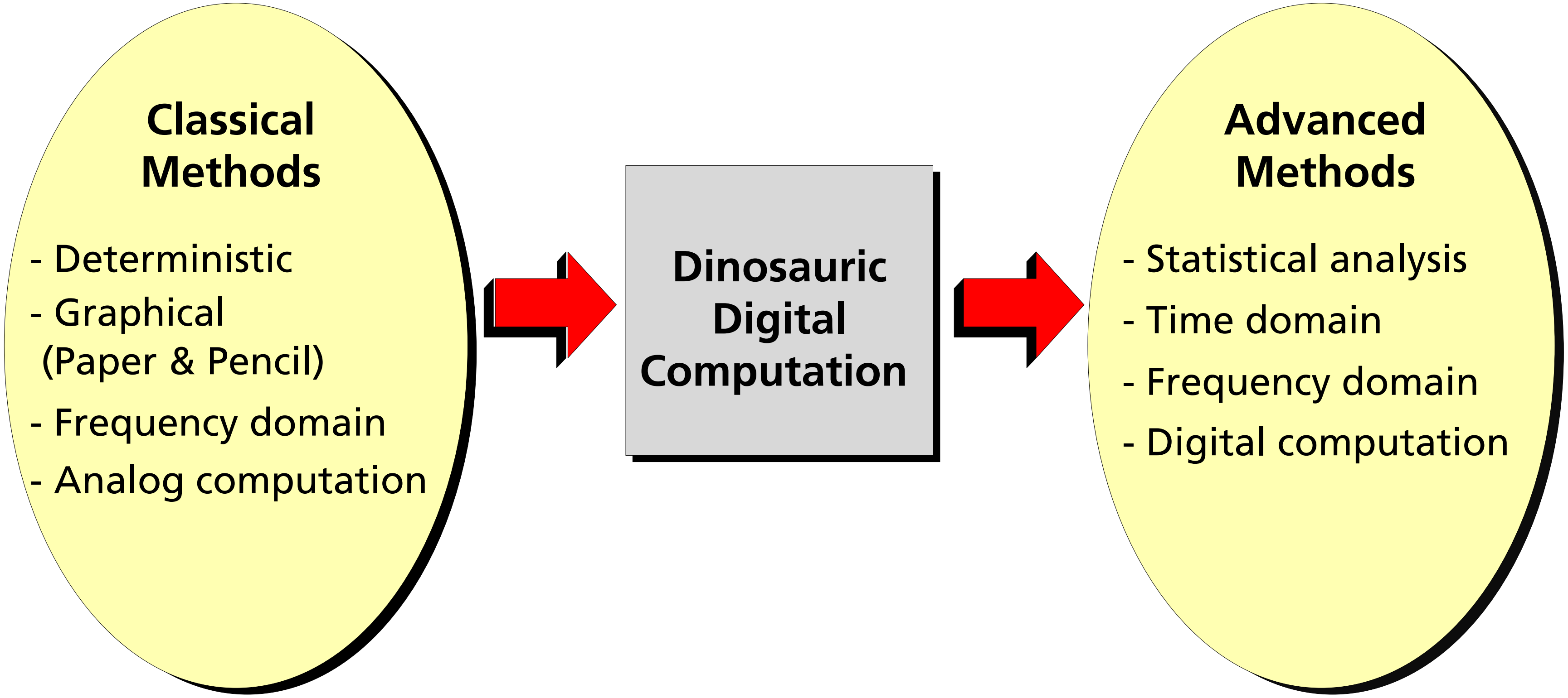
- **Aerodynamic databases from flight data**
  - Analytical estimates: validity and inadequate theory !
  - Wind-tunnel predictions: model scaling, Reynold's number, dynamic derivatives, cross coupling, aero-servo-elastic effects !!

Transition Phase

Classical Approach
1919 - mid 1960's

Late 1960's

Modern Era
1966 - 2008



Classical Methods

- Deterministic
- Graphical
  (Paper & Pencil)
- Frequency domain
- Analog computation

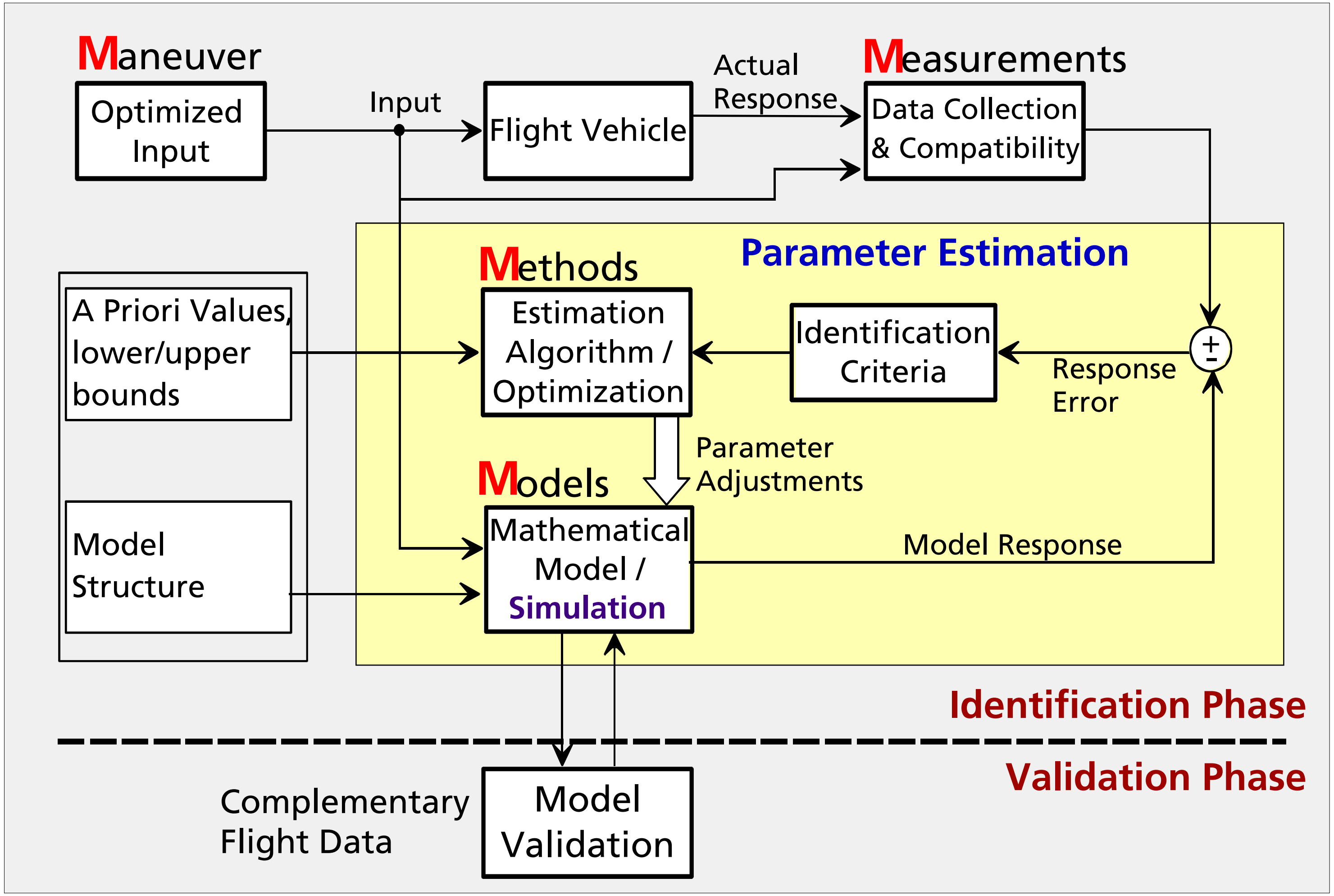
Dinosauric Digital Computation

Advanced Methods

- Statistical analysis
- Time domain
- Frequency domain
- Digital computation

Unified Approach to Flight Vehicle System Identification

Quad-M Basics



Aircraft Parameter Estimation Methods

Types and Classification

Stable Systems

Regression Analysis

- Linear modeling
- Data compatibility required
- Data partitioning

Output Error Method

- Accounts for measurement noise
- Time and frequency domain

Filter Error Method

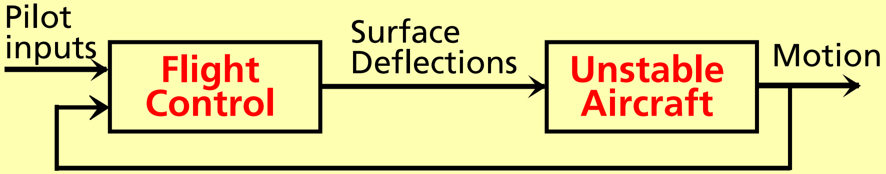
Accounts for both process noise (turbulence) and measurement noise

➔ Most general and most complex

Neural Networks

- Recurrent neural network
- Feed forward neural network
- Local model network

Unstable Systems



Difficulties:

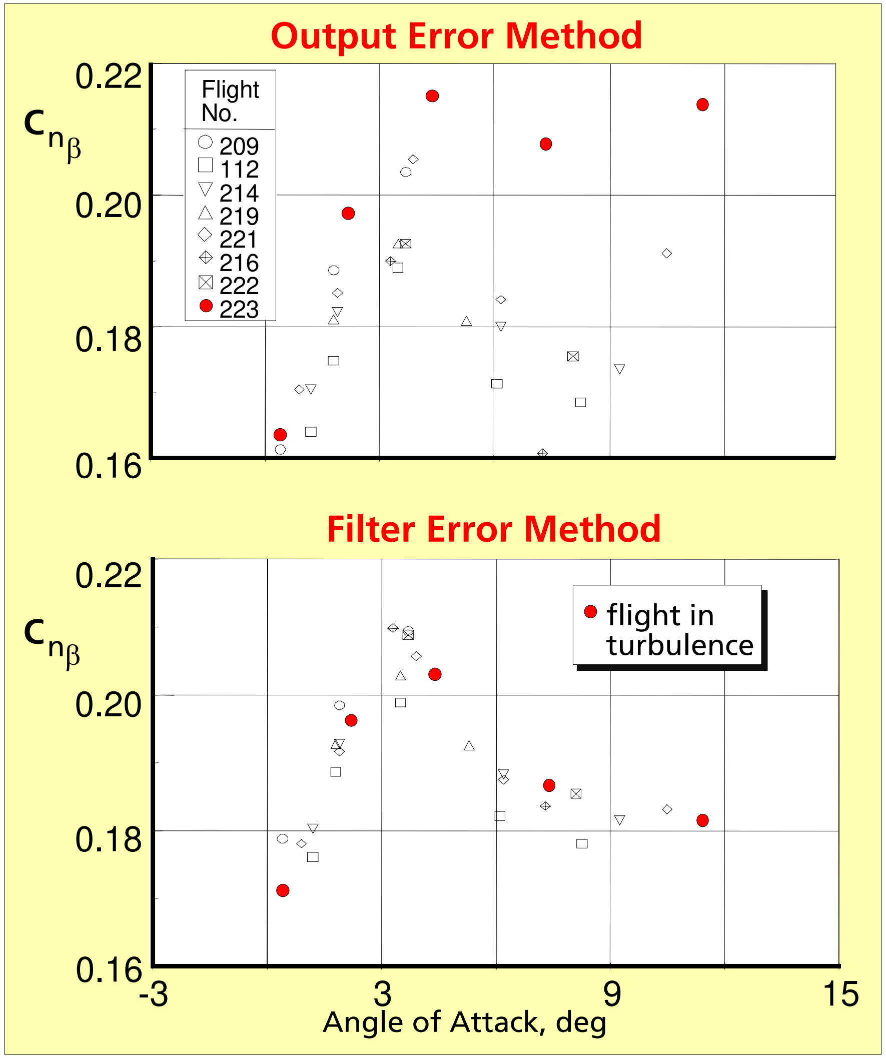
- Open loop plant identification: basic aircraft is unstable (due to the aerodynamic design)
- States and controls are highly correlated (due to the design of flight control laws)
- Aircraft may be excited by process noise (e.g., induced by forebody vortices)

Methods:

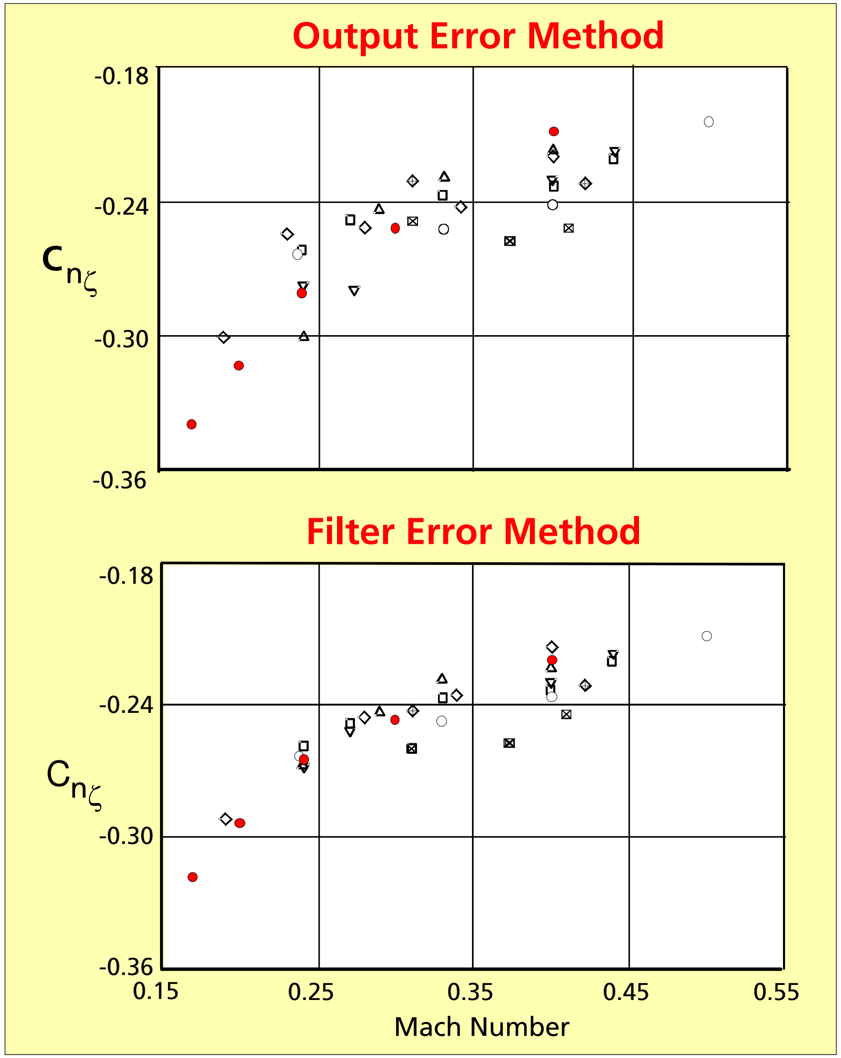
- **Regression Analysis**
- **Filter Error Method**
- **Extended Kalman Filter**
- **Output Error Method with artificial stabilization**

Parameter Estimation Accounting for Atmospheric Turbulence

Weathercock stability (yaw stiffness)



Rudder effectiveness



A Retrospective

Application Spectrum: Flight Vehicles

Software Tools: ESTIMA FITLAB

A318-121, 2002

Dyn. Simulation in WT, 1982

EC-135, 2001

Beaver DHC-2, 1983

A340-600, 2001

HFB-320, 1985

N250-PA1, 1999

ATTAS, 1989-90

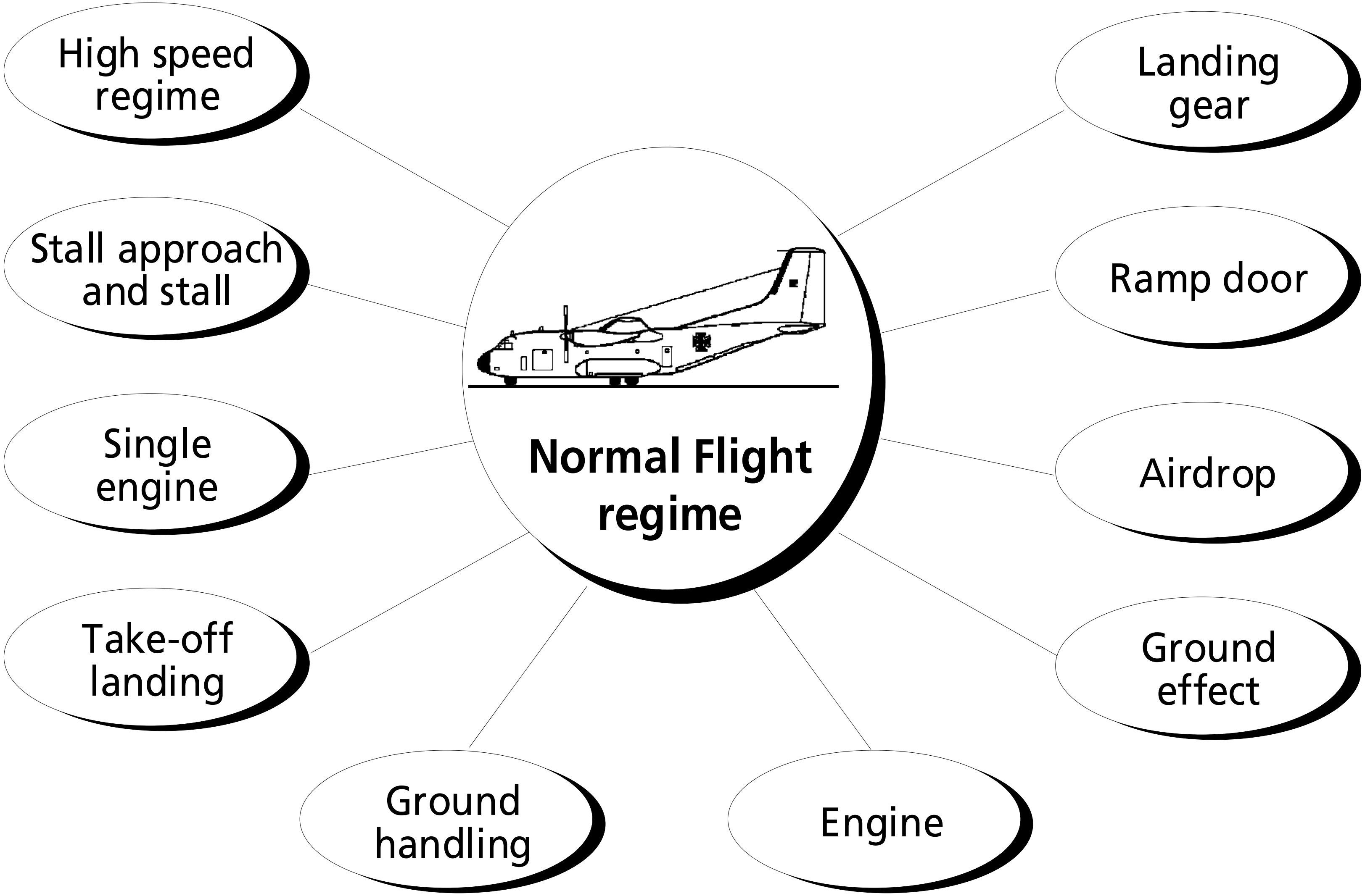
Dornier 328, 1995-96

XV-15, 1990-91

X-31A, 1992-94

Transall C-160, 1992-93

General Concept of Aerodynamic Model Identification



Normal Flight regime

High speed regime

Stall approach and stall

Single engine

Take-off landing

Ground handling

Engine

Ground effect

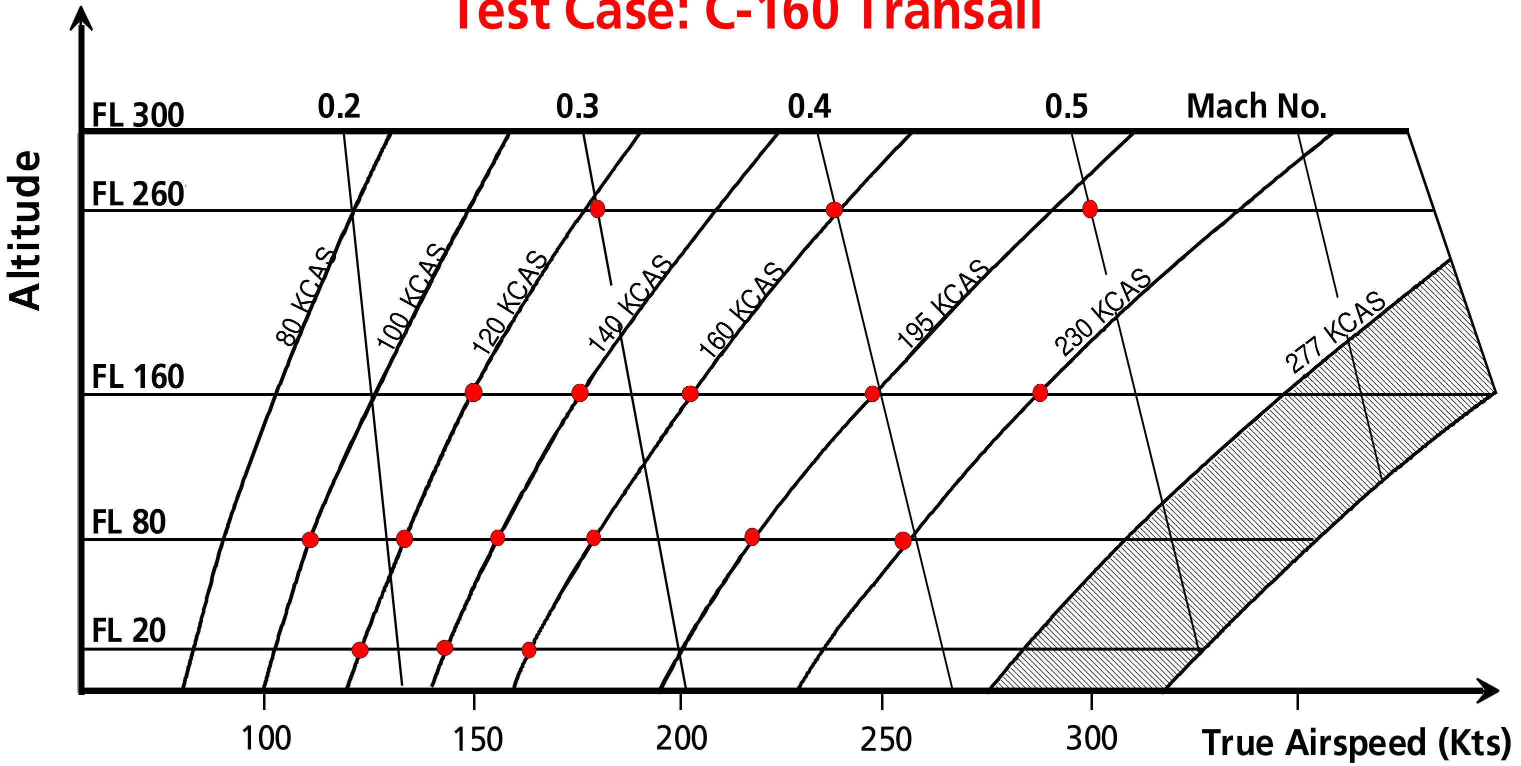
Airdrop

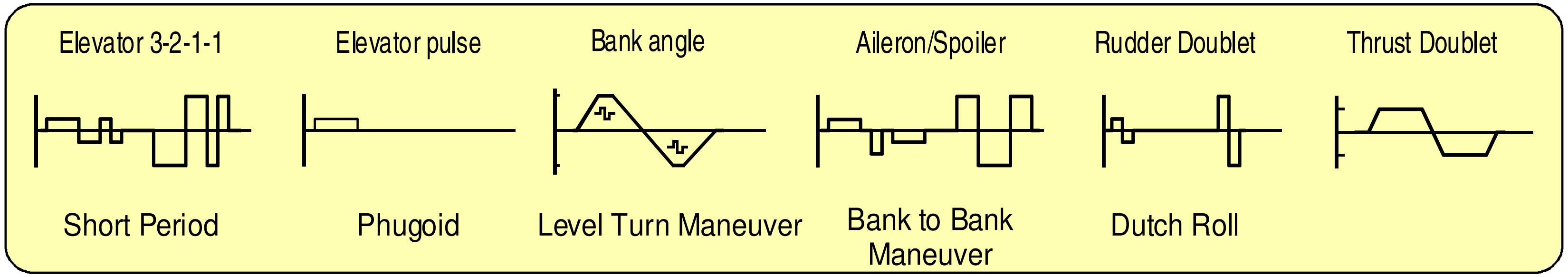
Ramp door

Landing gear

Typical Flight Test Program for System Identification

Test Case: C-160 Transall





Kinematic Consistency Checking of Recorded Data

General Approach, sensor model and estimation algorithm

- To ensure that the measurements are consistent and error free.
- Inertial measurements (accelerations and angular rates are highly accurate.
- Kinematic equations with no uncertainties; Accurate information about aircraft state;
- Means to calibrate parameters with lower accuracy (angle of attack & sideslip).

Sensor calibration model

Scale factor and bias

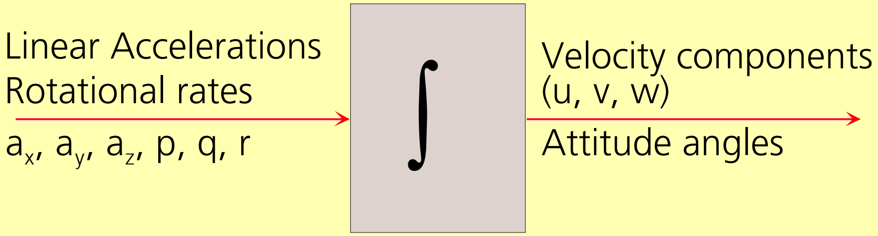
$$p_{d\alpha m} = K_\alpha \, p_{dyn} \, \alpha_{nb} + \Delta p_{d\alpha}$$

$$p_{d\beta m} = K_\beta \, p_{dyn} \, \beta_{nb} + \Delta p_{d\beta}$$

Time delay

$$p_{d\alpha m}(t) = K_\alpha \, p_{dyn}(t-\tau_{\bar{q}}) \, \alpha_{nb}(t-\tau_\alpha) + \Delta p_{d\alpha}$$

Kinematic Equations



Linear Accelerations
Rotational rates
a_x, a_y, a_z, p, q, r

$\int$

Velocity components (u, v, w)
Attitude angles

Initial conditions: u_0, v_0, w_0, p_0, q_0, r_0

Scale factors: K_p, K_q, K_r

Bias: Δa_x, Δa_y, Δa_z, Δp, Δq, Δr

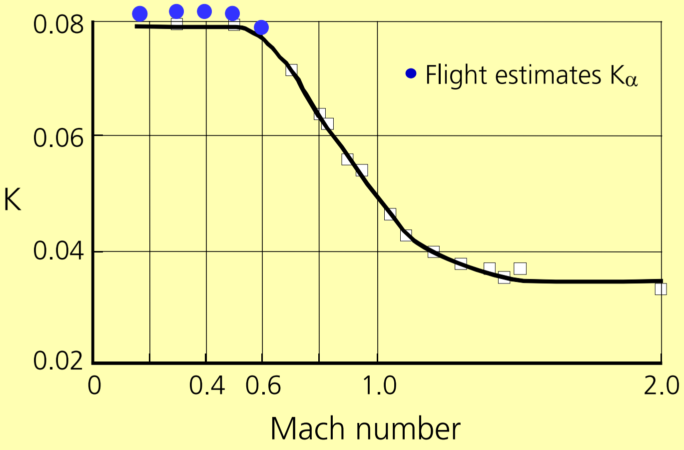
Parameter estimation

- Output error method for nonlinear systems
- Bounded-Variable Gauss-Newton algorithm
- Multiple experiment evaluation

$$K_\alpha, \; \Delta p_{d\alpha}, \; K_\beta, \; \Delta p_{d\beta}, \; \tau_\alpha, \; \tau_\beta, \; \tau_{\bar{q}}$$

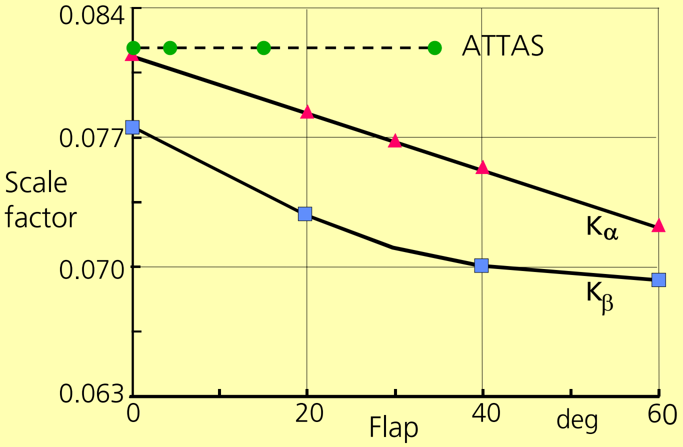
Noseboom Mounted 5 Hole Probe

Flight Validation ATTAS VFW-614



- **Calibration factors independent of configuration**

Flight Validation C-160



- **Calibration factors configuration dependent**

C-160: High-Fidelity Simulator Data Base

- Aerodynamic data base valid over the entire operational envelope
  - Nonlinear aerodynamics
  - Interference and coupling effects

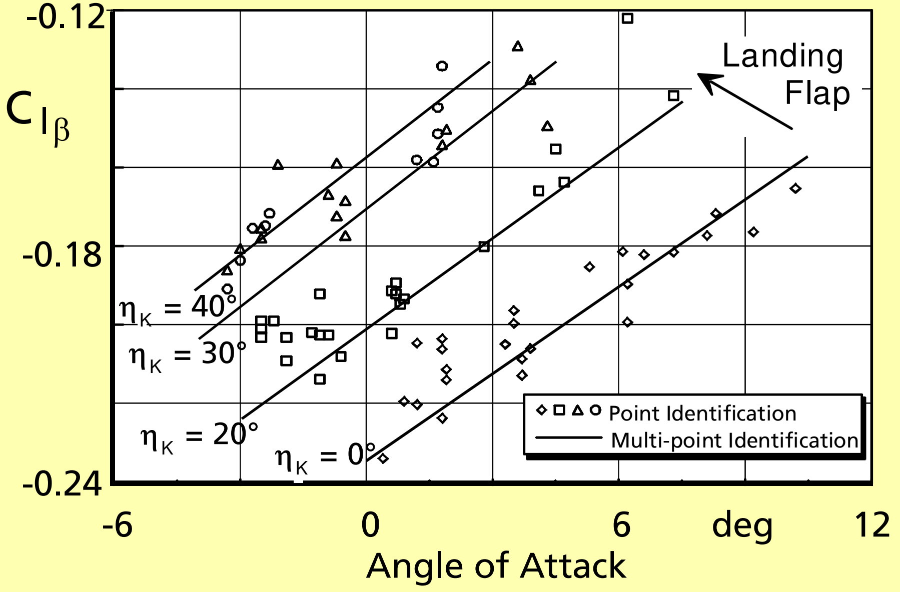
- Identification of C-160 specific operational characteristics
  - Ramp door interference,
  - air drop, etc.

- Identification of dynamic stall
  - Unsteady flow separation

- Identification of
  - Ground effect
  - Landing and Take-off
  - Failure states

- Validation of flight estimated database
  - FAA Level-D

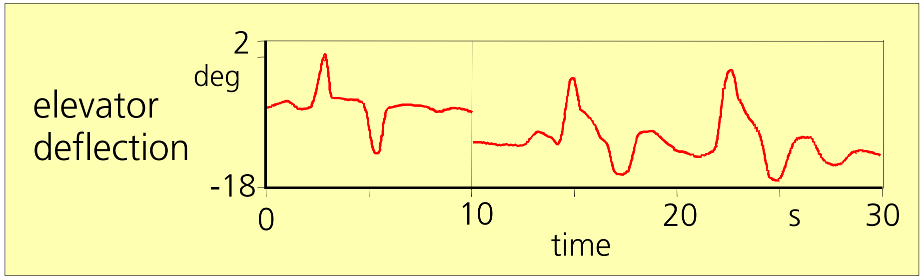
Flight estimate of dihedral effect

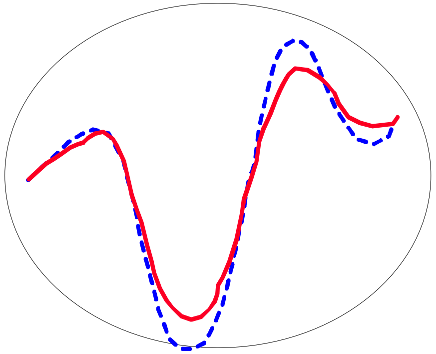


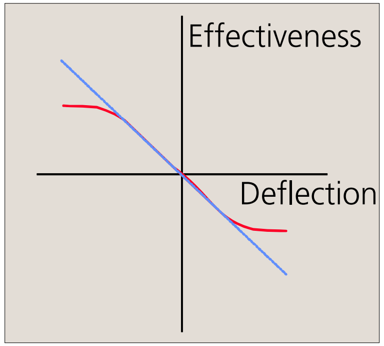
Point ID: Single trim points
Multi-Point ID: Several trim conditions

Identification of Elevator Control Effectiveness

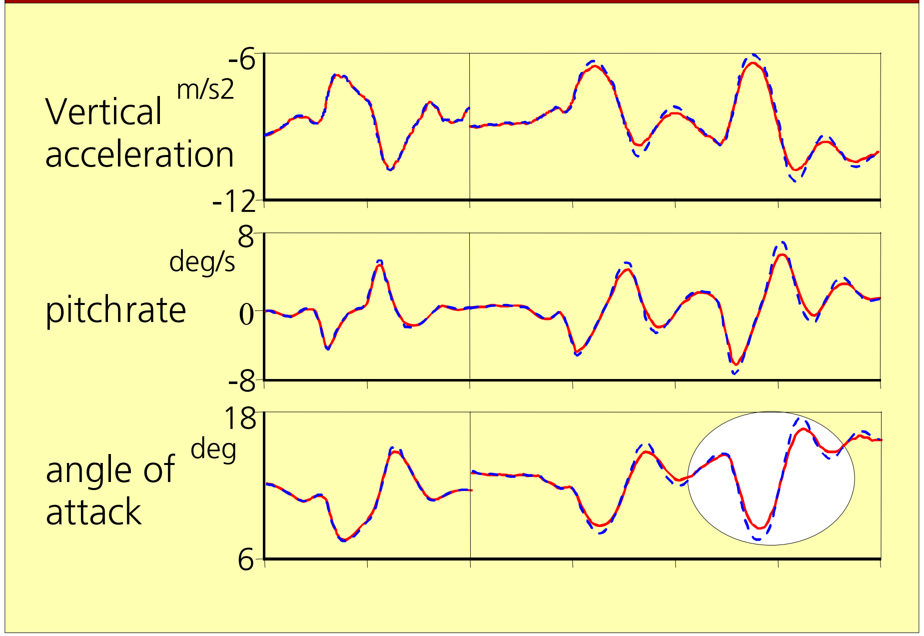
Test Case: Transall C-160



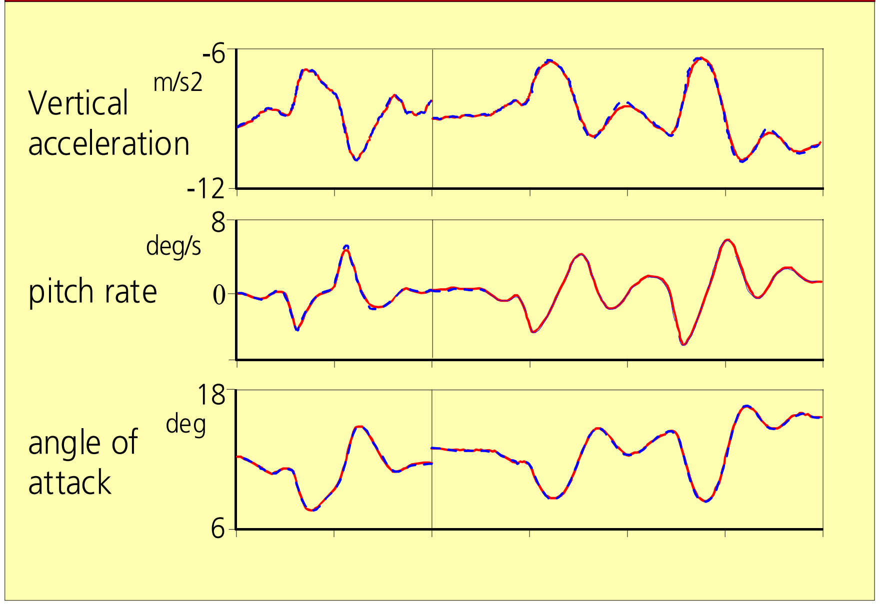




Linear model



Accounting for nonlinearity



Aerodynamic Modeling: Complex Models

- **Linear models** (e.g. Rolling moment coefficient)

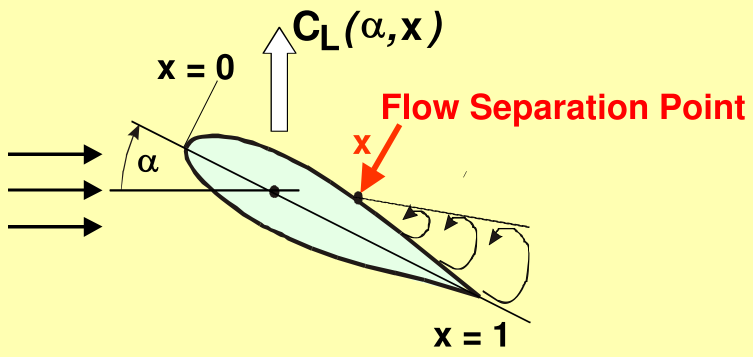
$$C_\ell = C_{\ell 0} + C_{\ell\beta}\,\beta + C_{\ell p}\,p + C_{\ell r}\,r + C_{\ell\xi}\,\xi + C_{\ell\zeta}\,\zeta$$

- **Nonlinear models** (e.g. Tail lift coefficient)

$$C_{L_T} = C_{L\alpha_T}\,\alpha_T + \left[C_{L\eta} + C_{L\eta_\alpha}\,\alpha_T + C_{L\eta_{\alpha^2}}\,\alpha_T^2 + C_{L\eta^3}\,\eta^2\right]\eta$$

- **Unsteady aerodynamics** (e.g. Stall hysteresis)

Unsteady Aerodynamic Model

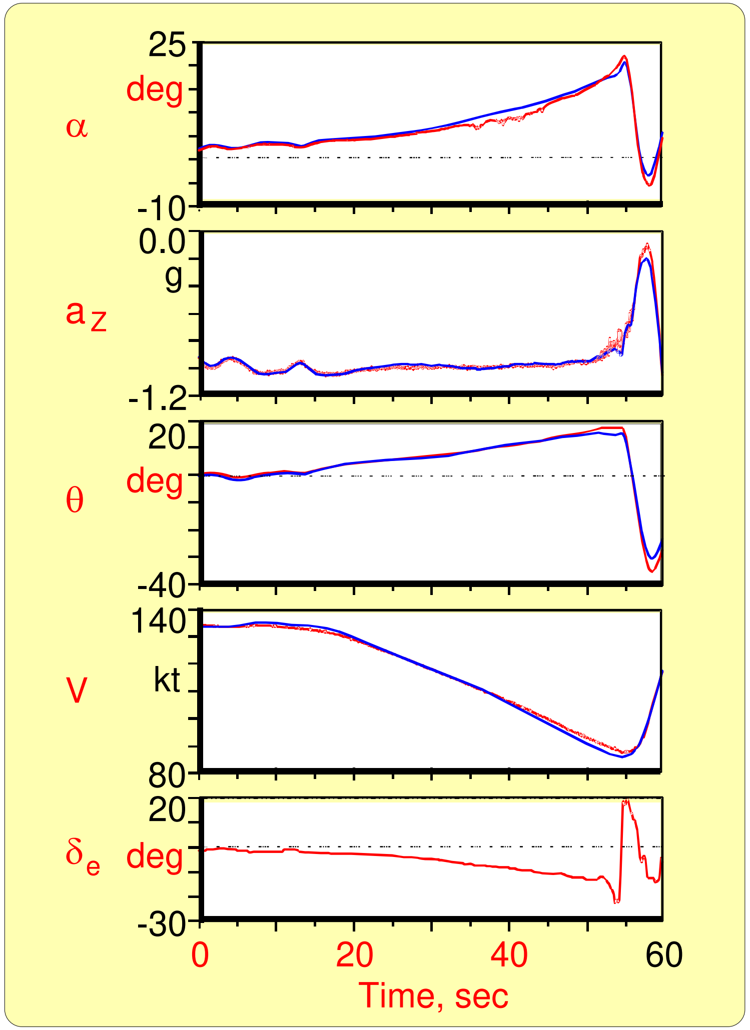


Lift coefficient

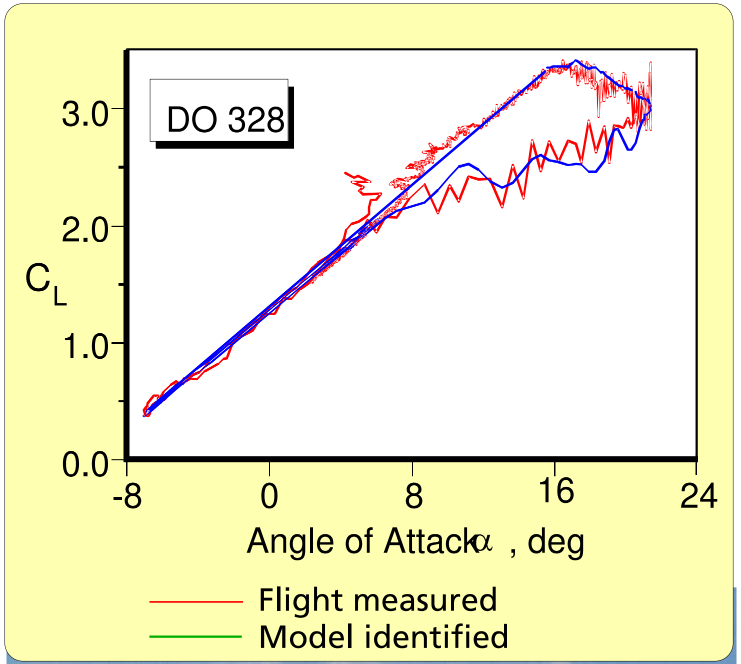
$$C_L\,(\alpha, x) = C_{L_\alpha}\left[\frac{1+\sqrt{x}}{2}\right]^2\alpha$$

Unsteady Aerodynamics

Time Responses



Lift Coefficient



Modeling of Landing Gear Effects (1)

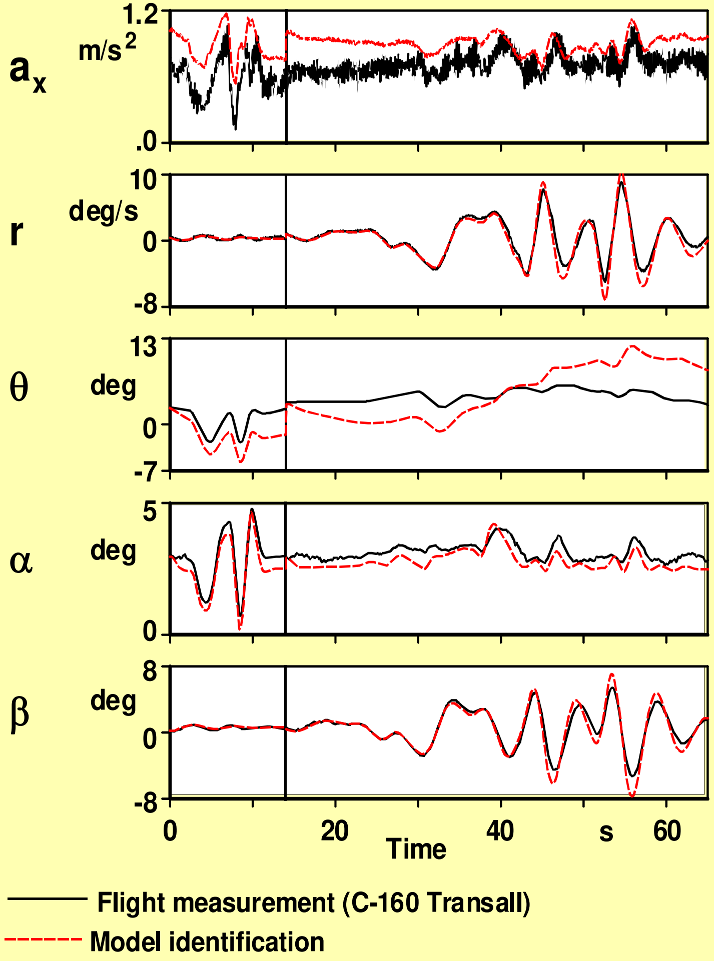
Test Case: Transall C-160

Modeling and Experimental Aspects

- Important for simulation of take-offs and landings
- Longitudinal and lateral-directional maneuvers with gear down

  8000 ft and 16000 ft
  120, 140 and 160 kts
- Basic aerodynamic model:
  Discernible deviations in
  - longitudinal motion
  - lateral-directional motion variables

Neglecting Landing Gear Effects



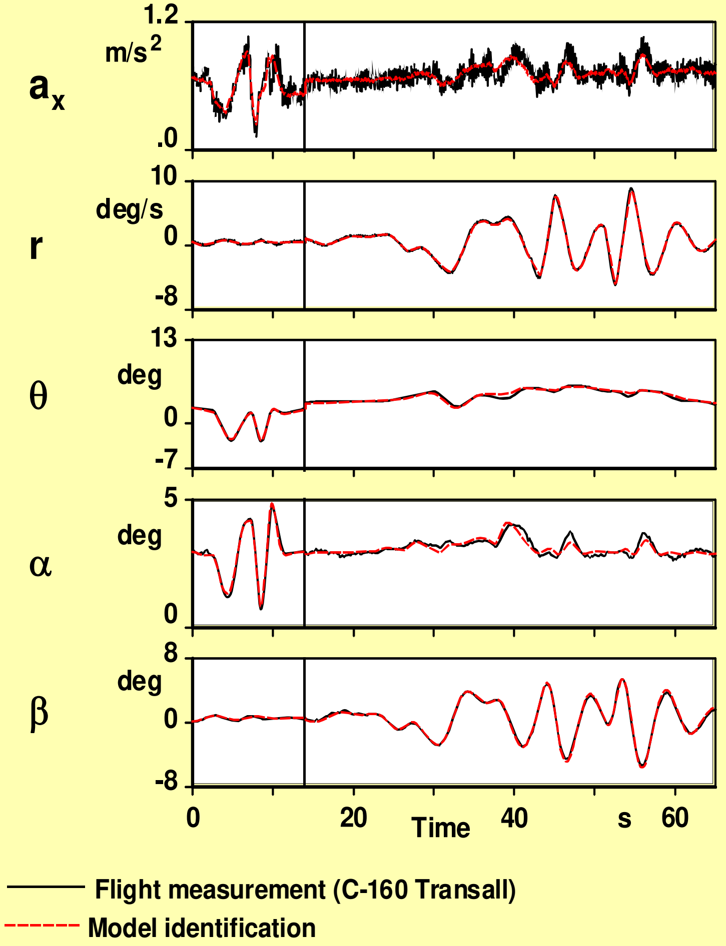
Modeling of Landing Gear Effects (2)

Test Case: Transall C-160

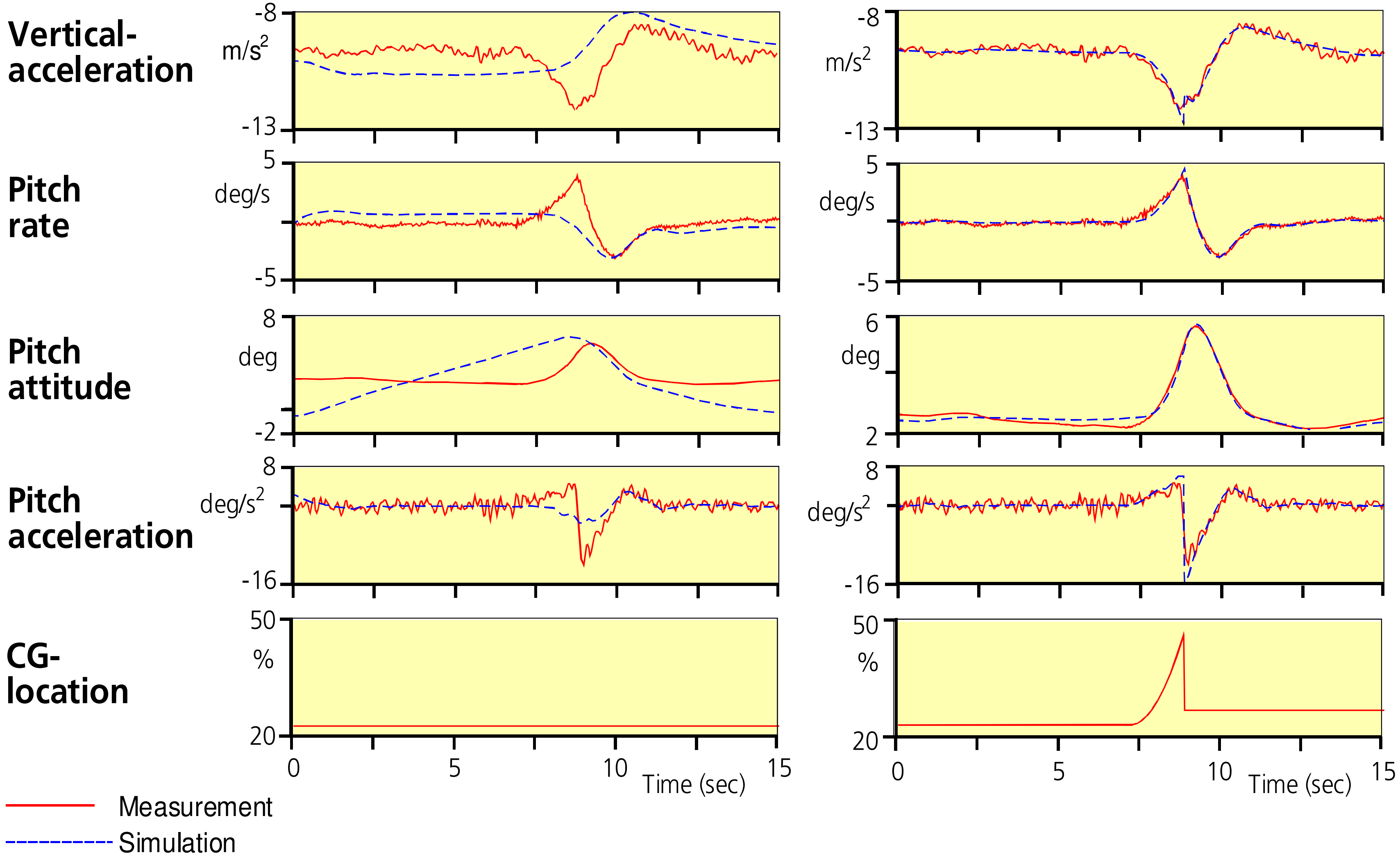
Modeling of Aerodynamic Effects due to LG

- Incremental aerodynamic modeling
- Longitudinal motion:
  Lift, drag and pitching moment coeff.
  ΔC_{LLG} , ΔC_{DLG} , ΔC_{mLG}
- Lateral-Directional motion:
  - Increased weathercock stability $\Delta C_{n\beta LG}$
  - Sideforce due to sideslip $\Delta C_{Y\beta LG}$

Accounting for Landing Gear Effects



C-160: Load Drop (4.6 t)



Neglecing Variations in Aircraft Mass Characteristics

Accounting for Variations in the Aircraft Mass Characteristics

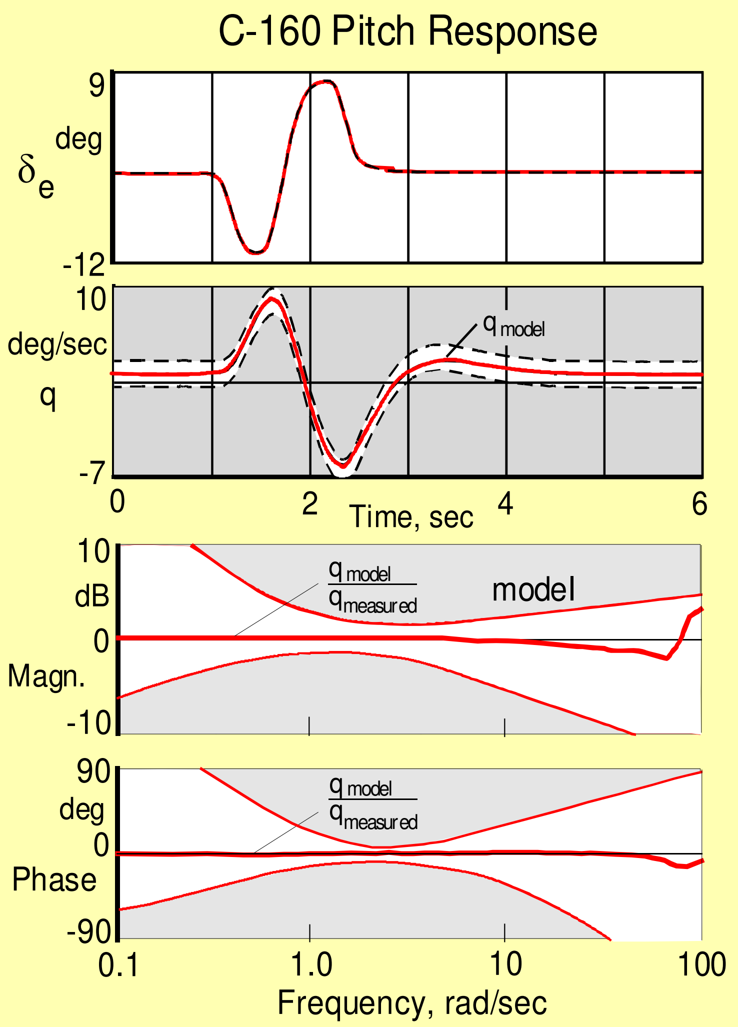
Data Base Validation (1)

How do you know that you got the right answer?

1. Standard derivations
2. Correlation among the estimates
3. Goodness of fit
4. Plausibility of estimates
   (WT data base)
5. Model predictive capability

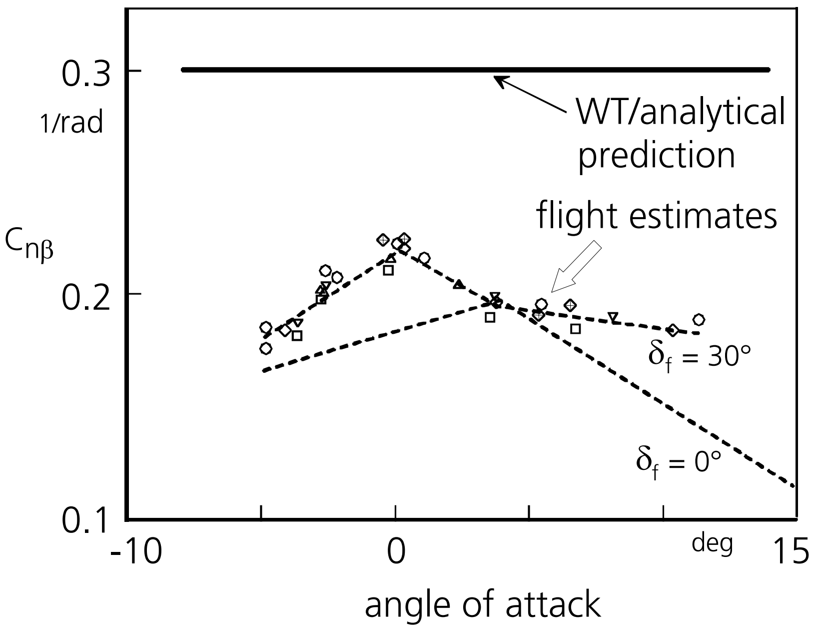
"ACID TEST"

Simulation and comparison with flight data not used in identification

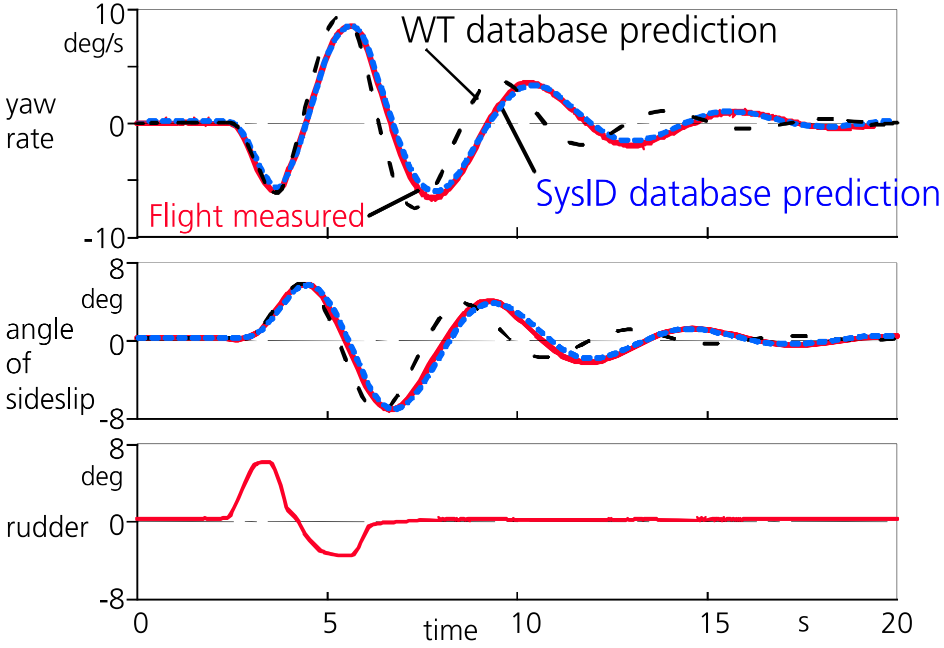

C-160 Pitch Response

Data Base Validation (2)

Weathercock stability



Dutch roll dynamics



Tolerances:

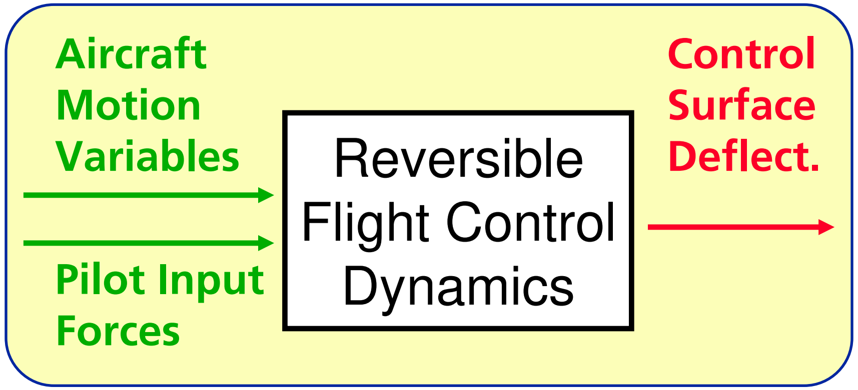
Frequency: +- 0.5 s or 10%

Damping: +- 0.02

WT-Predictions:	4.18 s	0.207
Flight estimated Database:	5.04 s	0.202
Flight recorded responses:	5.12 s	0.198

Data Base Validation (3)

Do-328: Stand-alone versus Integrated Models

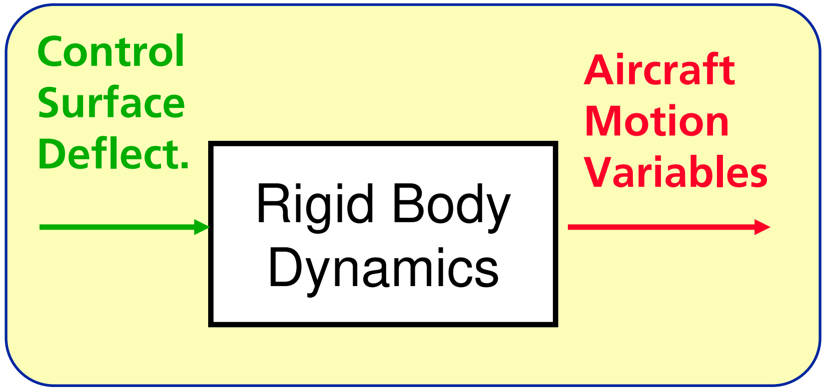

Aircraft Motion Variables

Pilot Input Forces

Reversible Flight Control Dynamics

Control Surface Deflect.

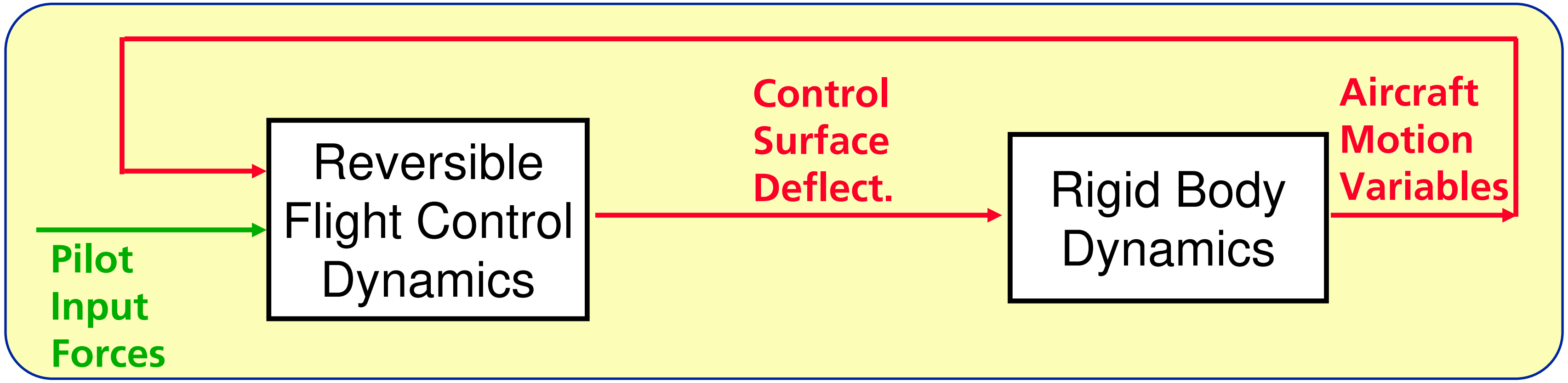
Flight controls stand-alone


Control Surface Deflect.

Rigid Body Dynamics

Aircraft Motion Variables

Rigid-body stand-alone


Pilot Input Forces

Reversible Flight Control Dynamics

Control Surface Deflect.

Rigid Body Dynamics

Aircraft Motion Variables

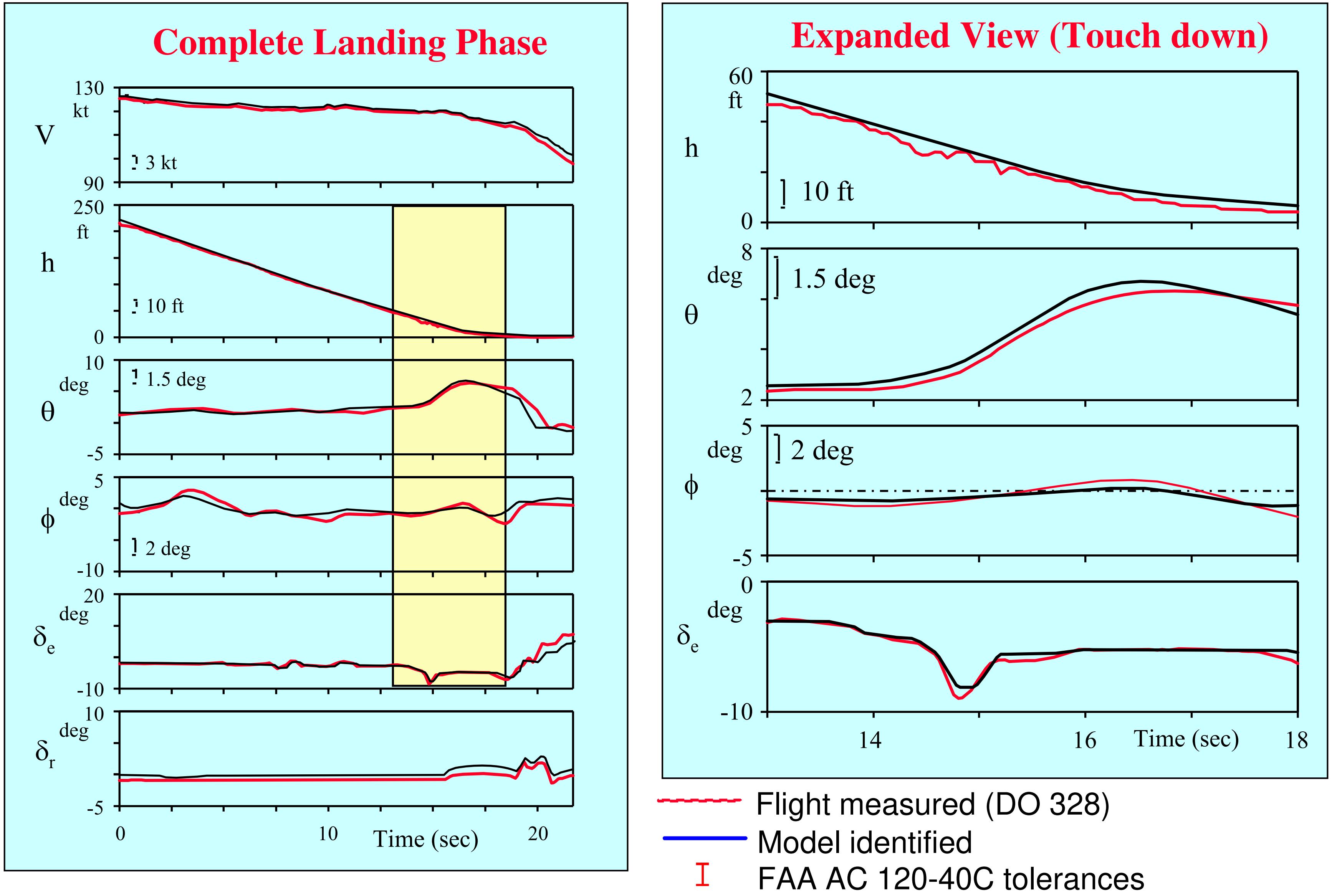
Integrated model

→ measured data

→ simulated data

Data Base Validation (4)

DO-328:Normal Landing



Data Base Validation (5)

Validation Example 3: Critical Engine Failure (DO 328)

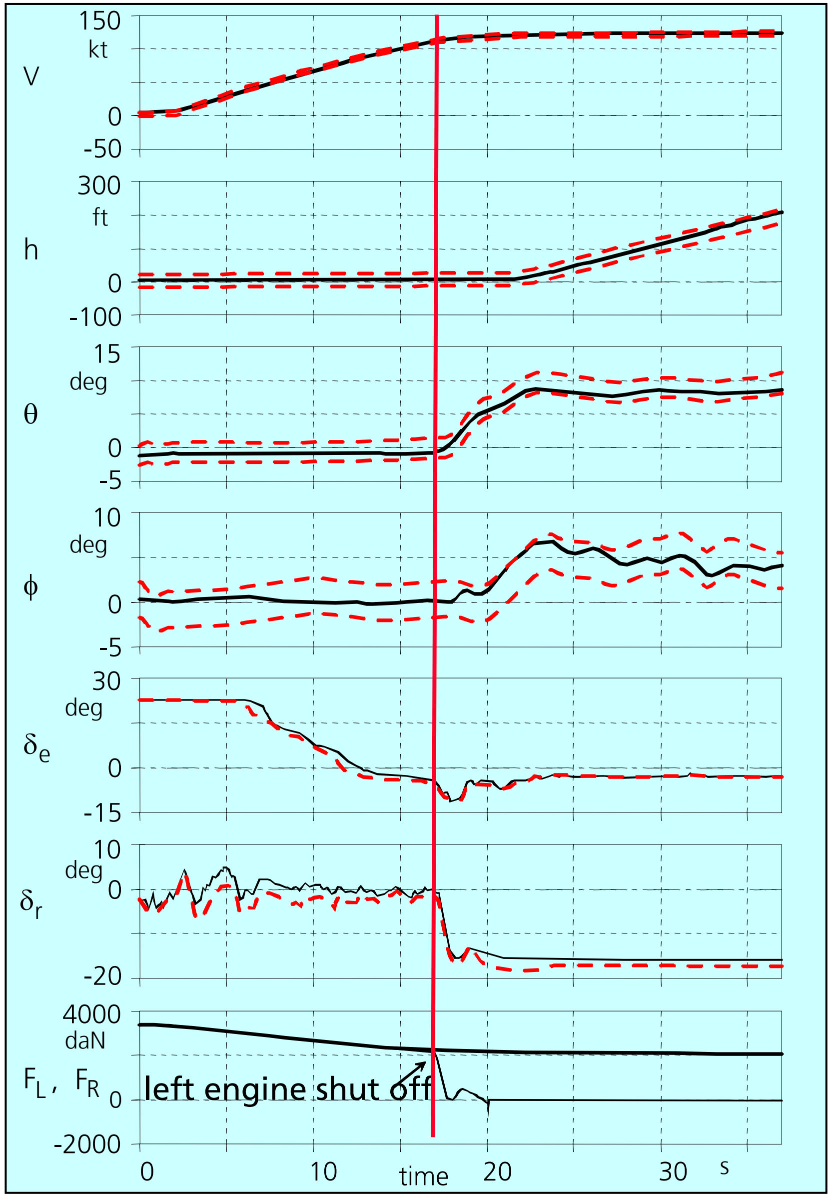
Engine failure during the critical phase of takeoff

Response to rudder and aileron important

Complete sequence as a single time segment (stand-still, acceleration, Rotation, and climb to 200 ft)

No closed-loop controller

Tolerances: 3 kt on airspeed
20 ft on altitude
1.5 deg on pitch attitude
2.0 deg on bank

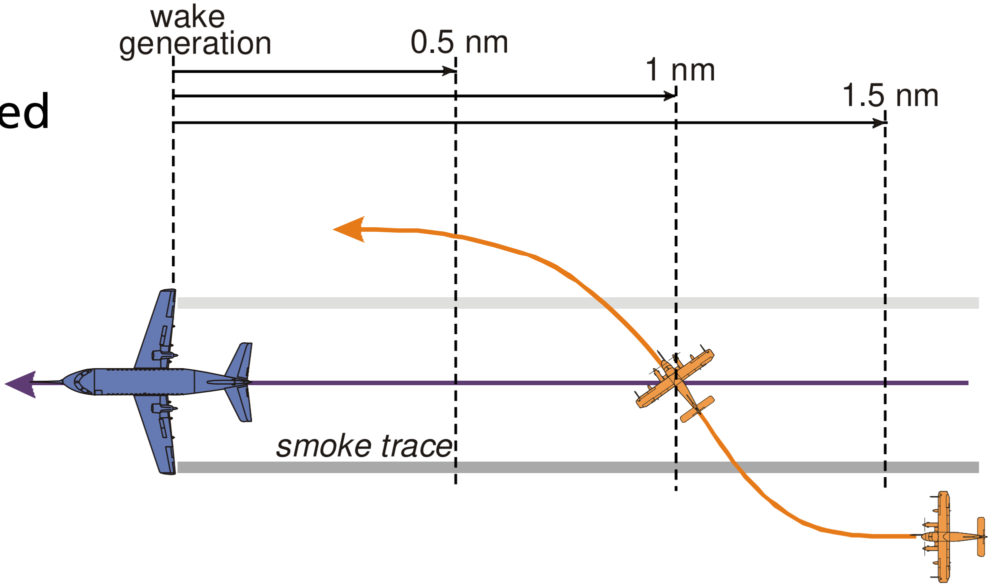


🟥 Flight measured

🟦 Model identified

Wake Vortex Aircraft Encounter Model (1)

Full Scale Flight tests: Data Gathering



Wake vortex encounters:

- Aircraft reaction dominantly affected
- Critical situation during safety-critical flight phases (landing, vicinity of airport)

Full scale flight tests with ATTAS
followed by Do-128 or Cessna Citation
➔ Separation class medium

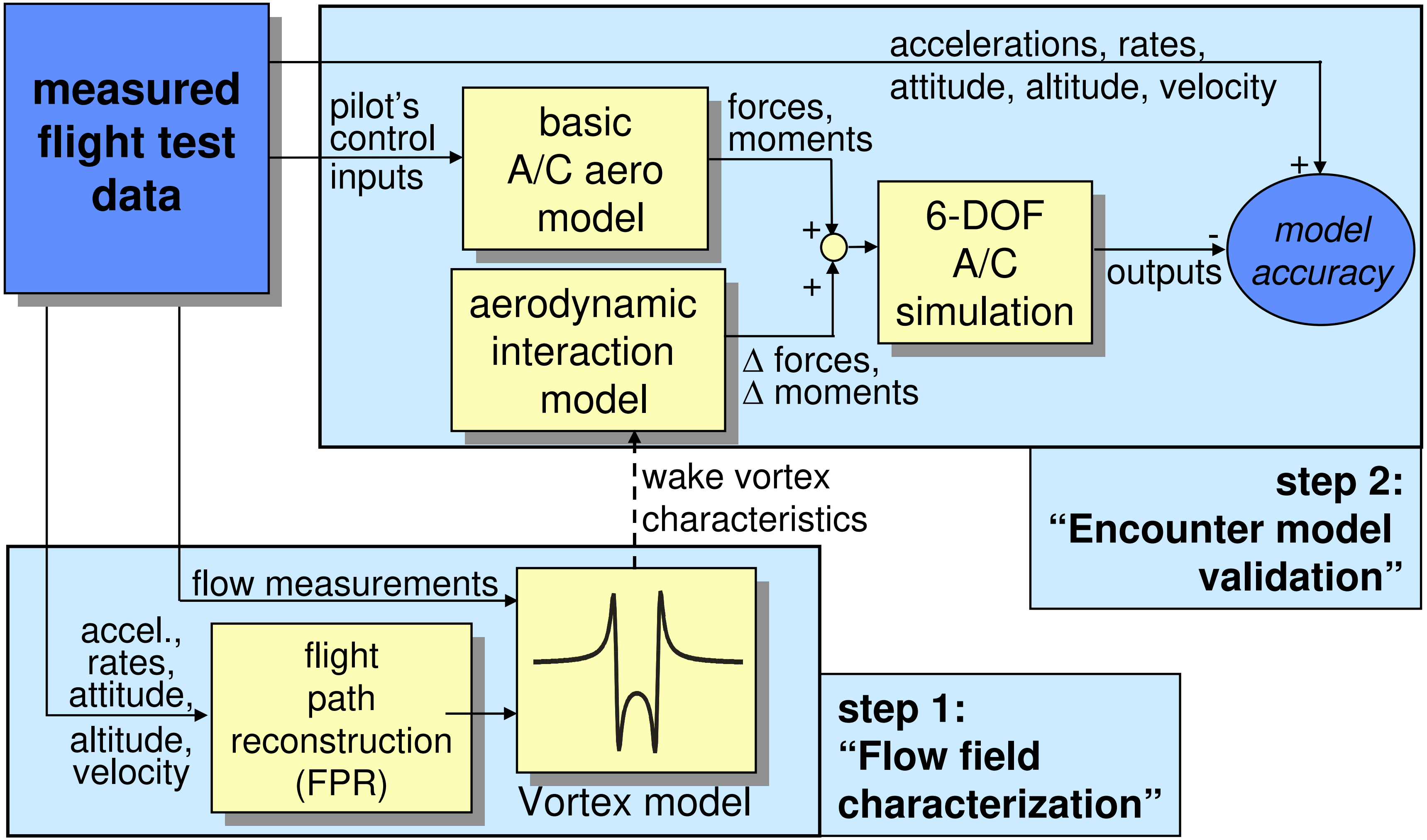
100 encounters under steady atmospheric conditions.

Reaction of follower Aircraft:

- Up to 80° bank angle; typical 30-40°; Bump; Uncomfortable; usually does not lead to loss of control (banking motion is averaged out)
- More important: lateral acceleration; may lead to injury to crew or Passenger

Wake Vortex Aircraft Encounter Model (2)

Schematic of Two Step Procedure for Vortex Model Identification



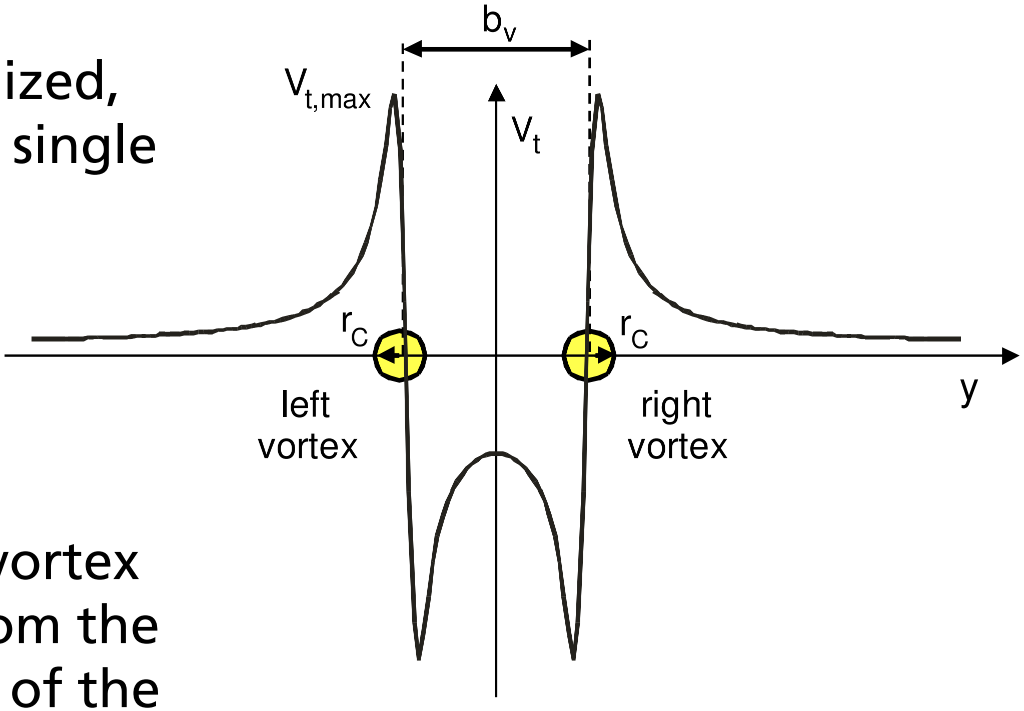
step 2: "Encounter model validation"

step 1: "Flow field characterization"

Wake Vortex Aircraft Encounter Model (3)

Analytical Model

The model consists of two idealized, superimposed counter-rotating single Vortices. Model parameters:
- vortex circulation Γ,
- core radius r_C,
- lateral vortex separation b_V,
- vortex location in space.



The tangential velocity of one vortex as a function of the distance from the core, $V_t(r)$, is described in terms of the circulation Γ and the core radius r_C:

$$Lamb-Oseen:$$

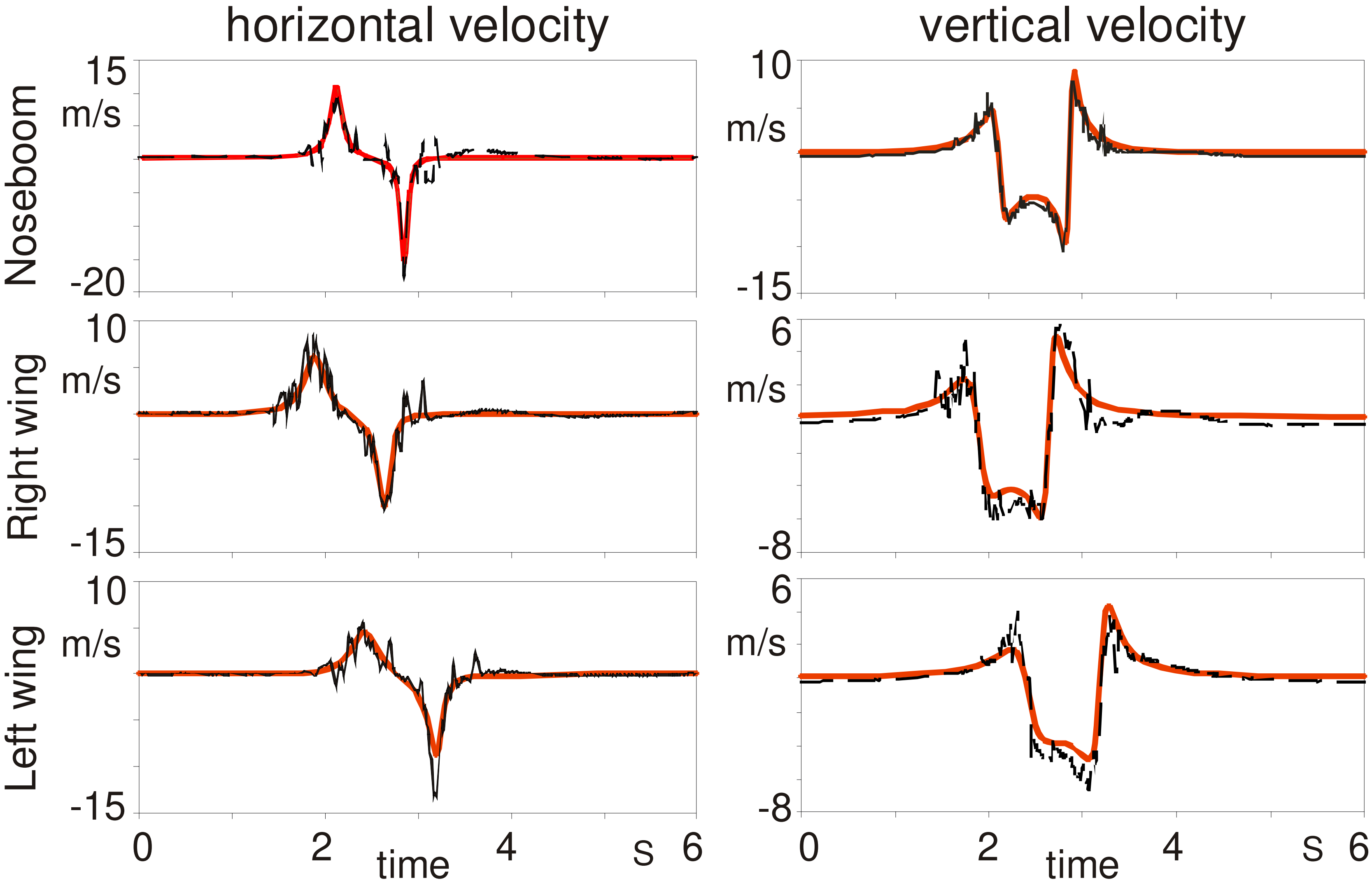
$$V_t(r) = \frac{\Gamma}{2\pi r}\left(1 - e^{-1.2544 r^2/r_c^2}\right)$$

$$Burnham-Hallock:$$

$$V_t(r) = \frac{\Gamma}{2\pi}\frac{r}{r_c^2 + r^2}$$

Wake Vortex Aircraft Encounter Model (4)

Wake velocity components during lateral encounter



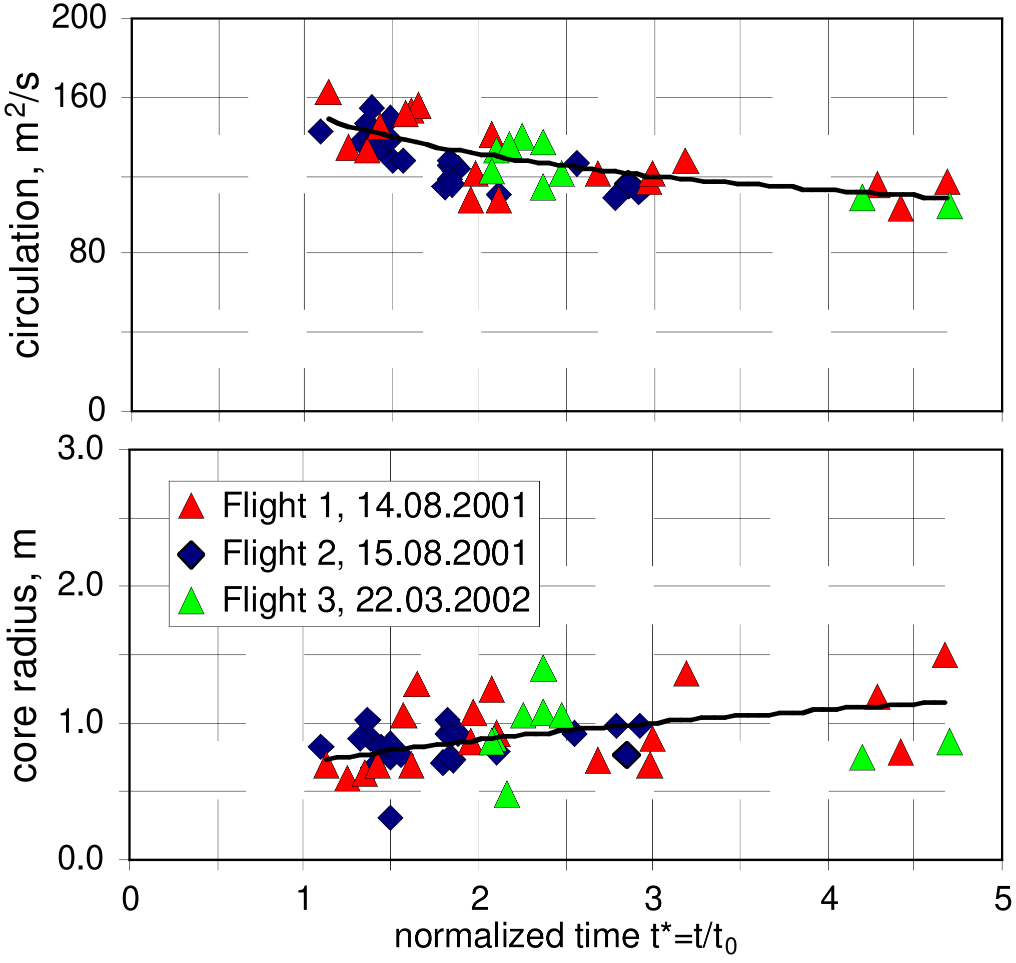
Wake Vortex Aircraft Encounter Model (5)

Flight estimated vortex model parameters

Identified core radius r_c and circulation Γ of the Burham-Hallock model for do-128 encounters from three flights.

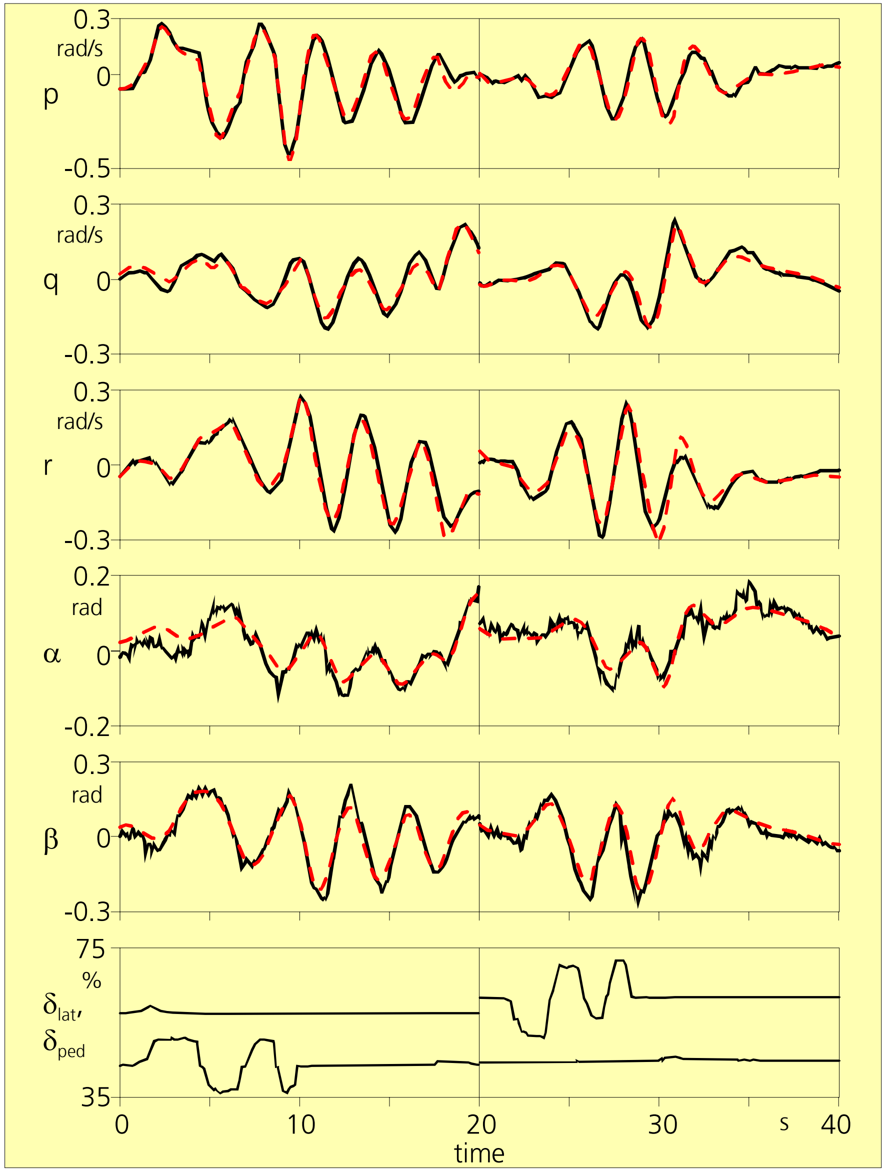
Conformance with Theory:

- Expected decay of circulation
- Increase of core radius
- Initial core radius ~ 0.75 m, (roughly 3.5% of the wake Generating wing span which Is somewhat smaller than Commonly stated value of 5%)



EC-135 Flying Helicopter Simulator (1)

Model Predictive Capability



Forward speed 60 kts:
Two flight maneuvers (Lateral and pedal inputs)

6-DOF Rigid-Body model:

- Angle of attack dependent lateral-directional derivatives
- Nonlinear aerodynamics; Weathercock stability for +ve and -ve sideslip angles

EC-135 Flying Helicopter Simulator (2)

Rotor Wake Modeling

Roll and pitch in hover and at low speeds:

unsymmetrical vortex compression and dilatation act on the induced velocity field in the proximity of the main rotor.

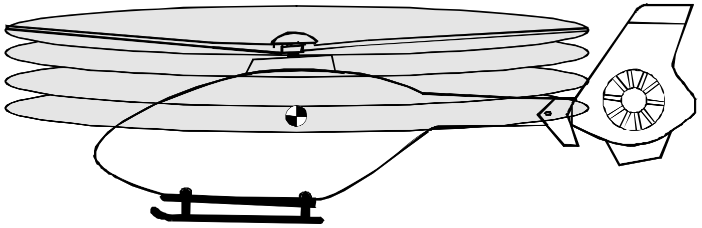
Effective AoA at the blade sections changed.

Aerodynamic rotor loads directly affected.

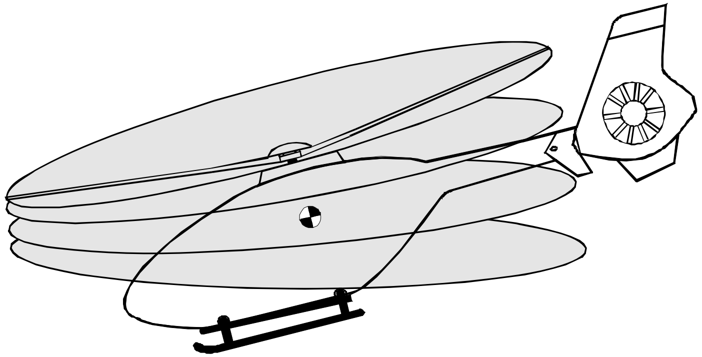
Rotor gyroscopic behavior due to the blade flapping dynamics forced by these loads leads to strong cross coupling effects of the helicopter due to the wake distortion.

Current research topic:

Suitable flight dynamic models describing this phenomenon to obtain improved simulation fidelity in off-axis response



Pure Hover



Pitching motion in Hover

EC-135 Flying Helicopter Simulator (3)

Dynamic Wake Model: Parametric extension of Pitt and Peters:

$$\underline{M}\,\dot{\underline{\lambda}} + \hat{\underline{L}}^{-1}\,\underline{\lambda} = \underline{c} + \frac{1}{\Omega}\,\hat{\underline{L}}^{-1}\begin{bmatrix} 0 \\ K_p\,(p-\dot{\beta}_s) \\ K_q\,(q-\dot{\beta}_c) \end{bmatrix}$$

$\underline{M}$: Apparent mass matrix associated with the acceleration terms from momentum theory

$\underline{L}$: gain matrix, $\underline{\lambda}$ $(=[\lambda_0, \lambda_s, \lambda_c]^T)$ the inflow ratio describing the first harmonic terms

$\underline{c}$ $(=[c_T, c_1, c_m]^T)$: rotor load coefficients wrt rotor thrust and aerodynamic pitch and roll moment,

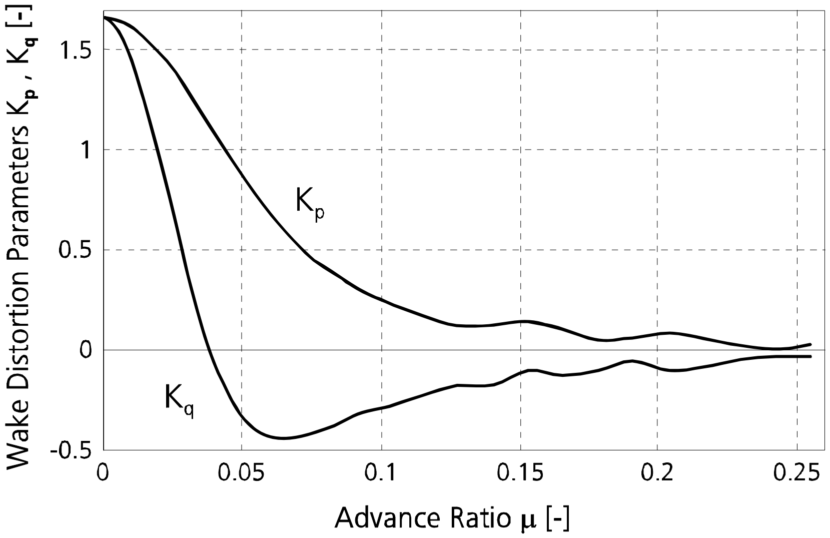
Ω: main rotor rotation speed

K_p and K_q: Wake distortion parameters for longitudinal and lateral distribution of the induced velocity.

Last term on RHS: Parametric term that feeds back the roll and pitch rates of the rotor tip path plane wrt to the surrounding air to the induced velocity distribution over the rotor disk

Estimate K_p and K_q

Theoretical estimates of Wake distortion parameters



From flight tests applying SysId methods:

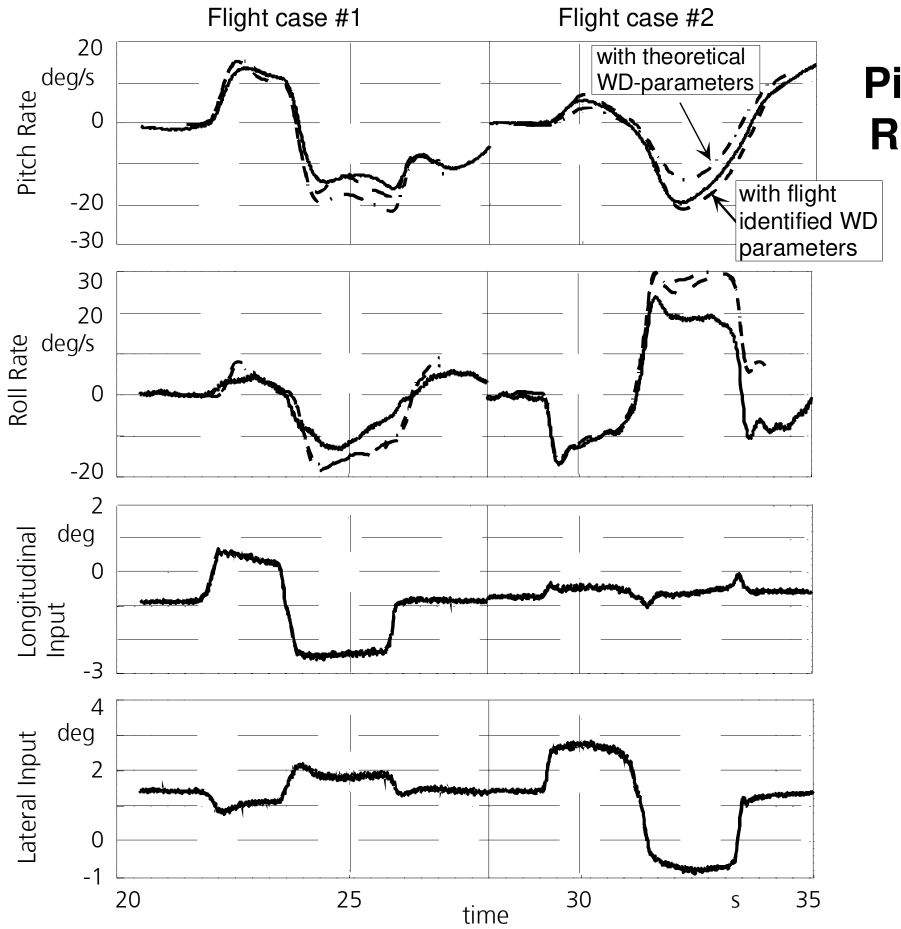
Kq = 1.6; Kp = 2.5 (μ = 0)

$\mu = V_H/\Omega R$; V_H: forward speed m/s; Ω: main rotor rotation speed rad/s; R: rotor radius in m.

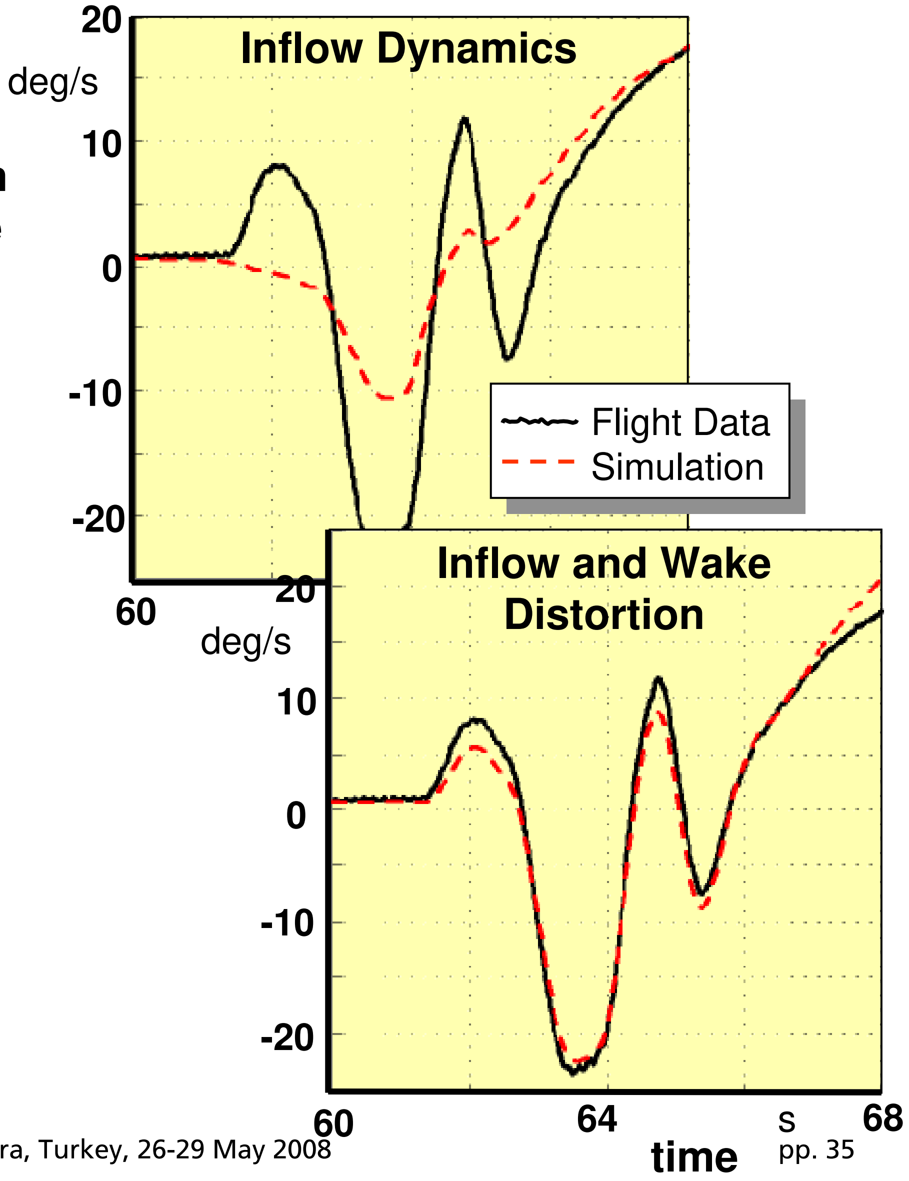
EC-135 Flying Helicopter Simulator (4)

Dynamic Wake Model: Parametric extension of Pitt and Peters:

Simulation fidelity at Hover



Pitch Rate



EC-135 Flying Helicopter Simulator (5)

Dynamic Wake Model: Parametric extension of Pitt and Peters:

Forward speed 40 m/s

$\mu = V_H/\Omega R = 0.18$

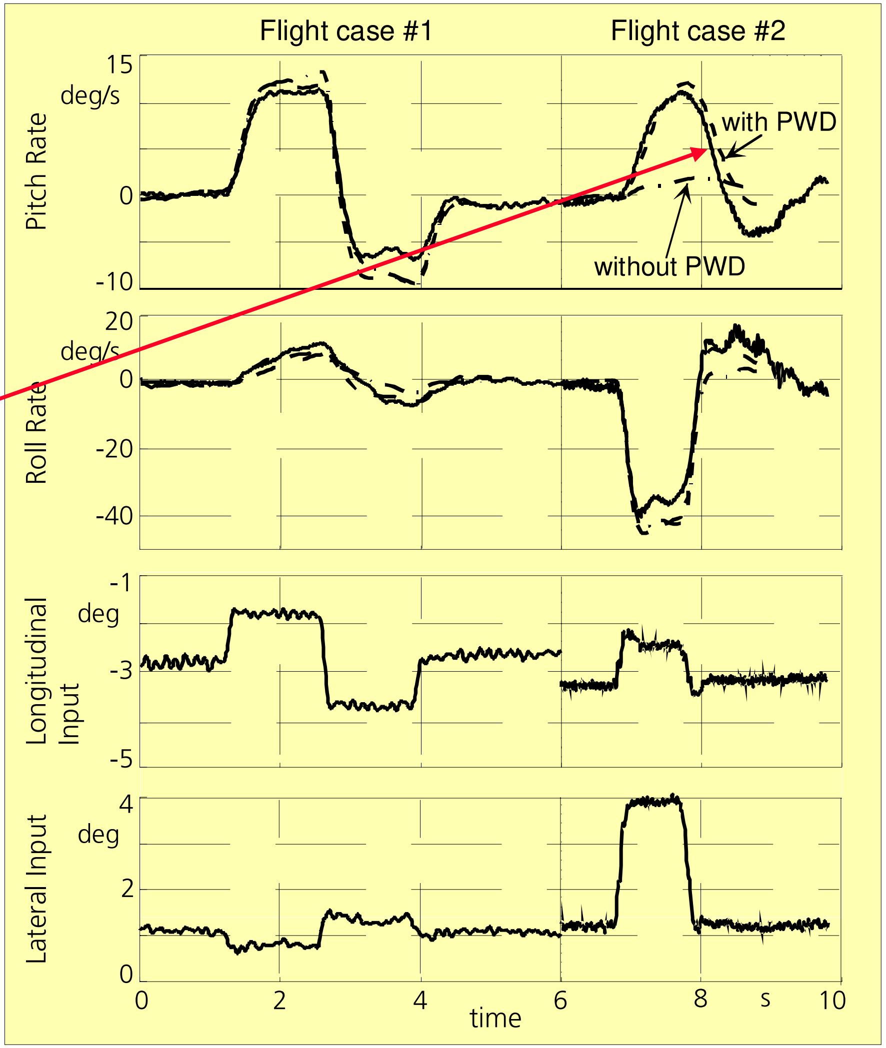
➔Theoretical estimate = 0

From flight tests applying SysId methods:

Kq = 1.6;   Kp = 1.1   Good match

But, estimates do not conform to The wake distortion theory.

Anomaly: Parameters do not Represent wake distortion which occurs at hover. They account for Other unmodeled effects (rigid / elastic blade formulation).



Phoenix: Reusable orbital glider (1)

Wind-tunnel testing in August 2003

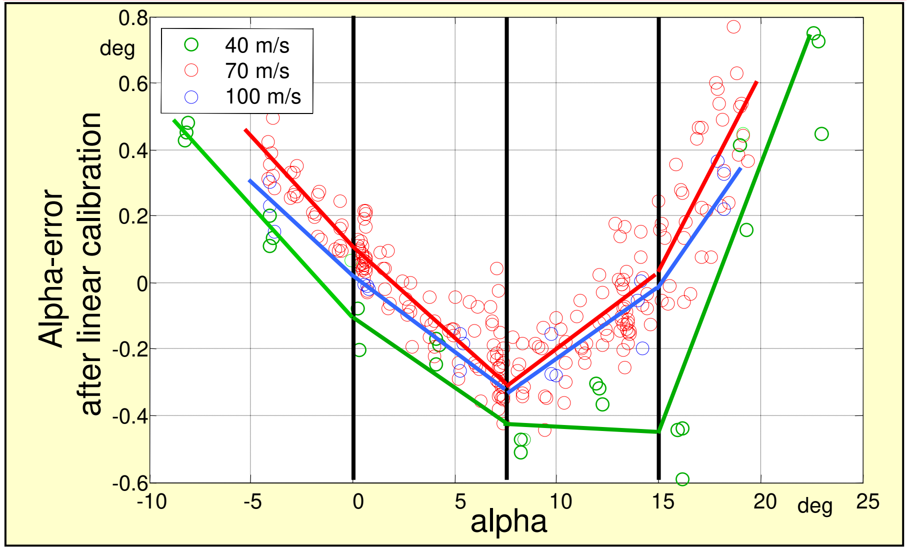
Pre-flight checks: April 2004

calibration of flow angles:

$$\alpha = \frac{p_{d\alpha}}{K_\alpha \, q_c} + korr_\beta \frac{p_{d\beta}}{q_c} + \alpha_{offset}$$

α-error nonlinear:
quadratic or piecewise linear

Accuracy:
AoA and AoS: < 0.5°
Horizontal velocity: 0.5 m/s

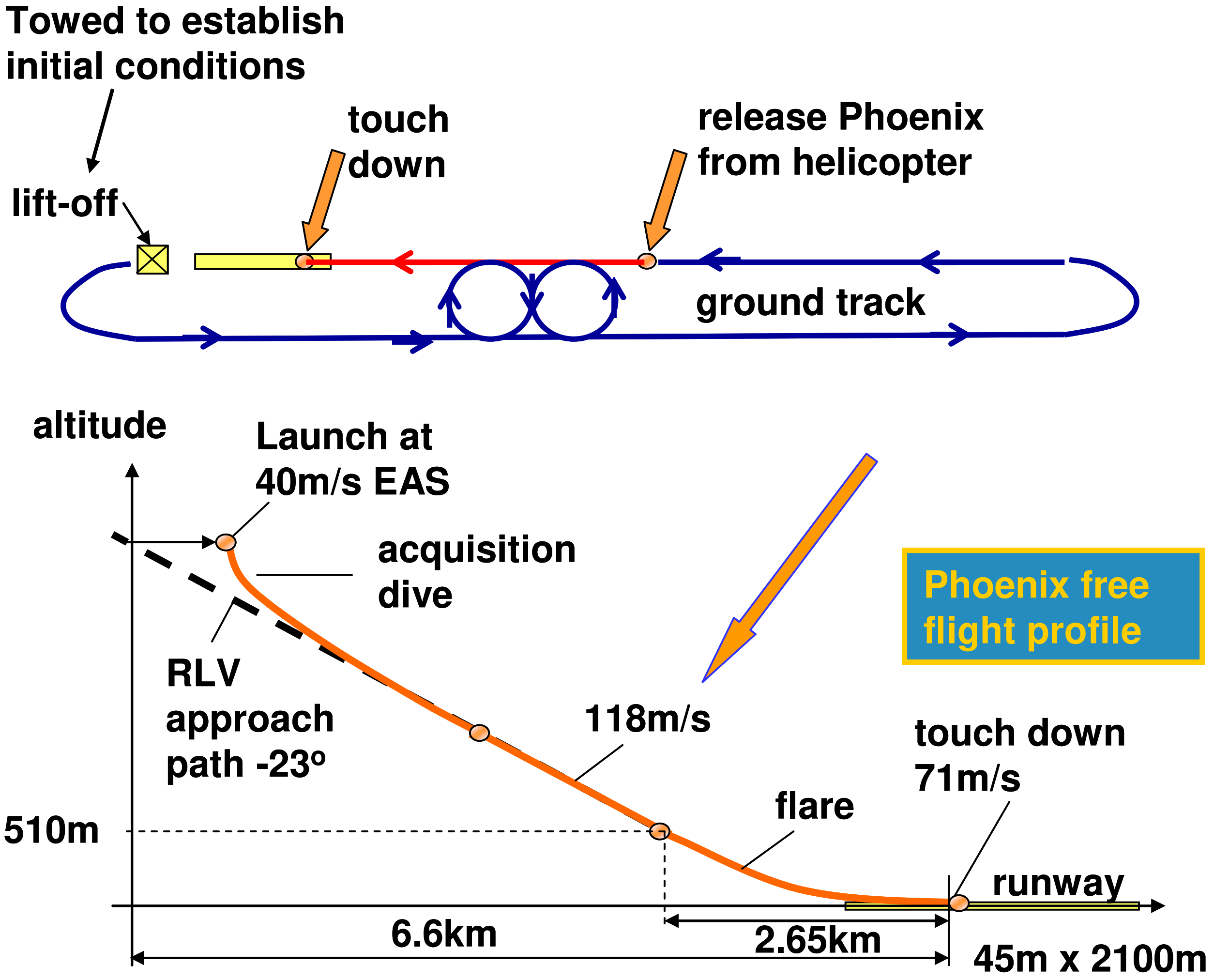


Phoenix: Reusable orbital glider (2)

Reference Mission:

Flight phases upon release:

1) Acquisition
2) Approach
3) Flare
4) Alignment
5) Derotation
6) Rollout



Phoenix: Reusable orbital glider (3)

Free flights:
Maiden flight on 8-May-2004
Repeat flight on 13-May-2004
3rd flight with Offset on 16-May-2004

Configuration:
Delta Wing, relatively low wing span
3 controls (flaperons and rudder)
Body flap and speed brake
1200 Kg
7m long
3,48 m span

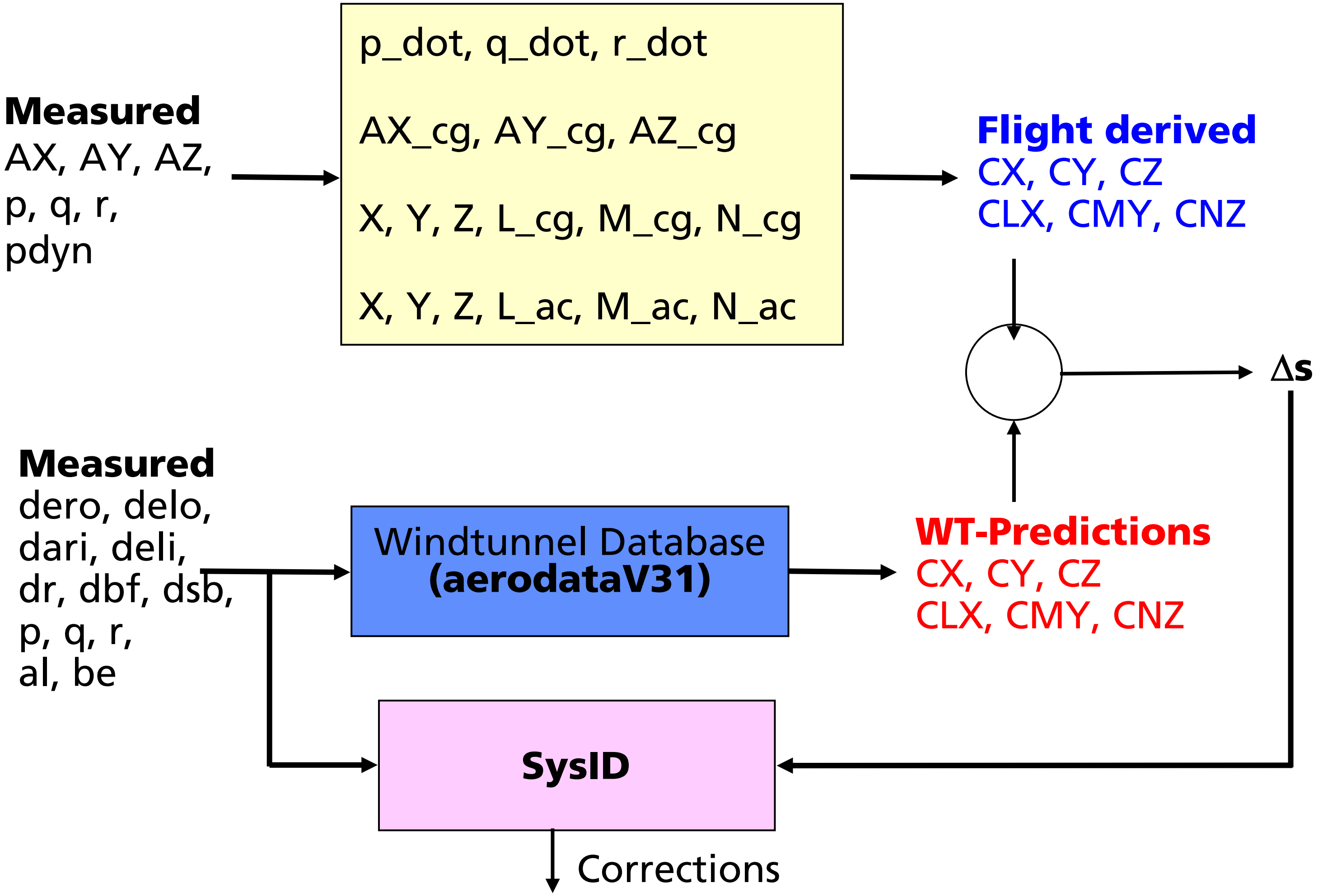
Highly dynamic behavior
High bandwidth control loops

Video
Flight 1 and Flight 3

Phoenix: Reusable orbital glider (4)

Aerodynamic Database:

Verification and Update -- Principle



Measured
AX, AY, AZ,
p, q, r,
pdyn

p_dot, q_dot, r_dot

AX_cg, AY_cg, AZ_cg

X, Y, Z, L_cg, M_cg, N_cg

X, Y, Z, L_ac, M_ac, N_ac

Flight derived
CX, CY, CZ
CLX, CMY, CNZ

Δ**s**

Measured
dero, delo,
dari, deli,
dr, dbf, dsb,
p, q, r,
al, be

Windtunnel Database
(aerodataV31)

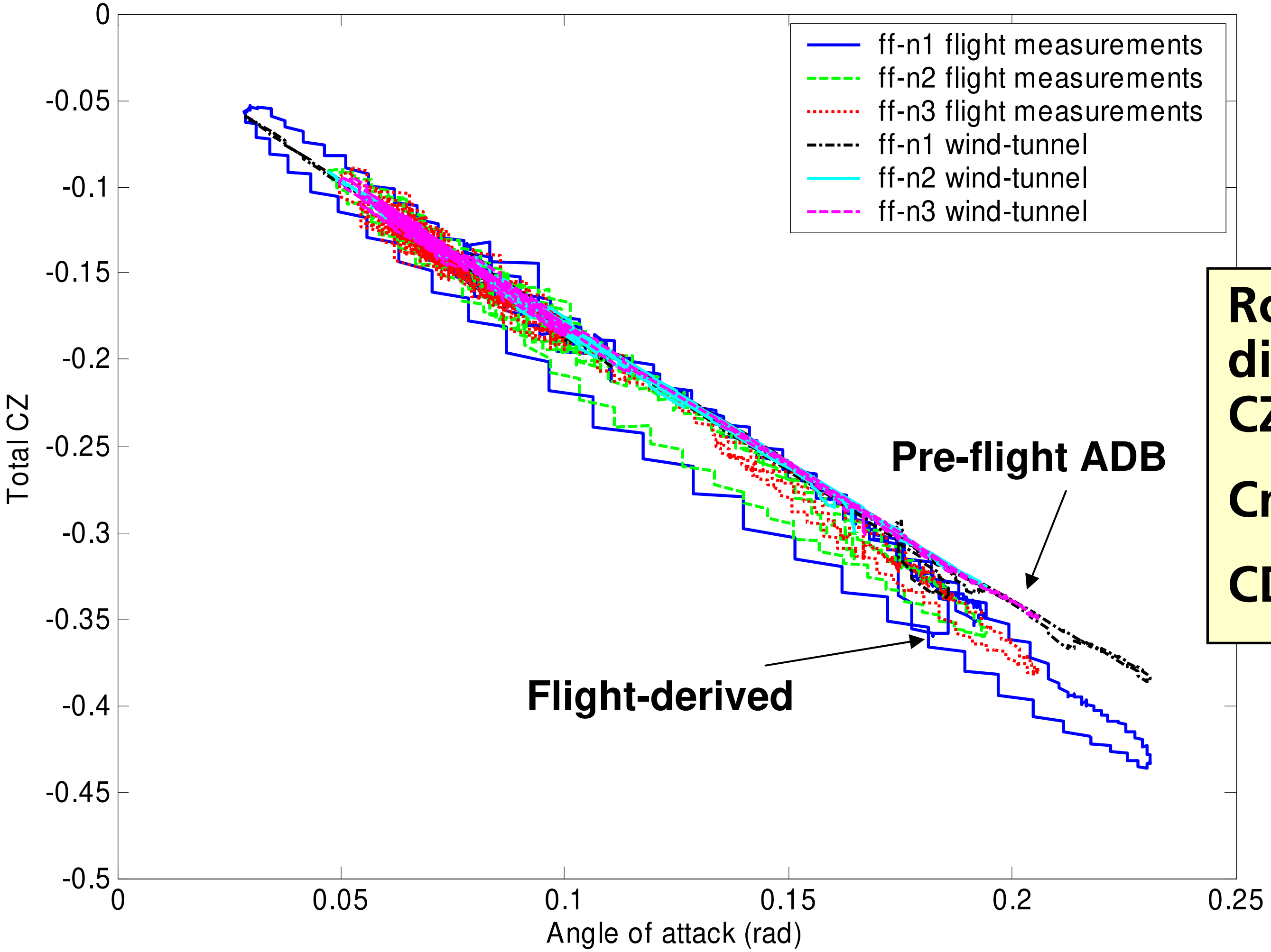
WT-Predictions
CX, CY, CZ
CLX, CMY, CNZ

SysID

Corrections

Phoenix: Reusable orbital glider (5)

Flight derived and WT predicted vertical force coefficient



Rough order of discrepancies:
CZ: 9-10%

Cm: < 3%

CD: ~10% Nonlinear

Phoenix: Reusable orbital glider (6)

Aero model update (In-Air)

$$\Delta CZ = CZ_0 + CZ_\alpha \, \alpha + CZ_q \frac{q}{L_{ref} V} + CZ_{\delta bf} \, \delta_{bf}$$

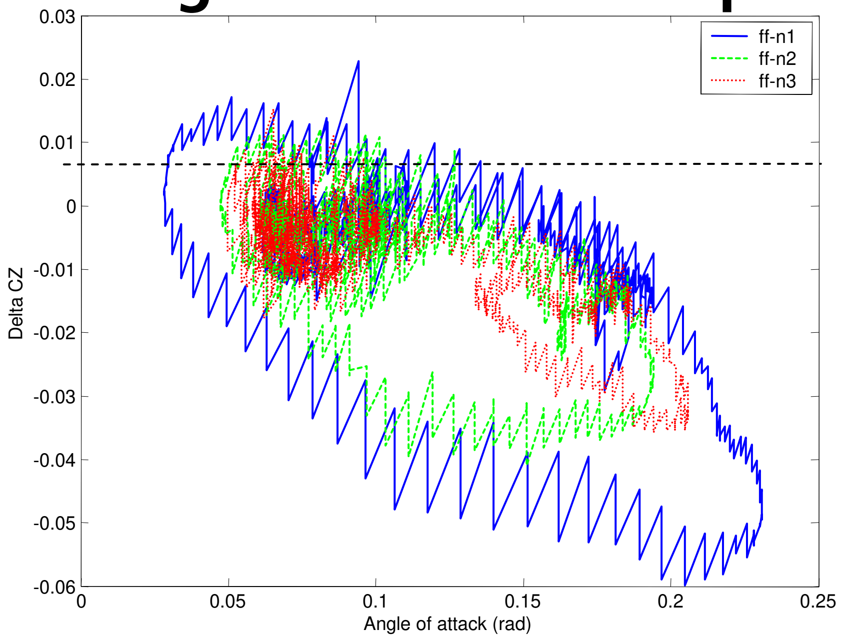
$$\Delta CX = CX_0 + CX_\alpha \, \alpha + CX_q \frac{q}{L_{ref} V} + CX_{\delta sb} \, \delta_{sb}$$

$$\Delta CMY = CM_0 + CM_\alpha \, \alpha + CM_{\delta e} \, \delta_e + CM_{\delta sb} \, \delta_{sb}$$

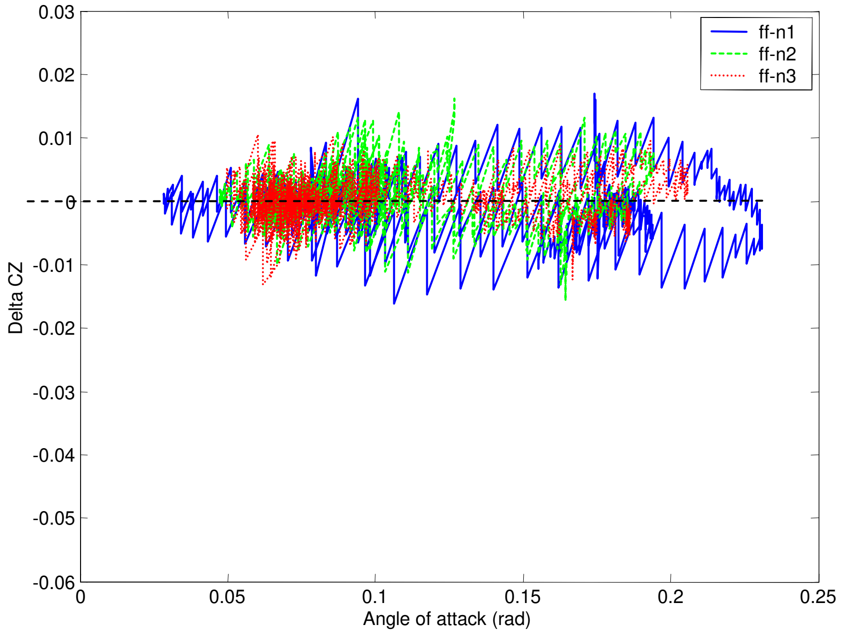
12 Parameters $CZ_{()}$, $CX_{()}$ and $Cm_{()}$ are estimated to reduce the deviations between flight measurements and WT-predictions.

Phoenix: Reusable orbital glider (7)

Flight derived and Updated database



Delta CZ versus AoA without and with update



Important Inferences:

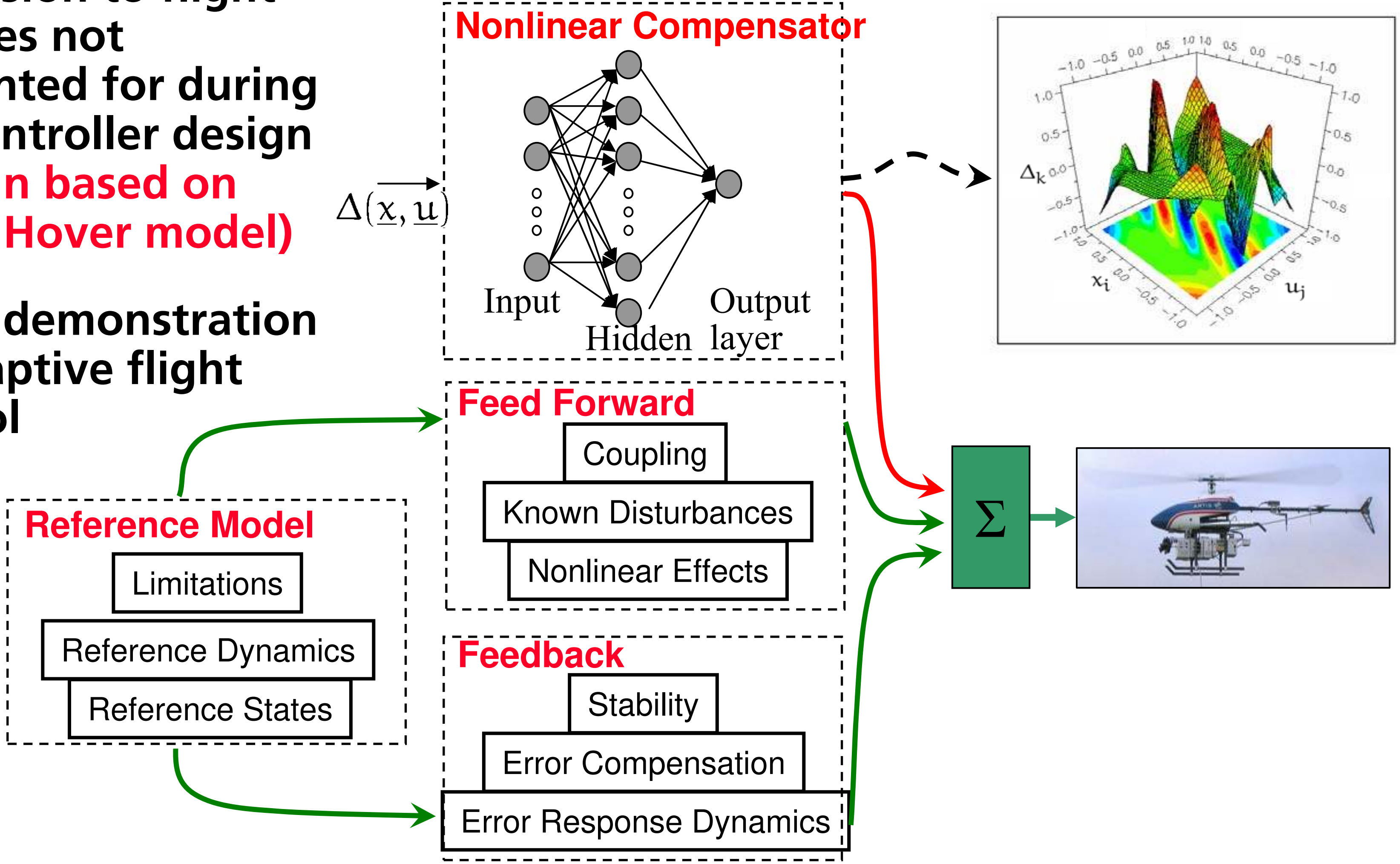
- lift generated in flight is higher
- component due to pitch rate in lift and drag is not adequately accounted for.
- basic longitudinal force coefficient for clean configuration underestimated,
- impact of speedbrakes overestimated.

Automatic Envelope Expansion through Adaptive Flight Control (1)

Expansion to flight regimes not accounted for during the controller design (Design based on linear Hover model)

Flight demonstration of adaptive flight control

Déjà-vu: Modules of adaptive control system



Nonlinear Compensator

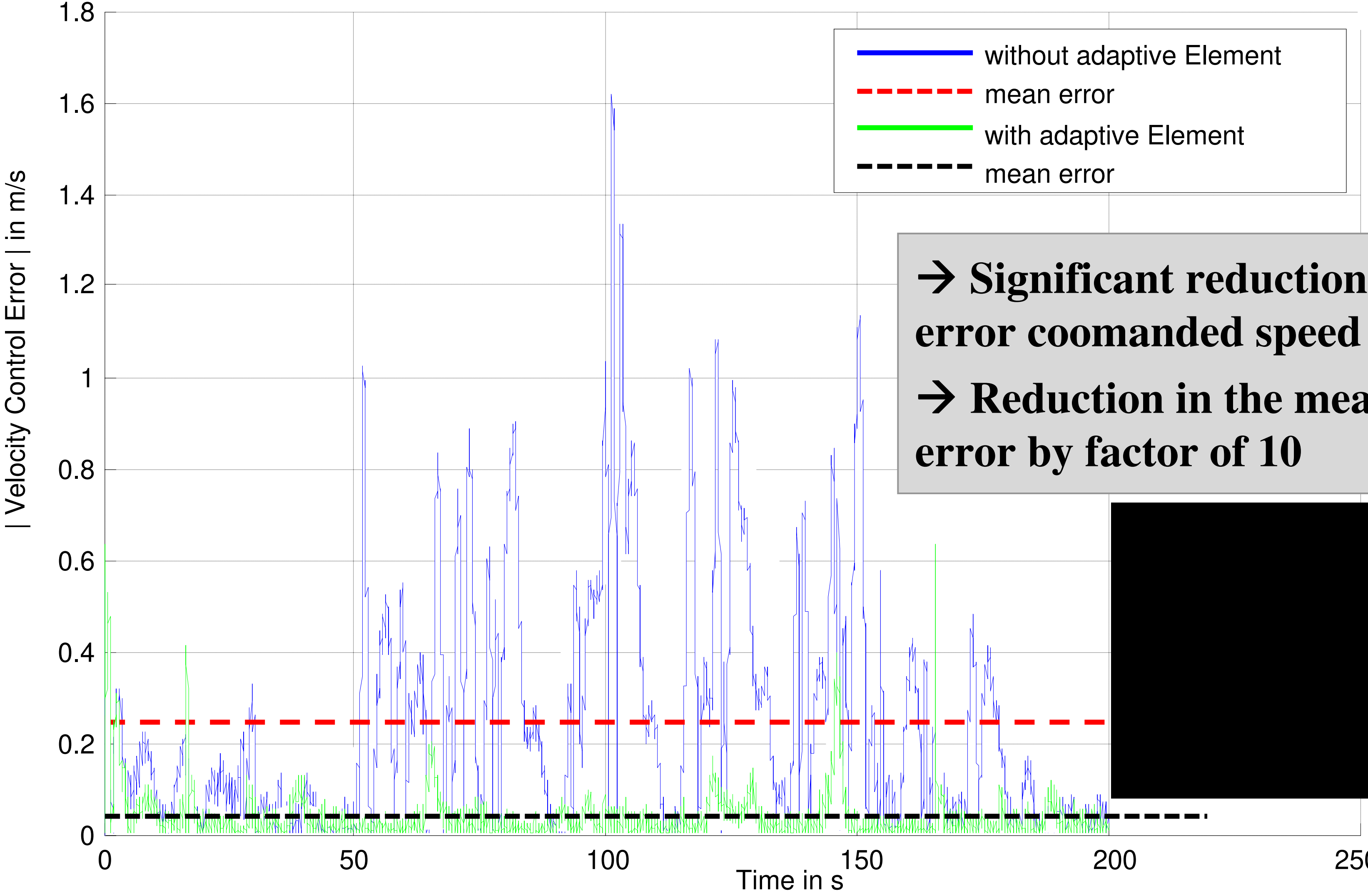
Feed Forward
- Coupling
- Known Disturbances
- Nonlinear Effects

Reference Model
- Limitations
- Reference Dynamics
- Reference States

Feedback
- Stability
- Error Compensation
- Error Response Dynamics

Automatic Envelope Expansion through Adaptive Flight Control (2)

Flight test results: Forward flight (>10m/s) with midiARTIS



→ **Significant reduction in error coomanded speed**

→ **Reduction in the mean error by factor of 10**

[redacted]

The Future

- Prime areas of applications:
  - Aerodynamic database generations
  - Modeling of nonlinear aerodynamics
  - Unstable aircraft
- New measuring techniques for air data
  - Flush air data sensors
  - optical sensors

- Real-Time parameter estimation is re-emerging (after seventies)
- Full flexible aircraft models (integration of flight mechanics and structural models) -- distributed mass models
- Modeling and identification of UAVs, mAVs
- Integrating System Identification and Computational Fluid Dynamics methodologies

Concluding Remarks

- Unified approach based on Quad-M basics and various aircraft parameter estimation methods

- Various examples covering global aerodynamic database, nonlinear effects, stall hysteresis, landing gear effects, load drop

  Modeling of wake vortex encounter

  Modeling of rigid-body and extended models for EC-135 helicopter

  Modeling of Reusable orbital glider

- Different aspects and examples of validation of identified models

Summary:

- SysID methods provide a well proven and highly sophisticated tool for aerodynamic modeling from flight data.
- Experience, engineering judgement and skill to interpret the modeling discrepancies and formulate them mathematically mainly limits the scope of applications.