The Role of Flight Tests and of Flight Simulation in Aircraft Design

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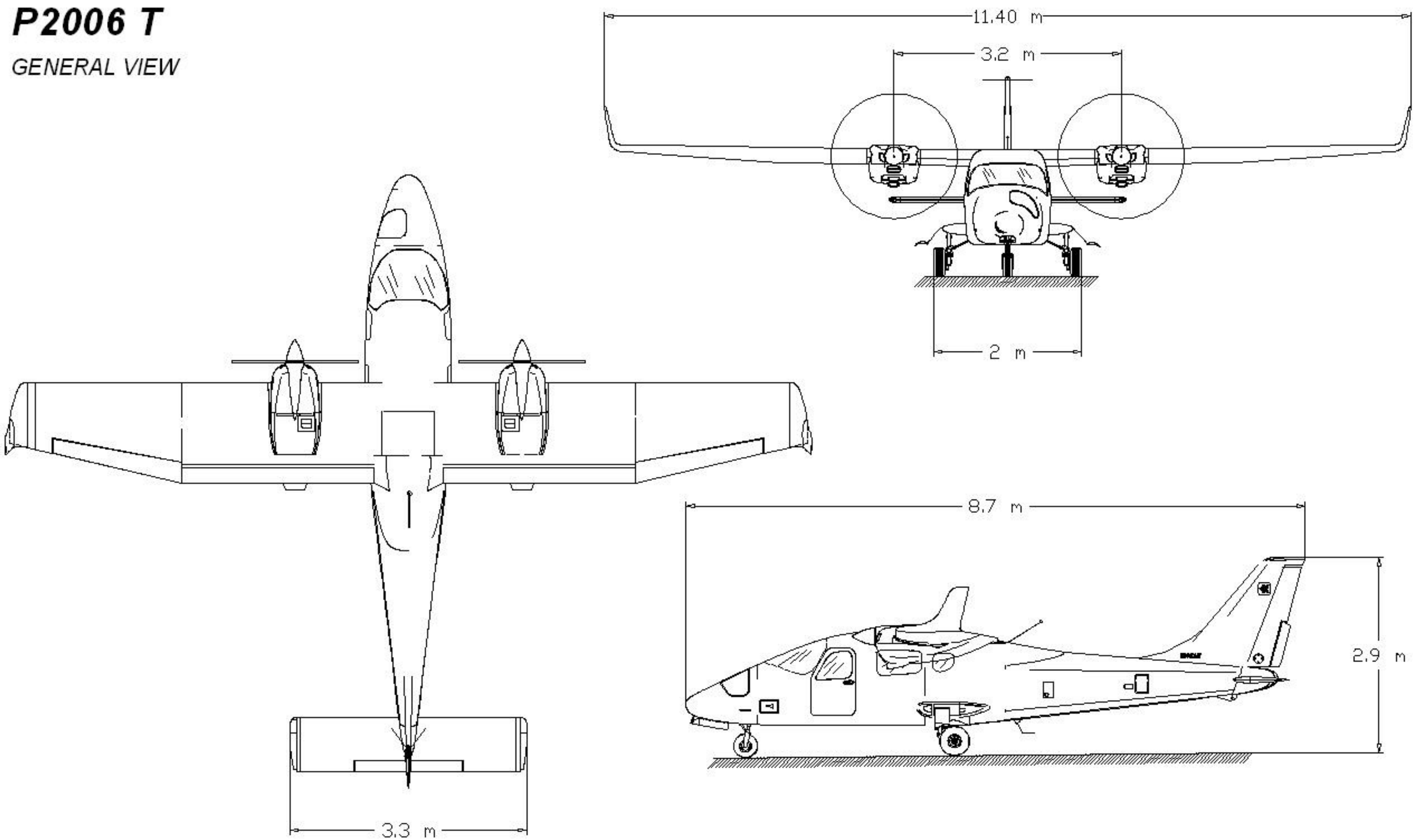
Layout of the presentation

- A case study: the Tecnam P2006T aircraft
  - Flight test instrumentation
  - Flight tests for certification
  - Evaluation of stability and flight qualities
  - Aircraft system identification (parameter estimation)

- JSBSim, an open source Flight Dynamics Model (FDM) software library
- Desktop 6DoF simulations
- Simulation-based aircraft design

P2006 T

GENERAL VIEW



TECNAM s.r.l.

P2006T aircraft

Cockpit

Baggage compartment

Table 1 P2006T aircraft geometric characteristics

Parameter	Value	Parameter	Value
Wing span	37.40 ft (11.4 m)	Fuselage length	28.50 ft (8.7 m)
Wing area, S	159.31 ft^2 (14.8 m^2)	Cabin width	48.03 in (1.22 m)
MAC, c	4.40 ft (1.34 m)	Cabin length (with baggage)	11 ft (3.35 m)
Wing aspect ratio, AR	8.76 (8.76)	Fuselage height	9.35 ft (2.85 m)

Table 2 P2006T aircraft weights and loading

Parameter	Value
MTOW, W_{TO}	2601 lb (1180 kg)
Maximum ramp weight	2601 lb (1180 kg)
Standard equipped weight	1675 lb (760 kg)
Standard useful load	926 lb (420 kg)
Limit load factors, n	+3.8 g/ − 1.9 g

Table 3 P2006T aircraft propulsion characteristics

Parameter	Value
Engine model	Rotax 912S
Takeoff power	100 hp (73 kW)
Maximum continuous power	92.4 hp (69 kW)
Propeller (two blades, constant speed, full feathering)	MTV-21-A-C-F/CF178-05

P2006T aircraft

CS-23/FAR-23 Certified

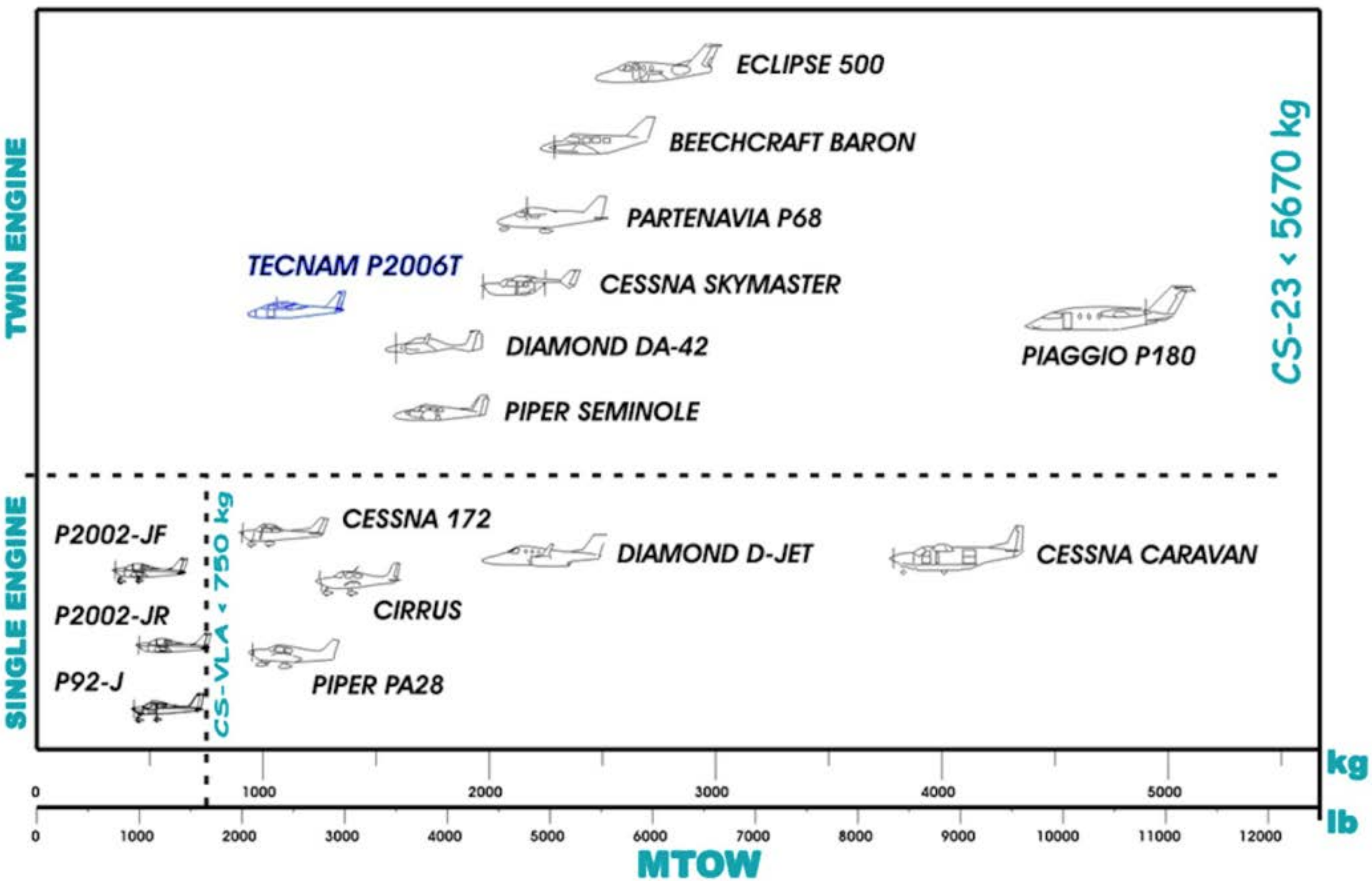
Table 4 P2006T Performances as measured from flight-certification tests

Parameter	Value
Max speed at S/L (full throttle, max RPM)	154 kt
Cruise speed (75%, 7000 ft)	145 kt
Cruise speed (65%, 9000 ft)	135 kt
Stall speed flap down	47 kt
V_A (maneuvering speed)	116 kt
V_{NE} (never exceed speed)	168 kt
Max RC, S/L	1210 ft/ min
Max RC, S/L ,OEI	350 ft/ min
Service ceiling (twin engine)	12,800 ft
Single-engine ceiling	6600 ft
Takeoff distance	1260 ft (384 m)
Takeoff ground run	968 ft (295 m)
Landing distance	1263 ft (385 m)
Landing ground run	734 ft (224 m)

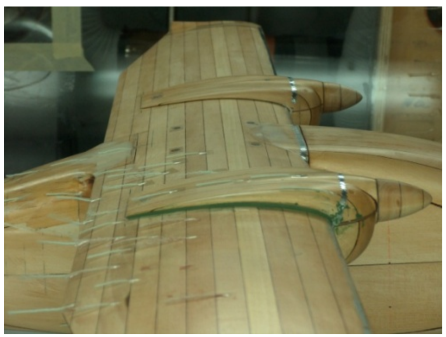
Table 5 Selected c.g. range for flight tests (useful load 420 kg)

	Max forward	Max aft
X_{cg}/c	16.5%	31%
Load	Pilot (90 kg)	Pilot (90 kg)
Condition	3 crew (270 kg)	2 crew, rear (160 kg)
	No baggage	80 kg baggage
	6- kg fuel	90 kg fuel

P2006T and other similar airplanes



Wind tunnel tests



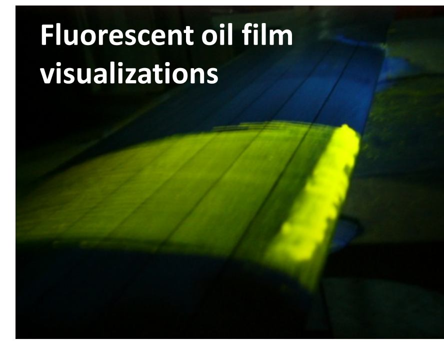
Turbulence Intensity
~ 0.1%

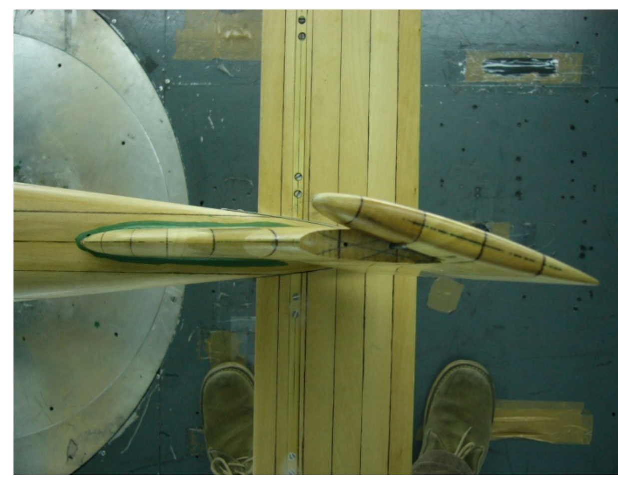
Max. speed
~ 45 m/s

Scale Model (1:6.5)

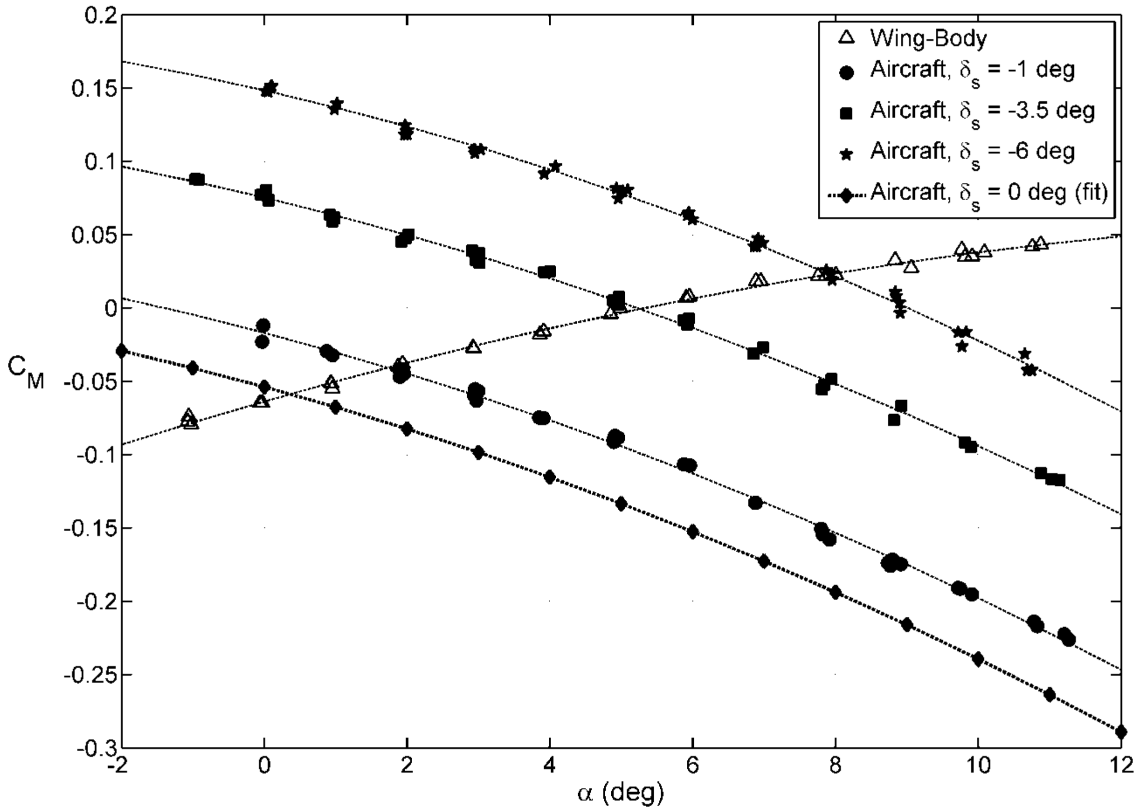
Re ≈ 0.6×10^6

In-Flight
Re ≈ 6.0×10^6



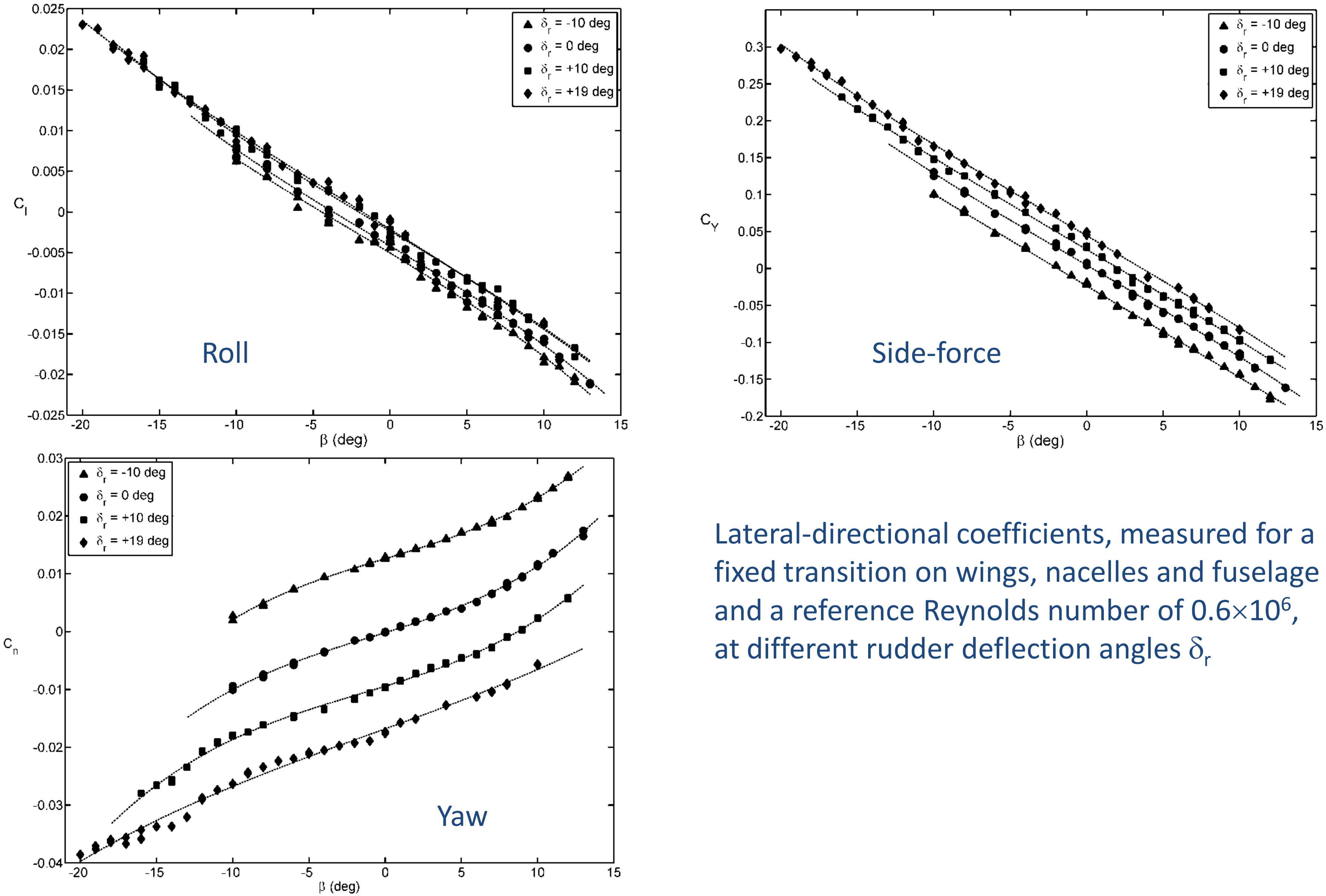


Wind tunnel test results



Pitching moment coefficient, measured for a fixed transition on wings, nacelles and fuselage and a reference Reynolds number of 0.6×10^6, at different stabilator deflection angles δ_s

Wind tunnel test results



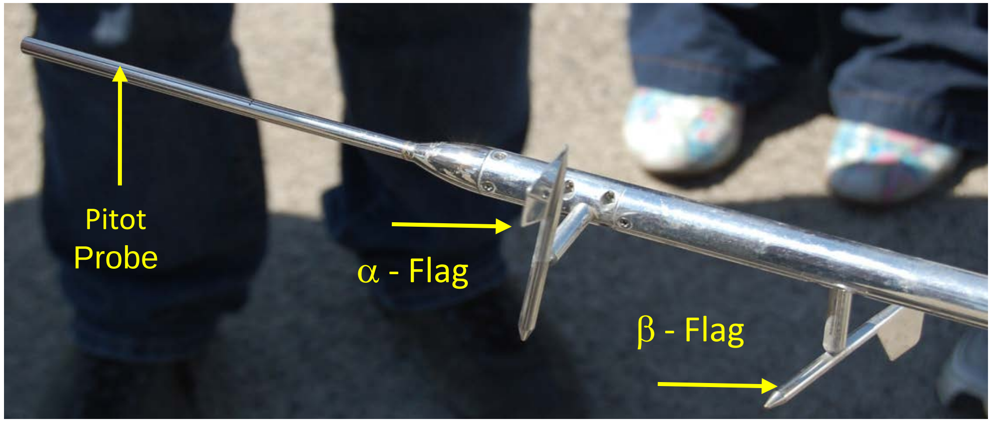
Lateral-directional coefficients, measured for a fixed transition on wings, nacelles and fuselage and a reference Reynolds number of 0.6×10^6, at different rudder deflection angles δ_r

Flight data acquisition system

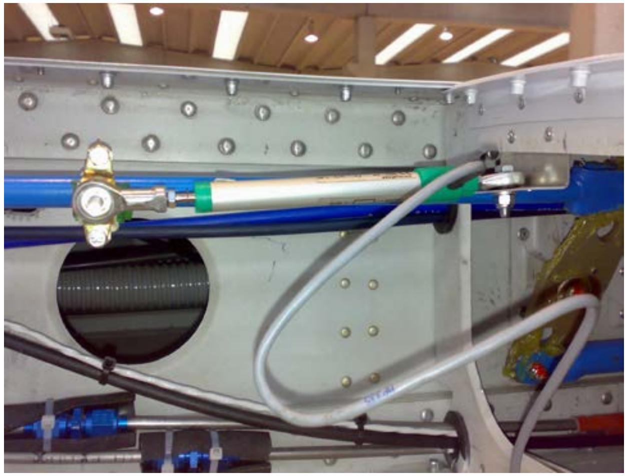
Control Unit (PC)

AHRS

GPS Antenna

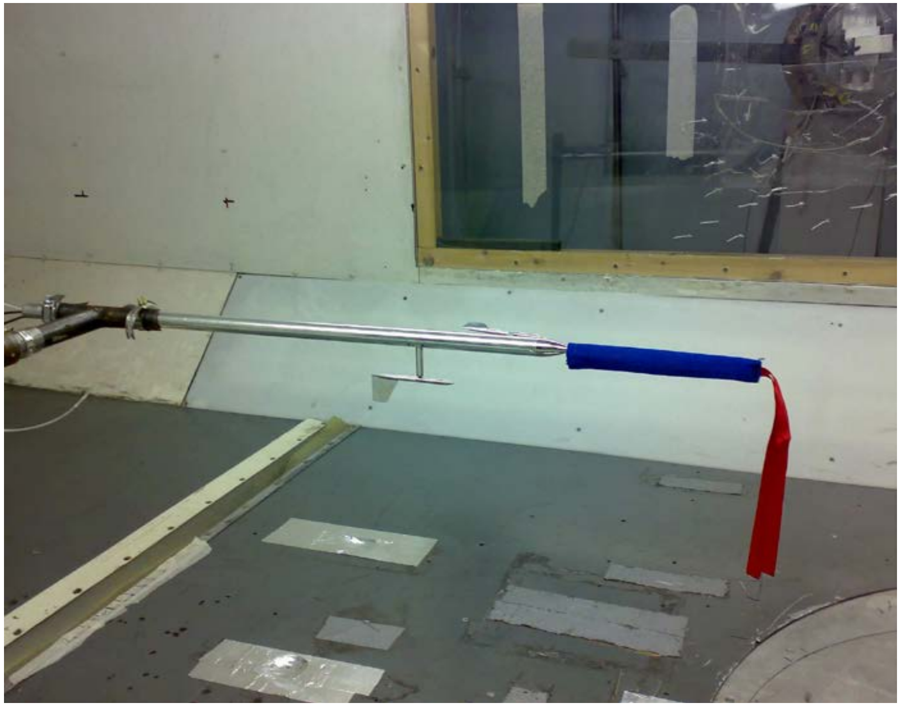


SpaceAge Control Mini Air Data Boom

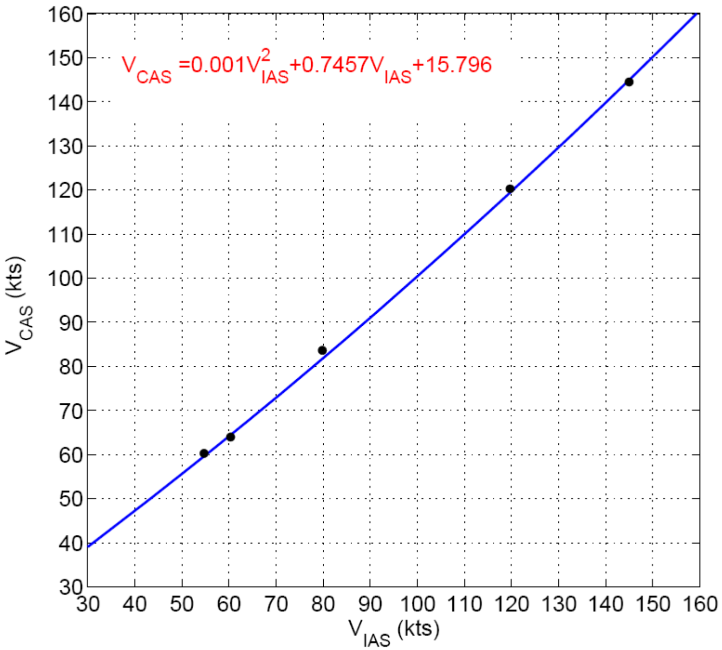


Aileron Deflection Potentiometer

Calibrations



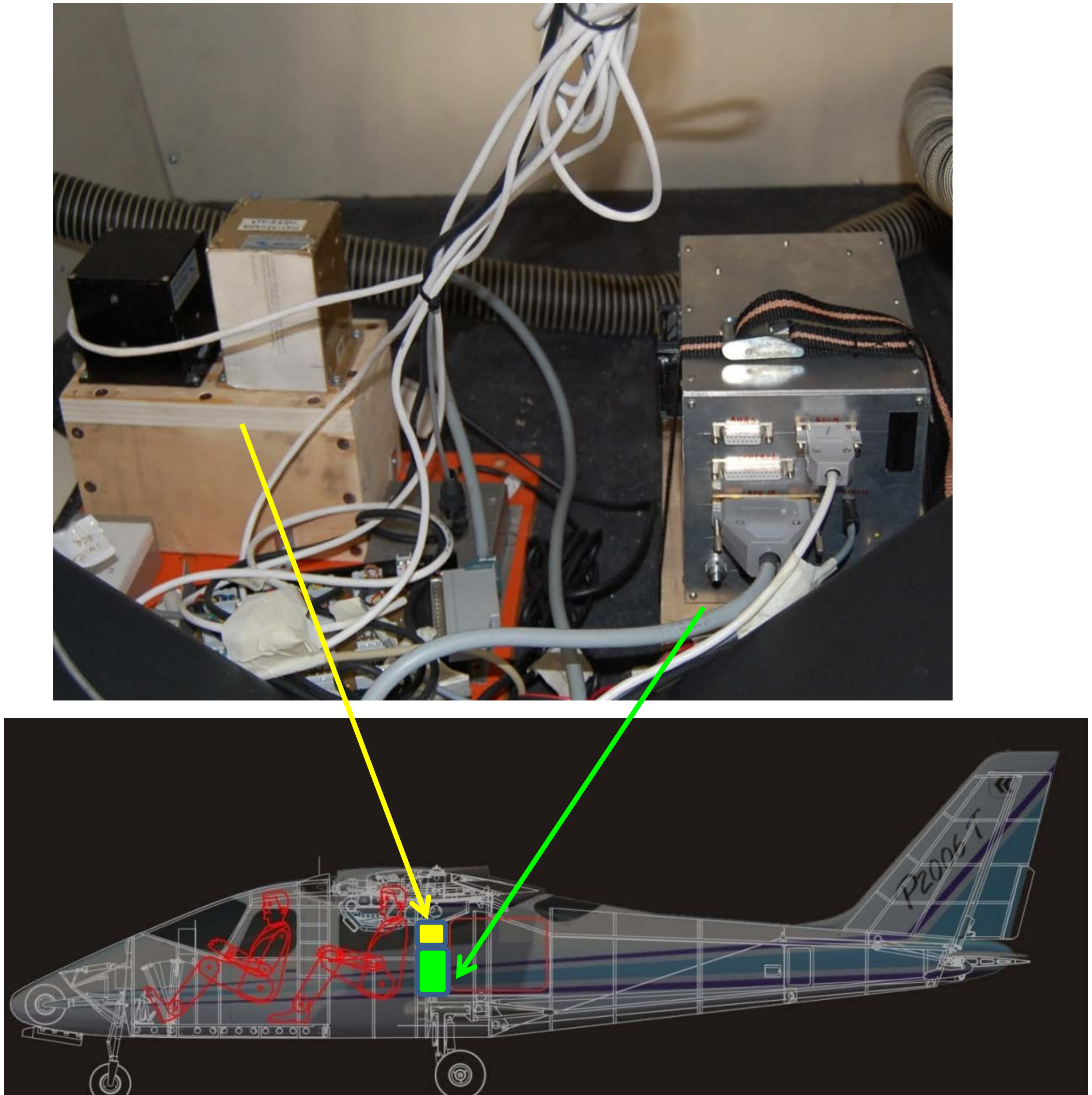
Load cell calibration.
Then applied to the control stick



COTS sensor
Angle α and β accuracy verified in wind tunnel: 0.2 deg
Used to calibrate aircraft pitot/static system

'Speed course' technique: evaluate CAS
Cross check with differential GPS outputs
CAS vs IAS

Flight data acquisition system



Stall tests

Requirements CS 23.49 and CS 23.201

- starting from a speed at least 10 kts above the stall speed
- longitudinal control must be pulled back
- rate of speed reduction will not exceed **1 knot/s** (level stall) and **3 knots/s** (turning stall)

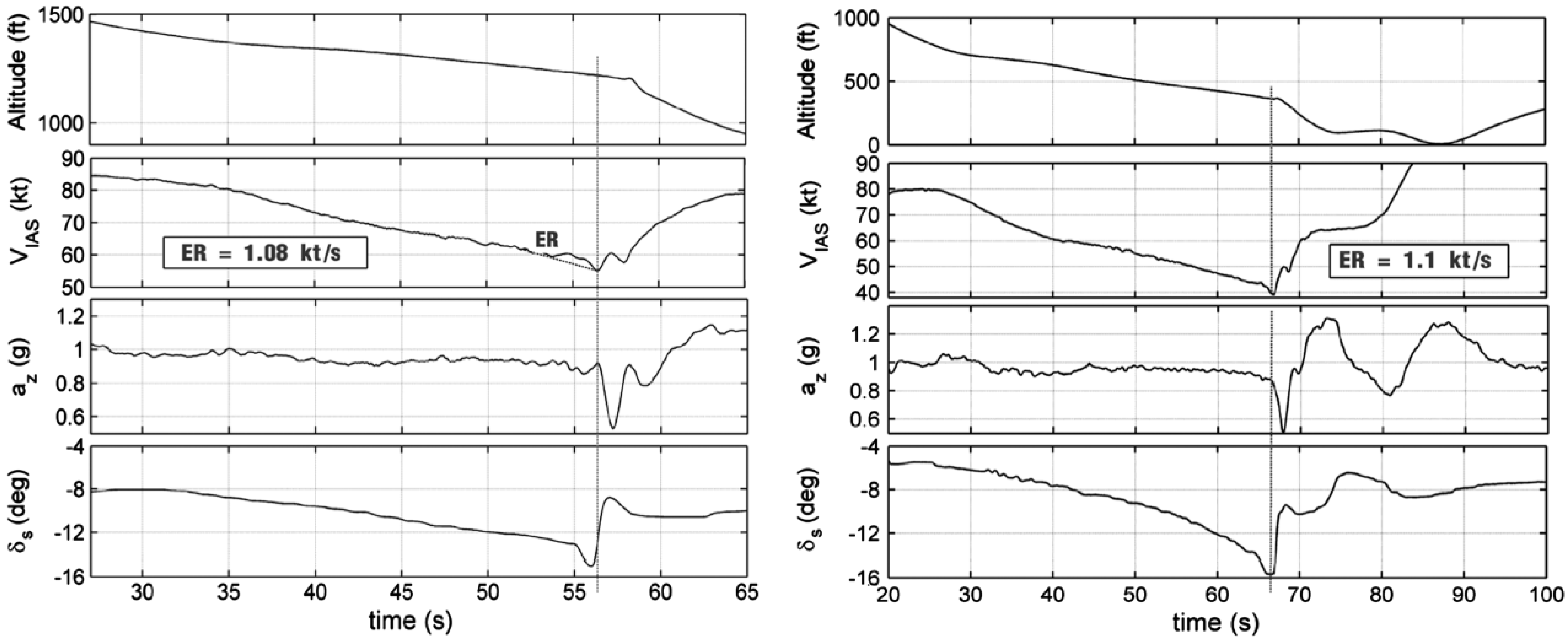
Tests have been performed in the following configurations and conditions:

- Maximum weight take off
- Engine running at 75% and idle
- Flap a 0^o, 15^o and full
- Landing gear retracted and extended
- Trim speed (= $1.5V_{S1}$)
- CG in the max forward and aft position.
- Turning stall with 30^o of bank

…leading to more than 100 stalls to accomplish certification requirements!

NO FLAP

WITH FLAP, landing conf.



a) Leveled; flap 0 deg; $X_{CG}/c = 16.5\%$

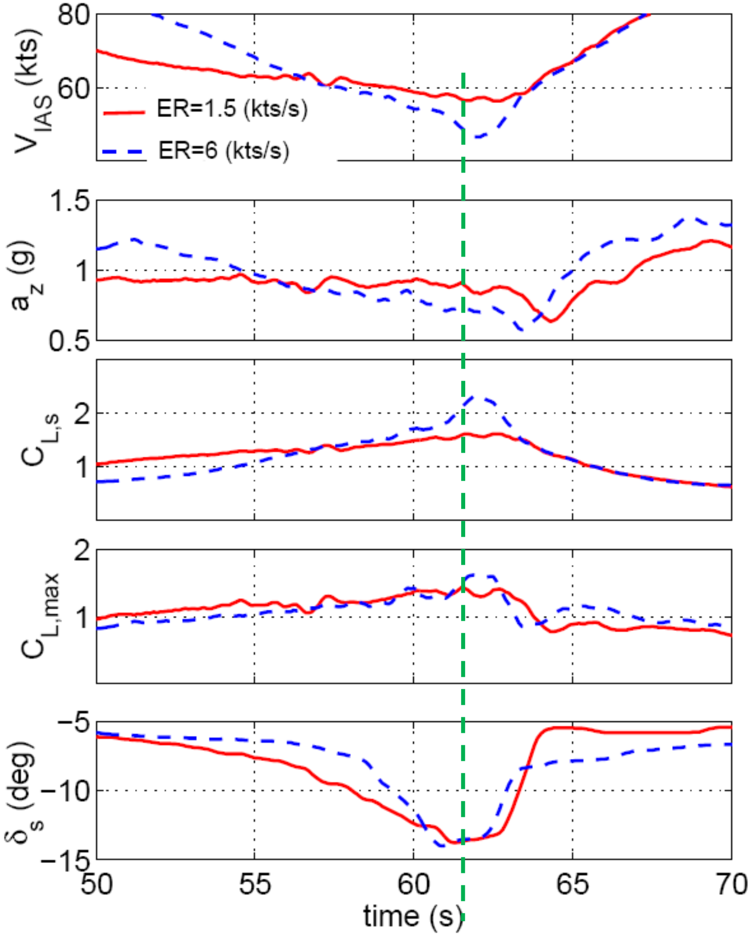
b) Leveled; flap 40 deg; $X_{CG}/c = 16.5\%$

Fig. 12 Leveled stall a) with flap retracted and (b) with a 40 deg (landing) flap deflection. Both tests are with engine idle and maximum forward position of c.g.

Stall tests · Entry rate effect

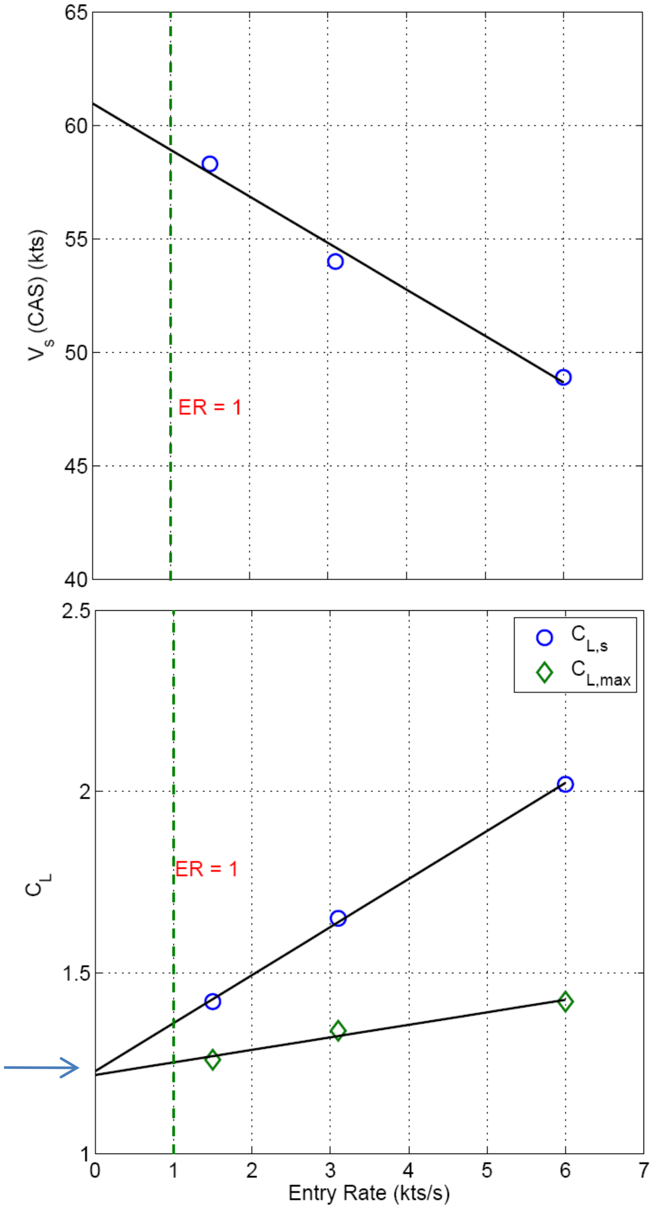
Level stall time histories – NO FLAP

*X*cg @ 16.5% MAC (max forward)



$$C_{L,max} = \frac{a_z W}{\frac{1}{2}\rho V^2 S} \quad (1)$$

$$C_{L,s} = \frac{W}{\frac{1}{2}\rho V^2 S} \quad (2)$$



Static C_{Lmax}=1.25
In cruise conf.

Stall test results

Table 7 Results of some stall tests performed for certification

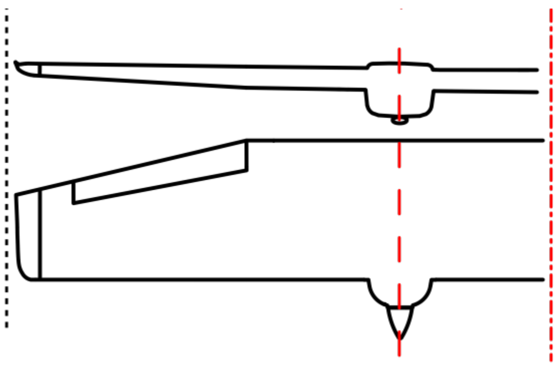
Type	Flap, deg	Landing gear	V_S, kt	a_z	ER,kt/s)	C_{Ls}, Eq. (2)	$C_{L\,\max}$, Eq. (1)
Stall tests c.g. max forward (16.5%)							
Leveled	0	Retracted	55.5	0.92	1.1	1.46	1.34
Leveled	0	Extended	60	0.92	0.8	1.26	1.16
Leveled	15	Extended	45.8	0.84	-	2.08	1.75
Leveled	40	Retracted	41.3	0.88	1.1	2.51	2.22
Leveled	40	Extended	43	0.84	0.7	2.33	1.97
Turn	0	Retracted	65.7	0.97	0.8	1.06	1.04
Turn	40	Retracted	54	1.14	0.5	1.75	1.53
Stall tests c.g. max aft (30.5%)							
Leveled	0	Retracted	55.2	0.93	2.7	1.47	1.38
Leveled	40	Retracted	47	0.89	1.9	1.98	1.78
Turn	0	Retracted	62	0.97	1.3	1.19	1.15
Turn	40	Retracted	53	0.97	2.5	1.59	1.54

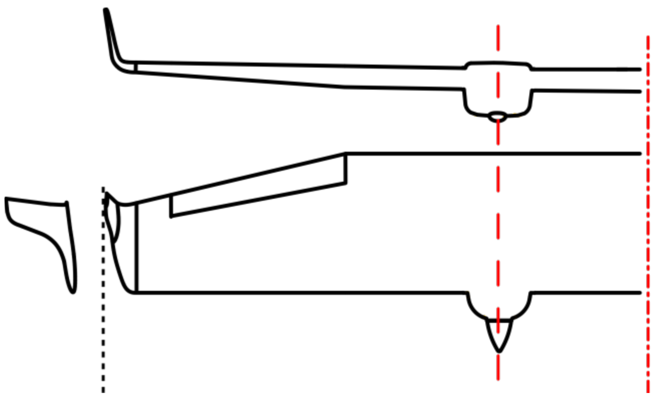
Table 8 Stall tests performed at different ER with flap retracted and c.g. maximum aft

Test	X_{cg}/c, %	V_{IAS}, kt	V_{CAS}, kt	a_z, g	ER, kt/s	C_{Ls}	$C_{L\,\max}$
1	30.5	58.7	60.7	0.91	1.2	1.31	1.19
2	30.5	56.3	58.3	0.89	1.5	1.42	1.26
3	30.5	51.4	54	0.81	3.1	1.65	1.34
4	30.5	46.5	48.9	0.7	6	2.02	1.41

Post-design modifications

b = 11.2 m   S = 14.7 m²





b = 11.4 m   S = 14.8 m²

First prototype, no winglets

Winglets installed

Winglet design

Initial climb tests with One Engine Inoperative (OEI) were unsatisfactory

$$C_D = C_{D_0} + \frac{C_L^2}{\pi \mathrm{AR} e}$$

Winglets designed to increase the aircraft's induced drag factor *e* with a very low penalty in level flight performances.

With respect to original wing

Wetted area is kept constant.
Wing span b only 0.2 m higher.
Wing area S is practically the same
Slight increase in AR
Δe = 0.10 (estimates from WT exp.)
Slight increase of MTOW, 20 kg

Table 9 Geometrical characteristics and Aircraft weight before and after winglet installation

	b, m	S, m^2	AR	W_{TO}, kg	e
No winglet	11.2	14.74	8.46	1160	0.72
With winglet	11.4	14.76	8.76	1180	0.82 (estimated)

Winglet design · "Engine chart" method

$$\mathrm{VIW} = V\sqrt{\sigma \frac{W_{std}}{W}}$$

Generalized Velocity Parameter

$$\mathrm{PIW} = \mathrm{THP}_r \sqrt{\sigma \left(\frac{W_{std}}{W}\right)^3}$$

Generalized Power Parameter

W_{std} = MTOW

- Thrust Horsepower (THP) and Brake Horsepower (BHP) determined from level-flight tests and engine charts.
- Net installed propulsive efficiency η_p determined by semi-empirical formulation
  η_p = 0.7 (low speed) ÷ 0.82 (high speed)

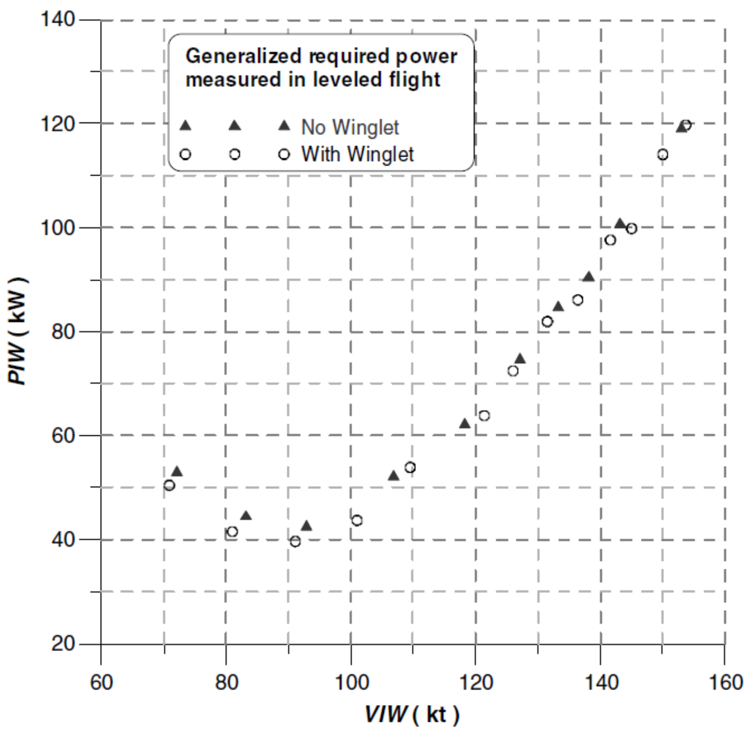


Fig. 17 Generalized velocity vs generalized power parameter, before and after winglet installation.

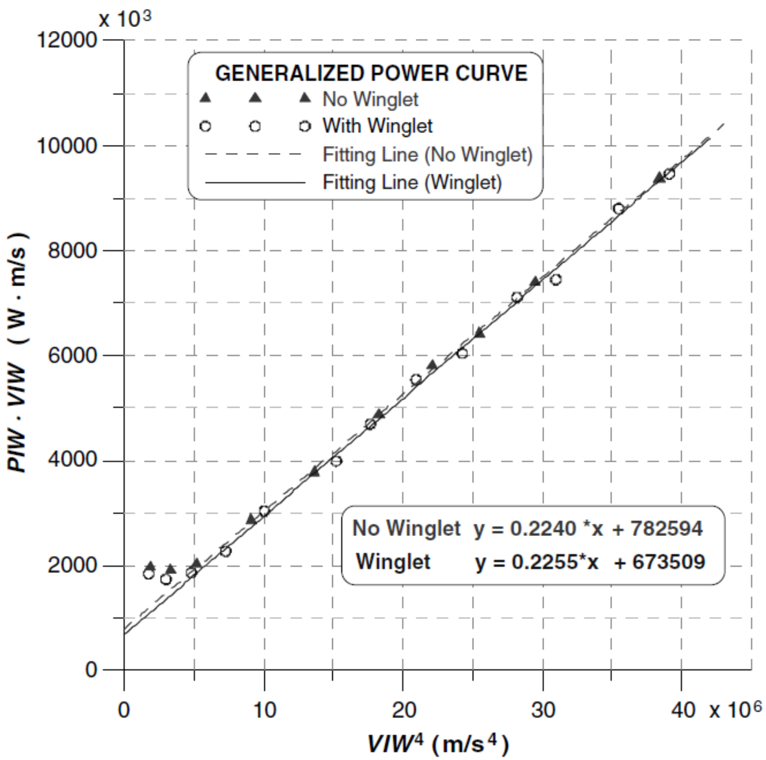


Fig. 18 Generalized power curve, before and after winglet installation.

Winglet design · "Engine chart" method

Table 10 Geometrical and aerodynamic characteristics before and after winglet installation

			C_{D0}		Oswald factor, e			
	S, m^2	AR	Estimated	Measured flight test	Estimated	Measured flight test	ARe	Max lev. speed, kt
No winglet	14.74	8.46	0.0258	0.0248	0.72	0.71	6.0	153
With winglet	14.76	8.76	0.0260	0.0249	0.82	0.80	7.0	154

$$C_D = C_{D_0} + \frac{C_L^2}{\pi \mathrm{AR} e}$$

$$\mathrm{VIW} = V\sqrt{\sigma \frac{W_{\mathrm{std}}}{W}}$$

Generalized Velocity Parameter

$$\mathrm{PIW} = \mathrm{THP}_r \sqrt{\sigma \left(\frac{W_{\mathrm{std}}}{W}\right)^3}$$

Generalized Power Parameter

W_{std} = MTOW

$$e = \frac{2W_{\mathrm{std}}}{B\rho_0 S\pi \mathrm{AR}}$$

$$C_{D_0} = \frac{2A}{\rho_0 S}$$

$$\boxed{y = A \cdot x + B}$$

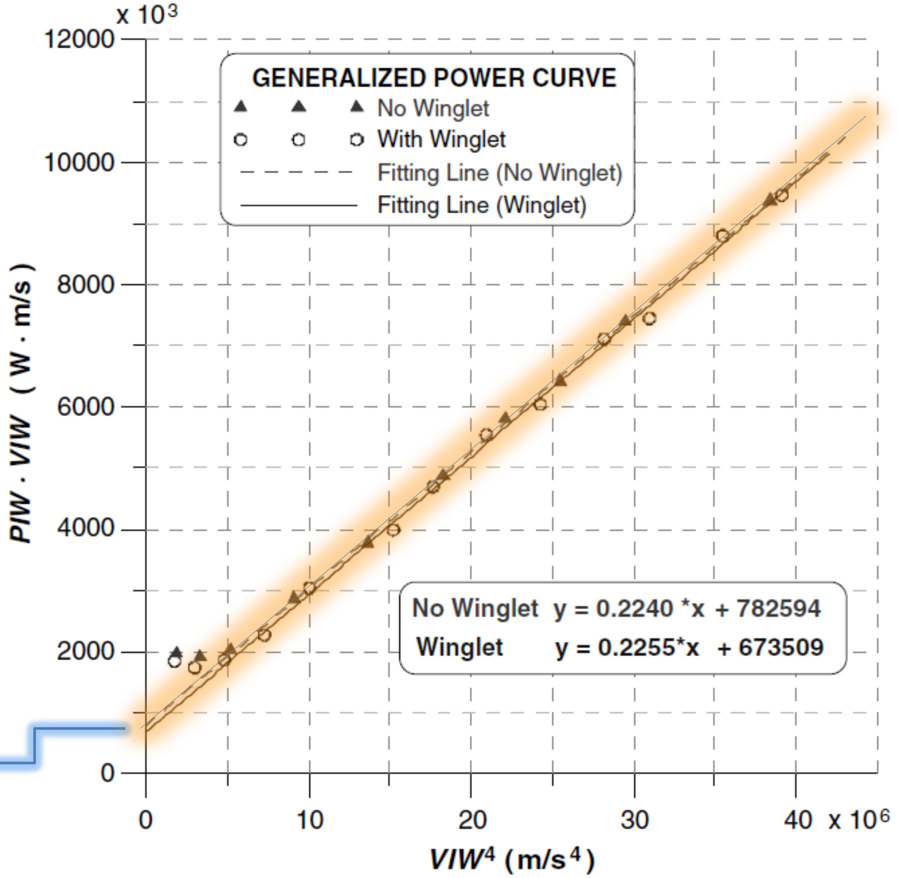
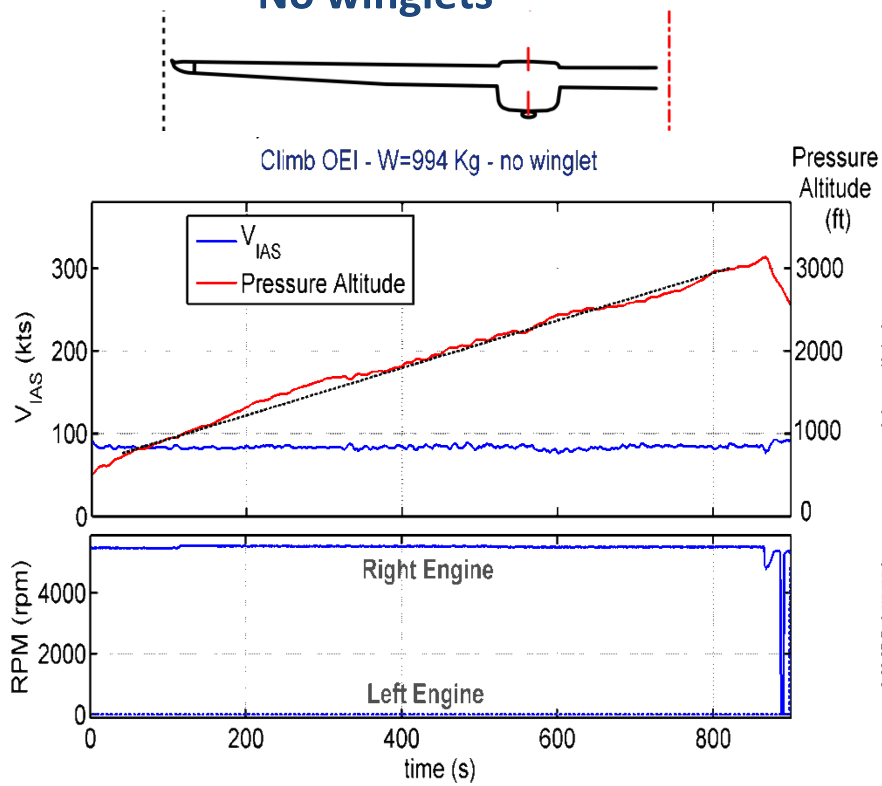


Fig. 18 Generalized power curve, before and after winglet installation.

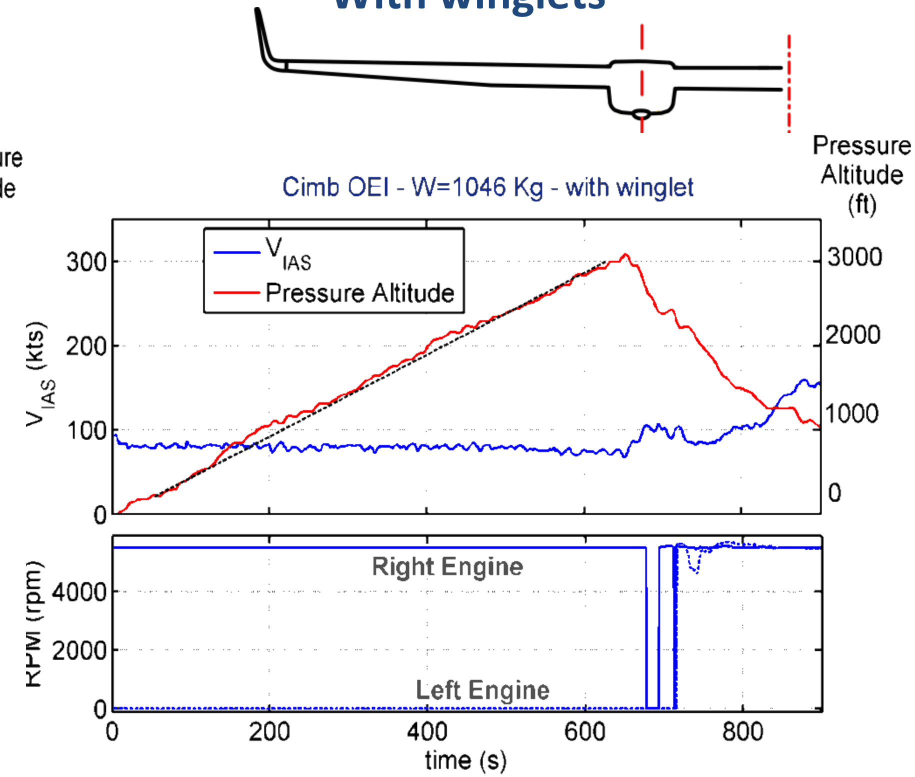
Winglets effect on climb performance

No winglets



Rate of Climb (at 800 ft)
169 ft/min

With winglets



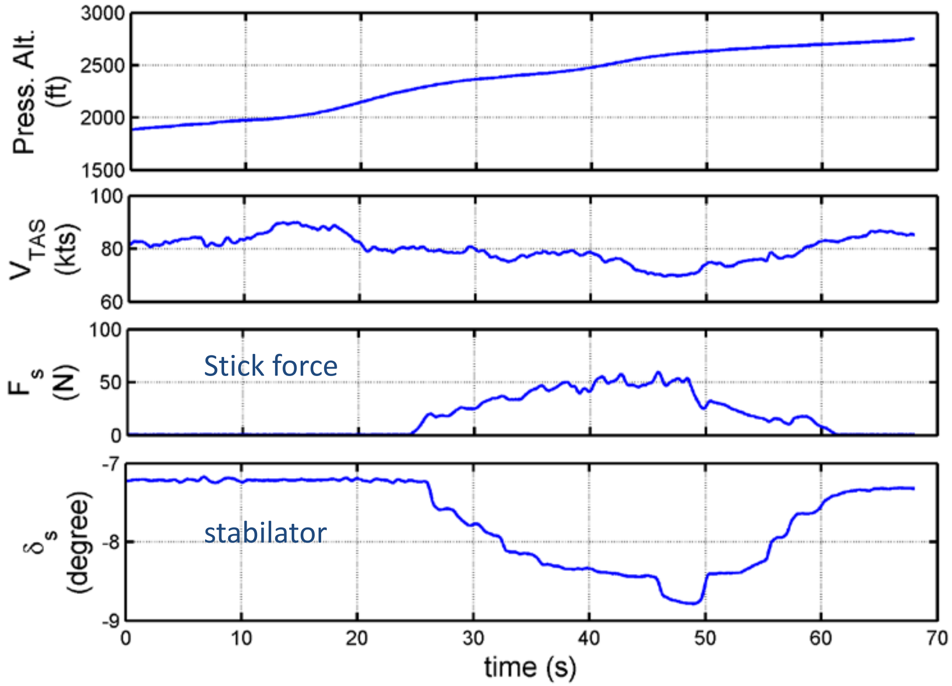
Rate of Climb (at 800 ft)
300 ft/min

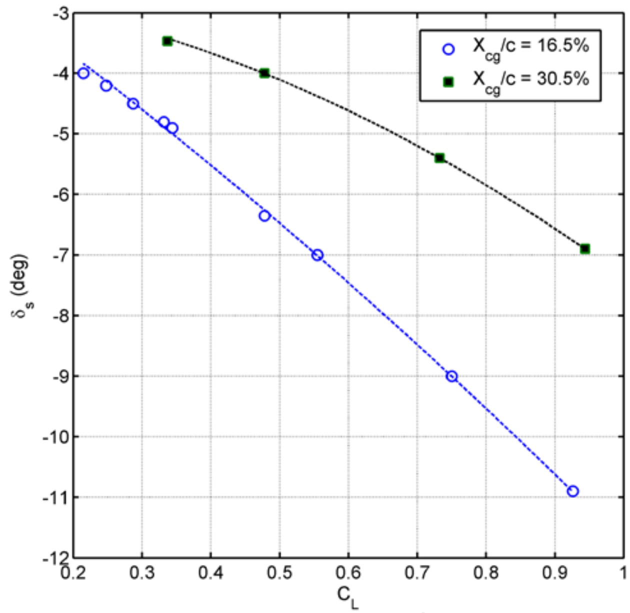
See: [1] **AIAA papers: AIAA-2010-7513** and **AIAA-2010-7947**

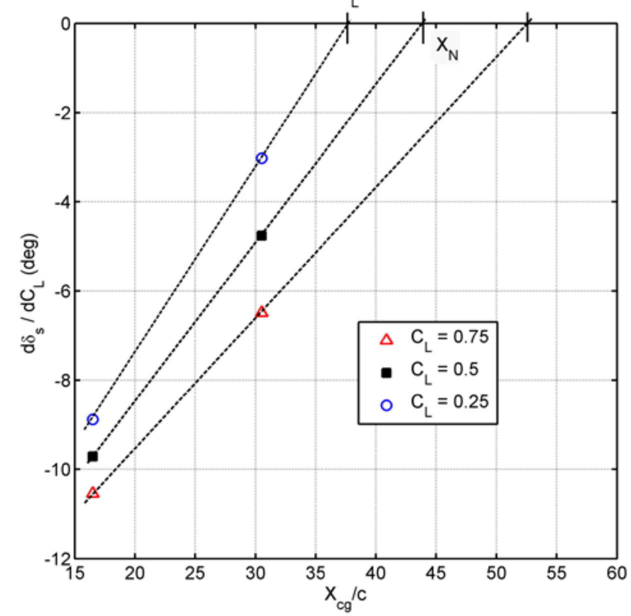
[2] Nicolosi F., De Marco A., Della Vecchia P., “Flight Tests, Performances and Flight Certification of a Twin-Engine Light Aircraft”. *AIAA Journal of Aircraft*, Vol 48, No. 1, January-February 2011.

Longitudinal static stability tests

When a trimmed condition is established, the pilot applies a gradual pulling to the longitudinal control and then releases the stick slowly.



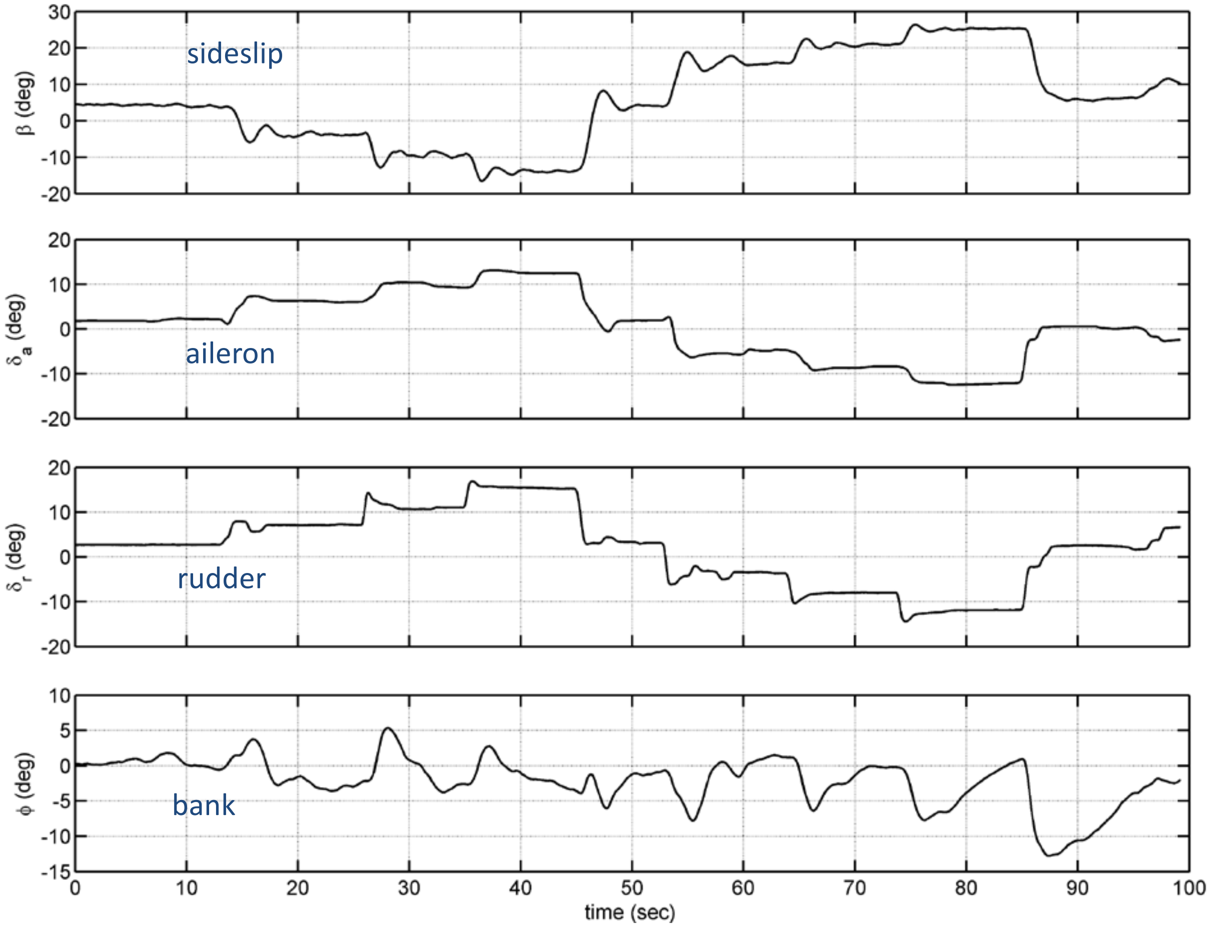


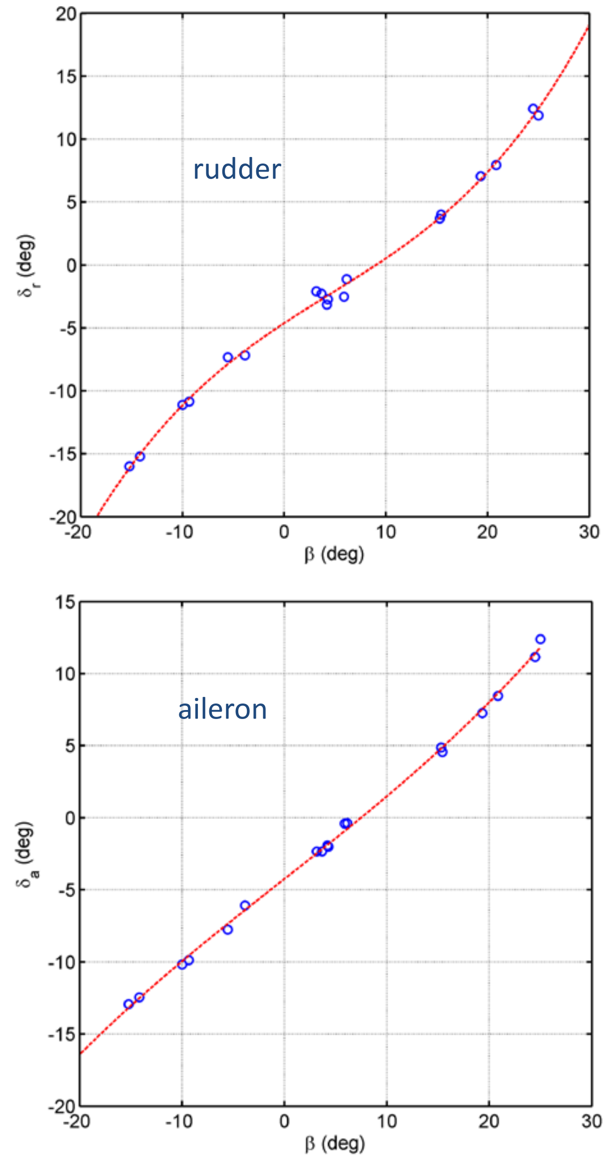


Top: required stabilator deflections for level flight (max fwd and max aft CG pos)

Bottom: stick-fixed Neutral point estimation at different level flight speeds

Steady heading/sideslip tests

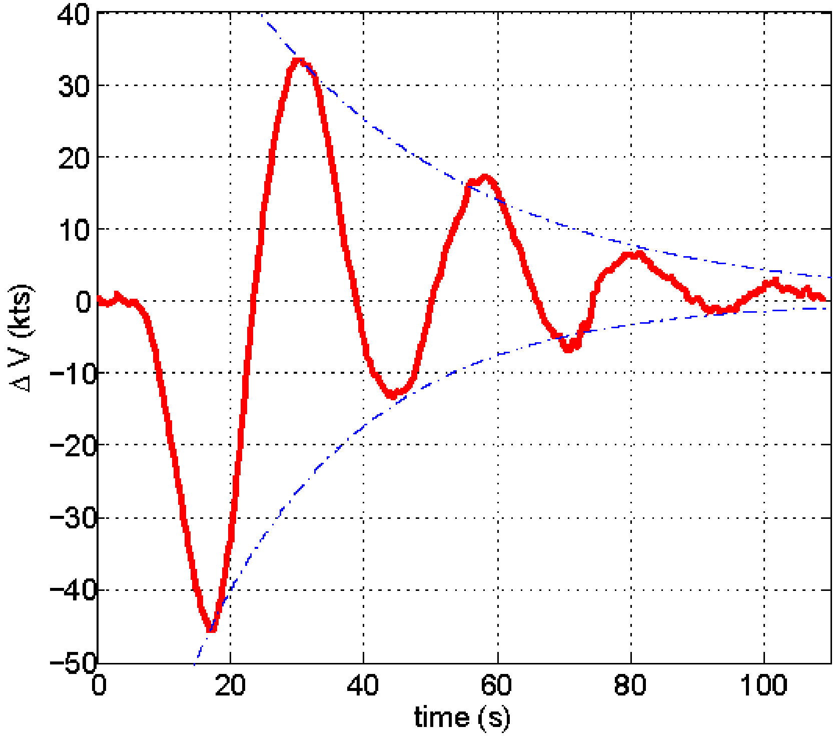


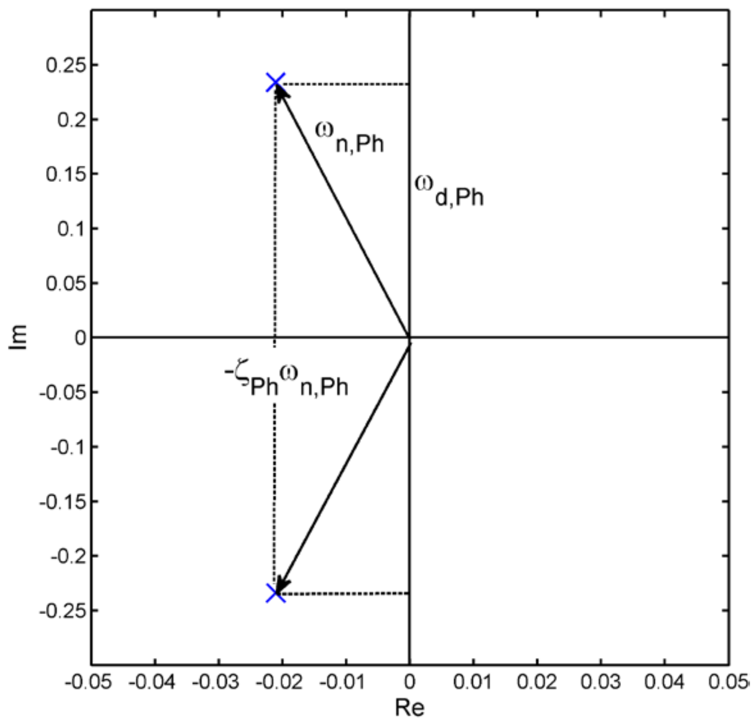


Average flight speed of 100 kt, in cruise configuration.

The airplane is kept for successive time intervals of approximately 10 seconds at different fixed sideslip angles.

Phugoid mode evaluation





Averaged damped oscillation parameters in the imaginary plane, extracted over a number of time histories

Typical phugoid response and characteristic roots.

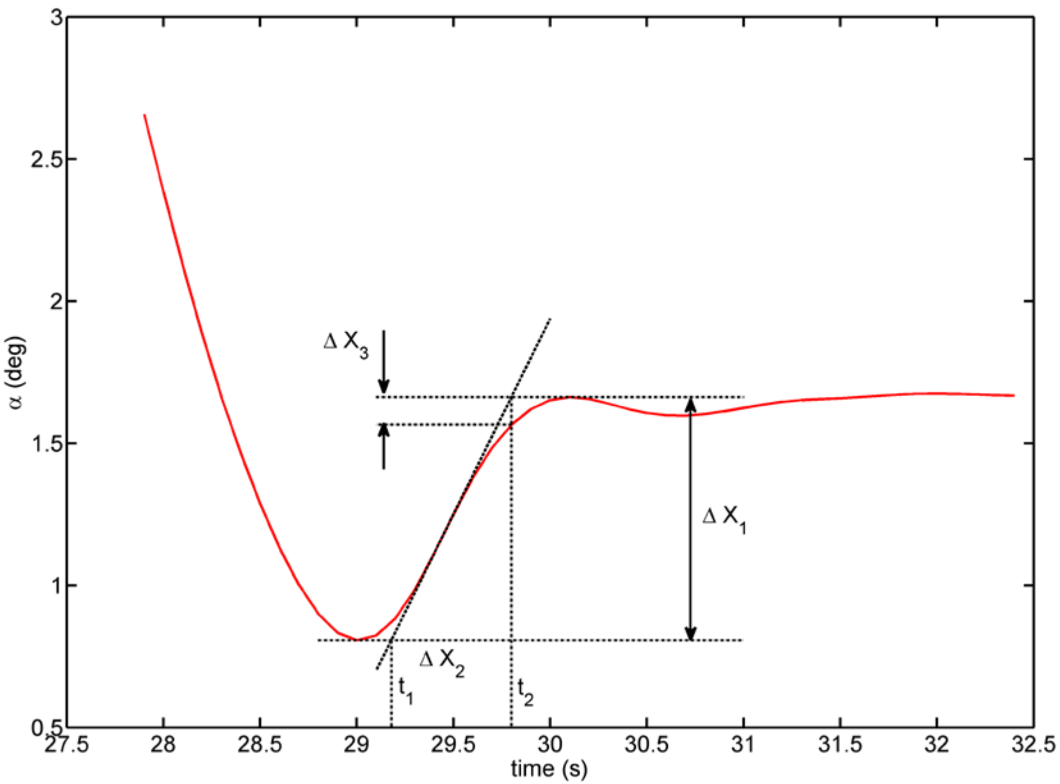
Speed variation, with respect to a trimmed condition in level flight at 110 kts.

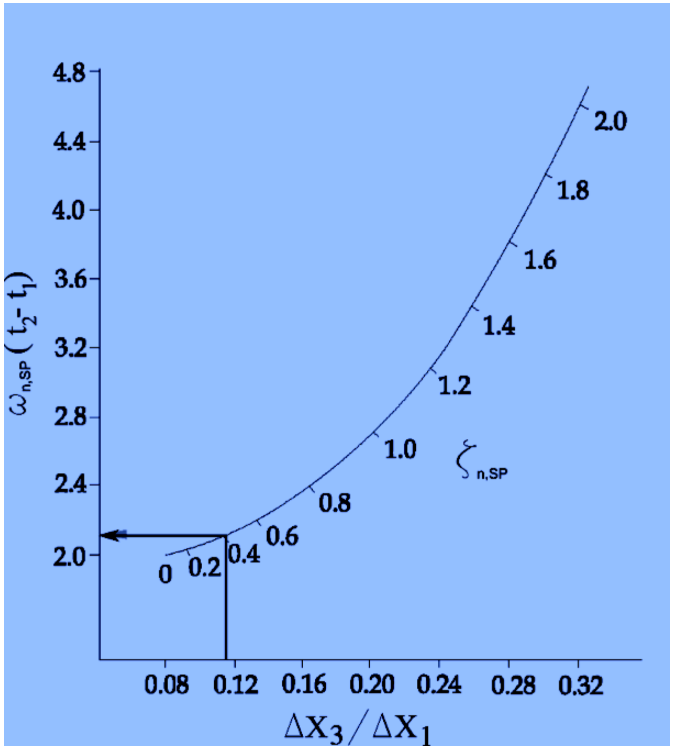
Obtained with a step stabilator deflection of –4 deg, kept for 10 seconds and set back to the original position

ζ_{Ph} is calculated using the transient-peak-ratio (TPR) method

Damped period, T_{Ph}	27 s
Damping ratio, ζ_{Ph}	0.09
Damped pulsation, $\omega_{d,Ph}$	0.233 rad/s
Natural pulsation, $\omega_{n,Ph}$	0.234 rad/s

Short period mode evaluation





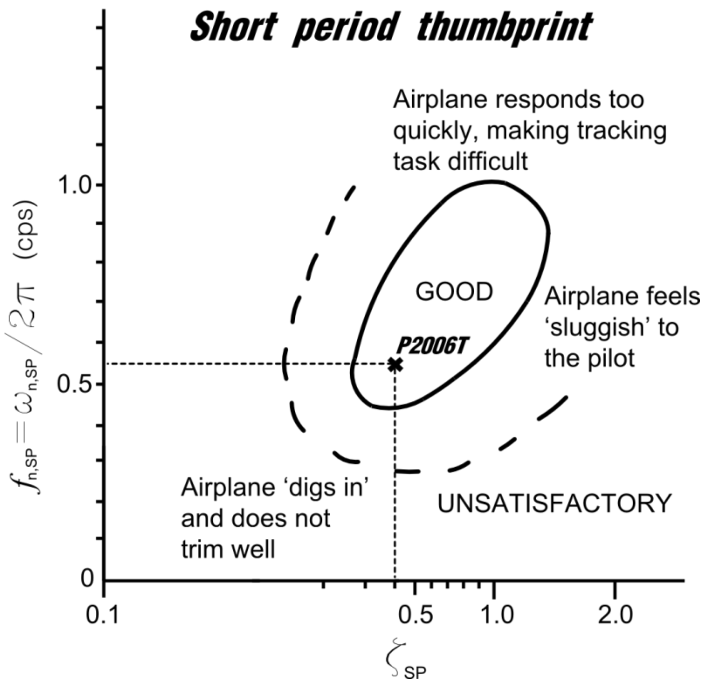
Typical short period response

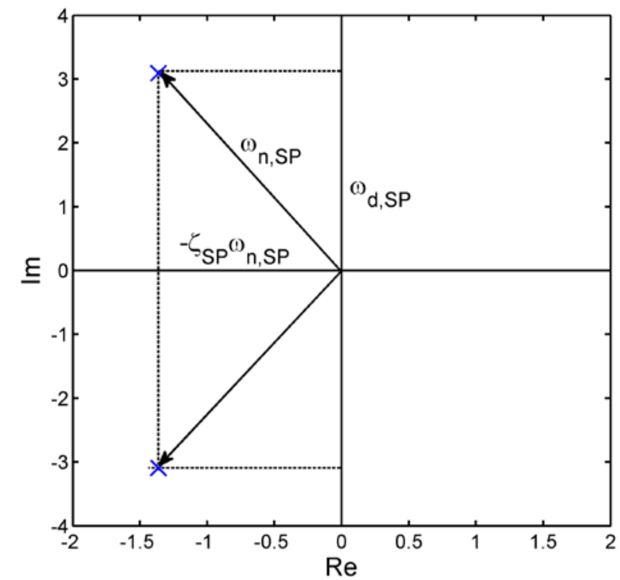
angle-of-attack time history, as a response to a '3-2-1-1-type' stabilator input

Maximum slope (MS) method, used to estimate the short period natural pulsation

(Kimberlin; Ward and Strganac)

Short period mode evaluation





Averaged damped oscillation parameters in the imaginary plane, extracted from a number of time histories (excited by '3211-type' longitudinal command input)

Time constant, τ_{SP}	0.0088 s
Damping ratio, ζ_{SP}	0.40
Damped pulsation, $\omega_{d,SP}$	3.125 rad/s
Damped period, T_{SP}	1.84 s
Natural pulsation, $\omega_{n,SP}$	3.410 rad/s
Natural frequency, $f_{n,SP}=\omega_{n,SP} / 2\pi$	0.54 cps

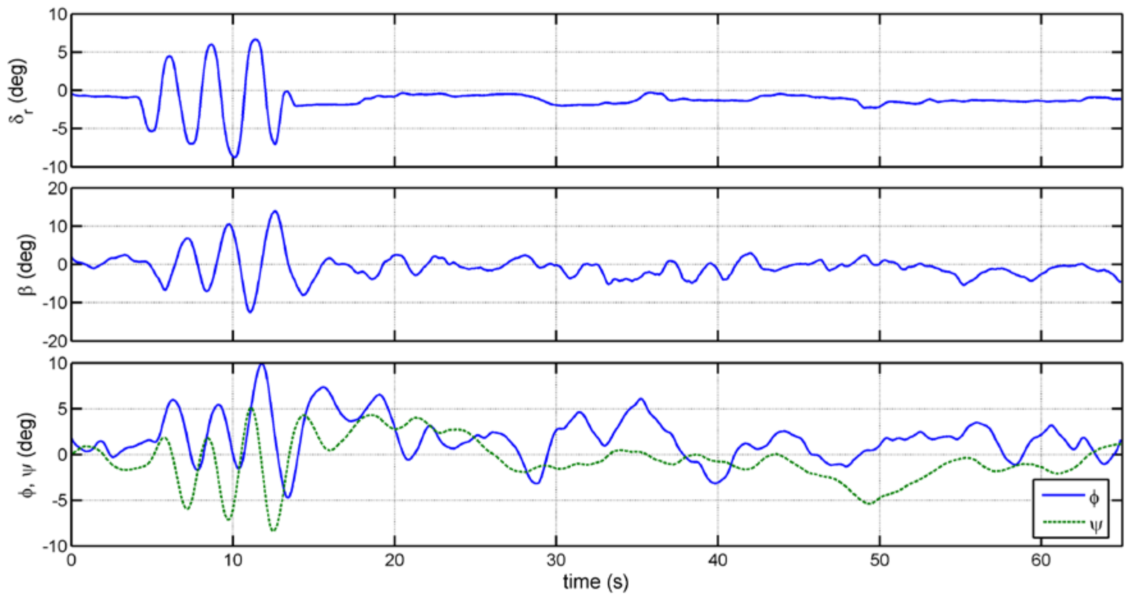
$\tau_{SP} = -1 / Z_\alpha = m / (Q_0 \, S \, C_{L\alpha})$

$\text{CAP} = \omega_{n,SP}^2 / n_\alpha \approx mg \, \omega_{n,SP}^2 / (Q_0 \, S \, C_{L\alpha}) = 1.009$

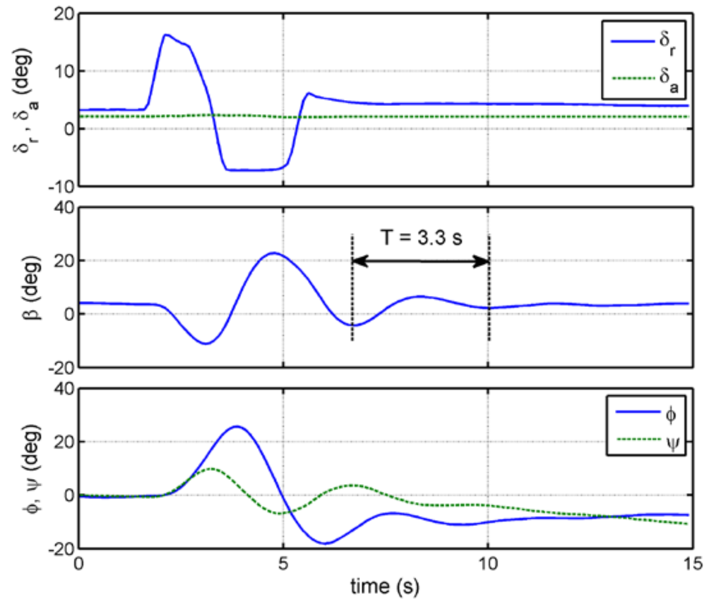
Within Level 1 range (Class I-B, MIL-STD-1797A)

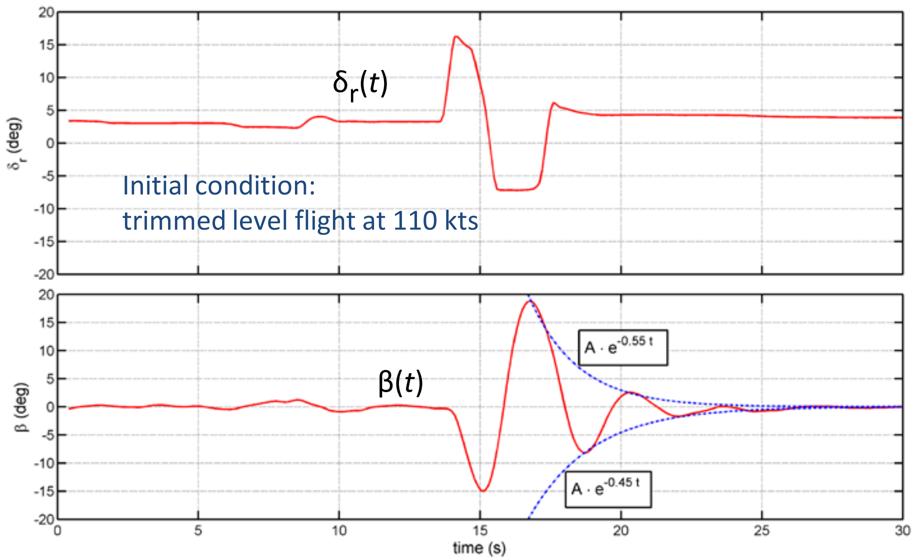
Dutch roll mode evaluation

multiple pedal doublets



Single pedal doublet



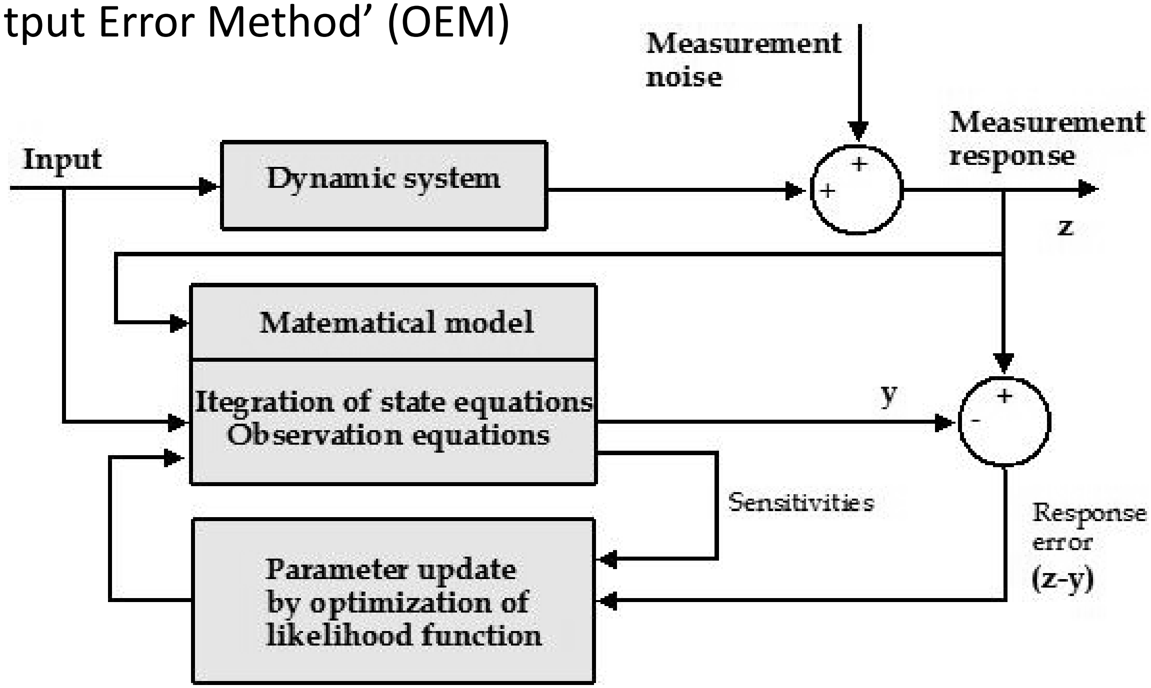


Damped period, T_{DR}	3.25 s
Damping ratio, ζ_{DR}	0.26
Damped pulsation, $\omega_{d,DR}$	1.93 rad/s
Natural pulsation, $\omega_{n,DR}$	2.00 rad/s
Time factor, $\eta_{DR} = \zeta_{DR}\omega_{n,DR}$	0.52 rad/s

Sideslip variation, with respect to a trimmed condition in level flight at 110 kts.

ζ_{Ph} is calculated using the transient-peak-ratio (TPR) method

- Key element: a computer program that seeks to replicate recorded flight test time histories of output variables by varying a given set Θ of coefficients in a linearized model of the aircraft (Jategaonkar, Matlab codes)
- Most of the elements of Θ are the desired values of aircraft stability derivatives referred to a given flight condition
- The selected technique of flight data analysis for the tests on P2006T aircraft is the one known as 'Output Error Method' (OEM)



Schematic of the OEM

Longitudinal model equations

State equations

$$\begin{cases} \dot{V} = \dfrac{QS}{m} C_D + g \sin(\alpha - \theta) + \dfrac{T}{m} \cos(\alpha + \sigma_T) \\ \dot{\alpha} = \dfrac{QS}{mV} C_L + q + \dfrac{g}{V} \cos(\alpha - \theta) + \dfrac{T}{mV} \sin(\alpha + \sigma_T) \\ \dot{\theta} = q \\ \dot{q} = \dfrac{QSc}{I_{yy}} C_M + \dfrac{T}{I_{yy}} (\ell_{T,x} \sin\sigma_T + \ell_{T,z} \cos\sigma_T) \end{cases}$$

Observation equations

$$\begin{cases} V_\mathrm{m} = V \qquad \alpha_\mathrm{m} = \alpha \qquad \theta_\mathrm{m} = \theta \qquad q_\mathrm{m} = q \\ \dot{q}_\mathrm{m} = \dfrac{QSc}{I_{yy}} C_M + \dfrac{T}{I_{yy}} (\ell_{T,x} \sin\sigma_T + \ell_{T,z} \cos\sigma_T) \\ a_{x\,\mathrm{m}} = \dfrac{Q\,S}{m} C_X + \dfrac{T}{m} \cos\sigma_T \\ a_{z\,\mathrm{m}} = \dfrac{QS}{m} C_Z + \dfrac{T}{m} \sin\sigma_T \end{cases}$$

state variables: $V, \alpha\,, \theta\,, q$

$$C_X = C_L \sin\alpha - C_D \cos\alpha \qquad C_Z = -C_L \cos\alpha - C_D \sin\alpha$$

Inputs: $\delta_\mathrm{s}\,, T$ (constant)

Aerodynamic model:

$$C_D = C_{D0} + C_{D_\alpha}\alpha \qquad C_L = C_{L0} + C_{L_\alpha}\alpha \qquad C_M = C_{M0} + C_{M_\alpha}\alpha + C_{M_q}\frac{qc}{2V_0} + C_{M_{\delta_\mathrm{s}}}\delta_\mathrm{s}$$

Unknown parameters:
(longitudinal)

$$\Theta_\mathrm{lon} = \left[\, C_{D0}\,,\, C_{D_\alpha}\,,\, C_{L0}\,,\, C_{L_\alpha}\,,\, C_{M0}\,,\, C_{M_\alpha}\,,\, C_{M_q}\,,\, C_{M_{\delta_\mathrm{s}}} \,\right]$$

Level flight thrust

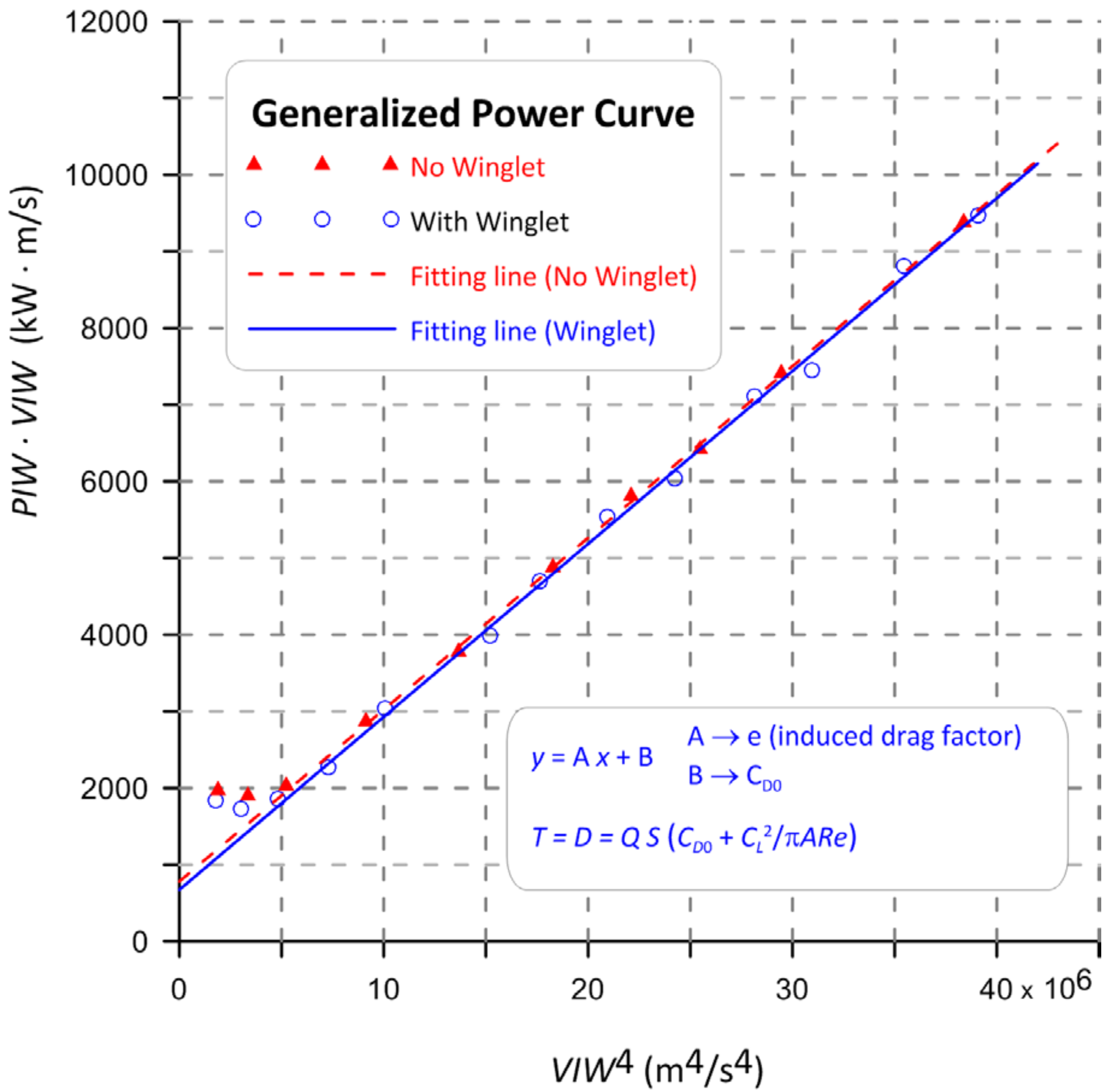
'Engine chart' method to determine **aircraft generalized required power** ***PIW***:

- *Uninstalled engine chart*
- *Map, rpm, altitude,*
- *prop efficiency chart*
- *A/C actual Weight*

VIW is a reduced CAS

Thrust estimation*:*

- Determine linear fit
- Estimate drag from *PIW*
- $T = D$ (0.8 ÷ 1.5 kN)



Scalar cost function

Cost function: $$J(\Theta) = \frac{N n_y}{2}\left(1 + \ln(2\pi) + \frac{N}{2}\ln(\det R)\right)$$

Covariance matrix: $$R = \frac{1}{N}\sum_{k=1}^{N}\left[z(t_k) - y(t_k)\right]\left[z(t_k) - y(t_k)\right]^T$$

OEM procedure

The Output Error Method is a relaxation procedure that can be summarized as follows:

1. A suitable initial set Θ_0 of values is chosen for Θ
2. System outputs y and the residuals $(z\text{-}y)$ are computed; the measurement noise covariance matrix R is also estimated
3. The cost-function $J(\Theta)$ is minimized with respect to Θ by applying one of the available nonlinear optimization methods
4. Step 2 is iterated until convergence, i.e. $J(\Theta)$ has reached its minimum

Lateral-directional model equations

State equations

$$\begin{cases} \dot{p} = \dfrac{QSb}{I_{xx}} \left(C_{l_p} \dfrac{pb}{2V_0} + C_{l_r} \dfrac{rb}{2V_0} + C_{l_\beta} \beta + C_{l_{\delta_a}} \delta_a + C_{l_{\delta_r}} \delta_r \right) + b_{x\dot{p}} \\ \dot{r} = \dfrac{QSb}{I_{zz}} \left(C_{n_p} \dfrac{pb}{2V_0} + C_{n_r} \dfrac{rb}{2V_0} + C_{n_\beta} \beta + C_{n_{\delta_a}} \delta_a + C_{n_{\delta_r}} \delta_r \right) + b_{x\dot{r}} \end{cases}$$

Observation equations

state variables: p, r

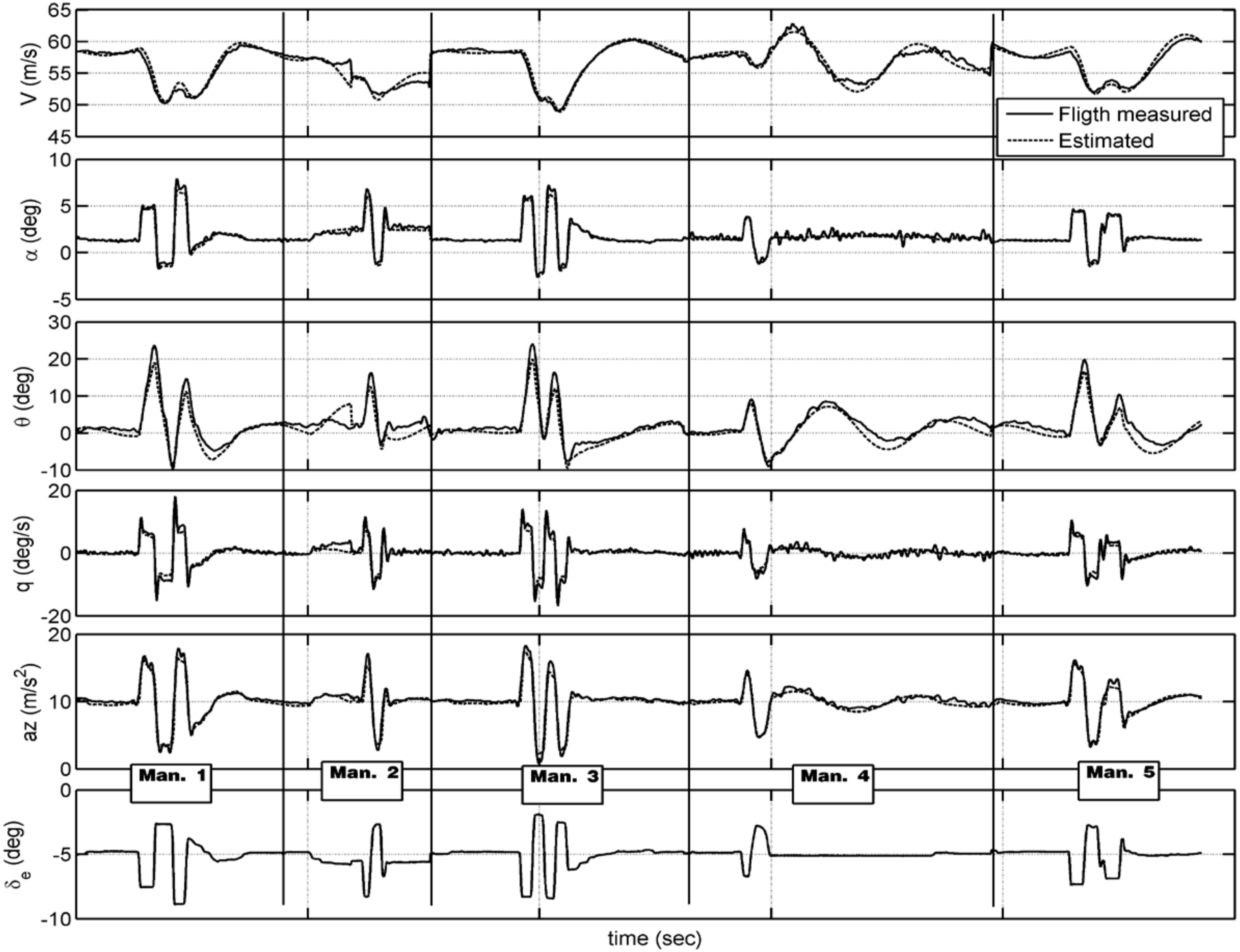
Inputs: δ_a , δ_r , V, Q

$$\begin{cases} \dot{p}_m = \dfrac{QSb}{I_{xx}} \left(C_{l_p} \dfrac{pb}{2V_0} + C_{l_r} \dfrac{rb}{2V_0} + C_{l_\beta} \beta + C_{l_{\delta_a}} \delta_a + C_{l_{\delta_r}} \delta_r \right) + b_{y\dot{p}} \\ \dot{r}_m = \dfrac{QSb}{I_{zz}} \left(C_{n_p} \dfrac{pb}{2V_0} + C_{n_r} \dfrac{rb}{2V_0} + C_{n_\beta} \beta + C_{n_{\delta_a}} \delta_a + C_{n_{\delta_r}} \delta_r \right) + b_{y\dot{r}} \\ a_{y\,m} = \dfrac{QS}{m} \left(C_{Y_p} \dfrac{pb}{2V_0} + C_{l_r} \dfrac{rb}{2V_0} + C_{Y_\beta} \beta + C_{Y_{\delta_a}} \delta_a + C_{Y_{\delta_r}} \delta_r \right) + b_{ya_y} \\ p_m = p + b_{yp} \\ r_m = r + b_{yr} \end{cases}$$

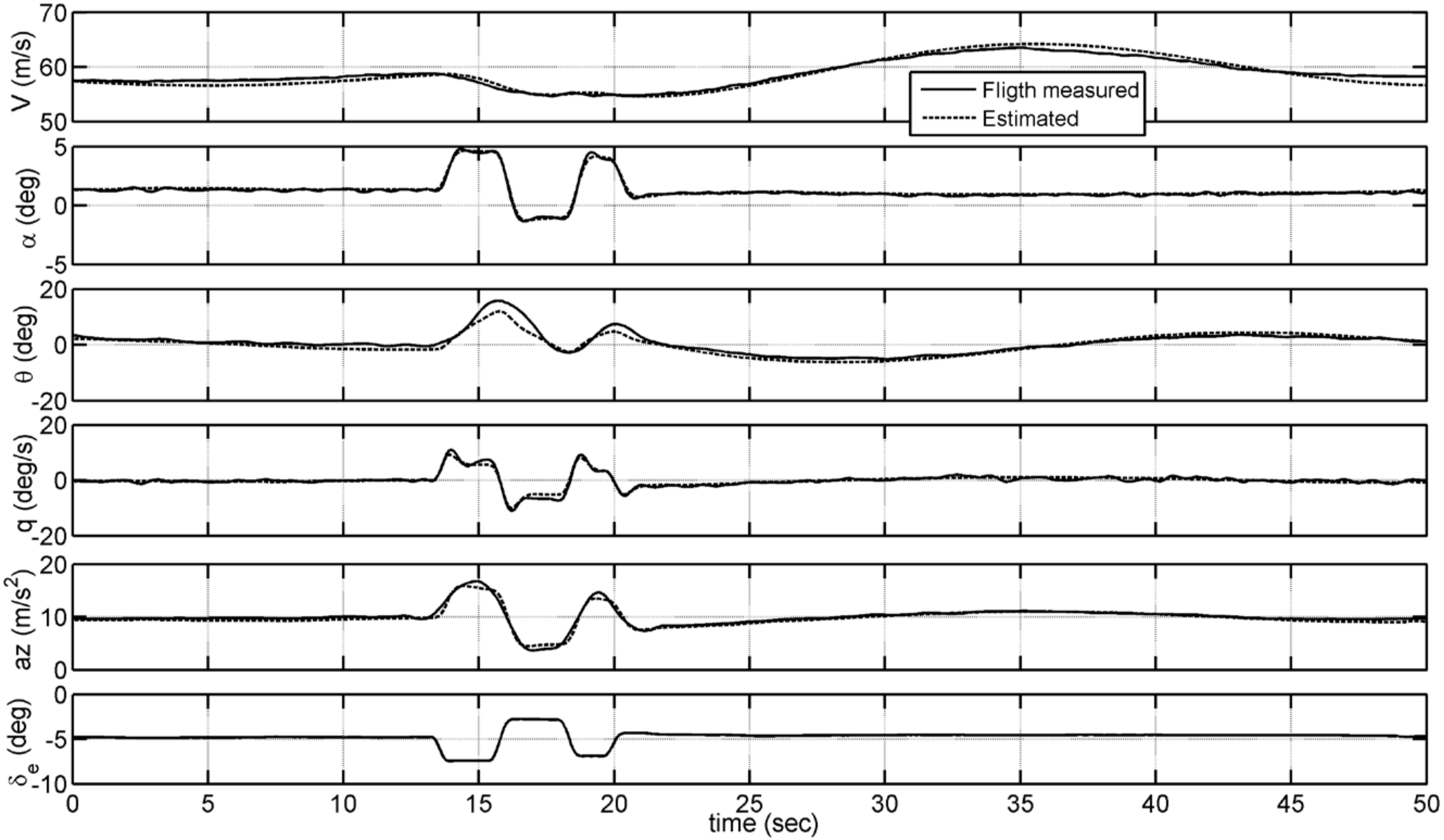
Unknown parameters:
(lateral-directional)

$$\Theta_{\text{lat-dir}} = \left[\left(C_{\xi_p}, C_{\xi_r}, C_{\xi_{beta}}, C_{\xi_{\delta_a}}, C_{\xi_{\delta_r}} \right)_{\xi=l,n,Y}, b_{x\dot{p}}, b_{x\dot{r}}, b_{y\dot{p}}, b_{y\dot{r}}, b_{ya_y}, b_{yp}, b_{yr} \right]$$

Multiple longitudinal maneuvers



Checking the converged results

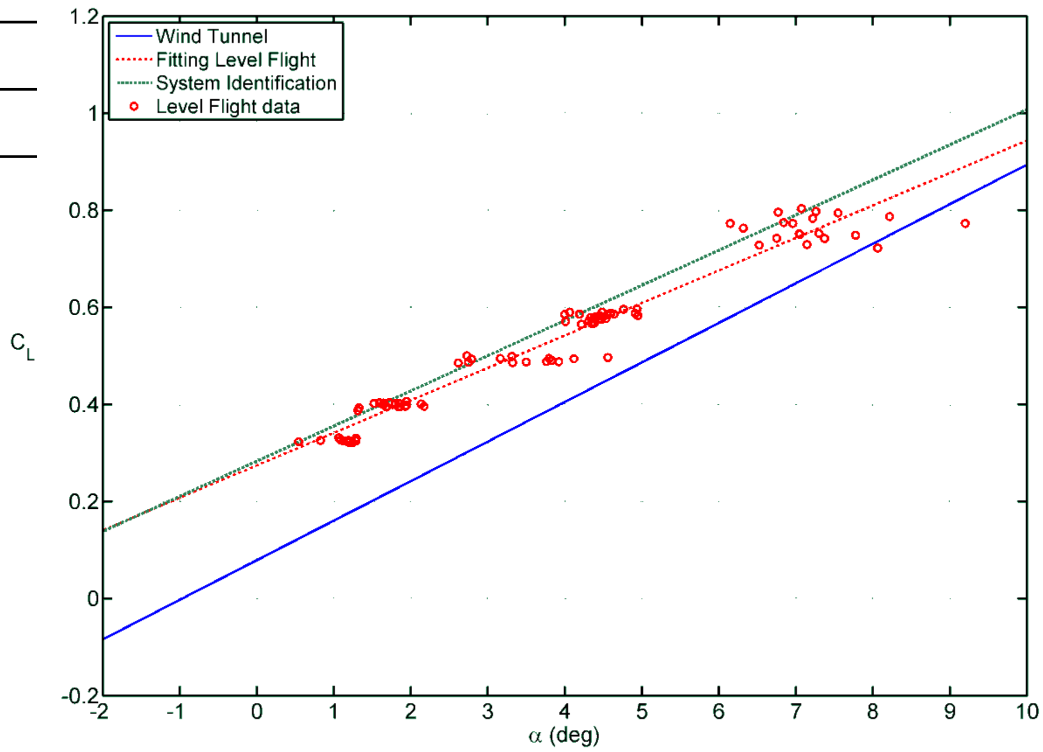


Dotted curves are the results of simulation, using the converged values of Θ_{lon}

Longitudinal aerodynamic coefficients

	Wind Tunnel (Re = 0.60×10^6)	Semi-Empirical	Estimated (Re ≈ 6×10^6)
$C_{D\,0}$	0.027	-	0.0334
$C_{D\,\alpha}$ (1/rad)	0.171	-	0.222
$C_{L\,0}$	0.153	-	0.289
$C_{L\,\alpha}$ (1/rad)	4.5	-	4.152
$C_{m\,0}$	–0.08	-	–0.922
$C_{m\,\alpha}$ (1/rad)	–0.80	-	–0.871
$C_{m\,q}$ (1/rad)	-	–19.05	–14.799
$C_{m\,\delta e}$ (1/rad)	–1.830	-	–1.811

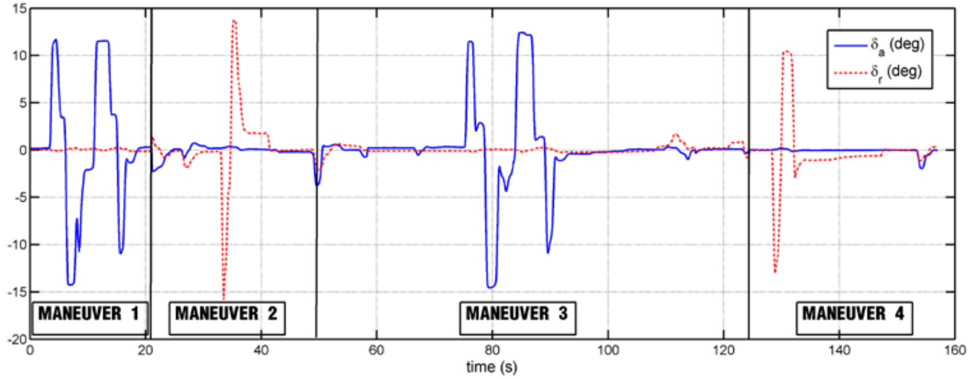
A Lift curve slope $C_{L\,\alpha}$ = 3.85 rad^{-1} has been determined through level flight test at different speeds
(with stabilator in different positions)



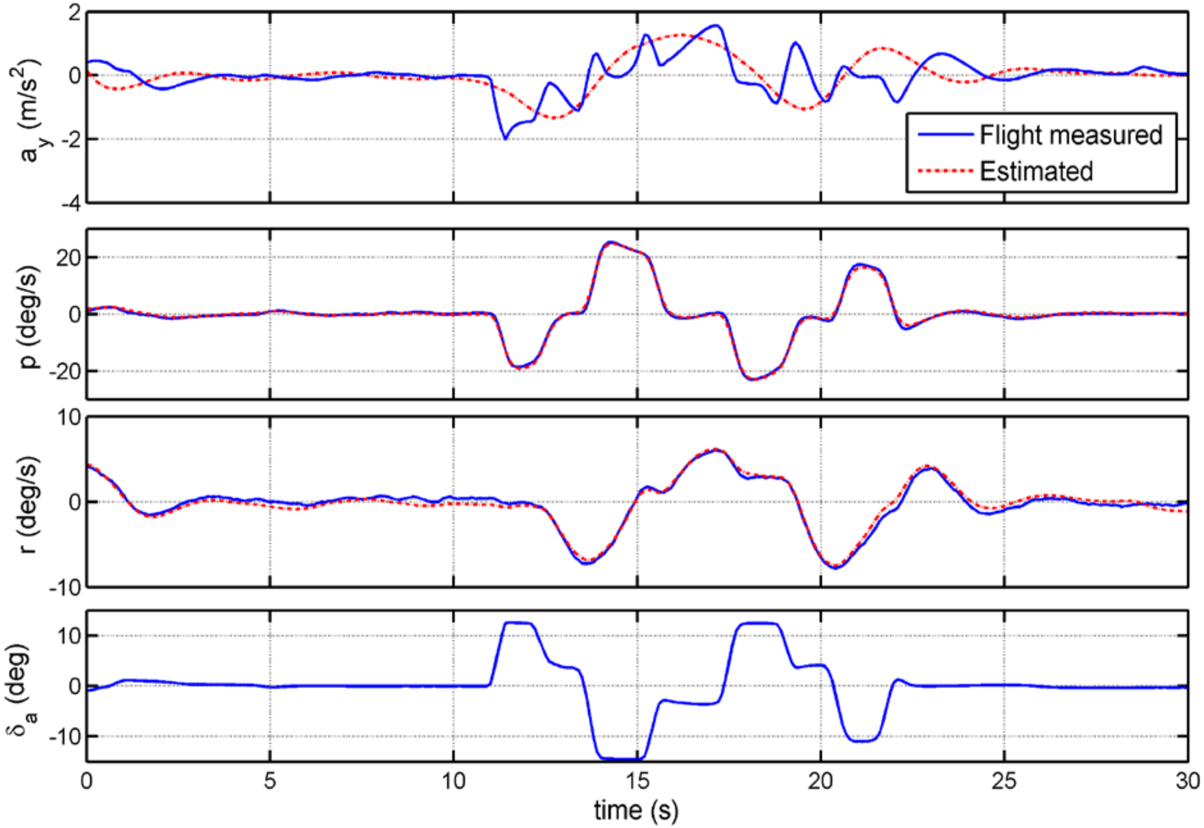
Wind tunnel result, level flight test result and estimation result compared

Wind tunnel and system identification output refers to a 'fixed' configuration

Lateral-directional results



Multiple δ_a , δ_r inputs



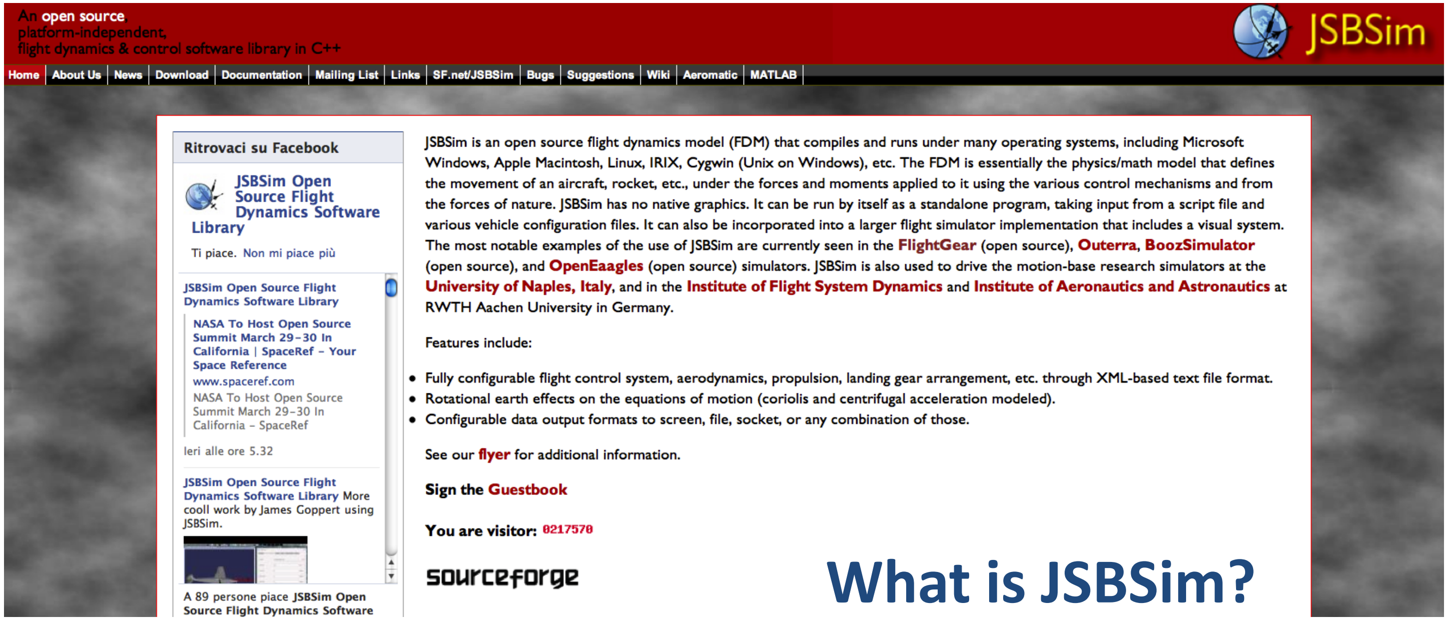
Dotted curves are the results of simulation, using the converged values of $\Theta_{lat\text{-}dir}$

Lateral-directional results

	Wind Tunnel (Re = 0.60×10^6)	Semi-Empirical	Estimated (Re ≈ 6×10^6)
$C_{l\,p}$	-	–0.529	–0.281
$C_{l\,r}$	-	-	0.057
$C_{l\,\delta a}$	-	–0.057	–0.045
$C_{l\,\delta r}$	0.0115	0.014	0.0009
$C_{l\,\beta}$	–0.0573	–0.061	–0.029
$C_{n\,p}$	-	-	–0.130
$C_{n\,r}$	-	–0.084	–0.106
$C_{n\,\delta a}$	-	-	–0.009
$C_{n\,\delta r}$	–0.0631	–0.0679	–0.0304
$C_{n\,\beta}$	0.05	0.096	0.0135
$C_{Y\,p}$	-	-	0.254
$C_{Y\,r}$	-	-	0.112
$C_{Y\,\delta a}$	-	0	0.127
$C_{Y\,\delta r}$	-	0.173	0.04
$C_{Y\,\beta}$	–0.688	–0.563	–0.355

Now some flight sim…

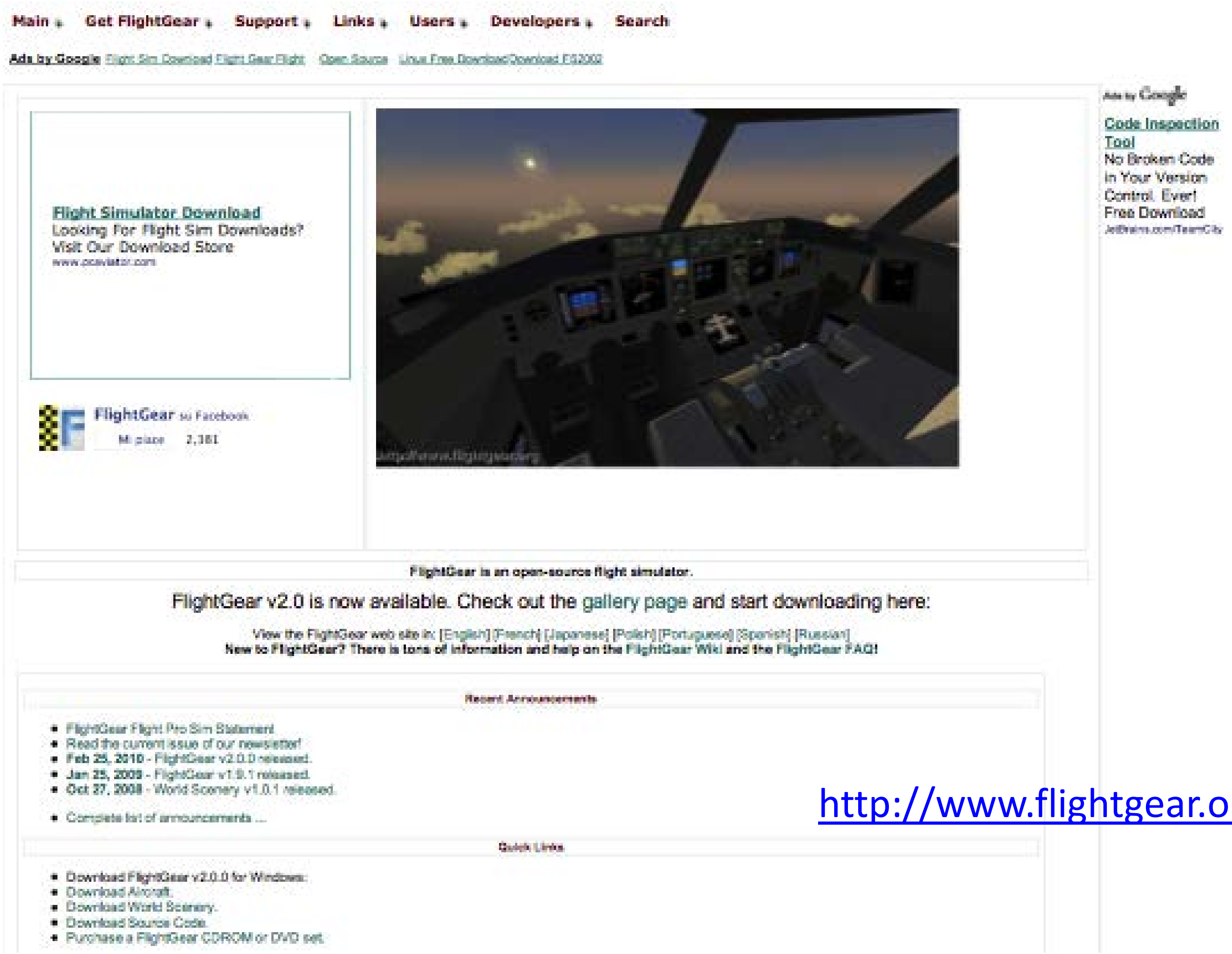
Flight simulation · JSBSim



- Flight dynamics and control S/W library
- ~50,000 lines of C++ code
- ~80 C++ classes
- In development since 1997
- Data driven
- XML configuration files

http://www.jsbsim.org

FlightGear



http://www.flightgear.org

Team of main developers, and a large base of users

An open source, platform-independent, flight dynamics & control software library in C++

JSBSim

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Jon Berndt,
(Texas, U.S.A.)
Lead S/W Architect & Development Coordinator

Jon designed the original architecture, and continues to refine it, with inputs from the other team members. He has worked with military and space training and engineering simulators for many years. Jon is an aero engineer (University of Minnesota).

His **web site**.

Tony Peden
(Washington, U.S.A.)
Co-Author

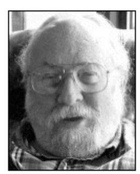
Tony has been contributing to the growth of JSBSim almost from day 1. He is responsible for integrating JSBSim with FlightGear, and for initialization and trimming. Tony also implemented David's property system into JSBSim. Tony hails from Ohio State University, with a degree in Aero and Astronautical Engineering.

David Culp
(U.S.A.)
Developer

David developed the turbine simulation for JSBSim, as well as aircraft models that use it, including the T-38. He has experience flying many types of military and commercial aircraft, including the T-38, and the Boeing 707, 727, 737, 757, 767, the SGS 2-32, and the OV-10. David is an aero engineer (USAF Academy).

Agostino De Marco
(Naples, Italy)
Developer/User

Agostino De Marco is a professor of aerospace engineering at the University of Naples in Italy.



Lee Duke
(Glasgow, Virginia)
User/Developer

Lee Duke, the Chief Engineer of Rain Mountain Systems since 2004, retired from the NASA Dryden Flight Research Center in 2002 where he worked in flight test, flight controls, modeling and simulation, atmospheric flight dynamics, flight systems, and applications of artificial intelligence to aircraft systems. He is a member of IEEE, AIAA, and AUVSI.

Mathias Froehlich
(Germany)
Developer

Mathias improved and corrected the equations of motion for an early version JSBSim, among other things. Mathias is a mathematician.

JSBSim has found a variety of uses in industry and academia, and has benefited from the exposure, through feature requests, shared expertise, suggestions, and trouble reports.

The simplest use of JSBSim:

```
#include <FGFDMExec.h>             // Include the executive header
int main(int argc, char **argv)  // Pass a script name via argv
{
  JSBSim::FGFDMExec FDMExec;     // Instantiate the Executive
  bool result = true;
  FDMExec.LoadScript(argv[1]);   // Load a script
  while (result)
    result = FDMExec.Run();      // Run until the script completes
}
```

The above code will model anything from a ball, an aircraft, and a car, to a rocket. The vehicle and simulation run specifics are all read from configuration files coded in XML format.

Vehicle Configuration File Format:

```
<fdm_config>
  <fileheader> … </fileheader>                         <!-- 0 or 1 instance  -->
  <metrics> … </metrics>                               <!-- 1 instance       -->
  <mass_balance> … </mass_balance>                     <!-- 1 instance       -->
  <ground_reactions> … </ground_reactions>             <!-- 1 instance       -->
  <external_reactions> … </external_reactions>         <!-- 0 or 1 instance  -->
  <buoyant_forces> … </buoyant_forces>                 <!-- 0 or 1 instance  -->
  <propulsion> … </propulsion>                         <!-- 0 or 1 instance  -->
  <system> … </system>                                 <!-- 0 to n instances -->
  <autopilot> … </autopilot>                           <!-- 0 or 1 instance  -->
  <flight_control> … </flight_control>                 <!-- 0 or 1 instance  -->
  <aerodynamics> … </aerodynamics>                     <!-- 1 instance       -->
  <input> … </input>                                   <!-- 0 or 1 instance  -->
  <output> … </output>                                 <!-- 0 to n instances -->
</fdm_config>
```

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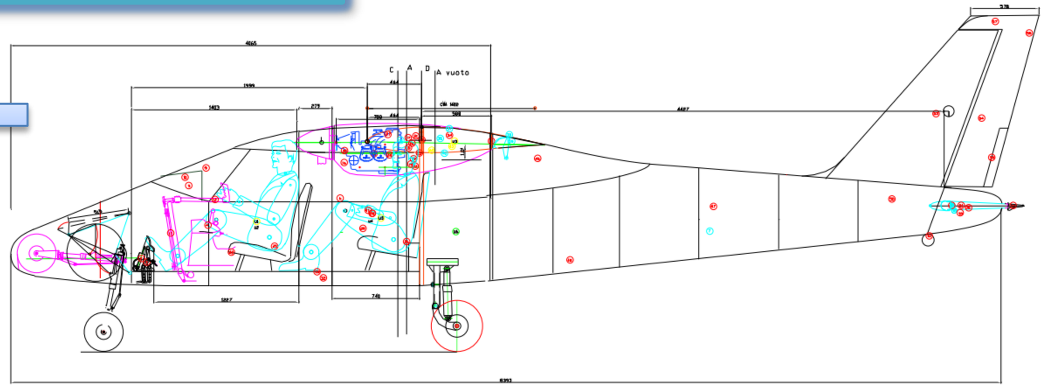
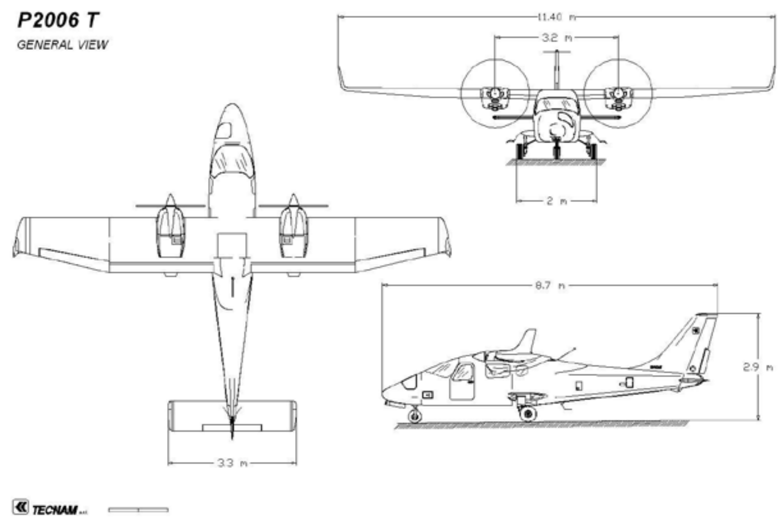
```
<metrics>
     <wingarea unit="M2"> 14.76 </wingarea>
     <wingspan unit="M">  11.4  </wingspan>
     <chord unit="M">      1.36 </chord>
     <htailarea unit="M2"> 2.57 </htailarea>
     <htailarm unit="M">   4.7  </htailarm>
     <vtailarea unit="M2"> 1.01 </vtailarea>
     <vtailarm unit="M">   1.04 </vtailarm>

     <location name="AERORP" unit="M">
         <x> 3.3  </x>
         <y> 0.0  </y>
         <z> 0.85 </z>
     </location>
     <location name="EYEPOINT" unit="M">
         <x> 2.15 </x>
         <y> 0.0  </y>
         <z> 0.72 </z>
     </location>
 </metrics>

 <mass_balance>
     <ixx unit="KG*M2"> 1617   </ixx>
     <iyy unit="KG*M2"> 1927   </iyy>
     <izz unit="KG*M2"> 2931   </izz>
     <ixy unit="KG*M2">     0  </ixy>
     <iyz unit="KG*M2">     0  </iyz>
     <ixz unit="KG*M2"> -221.3</ixz>
     <emptywt unit="KG"> 760 </emptywt>
             <location name="CG" unit="M">
         <x> 3.25 </x>
         <y> 0.0  </y>
         <z> 0.56 </z>
     </location>
             <pointmass name="PILOT">
                     <weight unit="KG">90</weight>
                     <location unit="M">
                             <x>  2.15 </x>
                             <y> -0.5  </y>
                             <z>  0.7  </z>
                     </location>
             </pointmass>
             <pointmass name="CO-PILOT">
         <weight unit="KG">90</weight>
         <location unit="M">
             <x> 2.15 </x>
             <y> 0.5 </y>
             <z> 0.7 </z>
```

Geometry

Masses





Initialization file:

```xml
<?xml version="1.0"?>
<initialize name="myreset">
  <!--
  This file sets up the aircraft @ 7000 ft
 altitude; @236 ft/s = 140 knots  (cruise speed);
  @ Naples.
  -->
  <ubody unit="FT/SEC">  202.5  </ubody>
  <vbody unit="FT/SEC">    0.0  </vbody>
  <wbody unit="FT/SEC">    0.0  </wbody>
  <latitude unit="DEG">   40.89 </latitude>
  <longitude unit="DEG"> 14.28 </longitude>
  <phi unit="DEG">          0.0  </phi>
  <theta unit="DEG">        0.0  </theta>
  <psi unit="DEG">        150.0  </psi>
  <altitude unit="FT">  2320.0  </altitude>
</initialize>
```

Script file:

```
<?xml version="1.0"?>
<?xml-stylesheet type="text/xsl" href="http://jsbsim.sourceforge.net/JSBSimScript.xsl"?>
<runscript xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
    xsi:noNamespaceSchemaLocation="http://jsbsim.sf.net/JSBSimScript.xsd"
    name="P2006T test">

     <use aircraft="p2006tv6" initialize="myreset"/>
     <run start="0.0" end="100" dt="0.0083333">

        <property> simulation/notify-time-trigger </property>
        <property value="1"> simulation/run_id </property>

        <event name="trim e setaggio comandi">
                <description>trim the aircraft</description>
                <condition>
                        simulation/sim-time-sec ge 0.0
                </condition>

                <set name="fcs/mixture-cmd-norm[0]" value="1.0"/>
                <set name="fcs/mixture-cmd-norm[1]" value="1.0"/>
                <set name="propulsion/magneto_cmd" value="3"/>
                <set name="fcs/throttle-cmd-norm[0]" value="0.0"/>
                <set name="fcs/throttle-cmd-norm[1]" value="0.0"/>
                <set name="propulsion/starter_cmd" value="1"/>
                <set name="fcs/mixture-cmd-norm" value="1.0"/>
                <set name="fcs/throttle-cmd-norm" value="1.0"/>
                <set name="simulation/do_simple_trim" value="0"/>
        </event>

         <event name="elevator step">
         <description>azione sul comando dell'elevatore</description>
         <condition>
              simulation/sim-time-sec >= 0.05
       </condition>

         <set name="fcs/elevator-cmd-norm" value="-0.2" action="FG_RAMP" tc="0.5"/>
         </event>

         <event name="remove">
         <description>rilascia l'elevatore</description>
         <condition>
              simulation/sim-time-sec >= 10.2
         </condition>

         <set name="fcs/elevator-cmd-norm" value="-0.02" action="FG_RAMP" tc="0.8"/>
         </event>
  </run>
</runscript>
```

Propulsion configuration files:

```xml
<?xml version="1.0"?>


<piston_engine name="ROTAX 912 S3">
  <minmp unit="INHG"> 18.0 </minmp>
  <maxmp unit="INHG"> 29.5 </maxmp>
  <displacement unit="IN3"> 82.6 </displacement>
  <cycles>         4.0 </cycles>
  <bore unit="IN"> 3.31</bore>
  <stroke unit="IN">2.4</stroke>
  <compressionratio>10.5</compressionratio>
  <maxhp>        95.30 </maxhp>
  <idlerpm>      900.0 </idlerpm>
  <maxrpm>      5800.0 </maxrpm>
  <maxthrottle>    1.0 </maxthrottle>
  <minthrottle>    0.1 </minthrottle>
  <sparkfaildrop>  0.0 </sparkfaildrop>
</piston_engine>
```

```xml
<?xml version="1.0"?>

<propeller name="MTV-21-A-C-F">
  <ixx unit="KG*M2"> 0.3 </ixx>
  <diameter unit="M">  1.78 </diameter>
  <numblades> 2 </numblades>
  <minpitch> 10.0 </minpitch>
  <maxpitch> 30.0 </maxpitch>


  <table name="C_THRUST" type="internal">
        <tableData>
                0.40000       0.10791
                0.50044       0.10426
                0.59935       0.099004
                0.69968       0.093108
                0.80003       0.086684
                0.89901       0.08017
                0.99801       0.07396
                1.09840       0.067659
                1.19880       0.061796
                1.30000       0.056902

     </tableData>
  </table>


  <table name="C_POWER" type="internal">
     <tableData>
         0.40000        0.052271
         0.50044        0.063186
         0.59935        0.071859
         0.69968        0.078893
         0.80003        0.083984
         0.89901        0.087283
         0.99801        0.089389
         1.0984         0.09
         1.1988         0.089717
         1.3            0.089583
     </tableData>
  </table>

</propeller>
```

FCS:

```
<flight_control name="FCS: p2006t">

    <channel name="Pitch">

        <summer name="Pitch Trim Sum">
            <input>fcs/elevator-cmd-norm</input>
            <input>fcs/pitch-trim-cmd-norm</input>
            <clipto>
                <min>-1</min>
                <max> 1</max>
            </clipto>
        </summer>

        <aerosurface_scale name="Elevator Control">
            <input>fcs/pitch-trim-sum</input>
            <gain>0.01745</gain>
            <range>
                    <min>-15</min>
                    <max> 4</max>
            </range>
            <output>fcs/elevator-pos-rad</output>
            </aerosurface_scale>

            <aerosurface_scale name="Elevator Position Normalized">
            <input>fcs/elevator-pos-deg</input>
            <domain>
                    <min>-15</min>
                    <max> 4</max>
            </domain>
            <range>
                <min>-1</min>
                <max> 1</max>
            </range>
            <output>fcs/elevator-pos-norm</output>
        </aerosurface_scale>

    </channel>
```

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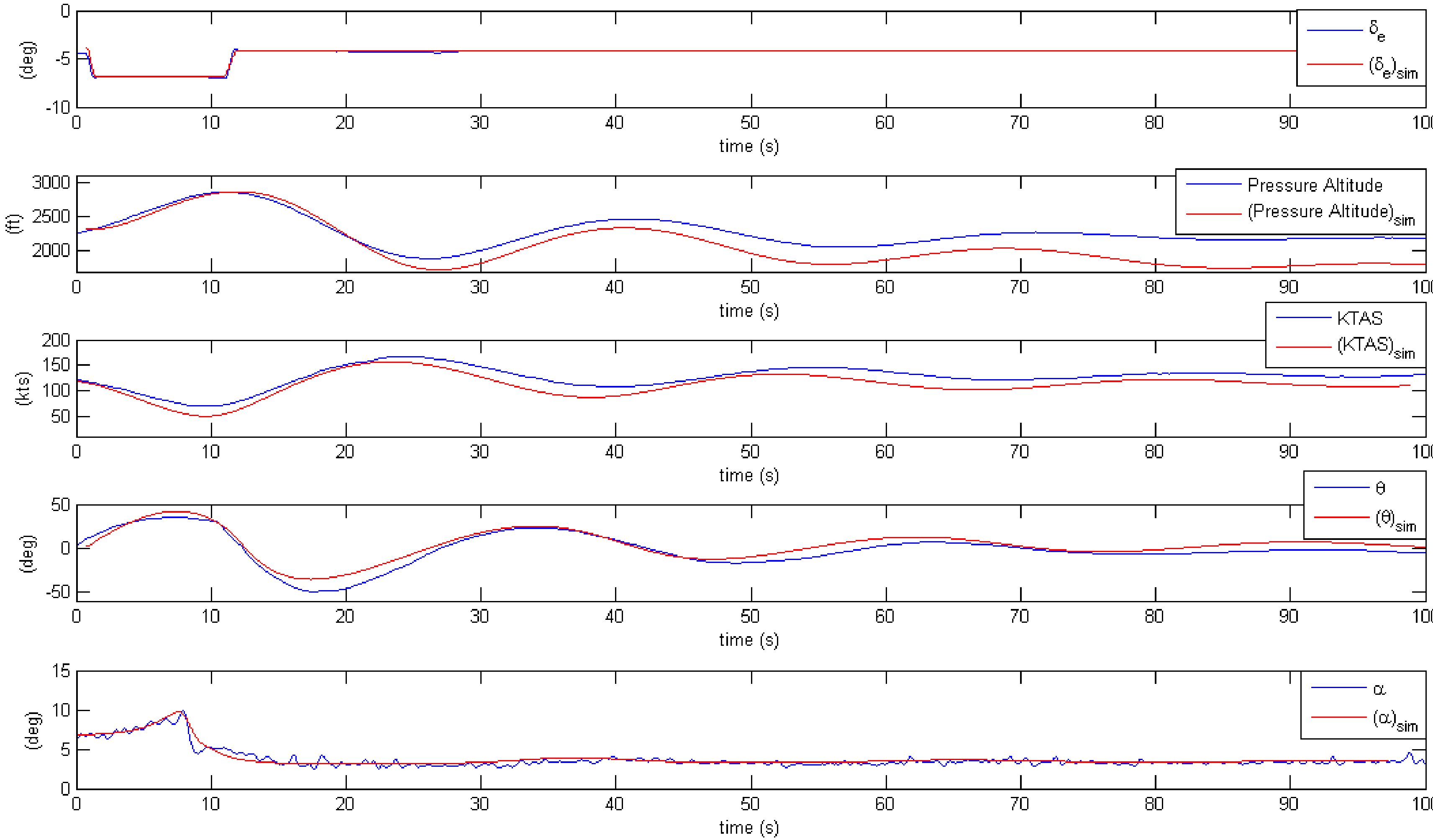
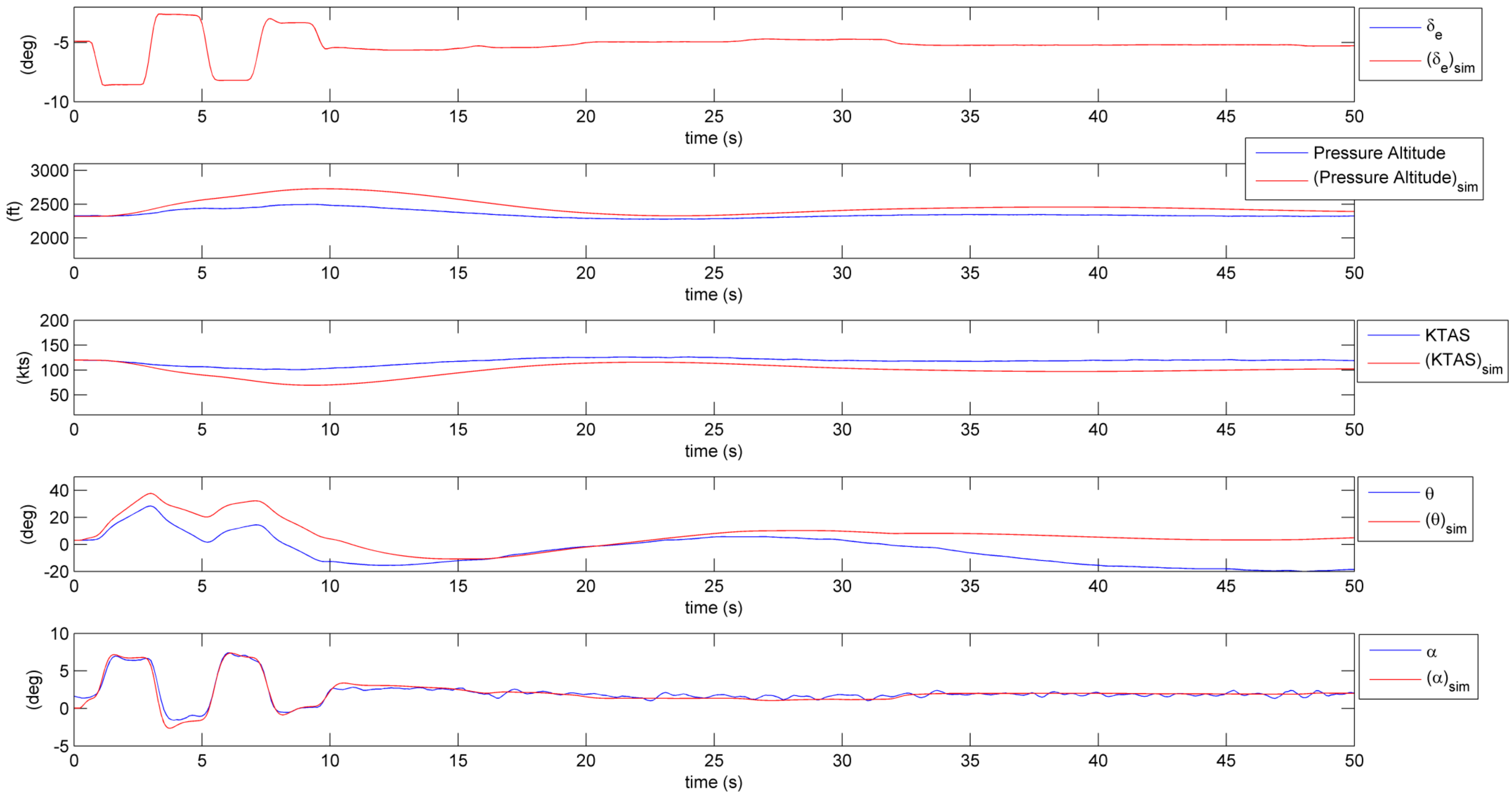


Flight simulation · JSBSim



JSBSim has been used in simulation–based aircraft design and analysis approaches.

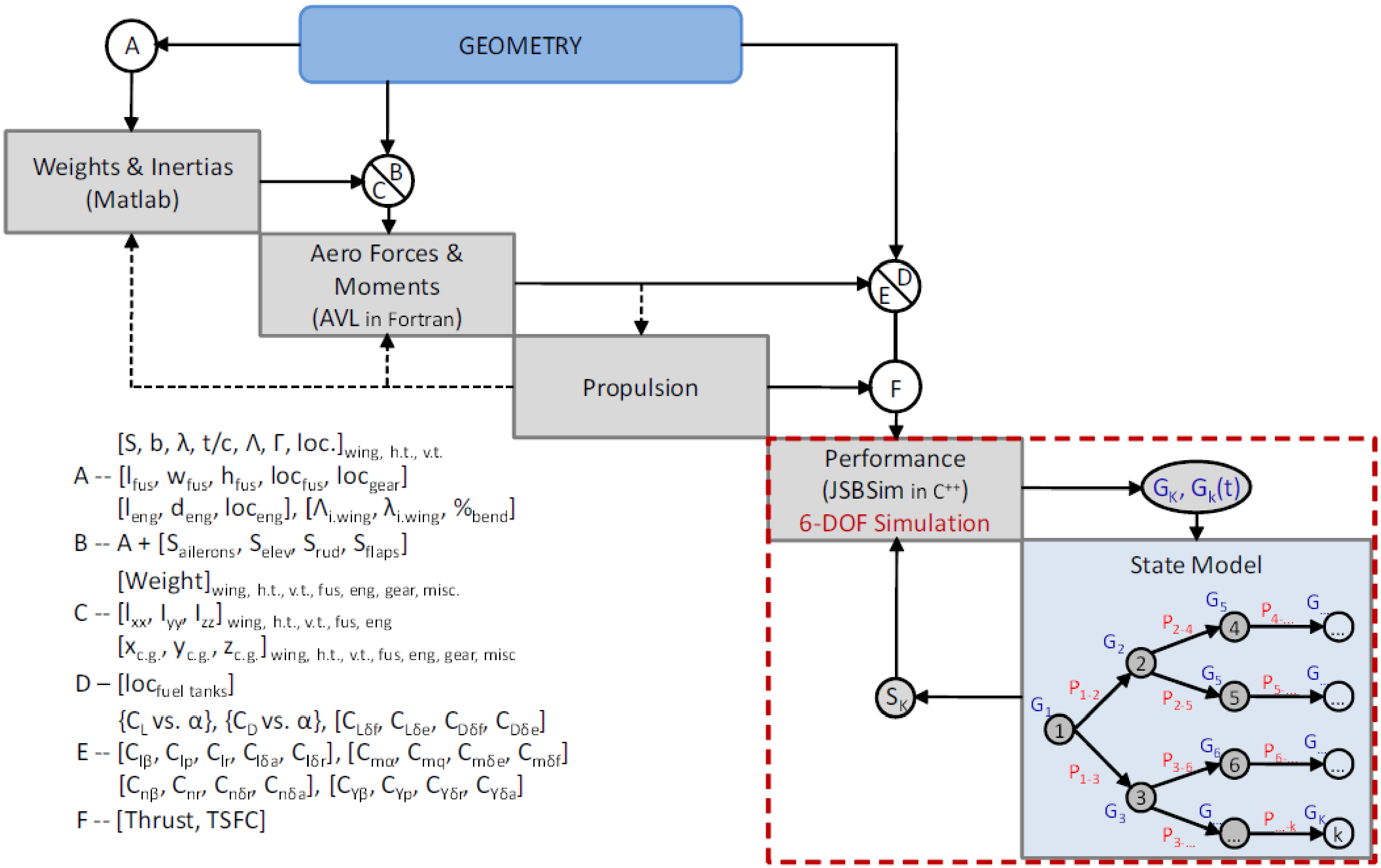
The focus is on the evaluation of aircraft as multi-state systems, i.e. one having a finite set of performance levels or ranges. Sometimes these ranges are differentiated by distinct levels of failure.

In order to accurately examine numerous aircraft performance states, a multi-disciplinary design model is used, a 6-DoF flight simulator integrated with a vortex lattice aerodynamics solver and a tool for calculation of weights and inertias.

The JSBSim batch running mode facilitates a global approach for concurrent analysis of aircraft expected performance and availability. Namely, by allowing systematic calculation of performance metrics for differing aircraft states, the relationship between an aircraft's global design variables and its performance and availability may be established.

Such an approach allows designers to identify those elements that might drive system loss probability through an analysis of performance changes across system states and their respective sensitivity to design variables.

Flight simulation · JSBSim



Aircraft integrated system model used at Draper Laboratory with behavioral–Markov failure modelling

Flight simulation · JSBSim

See: [1] Berndt J. S., "JSBSim: An Open Source Flight Dynamics Model in C++." AIAA 2004-4923, AIAA Modeling and Simulation Technologies Conference and Exhibit 16 - 19 August 2004, Providence, Rhode Island, USA.

[2] Coiro D. P., De Marco A., Nicolosi F., "A 6DOF Flight Simulation Environment for General Aviation Aircraft with Control Loading Reproduction." AIAA 2007-6364, AIAA Modeling and Simulation Technologies Conference and Exhibit 20-23 August 2007, Hilton Head, South Carolina, USA.

[3] Berndt J. S., De Marco A., "Progress on and Usage of the Open Source Flight Dynamics Model Software Library, JSBSim." AIAA 2009-5600, AIAA Modeling and Simulation Technologies Conference and Exhibit 10-13 August 2009, Chicago, Illinois, USA.

[3] Agte J., Borer N. K., de Weck O., "A Simulation-based Design Model for Analysis and Optimization of Multi-State Aircraft Performance." AIAA 2010-2997, 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 12-15 April 2010, Orlando, Florida.

Conclusions

The success story of P2006T aircraft post–design modifications.

Aircraft response modes and flight qualities.

Parameter estimation of stability derivatives.

Uses of the open source flight dynamics model software library JSBSim.

Thank you

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