FLIGHT TESTS OF A TWIN-ENGINE AIRCRAFT: PERFORMANCES, STABILITY AND PARAMETER ESTIMATION

Pierluigi Della Vecchia

Dipartimento di Ingegneria Aerospaziale
Università di Napoli "Federico II"
e.mail : pierluigi.dellavecchia@unina.it

Layout of the presentation

- Overview of the Tecnam P2006T aircraft
- Flight tests instrumentation
- Flight tests certification
- Stability and flight quality evaluation
- Aircraft parameter estimation

P2006T Aircraft

CS-23 Certification

Characteristics

Wing span	11.4 m (37.4 ft)
Wing area	14.8 m^2 (159.3 ft^2)
Fuselage length	8.7 m (28.5 ft)
AR	8.8

Engine: Rotax 912S (2×100 hp)

Performances

Max Level speed (at S/L)	155 kts
Cruise speed	145 kts
Max R/C (at S/L)	1202 ft/min
Take-off distance	450 m (1400 ft)
Landing distance	320 m (1050 ft)

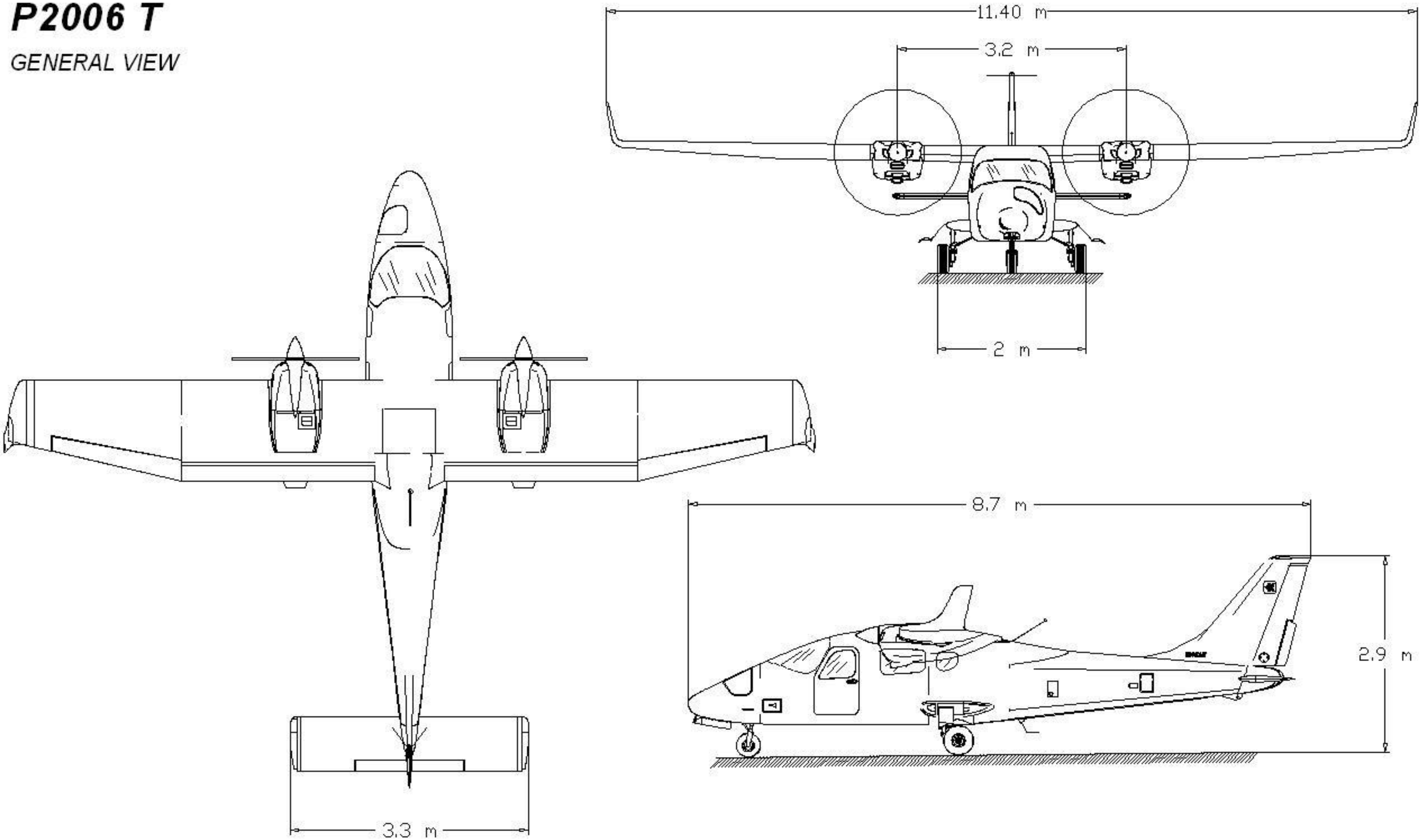
Weights & Balance

MTOW	1180 kg (2600 lb)
Std. Equipped Empty Weight	760 kg (1675 lb)
Max/Min load factors	+3.8 g / –1.9 g

	Max Fwd	Max Aft
XCG Position	16.5 %	31 %

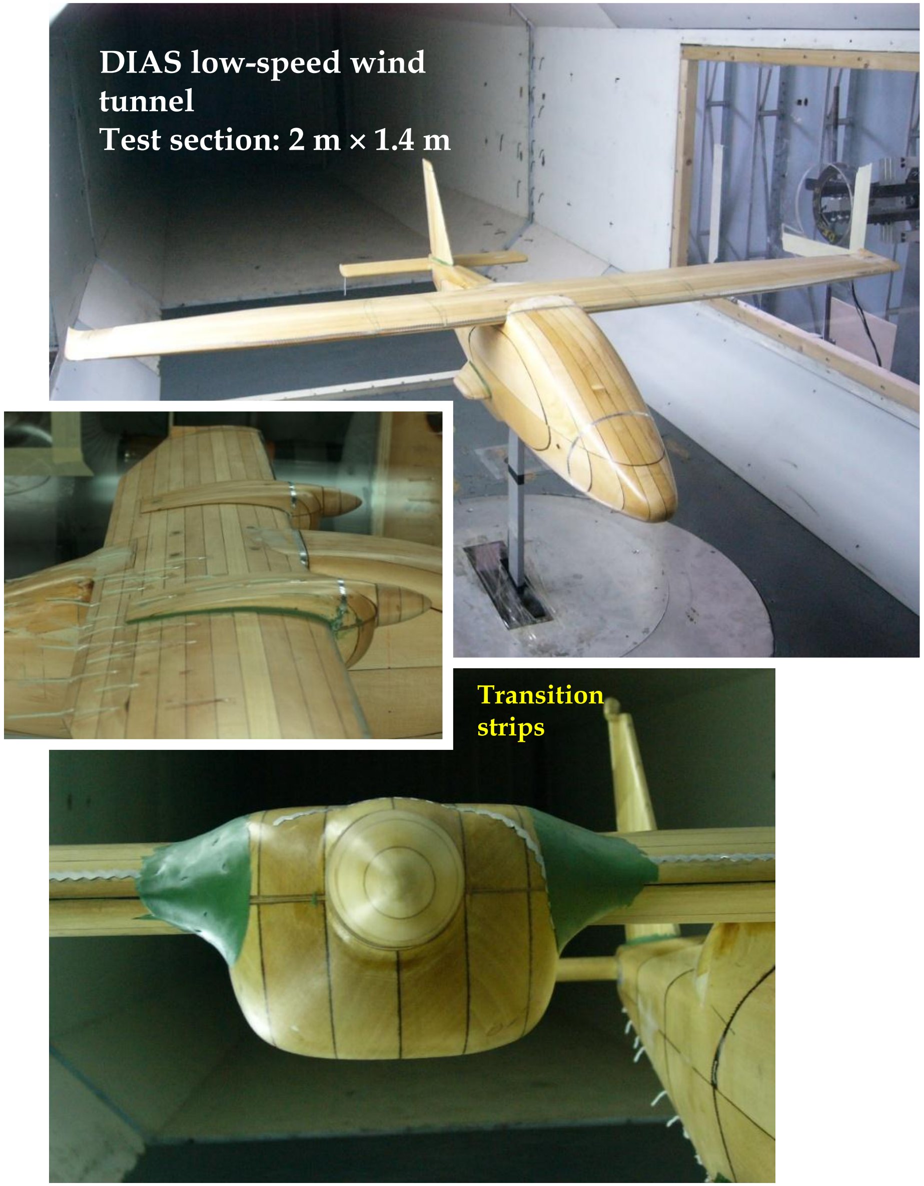
P2006 T

GENERAL VIEW



TECNAM s.r.l.

Wind tunnel tests



DIAS low-speed wind tunnel
Test section: 2 m × 1.4 m

Transition strips

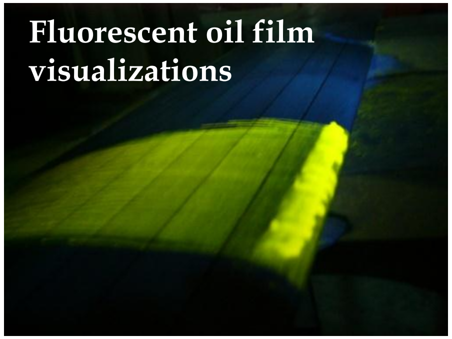
Turbulence Intensity
~ 0.1%

Max. speed
~ 45 m/s

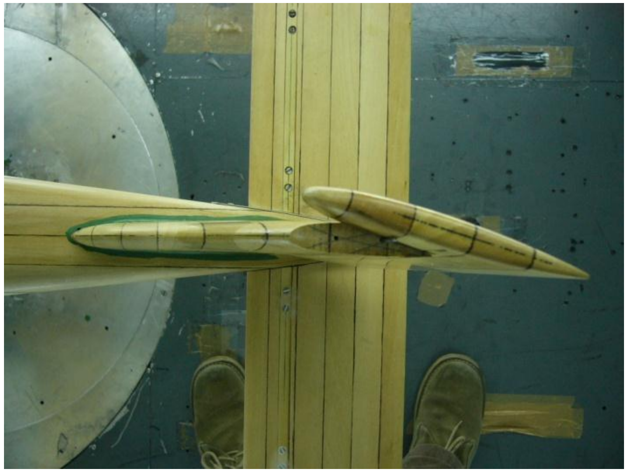
Scale Model
(1:6.5)

Re ≈ 0.6×10^6

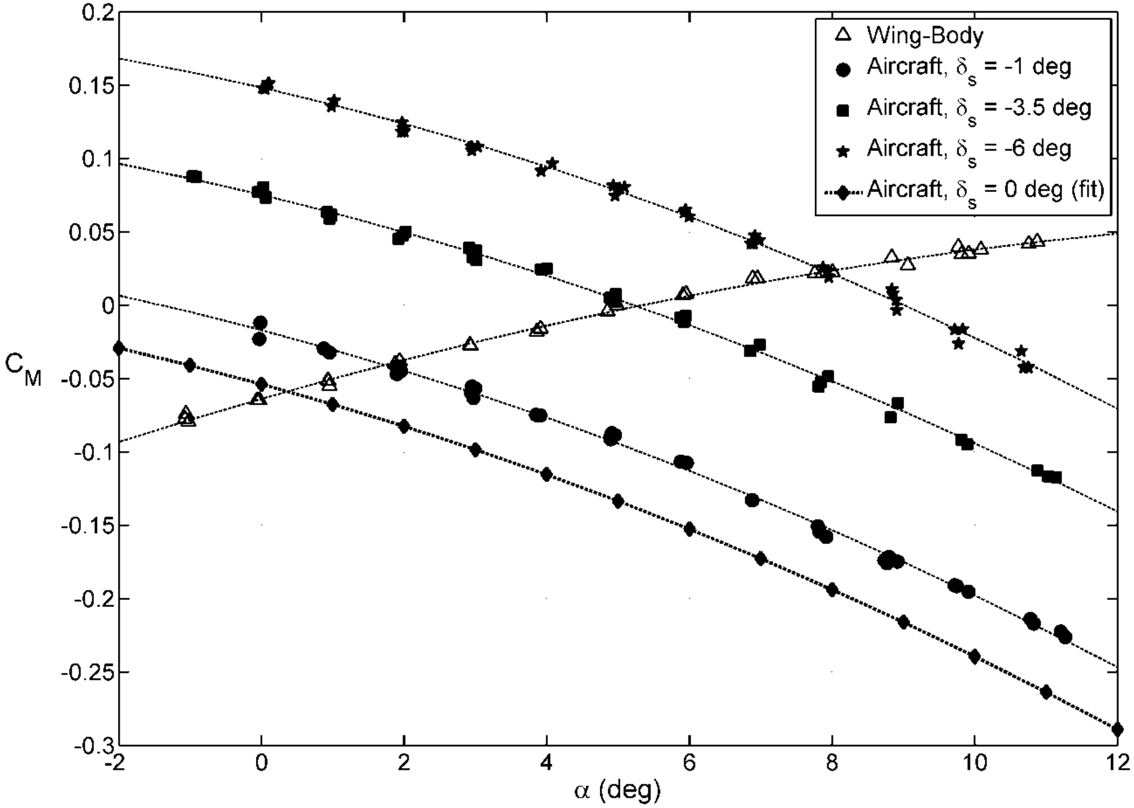
In-Flight
Re ≈ 6.0×10^6



Fluorescent oil film visualizations

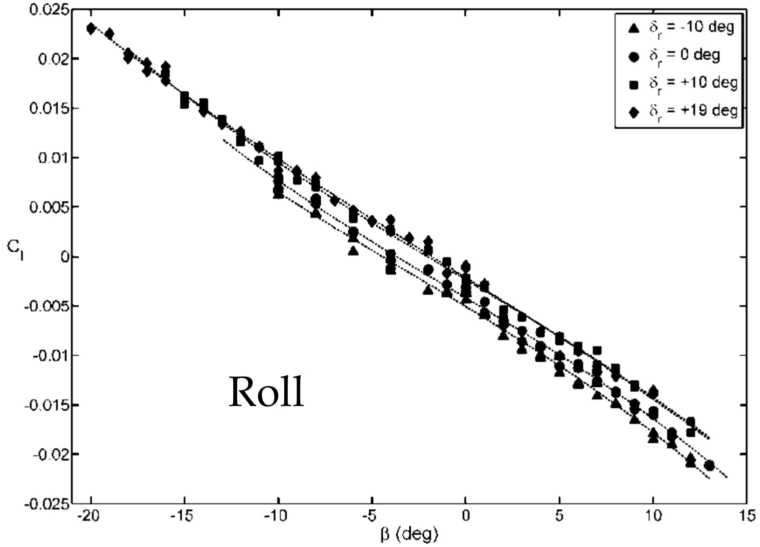


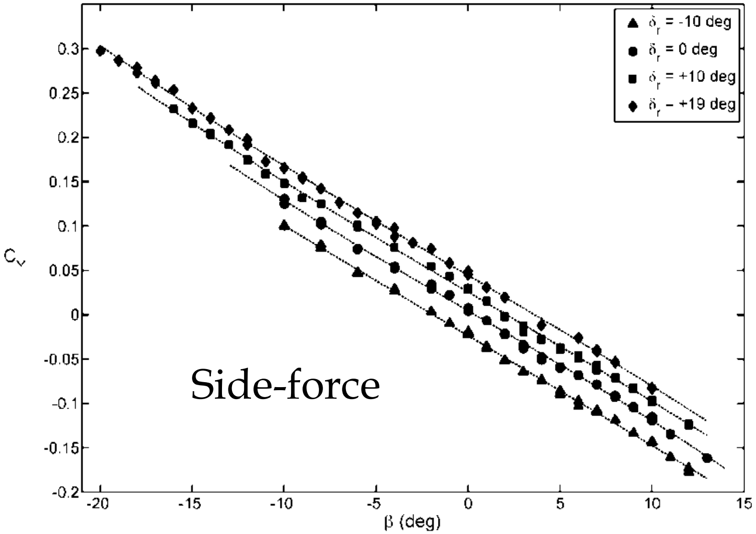
Wind tunnel test results

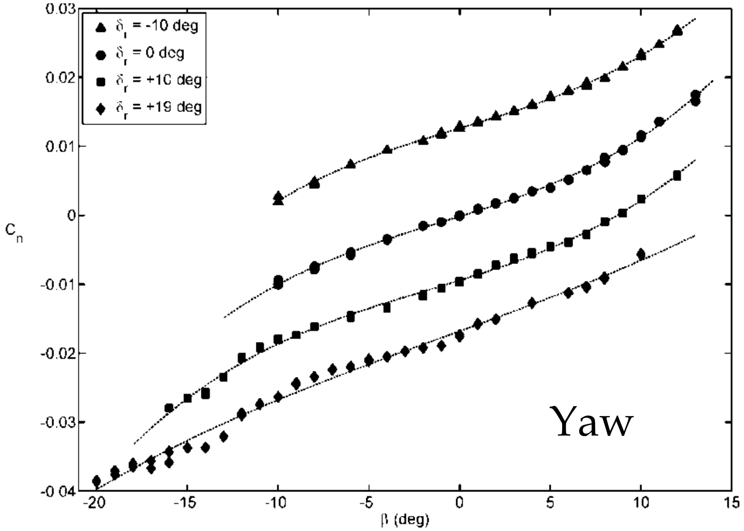


Pitching moment coefficient, measured for a fixed transition on wings, nacelles and fuselage and a reference Reynolds number of 0.6×10^6, at different stabilator deflection angles δ_s

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 Performances and certification

Flight tests carried out

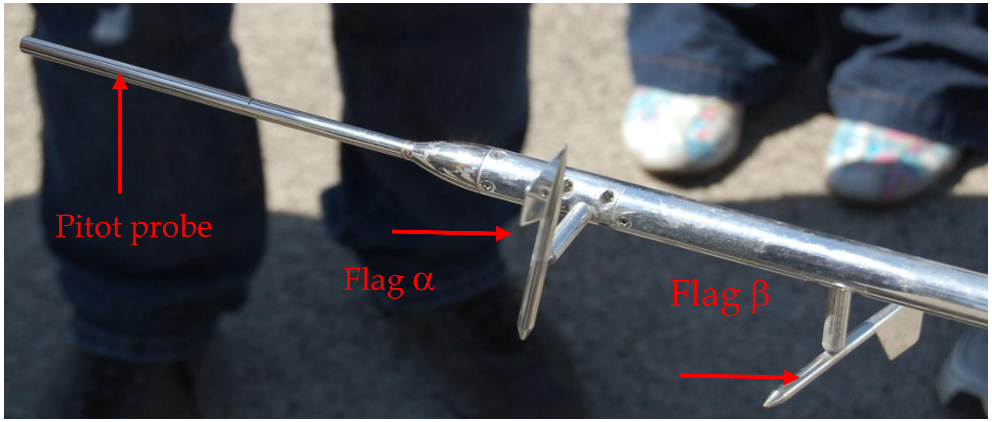
- to complete aircraft certification
- to release flight manual
- aircraft set up

Flight data acquisition system

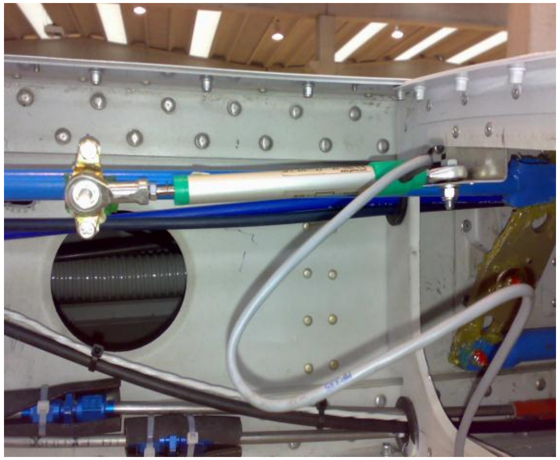
Box Megaris (PC)

AHRS

GPS Antenna

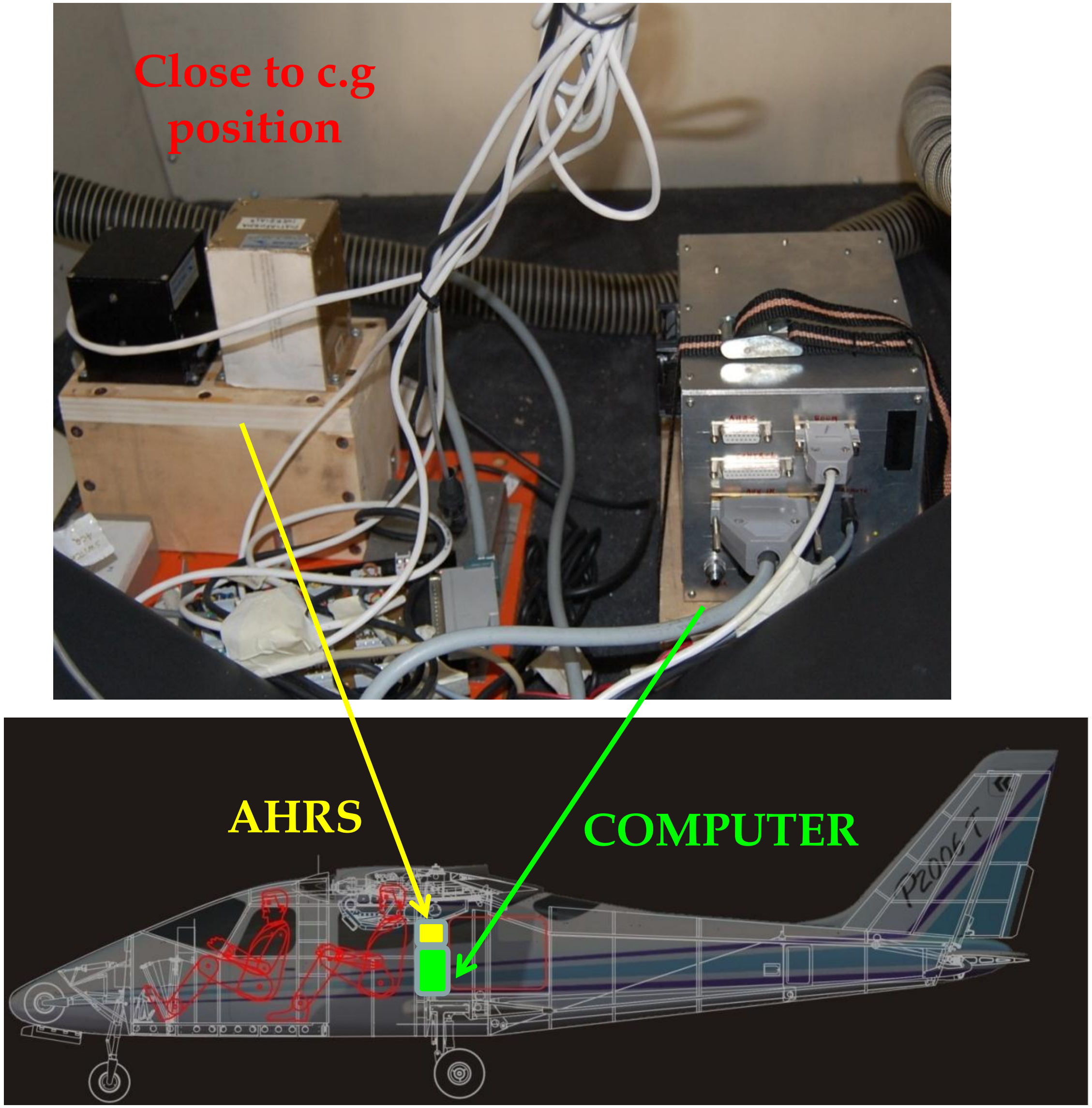


Mini Air DATA Boom



Aileron deflection

Flight data acquisition system

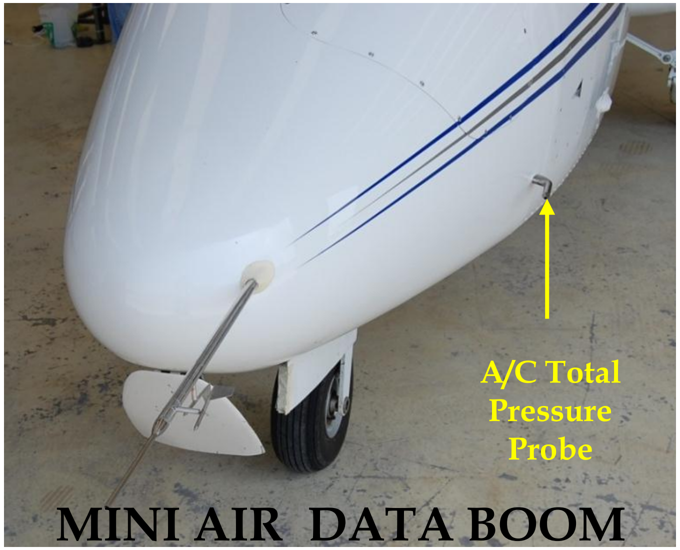


Close to c.g position

AHRS

COMPUTER

LOAD CELLS



A/C Total Pressure Probe

MINI AIR DATA BOOM

P2006T Flight Perormances and certification

Flight tests carried out

- to complete aircraft certification
- to release flight manual
- aircraft set up

In this presentation:

- Pitot-static system calibration
- Stall tests
- Climb (AEO , OEI) tests
- Take-off tests
- Static Stability tests

Pitot-static system Calibration

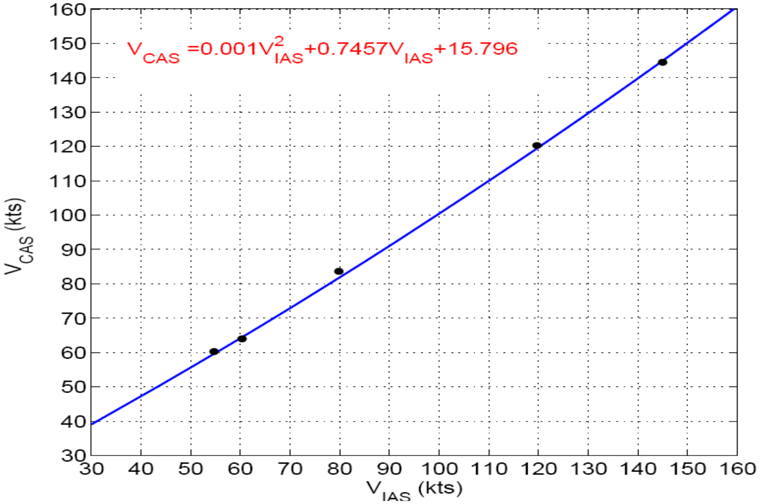
Speed course method together GPS measurements:

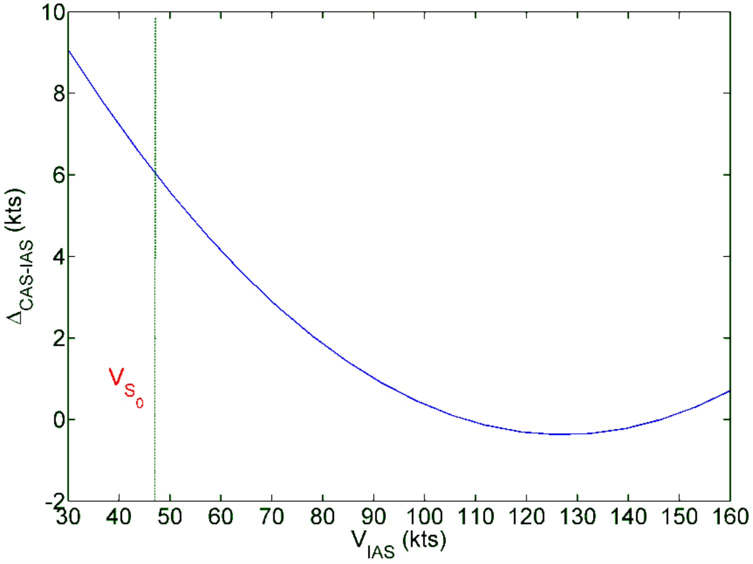
- a series of courses over a base of known length

Results summary

FLAPS (deg)	GEAR	average GS (kts)	V_{CAS} (kts)	V_{IAS} (kts)	ERROR %
0	Up	83.2	84.1	80	5.1
0	Up	119	120.3	120	0.3
0	Up	142	143.5	145	-1.0
take-off	Down	63	63.3	60	5.5
landing	Up	60.5	60.7	55	10.3

Calibration curve





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)**

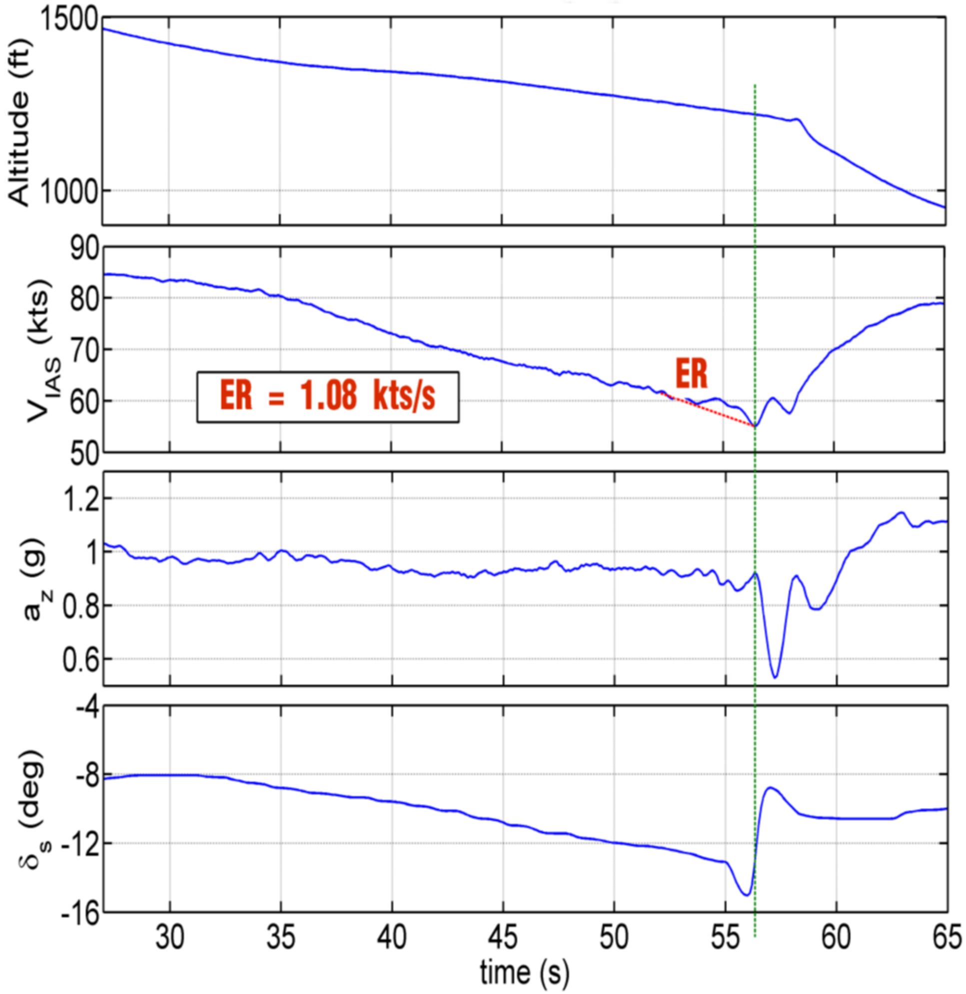
Tests have been performed in the following configurations and conditions:

- Maximum weight take off;
- Engine running at 75% and idle
- Flap a 0° , 15° and full;
- Landing gear retracted and extended;
- Trim speed (=1.5VS1).
- CG in the max forward and aft position.
- Turning stall with 30° of bank

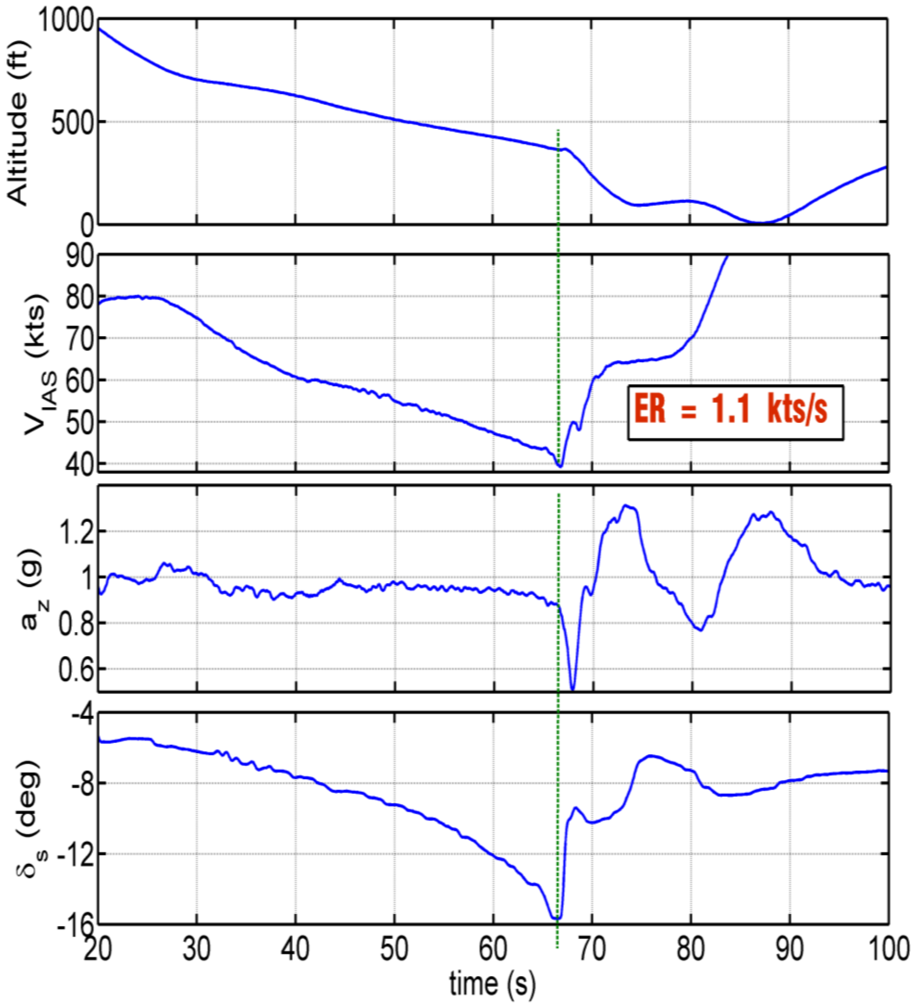
… leading to more than 100 stalls to accomplish certification requirements!

Stall Tests

Level stall time histories – NO FLAP



Level stall time histories – FLAP landing

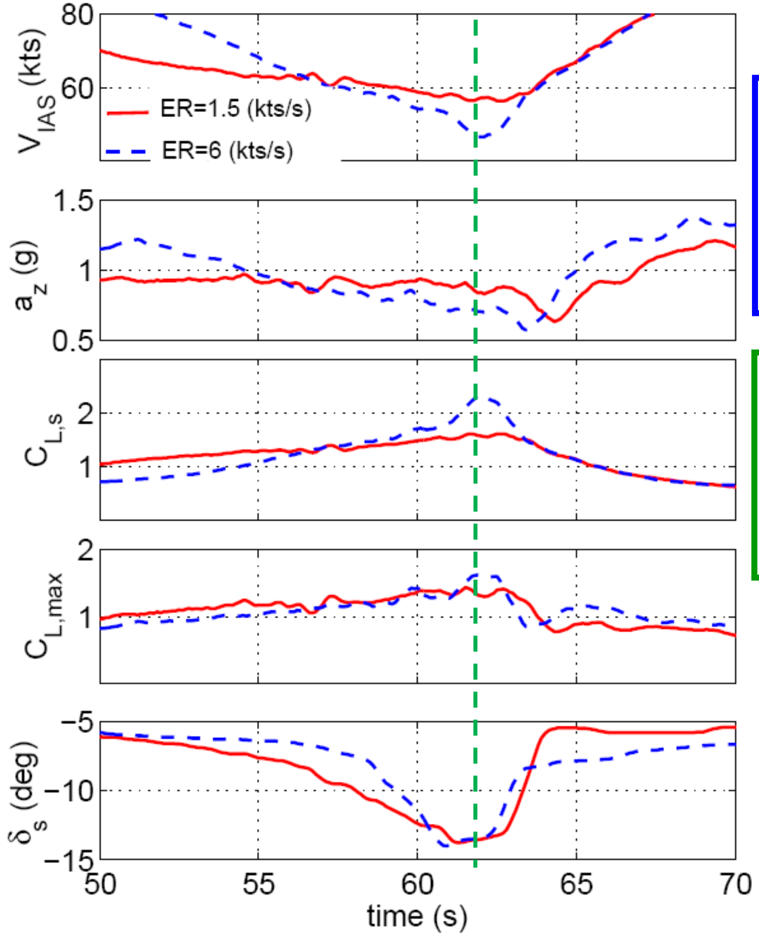


Stall Tests -Results

ENTRY RATE EFFECT

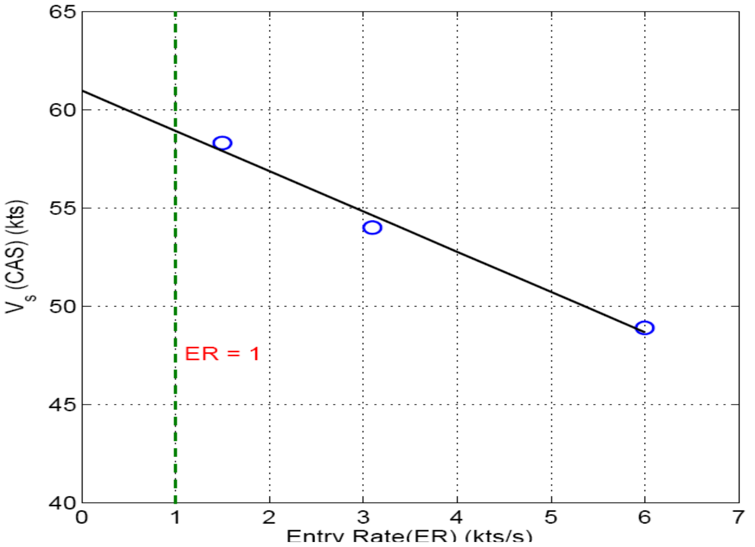
Level stall time histories – no FLAP

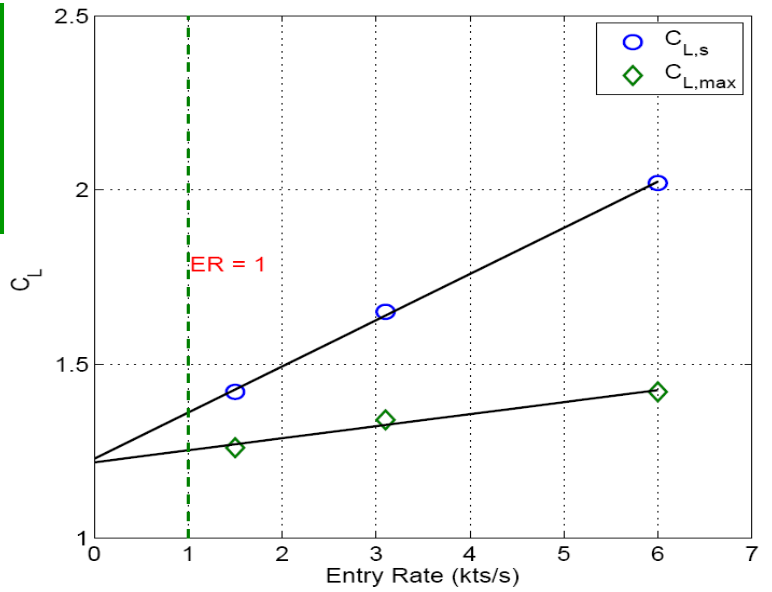
Xcg 16.5% MAC (max forward)



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

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





Stall Tests - Results

…more than 100 stalls have been performed !

Type	Flap (deg)	Land. gear	V_S (kts)	a_z	Entry rate (kts/s)	$C_{L,s}$	$C_{L,\mathrm{MAX}}$
Stall tests cg max forward (16.5%)							
Leveled	0	Retr.	**55.5**	0.92	1.1	1.46	1.34
Leveled	0	Ext.	60	0.92	0.8	1.26	1.16
Leveled	15	Ext.	45.8	0.84	-	2.08	1.75
Leveled	40	Retr.	41.3	0.88	1.1	2.51	2.22
Leveled	40	Ext.	43	0.84	0.7	2.33	1.97
Turn	0	Retr.	65.7	0.97	0.8	1.06	1.04
Turn	40	Retr.	54	1.14	0.5	1.53	1.75
Stall tests cg max aft (30.5%)							
Leveled	0	Retr.	55.2	0.93	2.7	1.47	1.38
Leveled	15	Ext.	**51**	0.84	-	1.85	1.56
Leveled	40	Retr.	**47**	0.89	1.9	1.98	1.78
Turn	0	Retr.	62	0.97	1.3	1.19	1.15
Turn	40	Retr.	53	0.97	2.5	1.59	1.54

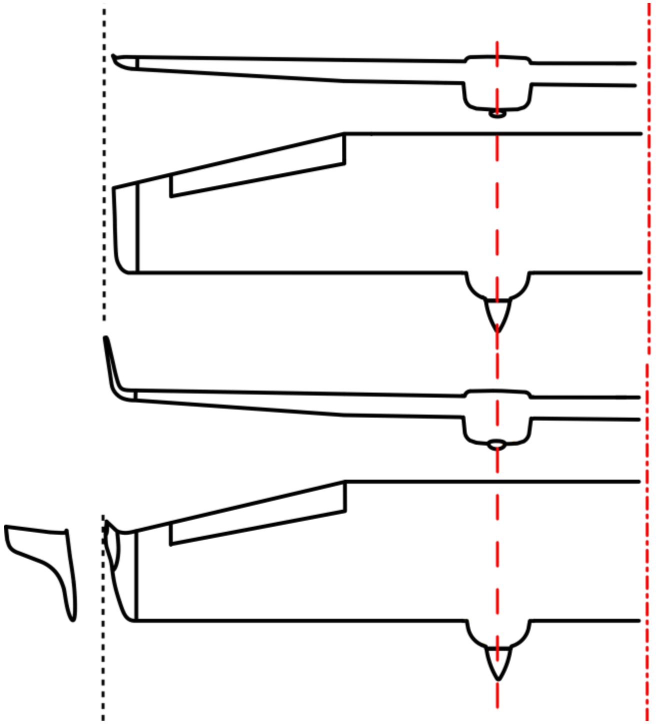
P2006T certified stall speeds

(CAS) **Vs_clean = 56 kts**
(CAS) **Vs_take_off = 51 kts**
(CAS) **Vs_landing = 47 kts**

CLIMB

Aircraft during pre-certification tests

b = 11.2 m S =14.7 m^2



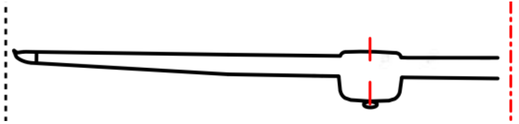
b = 11.4 m S =14.8 m^2

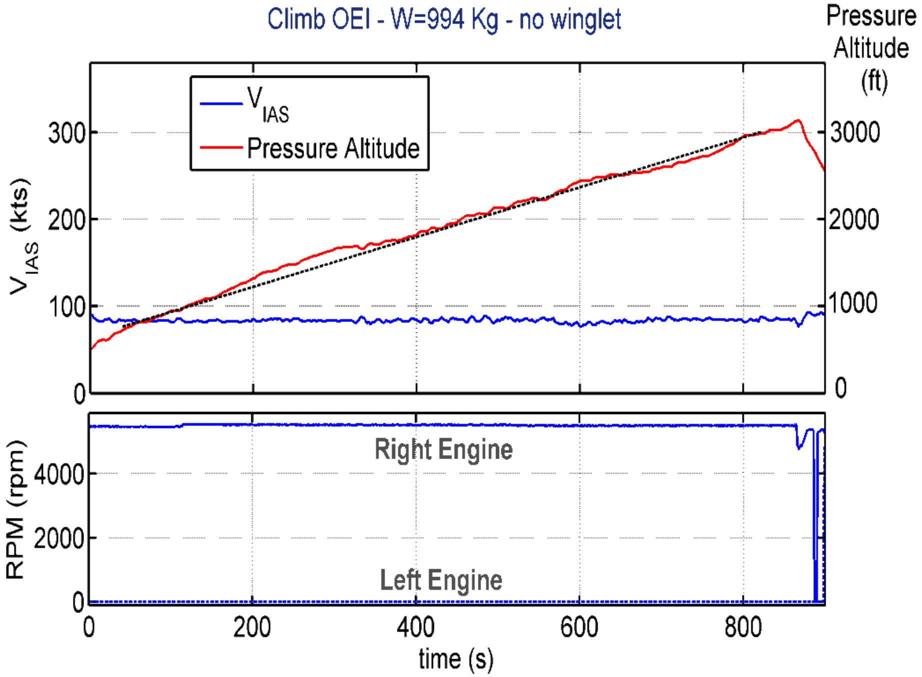
WINGLETS not installed

WINGLETS installed

CLIMB - OEI

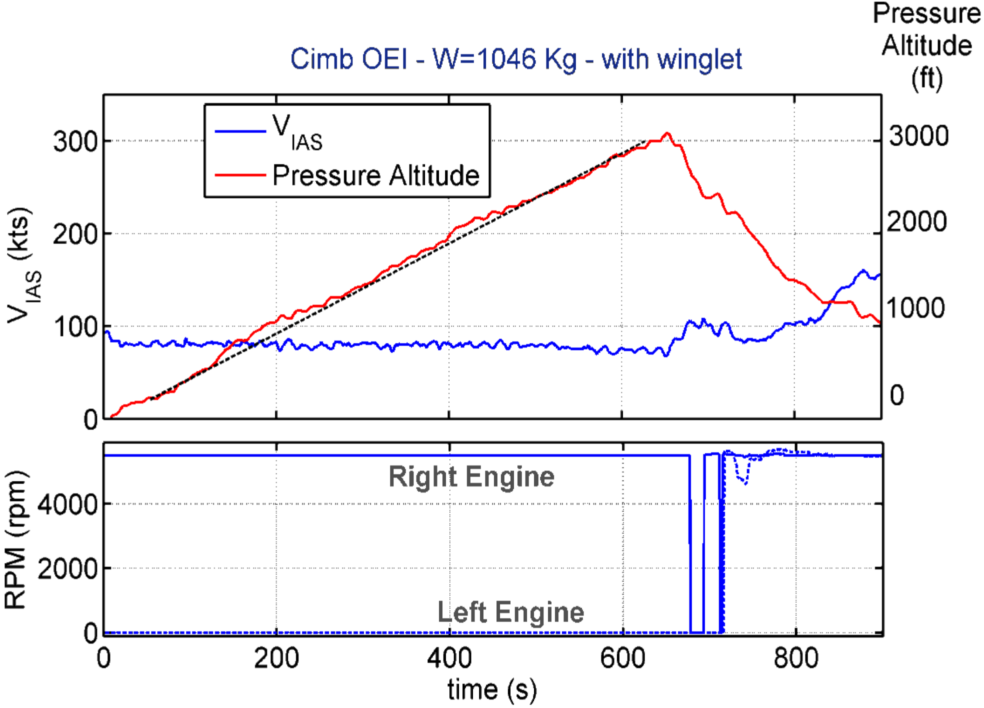
NO WINGLETS





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

WINGLETS



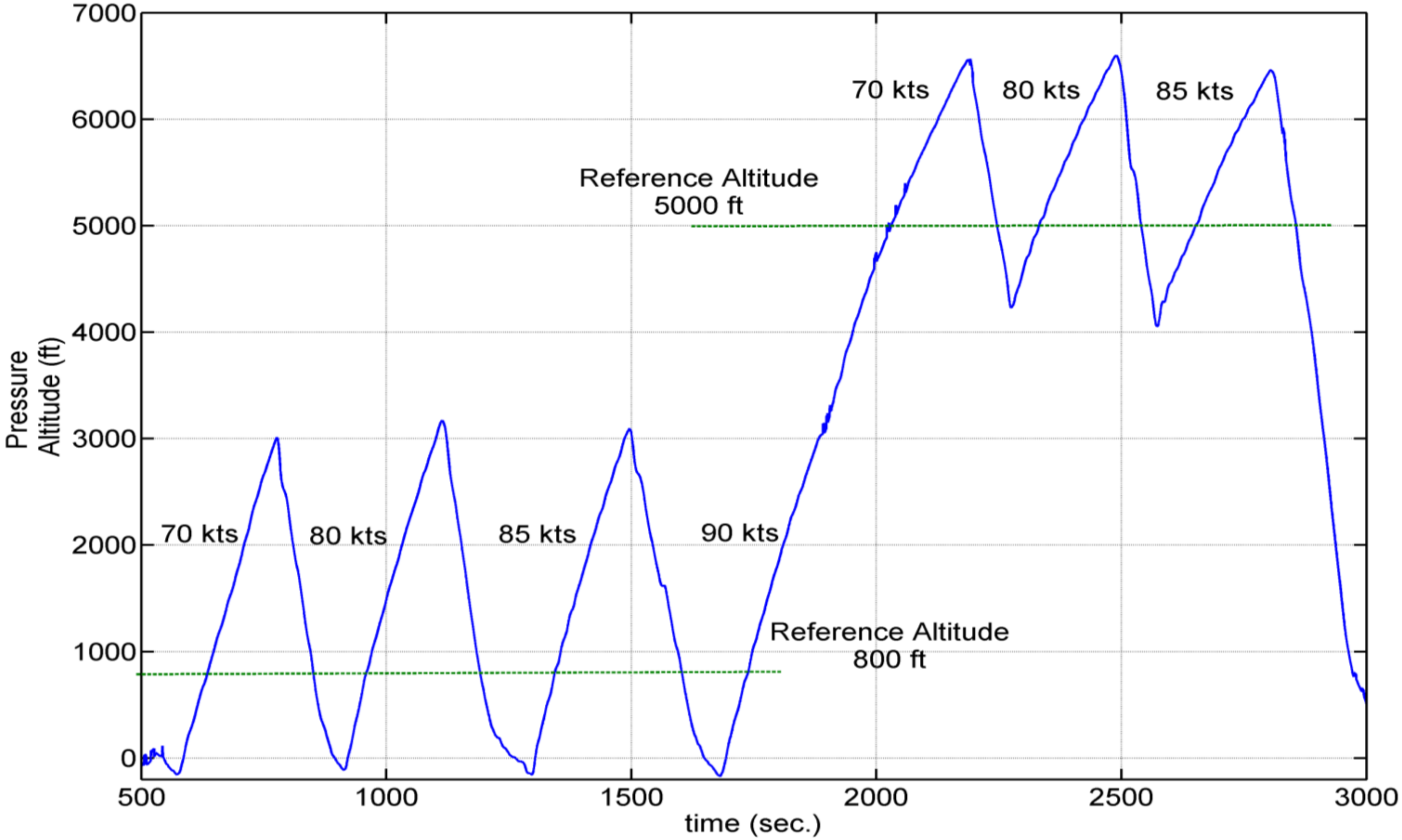
Rate of Climb (at 800 ft)
300 ft/min

Pilots reported an huge difference in climb capability of the aircraft!

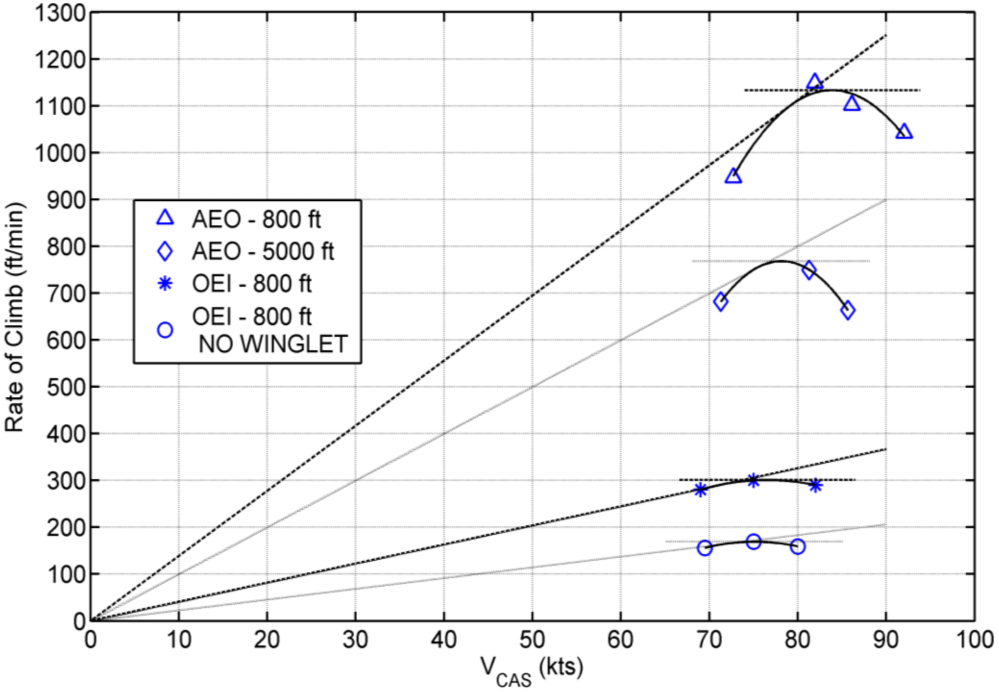
CLIMB - AEO

Flight certification tests

- SAW-TOOTH CLIMB
2 reference altitude (800ft and 5000 ft)



CLIMB – AEO&OEI



AEO

$$RC_{MAX}(800\,ft) = 1133.3\,ft/\min$$

$$RC_{MAX}(5000\,ft) = 768.1\,ft/\min$$

Steepest climb speed

$$V_X(800\,ft) = 75.37\,kts$$

$$V_X(5000\,ft) = 78.13\,kts$$

Fastest climb speed

$$V_Y(800\,ft) = 83.84\,kts$$

$$V_Y(5000\,ft) = 79.15\,kts$$

OEI

$$RC_{MAX}(800\,ft)_{NO\_WINGLET} = 169\,ft/\min$$

$$RC_{MAX}(800\,ft)_{WINGLET} = 300\,ft/\min$$

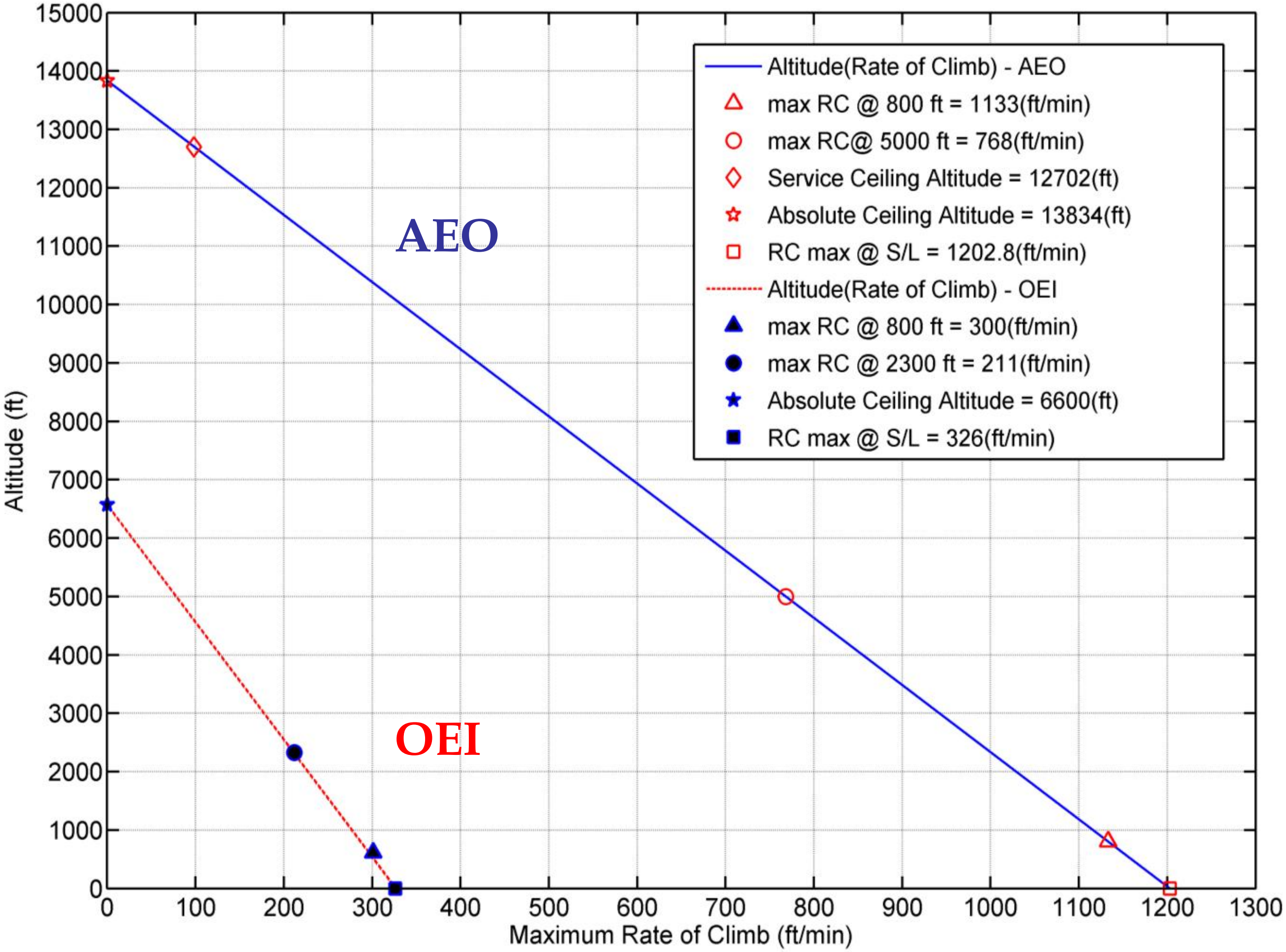
Steepest climb speed

$$V_X(800\,ft) = 69.5\,kts$$

Fastest climb speed

$$V_Y(800\,ft) = 76\,kts$$

CLIMB – AEO&OEI



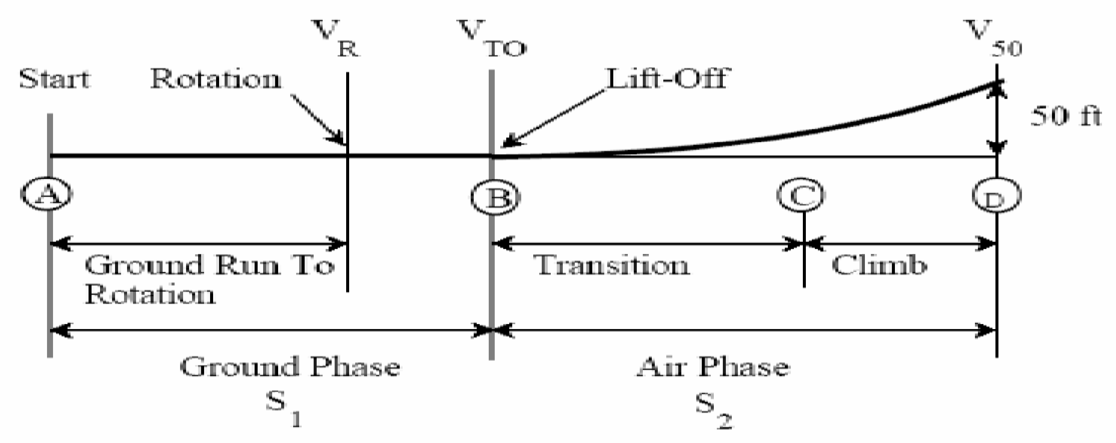
AEO

Best Rate of Climb @ sea level (ft/min)	*Absolute Ceiling Altitude* (ft)	*Service Ceiling Altitude* (ft)
1202.8	**13834**	**12702**

OEI

Best Rate of Climb @ sea level (ft/min)	*Absolute Ceiling Altitude* (ft)
326	**6600**

TAKE-OFF



- Ground Phase S1
- Air Phase S2

→ STO = S1+S2

Requirements: CS 23.51 – 23.53

- VR > 1.05 VMC(55.8 kts) or 1.1 VS1(56.1 kts)
- V50 > 1.1 VMC(58.3 kts) or 1.2VS1(61.2 kts)
- Flap take - off, landing gear down , maximum power
- Maximum Weight, Xc.g. max forward

TAKE-OFF

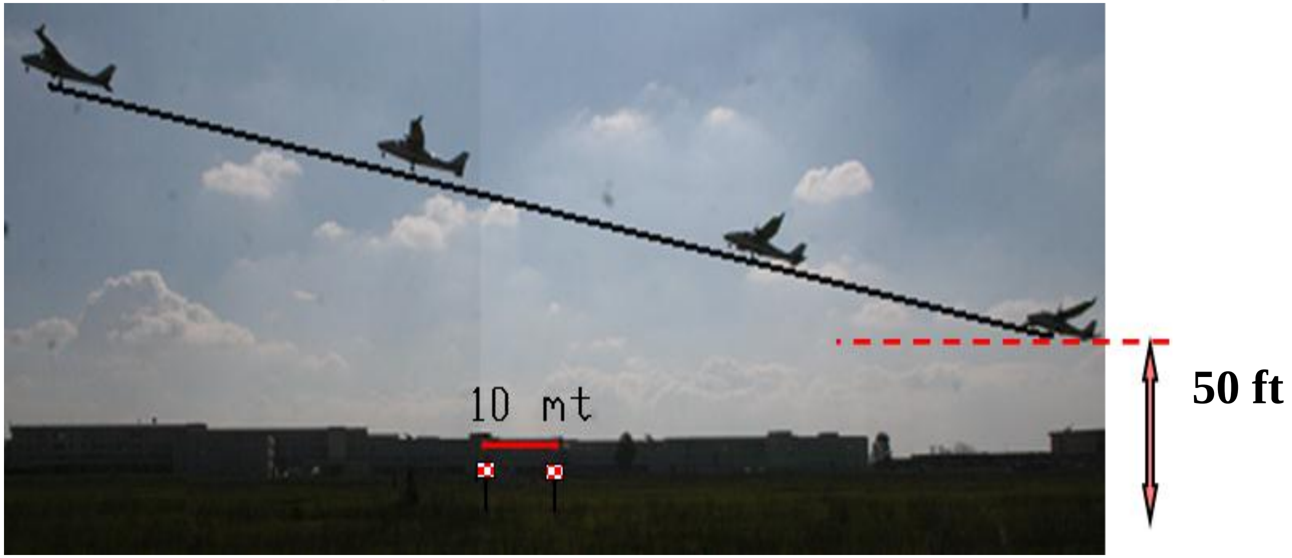
Ground Phase recontruction

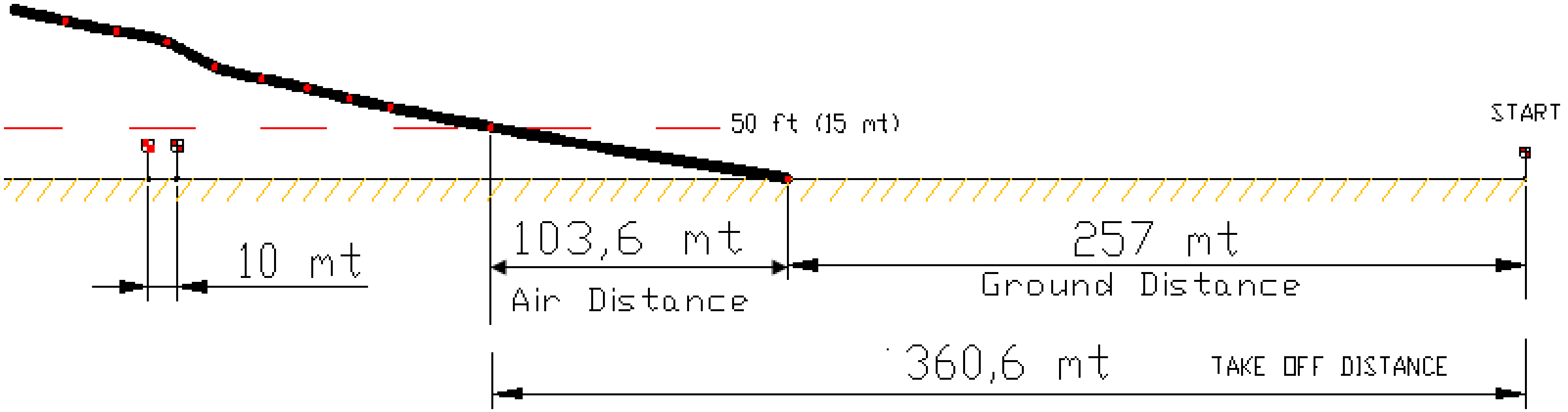
Pickets

Air Phase reconstruction

TAKE-OFF

TAKE-OFF reconstruction





TAKE-OFF- Results

Take-off	V_R	V_{TO}	V_{obs}	V_R*mean*	V_{TO}*mean*	V_{obs}*mean*
[n°]	*(kts)*	*(kts)*	*(kts)*	*(kts)*	*(kts)*	*(kts)*
1	57.4	57.8	65.5	**56.97**	**58.95**	**62.22**
2	57.2	58.7	63.2			
3	58.2	59.1	61.1			
4	56.3	58.5	61.3			
5	56.3	60.1	61.2			
6	56.4	60.1	61			
Standard Deviation	0.771	1.771	2.771			

Take-off	*Ground Distance Observed*	*Air Distance observed*	*Total distance observed*	*Ground Distance corrected*	*Air Distance corrected*	*Total Distance corrected*
	(m)	*(m)*	*(m)*	*(m)*	*(m)*	*(m)*
Mean	289.16	87.04	376.20	294.80	88.68	**383.47**

Results meet the demands

V_R> 56.1kts; V_50 = V_obs > 61.2kts; STO = 383 m

Static Longitudinal Stability

1. Aircraft equipped wiht an instrumentation to measure pilot efforts
2. Centre of gravity pos. must be the most unfavorable

Load cells

Aircraft configuration during the tests

Weight	**1050** kg
Xcg max aft	**31**%
Air Temperature	**24**° C
Wind speed	**0** kts

All flight tests show that the aircraft is stable (statically) !

Static Longitudinal Stability

CS 23.173 –CS 23.175

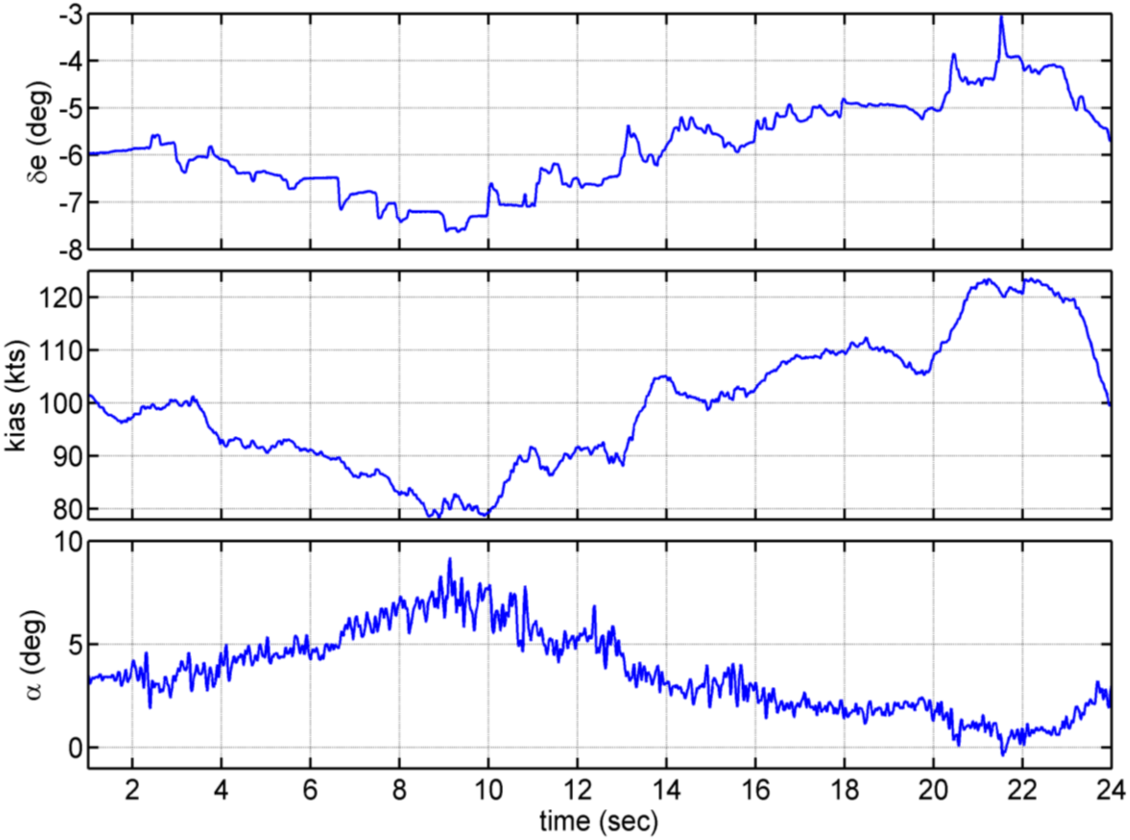
it must be demonstrated that:

1. “a pull must be required to obtain and maintain speeds below the specified trim speed, and a push required to obtain and maintain speeds above the specified trim speed”

2. “the airspeed must return to within 10% of the original trim speed when the control force is slowly released from any trim speed”.

3. a stable slope of stick force is required

V_trim = 100 kts
Clean configuration
Level flight

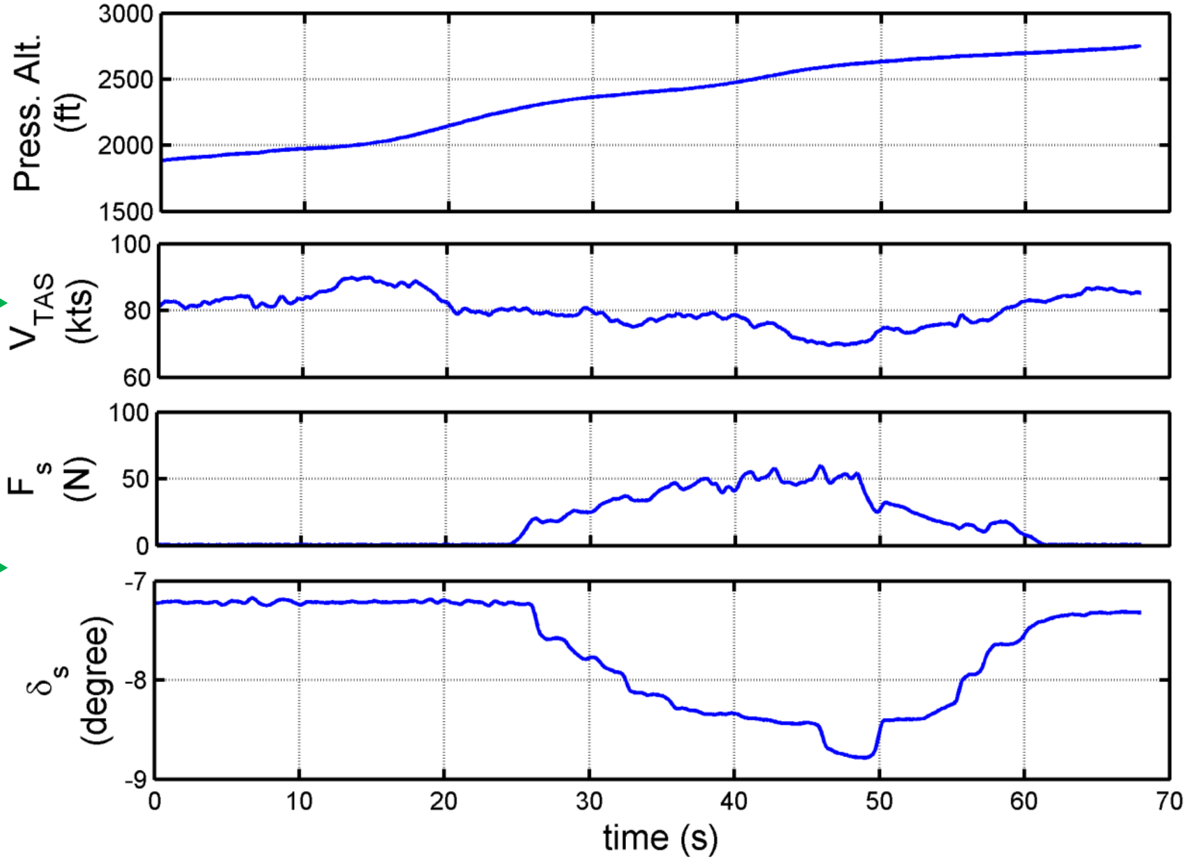


Static Longitudinal Stability

Demonstration of Static Longitudinal Stability: example during a climb

Speed returns to the trimmed speed (<10%)

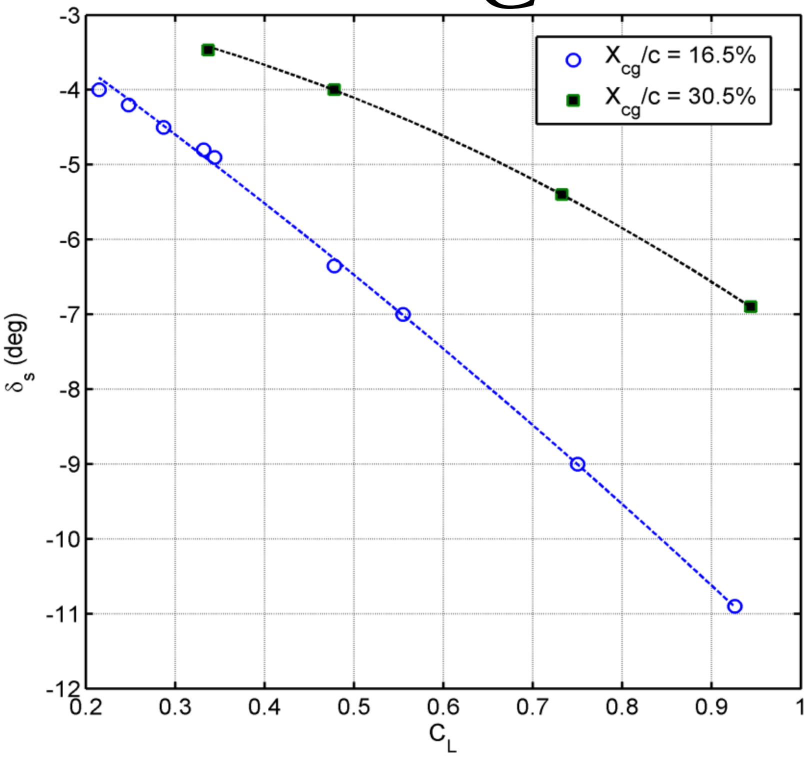
Stable slope of stick-force curve

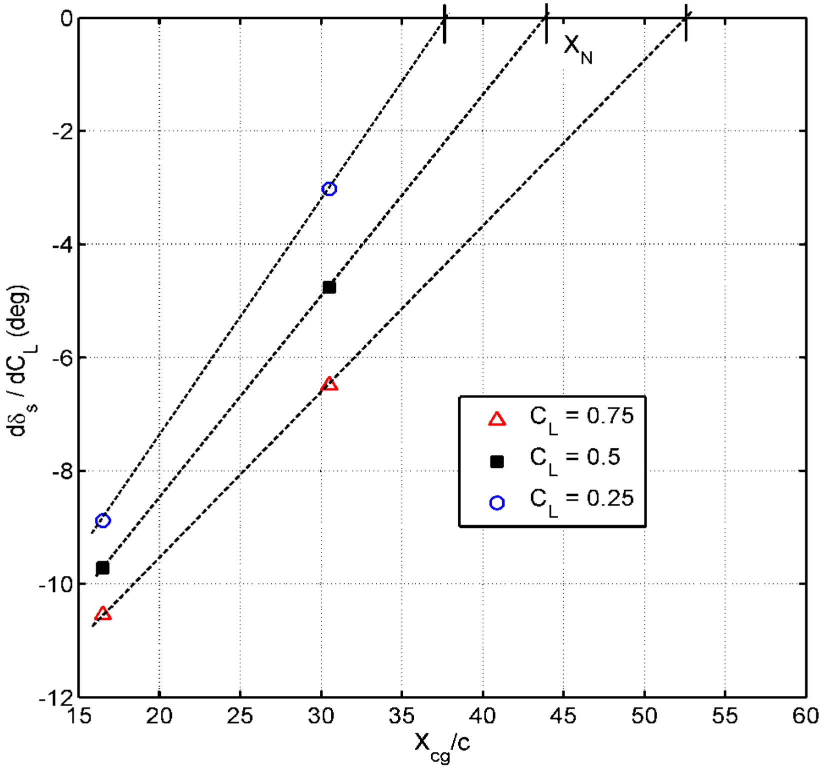


Neutral point

$$\left(\frac{dC_{M_{c.g.}}}{dC_L}\right) = \frac{X_{c.g.}}{\overline{C}} - N_0$$

$$\frac{d\delta_s}{dC_L} = \frac{(dC_M / dC_L)_{fixed}}{C_{M_{\delta_s}}}$$





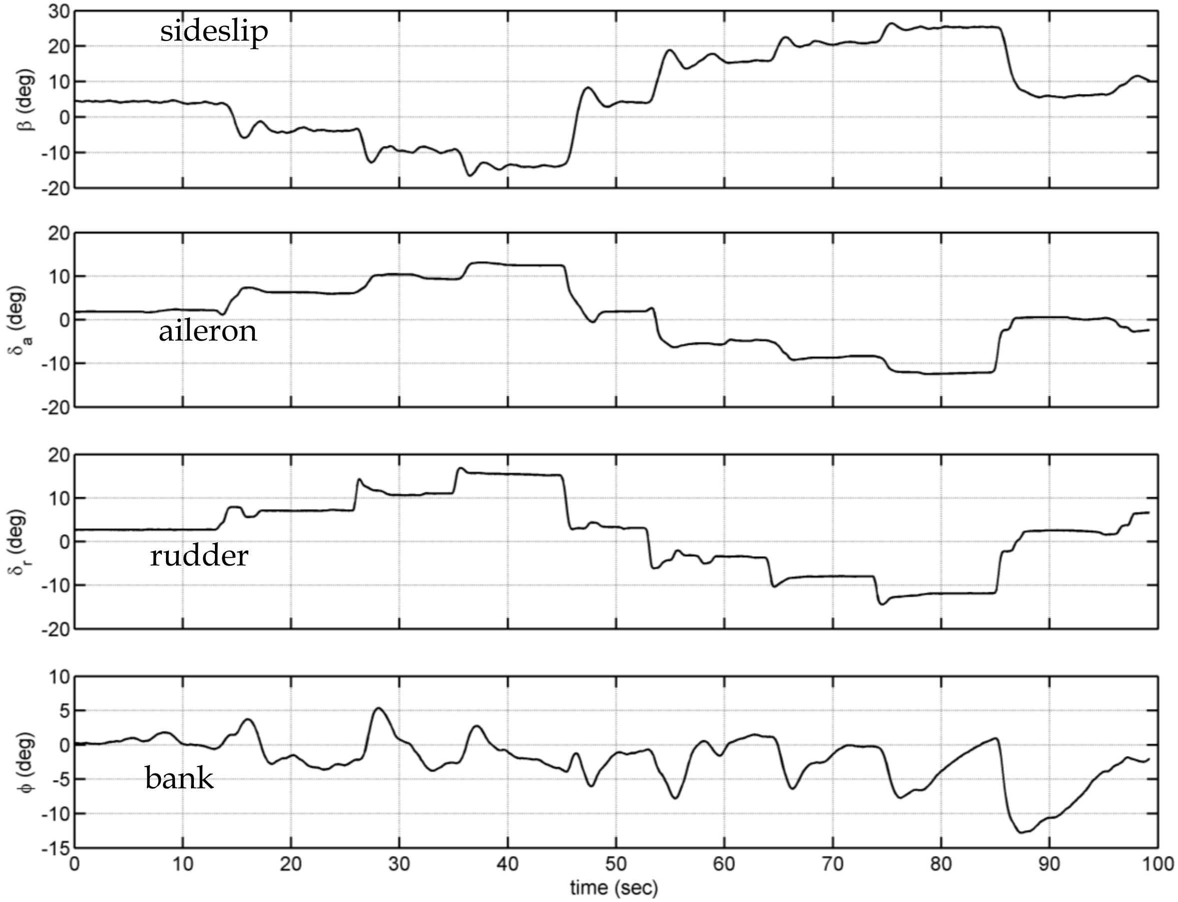
Neutral point position
Stick-fixed

CL = 0.75	CL = 0.5	CL = 0.25
59%	**44%**	37%

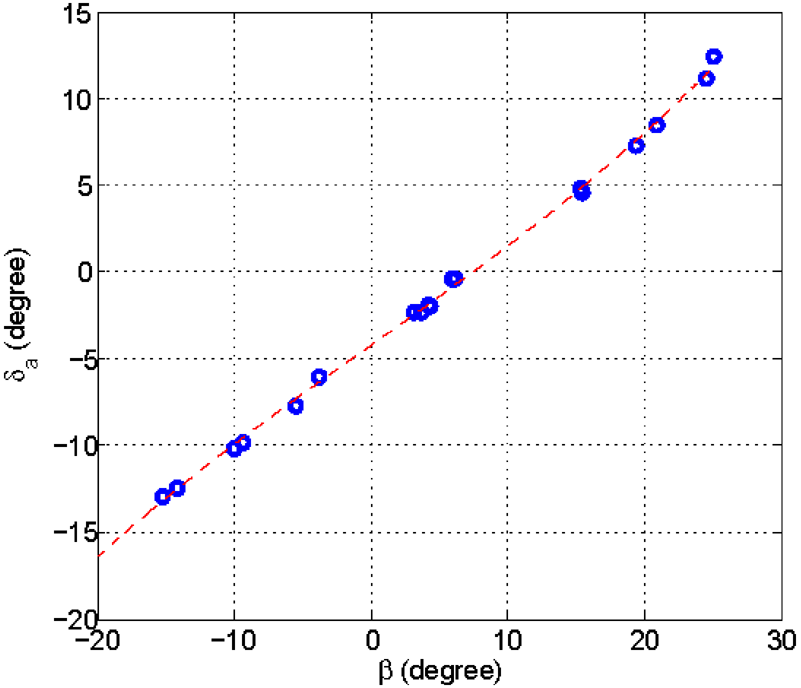
Static lateral-directional stability

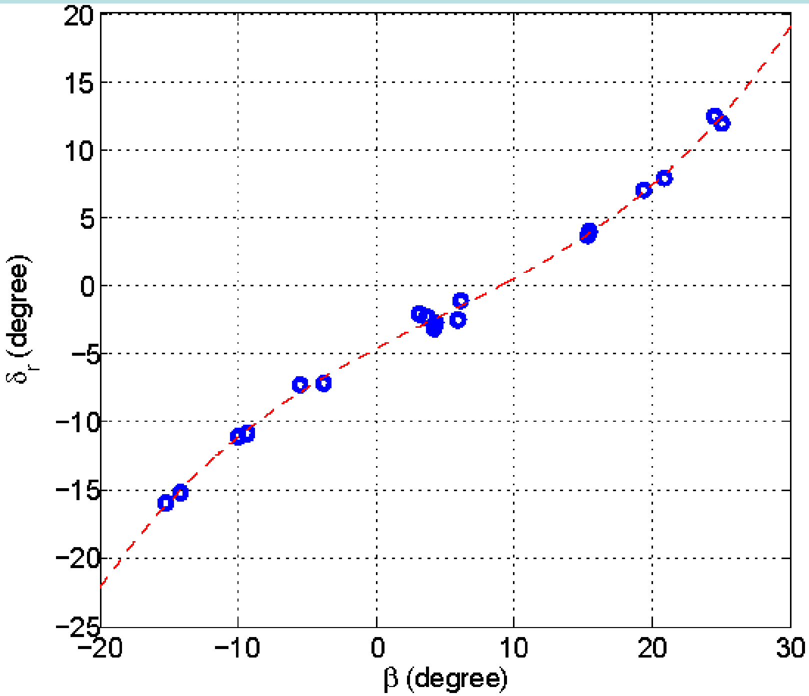
Steady-heading sideslip

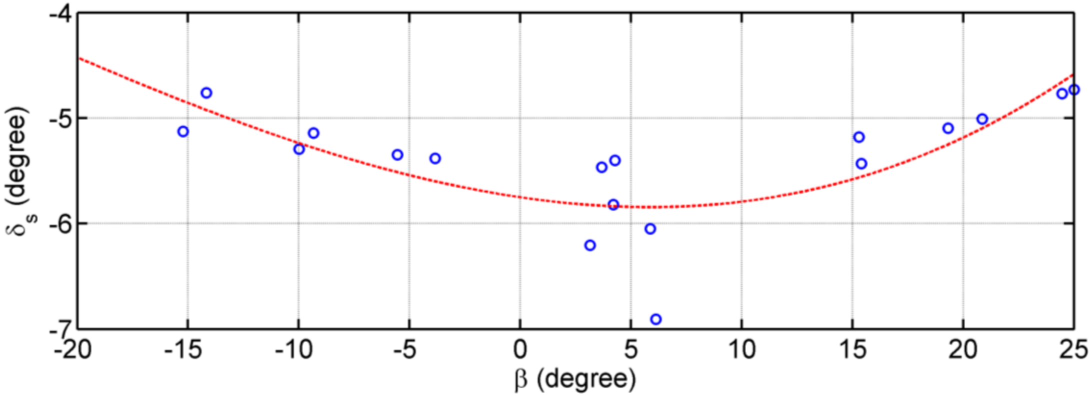
Aircraft must be stabilized, with wing leveled at higher sideslip angles with ailerons and rudder control, without particular elevetor control variation



Static lateral-directional stability

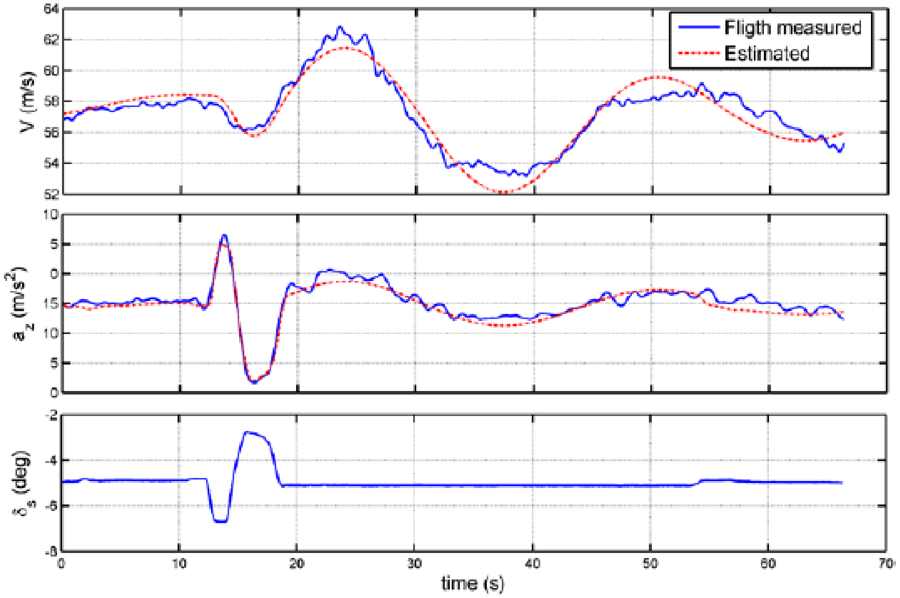






- DYNAMIC STABILITY

- SYSTEM IDENTIFICATION



Aircraft Dynamic Stability

-Longitudinal dynamic stability

1) **Short period** → well damped , oscillation in **α**
2) **Phugoid** → slightly damped, osclillation in altitude

-Lateral directional dynamic stability

1) **Roll** → well damped, not oscillatory
2) **Spiral** → almost neutral, very slow motion
3) **Dutch roll** → damped, combination in roll and yaw

Manoeuvers to excite the aircraft motion

- It is essential that the dynamic response exhibits frequency and damping of the oscillatory modes.

- It is recommended to start each manoeuvre from a trimmed level flght, and allow 5-6 s before applying a specif inputs, and, depending upon the mode of motion, to allow sufficient time after the input to allow the aircraft to ascillate.

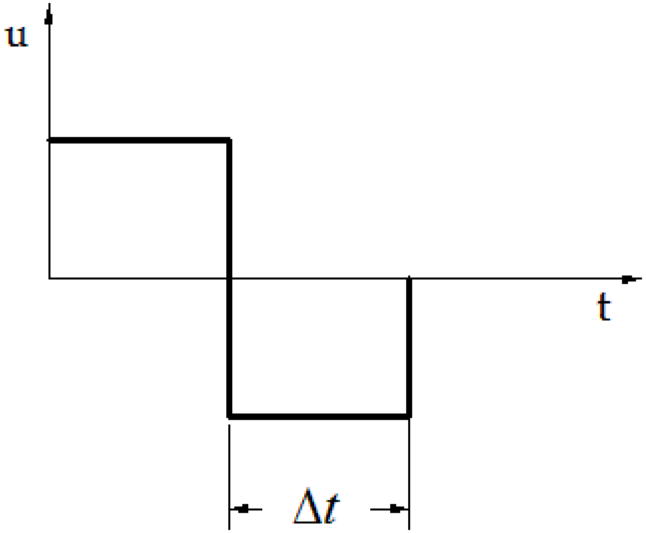
Manoeuvers to excite the aircraft motion

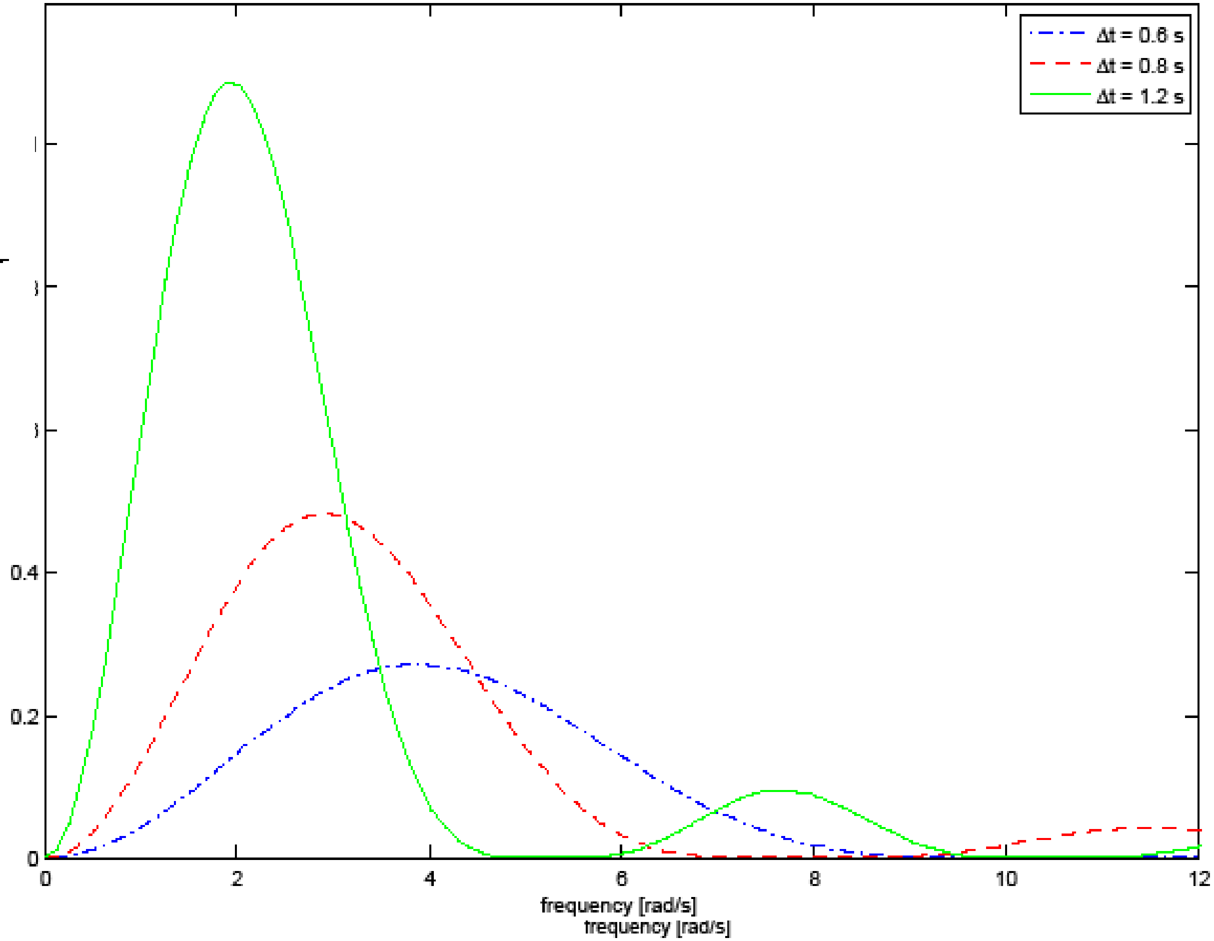
- Engineering approach
  - *multistep input signals based on the frequency content*

$$E(\omega) = 2\Delta t^2 \frac{1-\cos\Omega}{\Omega^2}\left[\sum_{i=1}^{N} V_i^2 + 2\sum_{j=1}^{N-1}\cos j\Omega \sum_{i=1}^{N-j} V_i V_{i+j}\right]$$

$E(\omega)$	energy spectrum
$\Omega = \omega\Delta t$	normalized frequency
$T = N\Delta t$	total duration of the input consisting of N impulses each of duration Δt
V_i	amplitude of for the current input

Manoeuvers to excite the aircraft motion

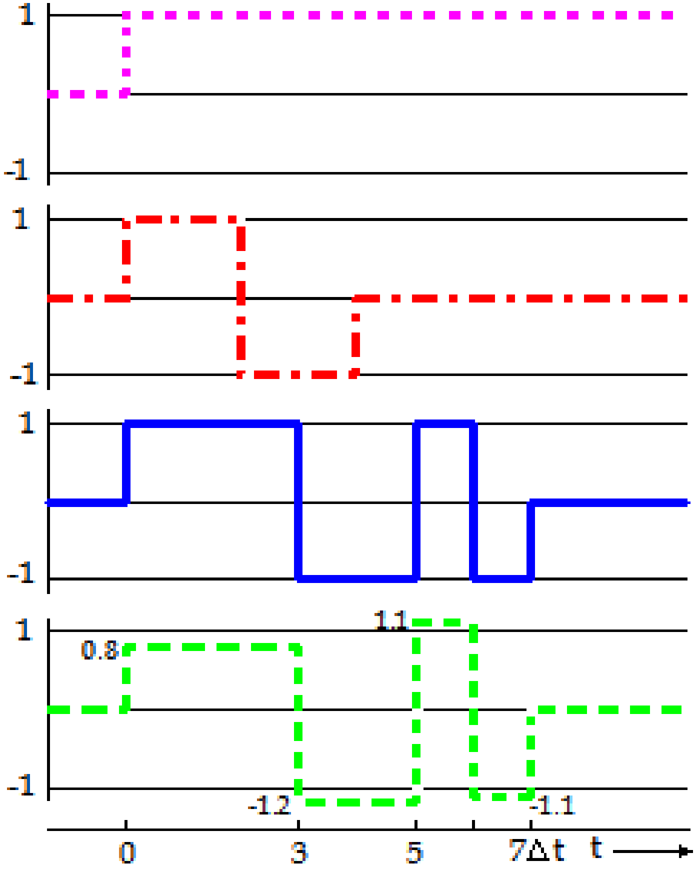


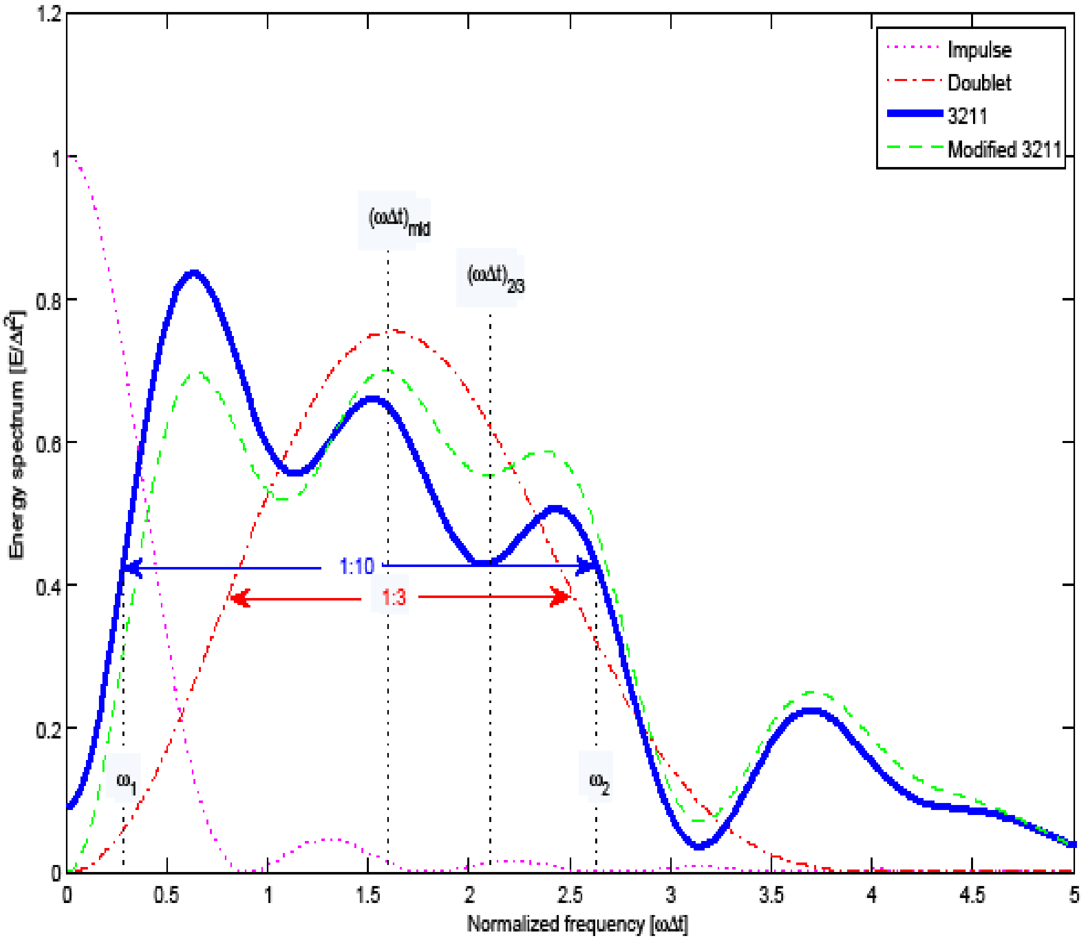


Suitable for
Phugoid(T = 25-30 sec.
f =0.2-0.3 rad/sec

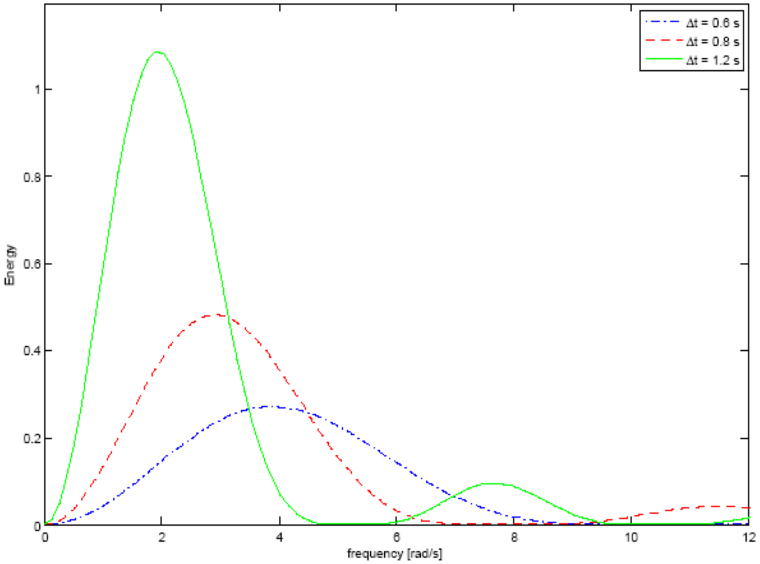
Suitable for
Short Period= 2-3 sec.
f =2-3 rad/sec)

Manovre per l'Identificazione Parametrica di un velivolo





Manoeuvres to excite aircraft motion



STEP ?

$$\omega_n \Delta t_{DBLT} \approx 2.3 \longrightarrow$$

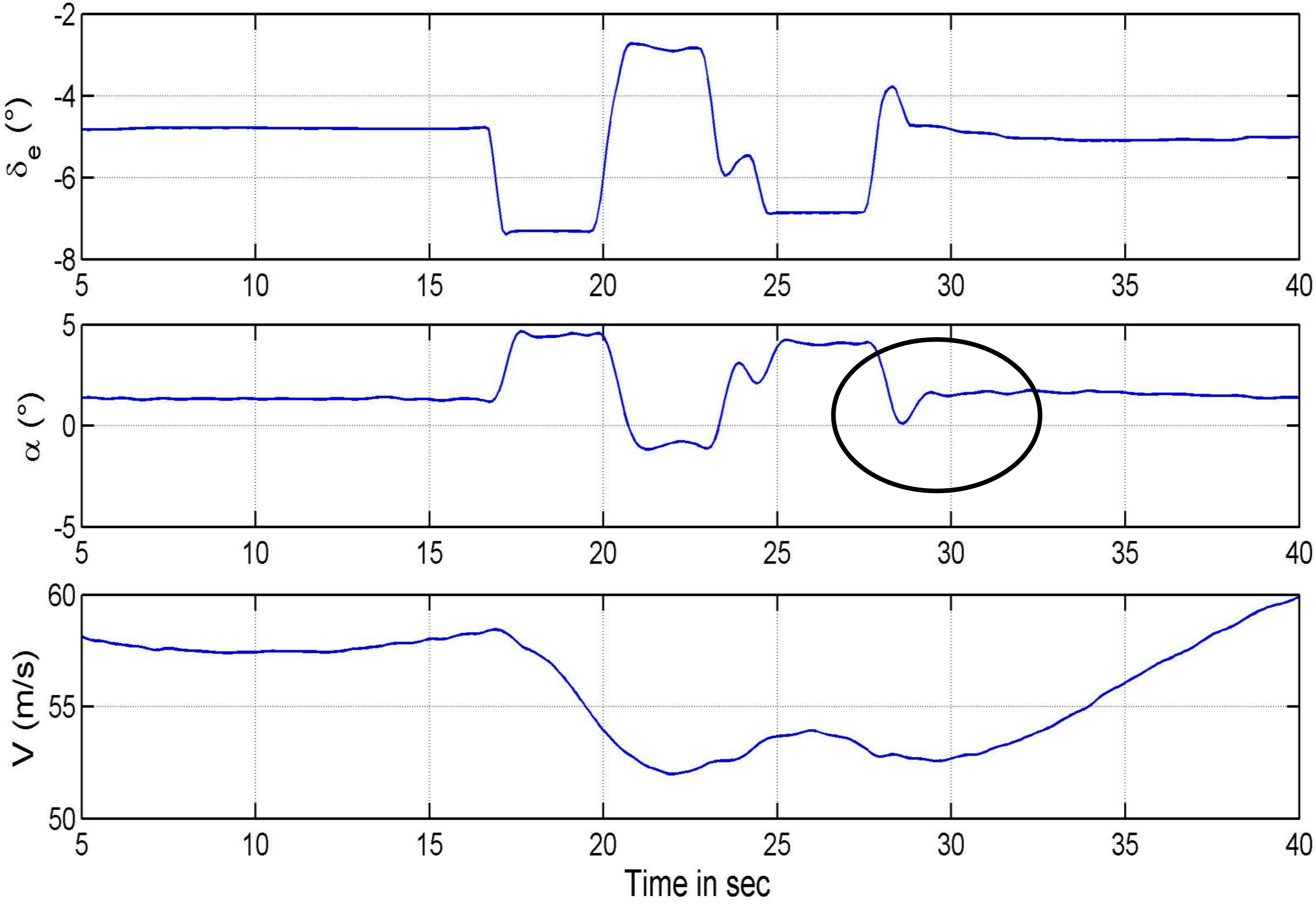
$$\Delta t_{DBLT} \approx \frac{2.3}{\omega_n} \approx \frac{2\pi}{2.7\omega_n} \approx \frac{1}{2.7} \cdot oscill.Period$$

→ $\Delta t\_{\mathrm{DOUBLET}}$ = 1/2.7 * Period of oscillation

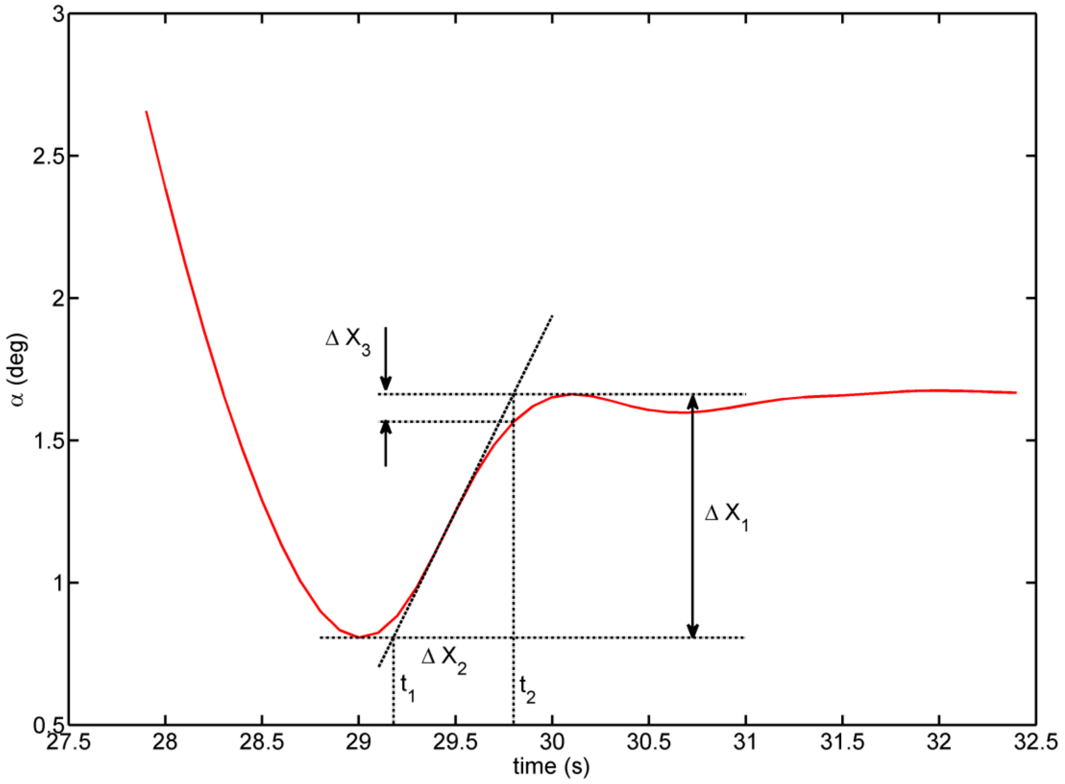
→ Δt_{3211} = 1/4 * Period of oscillation

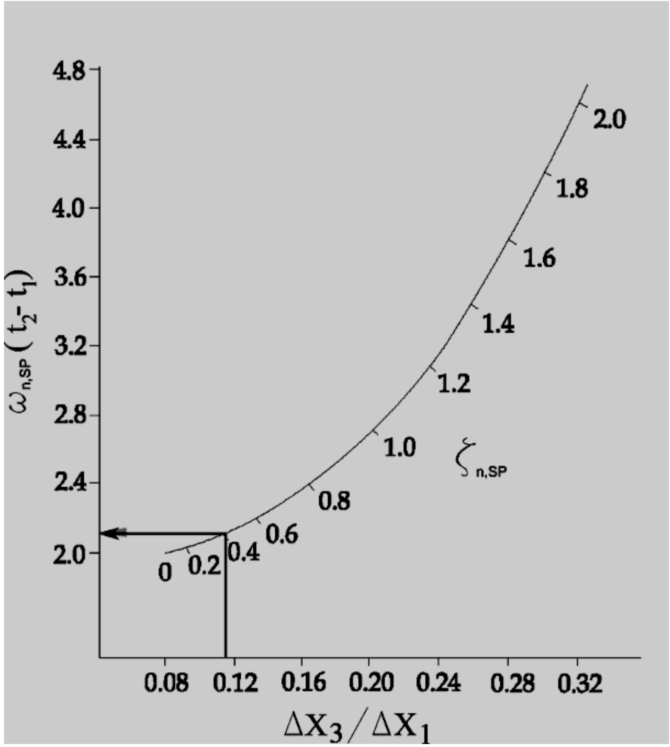
→ $\Delta t\_{\mathrm{SINGLE\_Impulse}}$ = 1/6 * Period of oscillation

Short Period - Time Histories & data reduction



Short period mode evaluation



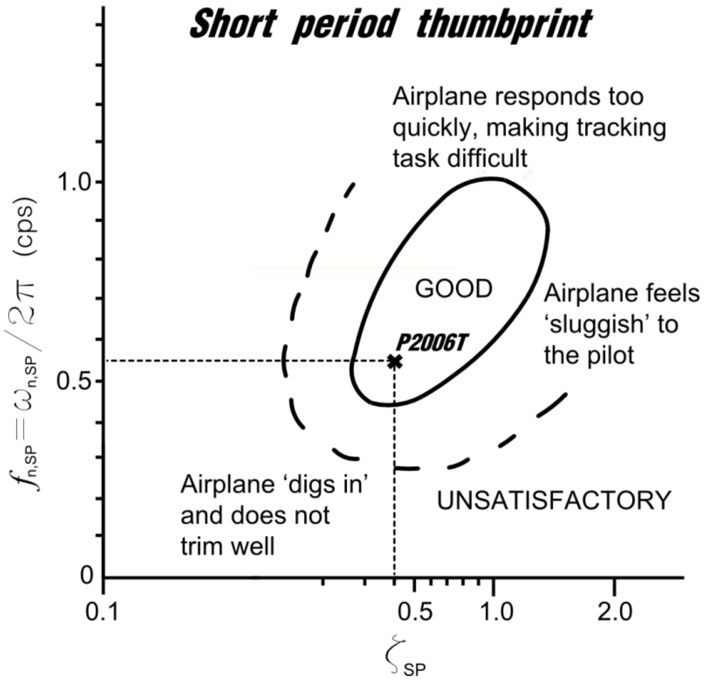


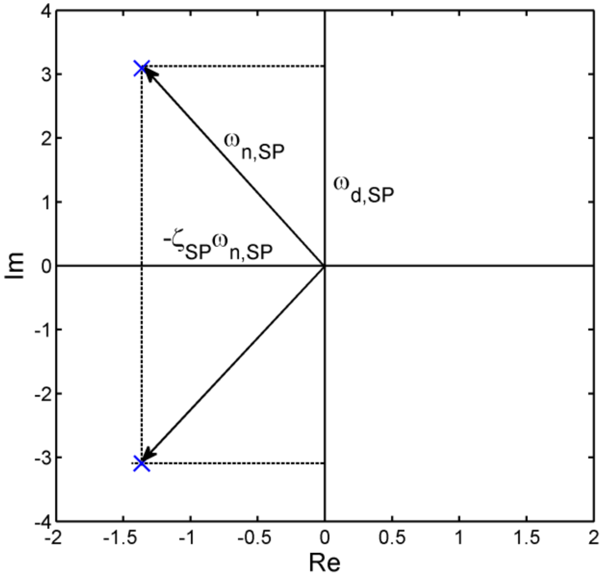
Typical short period response angle-of-attack time history, as a response to a ‘3-2-1-1-type’ stabilator input

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)

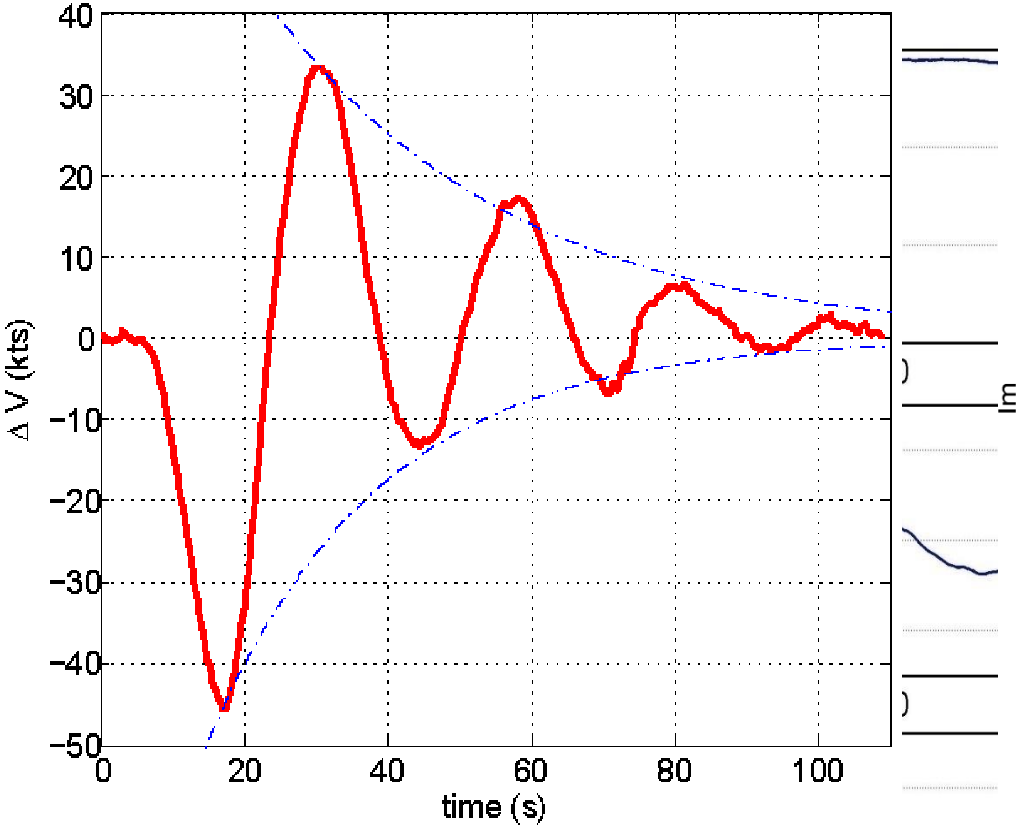
Time constant, τ_{SP}	0.0088 s
Damping ratio, ζ_{SP}	0.40
Damped pulsation, $\omega_{d,SP}$	3.125 rad/s
Damped period, T_{SP}	1.84 s
Natural pulsation, $\omega_{n,SP}$	3.410 rad/s
Natural frequency, $f_{n,SP}=\omega_{n,SP} / 2\pi$	0.54 cps

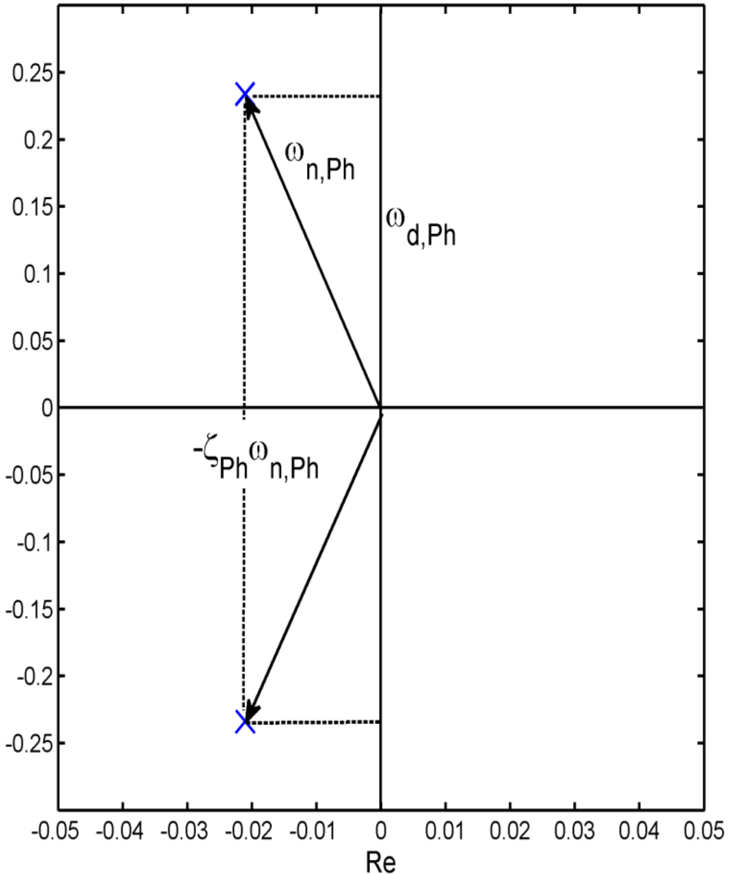
$$\tau_{SP} = -1 \,/\, Z_\alpha = m \,/\, (\, Q_0\, S\, C_{L\alpha} \,)$$

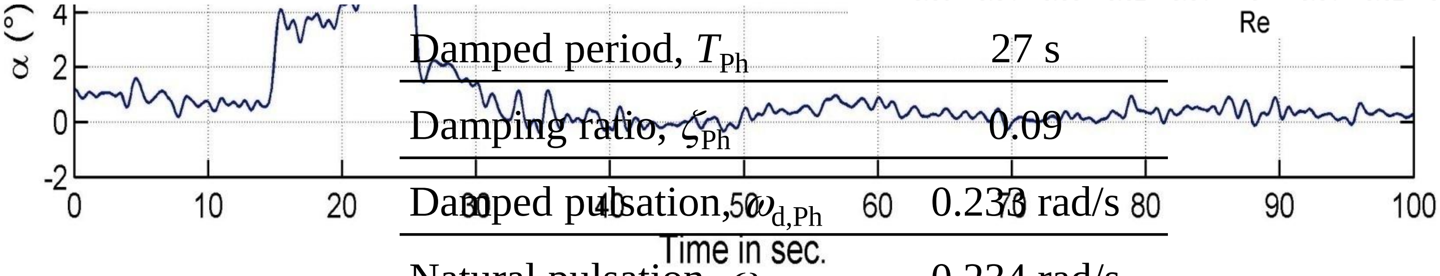
$$\text{CAP} = \omega_{n,SP}^2 \,/\, n_\alpha \approx mg\, \omega_{n,SP}^2 \,/\, (\, Q_0\, S\, C_{L\alpha} \,) = 1.009$$

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

Phugoid **-** Time Histories & data reduction



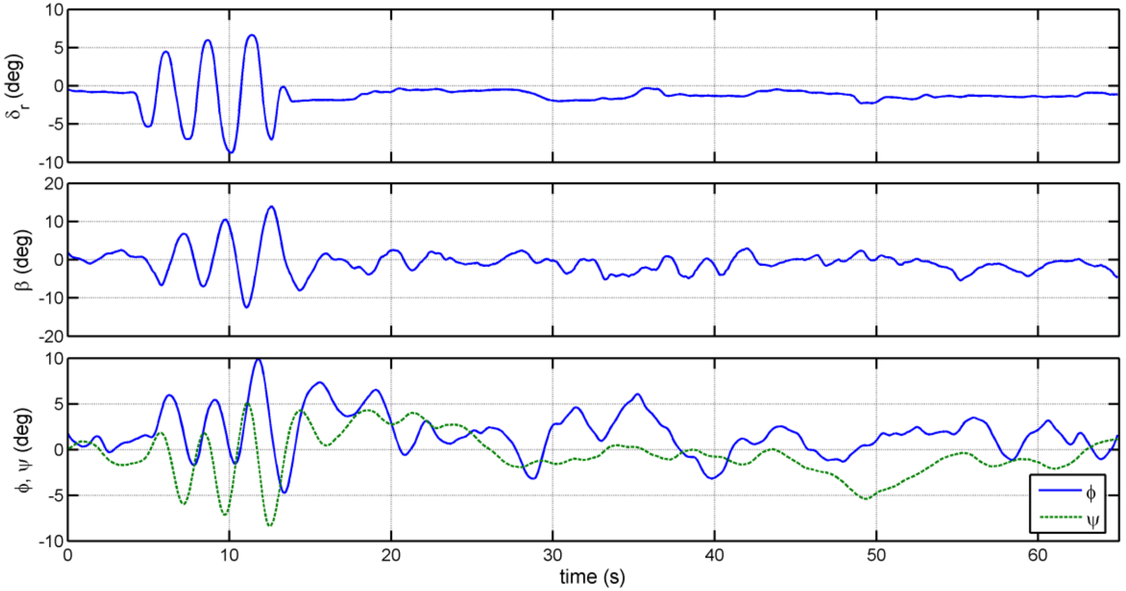




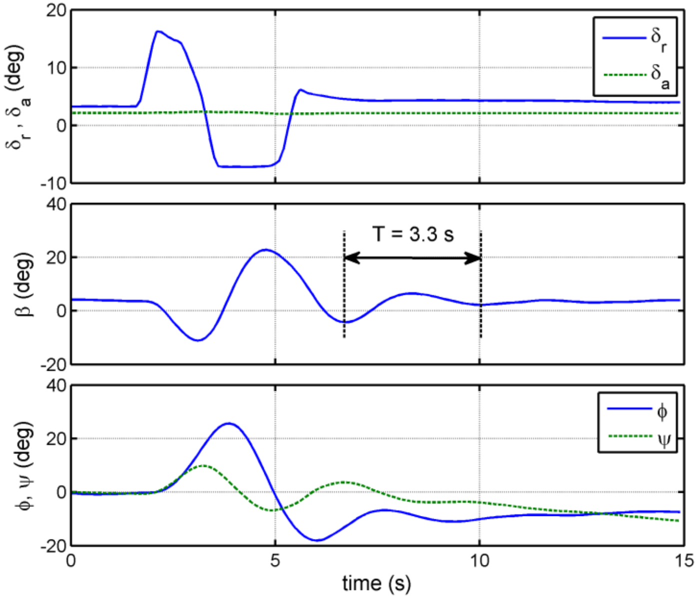
Damped period, T_{Ph}	27 s
Damping ratio, ζ_{Ph}	0.09
Damped pulsation, $\omega_{d,Ph}$	0.233 rad/s
Natural pulsation, $\omega_{n,Ph}$	0.234 rad/s

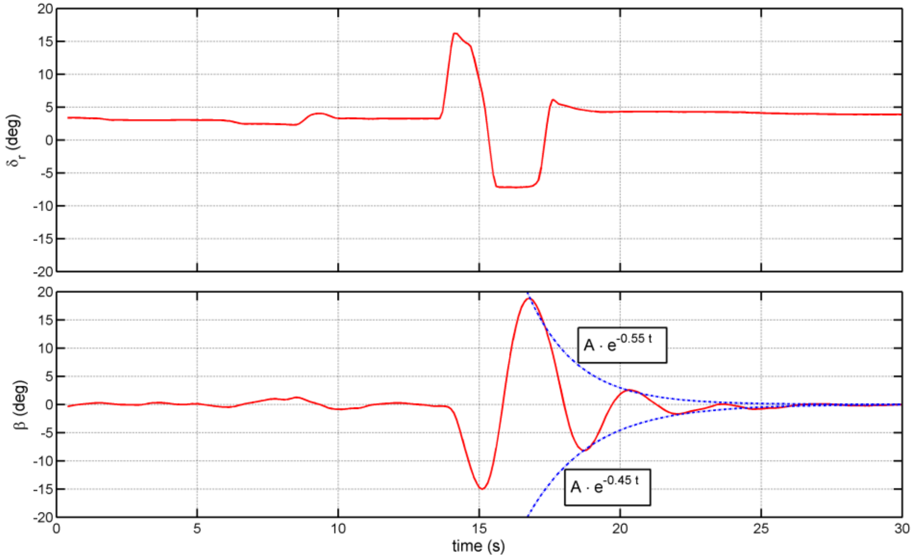
Dutch roll mode evaluation

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

System Identification

- Detemining the characteristics of a system(the aircraft) through a series of

BASIC PARAMETERS

System Identification -Approach

- Numeric (CFD – Semiempirical Formulas)
- Sperimental(Wind tunnel tests- Flight tests)

Sperimental Approach
Flight Tests

Model reconstruction through the aircraft flight tests measured response.

I fattori che determinano l'attendibilità dei parametri sono:

- **dati raccolti (*Data Gathering*)**
- **modello postulato (*Postulated Model*)**
- **algoritmo di analisi (*Output Error Method*)**

Data Gathering - Aspetti cruciali

- Affidabilità del Sistema di acquisizione
- Definizione dello scopo dei test
- Definizione di una opportuna sequenza di manovre da effettuare
- Scelta di una forma adeguata di input per eccitare il moto del velivolo in maniera ottimale

Modello postulato

- Modello nello Spazio degli Stati
- Equazione della dinamica del volo

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

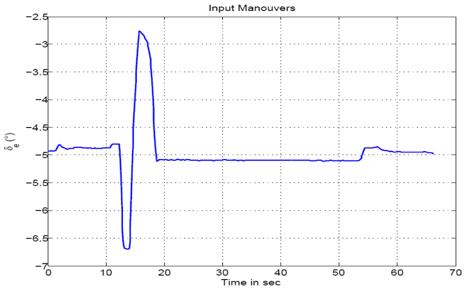
- Problema di valori iniziali

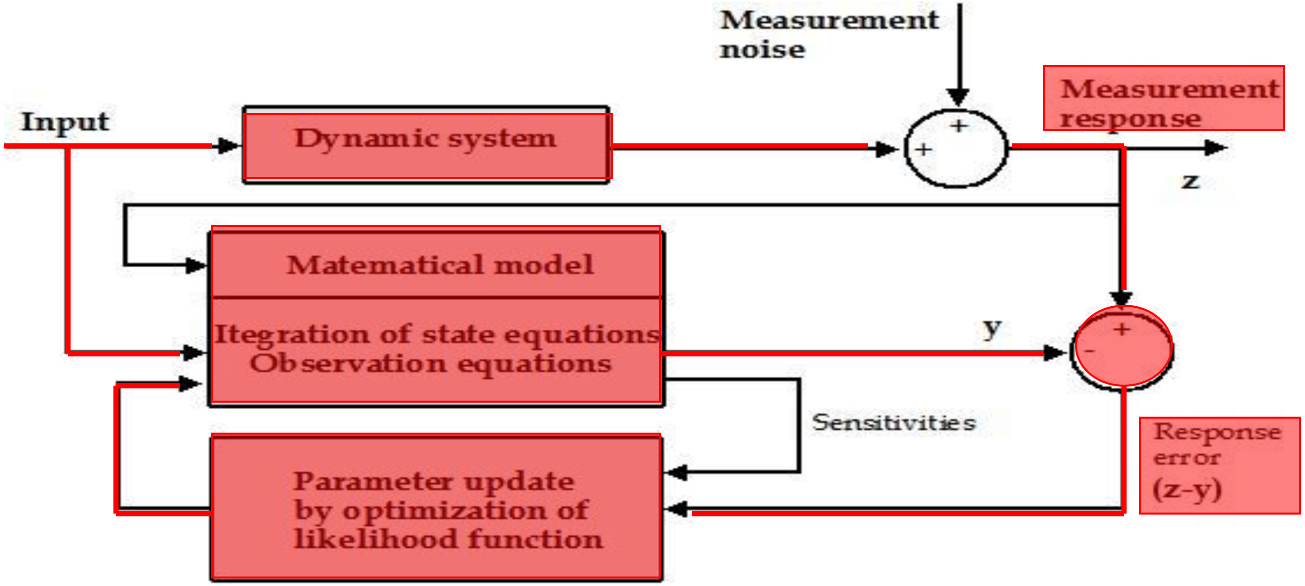
$$\{x(t=0)\} = \{x_0\}$$

- Metodo di Runge-Kutta al quarto ordine

Algoritmo di Analisi
Metodo di Output Error

Il codice utilizzato come post processing per l'Identificazione dei parametri del velivolo dalle prove dinamiche in volo è stato realizzato dal Prof. Ravindra V. Jategaonkar e si basa sul metodo OEM.





Measurement noise

Input

Dynamic system

Measurement response

z

Matematical model

Itegration of state equations
Observation equations

y

Sensitivities

Response error (z-y)

Parameter update by optimization of likelihood function

Algoritmo di Analisi
Principio della Massima Verosimiglianza

$$\left\{\dot{x}(t)\right\} = f\left(\{x(t)\},\{u(t)\},t\right), \qquad \{x(t=0)\} = \{x_0\}$$

$$\{y(t)\} = h\left(\{x(t)\},\{u(t)\},t\right)$$

$$\{z(t)\} = [C]\{x(t)\} + \{v(t)\}$$

L'esperimento dipende da k parametri $\underline{\Theta}_1, \underline{\Theta}_2, \ldots\ldots, \underline{\Theta}_k$ per i quali i valori osservati, contenuti nella matrice delle osservazioni **z**, sono i più probabili tra quelli stimati, a loro volta contenuti nella matrice delle variabili stimate **y**

matematicamente, bisogna massimizzare la *funzione di verosimiglianza* $p(z|\Theta)$

Algoritmo di Analisi Metodo di Output Error

IPOTIZZANDO CHE le osservazioni $\underline{z}_1, \underline{z}_2, \ldots\ldots, \underline{z}_k$

sono assunte variabili aleatorie statisticamente indipendenti.

Si può scrivere la funzione di verosimiglianza come

$$p(z|\Theta) = p(z_1|\Theta) \cdot p(z_2|\Theta) \cdot \ldots\ldots \cdot p(z_N|\Theta) = \prod_{k=1}^{N} p(z_k|\Theta)$$

Si passa al ln poiché accelera la convergenza essendo monotono

$$\frac{\partial \ln(p(z|\Theta))}{\partial \theta} = 0$$

Per il calcolo di $p(z|\Theta)$

Si definisce l'*innovazione* v all'istante t_k $v(t_k) = z(t_k) - y(t_k)$

Identificazione Parametrica delle Caratteristiche del Velivolo

Le fasi in cui si snoda il processo di stima dei parametri sono:

- scelta del modello di equazioni atto a descrivere il moto
- creazione della giusta sequenza di manovre e delle risposte misurate da fornire in ingresso
- determinazione dei parametri iniziali sulla base di analisi semiempiriche, analisi di galleria del vento
- determinazione dei parametri presenti nel modello base proposto dall'autore del codice di stima; si è quindi proceduto alla modifica del modello e alla stima dei parametri per gradi.
- esecuzione di una simulazione di verifica per ogni gruppo di parametri stimati, attraverso manovre di riserva per il moto longitudinale
- scelta dei parametri finali sulla base dei quali descrivere il modello finale del velivolo

Longitudinal model equations

State equations

$$\begin{cases} \dot{V} = \dfrac{QS}{m} C_D + g \sin(\alpha - \theta) + \dfrac{T}{m} \cos(\alpha + \sigma_T) \\[2ex] \dot{\alpha} = \dfrac{QS}{mV} C_L + q + \dfrac{g}{V} \cos(\alpha - \theta) + \dfrac{T}{mV} \sin(\alpha + \sigma_T) \\[2ex] \dot{\theta} = q \\[2ex] \dot{q} = \dfrac{QSc}{I_{yy}} C_M + \dfrac{T}{I_{yy}} (\ell_{T,x} \sin\sigma_T + \ell_{T,z} \cos\sigma_T) \end{cases}$$

Observation equations

$$\begin{cases} V_{\mathrm{m}} = V \qquad \alpha_{\mathrm{m}} = \alpha \qquad \theta_{\mathrm{m}} = \theta \qquad q_{\mathrm{m}} = q \\[2ex] \dot{q}_{\mathrm{m}} = \dfrac{QSc}{I_{yy}} C_M + \dfrac{T}{I_{yy}} (\ell_{T,x} \sin\sigma_T + \ell_{T,z} \cos\sigma_T) \\[2ex] a_{x\,\mathrm{m}} = \dfrac{Q\,S}{m} C_X + \dfrac{T}{m} \cos\sigma_T \\[2ex] a_{z\,\mathrm{m}} = \dfrac{QS}{m} C_Z + \dfrac{T}{m} \sin\sigma_T \end{cases}$$

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

state variables: V, α, θ, q

Inputs: δ_s, T (constant)

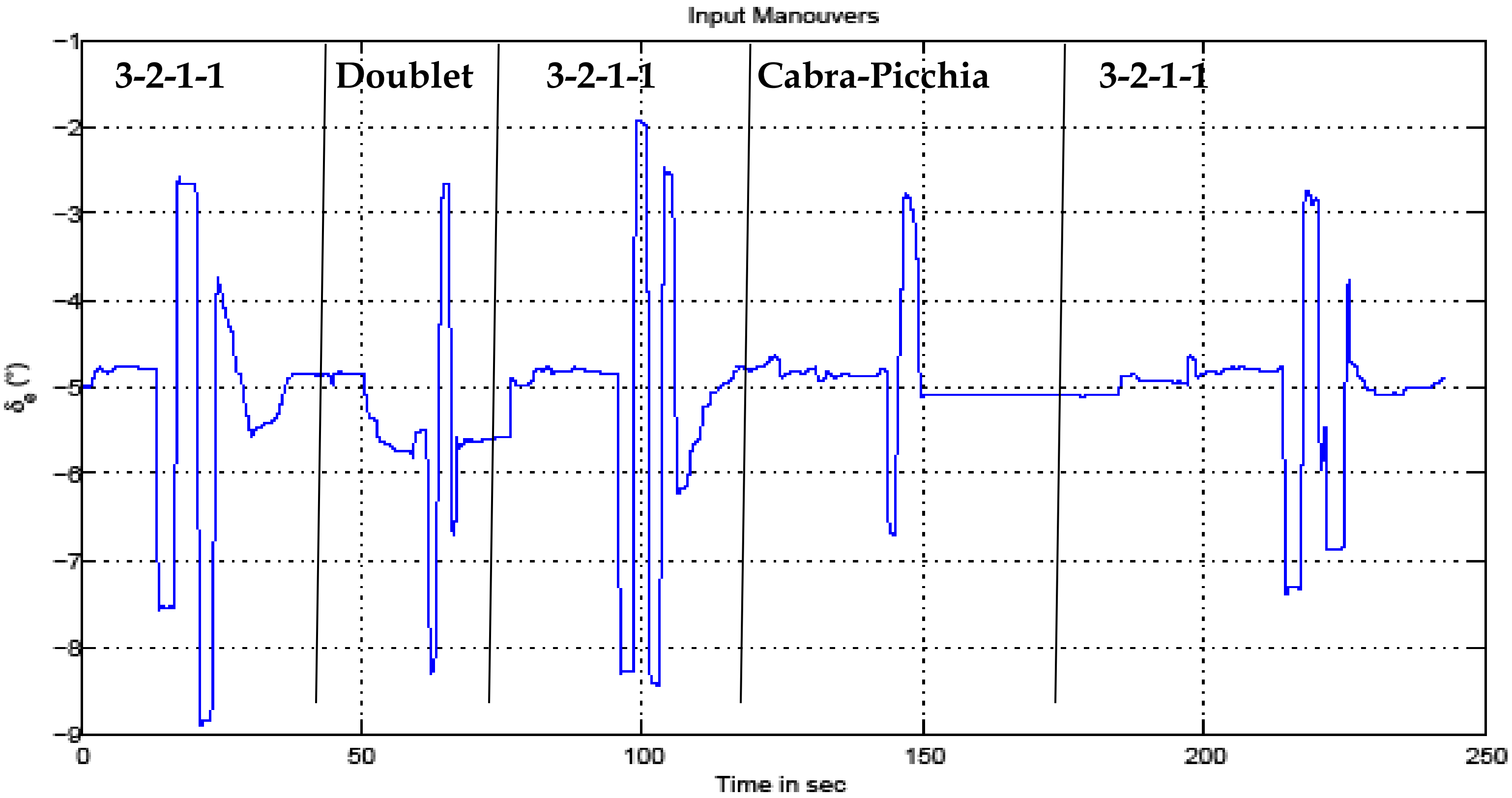
Aerodynamic model:

$$C_D = C_{D0} + C_{D\alpha}\alpha \qquad C_L = C_{L0} + C_{L\alpha}\alpha \qquad C_M = C_{M0} + C_{M\alpha}\alpha + C_{Mq}\frac{qc}{2V_0} + C_{M\delta_s}\delta_s$$

Unknown parameters:
(longitudinal)

$$\Theta_{\mathrm{lon}} = \left[C_{D0},\ C_{D\alpha},\ C_{L0},\ C_{L\alpha},\ C_{M0},\ C_{M\alpha},\ C_{Mq},\ C_{M\delta_s} \right]$$

Manovre concatenate
Caratteristiche Longitudinali del P2006T



Scelta delle condizioni iniziali e dei parametri iniziali

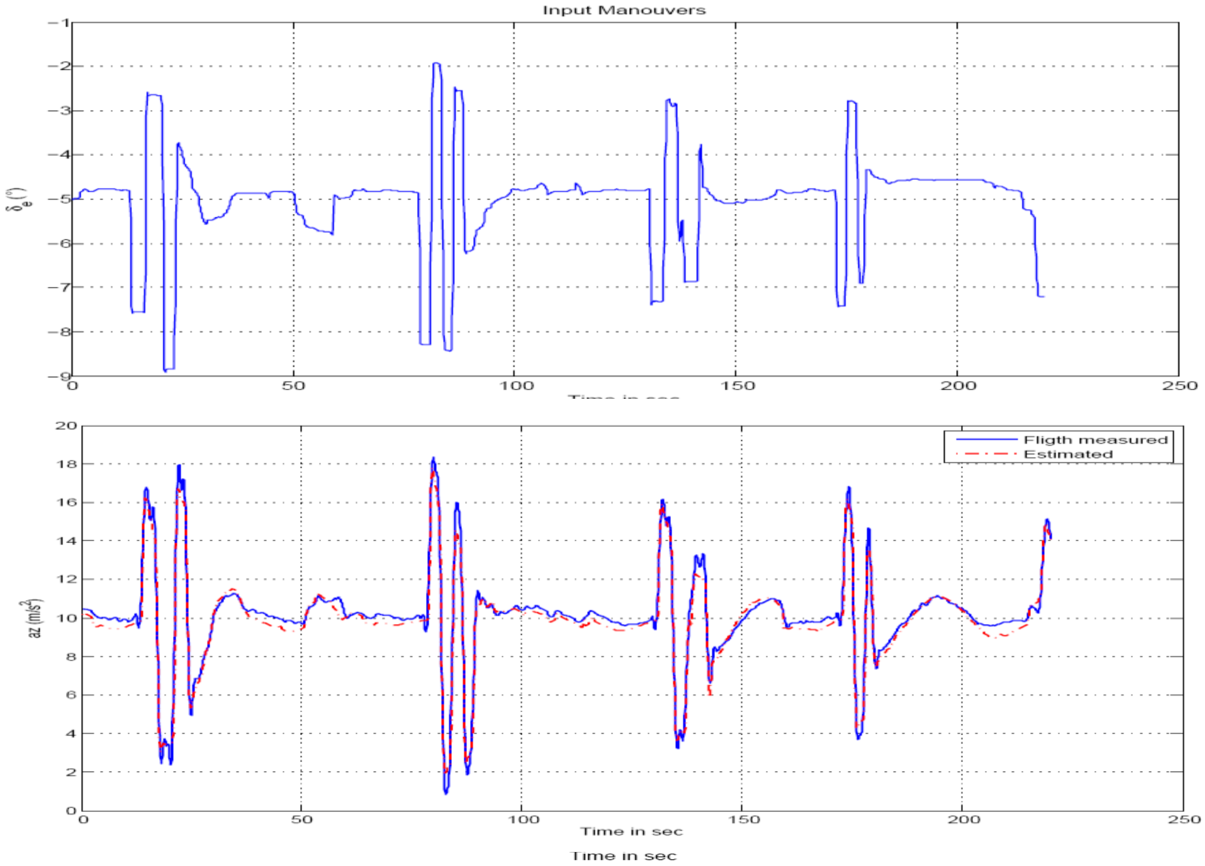
Per la risoluzione del sistema di equazioni differenziali e per l’utilizzo corretto del software del prof. Ravindra V. Jategaonkar occorre

- imporre delle condizioni iniziali, x_0
- imporre dei valori iniziali ai parametri incogniti, Θ

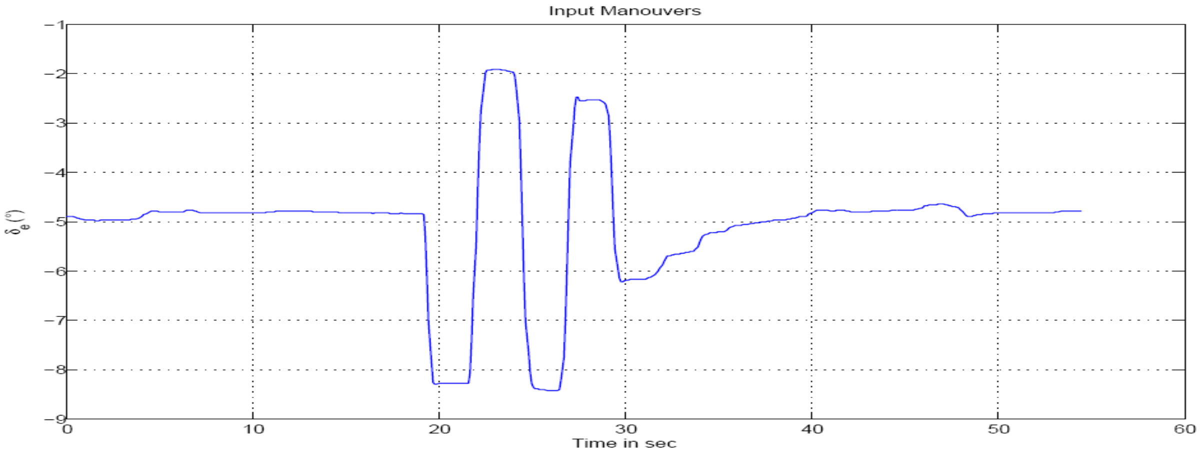
Questi parametri non possono essere scelti in maniera arbitraria, infatti questo comporterebbe una crisi nel codice proposto. È necessario quindi

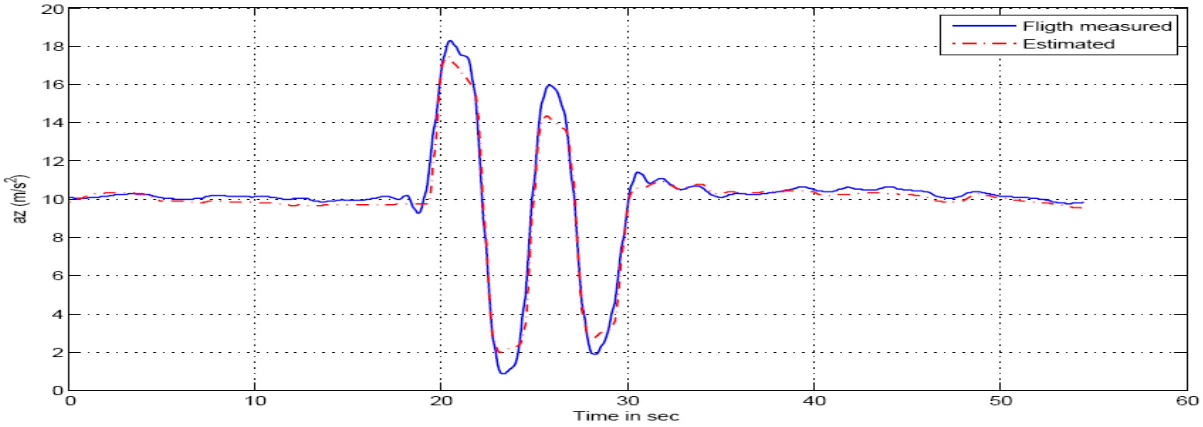
- un’analisi preliminare delle condizioni di volo di inizio manovra (che permettono una corretta stima delle condizioni iniziali),
- la ricerca di un set di parametri che si avvicinano a quelli del velivolo in esame.

Confronto dati misurati – dati stimati

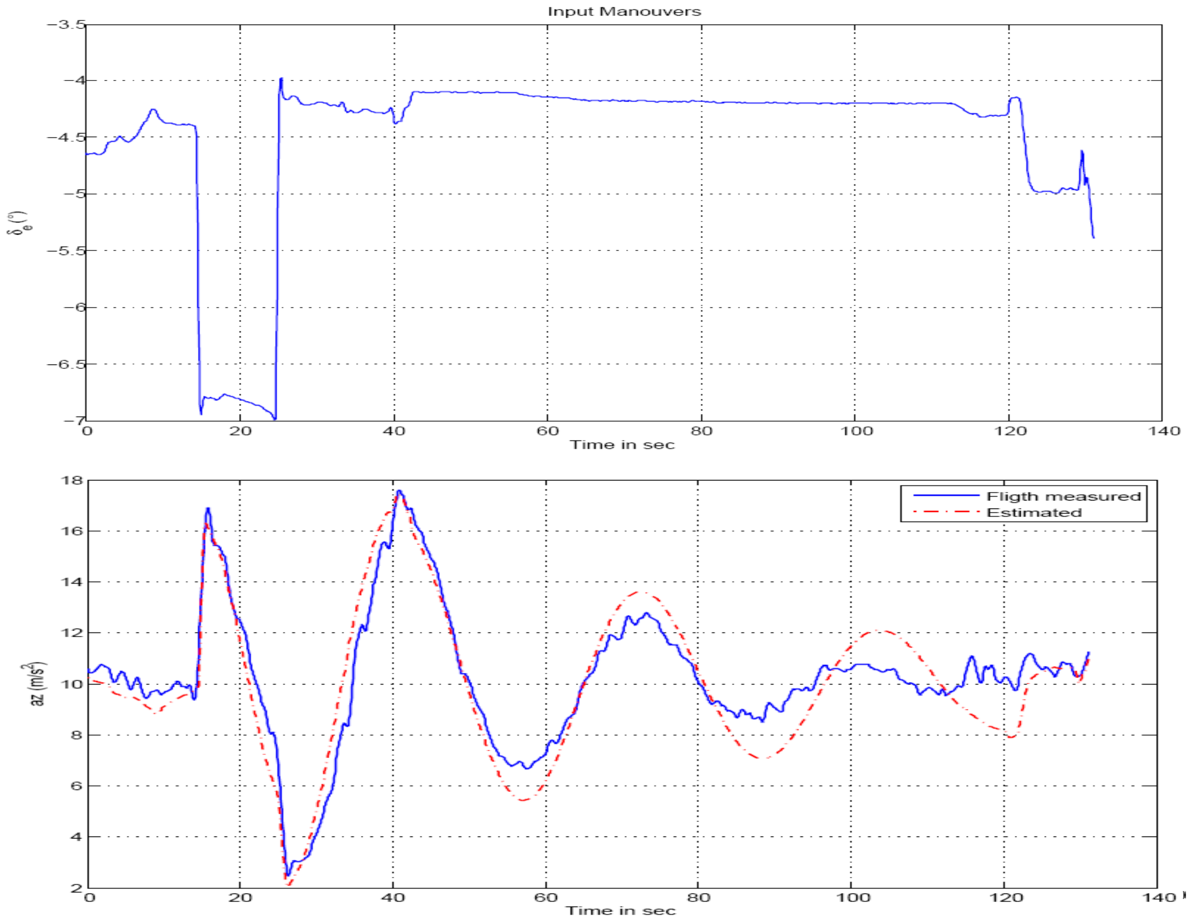


Confronto di verifica dati misurati – dati stimati Manovra 3-2-1-1

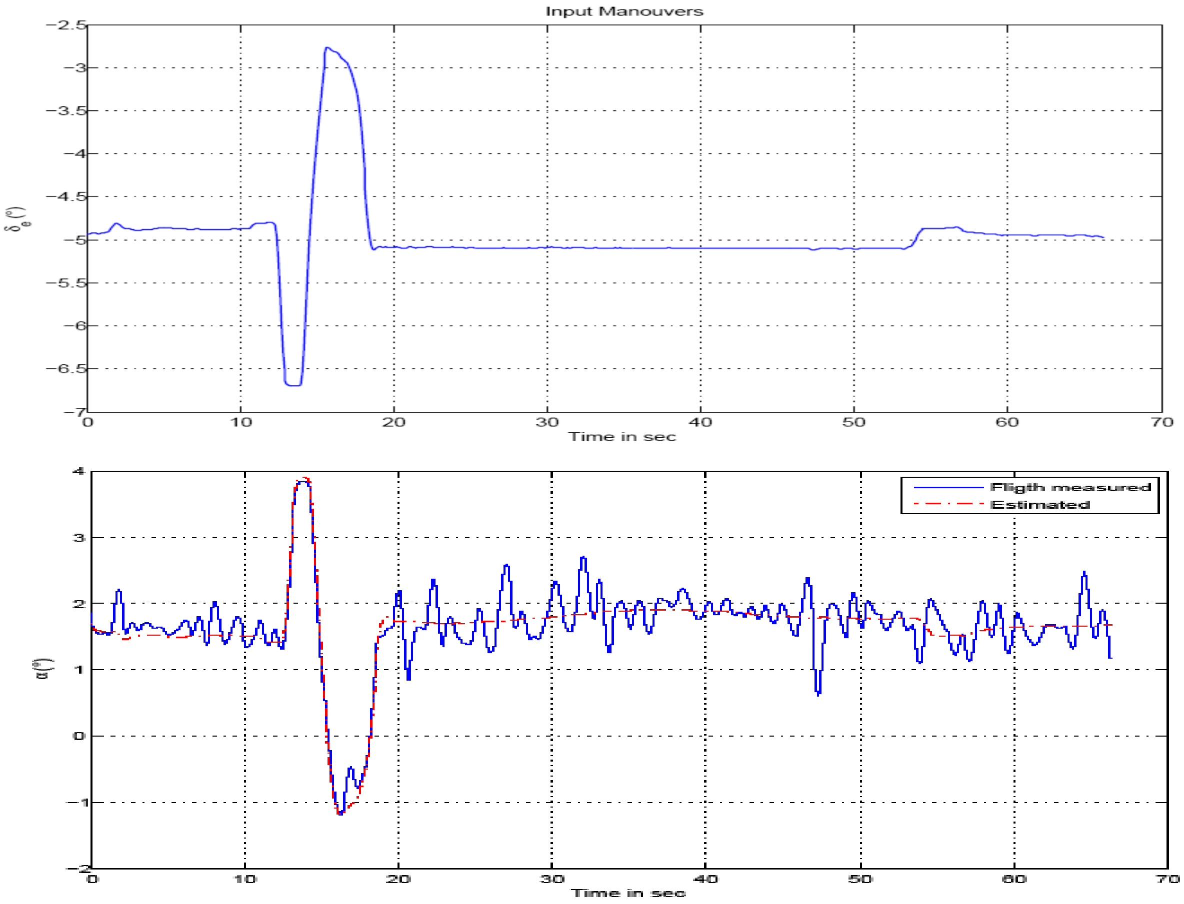




Confronto di verifica dati misurati – dati stimati
Manovra Impulso



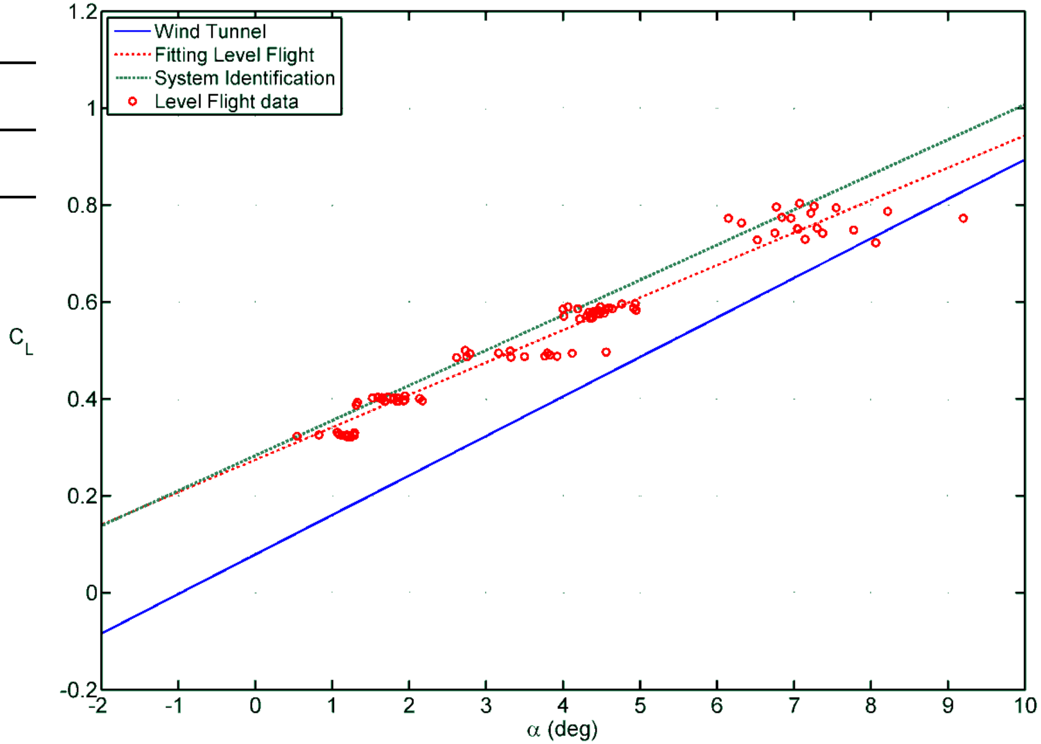
Confronto di verifica dati misurati – dati stimati
Manovra Cabra-Picchia



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

Next Generation – P2012 Traveller

- 12 seater
- CS 23 Ref.
- twin engine

ACTIVITY ON

- WT Tests

- Flight Simulation

info:
agostino.demarco@unina.it
fabrizio.nicolosi@unina.it
pierluigi.dellavecchia@unina.it