Aeronautical Society Of South Africa
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John Weston Memorial Lecture

Wind Tunnel Testing - A Career at High Speed - While Standing Still! 1990-2022

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Touching lives through innovation

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- Introduction
- John Weston
- Wind Tunnel Testing Basics
- Wind Tunnel Types
- Wind Tunnel Processes
- Wind Tunnel Balances
- Model Design and Procurement
- Test Types and Data

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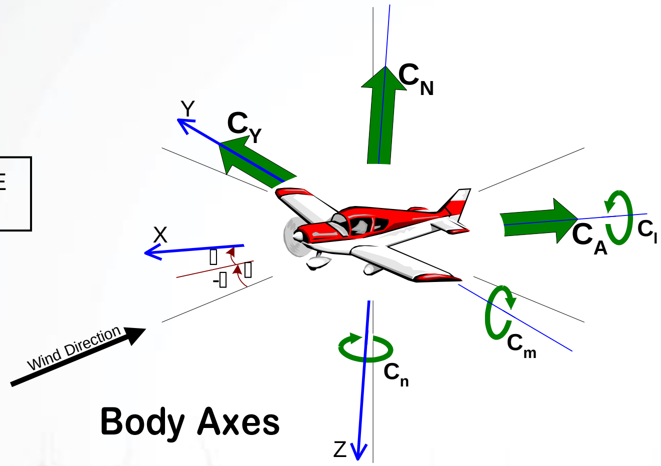
John Weston (1872–1950)

- Born: Maximillian, John Ludwick Weston
  - South African aeronautical engineer, pioneer aviator, farmer and soldier (en.Wikipedia.org)
  - Eclectic engineer, pioneer aviator, farmer, family man, soldier, globetrotter and overland traveller..in a caravan. (www.johnwestonaviator.uk)
  - He travelled extensively in a motor caravan (RV) that he designed and built himself. Weston was a pioneer of aviation in South Africa.
  - In 1911, Weston founded the Aeronautical Society of South Africa.
  - The Society hosts a bi-annual memorial lecture in his honour.

Wind Tunnel Testing Basics

AXIS AND REFERENCE CONVERSIONS



$$C = \frac{F}{qS}$$

$$C = \frac{M}{qS\ell}$$

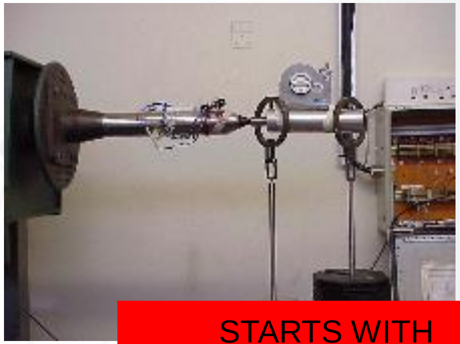
F= MEASURED FORCE

M= MEASURED MOMENT

Q= DYNAMIC PRESSURE

S= REFERENCE AREA

L= REFERENCE LENGTH



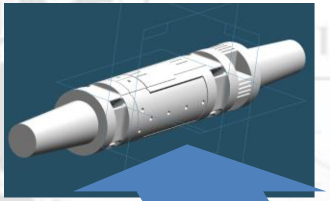
BALANCE MATRIX OBTAINED FROM WEIGHT CVALIBRATION PROCEDURE

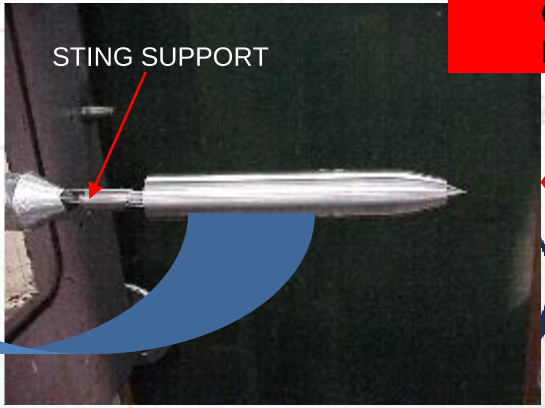
STARTS WITH CALIBRATION OF EQUIPMENT

Mv CONVERTED TO EU USING CALIBRATION MATRIX

NF	PM	SF	YM	RM	AF
43.8651	-0.27483	-1.66294	-1.71001	0.106575	0.806483
0.026485	0.844088	0.007516	-0.03652	-0.00691	-0.00201
0.99064	0.937745	43.18934	0.193615	0.552728	-0.05357
-0.00062	0.020417	0.022742	0.88596	0.003596	0.0094
1.225398	0.770396	0.186203	0.104531	43.6478	0.207634
-0.00908	0.008156	-0.01725	0.030446	0.001644	0.508367

BALANCE CALIBRATION MATRIX





BALANCE OUTPUT IN mv

LOAD MEASURING BALANCE

Wind tunnel testing basics

- Frank H. Wenham (1824-1908) credited with designing and operating the first wind tunnel in 1871
  - Member of the Aeronautical Society of Great Britain
- Wright Brothers conducted wind tunnel experiments in an upgraded wind tunnel in 1901, which led to the understanding of the wing performance of the Wright Flyer in 1903

- Replica of the Wright Brothers wind tunnel of 1901

- Orville Wright wind tunnel design 1916

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Wind tunnel testing basics

– Can experiments conducted on scale models of airframes be correlated to the aerodynamic behaviour of full-scale airframes?

- Osborne Reynolds (1842-1912) conducted experiments at the University of Manchester to demonstrate the validity of scale testing if certain fundamental non-dimensional parameters (ratios) were kept the same between scale model and full-scale airframe (principle of Aerodynamic Similarity)

  – **Reynolds number** (Viscous forces, flow pattern)
  – **Mach number** (Elastic forces, compressibility of the air)
  – **Froude number** (Gravitational forces, motion through the air)
  – **Reduced frequency** (Dynamic similarity, oscillations)

- **Reynolds** number presents the greatest mismatch in small scale testing
- **Mach** number similarity neglected in incompressible flow testing
- **Froude** number and reduced frequency neglected during static testing

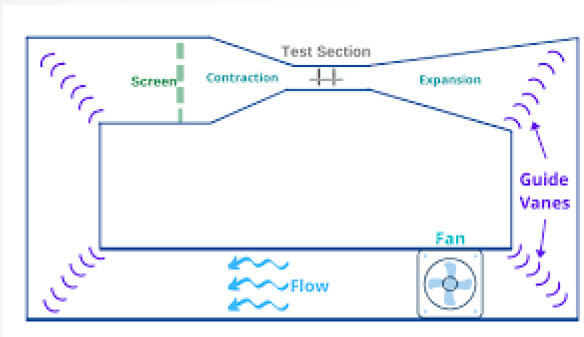
Wind tunnel types

– Wind tunnels can be classified according to:

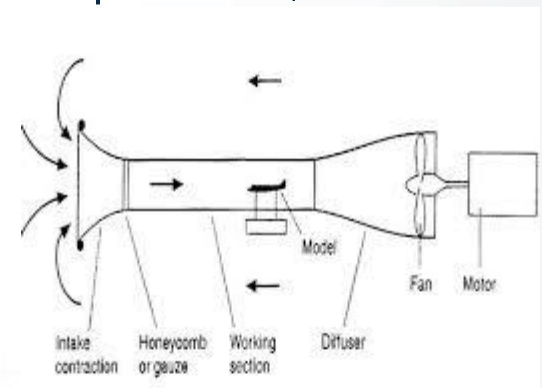
- Architecture
- Wind speed
- Mode of operation
- ..and many other attributes

Wind tunnel types

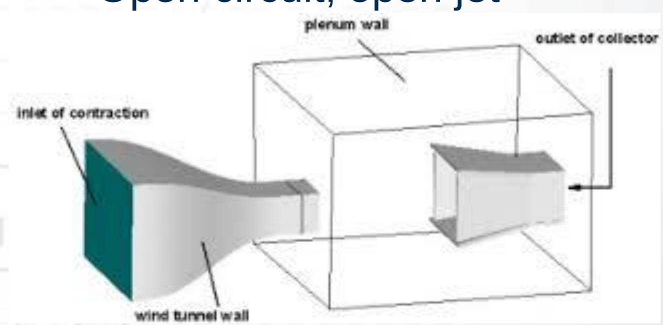
- Architecture
  - Closed circuit, closed test section



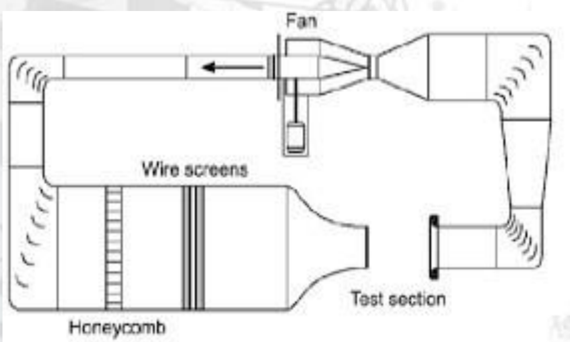
  - Open circuit, closed test section



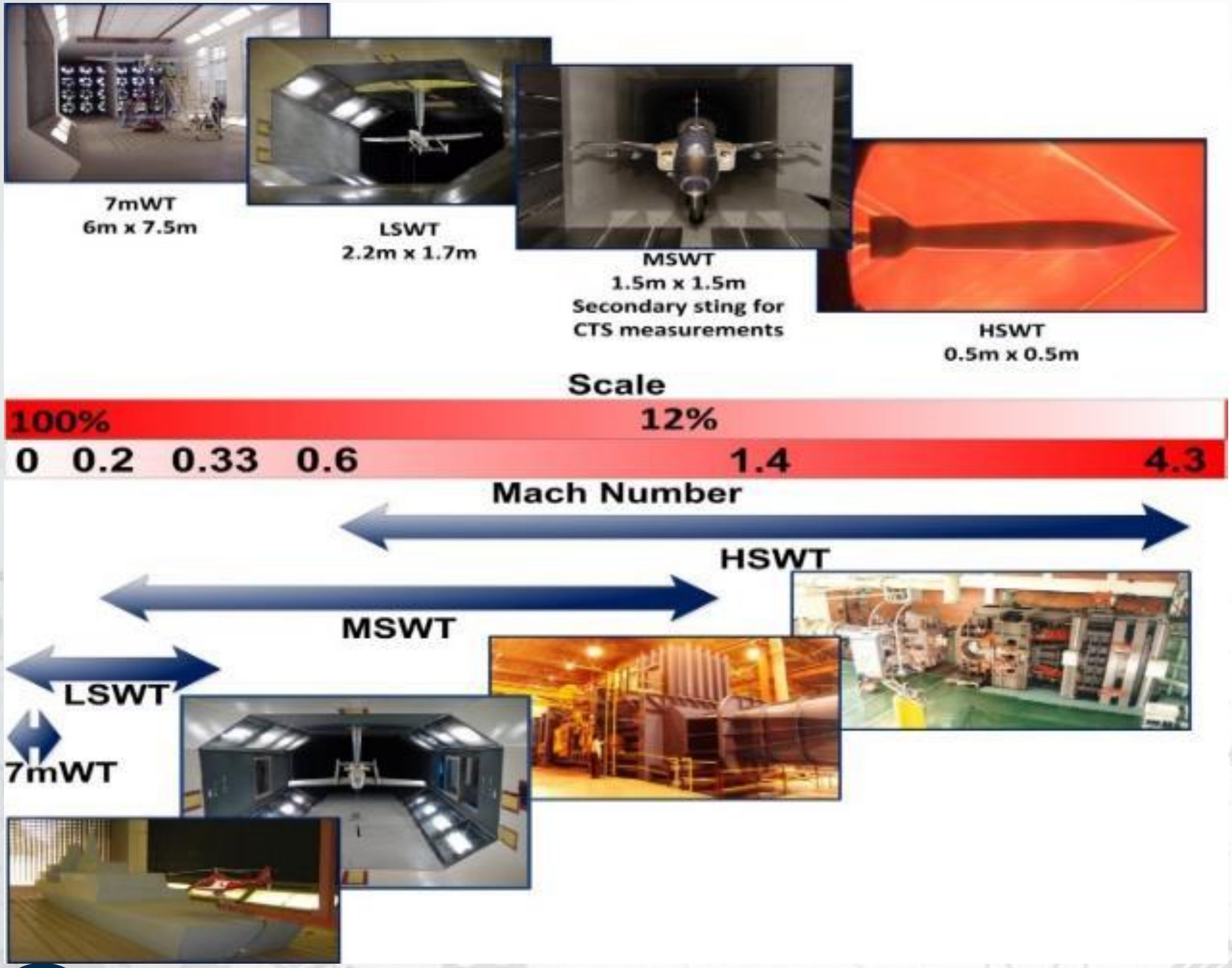
  - Open circuit, open jet



  - Closed circuit, open jet



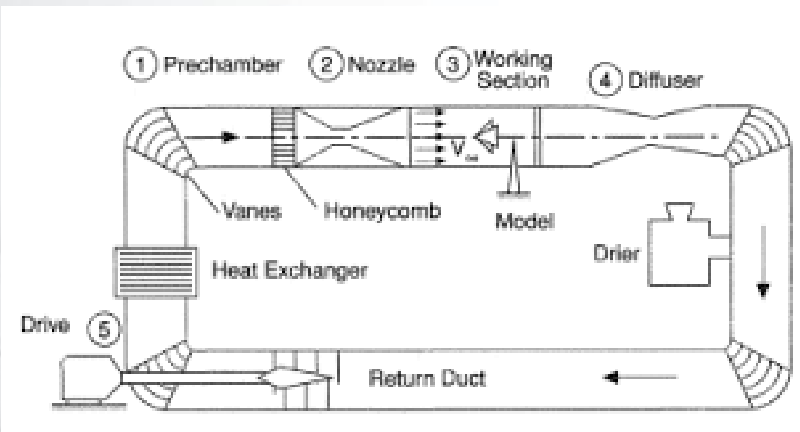
Wind tunnel types



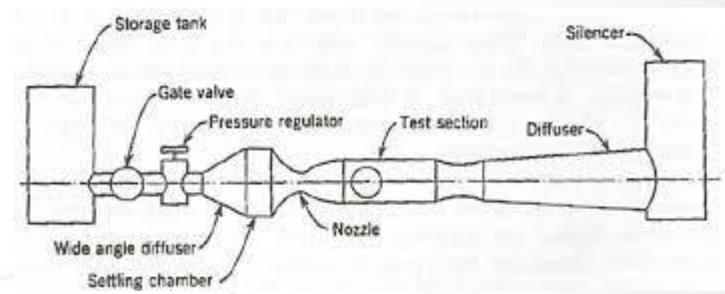
– Wind Speed
  - Subsonic (M0.1 – M0.8)
  - Transonic (M0.8 – M1.2)
  - Supersonic (M1.0 < M5.0)
  - Hypersonic (>M5.0)

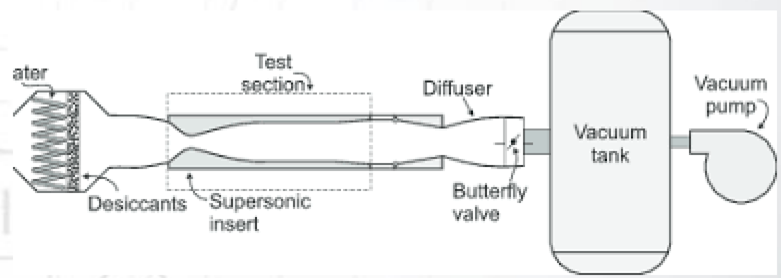
Wind tunnel types

- Mode of operation
  - Continuous



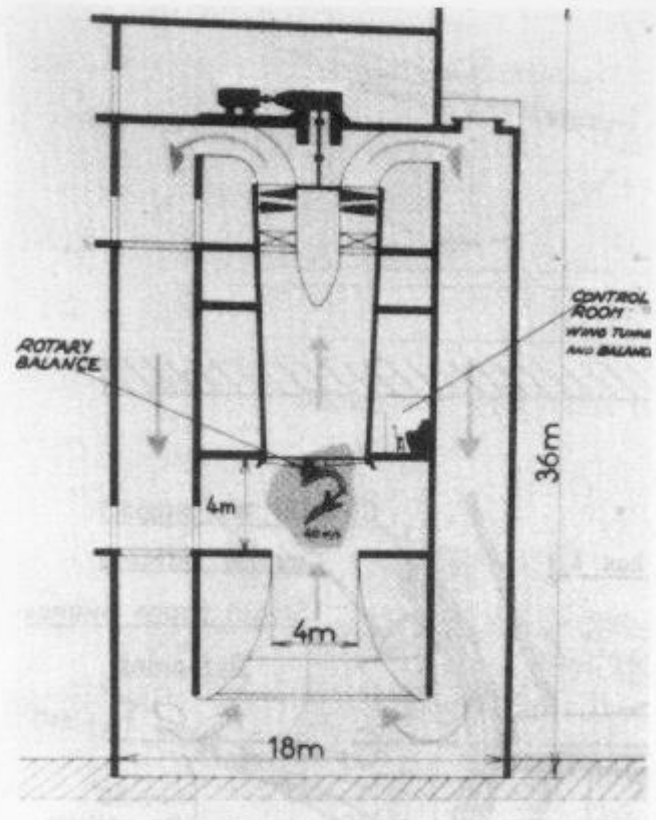
  - Intermittent



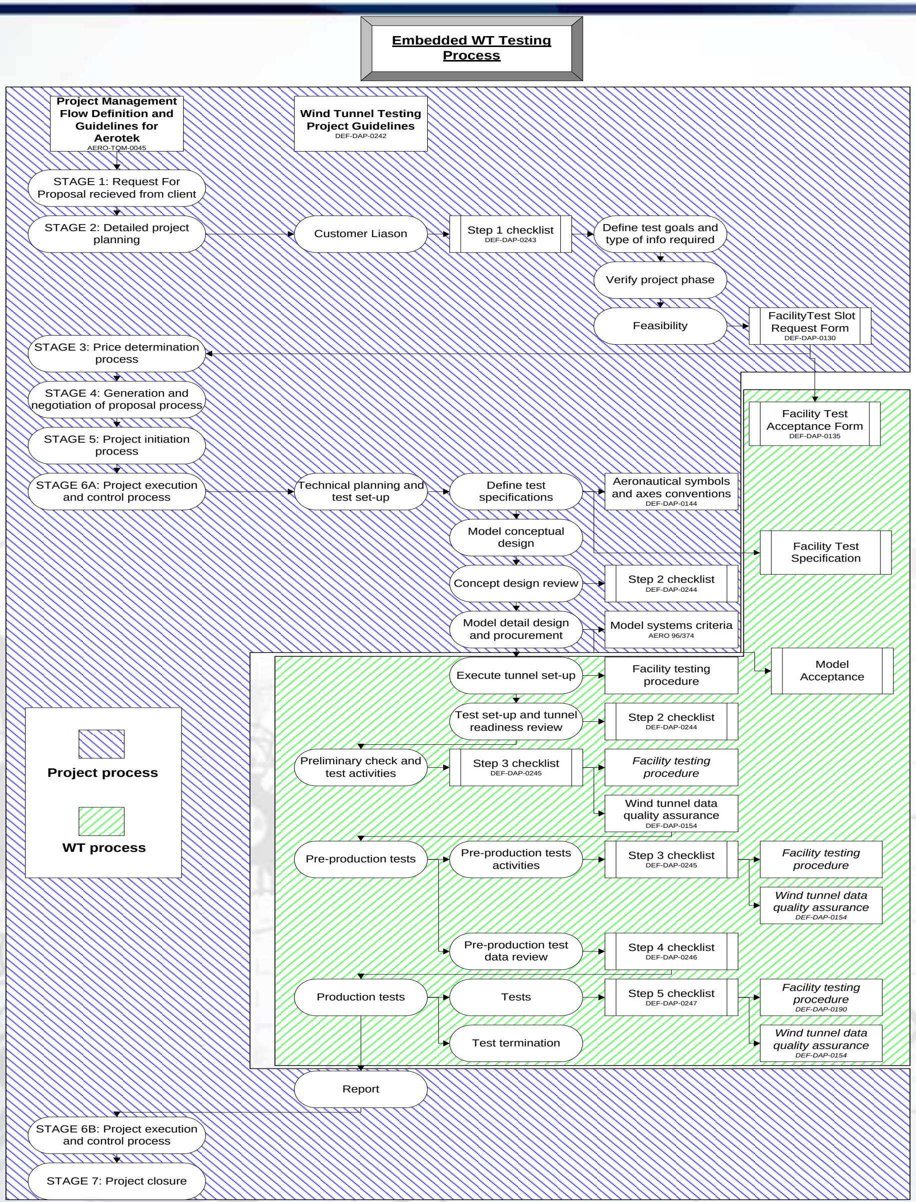


Wind tunnel types

– Particular tunnels:



Wind Tunnel Processes



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Wind Tunnel Processes

Wind tunnel balances

- Airframe aerodynamic load measuring device:
  - Most common type of measurement during wind tunnel testing
  - But one of many….

  - Complete airframe aerodynamic load measurements, generally 6 components:
    - NF, SF, AF, PM, YM, RM (5 or 4 components in particular cases)
    - Can be internal or external balances

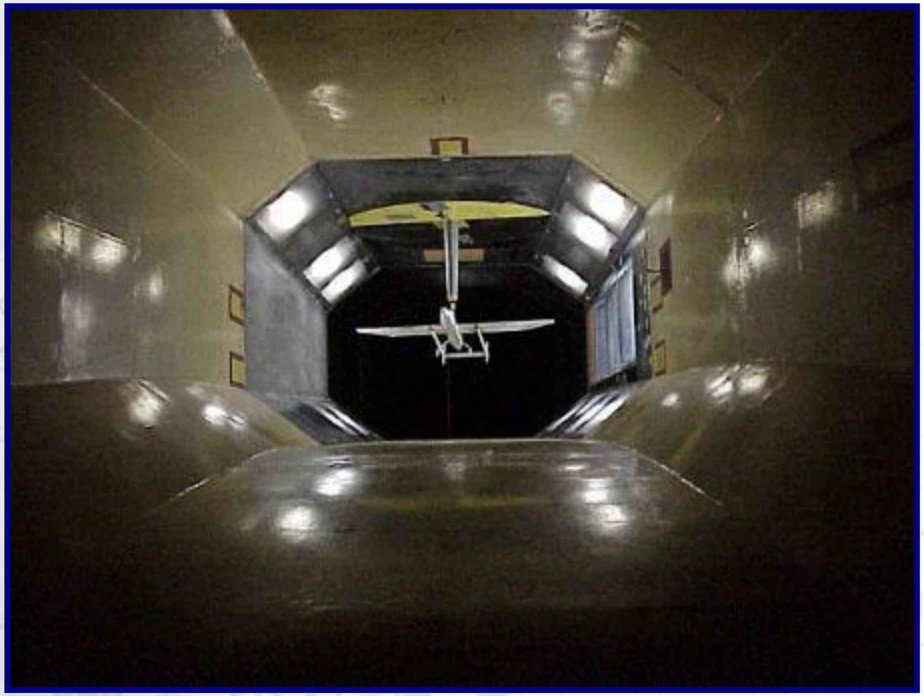
  - Control surface aerodynamic load measurements, 1, 2 or 3 component balances:
    - NF, HM, BM

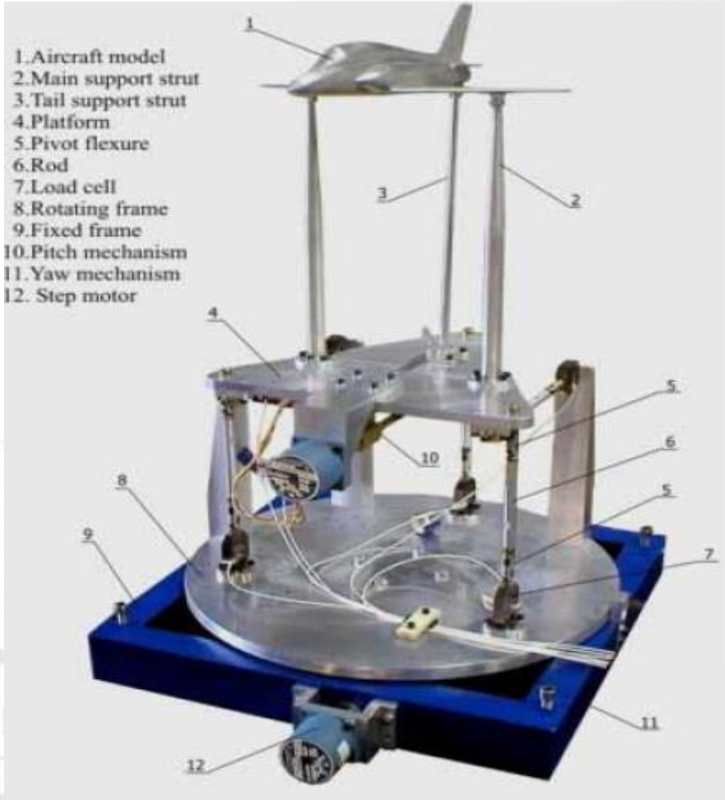
Wind tunnel balances

- Selecting a balance:
  - Balance sizing.
    - Consider balance for which max expected loads saturate from 50 to 85% of the balance design load range:
      - Good resolution and accuracy.
      - With reserve for unknown dynamic effects on the model
    - Consider balance diameter compatible with model internal spaces and tail pipe exit diameter.
    - Follow-up immediately with sting deflection calculations and internal and external "grounding" verifications.
      - Beware of oversimplifying assumptions when calculating sting deflections.
      - Consider that the balance could the most flexible element.
- Balance fitment
    - Ensure positive fit, rolling moment anti-torque devices.
    - Ensure positive, unique and measurable alignment.

Wind tunnel balances

- External balances:
  - Pyramidal or virtual centre balances





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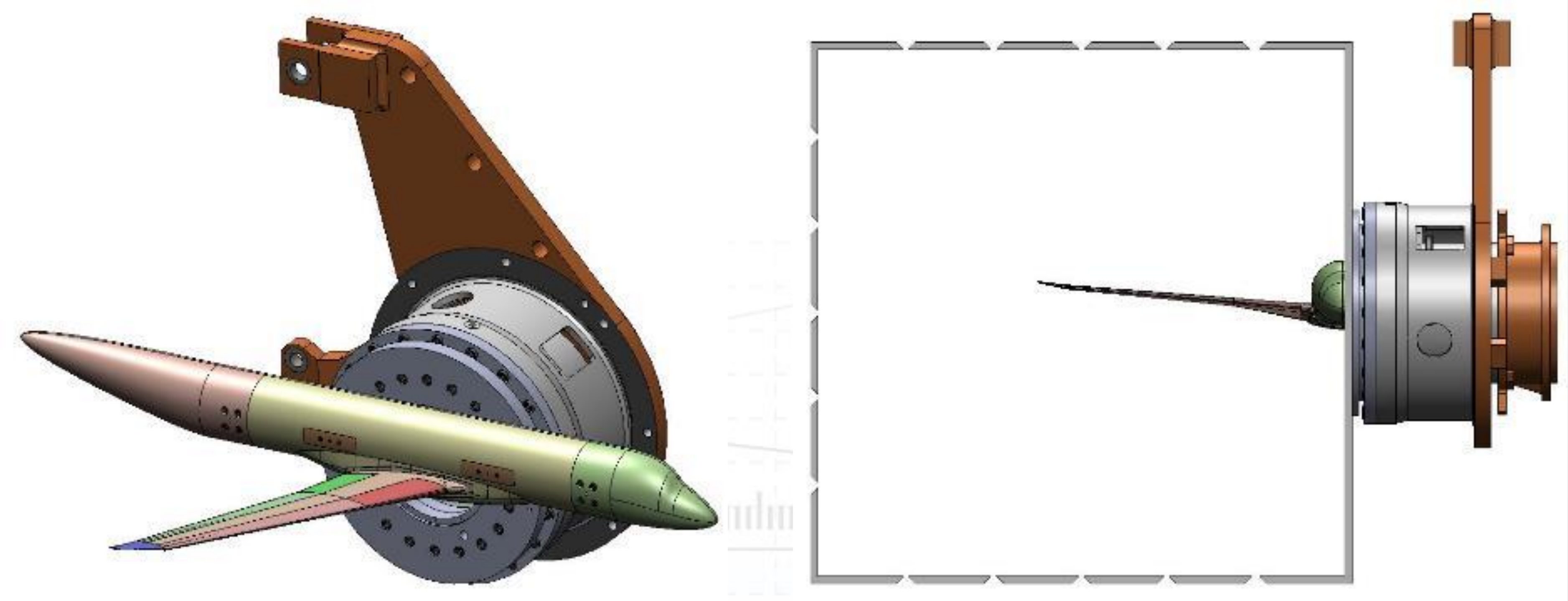
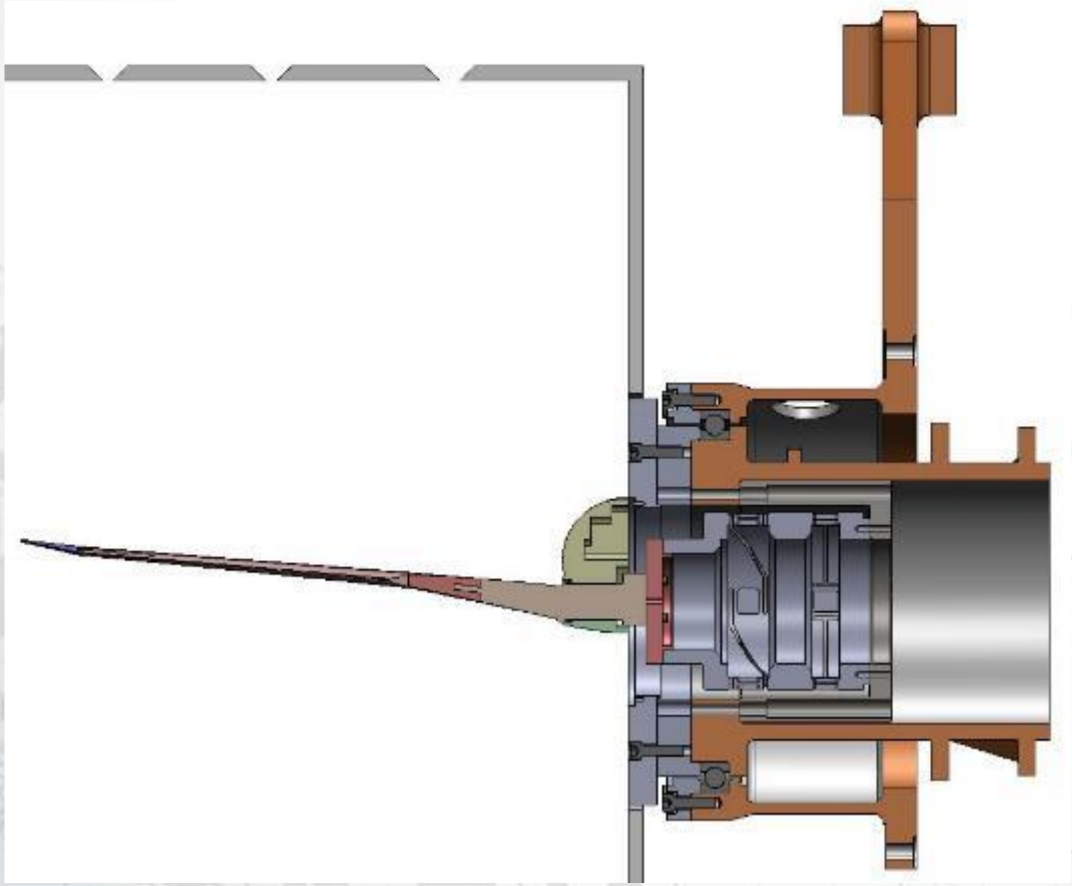
Wind tunnel balances

- External balances:
  - Side-wall balances



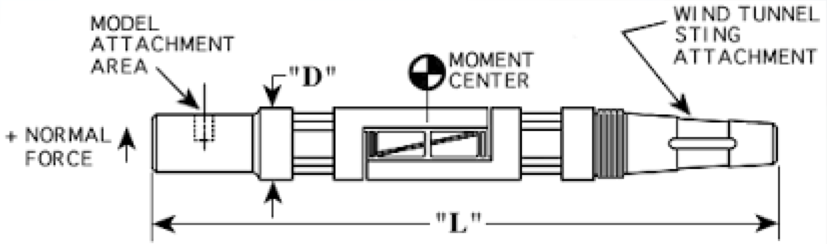
Wind tunnel balances

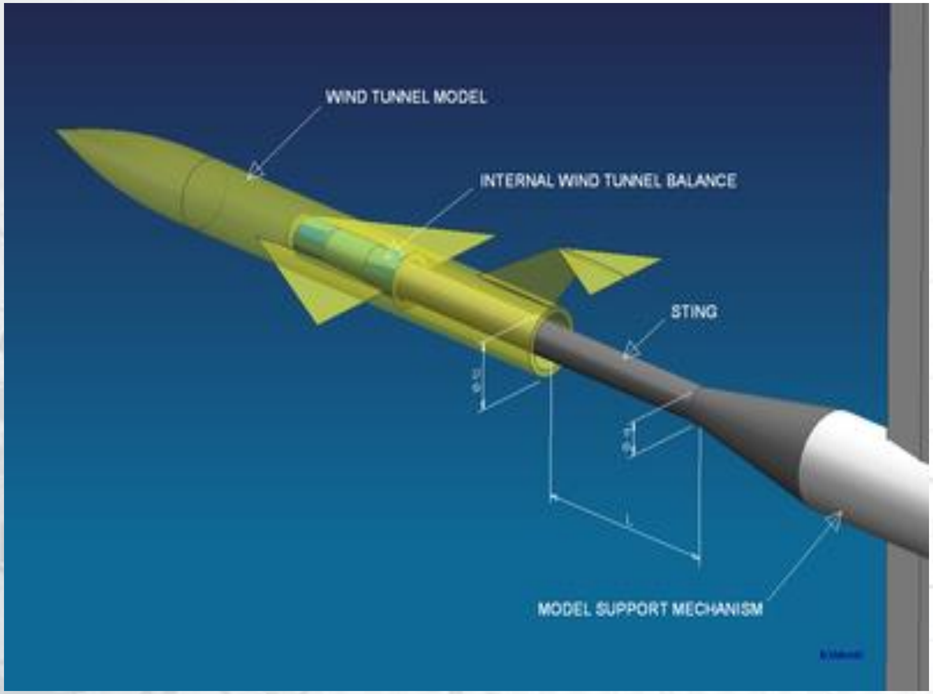
- External balances:
  - Side-wall balances



Wind tunnel balances

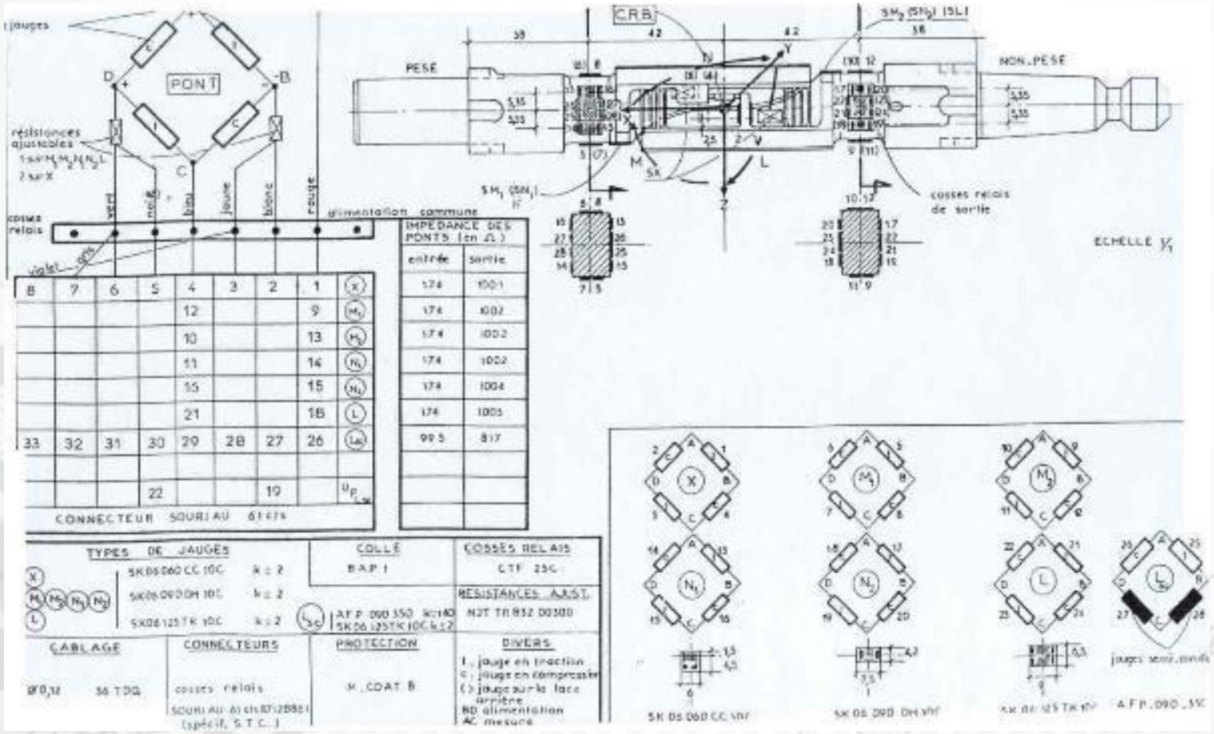
- Internal balances:
  - Sting balances





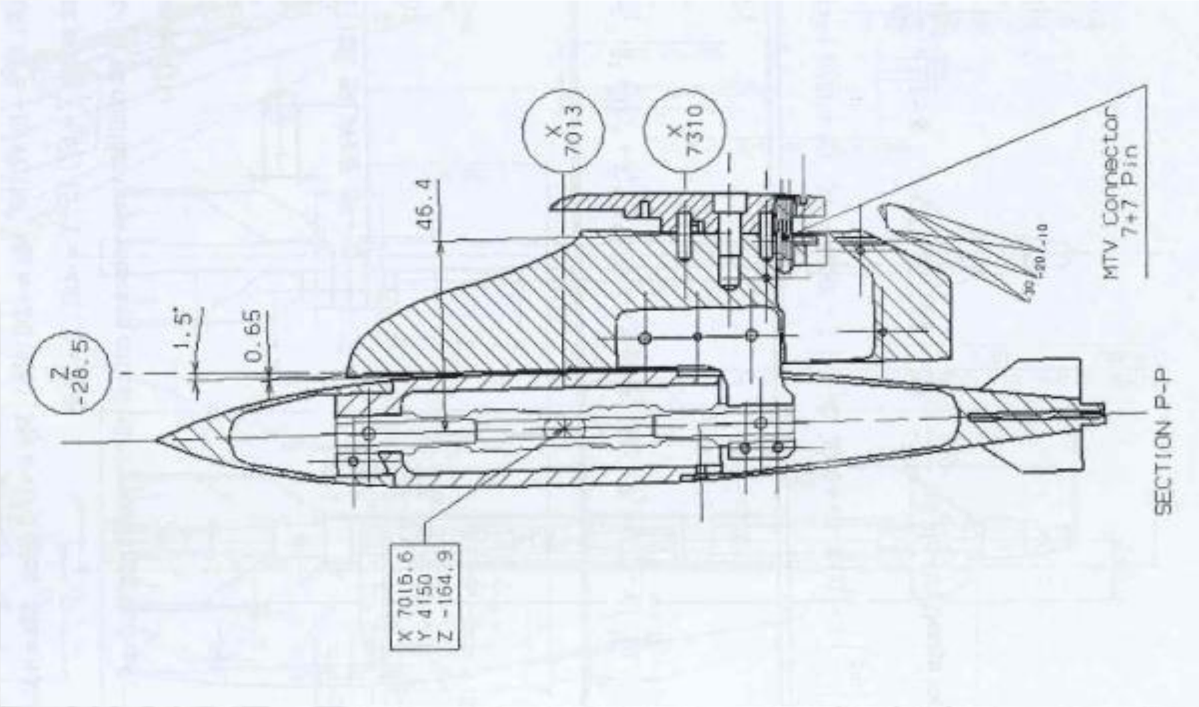
Wind tunnel balances

- Internal balances:
  - Sting balances



Wind tunnel balances

- Internal balances:
  - Carriage balances



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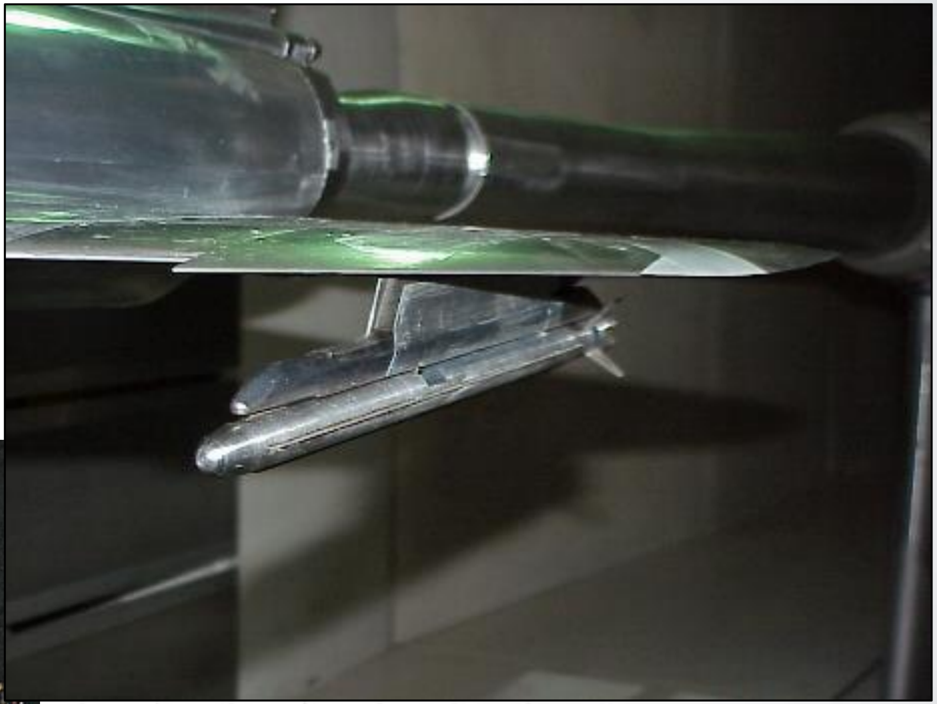
Wind tunnel balances

- Internal balances:
  - Carriage balances

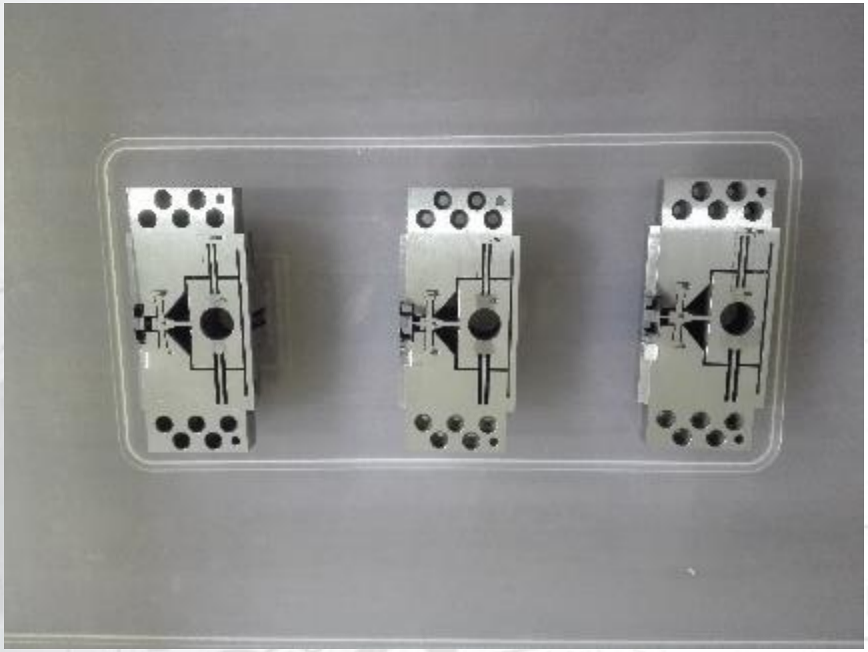


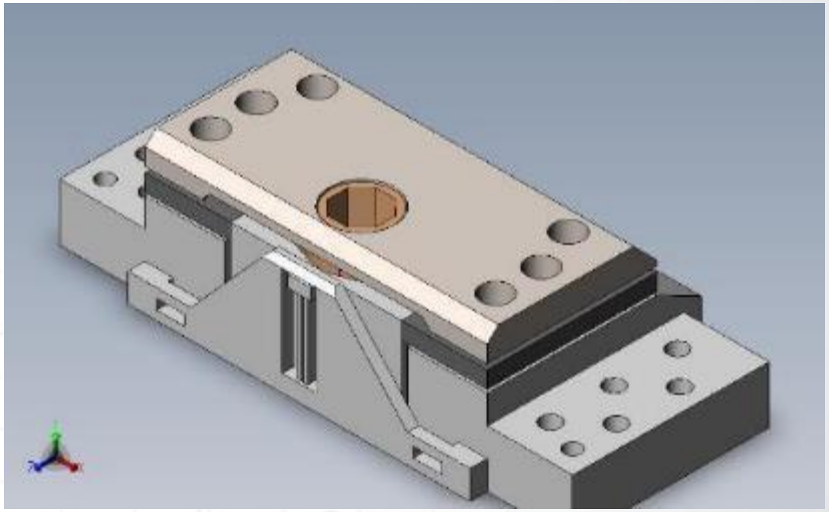
Wind tunnel balances

- Internal balances:
  - Special purposes balances
    - 3 component port and starboard wing balances

Wind tunnel balances

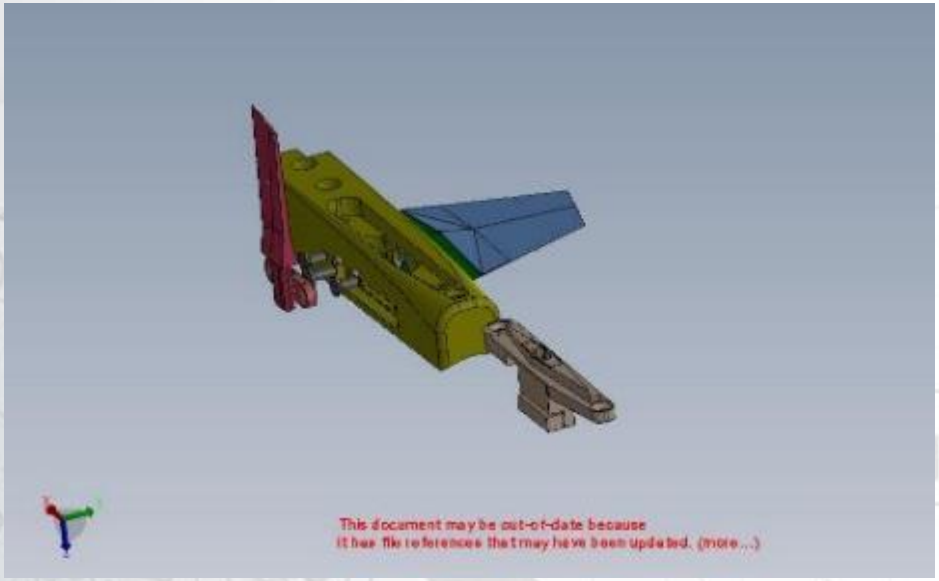
- Internal balances:
  - Special purposes 3 component fin balances on 4 fins

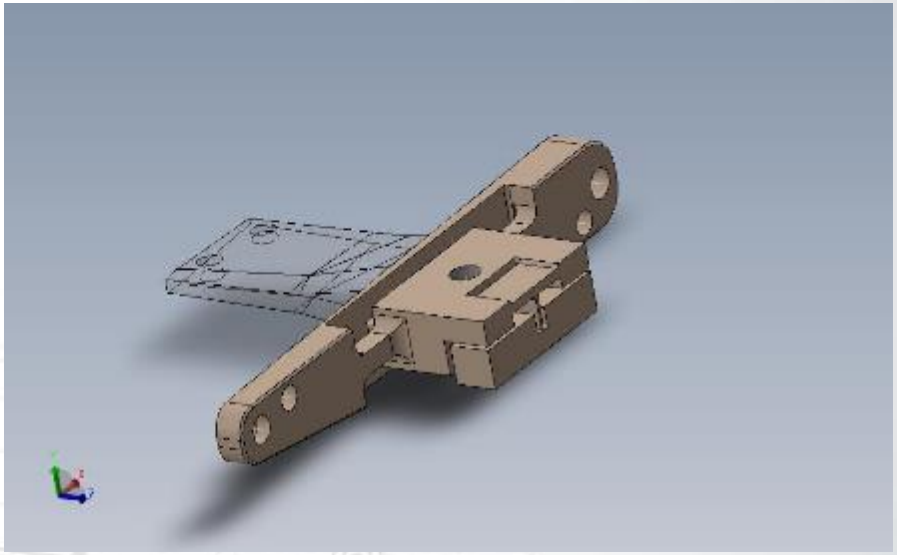




Wind tunnel balances

- Internal balances:
  - Special purposes 3 component fin balances on 2 fins

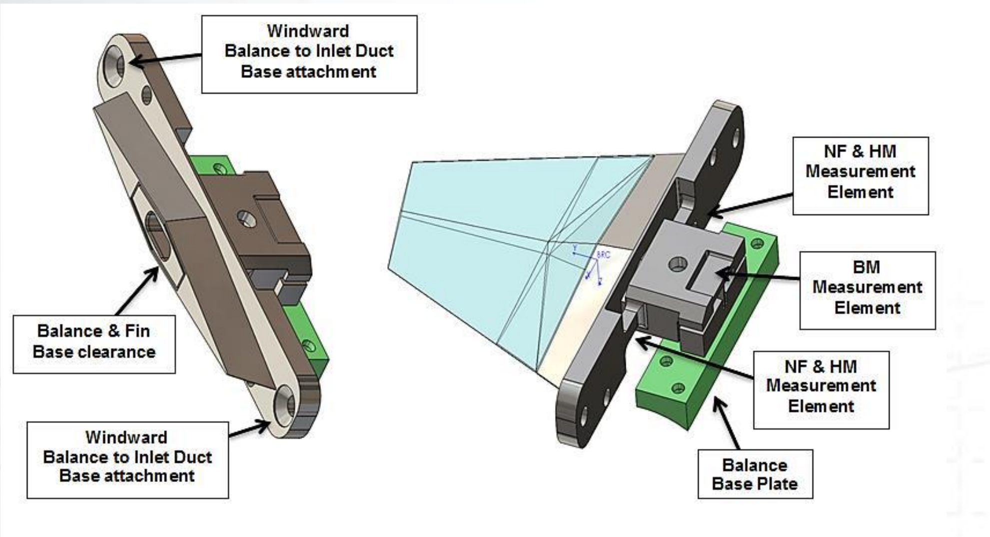


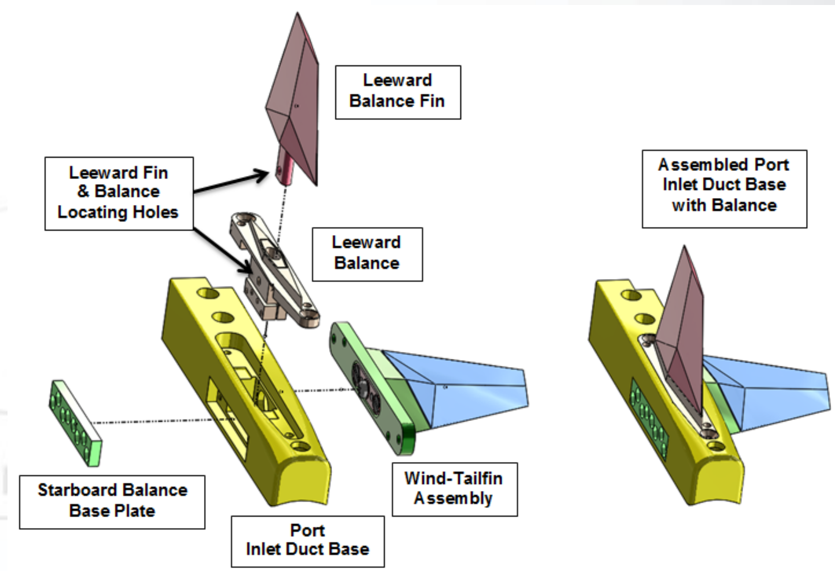


  - Length ~ 2.5 - 3 cm

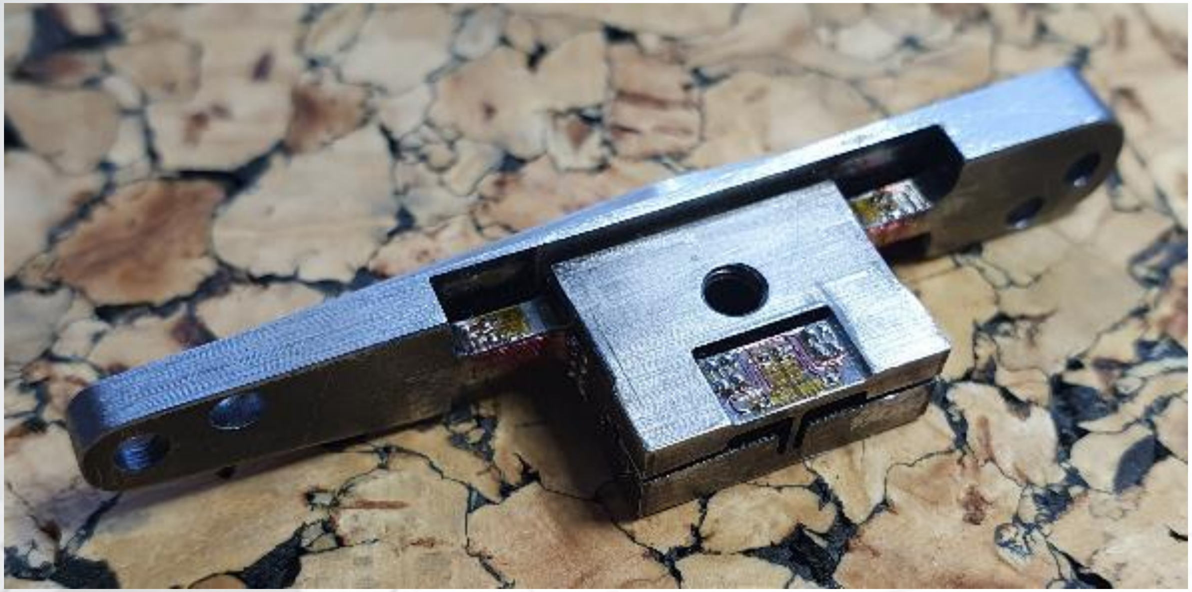
Wind tunnel balances

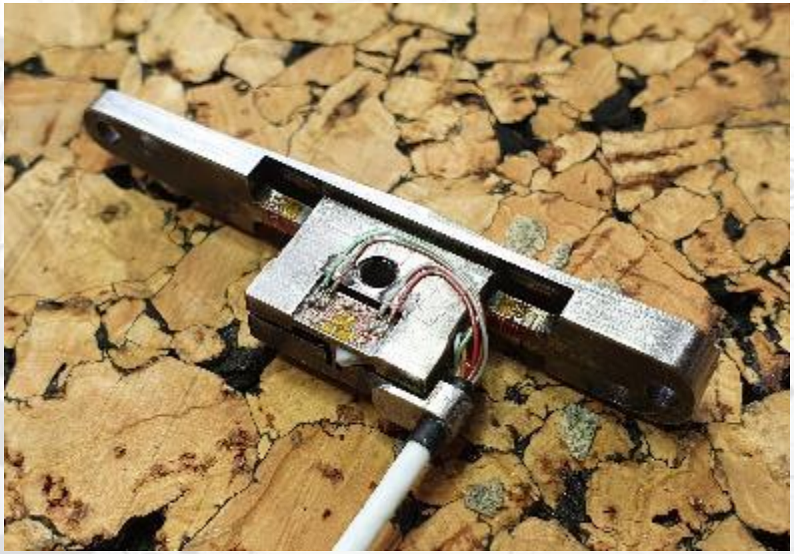
- Internal balances:
  - Special purposes 3 component fin balances on 2 fins





Wind tunnel balances





Model design and procurement

- Fundamental sizing aspects:
  - Need to reproduce every aerodynamically significant geometric detail..
    - Largest possible scale compatible with blockage ratio and wall interference effects.
  - In addition if supersonic speed tests are planned..
    - Largest possible scale compatible with shock rhombus compatibility
  - Select model support interface to wind tunnel systems.
    - Internal balance with sting support
    - Internal balance with ventral or dorsal blade support
    - External balance with strut supports
  - Calculate model loads.
    - Calculate loads at highest nominal Dynamic Pressure at which tests can be conducted
  - Select balance compatible with above model loads..
    - Iterate on dynamic pressure until a balance match has been obtained

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Model design and procurement

- Full-scale airframe geometry – model component breakdown…

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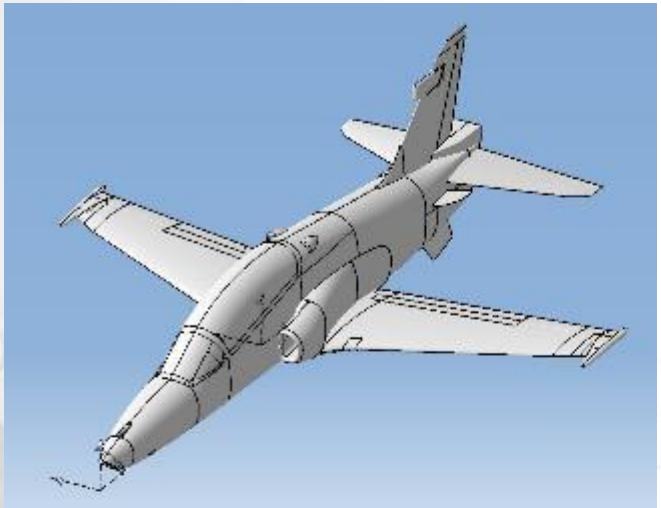
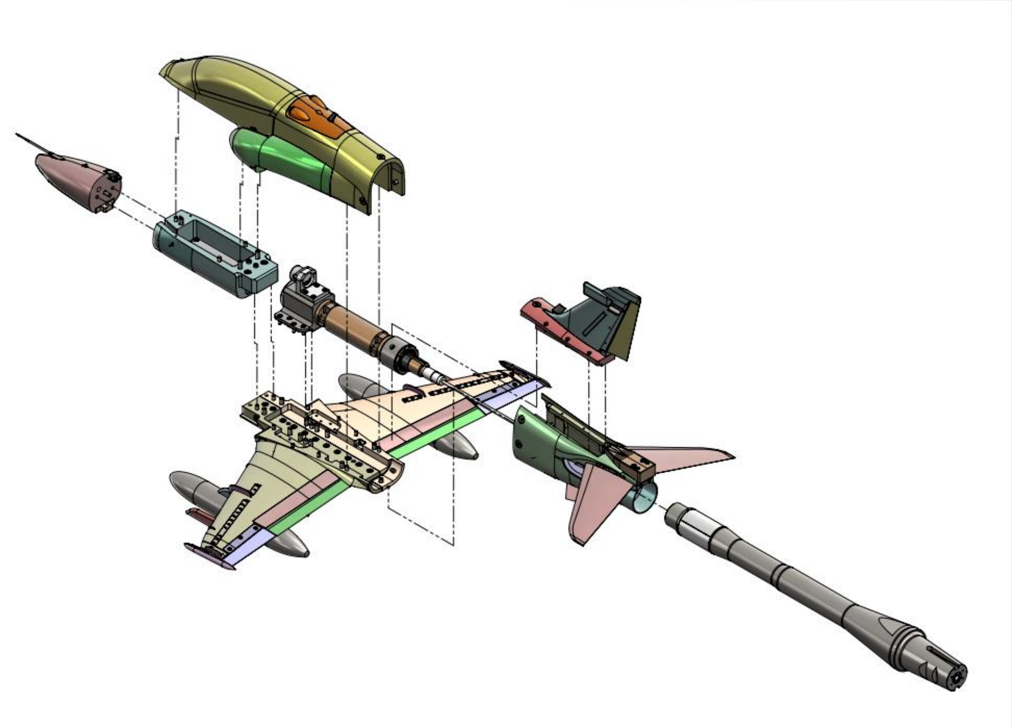
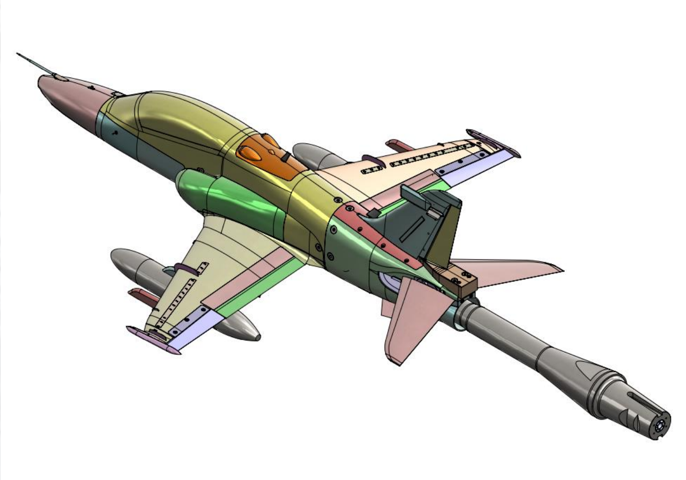
Model design and procurement

- Full-scale airframe geometry – model component breakdown…







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Model design and procurement

- Use of Additive Manufacturing to achieve detail….

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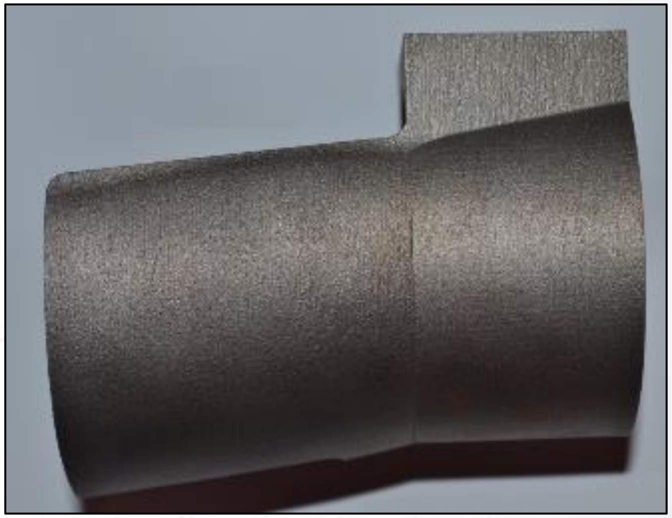
Model design and procurement

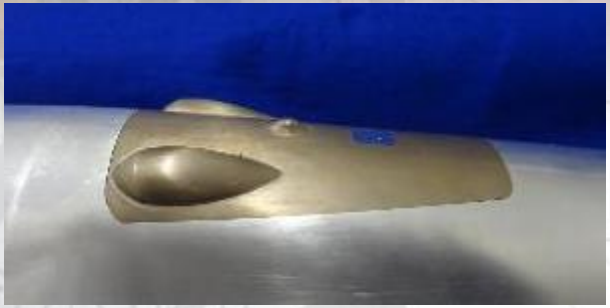
- Use of additive Manufacturing to achieve detail….

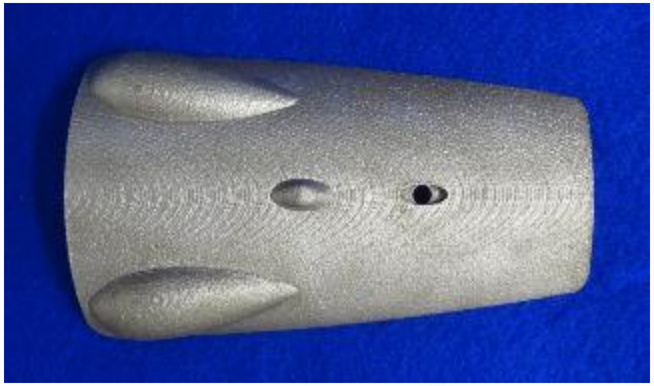


- Distorted tailpipe

Model design and procurement

- Use of additive Manufacturing to achieve detail….

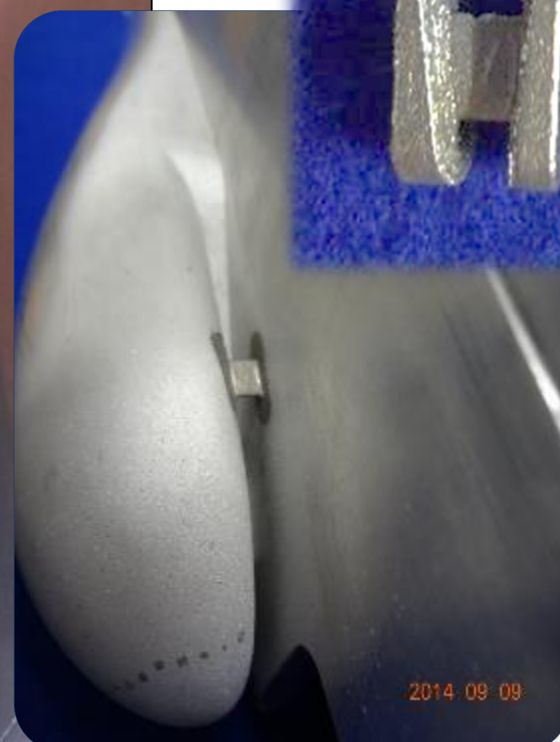




- ECS panel

Model design and procurement

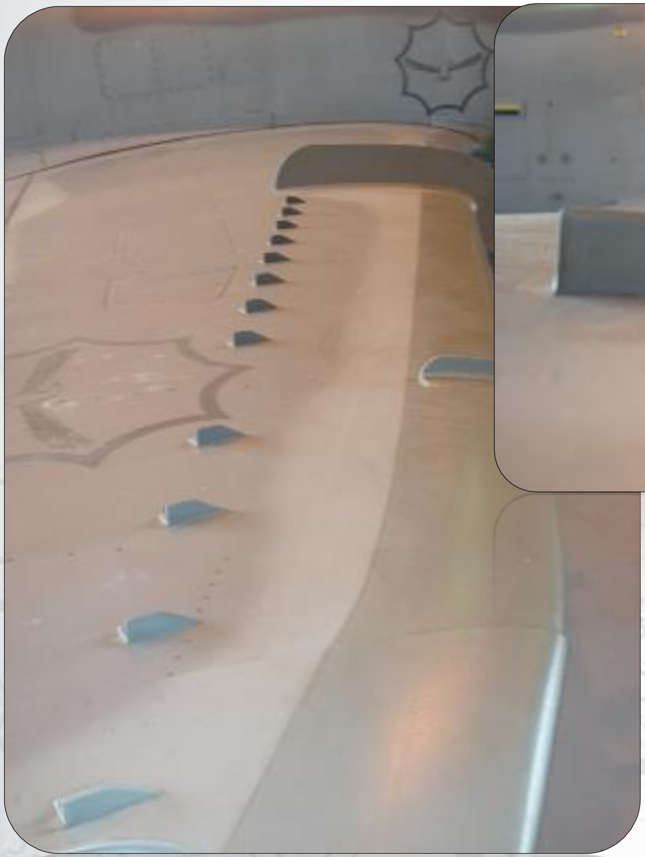
- Use of additive Manufacturing to achieve detail….



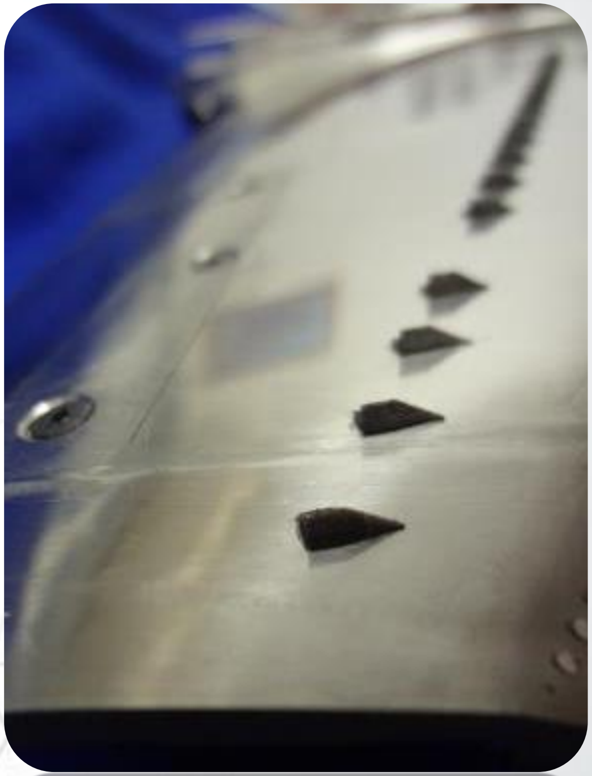
- Inlet brackets

Model design and procurement

- Use of additive Manufacturing to achieve detail….

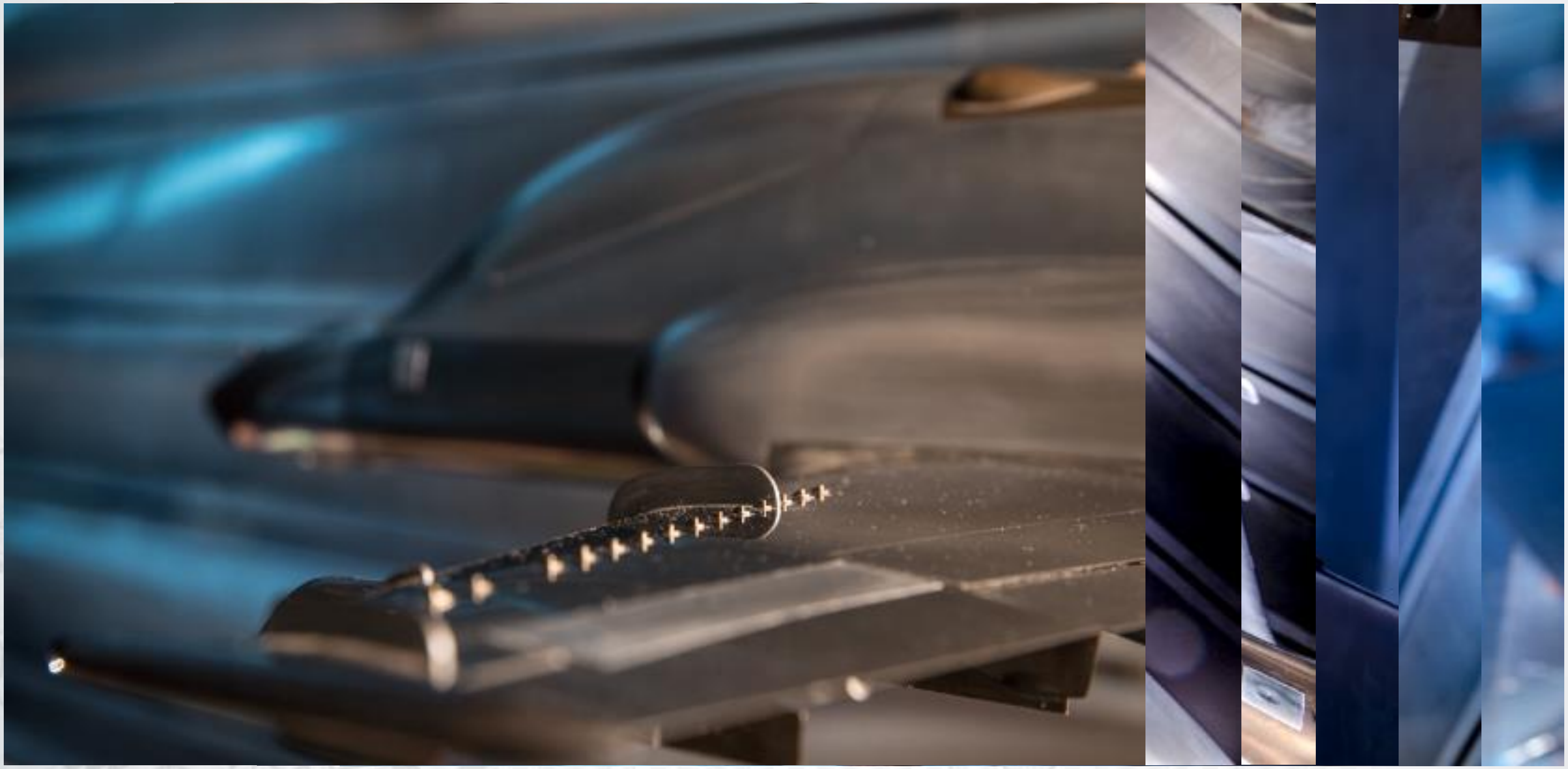


- Vortex generators



Model design and procurement

- The final product….



Model design and procurement

- The final product….

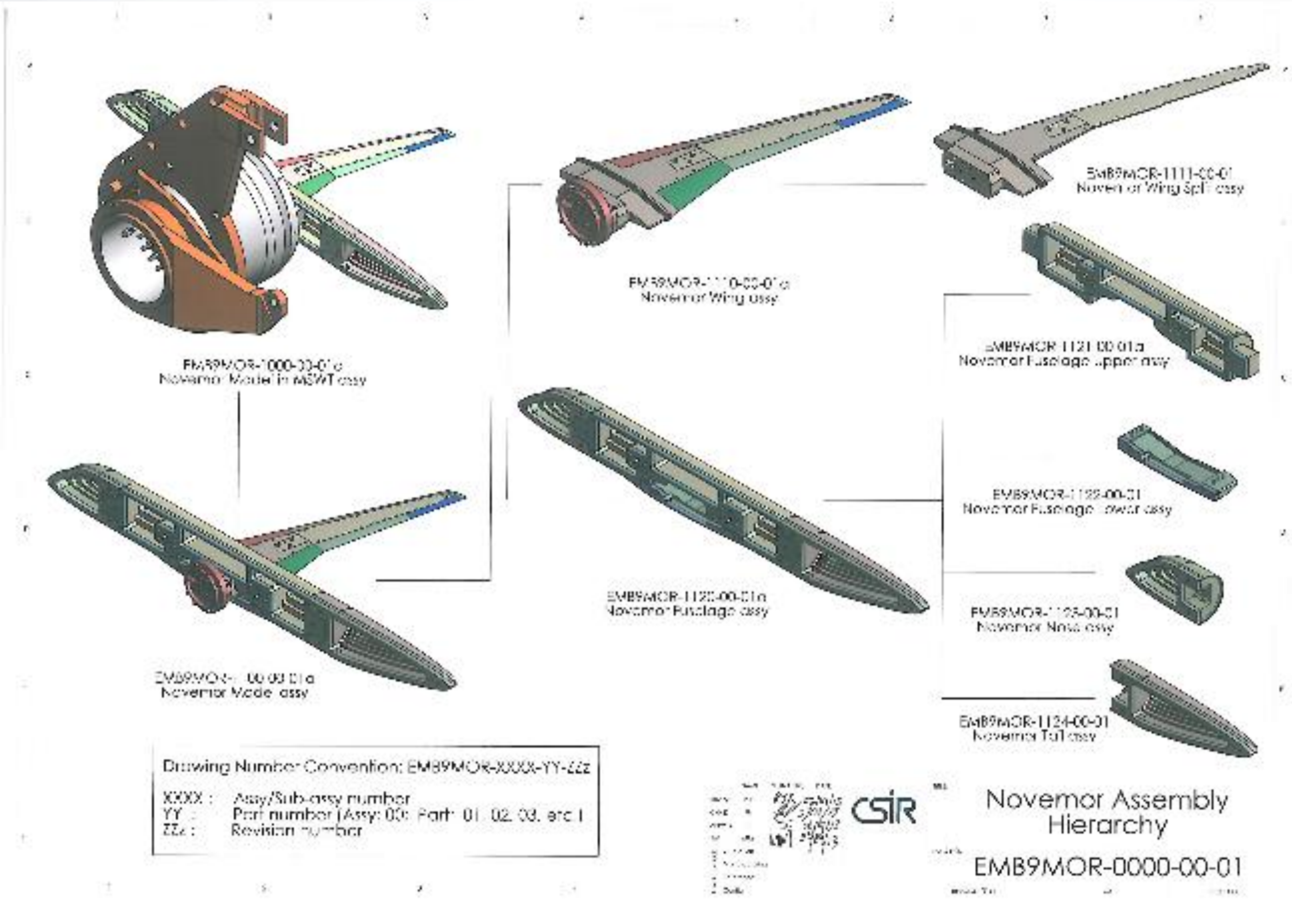
Model design and procurement

- Half model on side-wall balance….

…satisfied designer

Model design and procurement

- Half model on side-wall balance….



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Model design and procurement

- Half model on side-wall balance, phases of workmanship…

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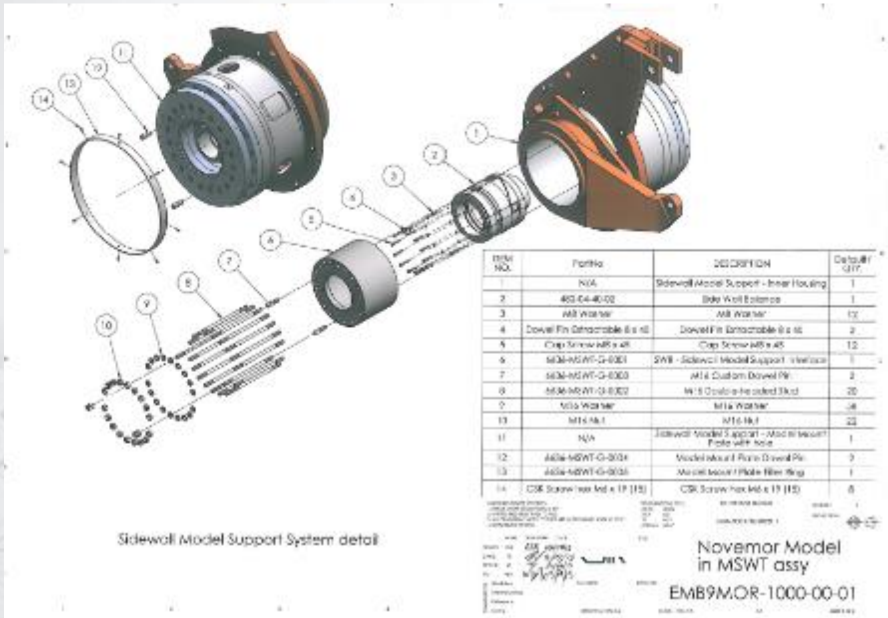
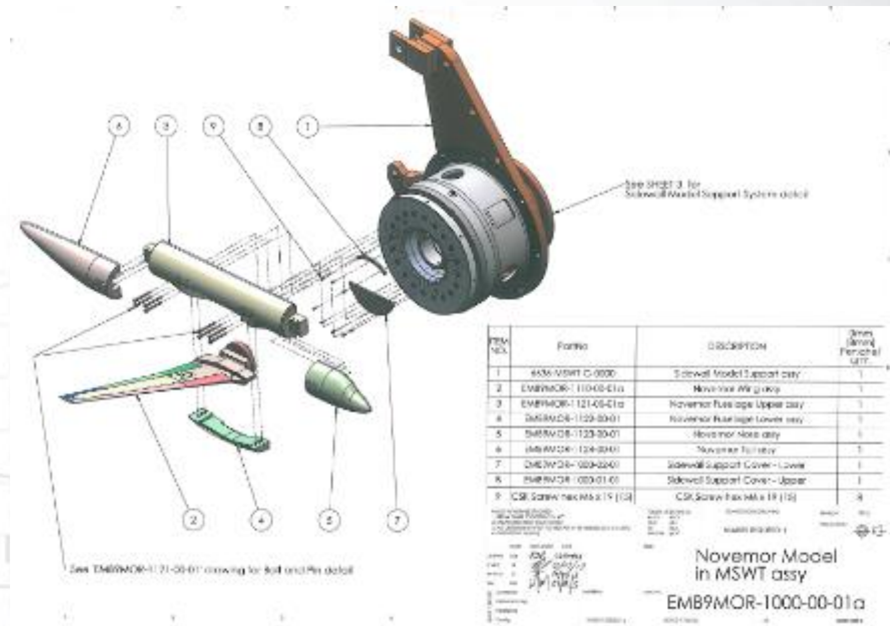
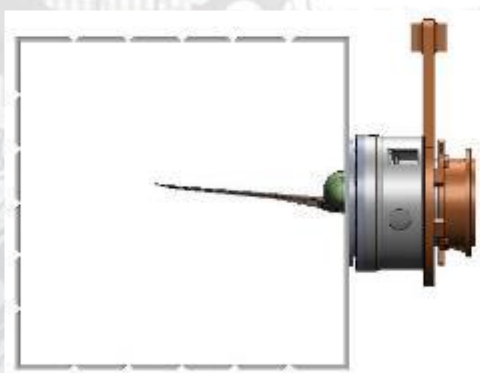
Model design and procurement

- Half model on side-wall balance, assembly diagrams…







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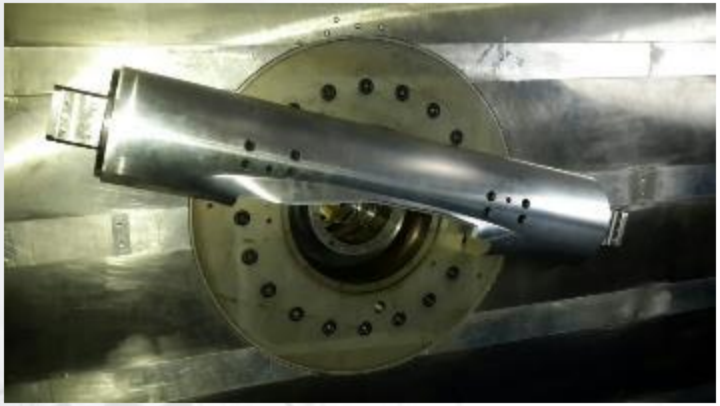
Model design and procurement

- Half model on side-wall balance, assembly and checkout…



Model design and procurement

- Half model on side-wall balance, final installation…

EMB9MOR model in MSWT

Test installation…..

- Support system angle calibrations
  - Pitch/roll
- Balance installation
  - Alignment with support
  - Checkloads
- Model installation
  - Alignment
  - Offset angles measurement

At the same time…

- Software setup
  - Test directories
  - Project specific calculation coding
  - Aerodynamic calculations ATPs

Finally….

- Tare measurement runs
- Air-off tare verification runs
- Data output formats verification
- Pre-test briefing

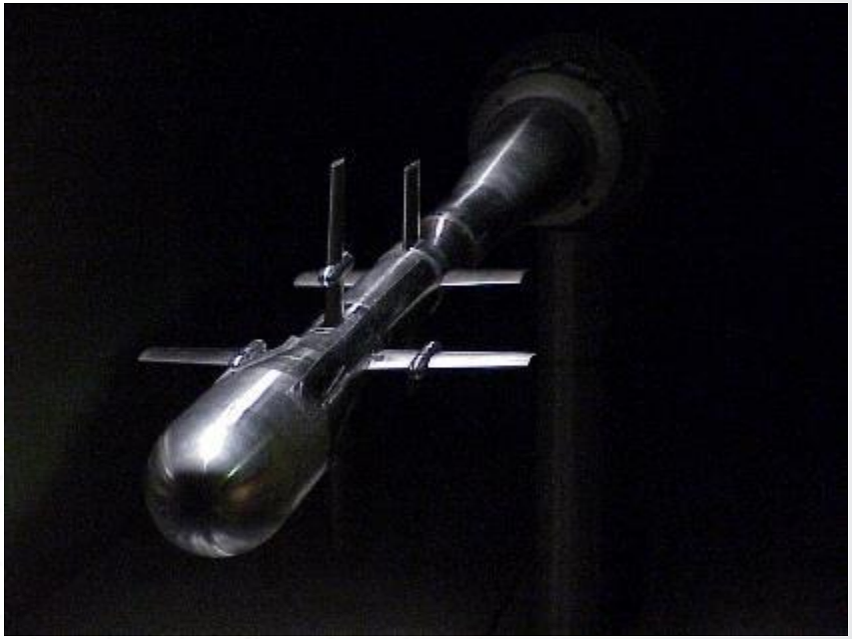
Test types and data

- There are many test types, essentially too many to list comprehensively:
- Description of most test types performed at the CSIR in addition to my own extemporary experience:
  - Static force tests
  - CTS/Grid testing
  - Static pressure tests
  - Subsonic inlet characterization
  - Dynamic derivatives evaluation

Static force tests

– Can be executed in 2 modes:

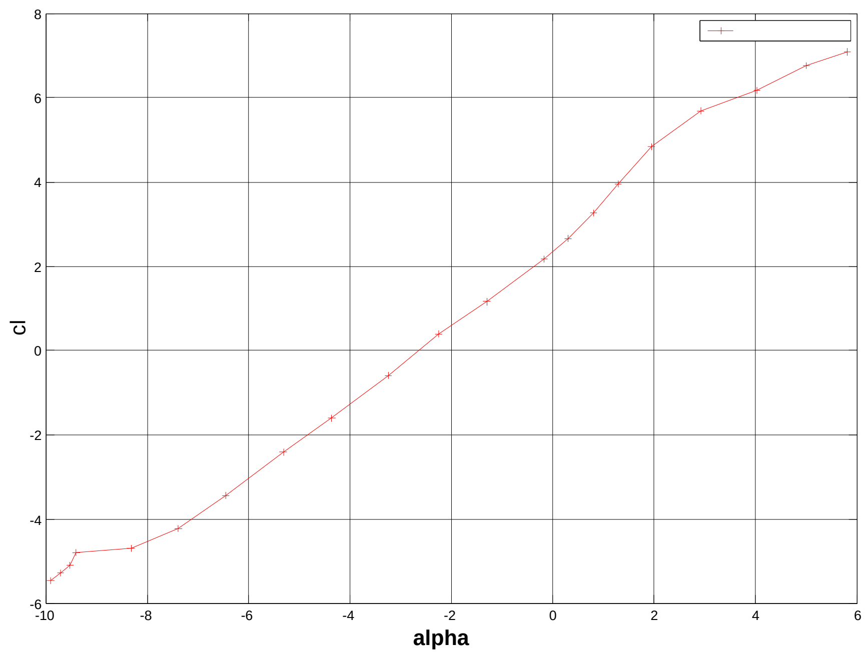
- ***Move-pause mode***
  - Pure static testing
  - Data taken when model is still at the desired attitude
  - Low sampling rates (~20Hz, data averaging, low pass filters set at 1-5Hz
  - Tight tolerances on tunnel environmental conditions



Condition	Tolerance	Units
Mach number	0.005	
Stagnation pressure	0.25	kPa
Stagnation temperature	1	K
Pitch	0.1	deg
Roll angle	0.1	deg

Static force tests

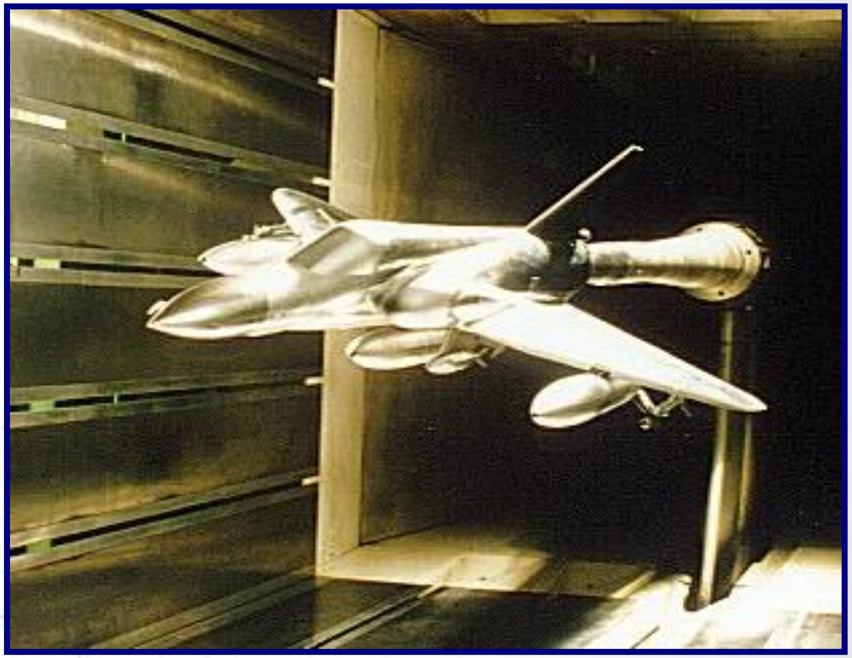
- ***Move-pause mode***
  - Highly Accurate data
  - Data sparse
  - Time consuming



Condition	Tolerance	Units
Mach number	0.005	
Stagnation pressure	0.25	kPa
Stagnation temperature	1	K
Pitch	0.1	deg
Roll angle	0.1	deg

Static force tests

- ***Continuous sweep mode***
  - Quasi-static testing
  - Low sweep rates (0.1-0.3 deg/s)
  - Data taken with model on the move
  - Low sampling rates (~20Hz, low data averaging, low pass filters set at 1-5Hz)
  - Lag in data due to hardware filters (need to correct with software)
  - Environmental set before start of sweep (no check between tunnel and data acq. during sweep)



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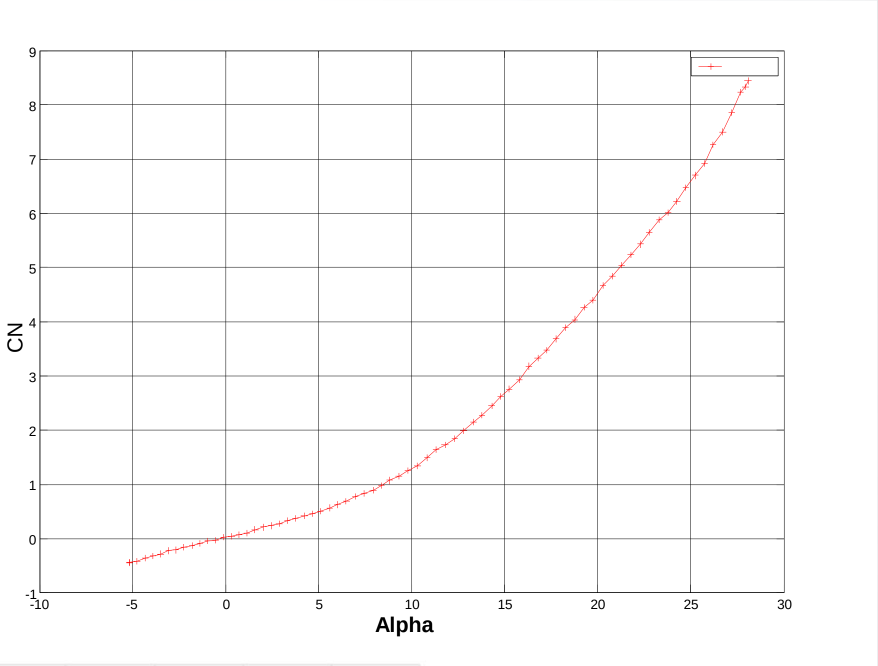
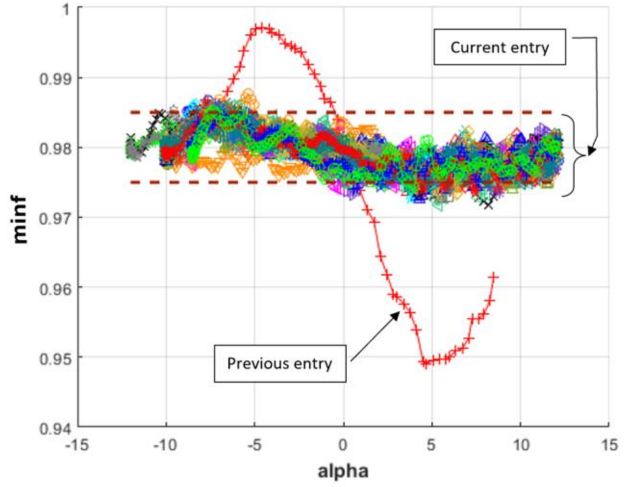
Static force tests

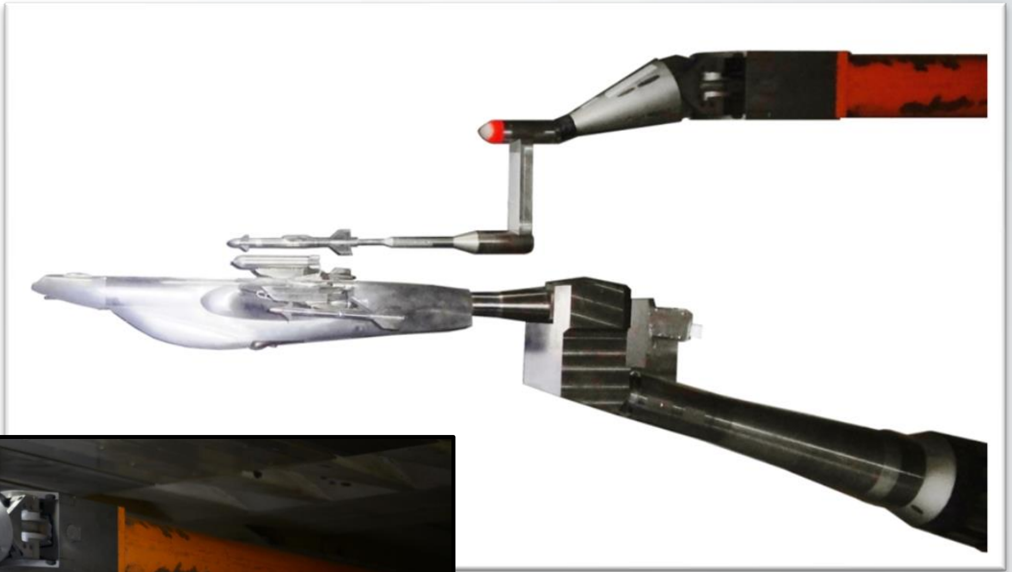
- ***Continuous mode***
  - Accurate data
  - Data more frequent
  - More efficient

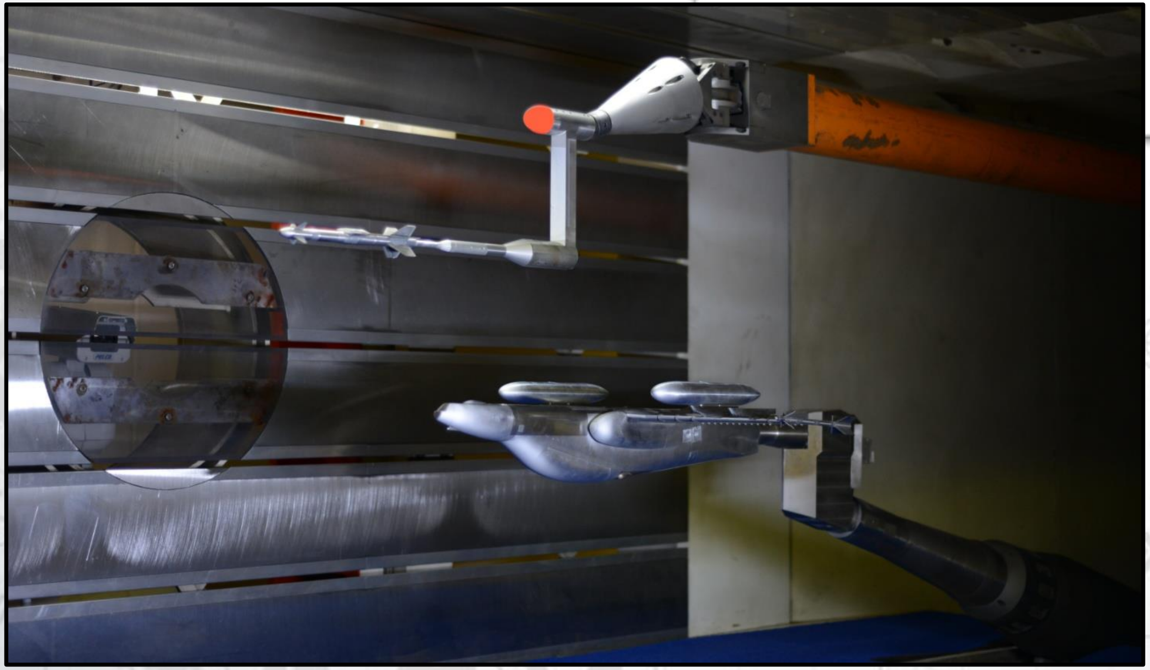




CTS/Grid Testing

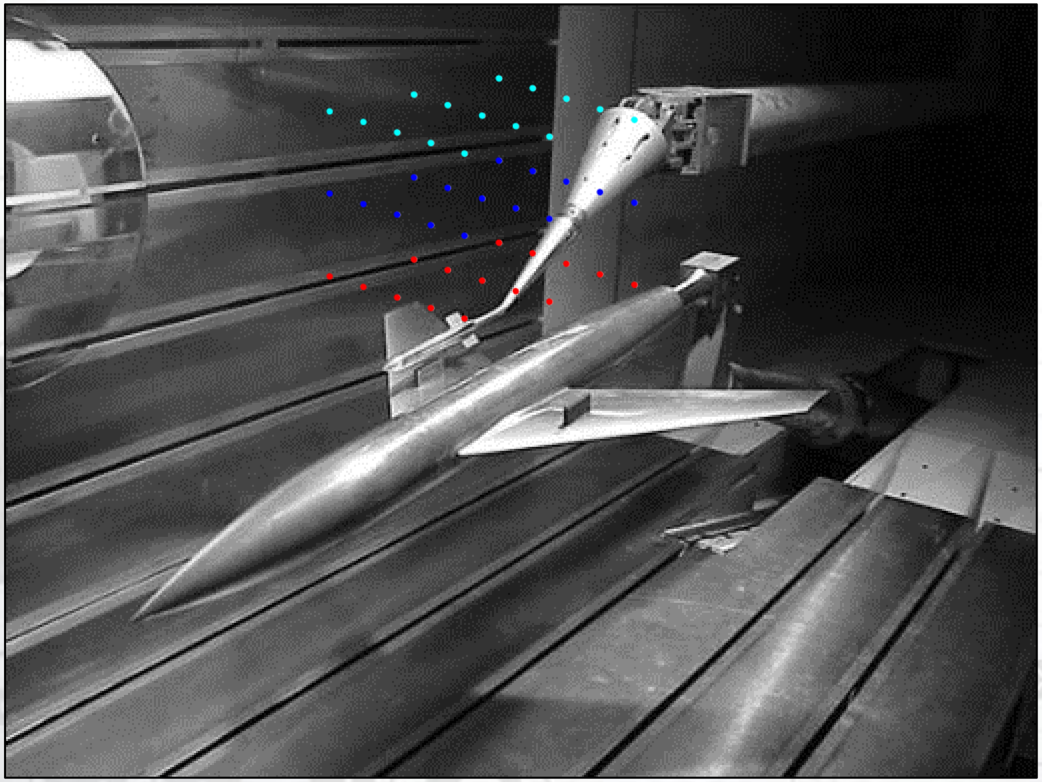
- ***Grid testing***
  - MSWT FFPS boom in addition to the MMS
    - Two model system:
      - Parent model on MMS
      - Store model on 6 DOF secondary support





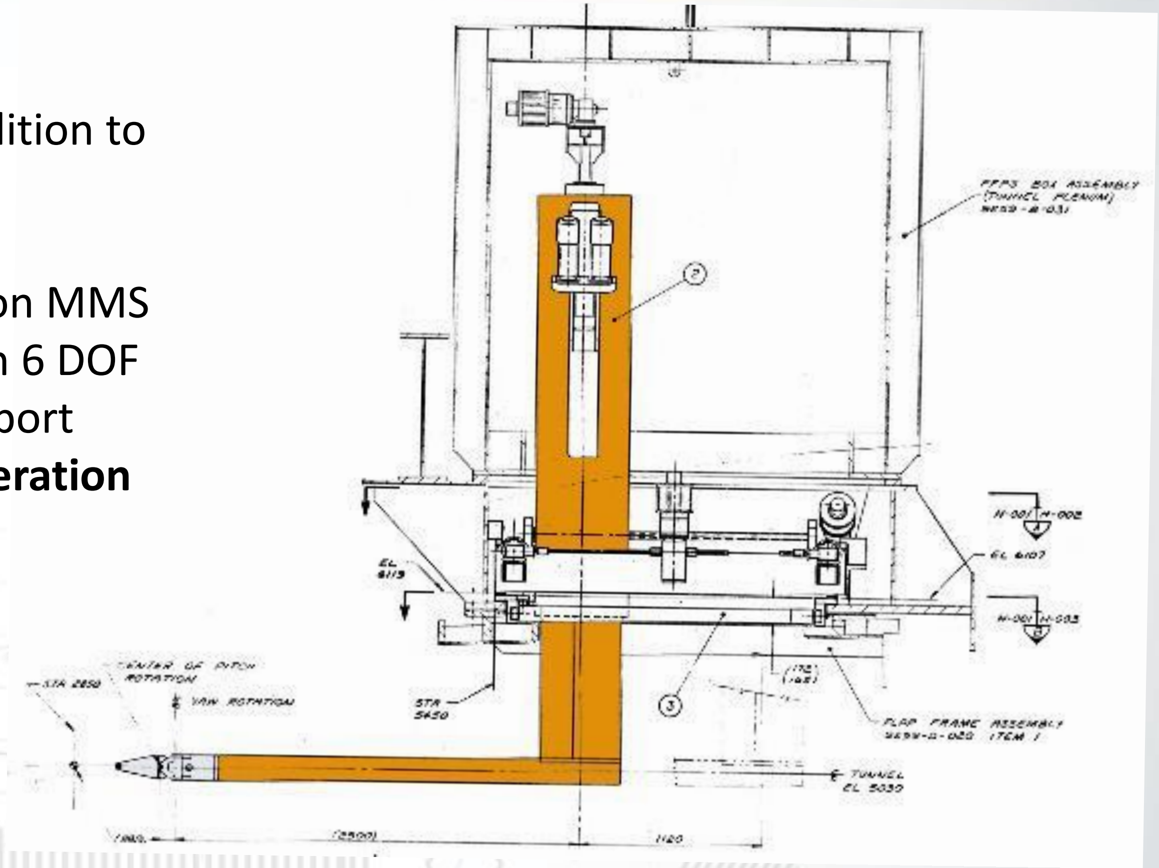
CTS/Grid Testing

- ***Grid testing***
  - To measure the effect of the interference flow field on the store while it is positioned at pre-determined distances and attitudes w.r.t the parent model.



CTS/Grid Testing

- ***Captive Trajectory Testing***
  - MSWT FFPS boom in addition to the MMS
    - Two model system:
      - Parent model on MMS
      - Store model on 6 DOF secondary support
    - **NB: Trajectory Generation software**.

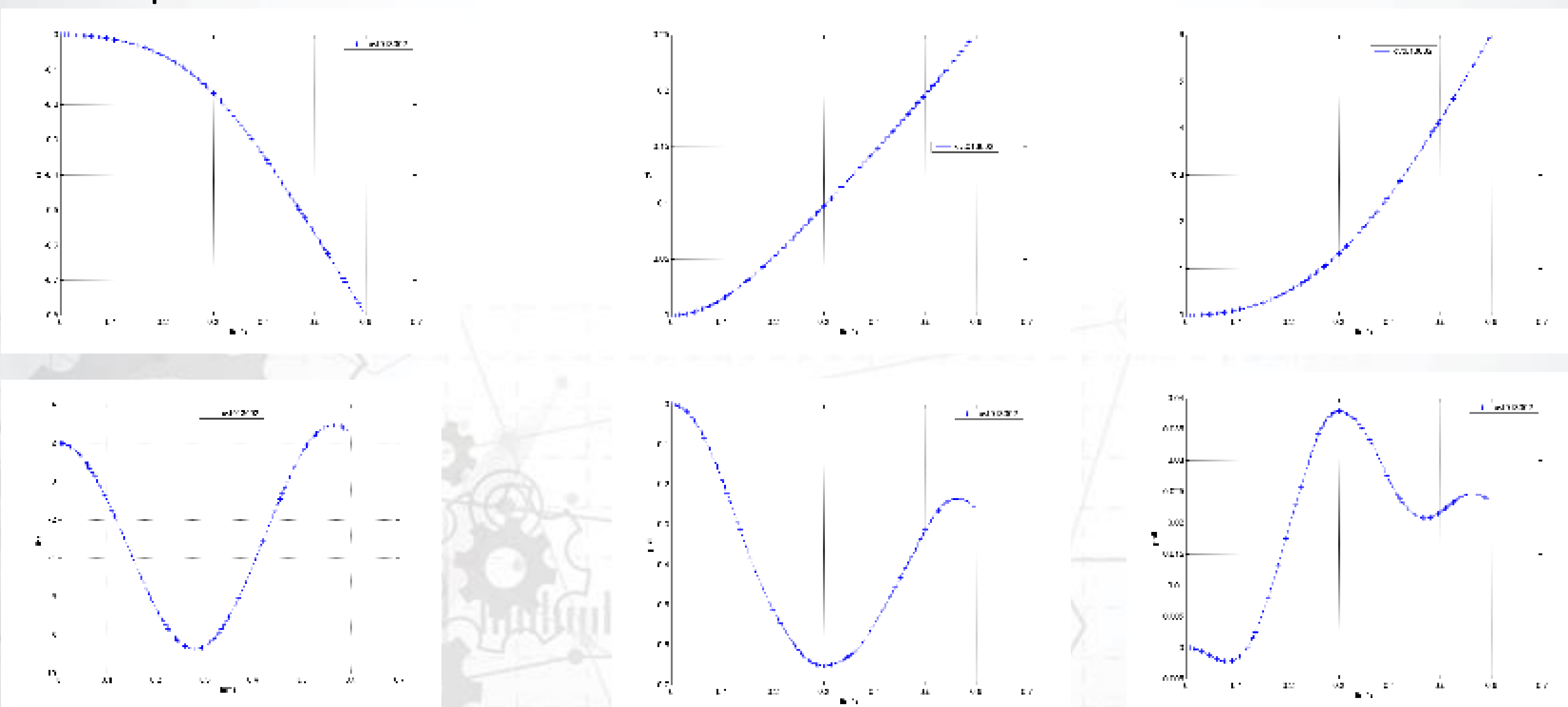


CTS/Grid Testing

- ***CTS testing***
  - To simulate the “real time” release path of the store w.r.t. the parent aircraft.

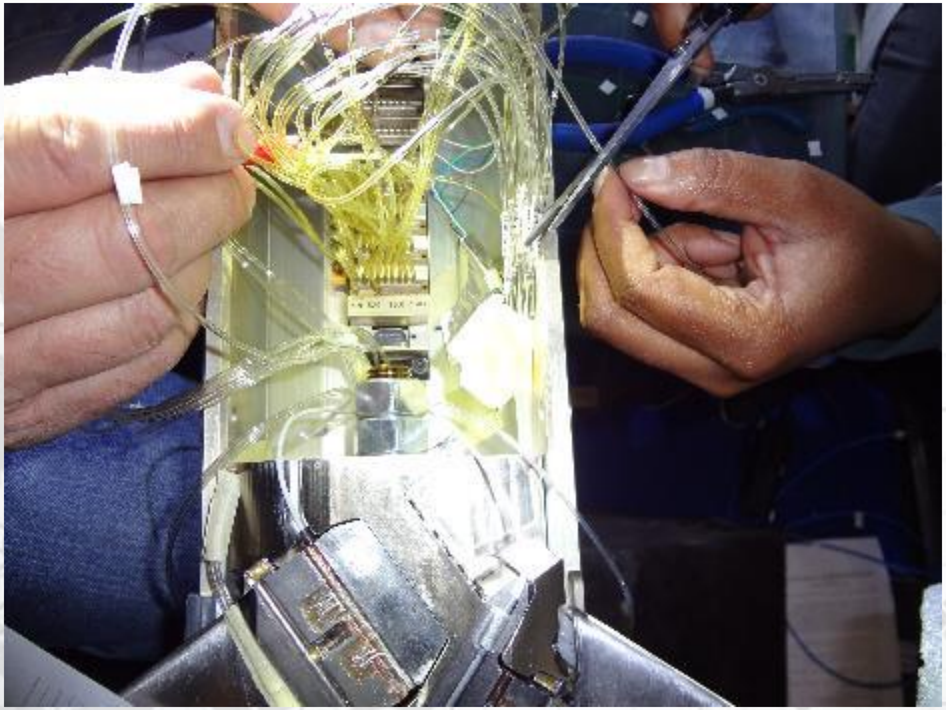
CTS/Grid Testing

- ***CTS testing***
  - To simulate the “real time” release path of the store w.r.t. the parent aircraft.



Static Pressure Testing

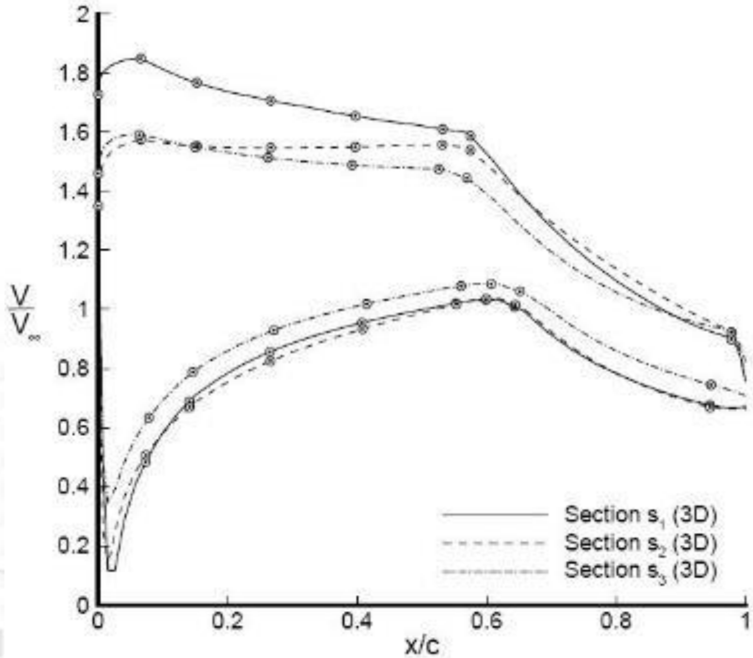
- ***Pressure testing***
  - Investigative technique
  - Complex in nature due to the requirement of surface pressure taps
  - Use of multi-channel ESPs
  - Complex model manufacture



Static Pressure Testing

- ***Pressure testing***
  - Limited discrete data

Figure 4.11: Location of control airfoils on wing of Example 3.



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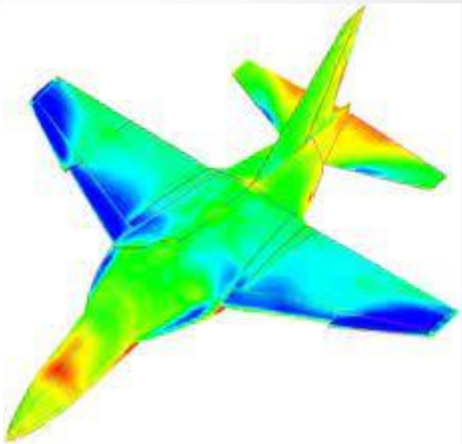
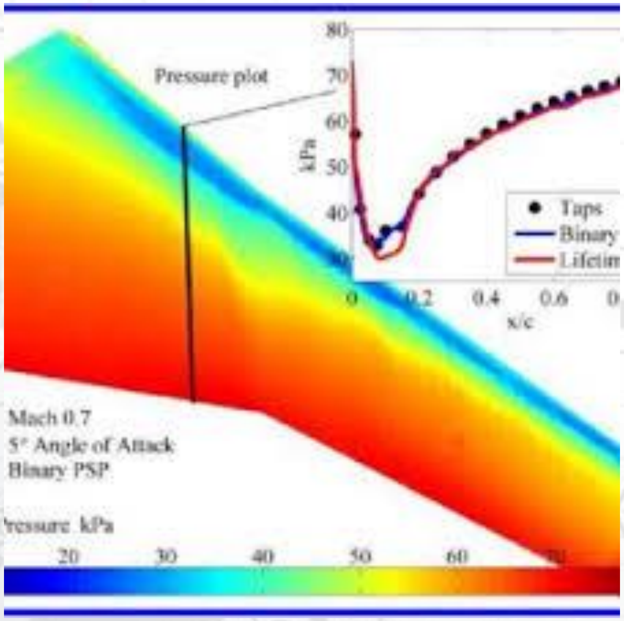
Static Pressure Testing

- ***Pressure testing***
  - Continuous pressure data using PSPs
    - Complex
    - Expensive
    - Very effective
      - Now both static and unsteady pressure

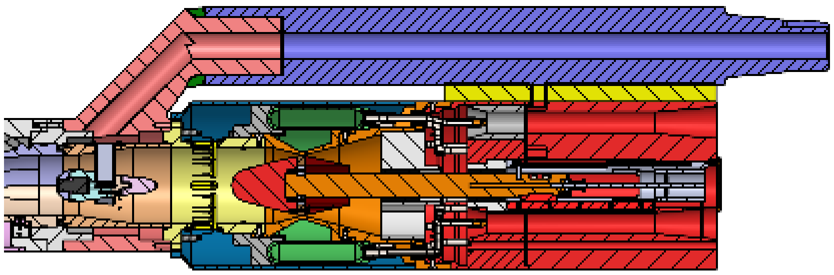
  - Not in use at the CSIR!





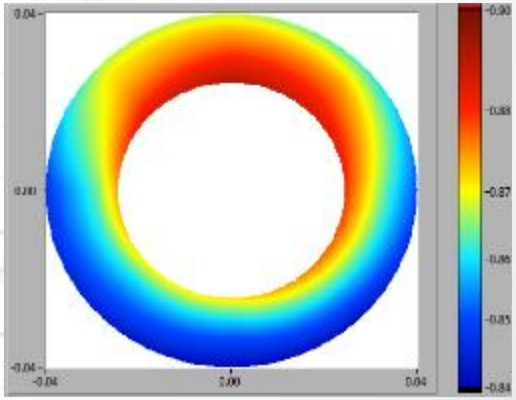
Subsonic inlet characterization

- ***Requirement:***
  - To characterize the AIP flow in terms of :
    - Total pressure recover
    - Distortion coefficients
  - Active mass flow control
  - Inlet duct pressure distribution and flow vizualisation



Subsonic inlet characterization

- ***Measurements:***
    - Scanivalve ESPs for the 40 probe rake
    - Scanivalve ESPs for the remaining pressures



Dynamic Derivatives

- ***Premise:***
  - Good fortune to encounter a job offer on wind tunnel testing of the Aermacchi M346 (now Leonardo-Finmeccanica Master)
  - Executed 4 test campaigns as company WT test engineer
    - 2 transonic external stores carriage loads entries at NLR Amsterdam
    - 2 low speed small-amplitude forced-oscillation tests to measure the aircrafts dynamic derivatives at ONERA in Lille.

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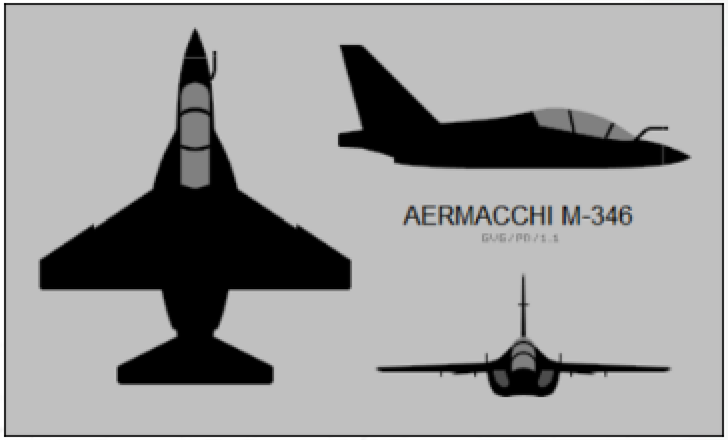
Dynamic Derivatives

- ***The Aircraft:***
  - Light weight two-seater twin-engine fly-by-wire trainer
  - Empty weight: 4900 kg
  - MTO weight: 9600 kg
  - Max speed: M0.95
  - Range: 1925 km
  - Endurance: 2hrs 45min
  - ***Operators:***
    - Italy
    - Isreal
    - Egypt
    - Greece
    - Azerbaijan
    - Nigeria
    - Poland
    - Qatar
    - Signapore
    - Turkmenistan



Dynamic Derivatives

- ***Requirements:***

	Dynamic Derivative Coefficients	Combined terms
from pitch-oscillations	$C_{Nq} + C_{N\alpha^*}$	
	$C_{mq} + C_{m\alpha^*}$	Damping derivative
from yaw-oscillations	$C_{nr} - C_{n\beta^*} \cos\alpha$	Damping derivative
	$C_{lr} - C_{l\beta^*} \cos\alpha$	Cross derivative
	$C_{Yr} - C_{Y\beta^*} \cos\alpha$	

- ***Oscillation around an axis methodology:***
  - Gives combined derivatives (except roll axis)

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Dynamic Derivatives

- ***Requirements:***

Configuration :	Nose Droops	Flaps	HT	VT
CRuise	0°	0°	0°	0°
MAN –20	-20°	0°	0°	0°
MAN –30	-30°	0°	0°	0°
MAN-30 HT off	-30°	0°	off	0°
MAN –30 VT off	-30°	0°	0°	off
LAND	-25°	37.5°*	0°	0°
TO	-20°	-20°	0°	0°

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Dynamic Derivatives

- ***Requirements:***
- Airframe attitudes and tunnel environmental parameters:
  - The test speed was chosen as *35m/s*, compatible with the model structural integrity
  - Angle-of-attack and sideslip ranges:
    - -10° to 30° or -10° to 60° depending on the configuration
    - With additional sweeps performed at 5° sideslip angle (only in pitch plane)
  - Oscillation frequencies:
    - ν = 1.2 Hz (Kc = 0.026 to comparable to TsAGI data)
    - ν = 3.0 Hz (Kc = 0.066, similar to 0.5Hz on Aircraft @ M0.2, 15Kft)
    - ν = 6.0 Hz (Kc = 0.133, similar to 1.0Hz on Aircraft @ M0.2, 15Kft)
  - Oscillation amplitude:
    - λ = 3° (compatible with required oscillation frequency values)
    - λ = 1° (to investigate oscillation amplitude effects on data)

Dynamic Derivatives

- Facility selection:
  - The approach selected was that of: “Small amplitude forced-oscillation tests” in a low-speed wind tunnel
  - The supplier required needed:
    - appropriate facilities
    - a proven track record in this type testing
    - as well as data post-processing capabilities
  - The supplier was identified as:

ONERA-Lille Center

In particular:

- The Applied Aerodynamics Department (DAAP) using the L1 wind tunnel

and in a second phase:

- The Systems Control and Flight Dynamics Department (DCSD) using the SV4 wind tunnel

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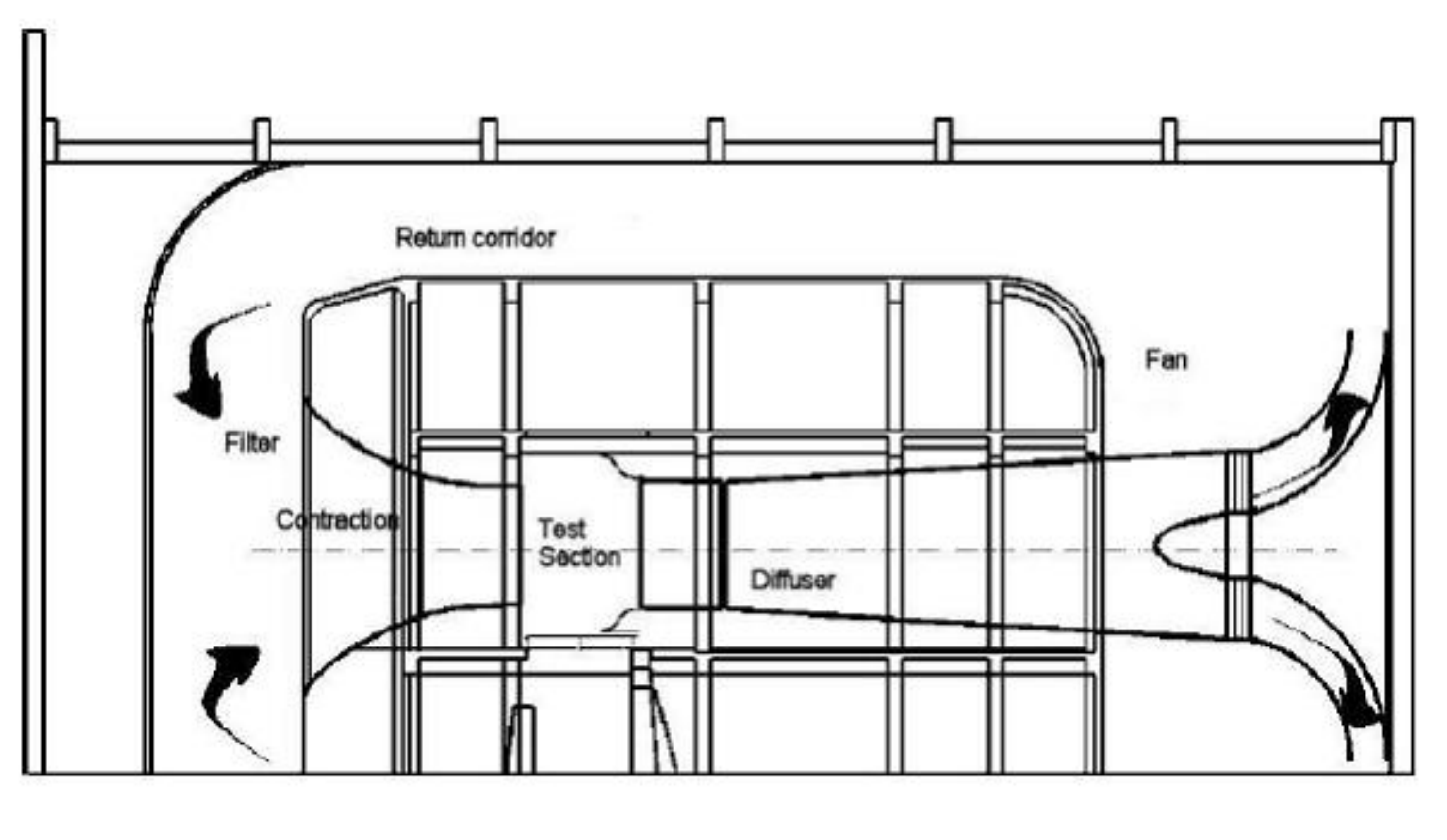
Dynamic Derivatives

- ONERA-Lille L1 wind tunnel:
  - Eiffel type, closed circuit wind tunnel
    - Open test section: 2.4m diameter, 2.4m test section length
    - Duct coefficient: 4.31
    - Max test speed: 60m/s
    - Turbulence: 1.3% (0-1KHz range)
    - Critical Re: 287000 (100mm sphere)

Dynamic Derivatives



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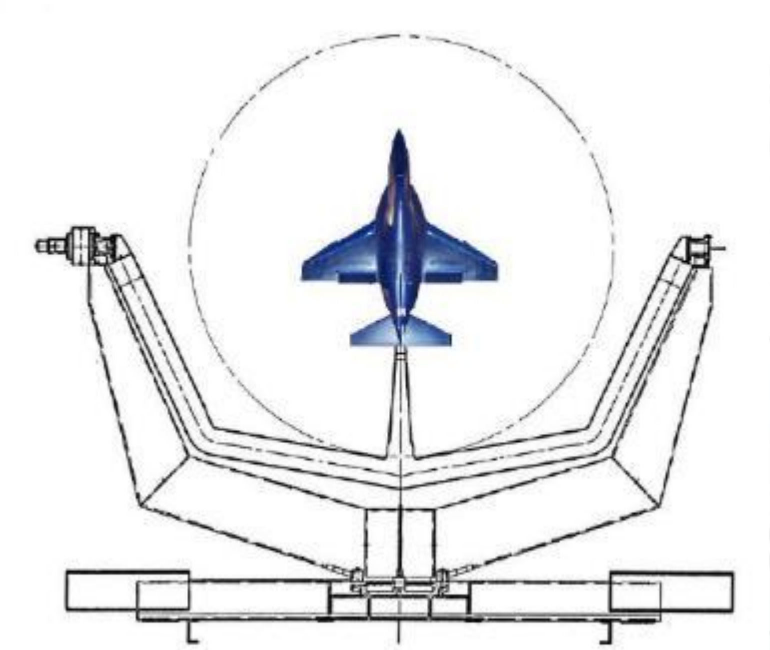
Dynamic Derivatives

PQR apparatus:

- *3 d.o.f. rotation rig about the main model axes:*
  - *Euler angles ϕ, θ and ψ and rotations p, q and r*
  - *-15° <ψ<20° manual, resolution of 0.05°*
  - *-50° <θ<90° motorised, θ'< 600° /s, θ"< 9000° /s^2, resolution 0.01°*
  - *-180° < ϕ<180° manual, 5° steps for straight sting*



Dynamic Derivatives

- Lateral dynamics in the ONERA-Lille SV4 vertical wind tunnel:
  - Eiffel type, closed circuit wind tunnel
    - Open test section: 4m diameter, 4m test section length
    - Duct coefficient: not available
    - Max test speed: 40m/s
    - Turbulence: not available
    - Critical Re: not available

"Tourne-broche" apparatus:

- *4 d.o.f. rotary balance rig:*
- *ϕ: lateral attitude of the model (roll), -180° <ϕ<180°, motorised ϕ'<2°/s*
- *θ: longitudinal attitude of the model, 0° <θ<45°, motorised θ'<0.3°/s*
- *ψ: heading angle of model, 0° <ψ<360°, motorised, Ω< 600°/s, Ω'< 50°/s^2*
- *λ: tilt angle between rotary axis and tunnel vertical axis;*
  - *0° <λ<30°, motorised, λ'<1°/s*

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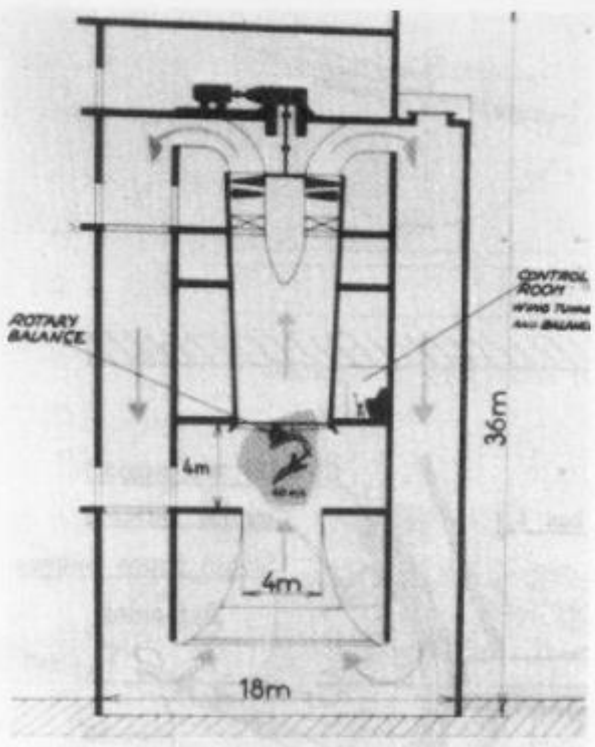
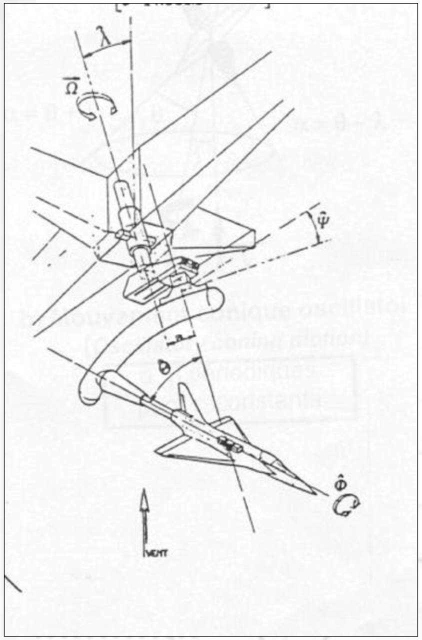
Dynamic Derivatives





Dynamic Derivatives

- Model characteristics:
  - Model main geometrical parameters:
    - Model scale: 1:11
    - Maximum fuselage length: 1.0445 m
    - Reference area, S_w: 0.1944 m^2
    - Reference span, b: 0.8836 m
    - Mean aerodynamic chord, C: 0.2436 m
  - Inertial parameters:
    - Model "gross" weight: 6.8 kg
    - Model ballast: 0.45 kg
    - Model CG: 4mm aft of B.R.C and PQR rotation centre
      21mm above B.R.C. and PQR rotation centre

Dynamic Derivatives

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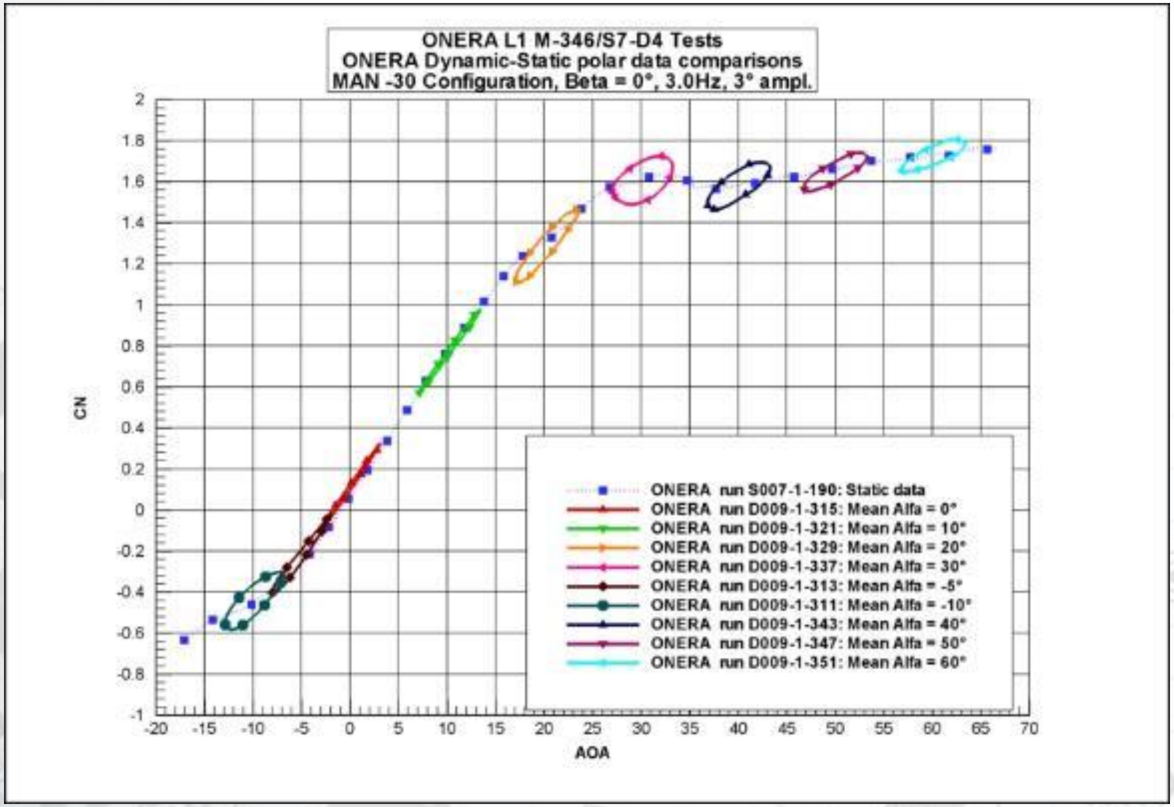
Dynamic Derivatives

- Instrumentation:
  - Same model instrumentation for both L1 and SV4 tunnel installations:
    - Load measurements:
      - ONERA Φ26 Nº6, 6 component internal strain-gauge balance, fitted to an ONERA straight sting in the L1 tunnel
      - In the SV4 tunnel, a sting was adapted to simulate the same set-up as in the L1 tunnel, so that the same balance and adaptors could be used.
    - Model acceleration measurements:
      - Adaptors for 5 accelerometers have been positioned in the aluminium stiffener structure:
        - » 2 forward accelerometers sensing in the Y-axis and Z-axis directions
        - » 2 rear mounted accelerometers sensing in the Y-axis and Z-axis directions
        - » 1 mid-mounted accelerometer sensing in the X-axis direction

Dynamic Derivatives

- L1 Results:
  - Some typical results (dynamic measurements):



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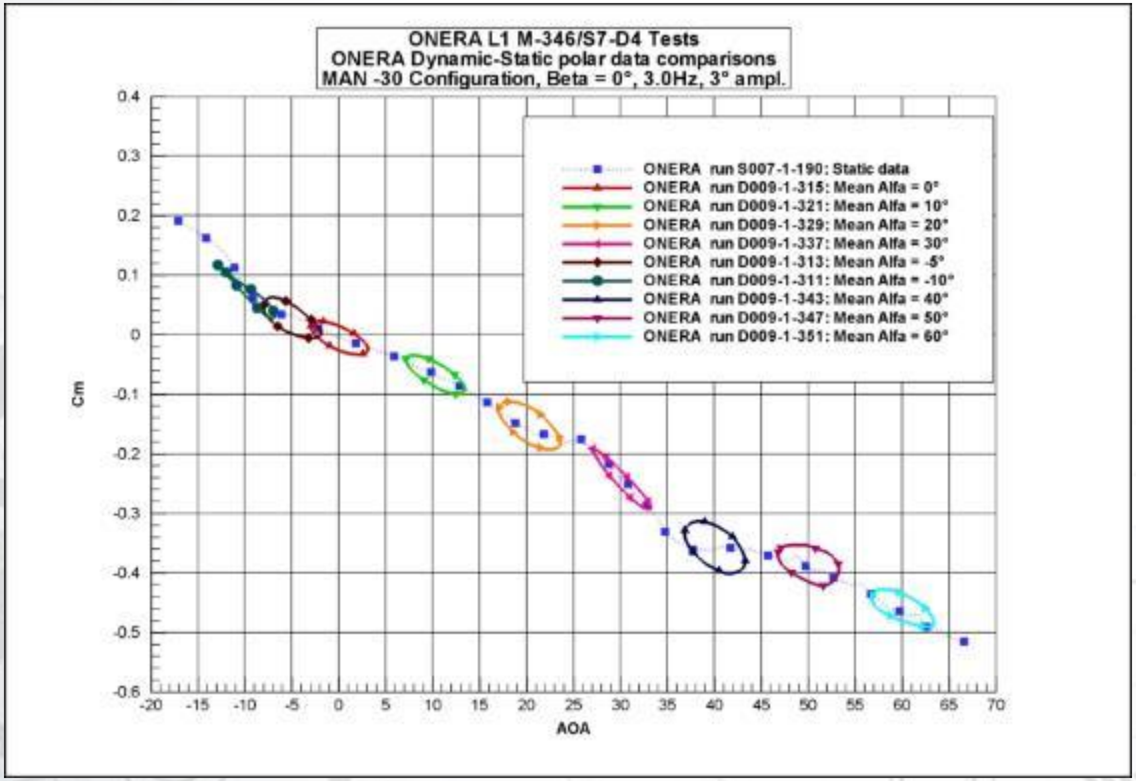
Dynamic Derivatives

- L1 Results:
  - Some typical results (dynamic measurements):



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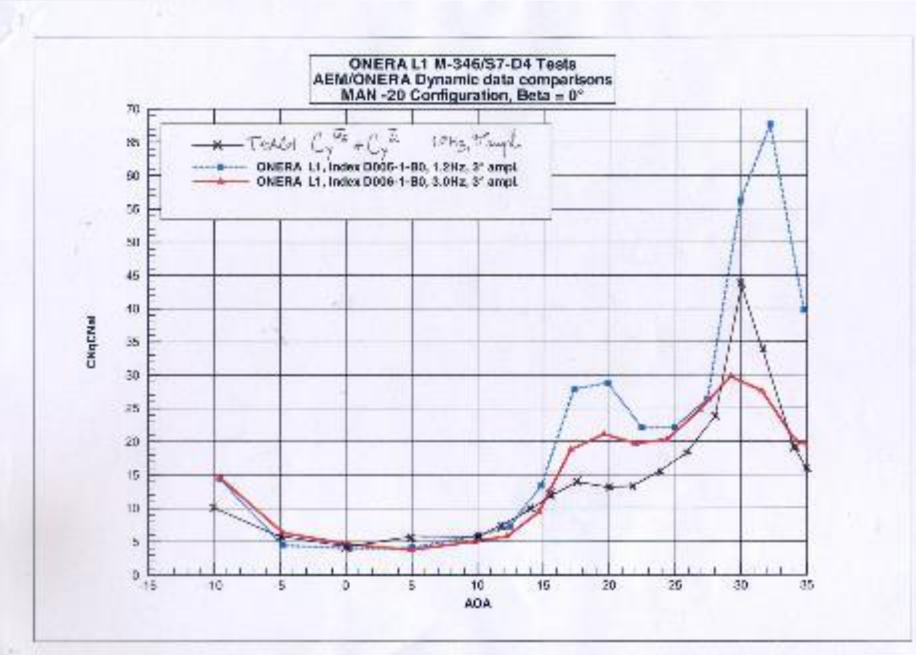
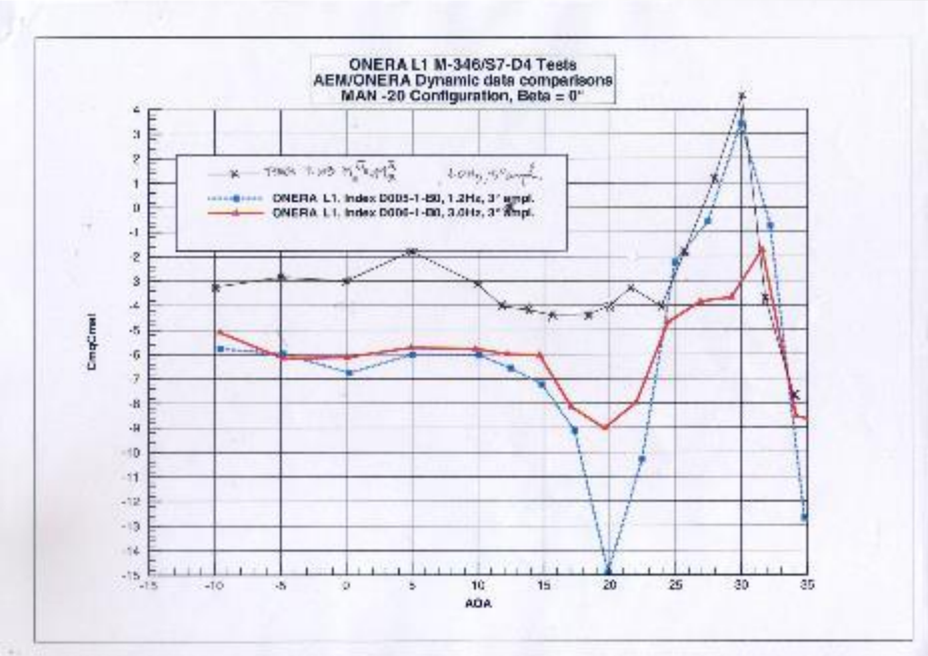
Dynamic Derivatives

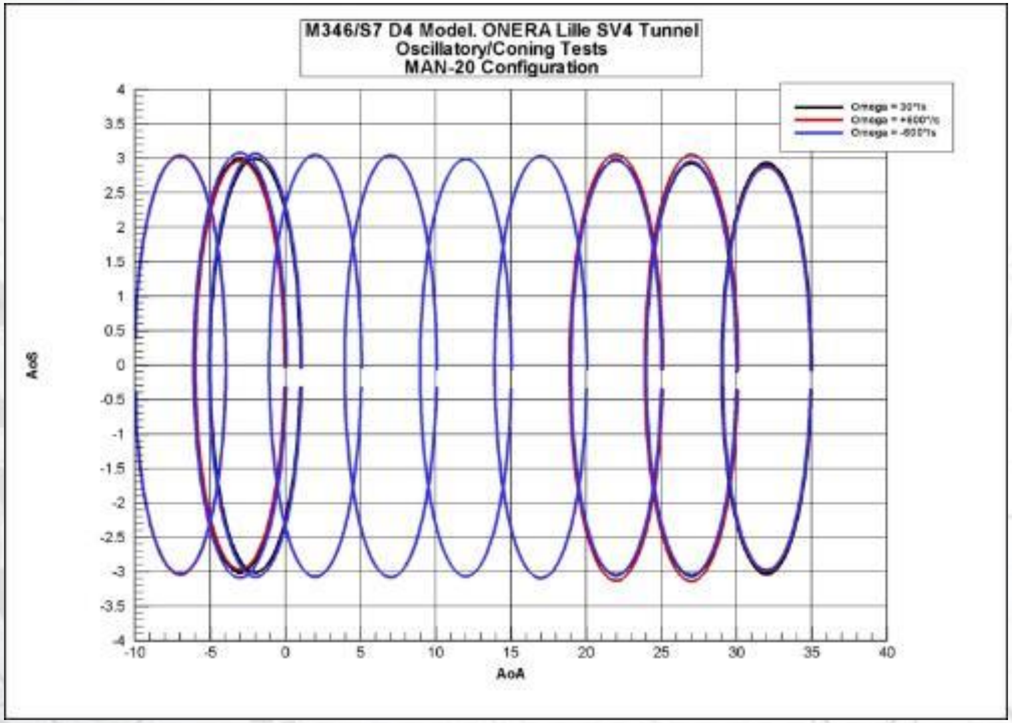
- L1 Results:
  - Some typical results (dynamic measurements):





Dynamic Derivatives

- SV4 Results:
  - Some typical results (oscillatory/coning test measurements):



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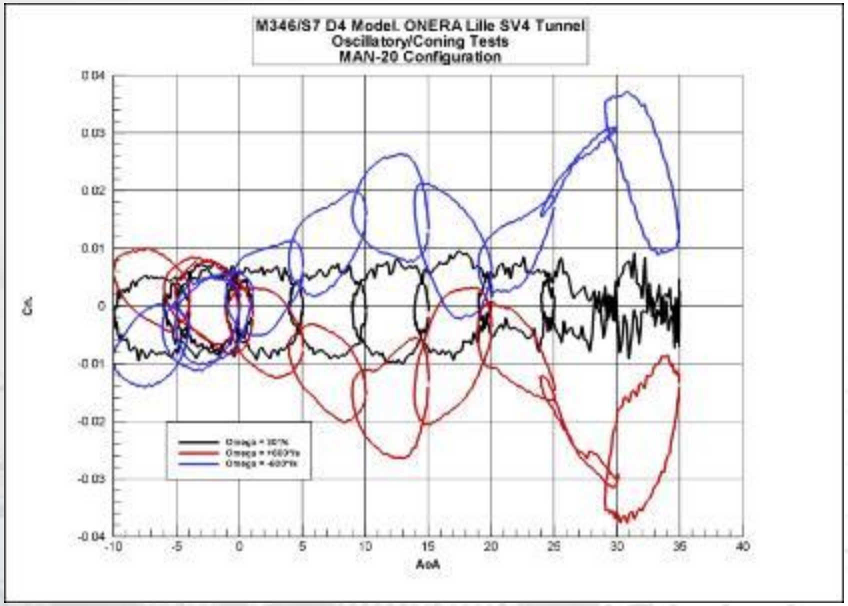
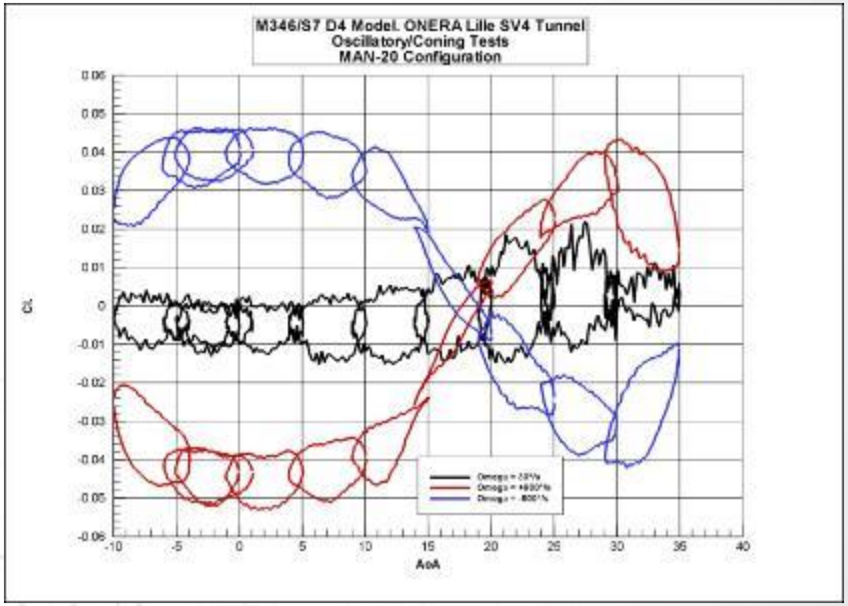
Dynamic Derivatives

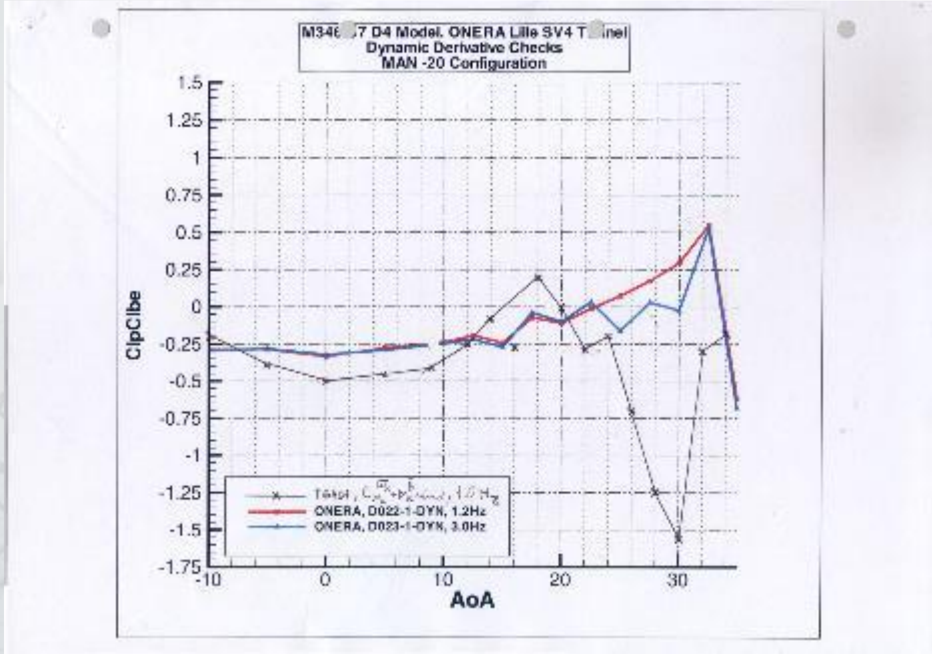
- SV4 Results:
  - Some typical results (oscillatory/coning test measurements):

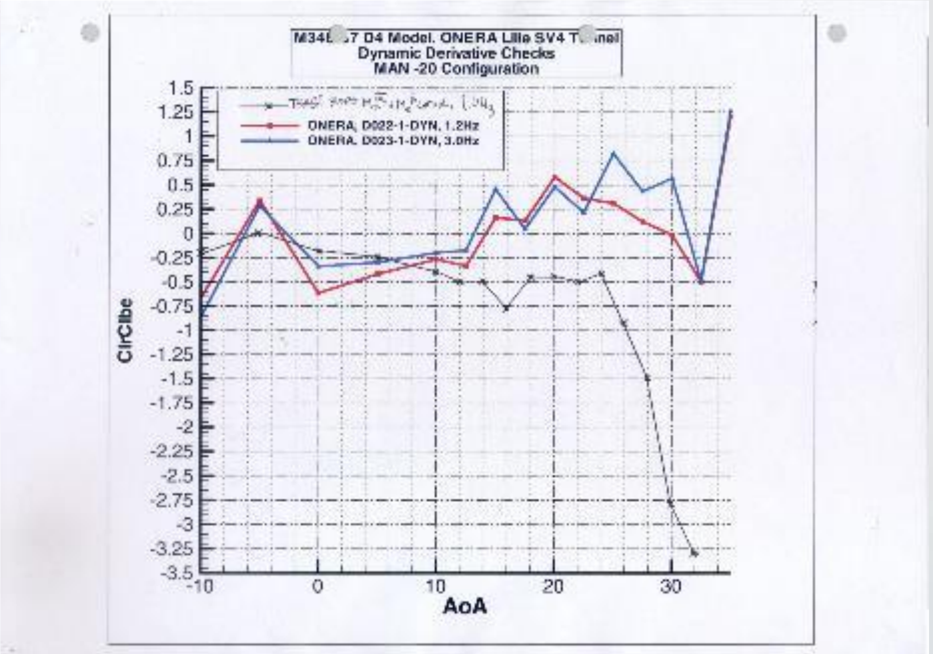




Dynamic Derivatives

- SV4 Results:
  - Some typical results (oscillatory/coning test measurements):





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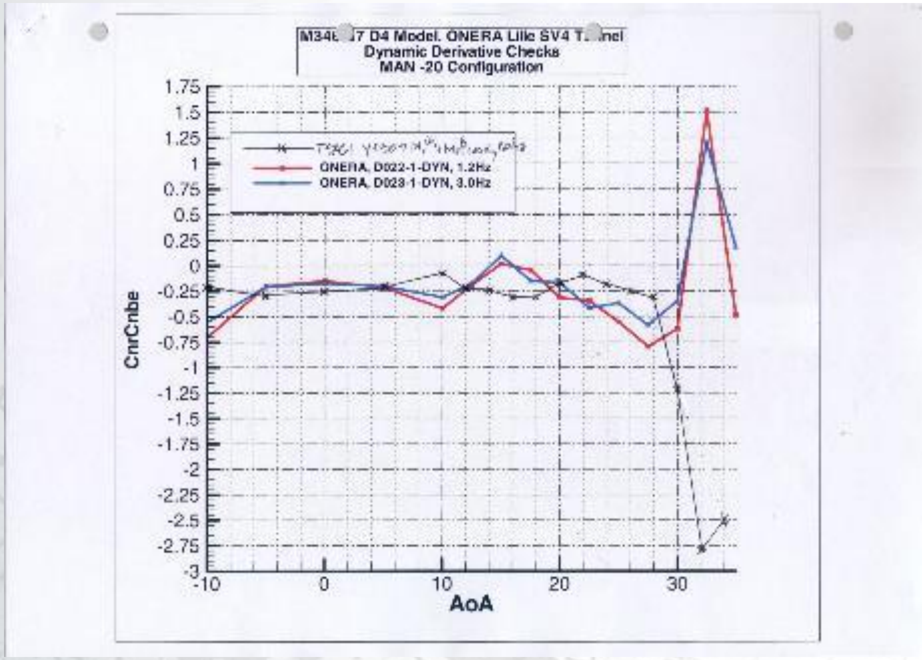
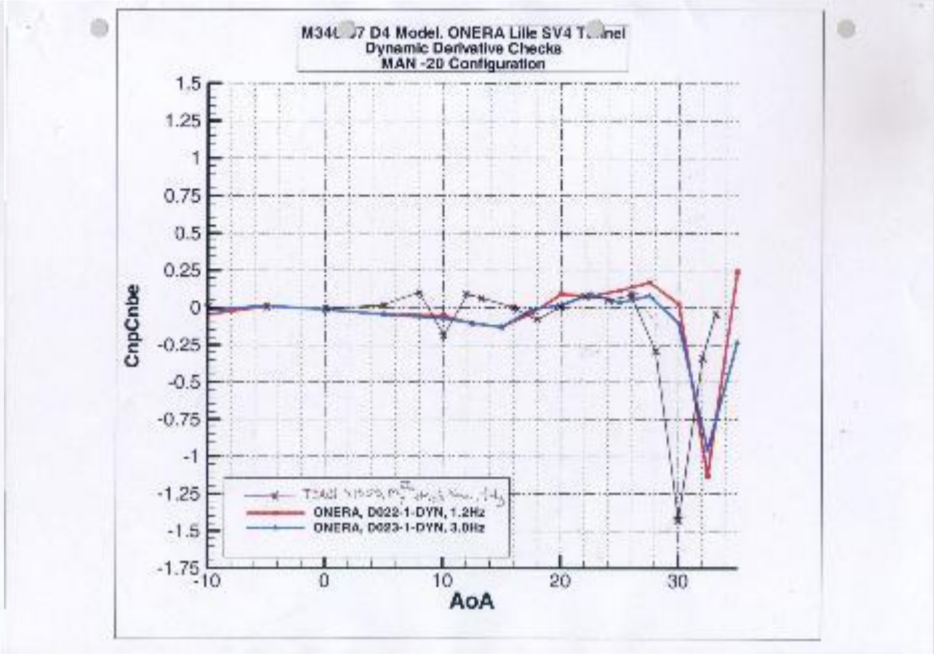
Dynamic Derivatives

- SV4 Results:
  - Some typical results (oscillatory/coning test measurements):





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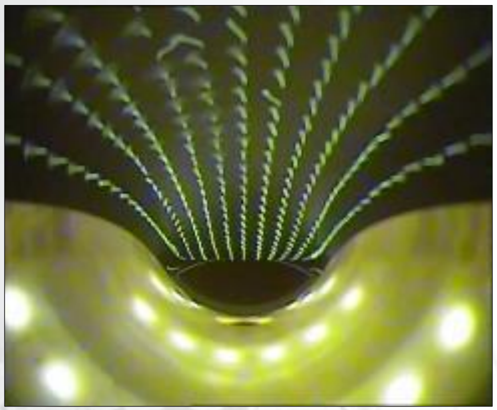
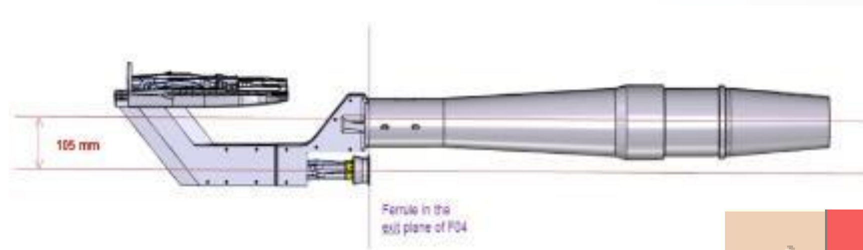
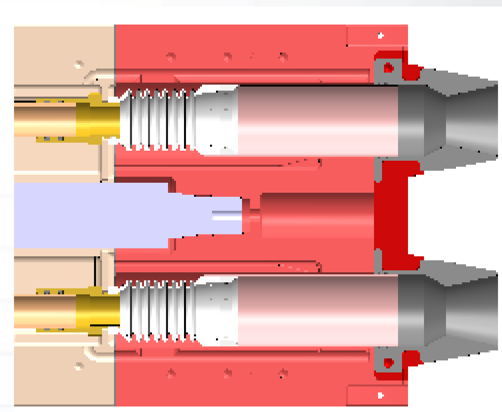
Wind tunnel techniques

– ….and many other techniques not described here!







– ….Thank you

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