

Nonlinear Aeroelasticity, LCO, and KTH Test Summary

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WORKSHOP ON NONLINEAR AEROELASTICITY AND LIMIT CYCLE
OSCILLATIONS

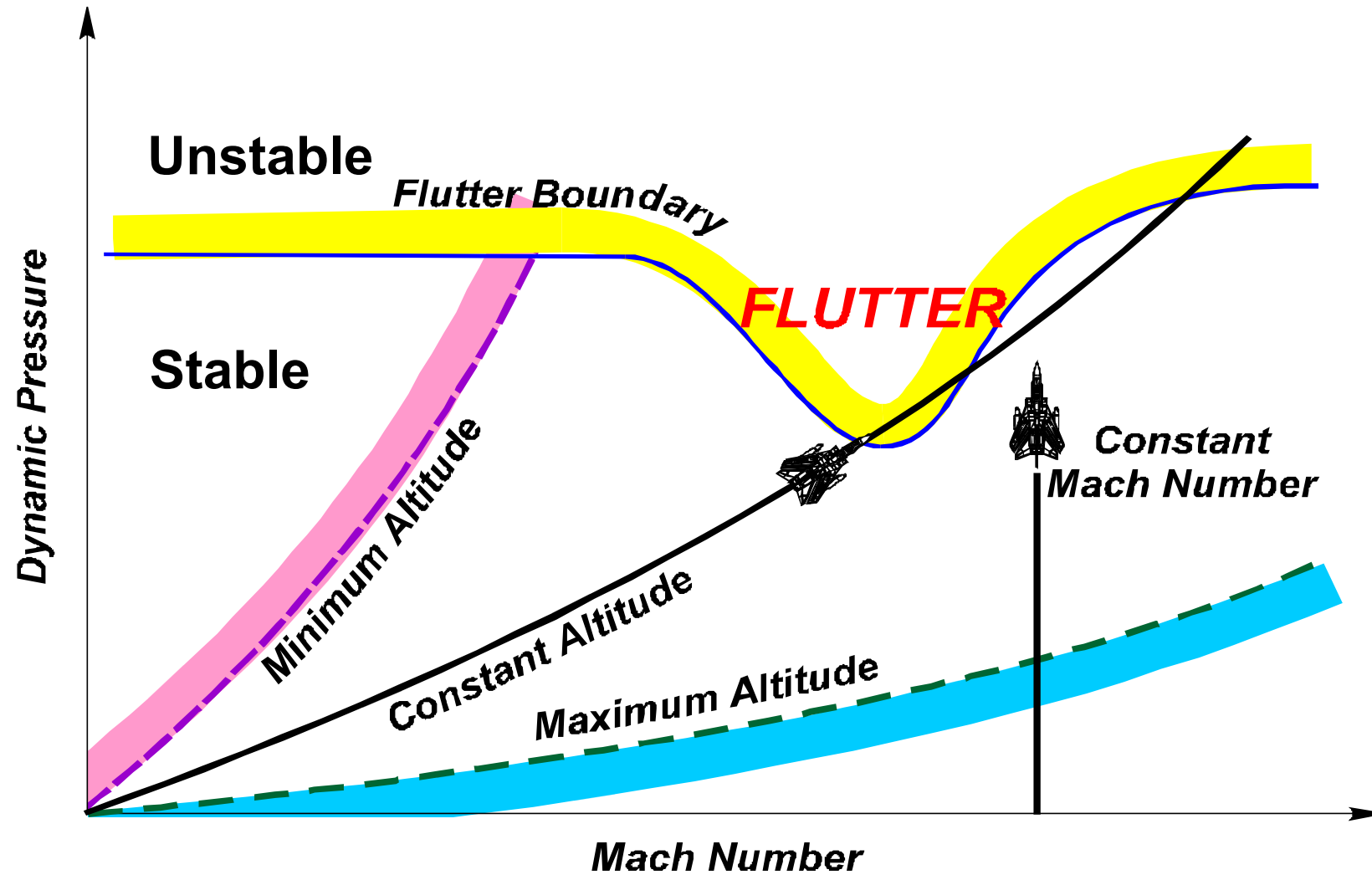
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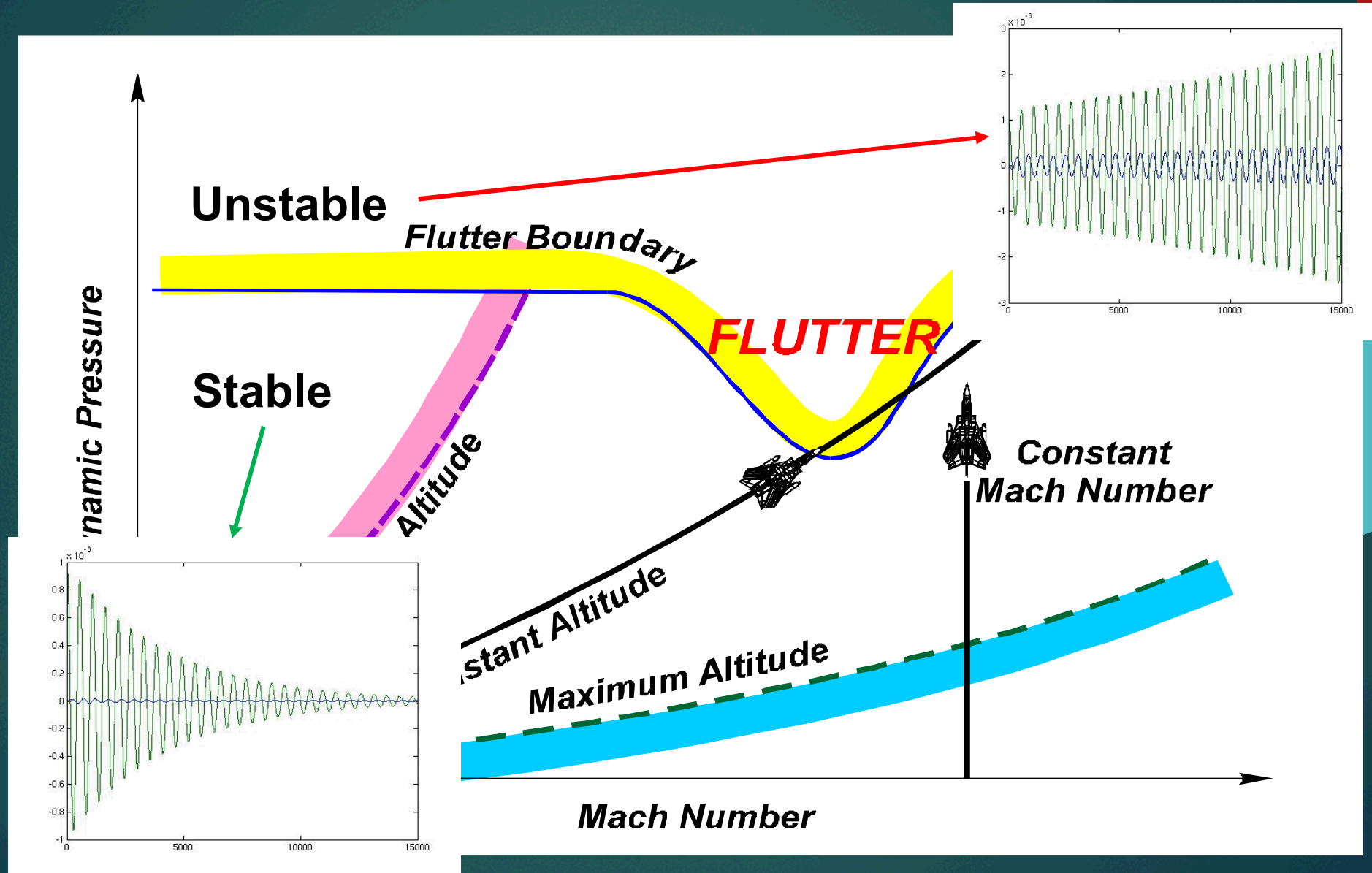
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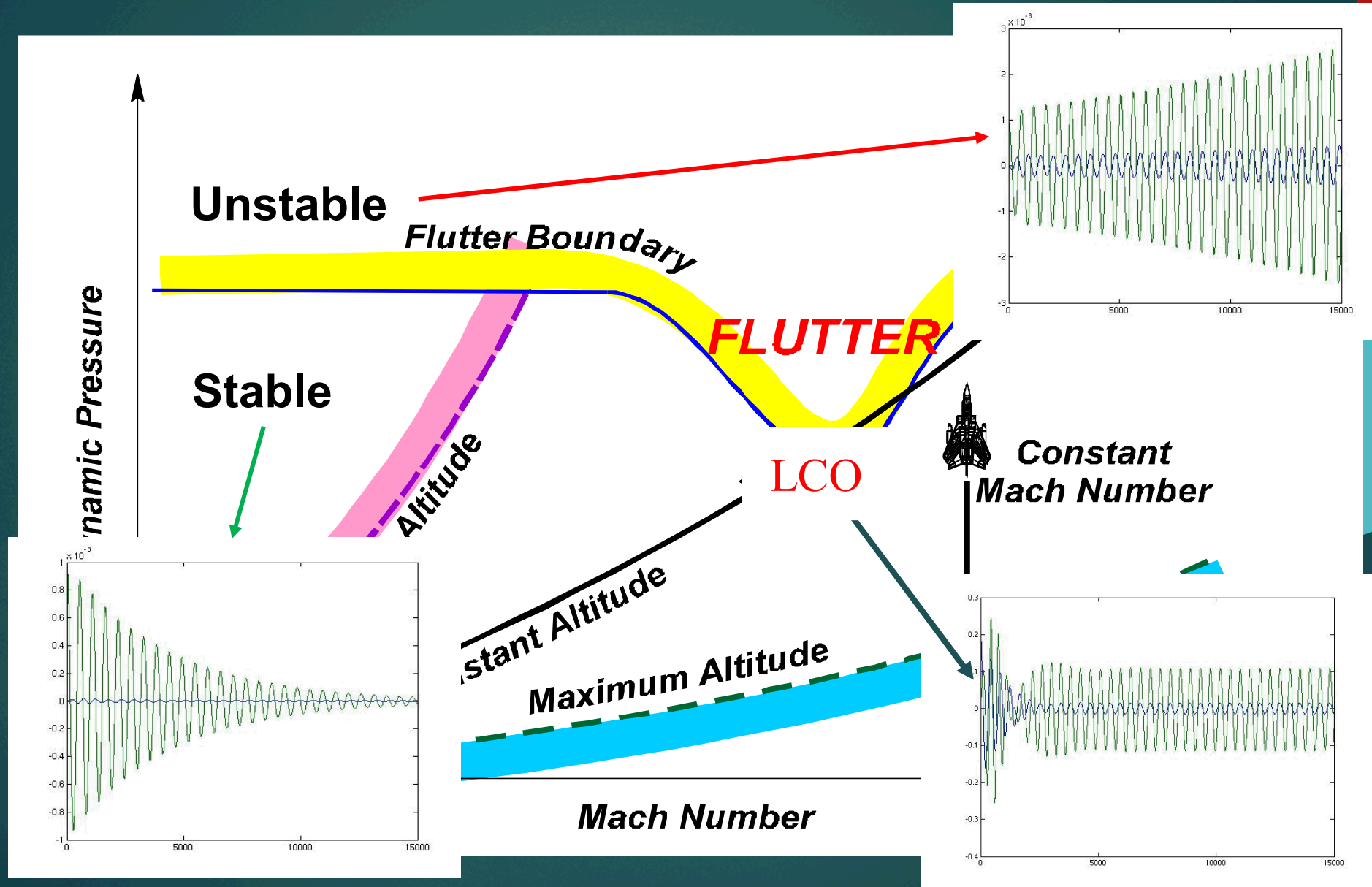
Flight Flutter Testing



Flight Flutter Testing



Flight Flutter Testing



Nonlinear Aeroelasticity and Limit Cycle Oscillations (LCO)



Linear Aeroelasticity

- ▶ Linear unsteady aerodynamic models
 - ▶ inviscid, irrotational, small disturbance
 - ▶ Planform model, panels (typically)
- ▶ Linear structural dynamic models (linear FEM or modal model)
- ▶ Fast, efficient solutions
- ▶ Static trim and loads
- ▶ Dynamic loads (gust) and flutter
- ▶ Used extensively by industry for parametric variations and certification analyses



Nonlinear Aeroelasticity

- ▶ Nonlinear unsteady aerodynamic models
 - ▶ TSD, Euler/Navier-Stokes (RANS), LES,...
 - ▶ Full geometry with details
- ▶ Nonlinear structural models (not modal models)
- ▶ Complex, expensive solutions
- ▶ Static trim and loads
- ▶ Dynamic loads (gust) and flutter
- ▶ CFD used by industry mostly for steady/static loads cases



Limit Cycle Oscillation (LCO)

- ▶ An equilibrium point of the nonlinear aeroelastic system
- ▶ Induced by nonlinear unsteady aerodynamics (shock dynamics, separated flow) and/or nonlinear structural dynamics (geometric and material nonlinearities)
- ▶ While Euler solutions can generate LCOs, viscosity yields improved accuracy (shock strength, position)
- ▶ Most common aeroelastic CFD codes currently consist of nonlinear unsteady aerodynamics with linear structural dynamics
- ▶ Van der Pol system is a simple example of LCOs

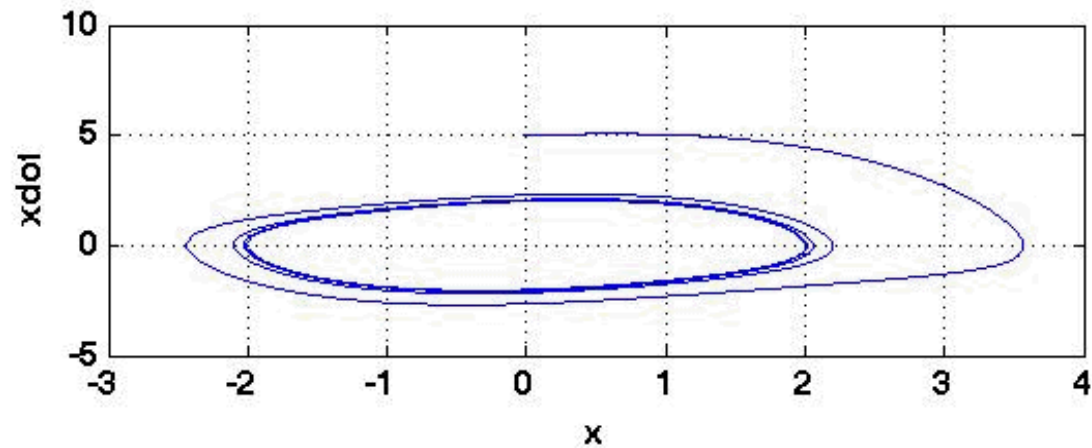
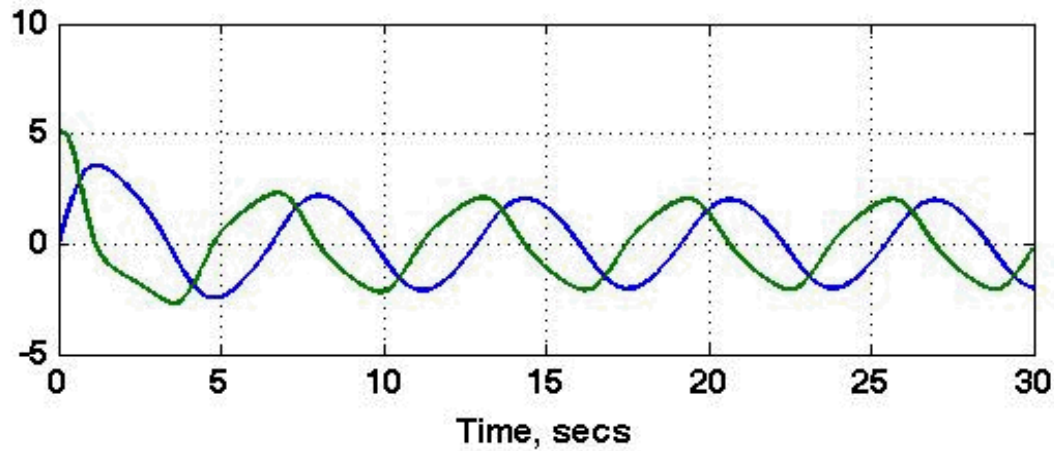
Van der Pol

$$\begin{aligned}\dot{x}_1 &= x_2 \\ \dot{x}_2 &= -x_1 + \varepsilon(1 - x_1^2) x_2\end{aligned}$$

- ▶ Classic nonlinear system
- ▶ Simplest nonlinear system that exhibits limit cycle oscillations
- ▶ LCOs evident across several engineering and science disciplines

Van der Pol

x and xdot

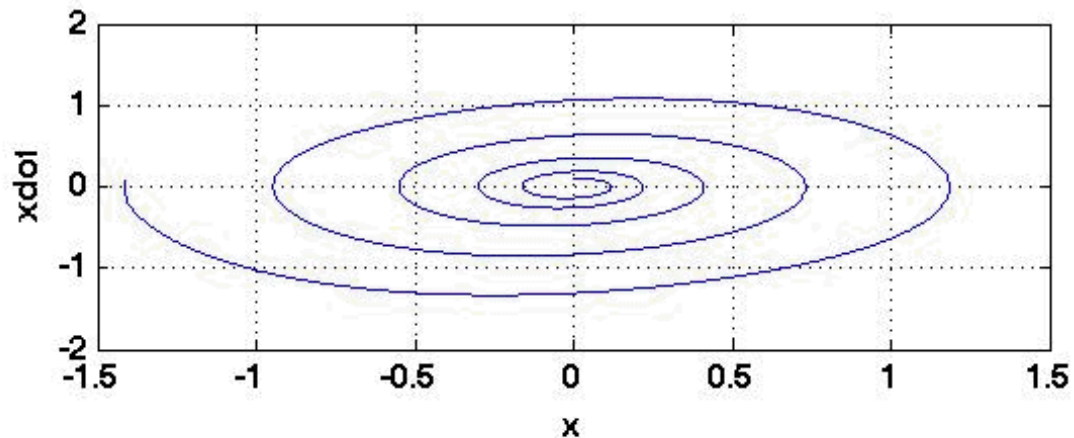
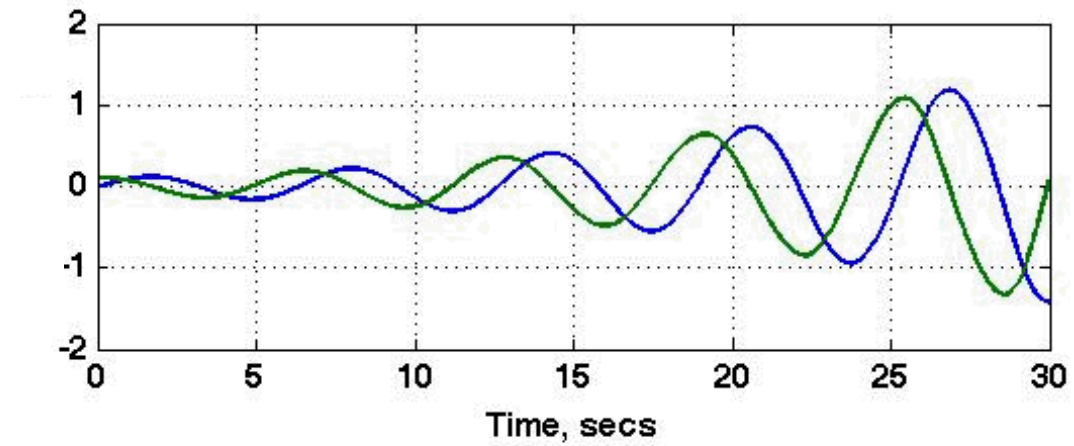


$$\varepsilon = 0.1$$

$$\text{IC: } x = 0, \dot{x} = 5.0$$

Van der Pol

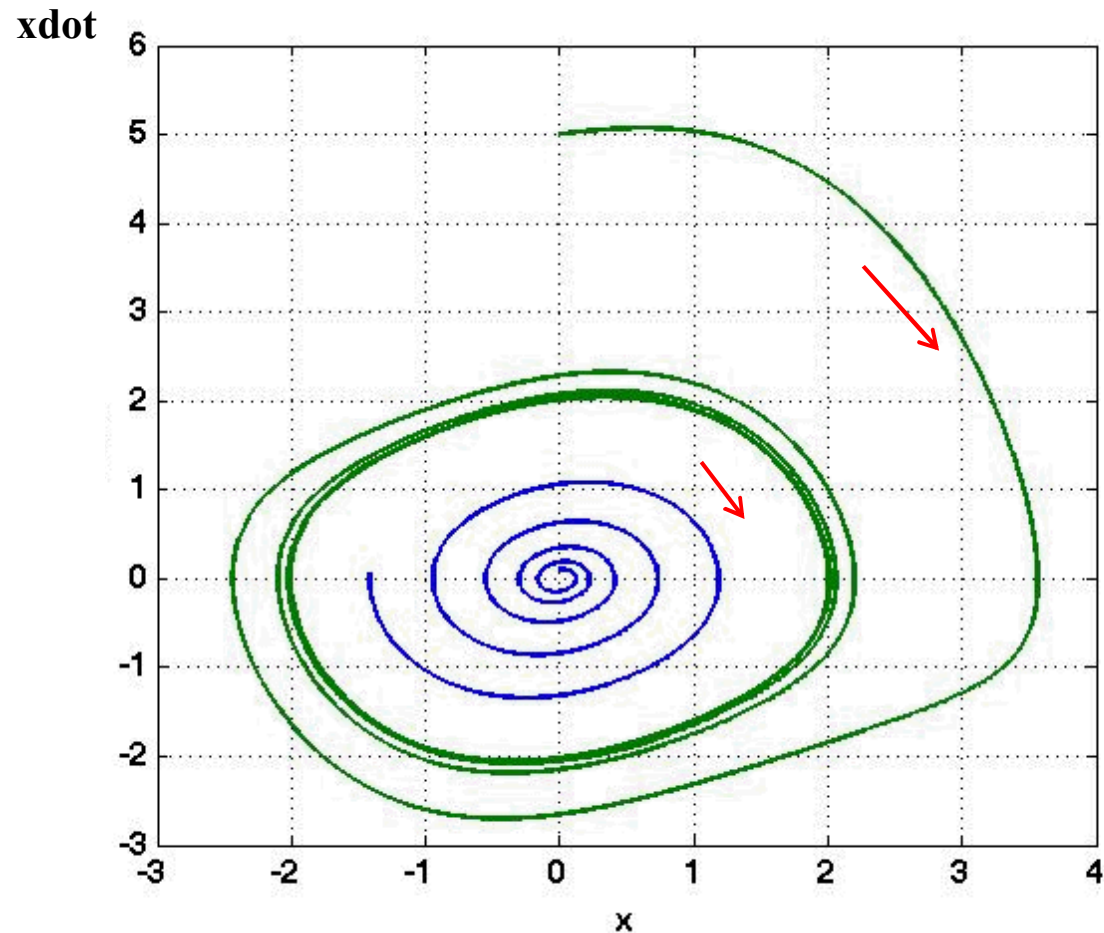
x and xdot



$$\varepsilon = 0.1$$

$$\text{IC: } x = 0, \dot{x} = 0.1$$

Van der Pol



$$\varepsilon = 0.1$$



F-16 LCO (Denegri)



Aircraft Flutter

Chuck Denegri (Eglin)

- Self-excited, divergent oscillation of a flexible airframe or airframe component during flight
- Energy is absorbed from the airstream and drives the oscillation
- Usually increases with airspeed and worsens with more flexible structure
- Often destructive
- Linear flutter - oscillations diverge at speeds above critical speed
 - Linear behavior represented well by linear analysis methods

Aircraft LCO

Chuck Denegri (Eglin)

- Self-sustained oscillation of an airframe or airframe component that achieves a constant amplitude for stabilized flight conditions
 - May be exacerbated or diminished with increasing load factor
 - Nondivergent, but not necessarily nondestructive
 - Nonlinear flutter - oscillations constant over a range of speeds
 - F-16 exhibits “classical” (linear) flutter in a few cases, but mostly exhibits LCO
- Nonlinear behavior requires development of pertinent nonlinear analysis methodologies
 - Classical linear flutter analyses fail to provide insight into LCO behavior (e.g., onset speed and response amplitude)
 - Some emerging methods

Background

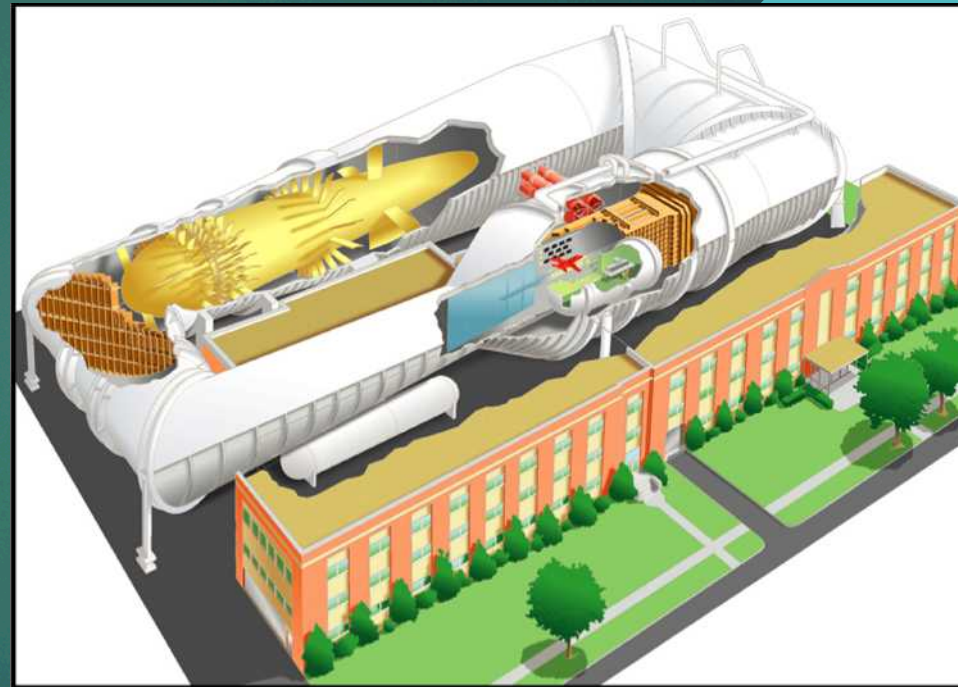
- ▶ Aeroelastic limit cycle oscillation (LCO) events are a problem for several military and commercial aircraft.
- ▶ LCO events can be manifested in the response of the structure and/or the control surfaces as a result of freeplay, other structural nonlinearities, and/or nonlinear aerodynamics.
- ▶ LCO events result in increased structural fatigue, resulting in a significant reduction to structural life and integrity.
- ▶ There is a great deal of research currently underway at various organizations to develop methods to predict and control LCO events.
- ▶ In order to provide serious validation to any of these methods, high-quality, transonic aeroelastic LCO data is necessary.

Background

- ▶ Although there have been several LCO-related experiments conducted by various organizations, these data are usually proprietary so cannot be shared amongst researchers across different organizations.
- ▶ A collaborative effort between the Royal Institute of Technology (KTH, Sweden) and NASA Langley Research Center seeks to acquire high-quality, transonic LCO data that can be shared across multiple organizations.
- ▶ The first test was conducted at the NASA Transonic Dynamics Tunnel (TDT) in summer of 2016.
- ▶ Effort funded by KTH and NASA (Commercial Supersonic Technology, Transformational Technologies & Tools, Advanced Air Transport Technologies, Aeronautics Evaluation & Test Capabilities, Research Directorate)

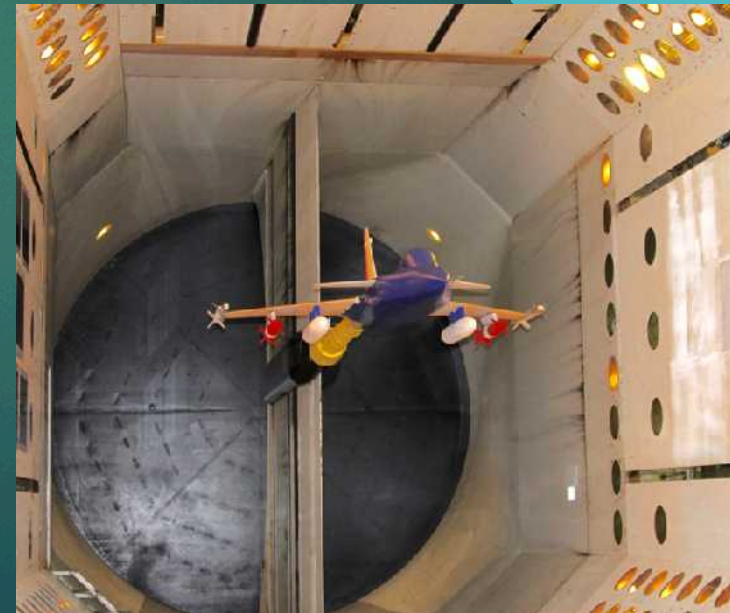
Transonic Dynamics Tunnel (TDT)

- ▶ Continuous flow transonic tunnel, slotted 16 x 16 feet test-section
- ▶ Up to $M=1.2$
- ▶ R-134a or Air
- ▶ Auxiliary tunnel systems
 - ▶ Safety features
 - ▶ Airstream oscillation system
 - ▶ Motor generator sets, with variable frequency
 - ▶ Hydraulic power
 - ▶ Chilled water cooling
 - ▶ High-pressure air or R-134a injection
- ▶ Dynamic synchronous data system

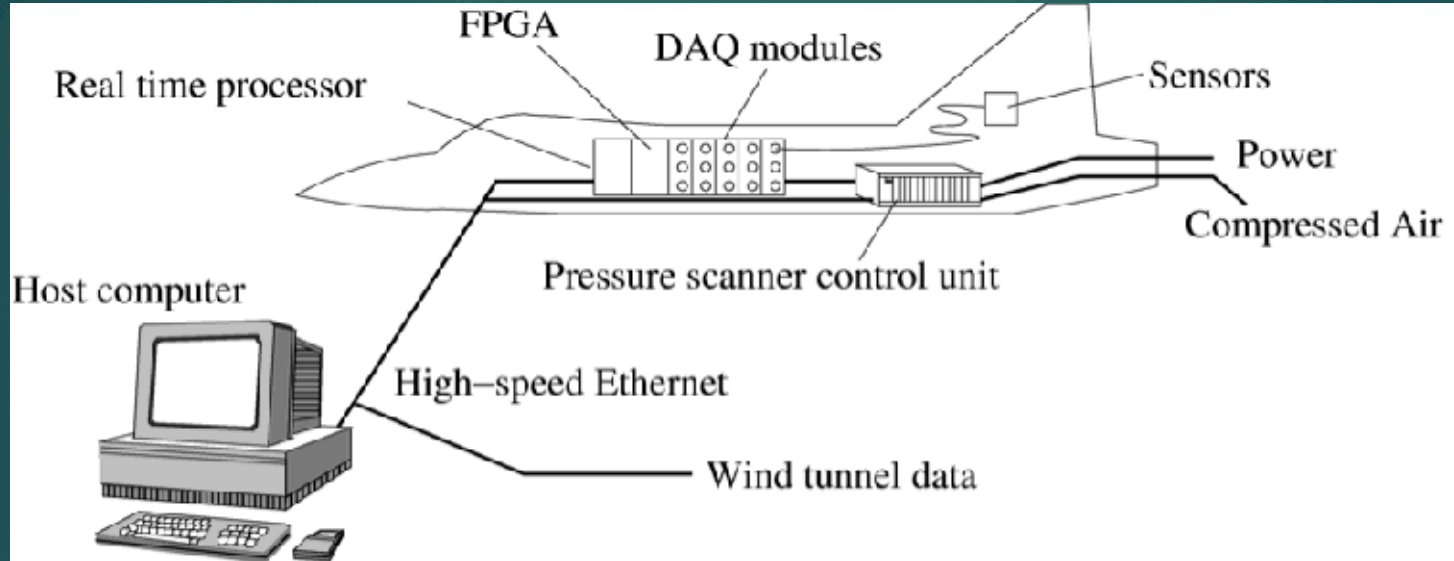


KTH-NASA Wind-Tunnel Model

- ▶ Based on a fighter configuration that was tested in the Transonic Dynamics Tunnel (TDT) in mid 1980s
- ▶ Full-span generic configuration, sting mounted
- ▶ 10' fuselage x 6' wing span
- ▶ Flexible wings with store attachments
- ▶ Rigid canards with freeplay
- ▶ Rigid fuselage and vertical tail
- ▶ On-board instrumentation
- ▶ Model designed and fabricated at KTH
- ▶ Composite (fiberglass) wings with foam core



Data Acquisition



- On-board processor and data acquisition package
- Data acquired in parallel with NASA data acquisition system
- Data transmittal via high-speed Ethernet connection
- Significantly reduces cabling that needs to be routed

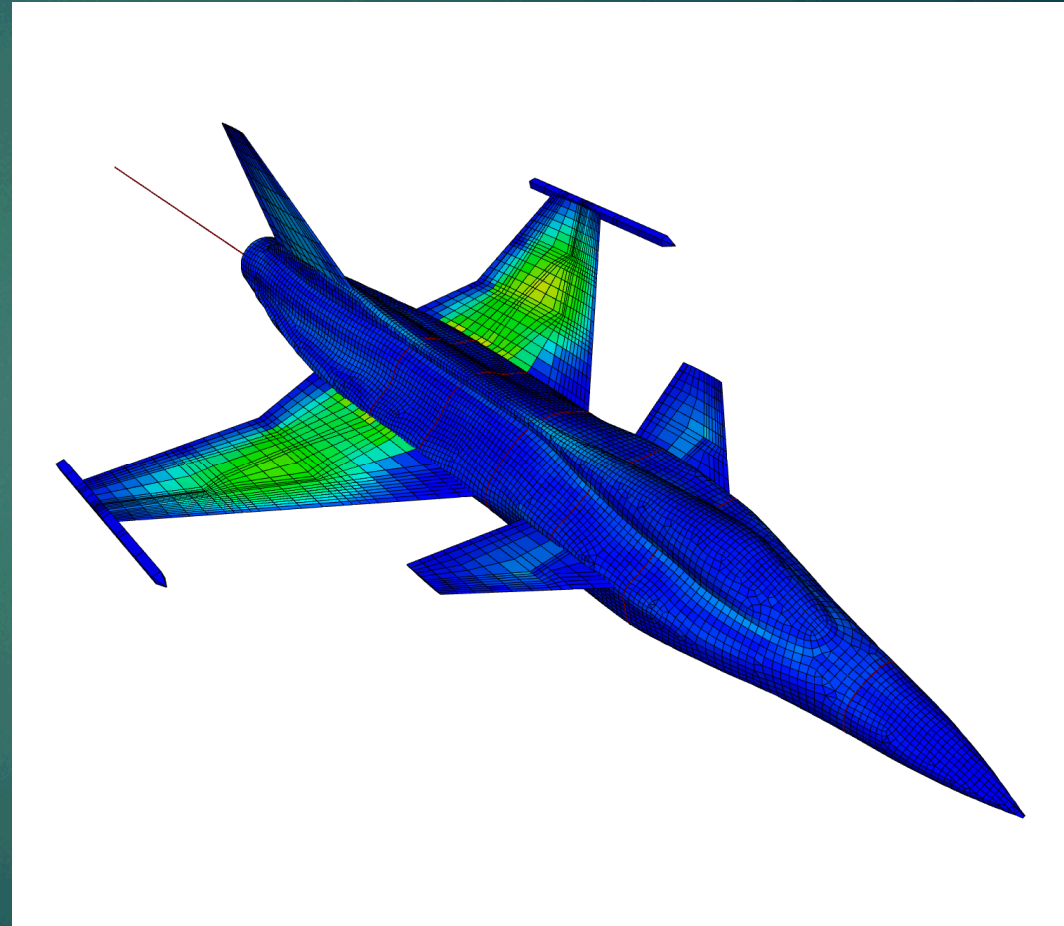
Deflection Measurement

- IR-based, noncontact system used to measure deflections (Qualisys)
- System has been used at the KTH low-speed wind tunnel
- System captures the positions of reflective targets at 500-1000Hz
- Can capture high-speed video
- The large targets in figure are used for calibration only, not during wind-on testing



Finite Element Model (FEM)

- ▶ Full-span configuration including sting
- ▶ 15,718 total grid points
- ▶ 17,913 total elements
- ▶ Material properties from supplier data sheets
- ▶ Some calibration performed using stiffness testing data
- ▶ Additional development and validation was performed based on available data

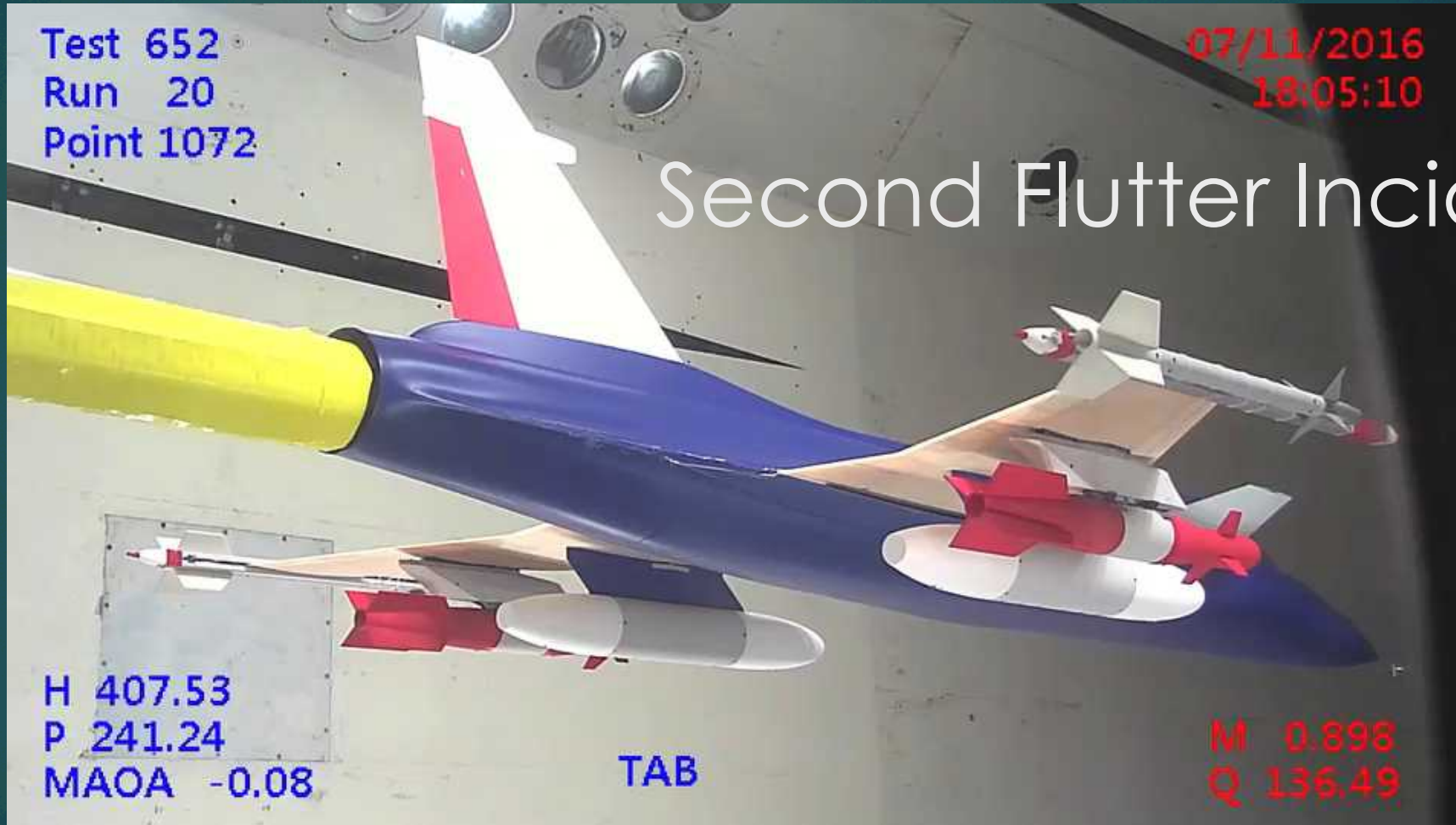


Wind-Tunnel Test (Flutter)

- ▶ Test lasted five weeks (end of May to early July, 2016)
- ▶ Three configurations tested, in this order:
 - ▶ Configuration 1: “Clean” wing (includes tip stores)
 - ▶ Configuration 2: Configuration 1 plus under wing stores
 - ▶ Configuration 3: Configuration 2 plus ballast added to tip stores
- ▶ Large amounts of data acquired continuously by KTH data acquisition process
- ▶ Two flutter mechanisms encountered (Configuration 3) at transonic conditions
- ▶ Safely pulled away from first flutter incident
- ▶ Second flutter incident resulted in damage to wing tips



KTH Flutter Testing: View from the Control Room



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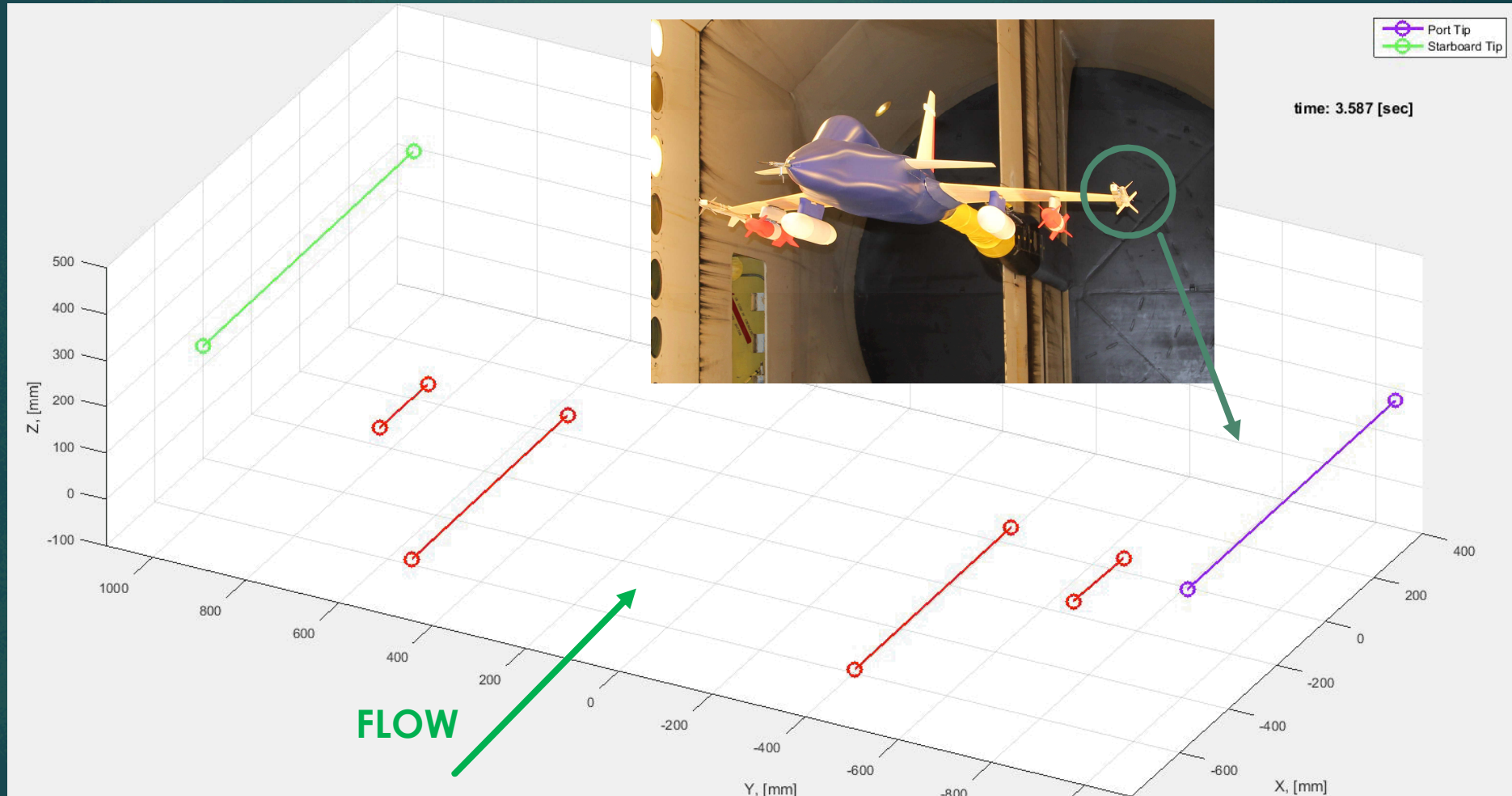
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Second Flutter Incident



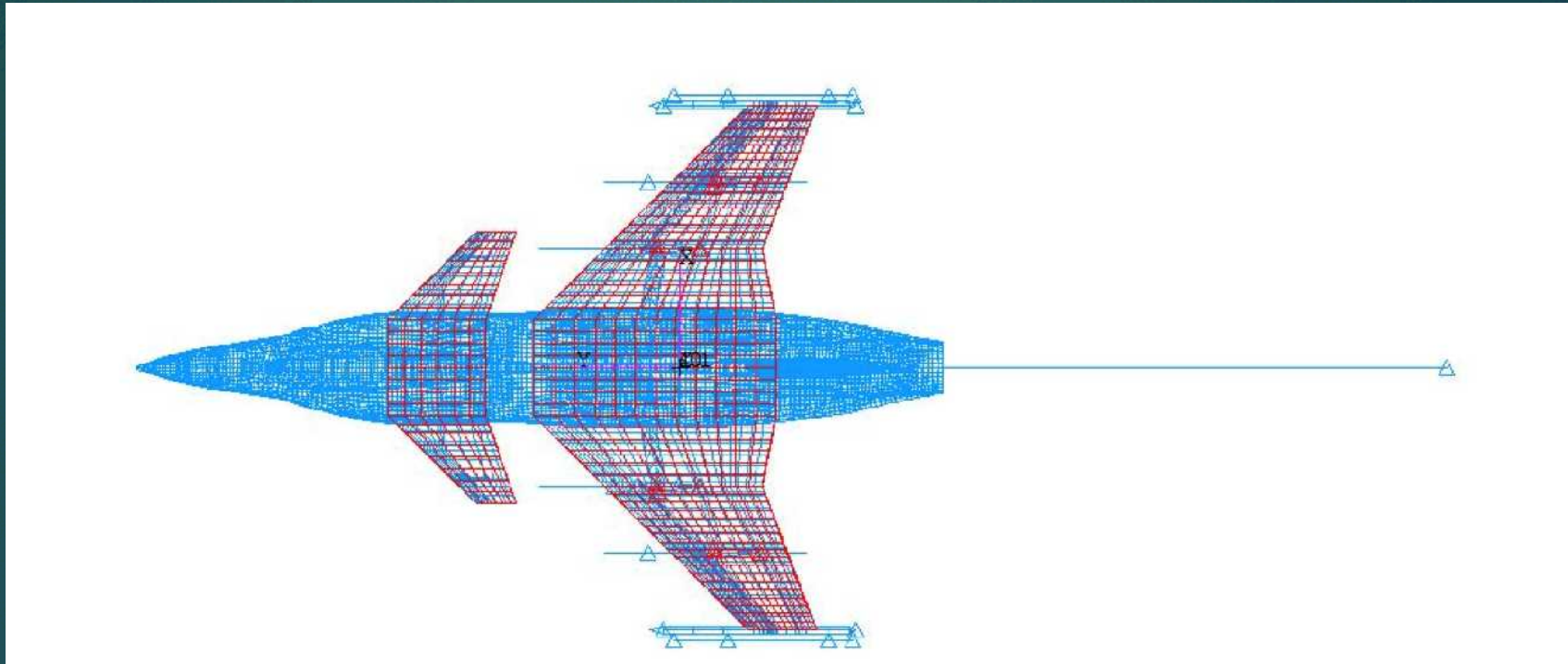
Unsteady deflection measurements

Computational Models and Results



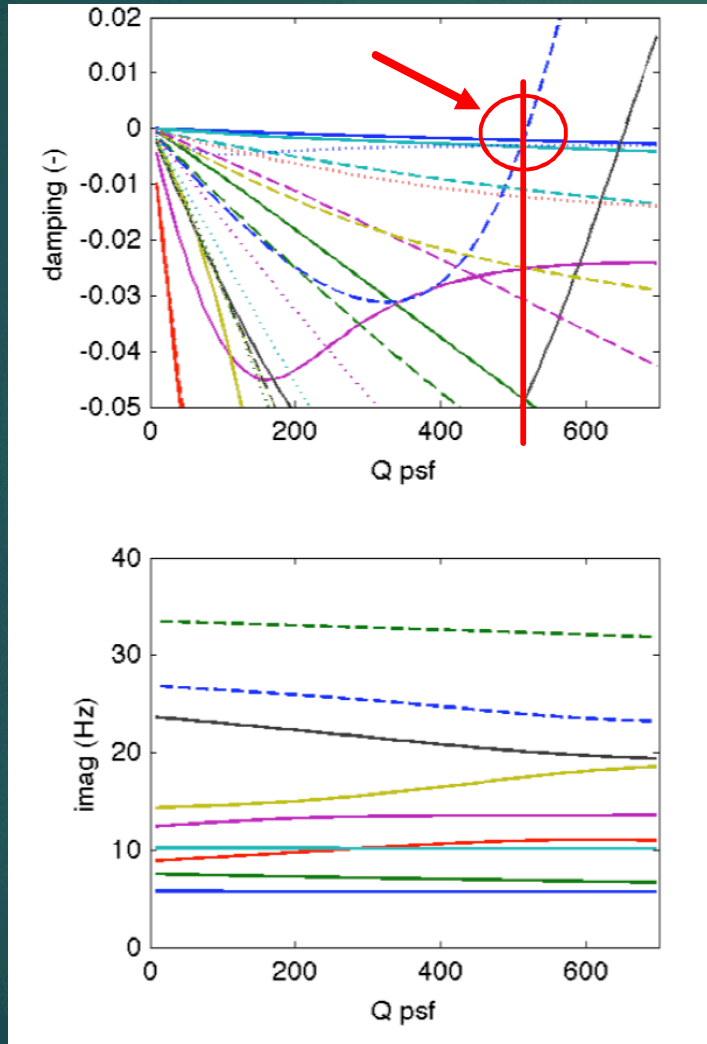
- ▶ Linear NASTRAN aeroelastic models and analyses generated
- ▶ Inviscid and viscous unstructured grids generated by KTH and NASA for use in Edge and FUN3D codes
- ▶ Rigid CFD analyses used for loads estimation
- ▶ Rigid and static aeroelastic analyses performed (FUN3D) for comparison with test data
- ▶ Reduced-order model (ROM) generated for Configuration 1
- ▶ Additional aeroelastic and ROM analyses underway

Linear Aeroelastic Analyses

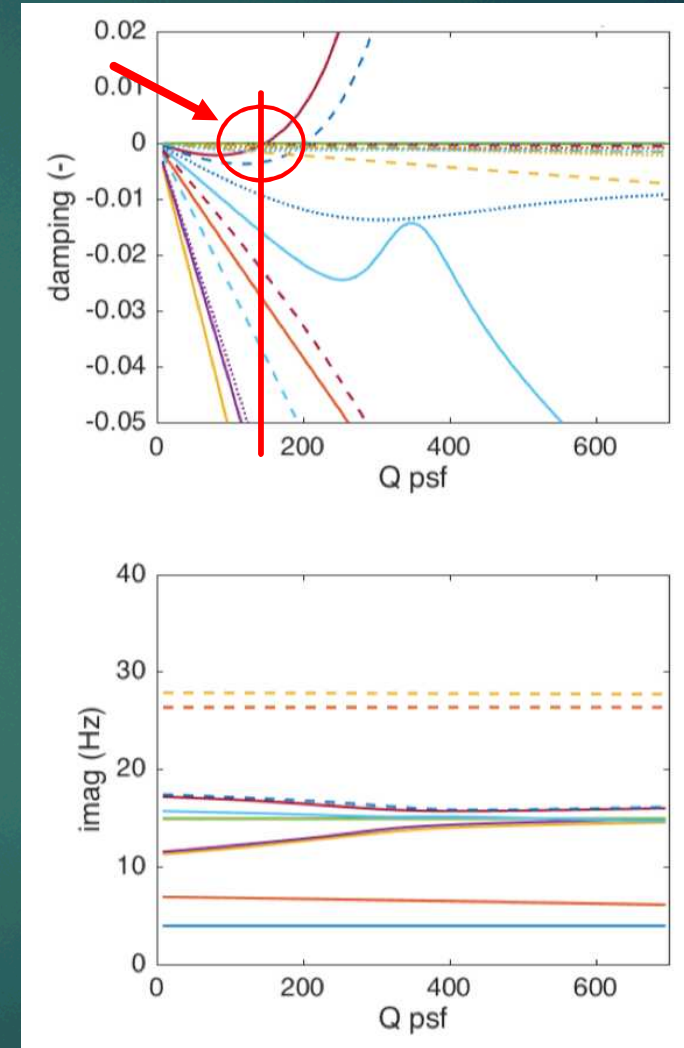


Doublet-lattice boxes (816) superimposed on the FEM

Linear Aeroelastic Analyses

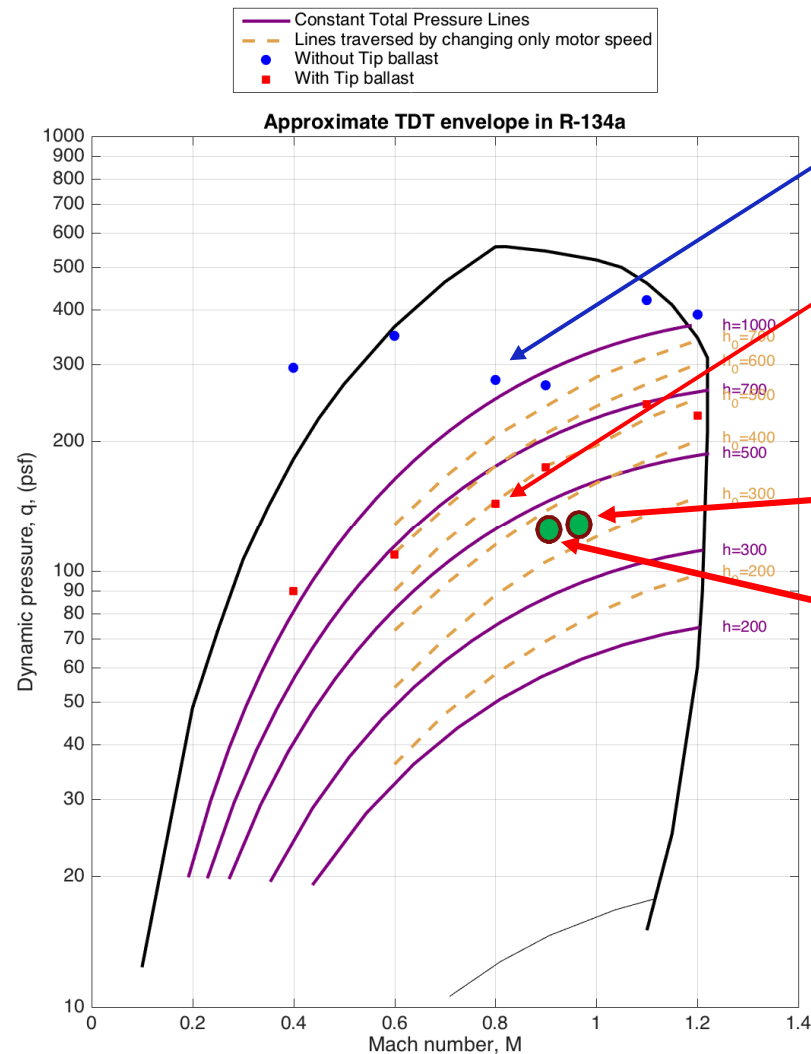


Configuration 2



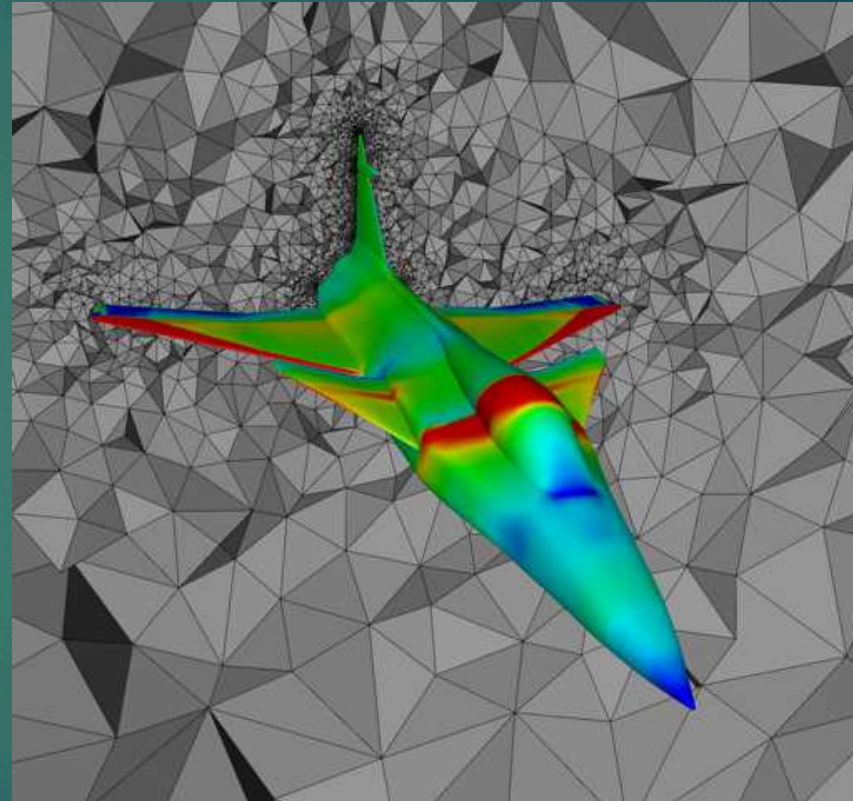
Configuration 3

Linear Aeroelastic Analyses



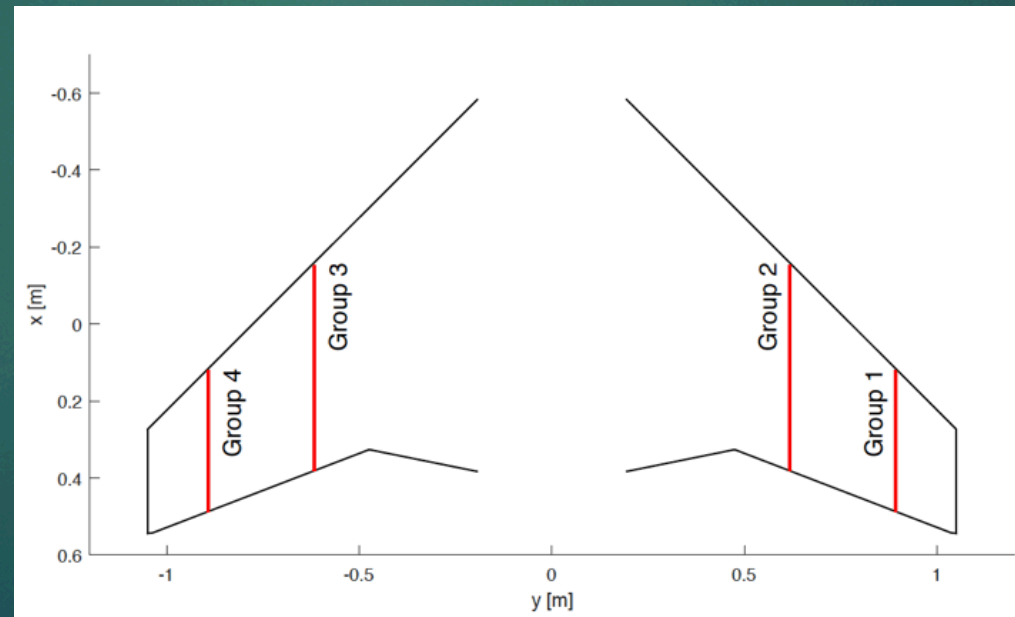
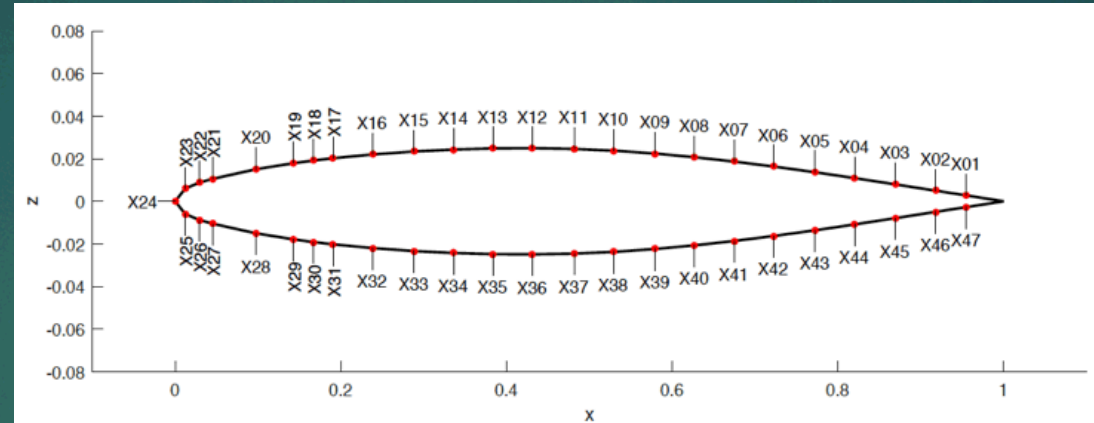
CFD Grids and Results

- ▶ CFD unstructured grids generated
- ▶ Inviscid, Viscous
- ▶ Preliminary analyses used to estimate loads
- ▶ Wind-tunnel model CFD grid inserted into TDT CFD grid



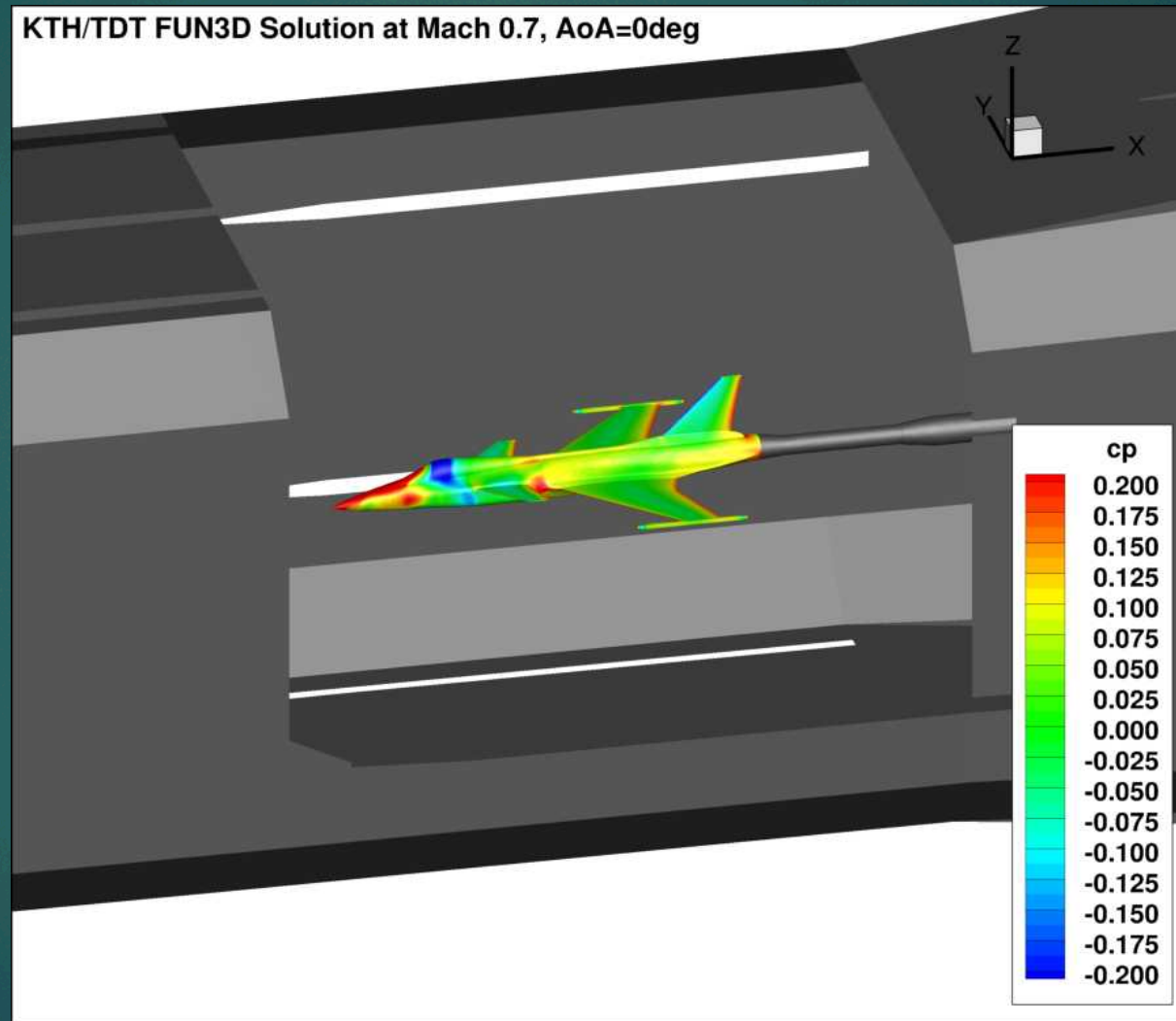
Steady pressures at $M=0.87$, $AoA=7^\circ$

Pressure Instrumentation Locations



Spanwise and chordwise pressure port locations

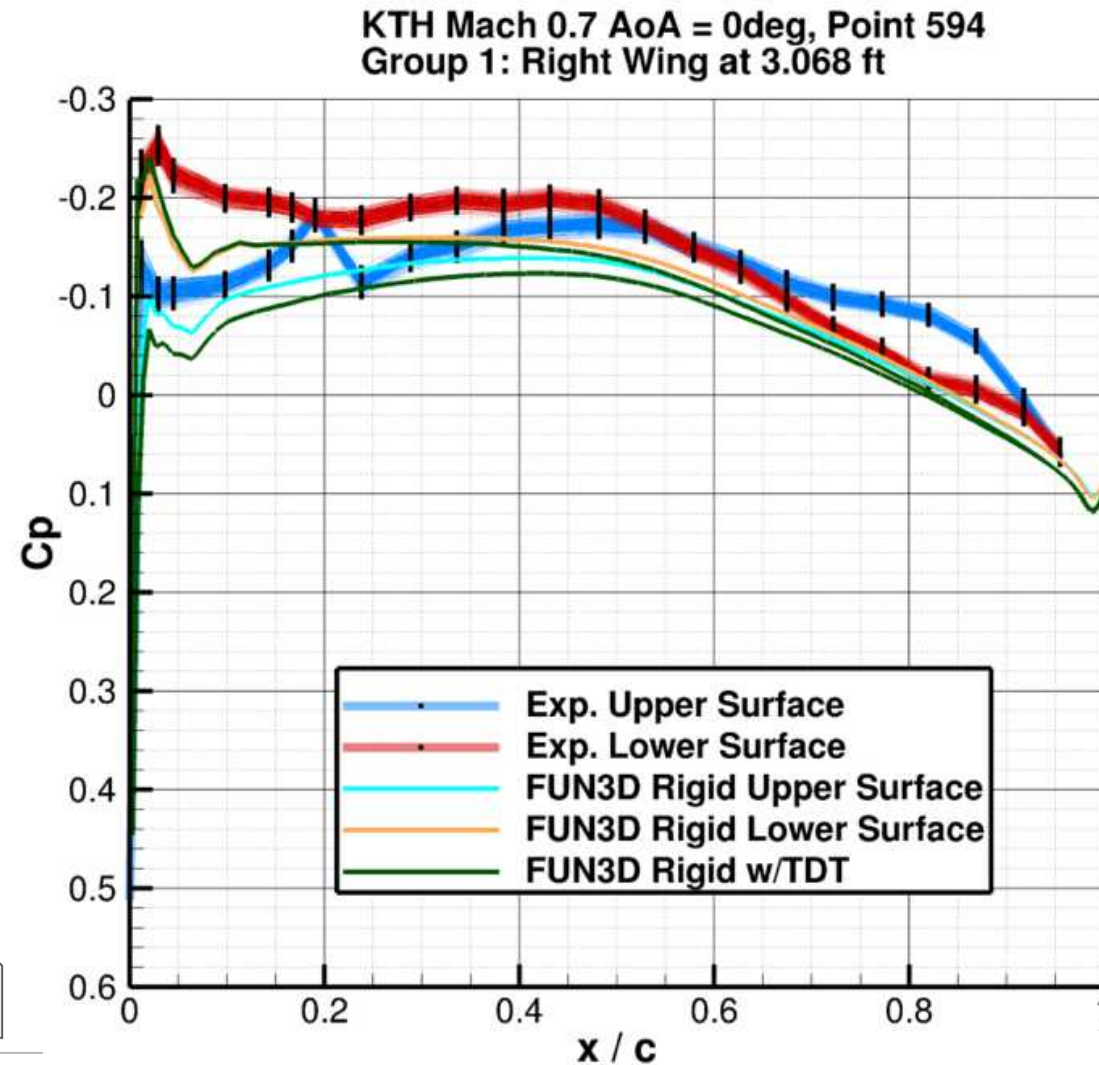
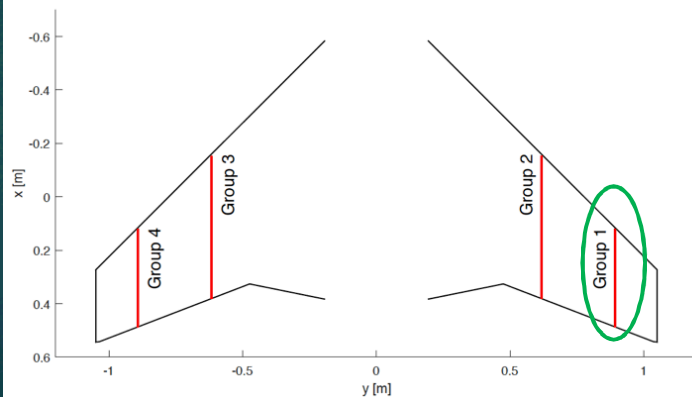
Wind-Tunnel Model and TDT CFD Grids



Installation of wind-tunnel model grid into TDT CFD grid

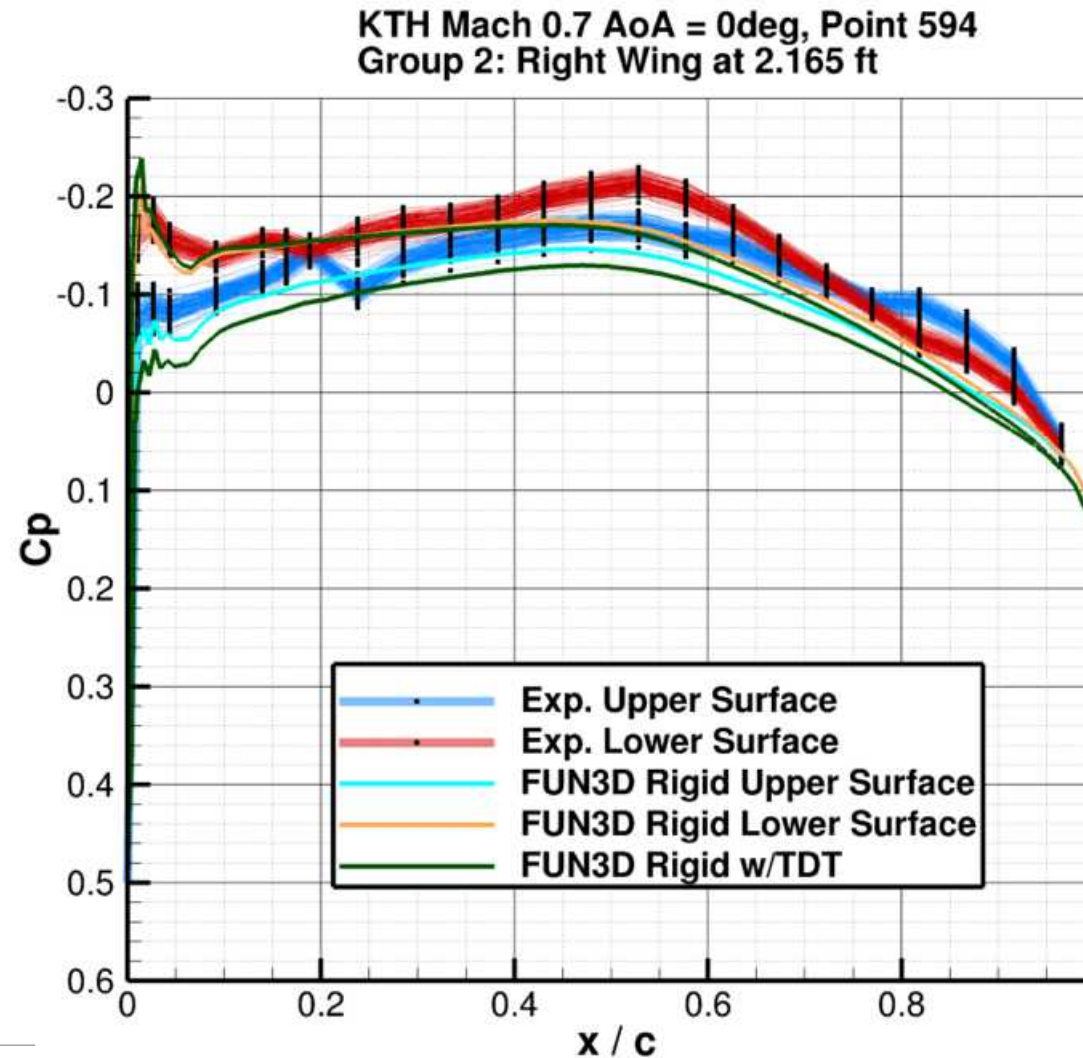
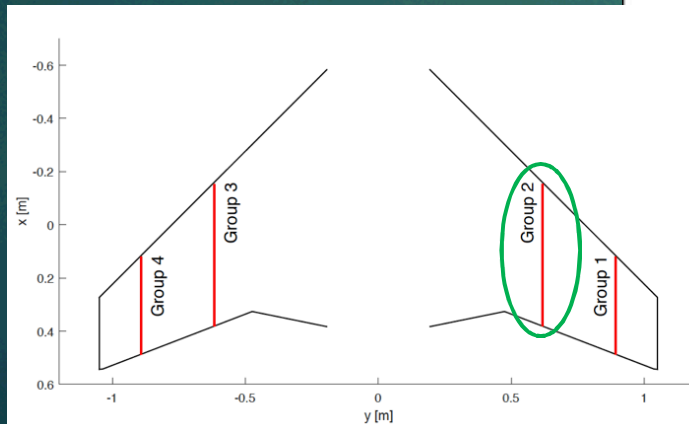
CFD and Experimental Results

Group 1



CFD and Experimental Results

Group 2



Concluding Remarks

- ▶ A collaborative KTH-NASA aeroelastic wind-tunnel test was performed in summer of 2016.
- ▶ Large amounts of data were acquired including accelerometer, pressure, and deflection measurements.
- ▶ Linear and CFD-based aeroelastic analyses have been performed with more analyses underway.
- ▶ Two flutter incidents were encountered, with the second incident resulting in damage to the wing tips and subsequent end of test.
- ▶ Current goal is to repair the wings (KTH) and return for more testing in 2020.