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Linear Frequency Domain Method for Aerodynamic Applications

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Derivatives of Unsteady air loads

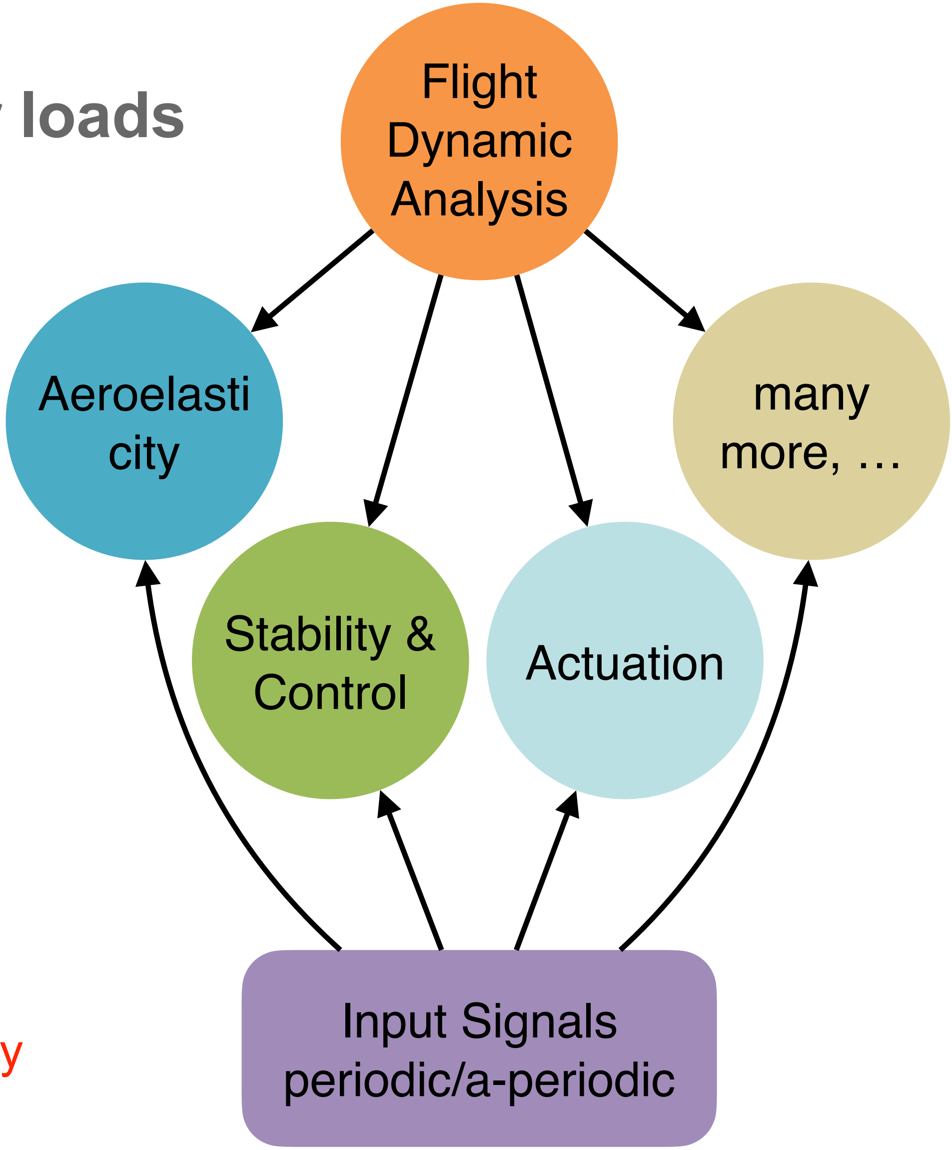
Motivation

Air load derivatives in form of
    Integral values
    Surface distributions

Used as input for many applications
    Rigid/Flexible a/c
    Extend flight envelope

Excitation signals
    Damped harmonic oscillation
    Gust response (1-cos)
    Pulse

Remain compressibility and viscosity
    DLM(VLM) - URANS - Frequency Domain Method



Flight Dynamic Analysis

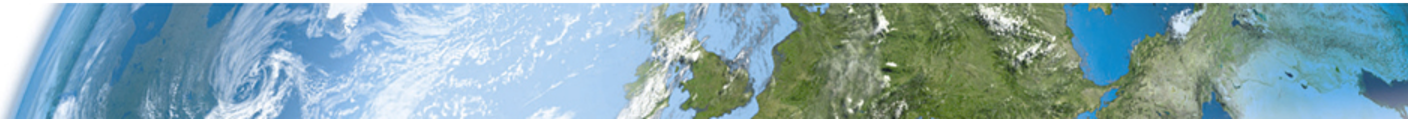
Aeroelasticity

Stability & Control

Actuation

many more, …

Input Signals periodic/a-periodic



Linear Frequency Domain Solver (LFD)

Numerical approach

Small perturbation approach, periodic motion, harmonic response

$$W(t) - \overline{W} = \widetilde{W}(t) \approx \mathrm{Real}(\widehat{W} e^{i\omega t})$$

$$x(t) - \bar{x} = \tilde{x}(t) \approx \mathrm{Real}(\hat{x} e^{i\omega t})$$

W … conservative flow state vector

x … grid-node vector

Semi-discrete URANS (**Spalart-Allmaras one equation turbulence model)**

$$\frac{\mathrm{d}(M(x)W)}{\mathrm{d}t} + R(W, x, \dot{x}) = 0$$

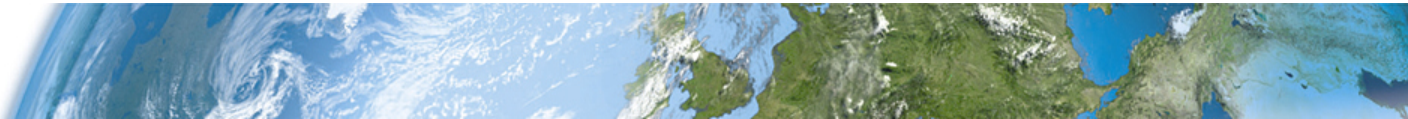
M … mass (cell volume) matrix

R … spatially discretised residual

Consistent linearisation - complex-valued linear system of equations

$$\left[i\omega^{\star}\overline{M} + \frac{\partial R}{\partial W} \right] \widehat{W} = -\left[\frac{\partial R}{\partial x} + i\omega^{\star} \left(\frac{\partial R}{\partial \dot{x}} + \overline{W} \frac{\partial M}{\partial x} \right) \right] \hat{x} \quad \rightarrow \quad A\widehat{W} = b$$

Solution scheme: Direct solver, ILU-preconditioner, Krylov-GMRes



Input for Aeroelasticity Analysis

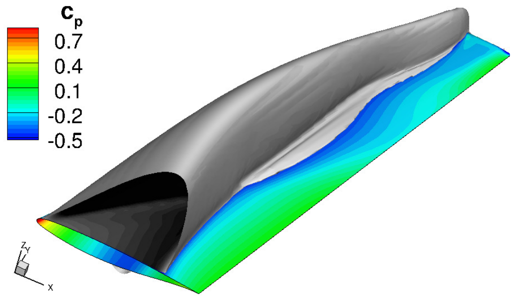
Complex-valued Surface Distributions

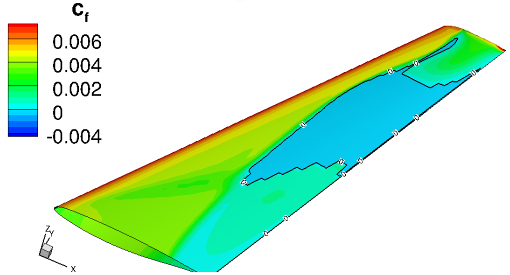
LANN CT9 - transonic/partly separated flow

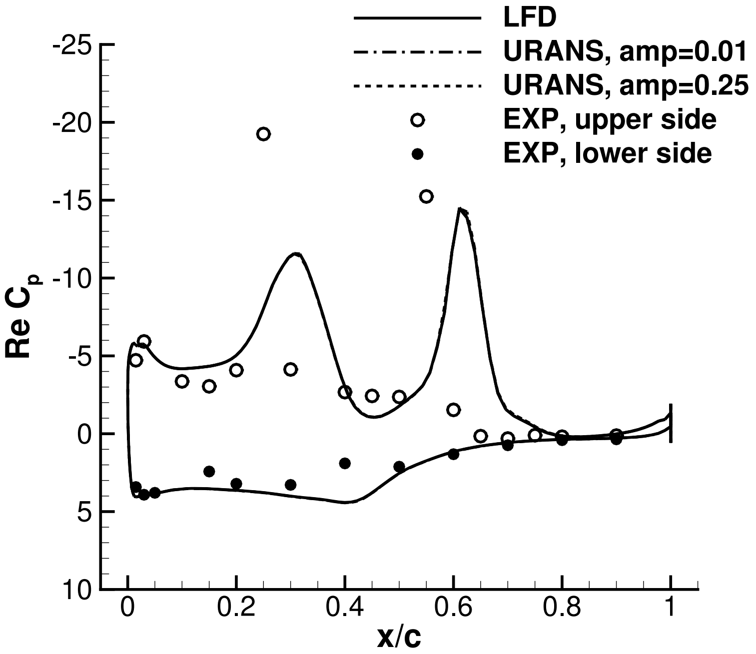
M = 0.82, Re = 7.3x10^6, α = 2.6°, red. f = ω* = 0.2

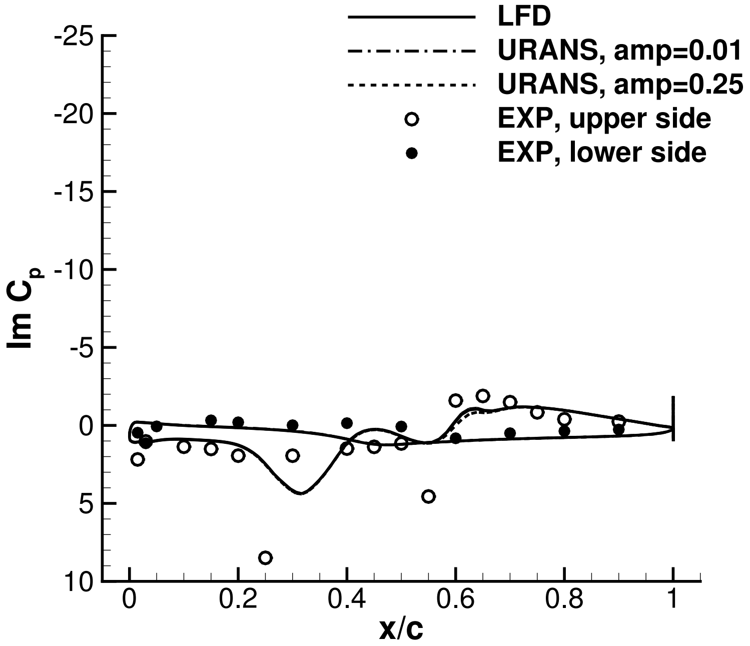
Harmonic pitch oscillations, $\alpha(t) = \alpha_0 \sin(\omega t)$

LFD/URANS - Experiments, y/b = 0.2









Stability & Control

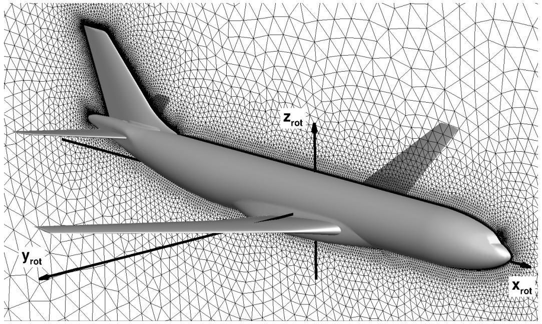
Steady-state static and dynamic Derivatives

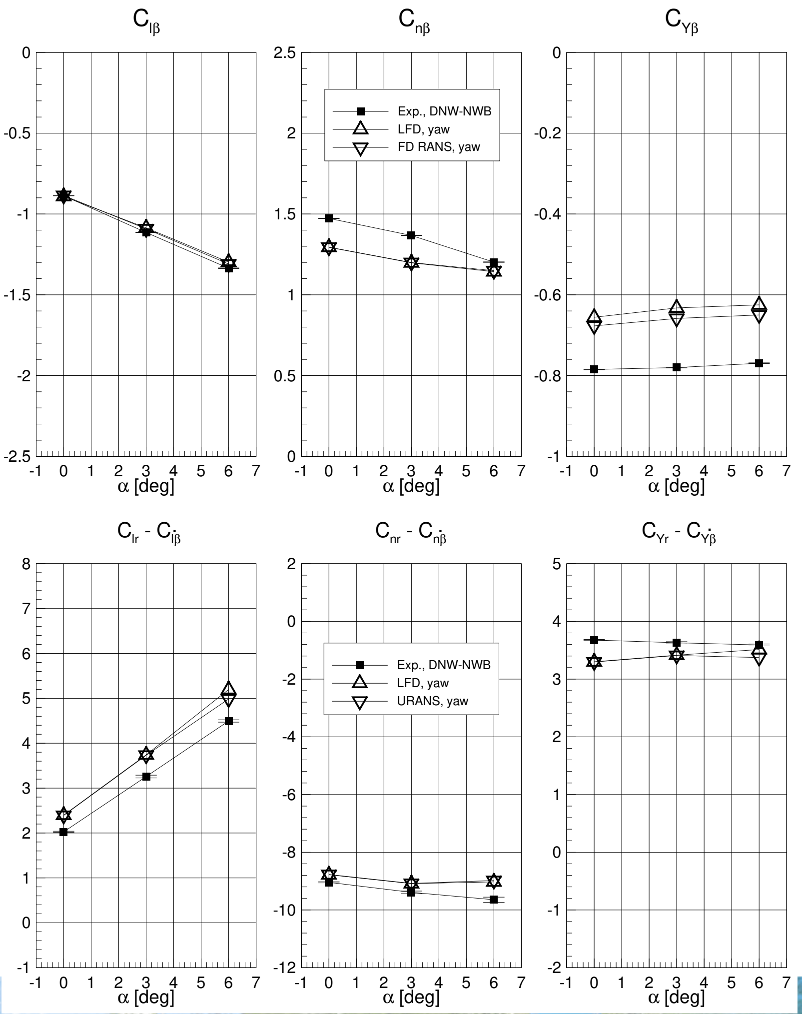
DLR-F12 wind tunnel experiment

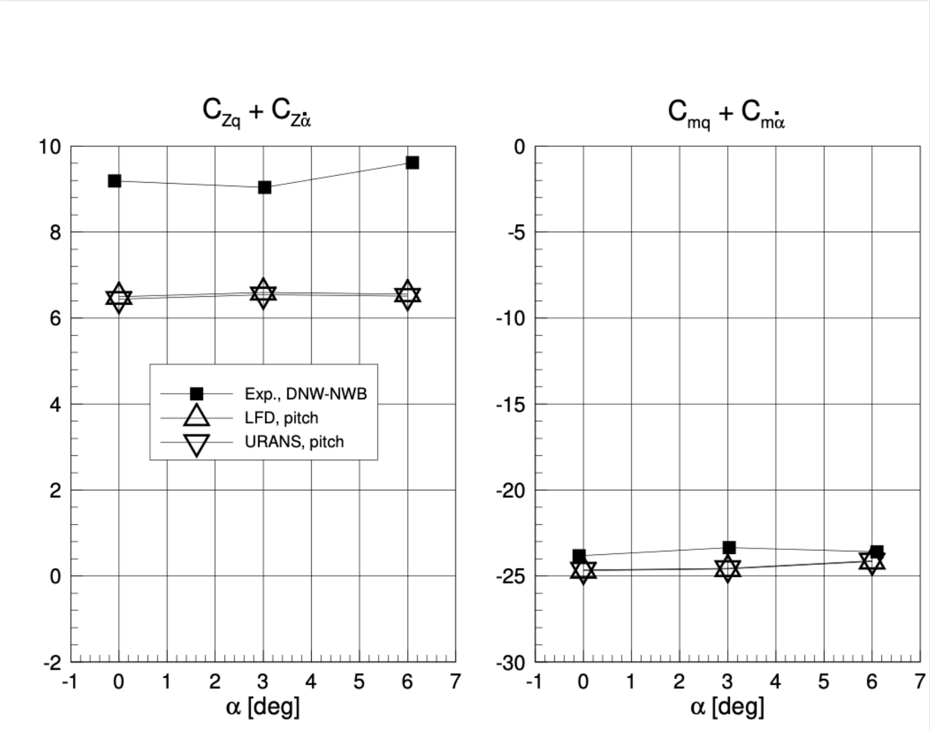
U = 70 m/s, Re = 1.28x10^6, α = 0°

Sinusoidal, f = 3 Hz, ω* = 0.068

Pitch - Roll/Yaw







Stability & Control

Flight dynamic stability

DLR-F12 wind tunnel experiment

U = 70 m/s, Re = 1.28x10^6, α = 0°

Longitudinal and lateral/directional aircraft modes

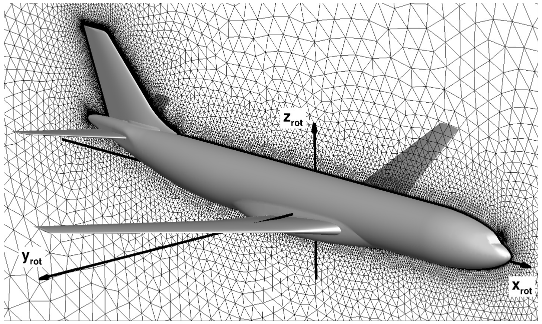
Comparison between Vortex-Lattice (VLM) and LFD method obtained aircraft modes

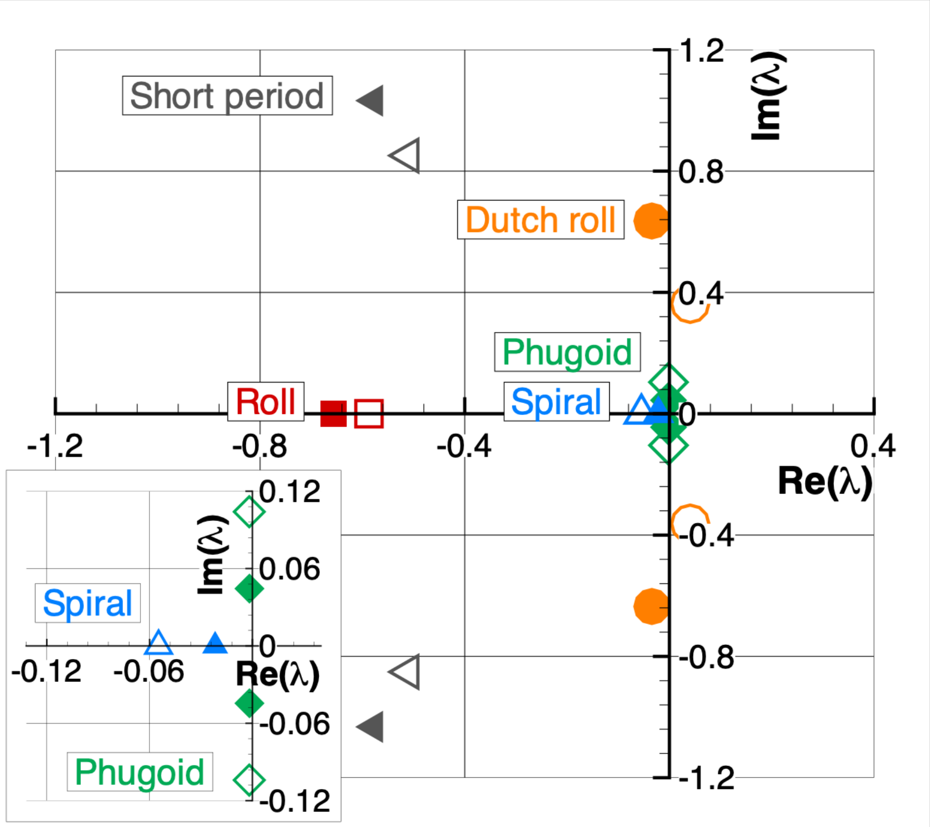
VLM

Inviscid + incompressible

LFD

Viscous + compressible





Stability & Control

Control surface derivatives

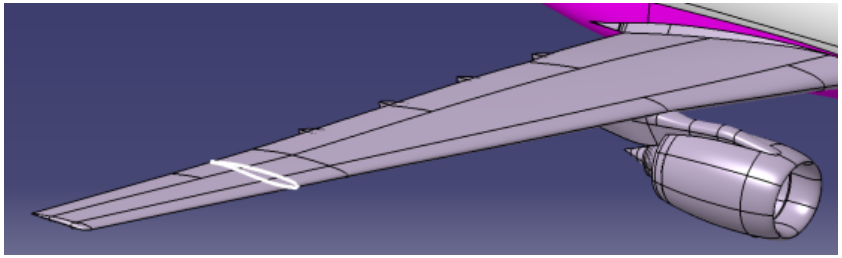
Fowler and a plain flap
M = 0.18, Re = 20x10^6, α = 0°

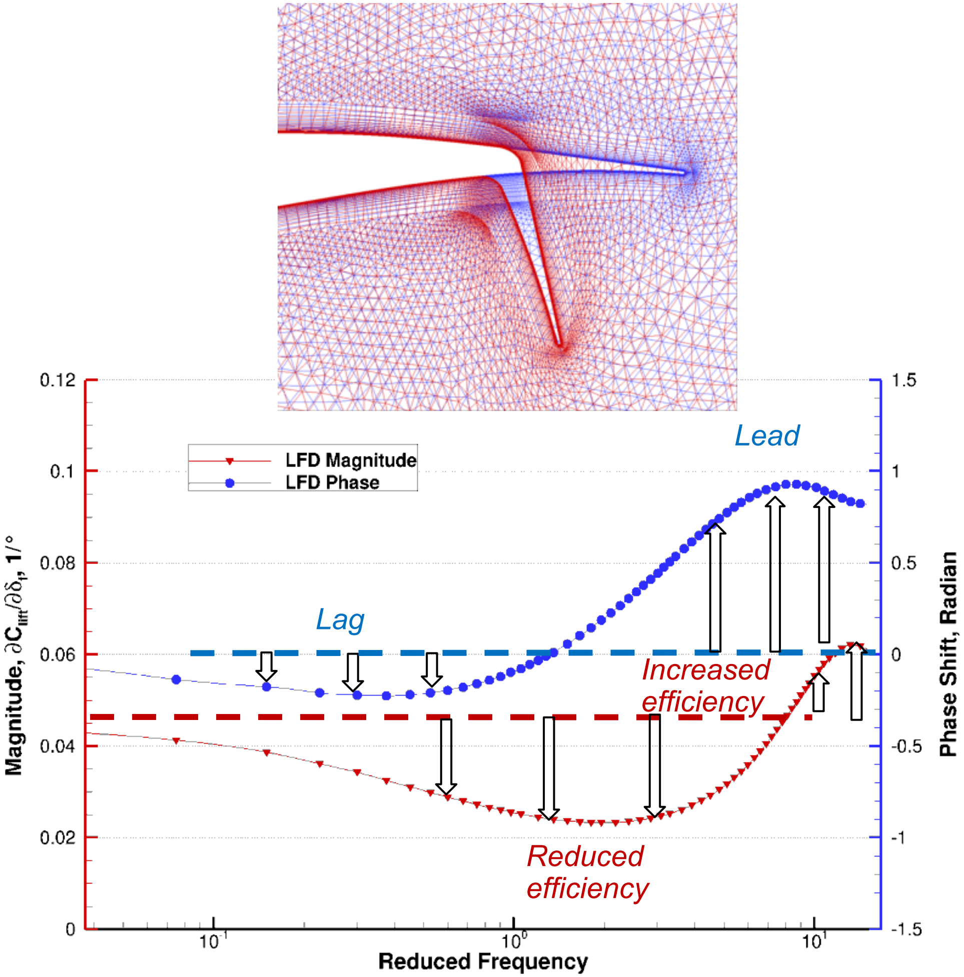
Deflection of the flap is implemented as a deformation in the mesh for the LFD-Solver

Frequencies from 0 to 40 Hz

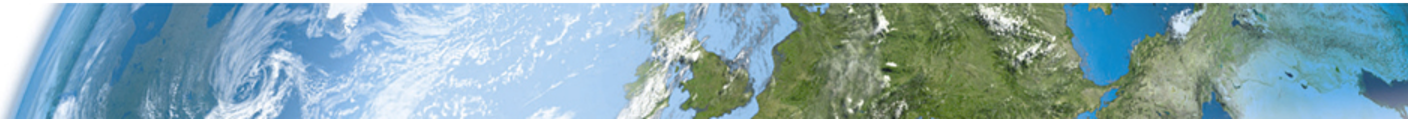
Magnitude describes the **Control derivative** of the flap
Phase shift describes the **Time Lead and Lag** of the flap

LFD gives full frequency response and allows the computation for **arbitrary flap deflections** in the time domain





Frequency response of the aileron



Stability & Control

Control surface derivatives

Arbitrary flap deflections

$M = 0.2$, $Re = 25x10^{6}$, $\alpha = 2°$

A-periodic predefined flap motion - **black**

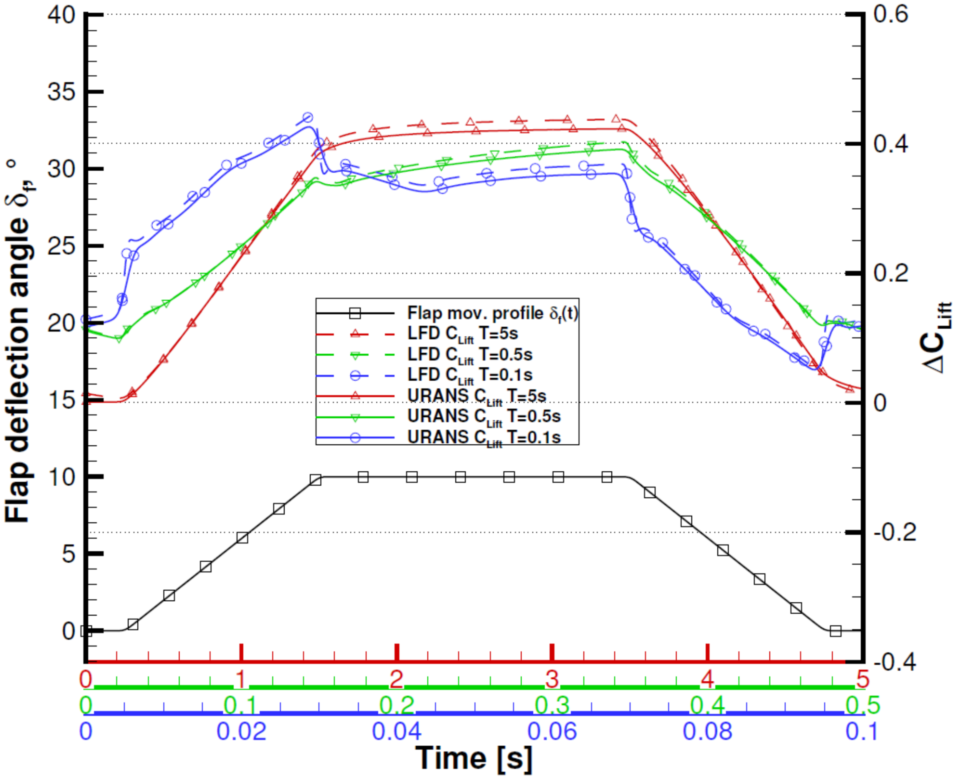
Different time scales

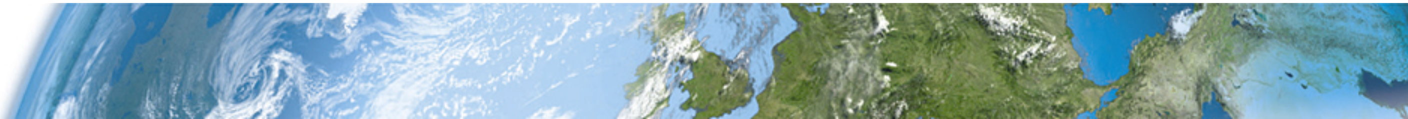
t = 5 s, t = 0.5 s, t = 0.1 s

Steady/Unsteady effects

Linear combination of n times LFD(f) solutions

Good agreement in terms of accuracy even for strong unsteady aerodynamic effects in the flow





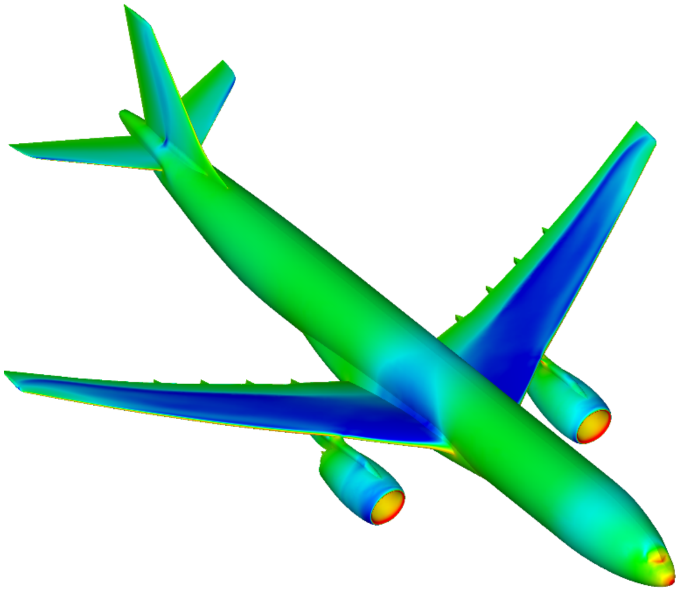
A-periodic signals - Gust

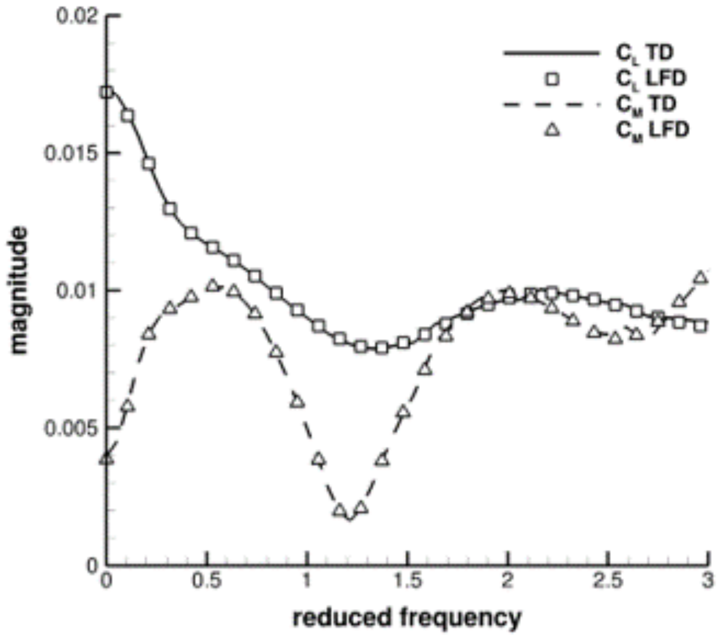
XRF1 Gust Response simulations

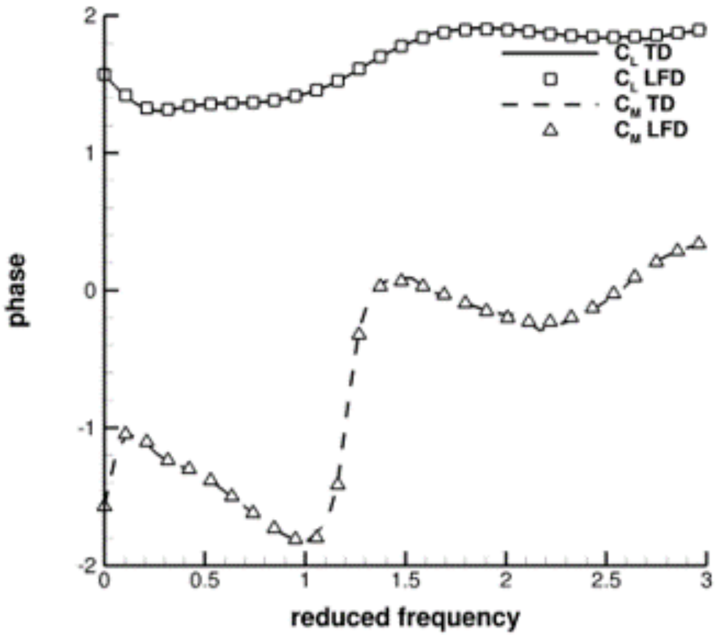
Results over reduced frequency range

Transonic flow conditions featuring a shock

Lift and pitching moment coefficient



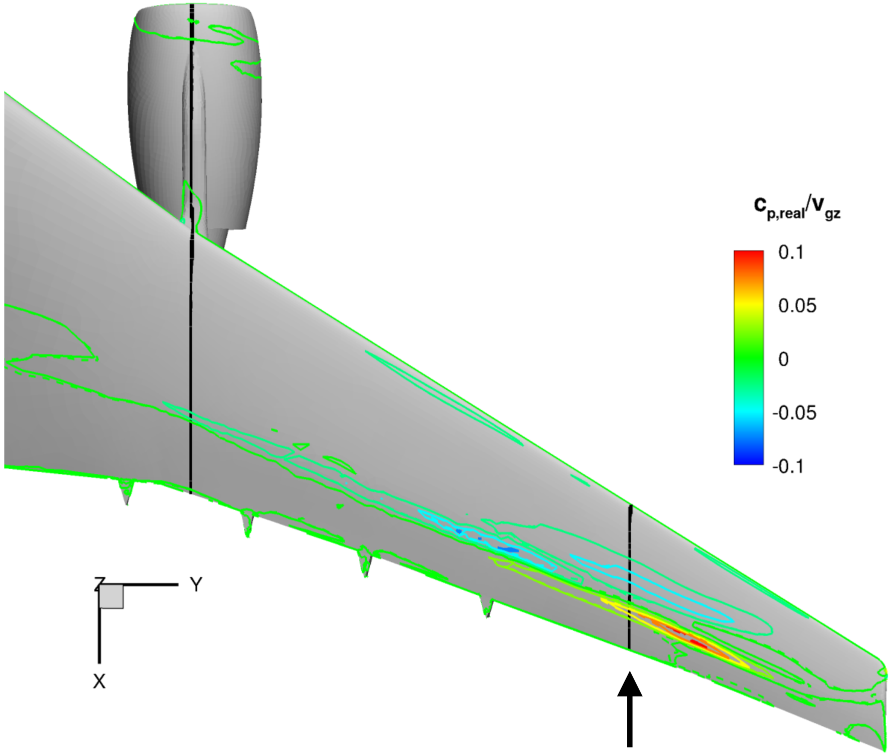




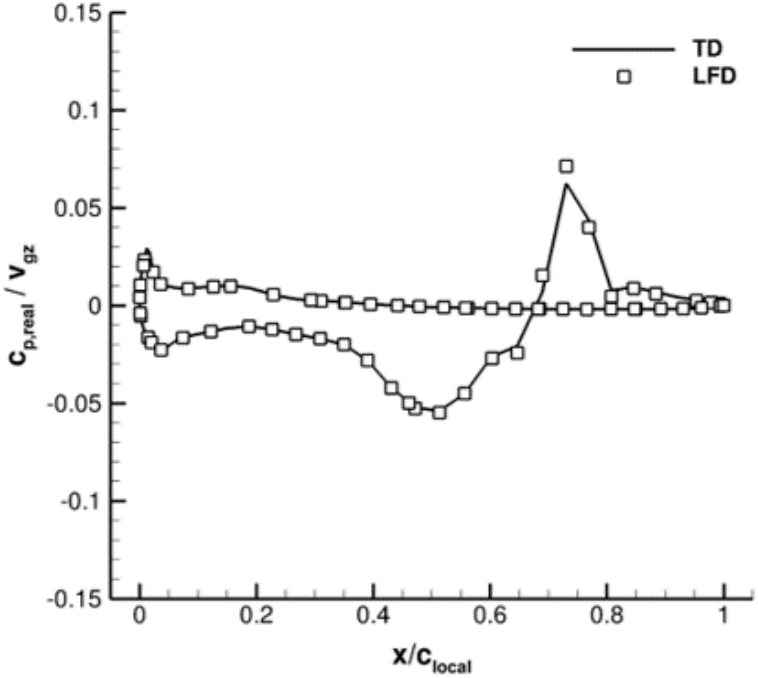
A-periodic signals - Gust

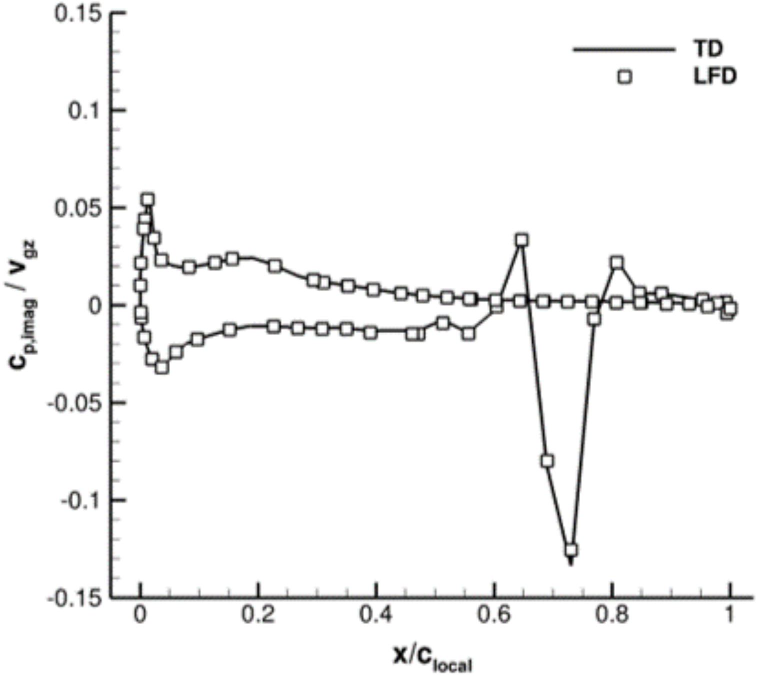
XRF1 Gust Response simulations

Complex surface pressure distributions for reduced frequency of 0.53



Slice for Cp





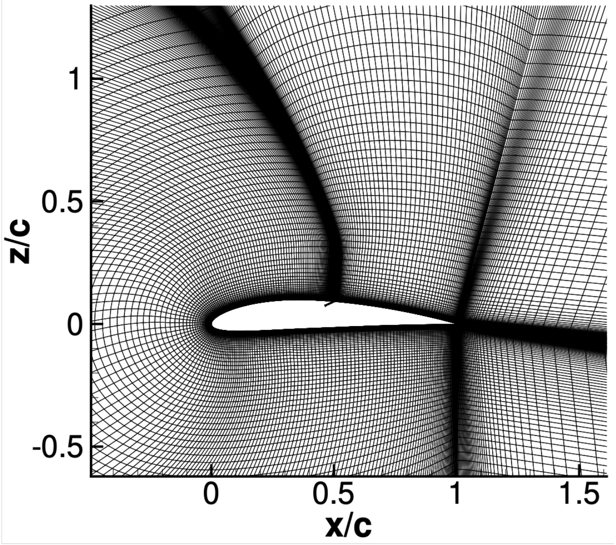
A-periodic signal - Actuation

Constant and Sinusoidal blowing

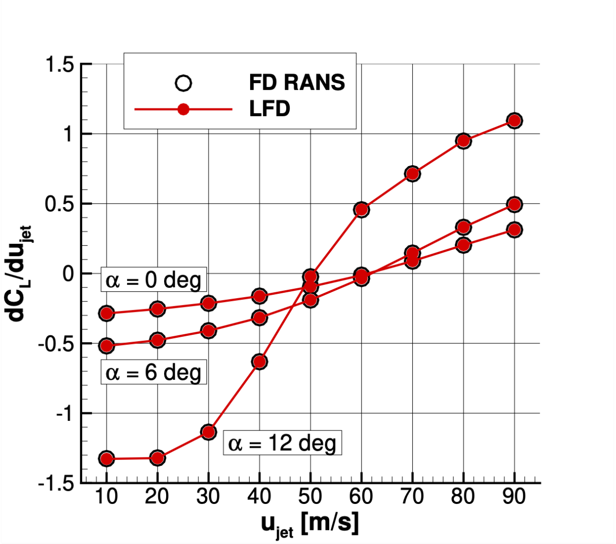
Blowing NACA4412 - single slot

Static/Dynamic derivatives

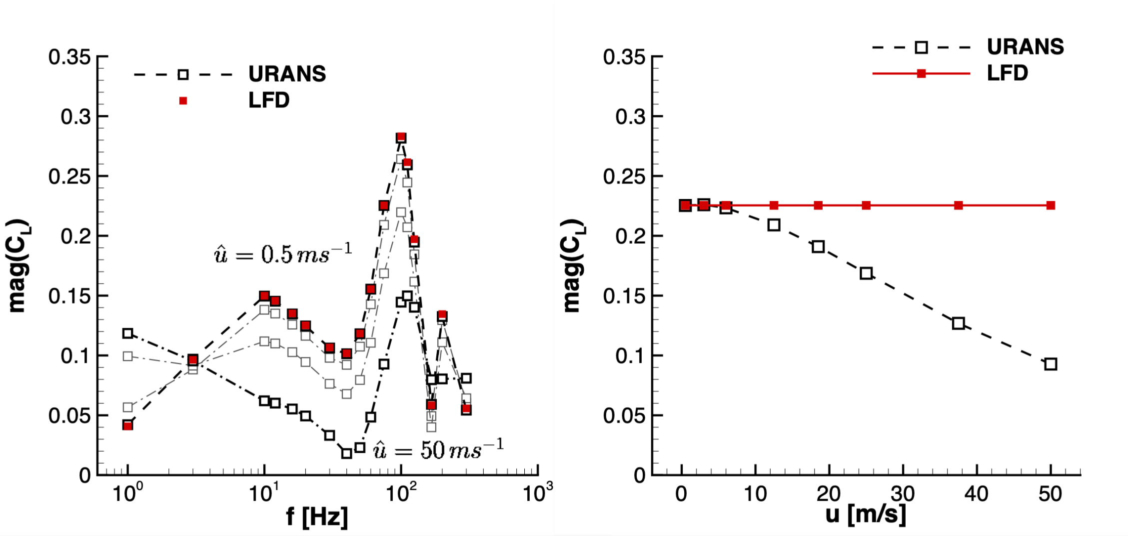
α [deg]	U [m/s]	T [K]	p [Pa]	Re	c
0/6/12	92.6	288	101325	6.3×10^6	1



Static



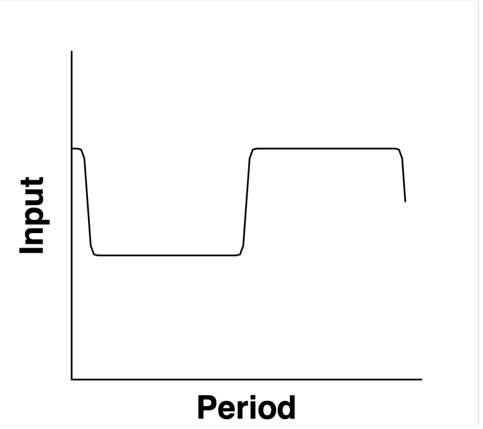
Dynamic



Application - Actuation

Pulsed blowing - Pulse Train

Blowing NACA4412 - single slot

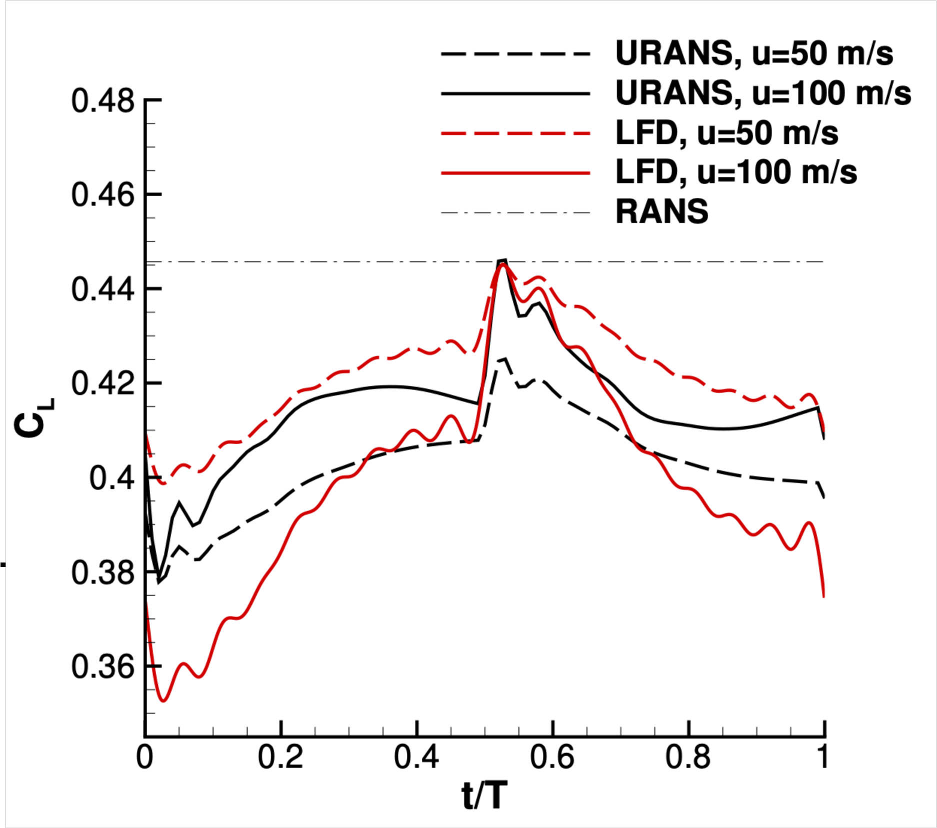


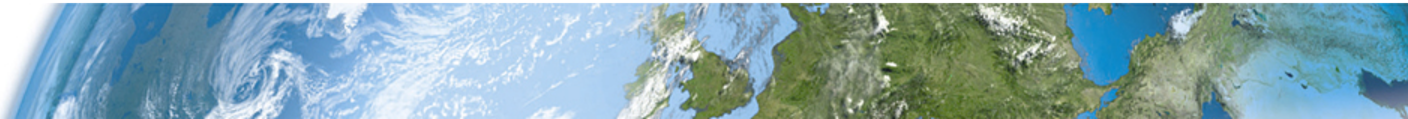
Time signal recovery with 15 LFD simulations for pulse train

Linear combination of each single harmonic LFD simulation based on Discrete Fourier Transform (DFT) - weights

LFD relies on small perturbations approach

- Shape is well resolved
- Magnitude of lift decrease is over-predicted





Conclusion

Linear Frequency Domain method (LFD) - Small perturbation approach

- LFD provides a **speed-up** of about **2 orders of magnitude** with the accuracy of URANS for small perturbations of motions
- RANS (viscosity) properties remain

- **Good agreement** of LFD results in comparison with URANS for harmonic oscillations
  - **Consistent linearisation** of the Jacobians
  - Linearization of **turbulence model** is a **key feature**

- Robust method, almost inherent of excitation frequency
  - **Preconditioner** and **Krylov-GMRes** dramatically **increase** the **robustness** compared with multigridding
  - Direct solver: **Trade off between robustness and memory usage**

Viscosity/Turbulence

- **Important** to be included **- Separation**

Outlook

Damped harmonic oscillator - LFD

Problem reduction of complex aerodynamic system important for many unsteady applications

Further applications of small disturbance RANS-based LFD method

Control circuits - Frequency response functions/modulation

Control surfaces - ailerons, rudder, elevator, ….

Air load alleviation - Active flow control - Energy efficiency

Optimisation including Stability & Control

MDO - air loads (LFD - ROM) - Uncertainty quantification