FLIGHT DYNAMIC STABILITY PREDICTION FOR AN AIRCRAFT IN TRANSONIC SEPARATED FLOW CONDITIONS WITH A LINEAR FREQUENCY DOMAIN SOLVER

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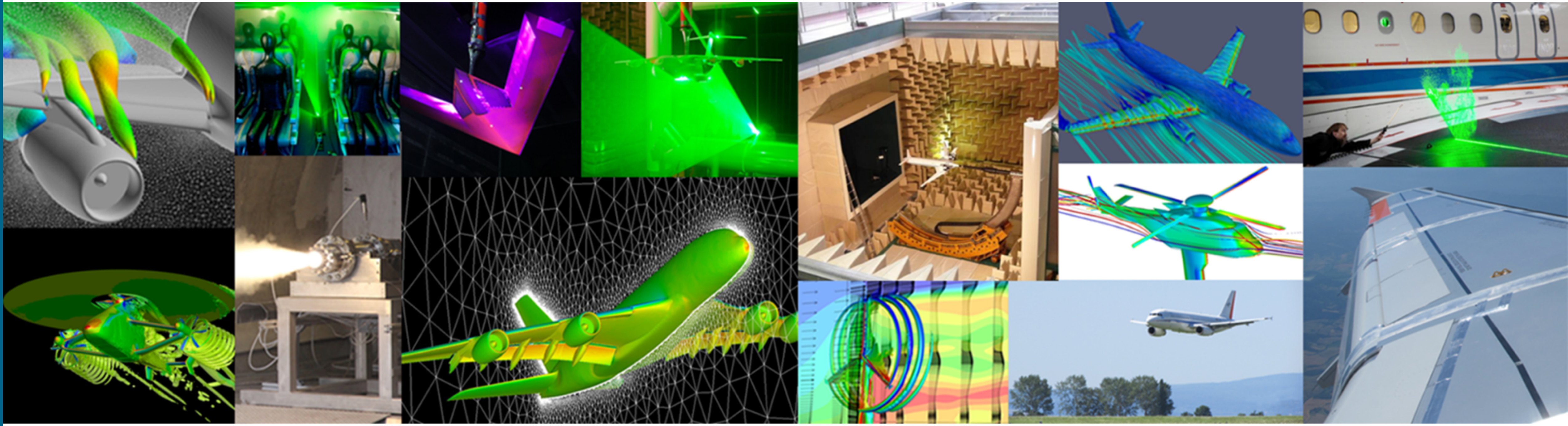
DLR, Institute of Aerodynamics and Flow Technology, C²A²S²E

FH Wiener Neustadt, 1. December 2023

DLR

Research Areas
at the Institute of Aerodynamics and Flow Technology



In the research domain of fluid physics the institute provides the link between basic research and industrial implementation. Our knowledge base is embedded into an international framework of research establishments and industry.

Organization | Sites of the Institute

Braunschweig: ~ 150 Employees

Göttingen / Köln: ~ 200 Employees

Gesamt: ~ 350 Employees

(exept internships, students, temporary support staff)

Status: May 2023

$C^2A^2S^2E$ Braunschweig | Where am I located ?

$C^2A^2S^2E$
Braunschweig

SUM
Surrogate and Uncertainties Modeling

MDAO
Multidisciplinary Design Analysis and Optimisation

CODA
Next Generation flow solver

Numerical Methods
TAU

Ice Accretion

Data Driven Modeling

Adjoint Technique
Frequency Domain solver

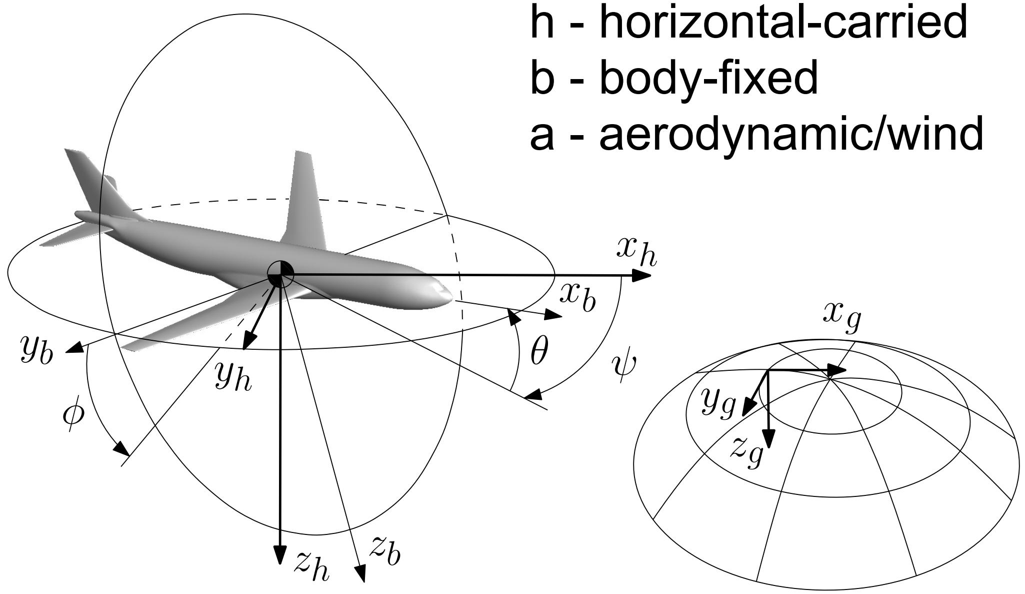
Interaction aerodynamic/ aeroelasticity

Status: May 2023

FLIGHT DYNAMIC STABILITY

Flight Dynamics

g - geodesic
h - horizontal-carried
b - body-fixed
a - aerodynamic/wind



Aircraft motion - three axes (t/r)

Arbitrary flight-orientation

Considerations

Flight trajectory

Aircraft - Fluid interaction

Subsonic-Transonic flow region

Question: Is flight vehicle stable or unstable after perturbation from trimmed state?

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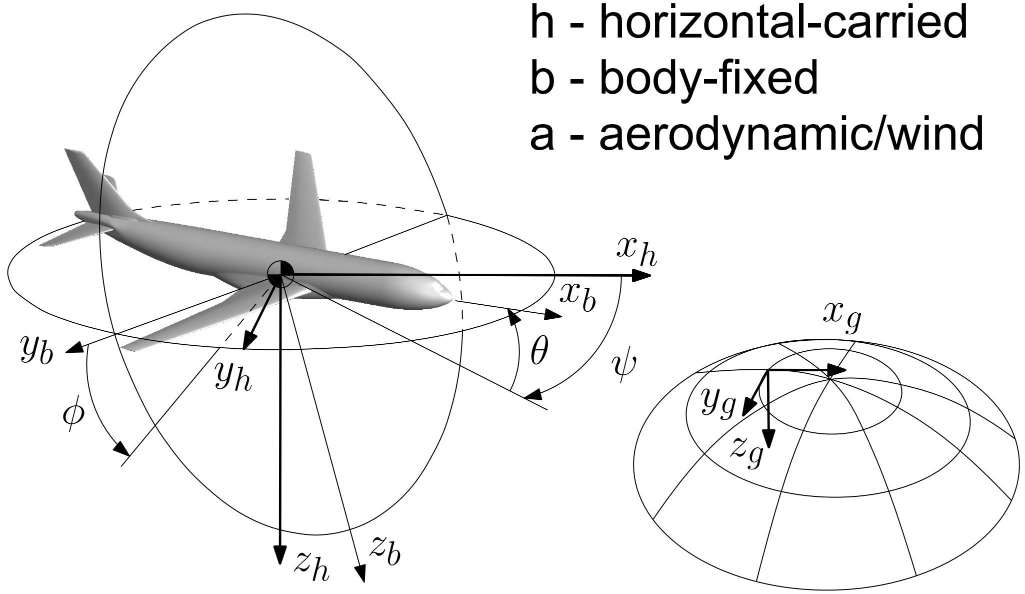

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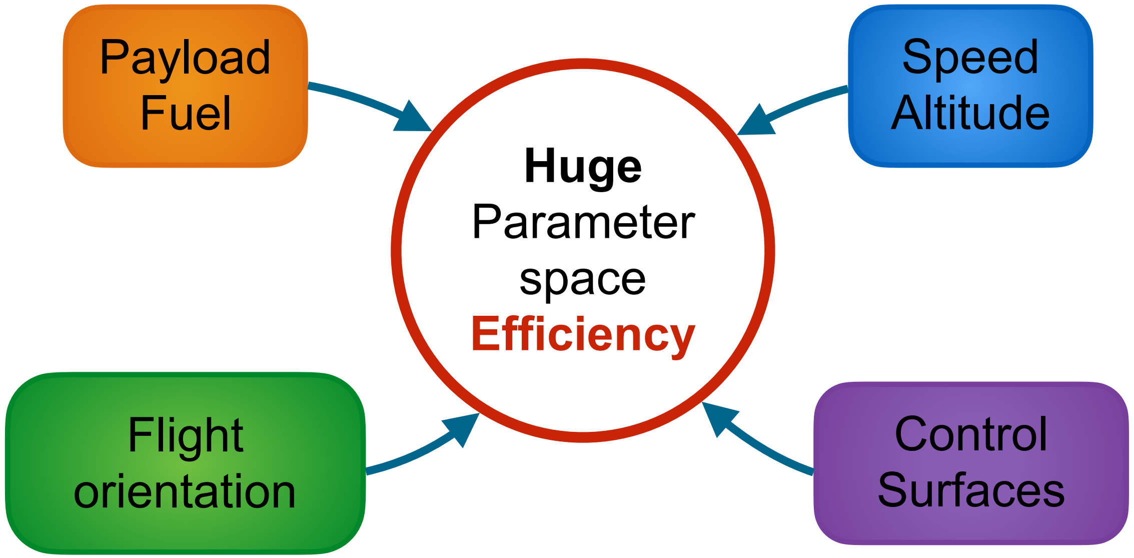


Why so difficult? Transonics and its traps

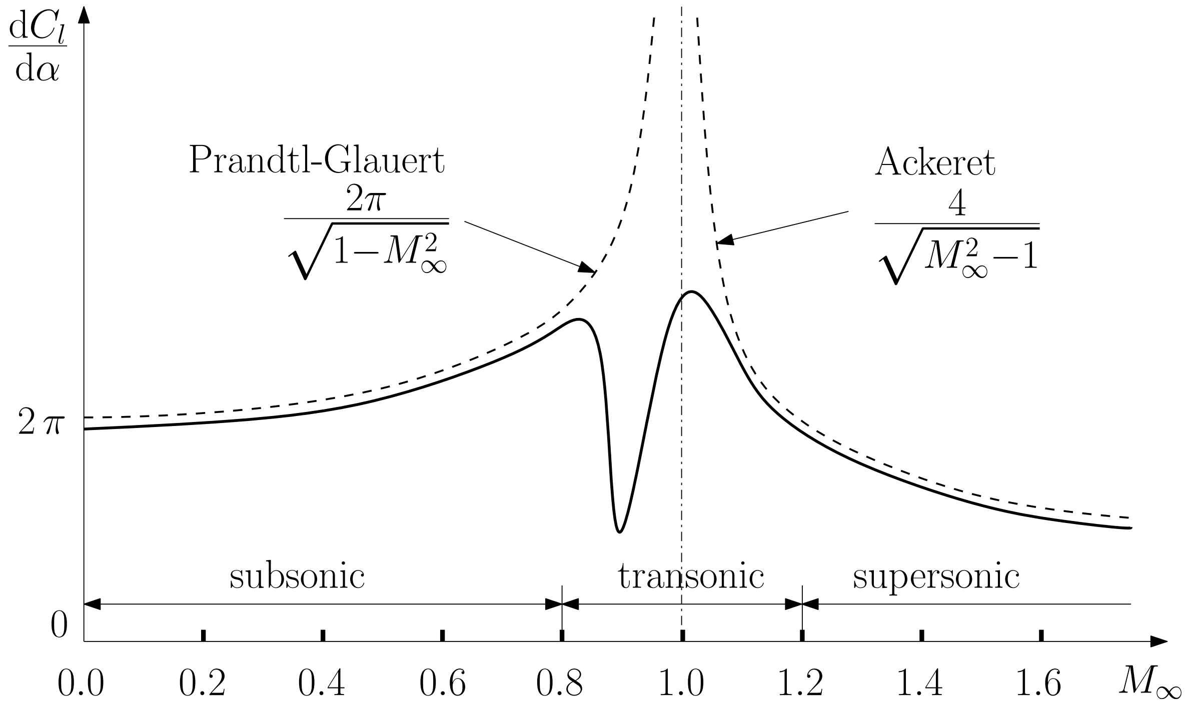
Transonic flow region
    linear - nonlinear

Shocks

Influence of viscosity
(flow separation)

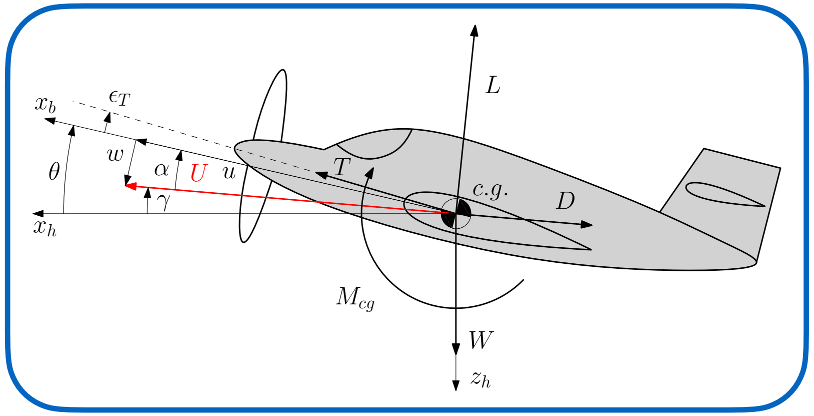
To reflect this flow phenomena,
demand of certain numerical schemes:
    Navier-Stokes Eqn.

Accuracy



Problem reduction

Flight vehicle - Flight state



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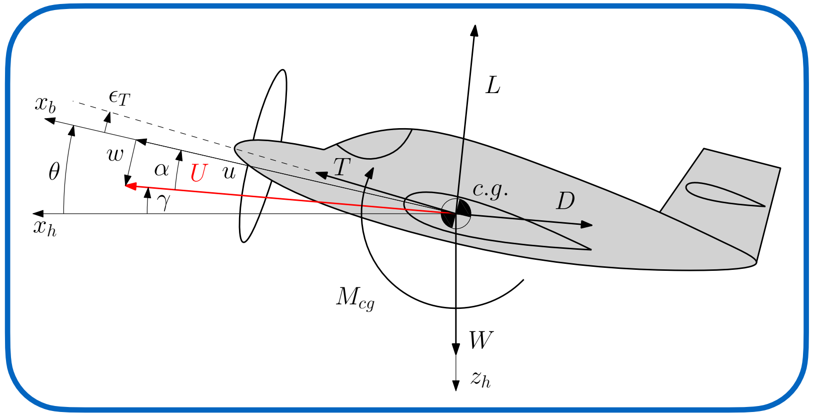
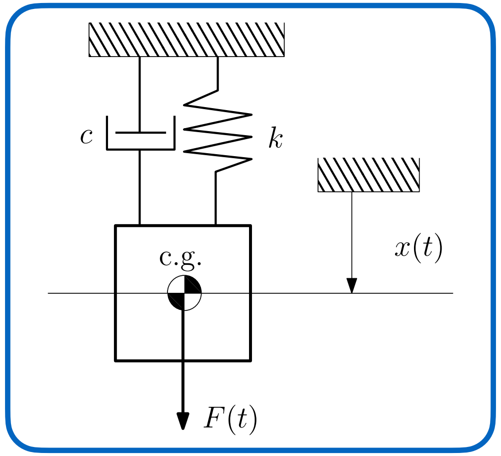


Spring-mass damper oscillator



Nonlinear equations of motion

$$\mathbf{x} = [x, y, x]^T, \qquad \varphi = [\phi, \theta, \psi]^T,$$
$$\dot{\mathbf{x}} = \mathbf{T}_{hb}\mathbf{U}, \qquad \dot{\varphi} = \mathbf{R}_{bh}^{-1}\omega_b,$$
$$\ddot{\mathbf{x}} = \frac{1}{m}\mathbf{X} + \mathbf{T}_{hb}\mathbf{W} + \omega_b \times \mathbf{U}, \qquad \ddot{\varphi} = \mathbf{I}^{-1}(\mathbf{M} - \omega_b \times \mathbf{I}\omega_b)$$

Initial conditions
Small perturbations
Linearisation - Taylor series

$$\mathbf{f}[\mathbf{x}(t), \dot{\mathbf{x}}(t)] = 0, \quad \mathbf{f}[\bar{\mathbf{x}}, \dot{\bar{\mathbf{x}}}] = 0,$$
$$\mathbf{x}(t) \approx \bar{\mathbf{x}} + \tilde{\mathbf{x}}(t),$$
$$\dot{\mathbf{x}}(t) \approx \dot{\bar{\mathbf{x}}} + \dot{\tilde{\mathbf{x}}}(t),$$
$$\mathbf{f}(t) \approx \mathbf{f}[\bar{\mathbf{x}}, \dot{\bar{\mathbf{x}}}] + \frac{\partial \mathbf{f}}{\partial \mathbf{x}}\tilde{\mathbf{x}} + \frac{\partial \mathbf{f}}{\partial \dot{\mathbf{x}}}\dot{\tilde{\mathbf{x}}} = 0$$

$x(t) = x_0 \sin(\omega t)$
Harmonic response
Stability $F(t) = 0$

$$\dot{\tilde{x}} = A\tilde{x}$$

Jacobian, state matrix A,
exact symmetry x-z, longitudinal + lateral/directional

$$\mu = \frac{2m}{\rho_\infty S\, l_\mu}$$

body-fixed (u,v,w)

$$\mathbf{A}'_{\text{long},b} = \begin{bmatrix} \frac{1}{2\mu}C_{X_u} & \frac{1}{2\mu}C_{X_w} & \frac{1}{2\mu}C_{X_q} - \frac{\bar{w}}{U_\infty} & -\frac{1}{2\mu}C_G\cos\bar{\theta} \\ \frac{1}{2\mu}C_{Z_u} & \frac{1}{2\mu}C_{Z_w} & \frac{1}{2\mu}C_{Z_q} + \frac{\bar{u}}{U_\infty} & -\frac{1}{2\mu}C_G\cos\bar{\phi}\sin\bar{\theta} \\ \frac{1}{i_{yy}}C_{m_u} & \frac{1}{i_{yy}}C_{m_w} & \frac{1}{i_{yy}}C_{m_q} & 0 \\ 0 & 0 & \cos\bar{\phi} & 0 \end{bmatrix}$$

trimmed state

arbitrary flight orientation

no simplification velocity components

aerodynamic (U, α, β)

$$\mathbf{A}'_{\text{long},w} \approx \begin{bmatrix} -\frac{1}{2\mu}C_{D_U} & \frac{1}{2\mu}(\bar{C}_L - C_{D_\alpha}) & -\frac{1}{2\mu}C_{D_q} & -\frac{1}{2\mu}C_G\cos\bar{\theta} \\ -\frac{1}{\phi}C_{L_U} & -\frac{1}{\phi}(\bar{C}_D + C_{L_\alpha}) & \frac{1}{\phi}(2\mu - C_{L_q}) & -\frac{1}{\phi}C_G\sin\bar{\theta} \\ a_{31} & \frac{1}{i_{yy}}(C_{m_\alpha} - C_{m_{\dot{\alpha}}}\frac{(\bar{C}_D + C_{L_\alpha})}{\phi}) & \frac{1}{i_{yy}}(C_{m_q} + C_{m_{\dot{\alpha}}}\frac{(2\mu - C_{L_q})}{\phi}) & -\frac{C_{m_{\dot{\alpha}}}C_G\sin\bar{\theta}}{i_{yy}\phi} \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$\text{with}: \quad \frac{1}{\phi} = 2\mu + C_{L_{\dot{\alpha}}}, \quad a_{31} = \frac{1}{i_{yy}}\left(C_{m_U} - C_{m_{\dot{\alpha}}}\frac{C_{L_U}}{\phi}\right)$$

trimmed state, second column: sin α = w/U

α ≈ β ≈ 0°, sin α ≈ α, cos α ≈ 1

v ≈ w ≈ 0, $\dot{v} \approx \dot{w} \approx 0$

$$A - I\lambda = 0 \;\rightarrow\; \lambda = \sigma \pm i\omega \;\rightarrow\; x(t) = x_0 e^{\sigma t}\cos(\omega t + \varphi)$$

state matrix A: dynamic / steady-state static, quasi-steady and dynamic derivatives

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DLR

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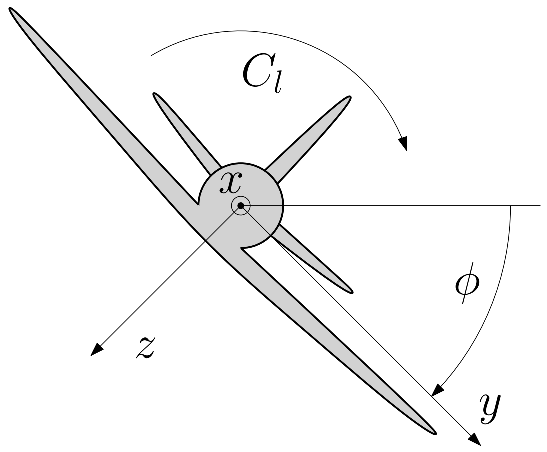
Coupled motion

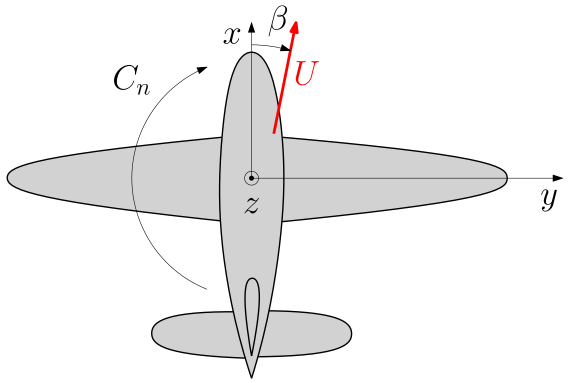
$$\mathbf{A}'_{\mathrm{lat/dir},b} =$$

$$\begin{bmatrix} \frac{1}{2\mu}C_{Y_v} & \frac{1}{2\mu}C_{Y_p} + \frac{\bar{w}}{U_\infty} & \frac{1}{2\mu}C_{Y_r} - \frac{\bar{u}}{U_\infty} & \frac{1}{2\mu}C_G \cos\bar{\theta} \\ \frac{1}{i_D}(i_{zz}C_{l_v} + i_{xz}C_{n_v}) & \frac{1}{i_D}(i_{zz}C_{l_p} + i_{xz}C_{n_p}) & \frac{1}{i_D}(i_{zz}C_{l_r} + i_{xz}C_{n_r}) & 0 \\ \frac{1}{i_D}(i_{xz}C_{l_v} + i_{xx}C_{n_v}) & \frac{1}{i_D}(i_{xz}C_{l_p} + i_{xx}C_{n_p}) & \frac{1}{i_D}(i_{xz}C_{l_r} + i_{xx}C_{n_r}) & 0 \\ 0 & 1 & \tan\bar{\theta} & 0 \end{bmatrix}$$



$$\mathbf{A}'_{\mathrm{lat/dir},w} \approx$$

$$\begin{bmatrix} \frac{1}{2\mu}C_{Y_\beta} & \frac{1}{2\mu}C_{Y_p} & \frac{1}{2\mu}C_{Y_r} - 1 & \frac{1}{2\mu}C_G \cos\bar{\theta} \\ \frac{1}{i_D}(i_{zz}C_{l_\beta} + i_{xz}C_{n_\beta}) & \frac{1}{i_D}(i_{zz}C_{l_p} + i_{xz}C_{n_p}) & \frac{1}{i_D}(i_{zz}C_{l_r} + i_{xz}C_{n_r}) & 0 \\ \frac{1}{i_D}(i_{xz}C_{l_\beta} + i_{xx}C_{n_\beta}) & \frac{1}{i_D}(i_{xz}C_{l_p} + i_{xx}C_{n_p}) & \frac{1}{i_D}(i_{xz}C_{l_r} + i_{xx}C_{n_r}) & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$



Stability Derivatives

VLM - Vortex-Lattice
DLM - Doublet-Lattice
URANS - Unsteady R-A Navier-Stokes
LFD - Linear Frequency Domain

Unsteady motion

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Unsteady motion

VLM/DLM

Lifting surface theory

Inviscid treatment - no viscosity

No shock treatment

Extremely fast

Resolution of aircraft ?

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Complete resolution of motion in the time domain

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Full frequency spectrum

Intensive in time and computational resources

High resolution of aircraft

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LFD

URANS-based - RANS properties remain

Small perturbations
Excitation independent

Solved in the frequency domain for one frequency

High resolution of aircraft remains

Linear Frequency Domain Method - LFD

Small perturbation approach, periodic motion, harmonic response

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

W … conservative flow state vector

x … grid-node vector

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

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

Consistent linearisation - complex-valued linear system of equations

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

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

Problem reduction | Complex-valued linear system

$$Ax = b$$

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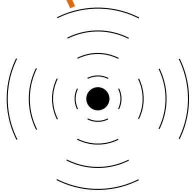
Perturbation



Change of vector **b**

- Self-induced forces
  - Rigid body motion
- Induced forces
  - Atmospheric (Gust)
- Rigid / Elastic Deformation

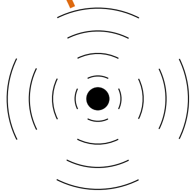
Problem reduction | Complex-valued linear system

How does the disturbance spread

Linearisation according to the flow variables

$$Ax = b$$

Perturbation



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Problem reduction | Complex-valued linear system

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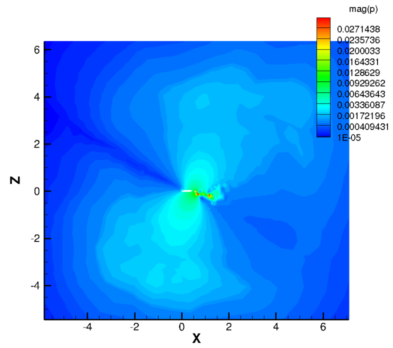
$$Ax = b$$

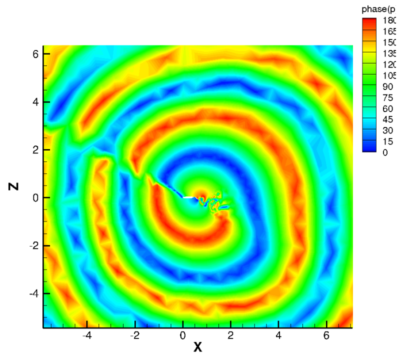
Solution

Perturbation

Magnitude



Phase



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Jacobians and Perturbation

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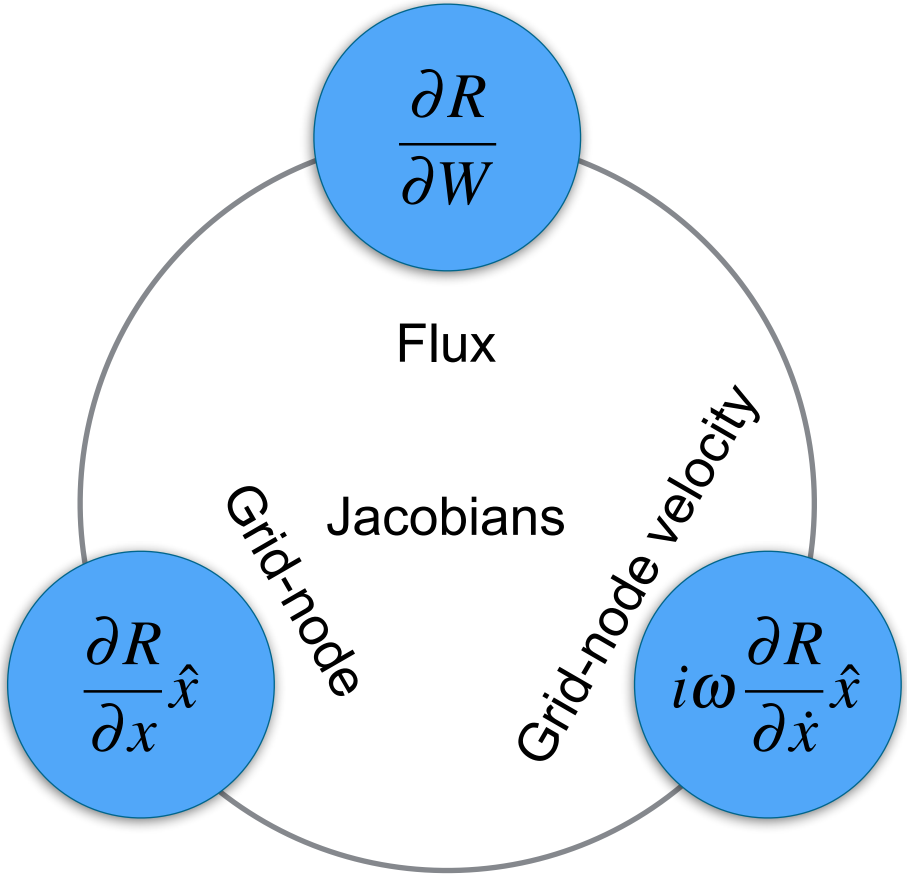


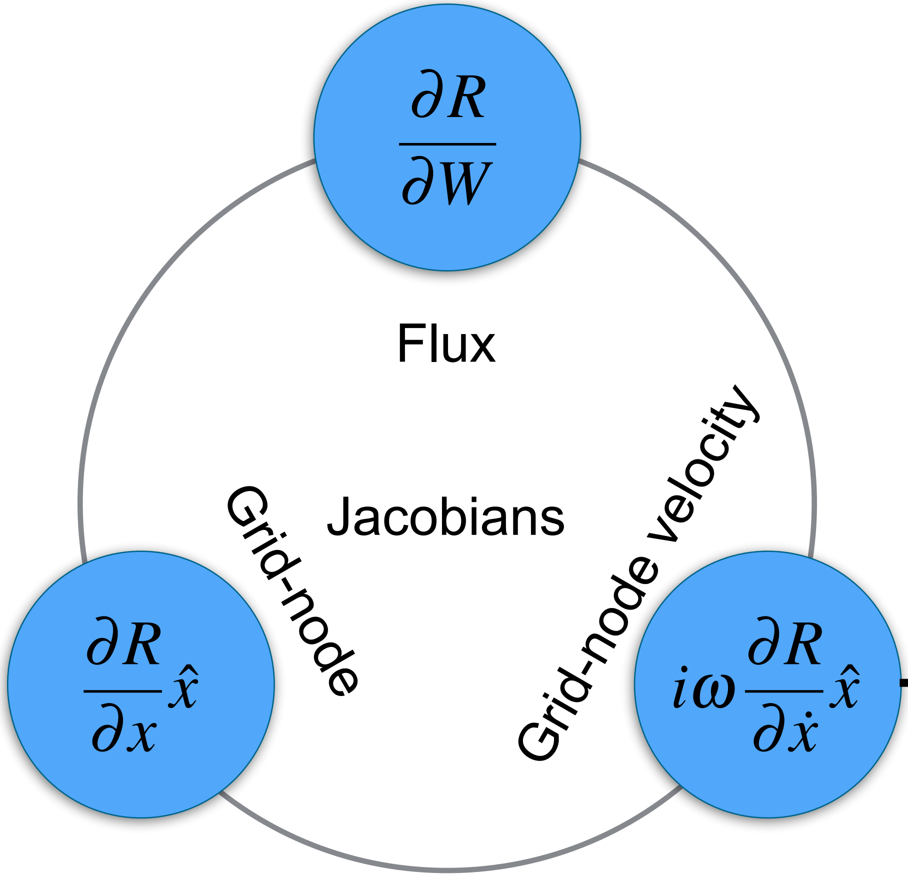
Analytic derivation

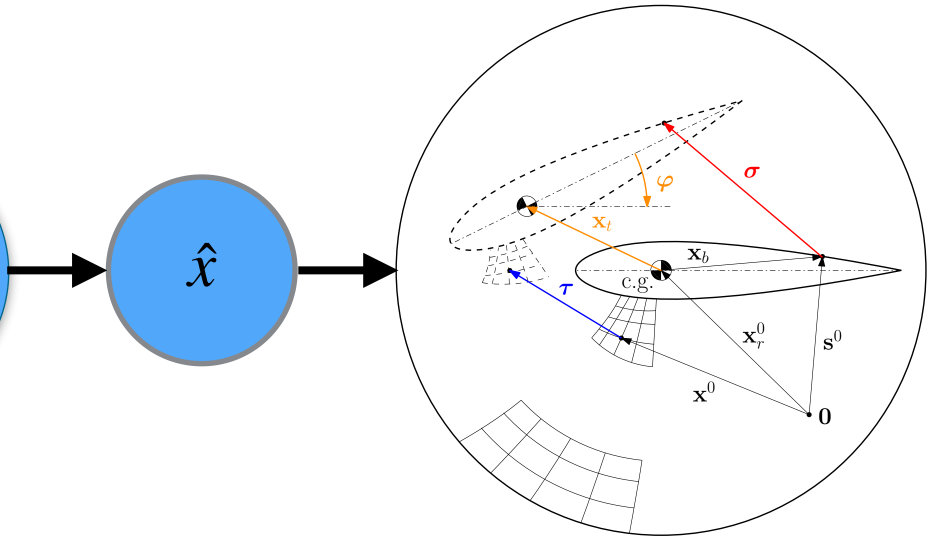
- Consistency, R = 0 (RANS)

Dimension

- nodes x nodes → quadratic increase

Jacobians and Perturbation





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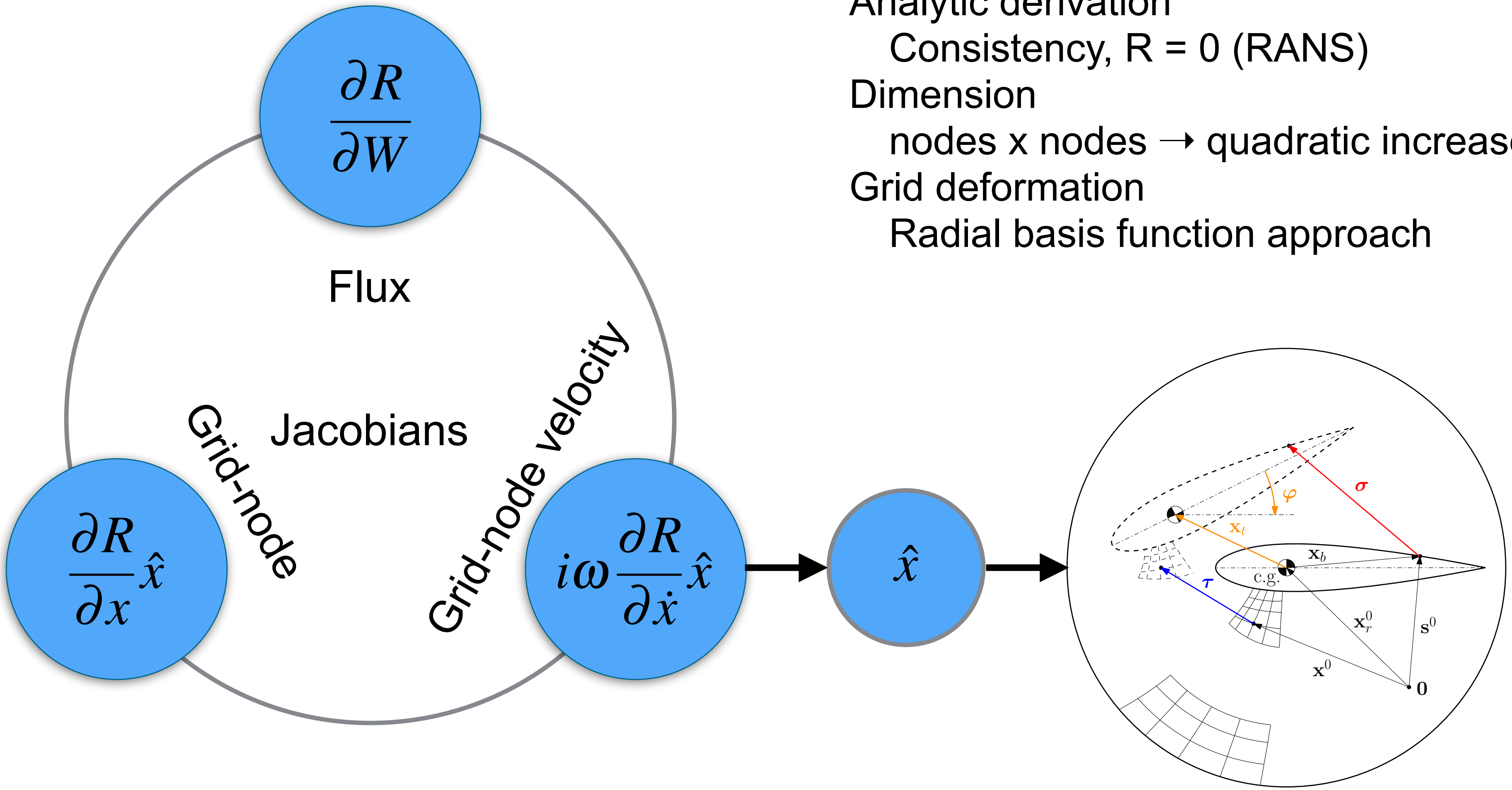
Grid deformation
- Radial basis function approach

Jacobians and Perturbation



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  - nodes x nodes → quadratic increase
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Turbulence model - Spalart-Allmaras

Importance of Linearisation of Turbulence Model

NACA 64A010, M=0.8, Re=12.5 mill., α=0/**2** deg

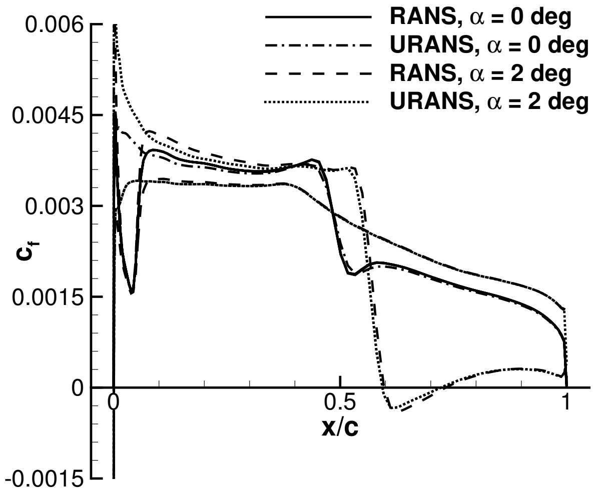
Why so important?

One-equation Spalart-Allmaras

Attached flow, α = 0 deg

Partly separated flow, α = 2 deg

FEVA - Frozen Eddy Viscosity Approach



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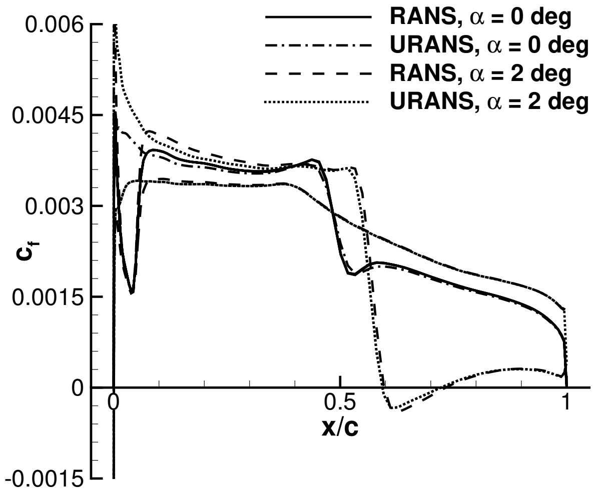

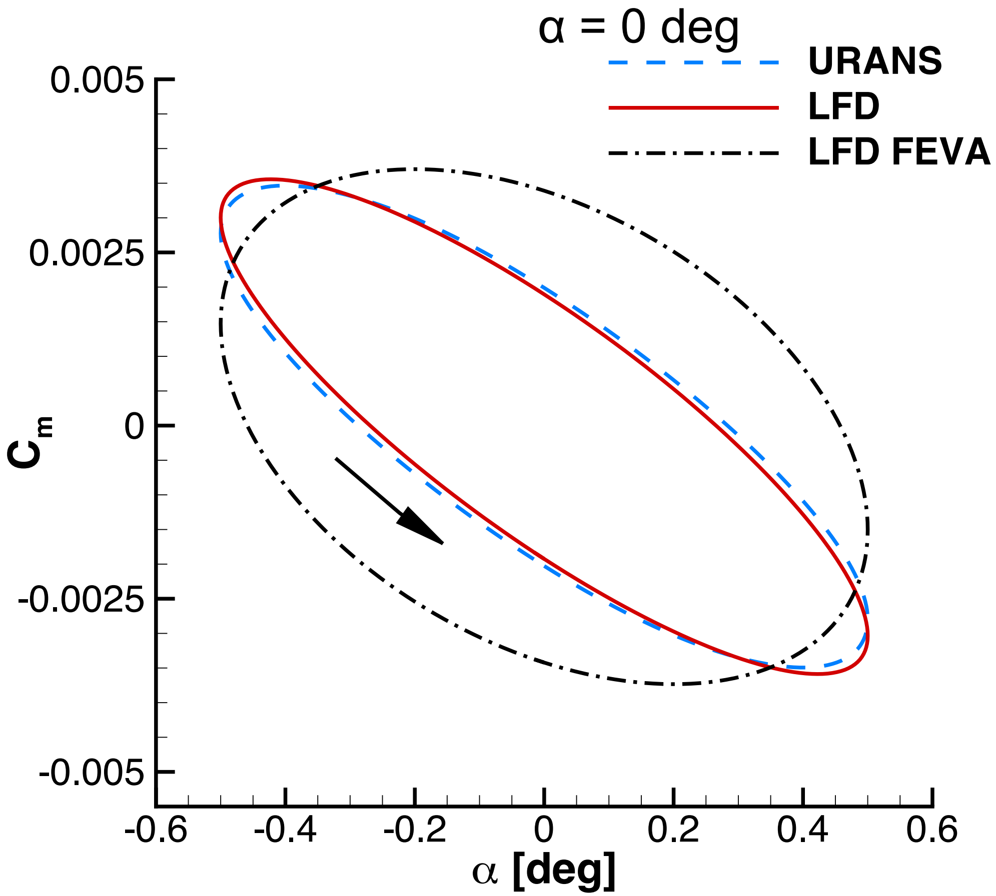

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FEVA - unacceptable

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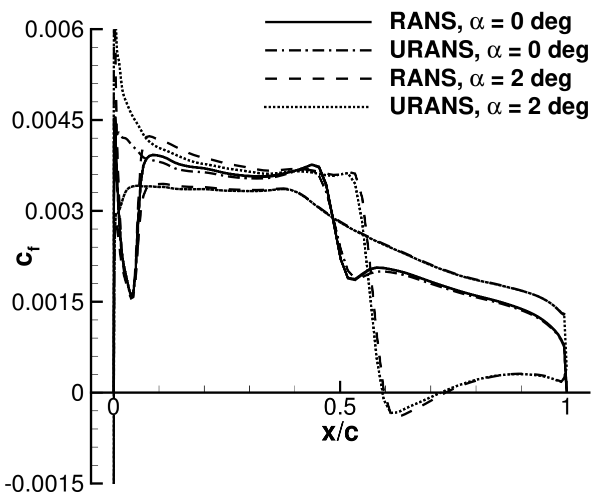
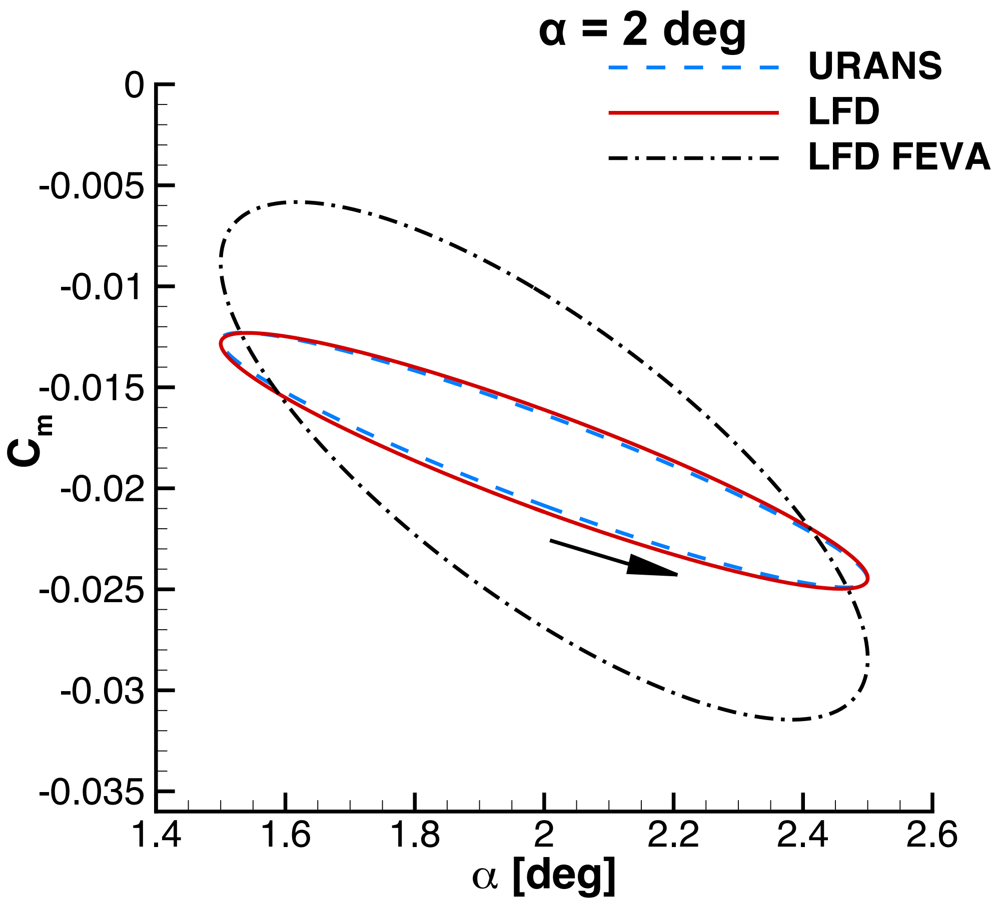
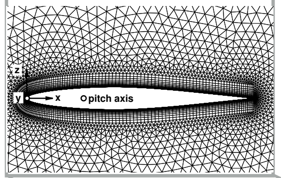




LFD - Validation

NACA 64A010

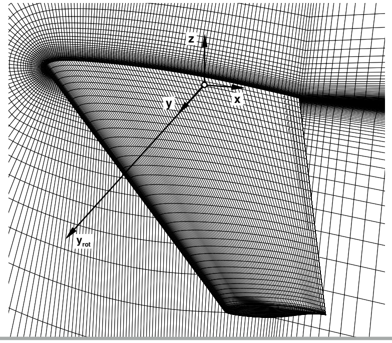
$\bar{\alpha}$ [deg]	M_∞ [-]	Re_∞ [1×10^6]	$l_{ref} = c$ [-]	f [Hz]	k [-]	$\hat{\alpha}$ [deg]
0	0.8	12.5	1	4.3	0.2	0.5



Initial investigation
Turbulence Model

LANN wing CT5/CT9

Case	$\bar{\alpha}$ [deg]	M_∞ [-]	Re_∞ [1×10^6]	T [K]	$l_{ref} = c_r$ [m]	f [Hz]	k [-]	$\hat{\alpha}$ [deg]
CT5	**0.6**	0.82	7.3	302	0.3608	24	0.2	0.25
CT9	**2.6**							

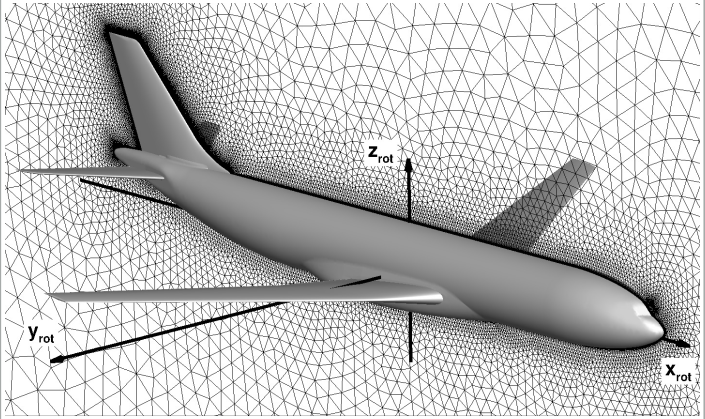


Solution techniques
breakthrough
speed up

years of extensive testing

DLR-F12

motion	$\bar{\alpha}$ [deg]	U_∞ [$m\,s^{-1}$]	Re_∞ [1×10^6]	l_μ [m]	f [Hz]	$\hat{\alpha}$ [deg]
roll/pitch/yaw	[0,3,6]	70	1.28	0.2526	3	4.86/4.52/4.32



Experimental data
roll/pitch/yaw

LFD - Validation

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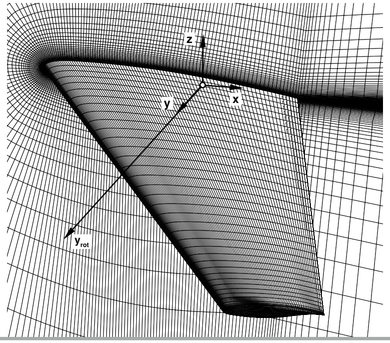

LFD - Validation

Case	$\bar{\alpha}$ [deg]	M_∞ [-]	Re_∞ [1×10^6]	T [K]	$l_{ref} = c_r$ [m]	f [Hz]	k [-]	$\hat{\alpha}$ [deg]
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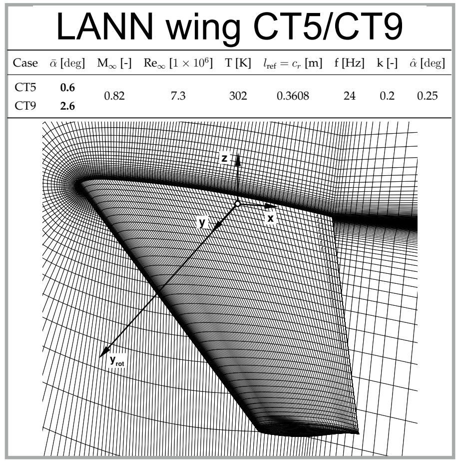
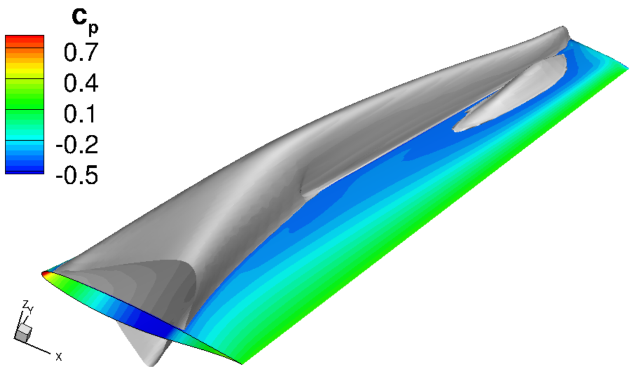
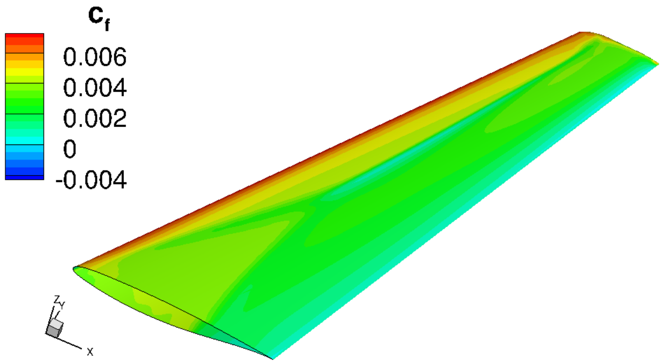
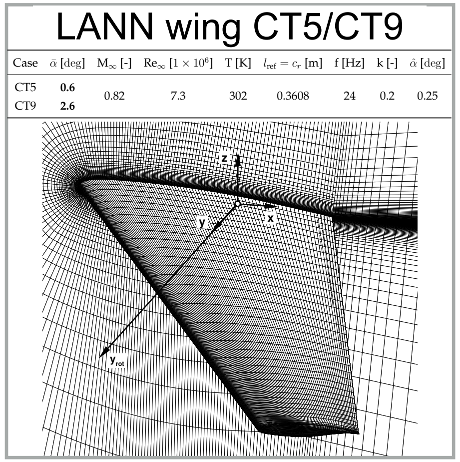






CT5

LFD - Validation



Case	$\bar{\alpha}$ [deg]	M_∞ [-]	Re_∞ [1×10^6]	T [K]	$l_{ref} = c_r$ [m]	f [Hz]	k [-]	$\hat{\alpha}$ [deg]
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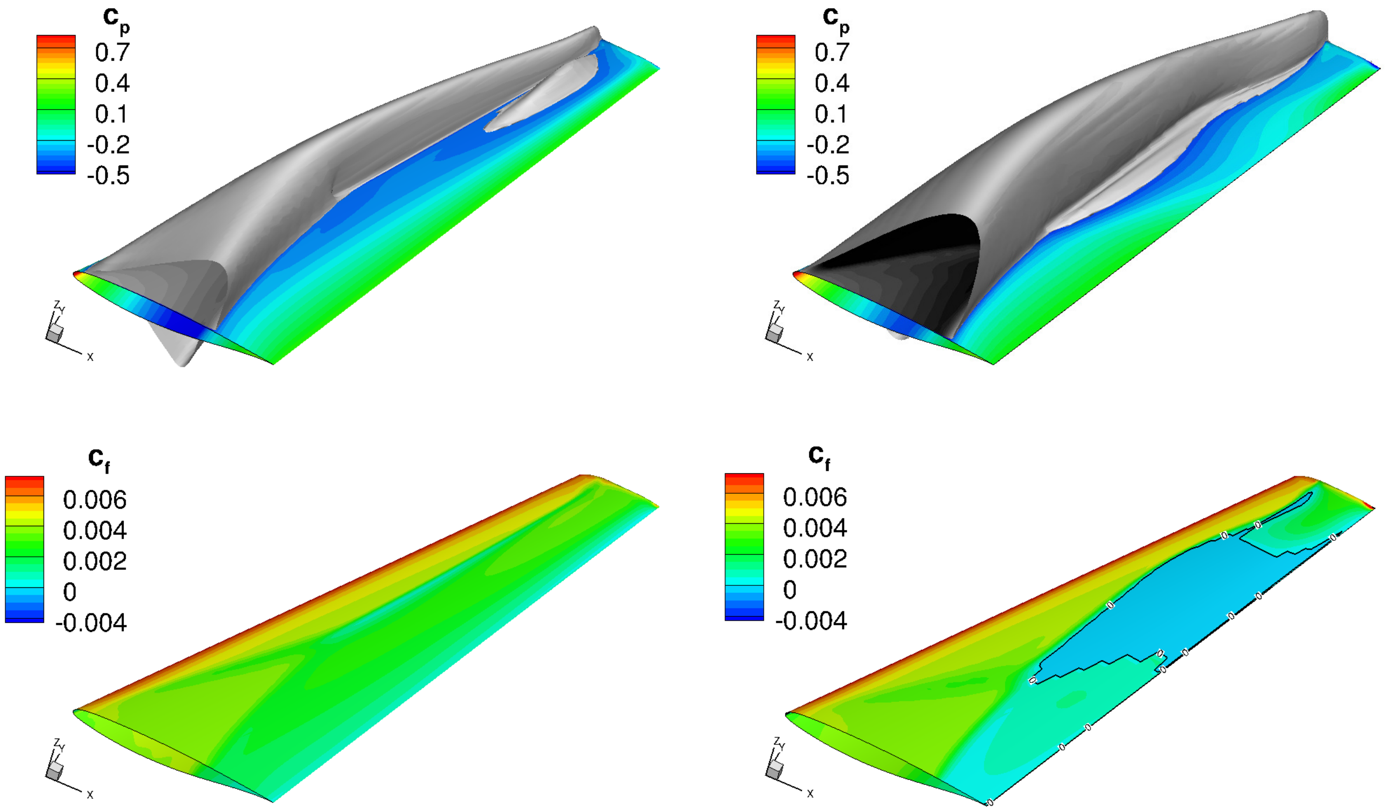

CT5

CT9

Frequency/Amplitude Response Function (FRF/ARF)

Rigid motion in pitch - Lift

Frequency/Amplitude Response Function (FRF/ARF)
Rigid motion in pitch - Lift

LANN wing CT5/CT9

Case	$\bar{\alpha}$ [deg]	M_∞ [-]	Re_∞ [1×10^6]	T [K]	$l_{ref} = c_r$ [m]	f [Hz]	k [-]	$\hat{\alpha}$ [deg]
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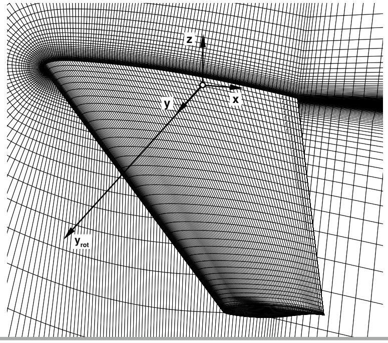
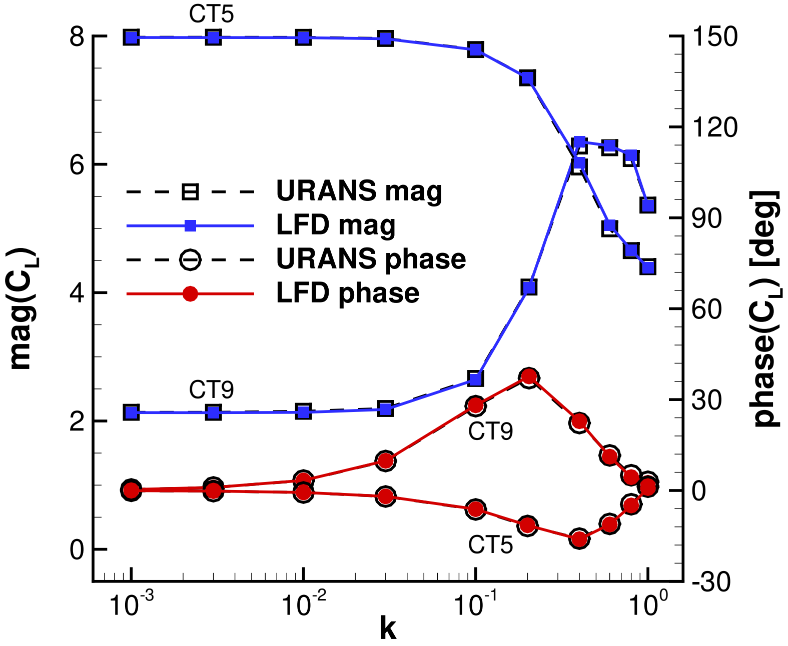


Phase lag / lead - Dynamically linear / non-linear



Pitch FRF CT5/CT9

Frequency/Amplitude Response Function (FRF/ARF)

Rigid motion in pitch - Lift

LANN wing CT5/CT9

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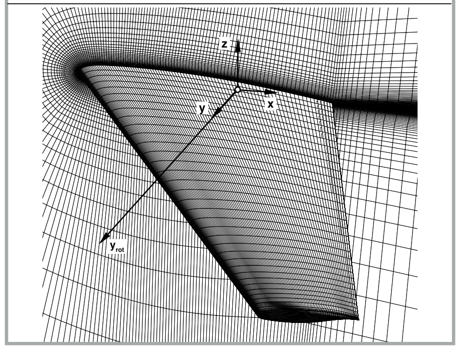

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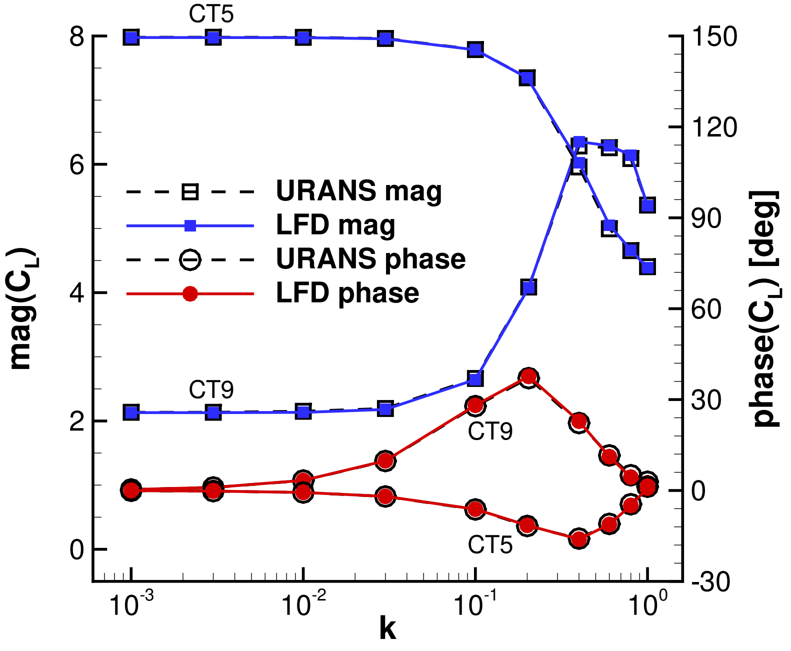
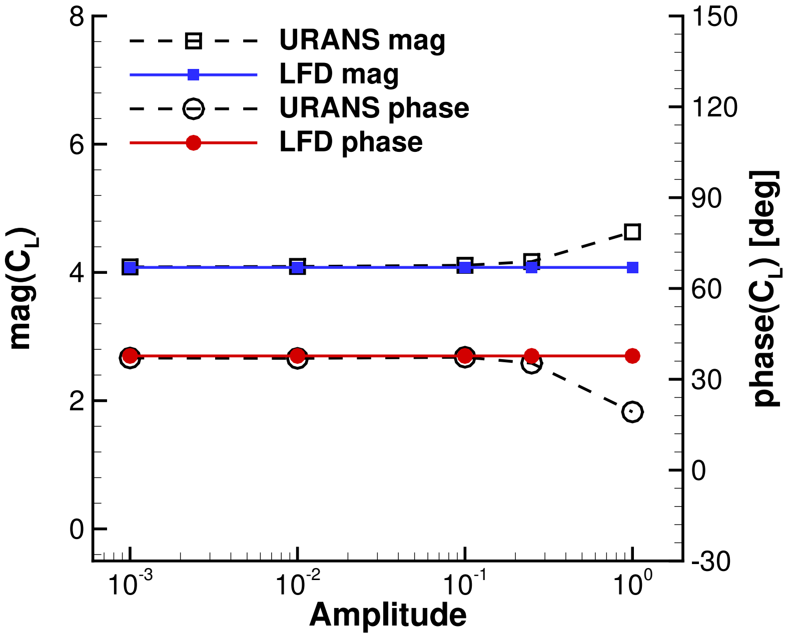


Pitch FRF CT5/CT9



ARF CT9

Frequency/Amplitude Response Function (FRF/ARF)
Rigid motion in pitch - Lift

LANN wing CT5/CT9

Case	$\bar{\alpha}$ [deg]	M_∞ [-]	Re_∞ [1×10^6]	T [K]	$l_{ref} = c_r$ [m]	f [Hz]	k [-]	$\hat{\alpha}$ [deg]
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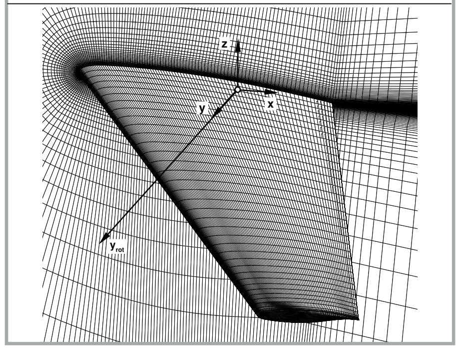
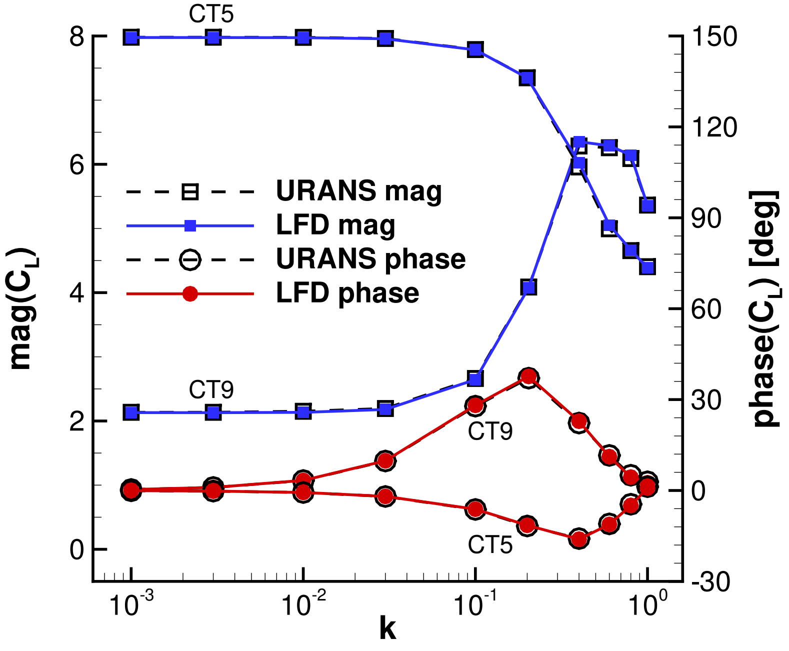
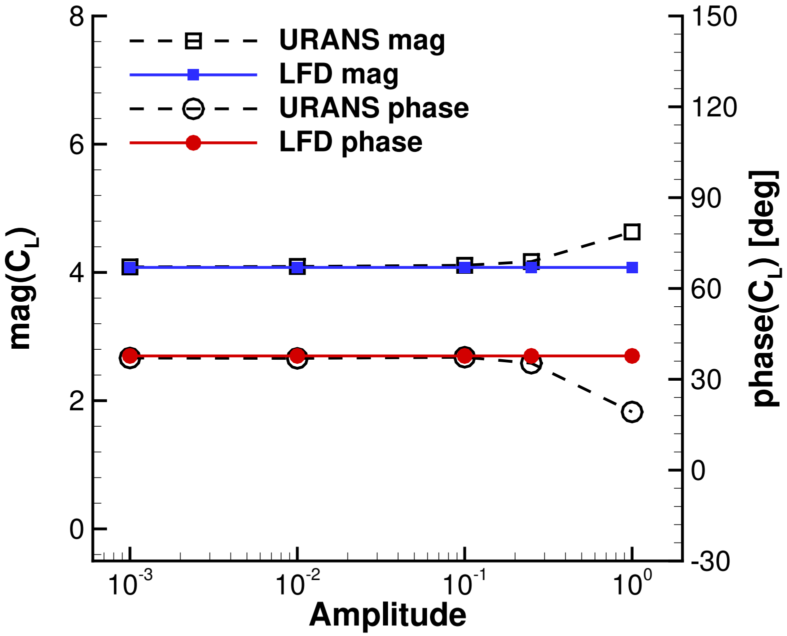


Phase lag / lead - Dynamically linear / non-linear

CASE	CPU-time (h)		URANS/LFD
	URANS	LFD	
CT5	994	6.7	148
CT9	5512	32	172

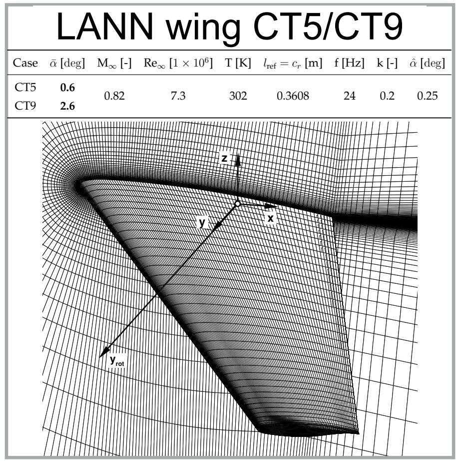


Pitch FRF CT5/CT9



ARF CT9

Frequency/Amplitude Response Function (FRF/ARF)
Rigid motion in pitch - Lift



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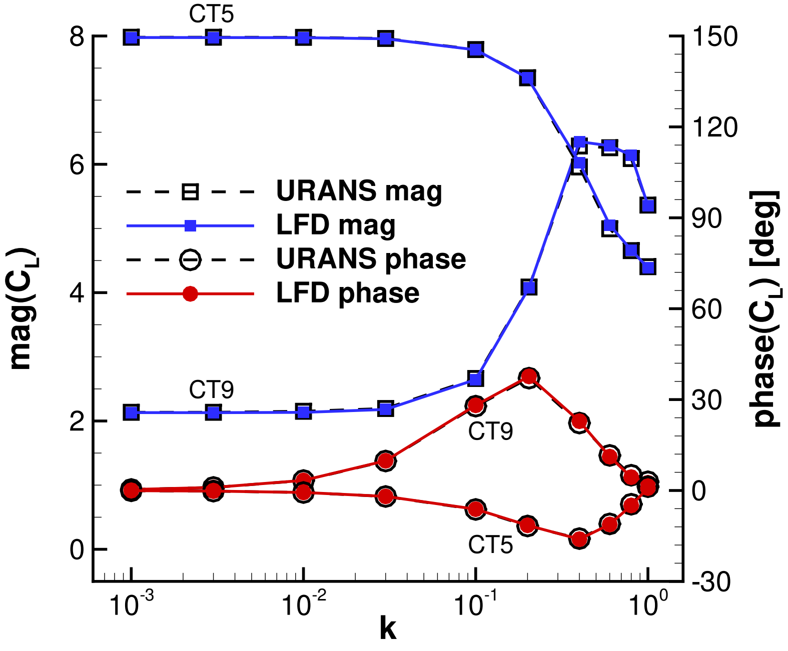
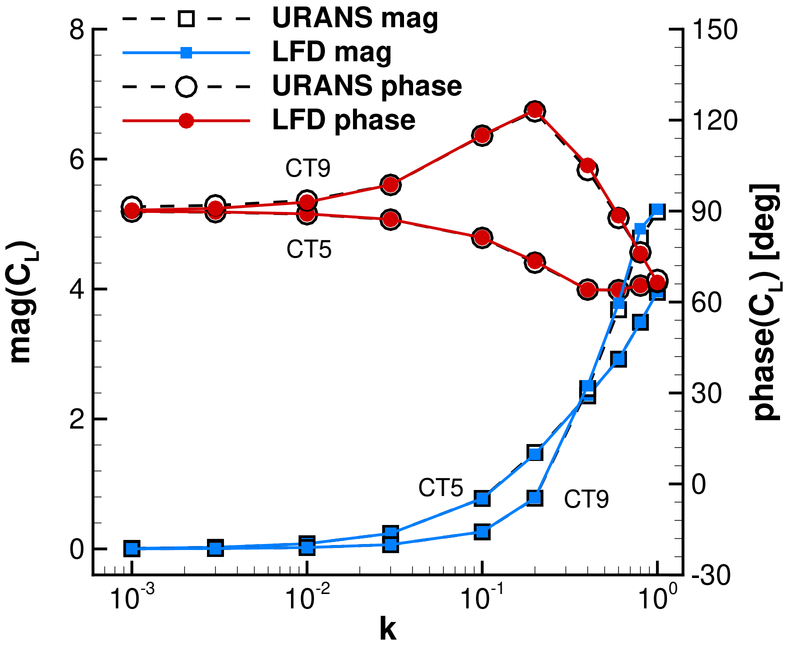


Pitch FRF CT5/CT9



Heave - FRF CT5/CT9

Frequency/Amplitude Response Function (FRF/ARF)

Rigid motion in pitch - Lift

LANN wing CT5/CT9

Case	$\bar{\alpha}$ [deg]	M_∞ [-]	Re_∞ [1×10^6]	T [K]	$l_{ref} = c_r$ [m]	f [Hz]	k [-]	$\hat{\alpha}$ [deg]
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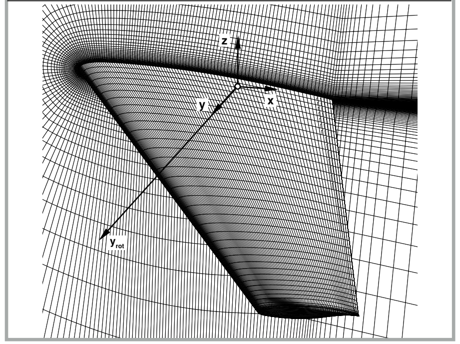

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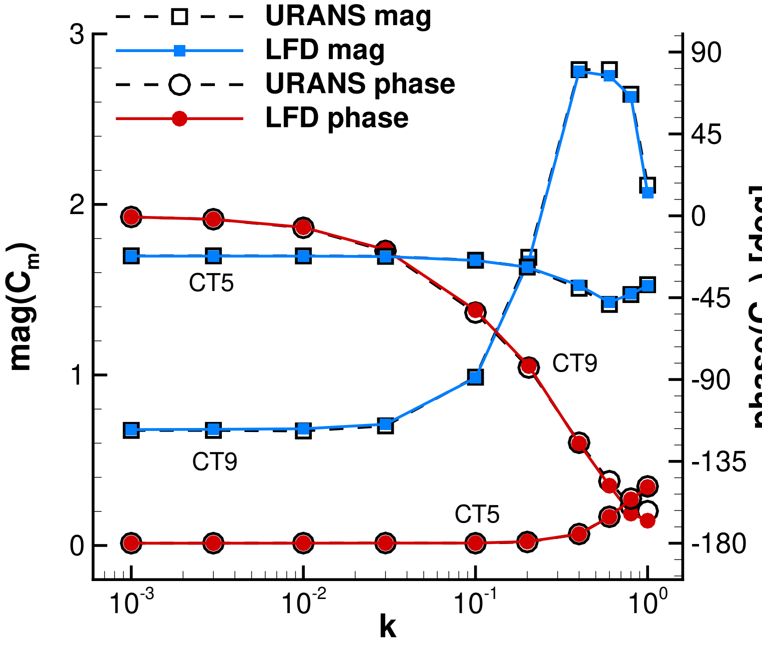
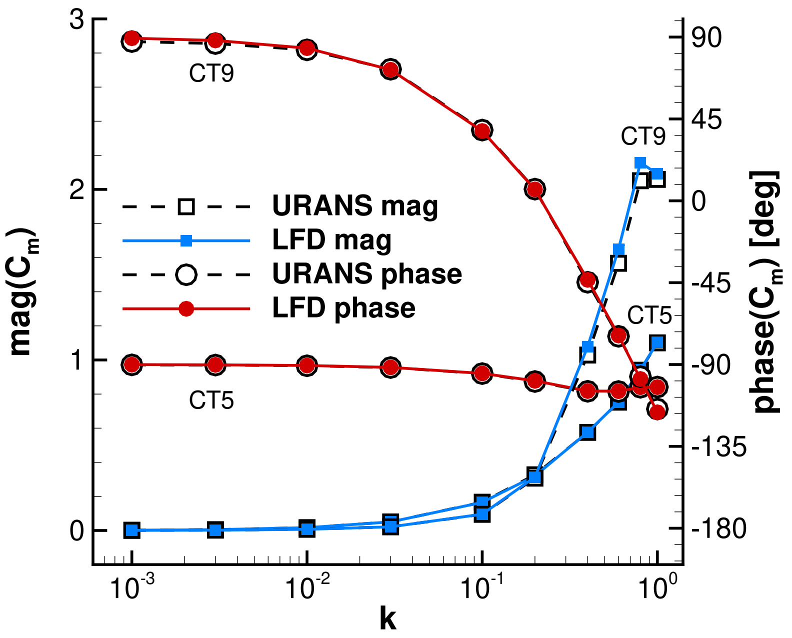
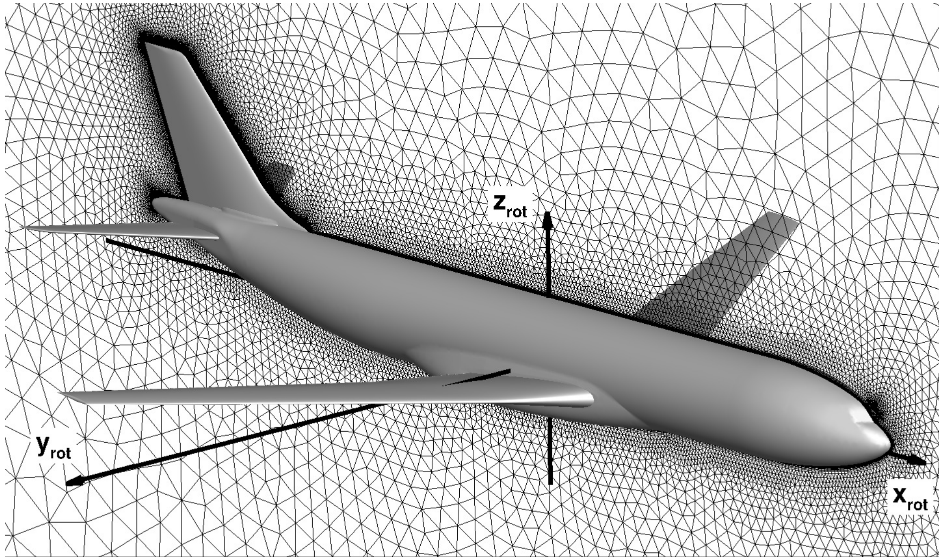


Pitch FRF CT5/CT9



Heave - FRF CT5/CT9

Flight stability prediction
DLR-F12 subsonic case



Full scale DLR-F12

Parameter	value
l_μ (MAC)	7.2705 m (0.252 625 m)
scale	28.78
S	367.87 m^2 (0.444 14 m^2)
m	193 t
I_{xx}	1.50×10^7 kg m^2
I_{yy}	2.02×10^7 kg m^2
I_{zz}	3.46×10^7 kg m^2
I_{xz}	-7.70×10^5 kg m^2
$\mathbf{x}_{c.g.}$	[30.18, 0.0, -0.87] m ([1.049, 0.0, -0.030] m)
$x_{\text{LE-MAC}}$	27.0 m (0.9381 m)

Parameter space DLR-F12

Parameter	value/range
f [Hz]	[(0.0), 0.15, 0.3, 0.8, 1.5, 3.0, 8.0, 15.0, 33.0]
$\bar{\alpha}$ [deg]	[0, 3, 6]
U_∞	70 m s^{-1}
ρ_∞	1.225 kg m^{-3}
p_∞	101 325 Pa
T_∞	288.15 K
$\mu = \frac{2m}{\rho_\infty S l_\mu}$	118.2
I_{ref}	21 651 kg m^2

Full scale DLR-F12
Subsonic case - Flight Stability

LFD (filled) - VLM (lucent, M. Hepperle)
M = 0.206, Re = 1.28 m., α = β = 0°
Trimmed case
Five typical aircraft modes

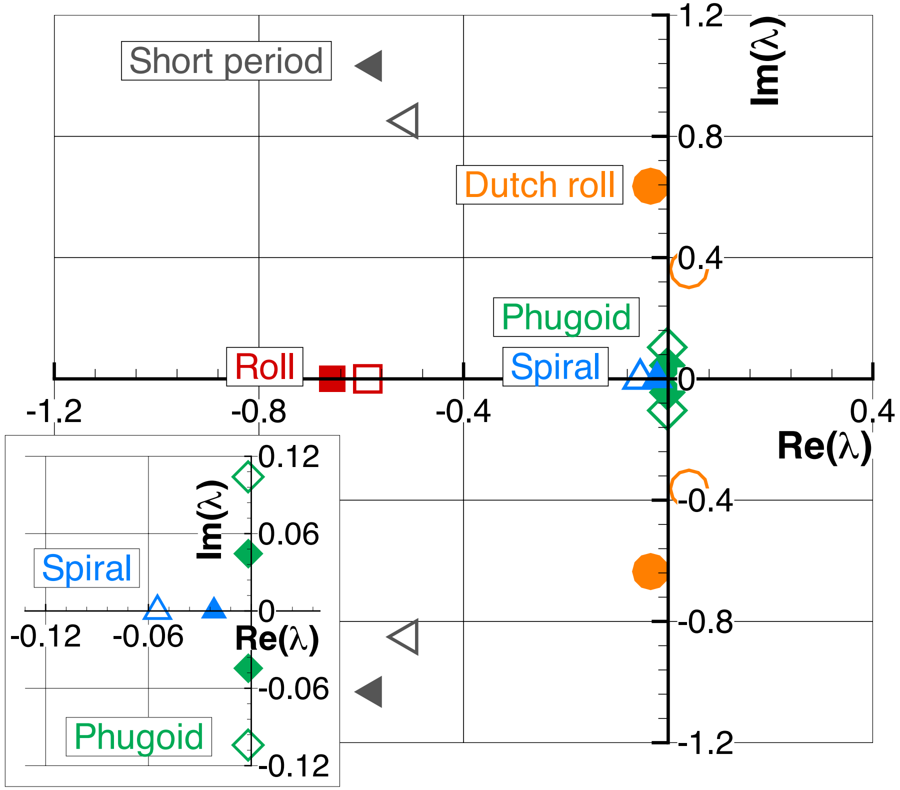
Longitudinal

Short period mode
Phugoid (viscosity)
2nd order time response

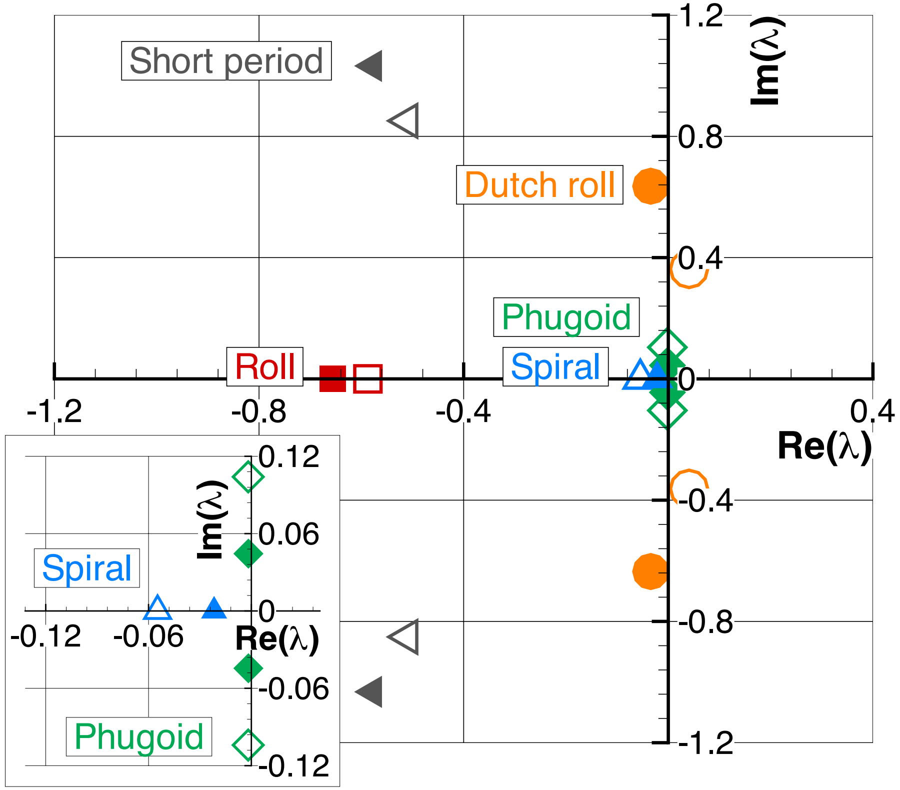
Lateral/Directional

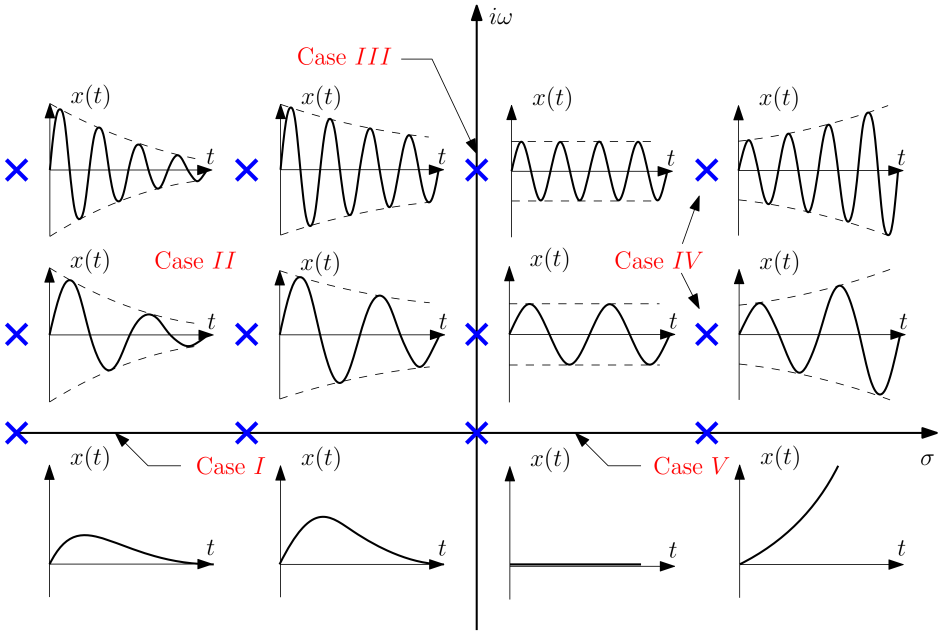
Dutch roll mode
2nd order time response

Roll mode
Spiral mode
1st order time response



Full scale DLR-F12
Subsonic case - **Flight Stability**



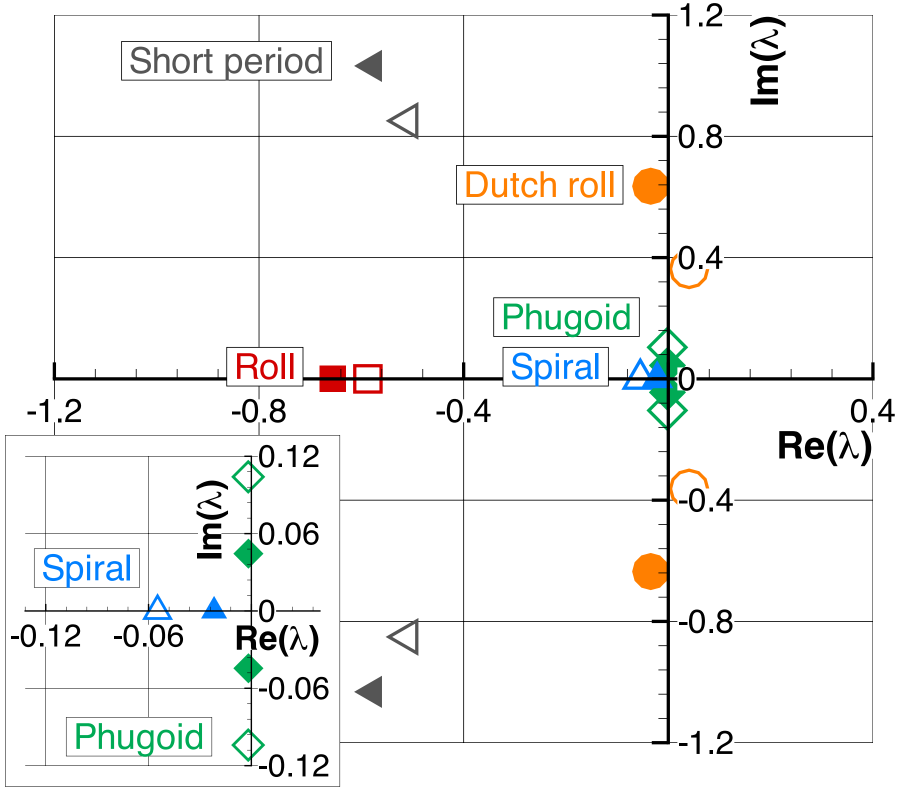


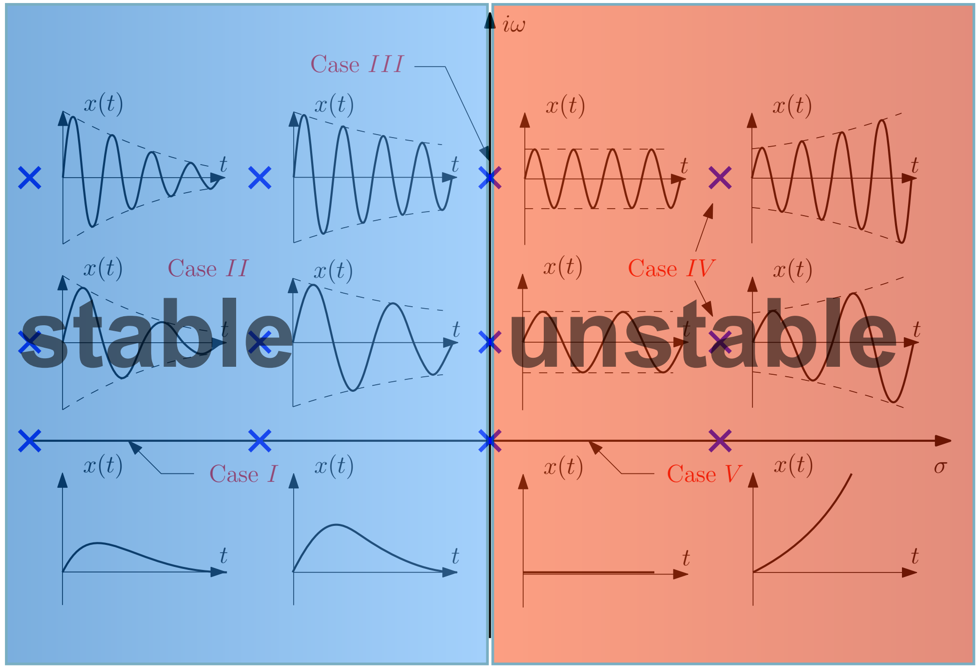
CASE I/V
1st order response
transient

CASE III
Undamped Oscillation

CASE II/IV
2nd order response
oscillation

Full scale DLR-F12
Subsonic case - **Flight Stability**





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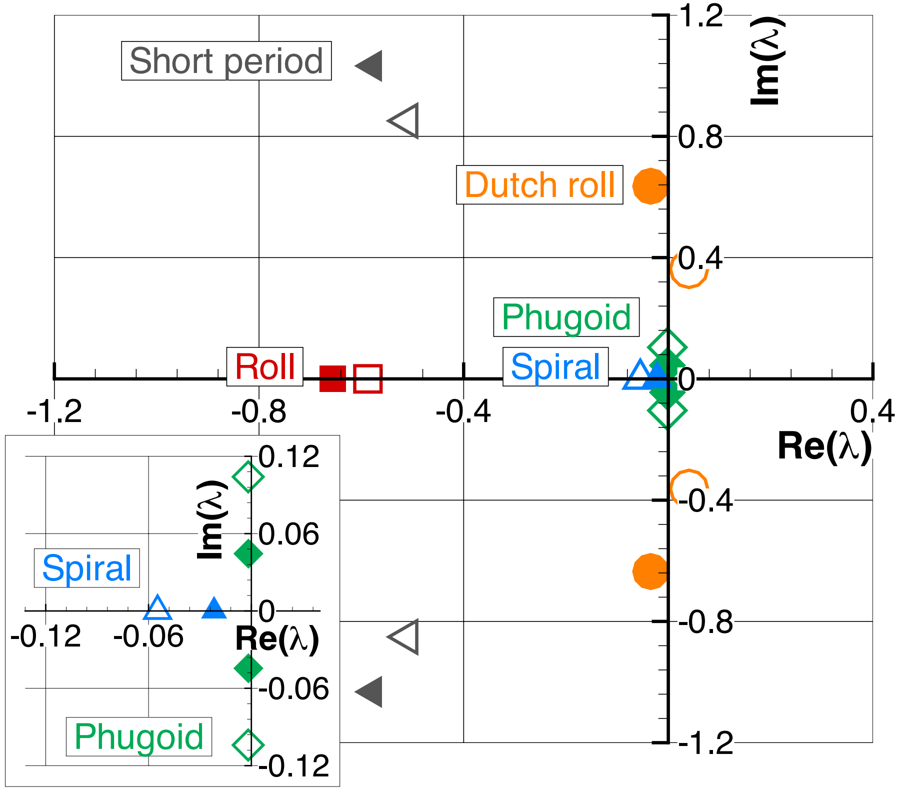
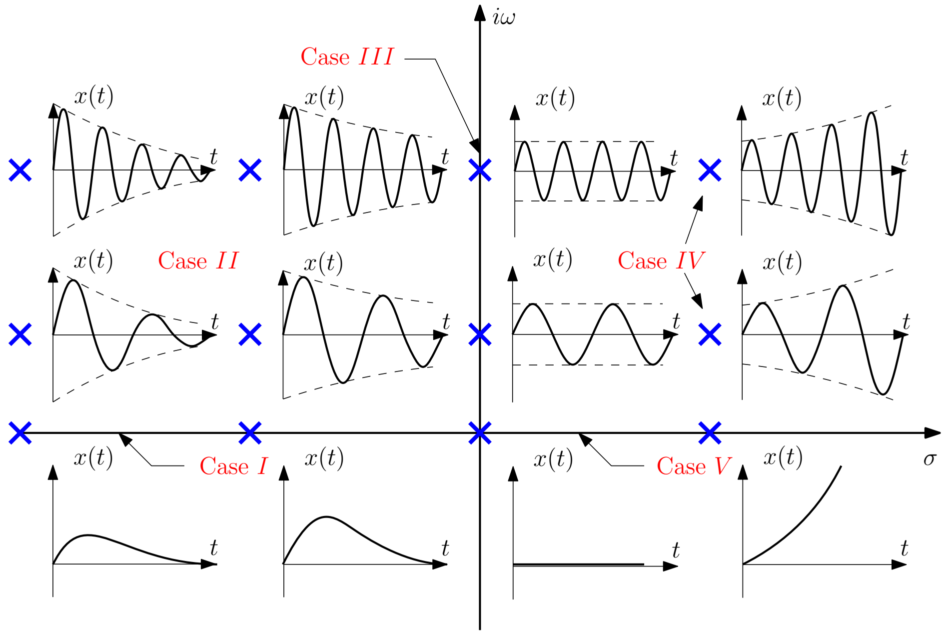
Full scale DLR-F12
Subsonic case - **Flight Stability**





CASE I/V
1st order response
transient

CASE III
Undamped Oscillation

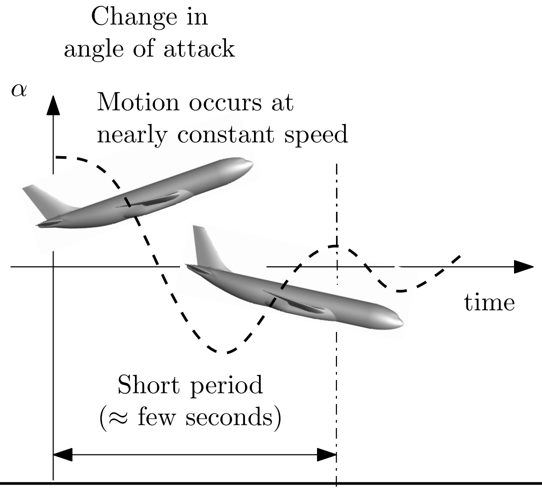
CASE II/IV
2nd order response
oscillation

Five typical aircraft modes

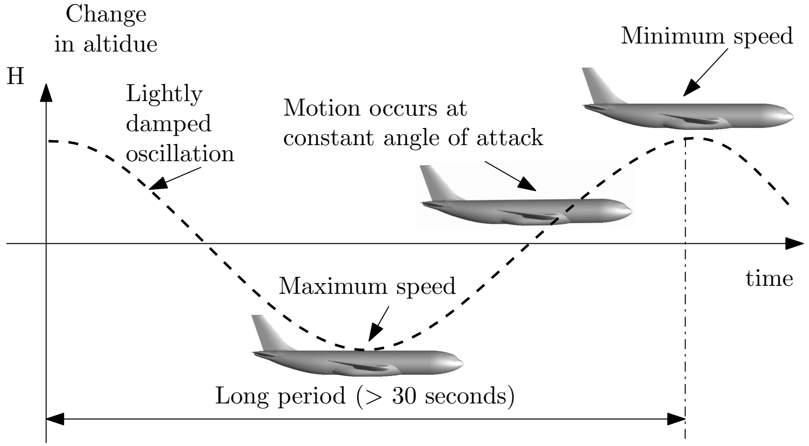
DLR

Longitudinal

Short period mode

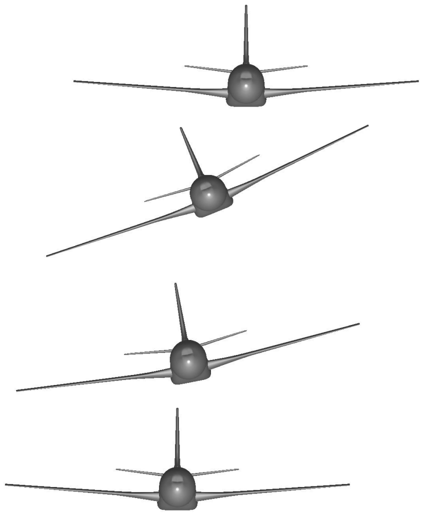


Long period mode (Phugoid)

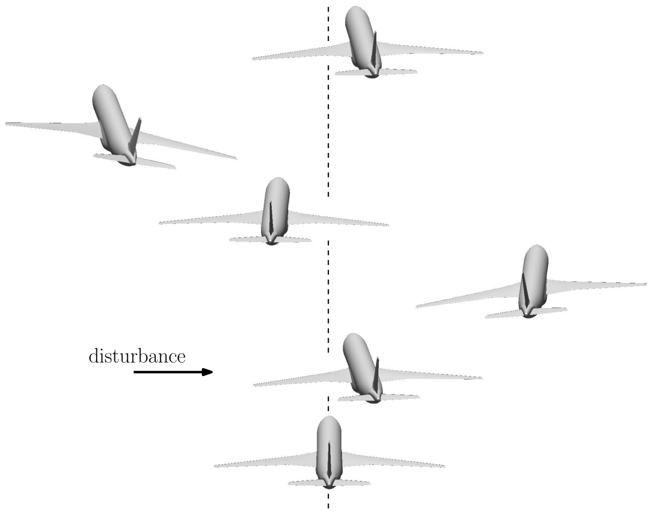


Lateral/ Directional

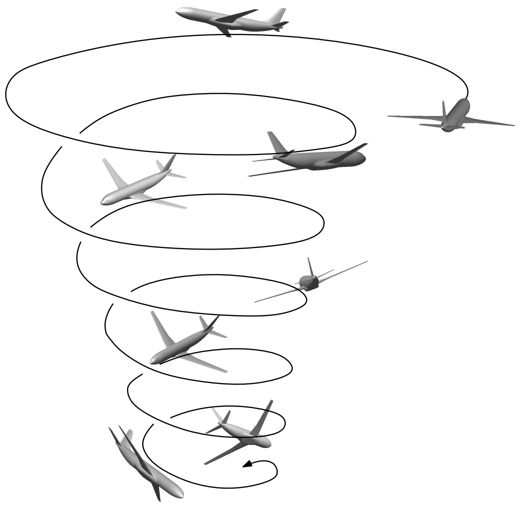
Roll mode



Dutch roll mode



Spiral



Full scale DLR-F12

Subsonic case - Flight Stability

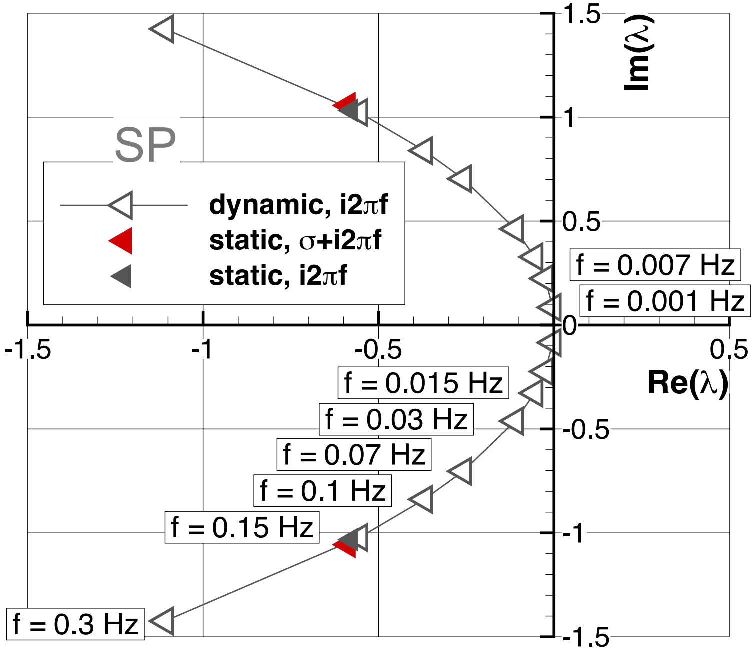
M = 0.206, Re = 1.28 m., α = 0°, β = 0°

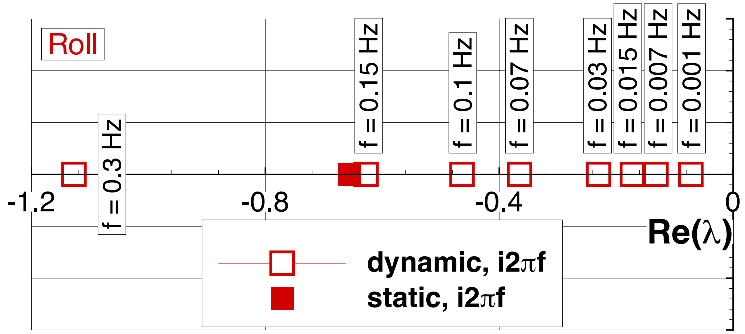
LFD - 2nd order time response

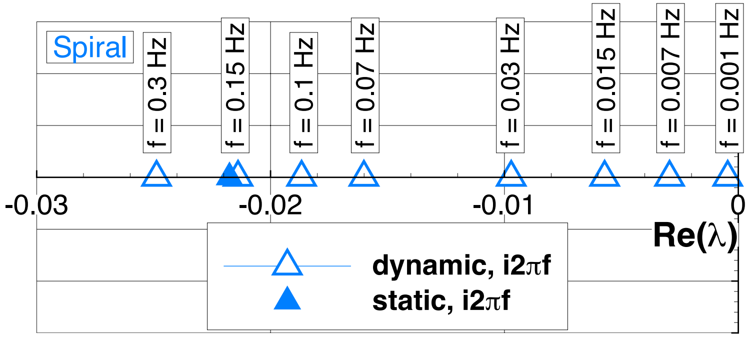
- Short period mode
- Phugoid
- Dutch roll mode

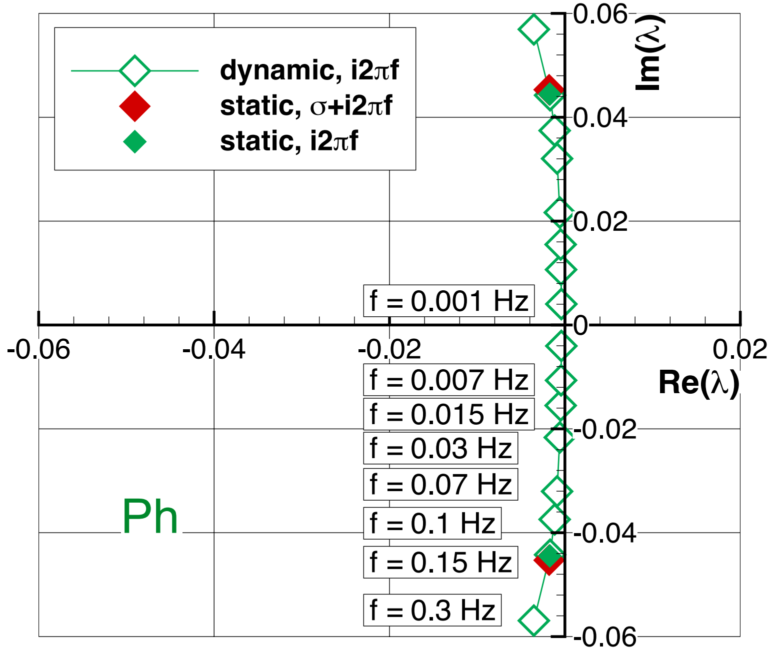
1st step: λ = iω, harmonic

iterative: λ = σ ± iω, damped harmonic









DLR

Full scale DLR-F12
Subsonic case - Flight Stability

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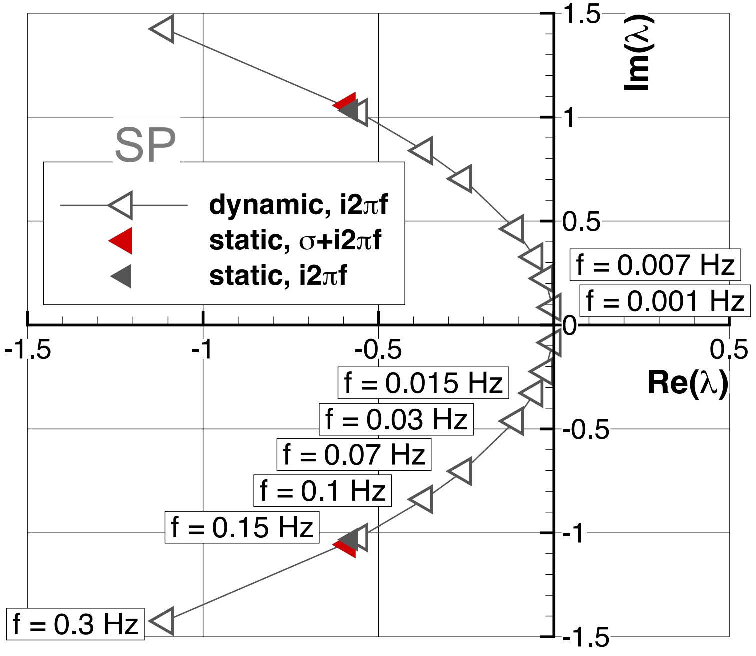
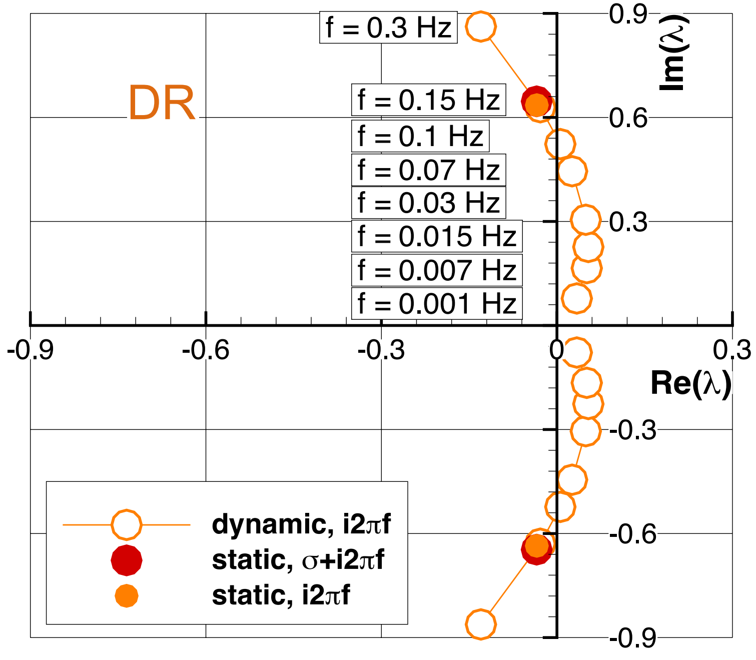
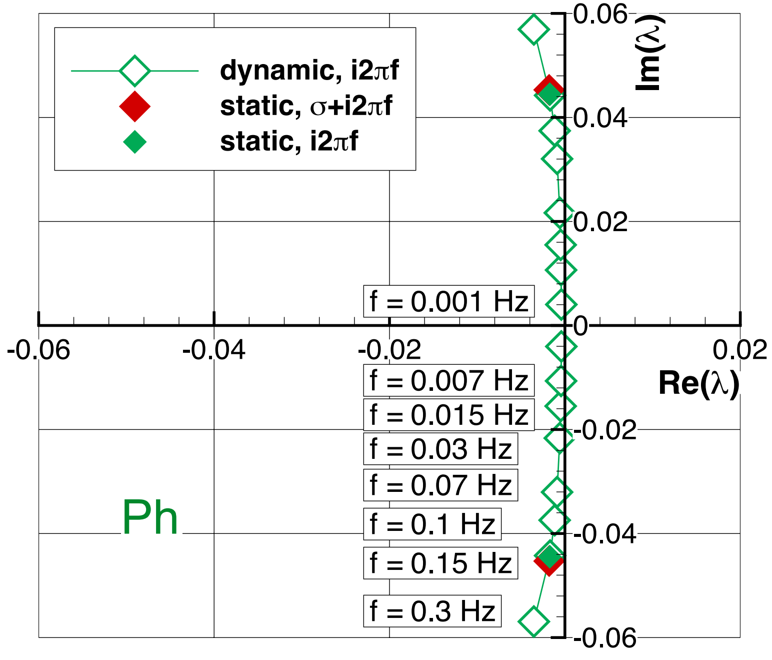
1st step: $\lambda = i\omega$, harmonic

iterative: $\lambda = \sigma \pm i\omega$, damped harmonic





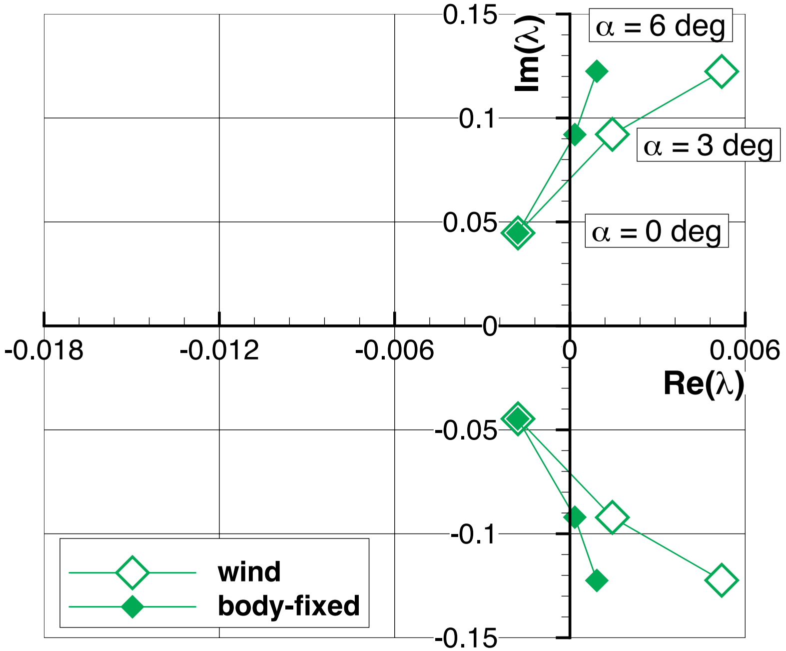


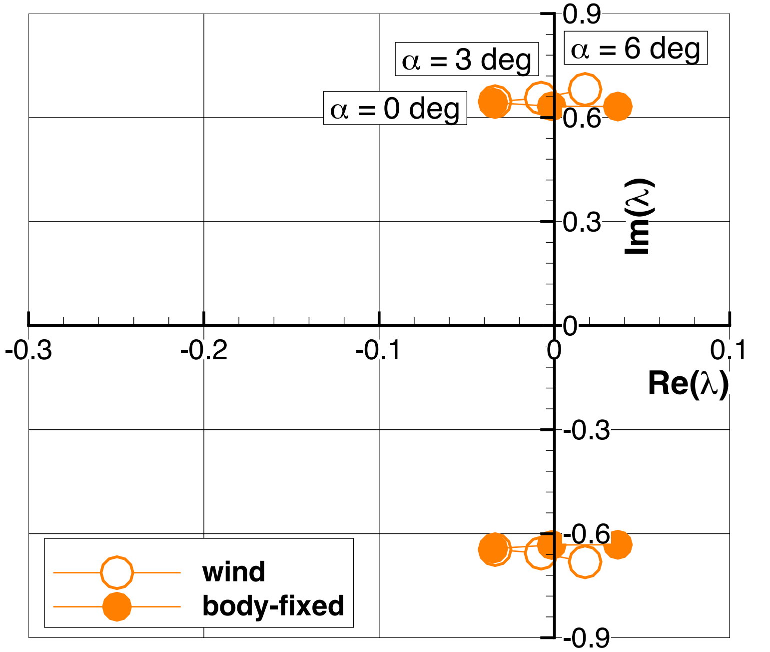
Full scale DLR-F12
Subsonic case

LFD investigation - Angle of attack variation
M = 0.206, Re = 1.28 m., β = 0°
Phugoid: C_{Xu}, C_{Zu}, and C_g
Dutch roll mode: C_{Yv}, C_{Yr}, C_{lv}, C_{lr}, C_{nv} and C_{nr} (v - β)

Comparison between wind and body-fixed Deviation fro

- Oscillation frequency almost inherent
- Wind
    - PH, DR: Damping deviates
- Body-fixed
    - PH: Accurate C_{Xu} and C_{Zu}
    - DR: Coupling of roll-yaw





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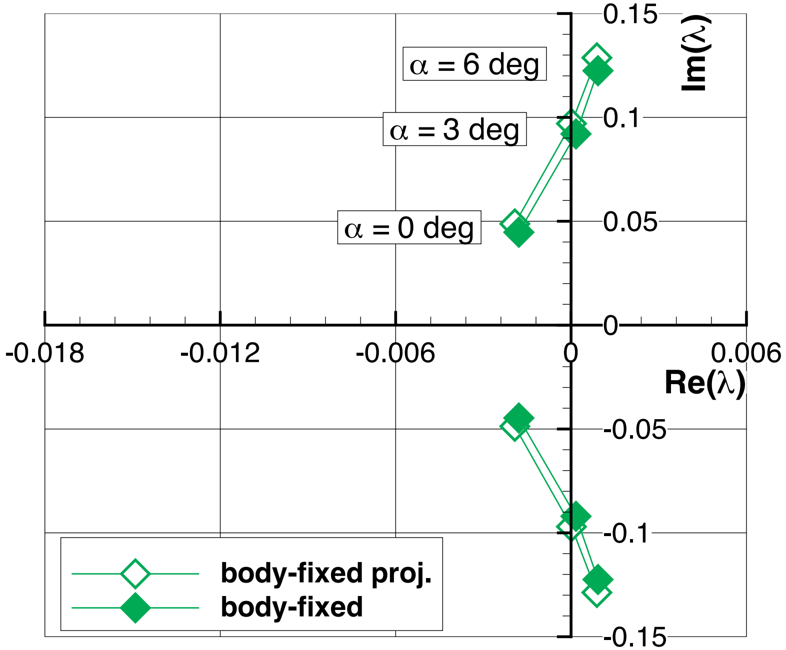
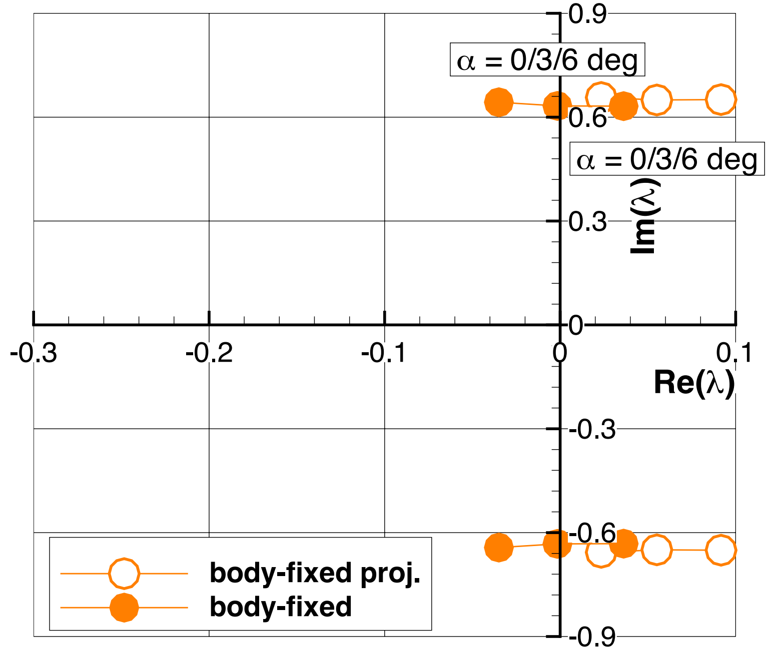


Comparison between body-fixed projection and body-fixed

Scalar treatment - Pendulum Approach

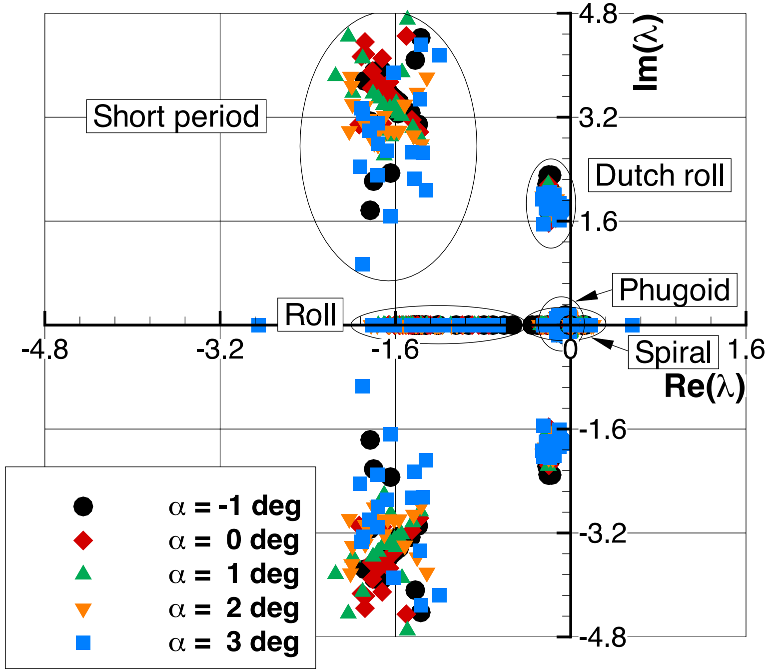
PH: Similar results
DR: Projection - C_{lv} and C_{nr} are similar to values of VLM and thus smaller in magnitude
Projection shifts EV entirely into unstable region



Time reduction - full scale DLR-F12 - transonic

Time reduction - full scale DLR-F12 - transonic

Transonic parameter space
19 Mach numbers: 0.7-0.96
5 angles of attack: -1,0,1,2,3 deg
8 frequencies
6 motions (trans+rot)
4845 LFD simulations



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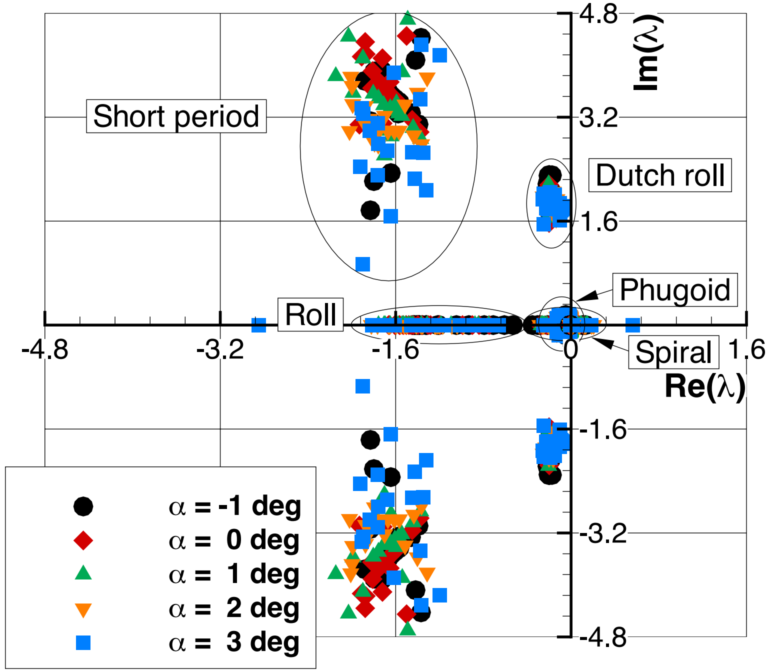

Method	CPUs	# sim.	t/sim. [hours]	t_{tot} [days]
RANS	72	19 x 5	12.1	48
LFD	72 (120)	19 x 5 x 48[1]	1.67	$\approx$ 318 (191)
URANS (estimated)				
$M_\infty = 0.70 - 0.85$	72	8 x 5 x 48	≈ 77[2]	6160
$M_\infty = 0.86 - 0.90$	72	5 x 5 x 48	≈ 96[3]	4813
$M_\infty = 0.91 - 0.96$	72	6 x 5 x 48	≈ 116[4]	6960
$\sum$ URANS				17933
ζ_{CPU}				$\approx$ 56

[1] 19 Mach numbers, 5 angles of attack, 48: 8 frequencies x 6 motions
[2] 300 pseudo time iter., 3W, 80 steps/period, 4 periods
[3] 1000 pseudo time iter., sg, 80 steps/period, 5 periods
[4] 300 pseudo time iter., 3W, 80 steps/period, 6 periods

RANS simulations are neglected URANS/LFD

All LFD simulations converged

URANS simulations are estimated

Time reduction URANS / LFD: **about 60**
Effective time:
RANS/LFD about 1 year
RANS/URANS about 60 years

Conclusion

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**

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

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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

Game changer whenever **separation** appears

Conclusion

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Body-fixed versus aerodynamic frame of reference

- **Body-fixed** is necessary for **arbitrary oriented aircraft**
  - Critical aircraft modes - Phugoid, Spiral and Dutch roll mode
- Scalar versus vector-valued treatment
  - Critical aircraft modes - Dutch roll mode and Spiral
  - Scalar - similar to VLM results
- Plain input of LFD results into state matrix - one motion/one column
- Straightforward extension to three dimensional stability state matrix
  - Drawback: Identification of typical aircraft modes challenging

- Retaining with vector based notation
- **Note:** All six degree of freedom need to be evaluated

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Description in principal axes

- Most accurate - Lagrangian equation of motion

Outlook

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High Resolution of flight vehicle (LFD vs VLM/DLM)

No more correction factors for body/any mountings/high-lift devices aso

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Damped harmonic oscillator - LFD

Problem reduction of complex aerodynamic system important for many unsteady applications

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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 - Actuation jet velocity
Optimisation including Stability & Control
MDO - air loads (LFD - ROM) - Uncertainty quantification

The end result of a well executed spiral dive

Imprint

Topic: Flight Dynamic Stability Prediction for an Aircraft in Transonic Separated Flow Conditions with a Linear Frequency Domain Solver

Date: 1. December 2023

Author: Markus Widhalm

Institute: Institute of Aerodynamics and Flow Technology

Images: DLR

[DLR.de/as/en](DLR.de/as/en)