Multi-Output Auto-Regressive Modeling of Transonic Unsteady Aerodynamics for Flutter Prediction of the Benchmark Supercritical Wing

Ron Efrati, Daniella Raveh

Technion – Israel Institute of Technology

AePW4 Workshop 2026

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Introduction

- A data-driven <u>time-domain</u> approach is investigated for CFD-based flutter prediction of the BSCW
- Time domain approach is preferred mainly due to increased efficiency in reference data generation
- 2D aerodynamics are considered for computational efficiency (Case 3)
- Analysis is performed for:
  - Subsonic flow for model validation in a linear flow case
  - Transonic flow for flutter prediction in presence of a nonlinear flow field

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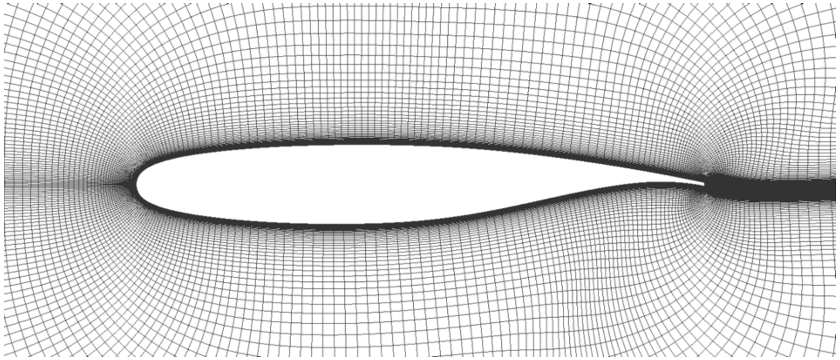
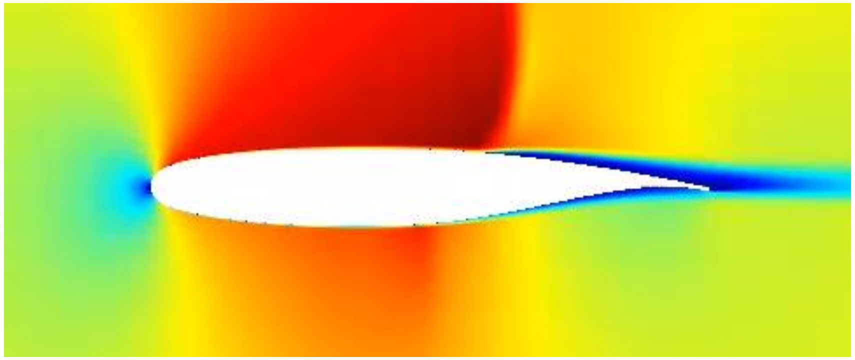
Unsteady Aerodynamic ROM

- Infinite-wing aerodynamics
- Small-amplitude prescribed heave-pitch motion CFD simulations → Reference aerodynamic dataset $\hat{\mathbf{y}}(k), \hat{\boldsymbol{\xi}}(k)$
- EZAir - Structured finite volume code with the k-ω SST turbulence model, and a 2nd order accurate HLLC convective scheme





Reduced-Order Model Formulation

- **Linearization**: Multi-Output Auto-Regressive Exogenous (MOARX)[1]

$$\mathbf{y}(k) = \sum_{i=1}^{na} \mathcal{A}_i \mathbf{y}(k-i) + \sum_{i=0}^{nb} \mathcal{B}_i \boldsymbol{\xi}(k-i)$$

- Least-squares approach to compute $\mathcal{A}_i, \mathcal{B}_i$ from a reference dataset $\hat{\mathbf{y}}(k), \hat{\boldsymbol{\xi}}(k)$

$$\mathbf{x}_A(k+1) = A_A \mathbf{x}_A(k) + B_A \boldsymbol{\xi}(k)$$

$$\mathbf{GF}(k+1) = C_A \mathbf{x}_A(k) + D_A \boldsymbol{\xi}(k)$$

[1] Gupta, K., Cowan, T., and Arena, A., Jr, "Development of a discrete-time aerodynamic model for CFD-based aeroelastic analysis," *37th Aerospace Sciences Meeting and Exhibit*, 1999, p. 765.

Aeroelastic Coupling

- Aeroelastic equations of motion in SS form

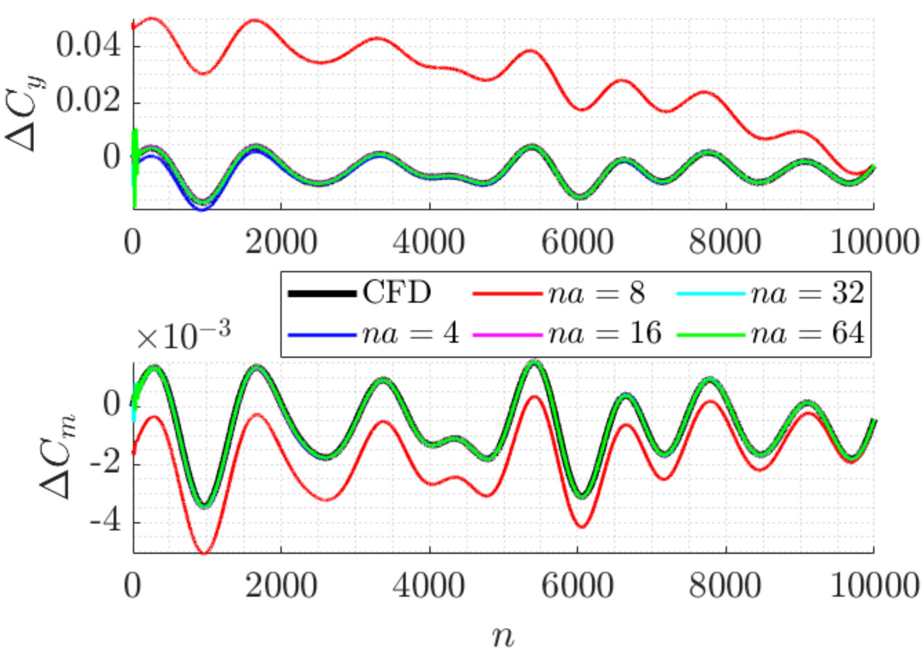
$$\begin{Bmatrix} \mathbf{x}_S(k+1) \\ \mathbf{x}_A(k+1) \end{Bmatrix} = \begin{bmatrix} A_S + q_\infty B_S D_A C_S & q_\infty B_S C_A \\ B_A C_S & A_A \end{bmatrix} \begin{Bmatrix} \mathbf{x}_S(k) \\ \mathbf{x}_A(k) \end{Bmatrix}$$

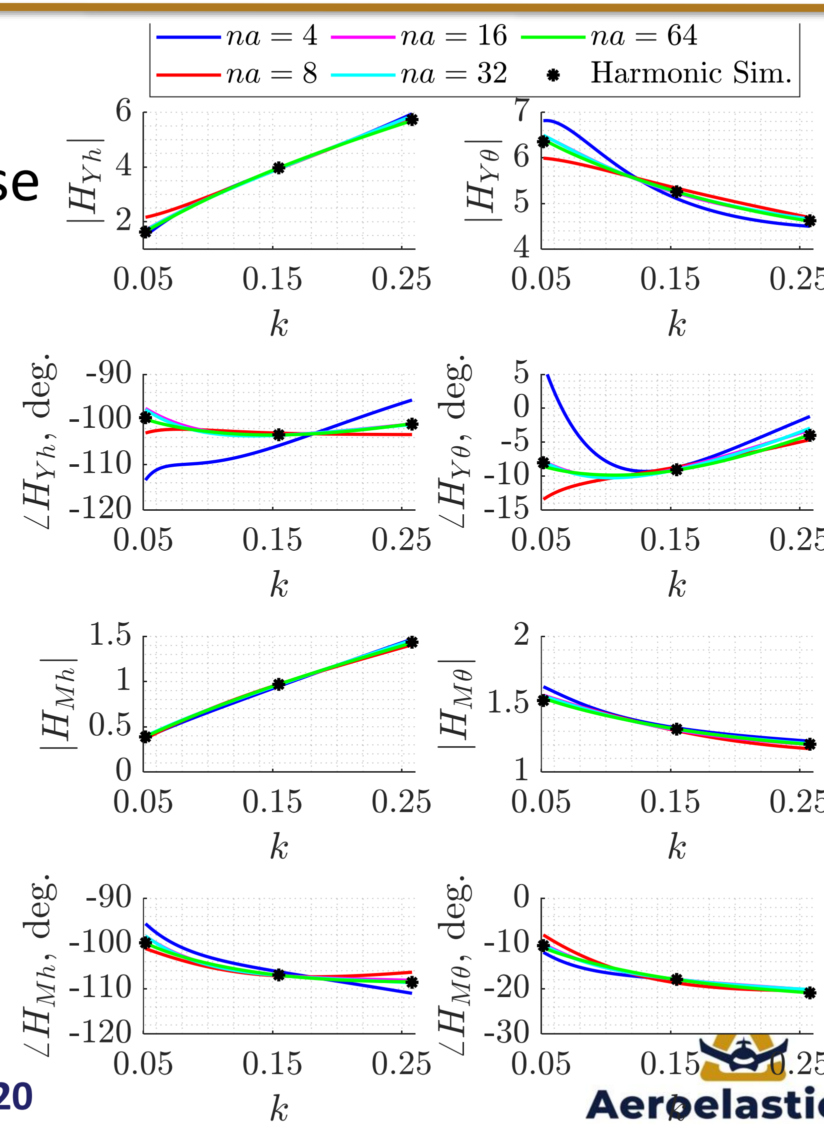
$$\boldsymbol{\xi}(k) = \begin{bmatrix} C_S & 0 \end{bmatrix} \begin{Bmatrix} \mathbf{x}_S(k) \\ \mathbf{x}_A(k) \end{Bmatrix}$$

- Aeroelastic damping and frequencies are computed by EV of state matrix

Identification Results at Mach 0.3

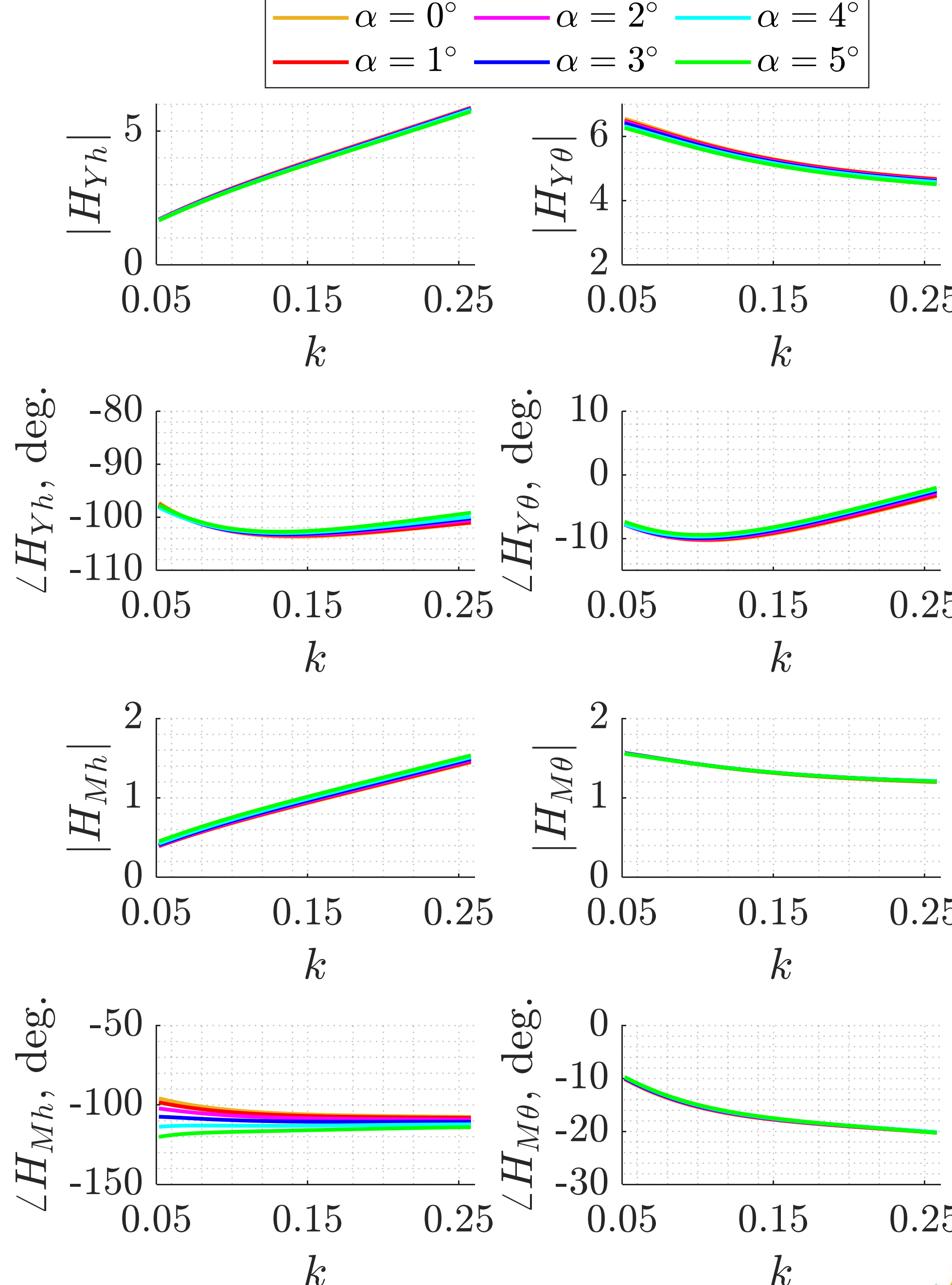
- Linear flow regime
- Unsteady aerodynamic response independent of AoA





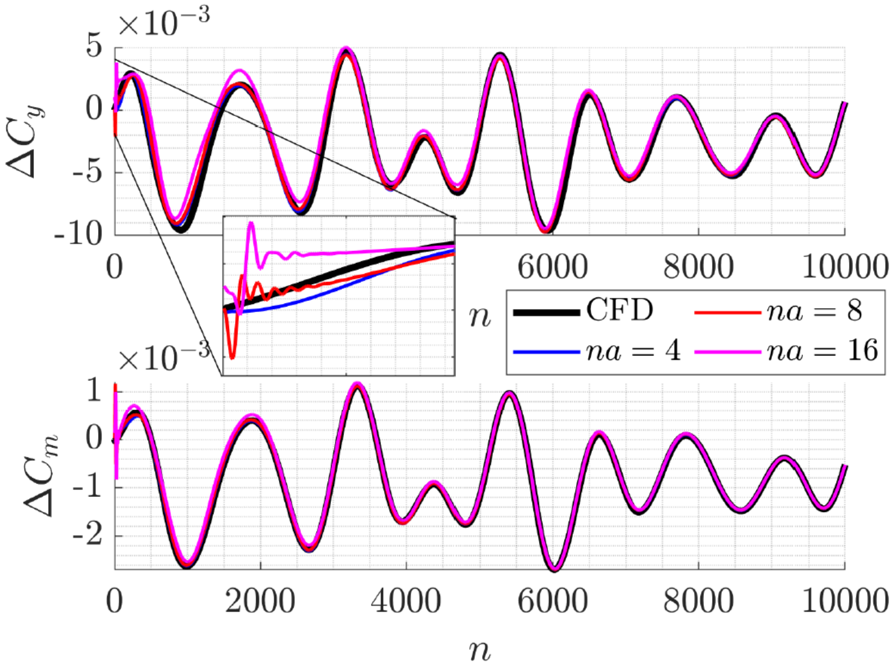
Identification Results at Mach 0.3

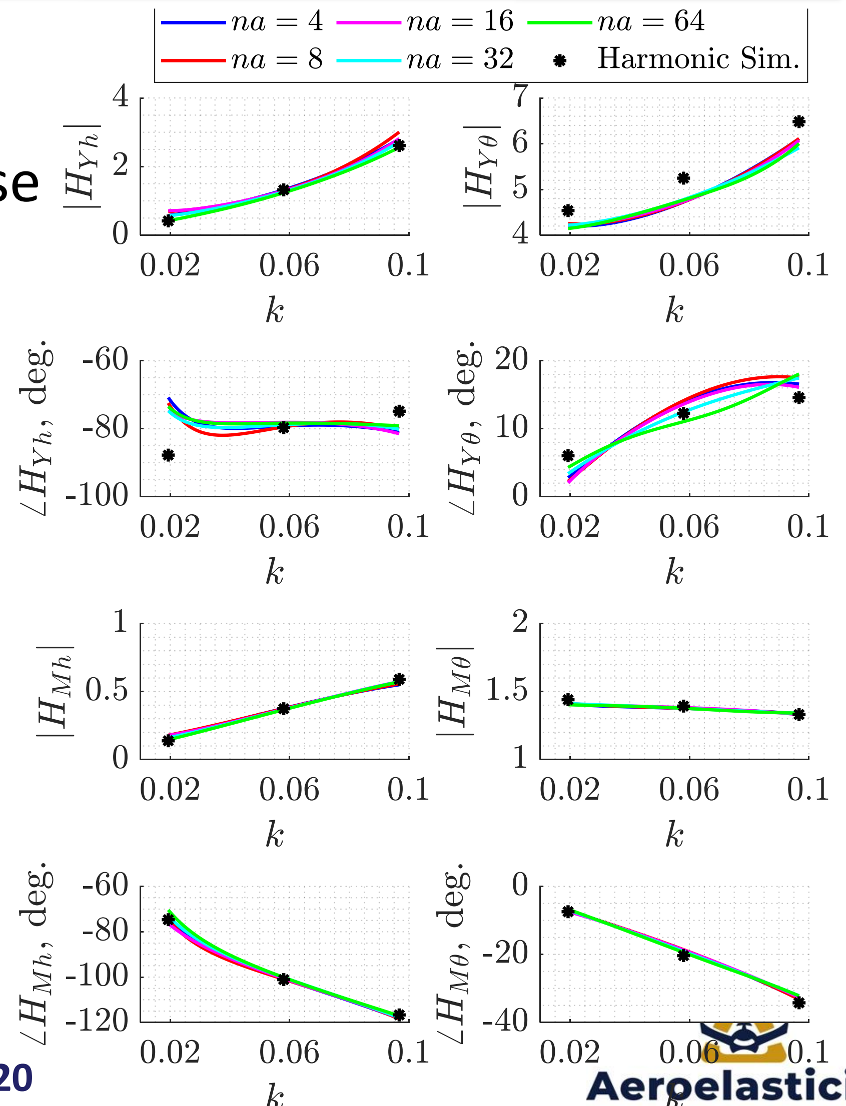
- Impact of angle of attack on aerodynamic FRFs with model order $na = 16$



Identification Results at Mach 0.8

- Non-linear flow regime
- Unsteady aerodynamic response is AoA-dependent





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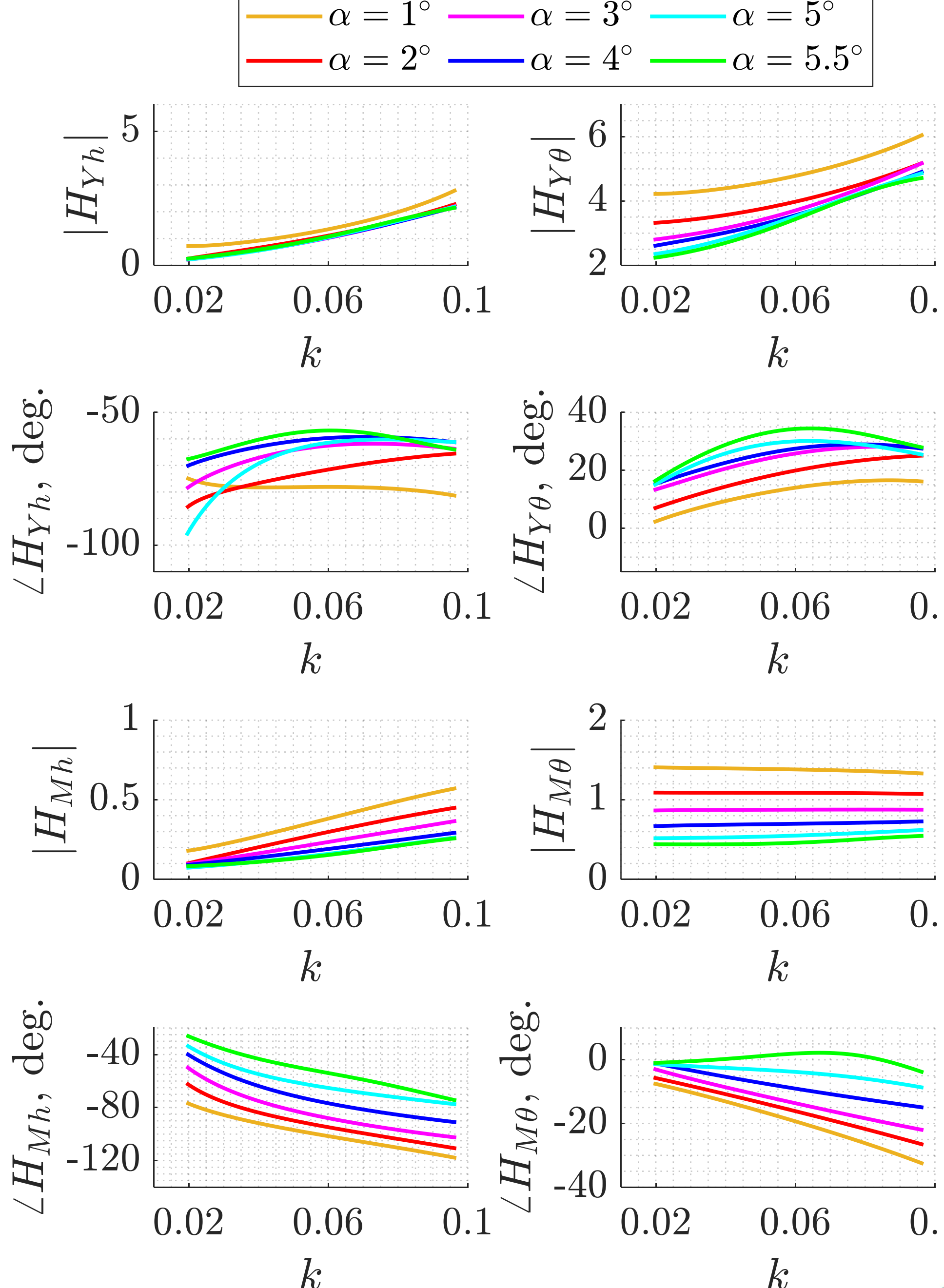

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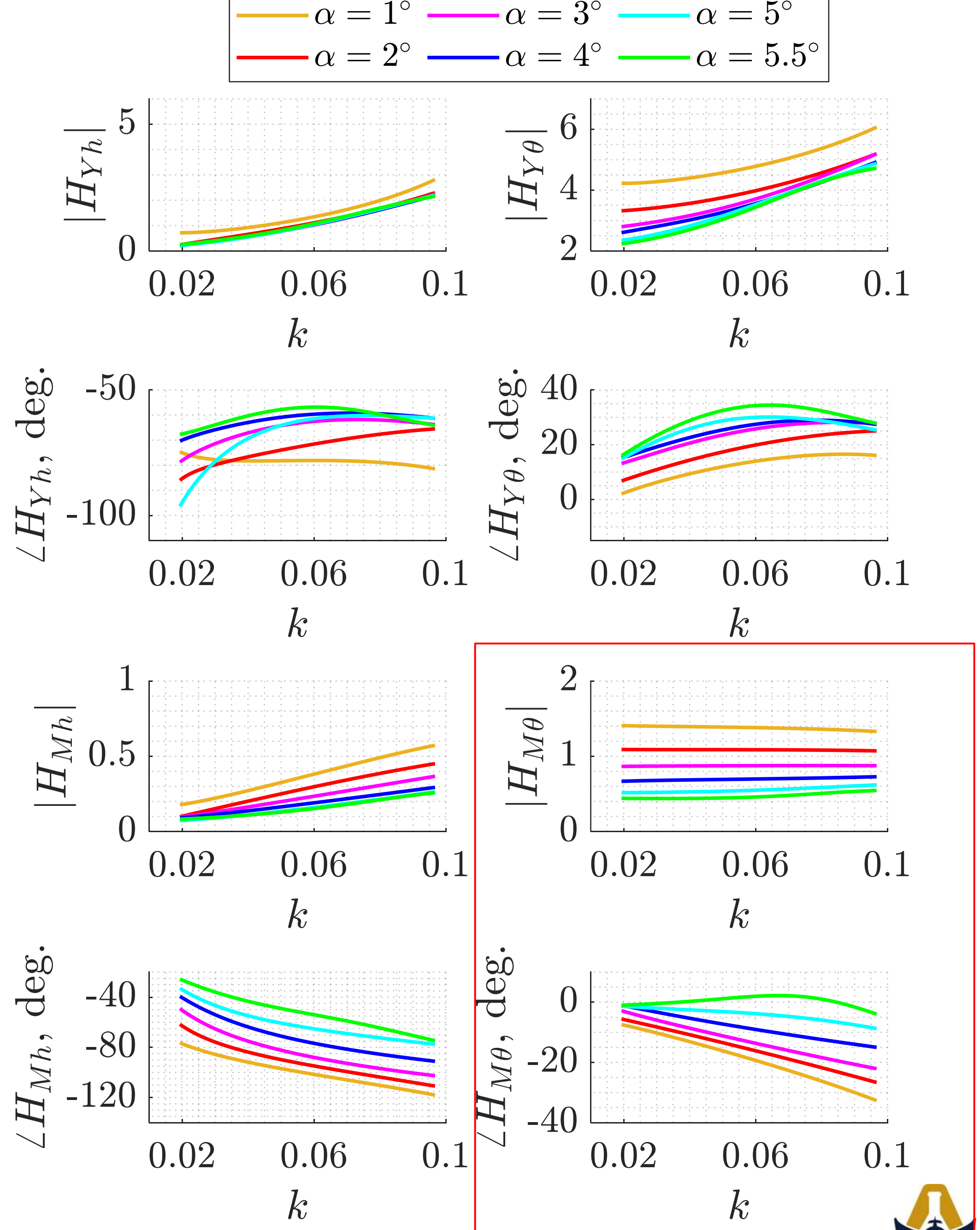

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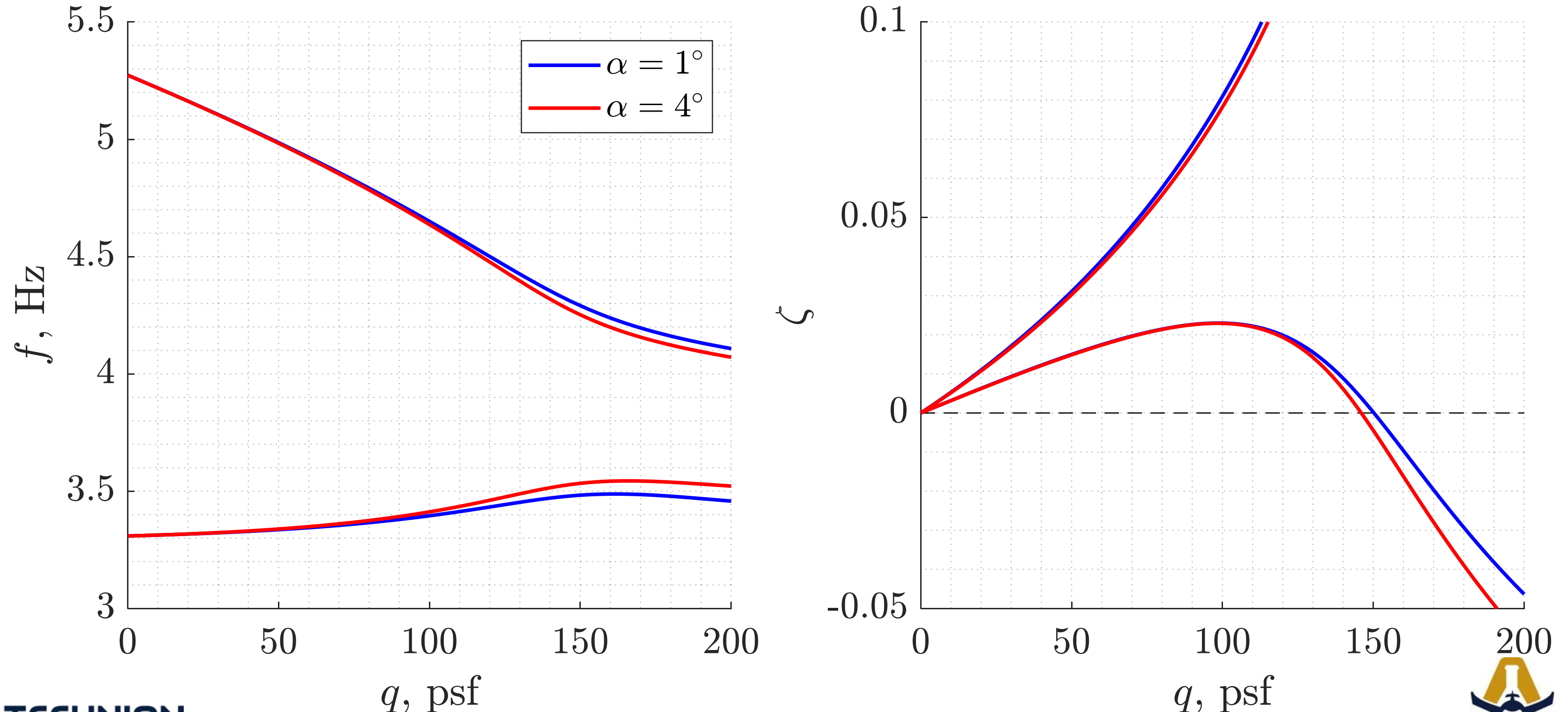
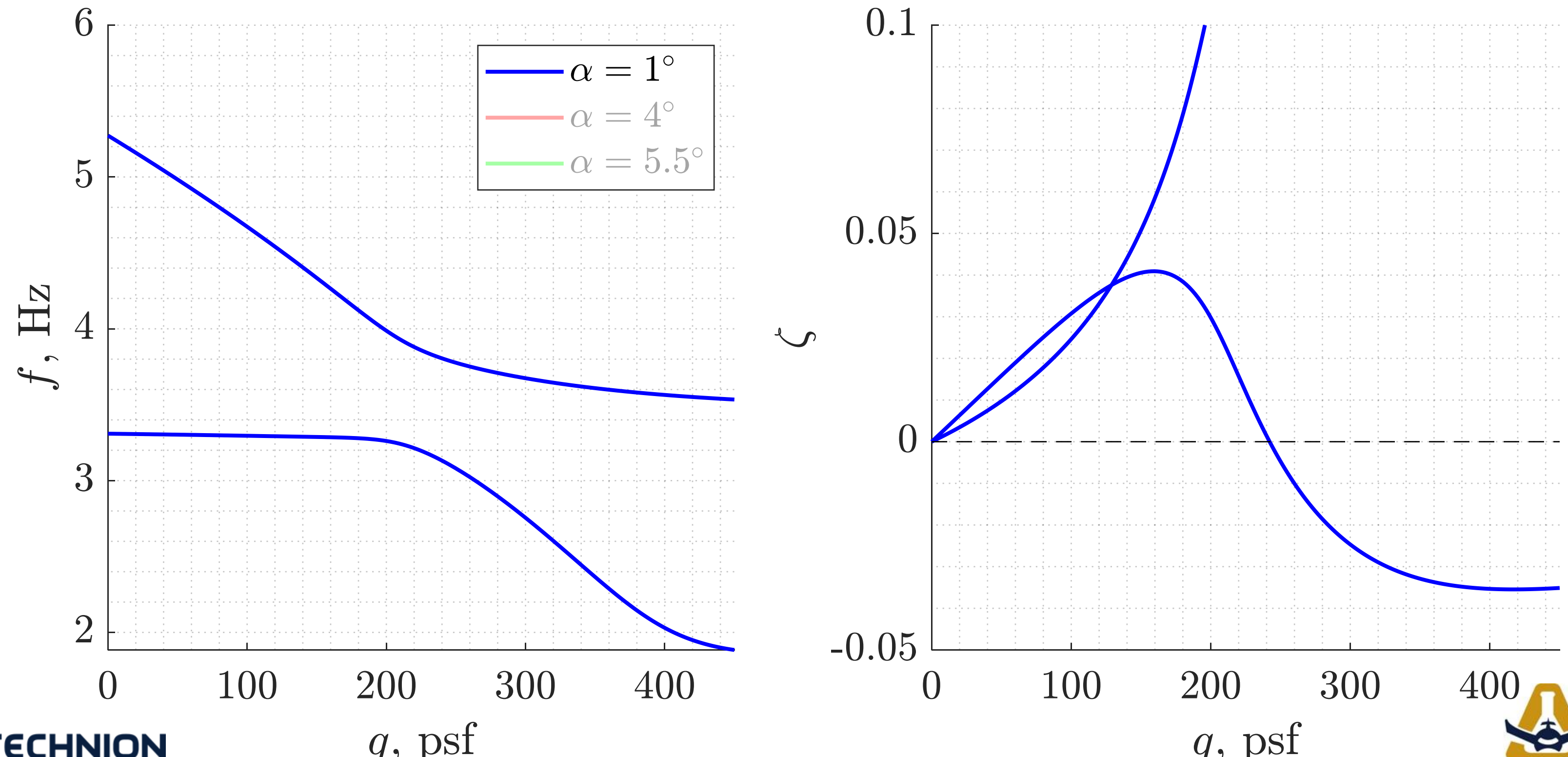
Flutter Computation at Mach 0.3

- ω-V-g at angles of attack 1 and 4 degrees



Flutter Computation at Mach 0.8

- ω-V-g at angles of attack 1, 4, and 5.5 degrees



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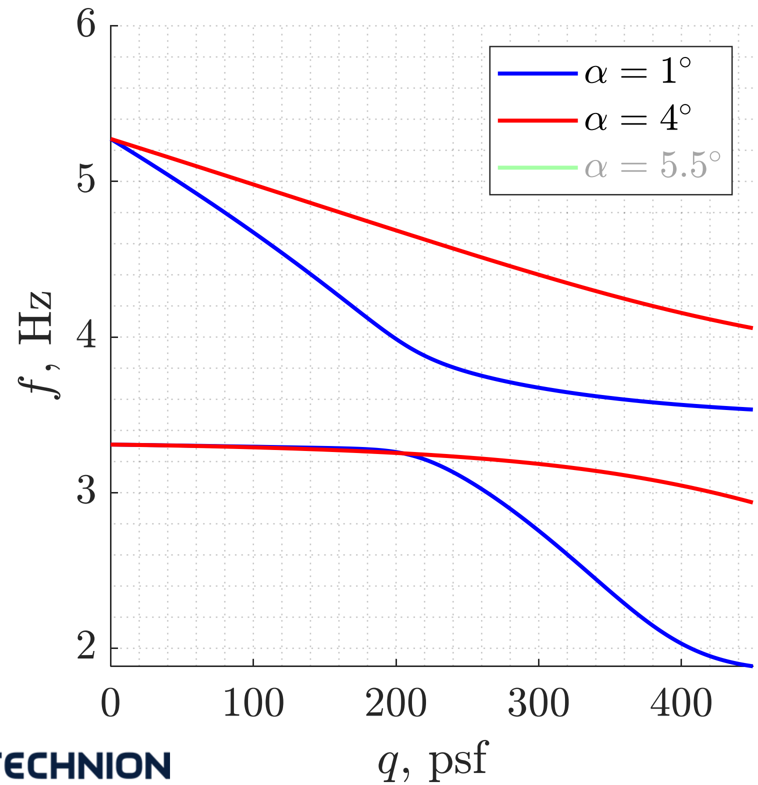

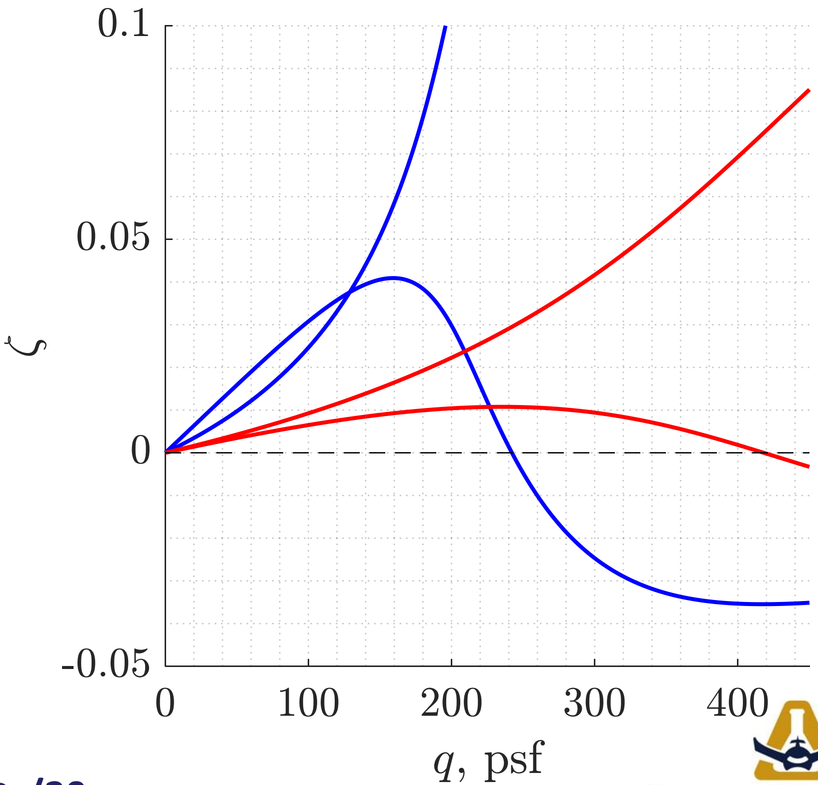

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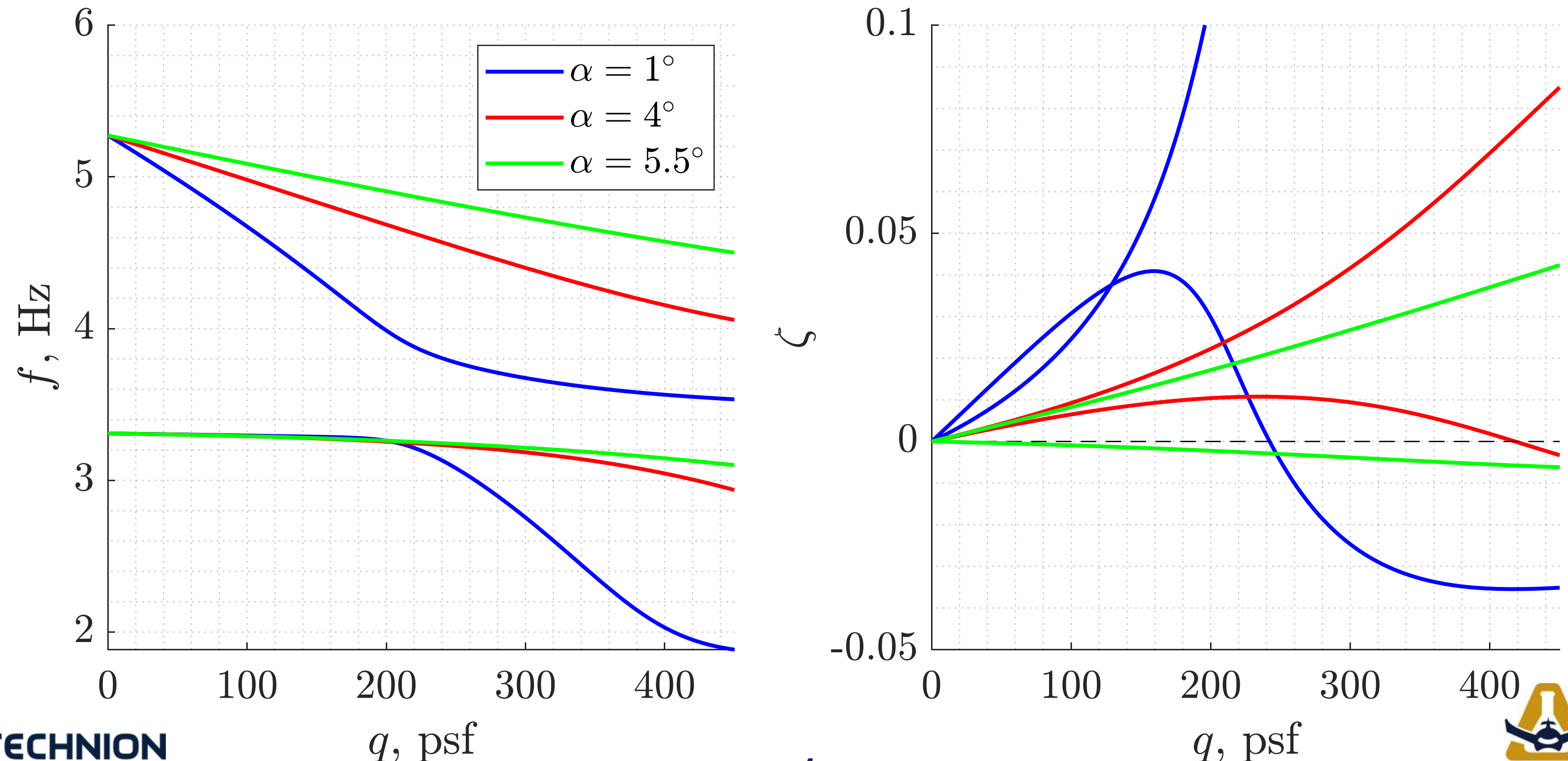

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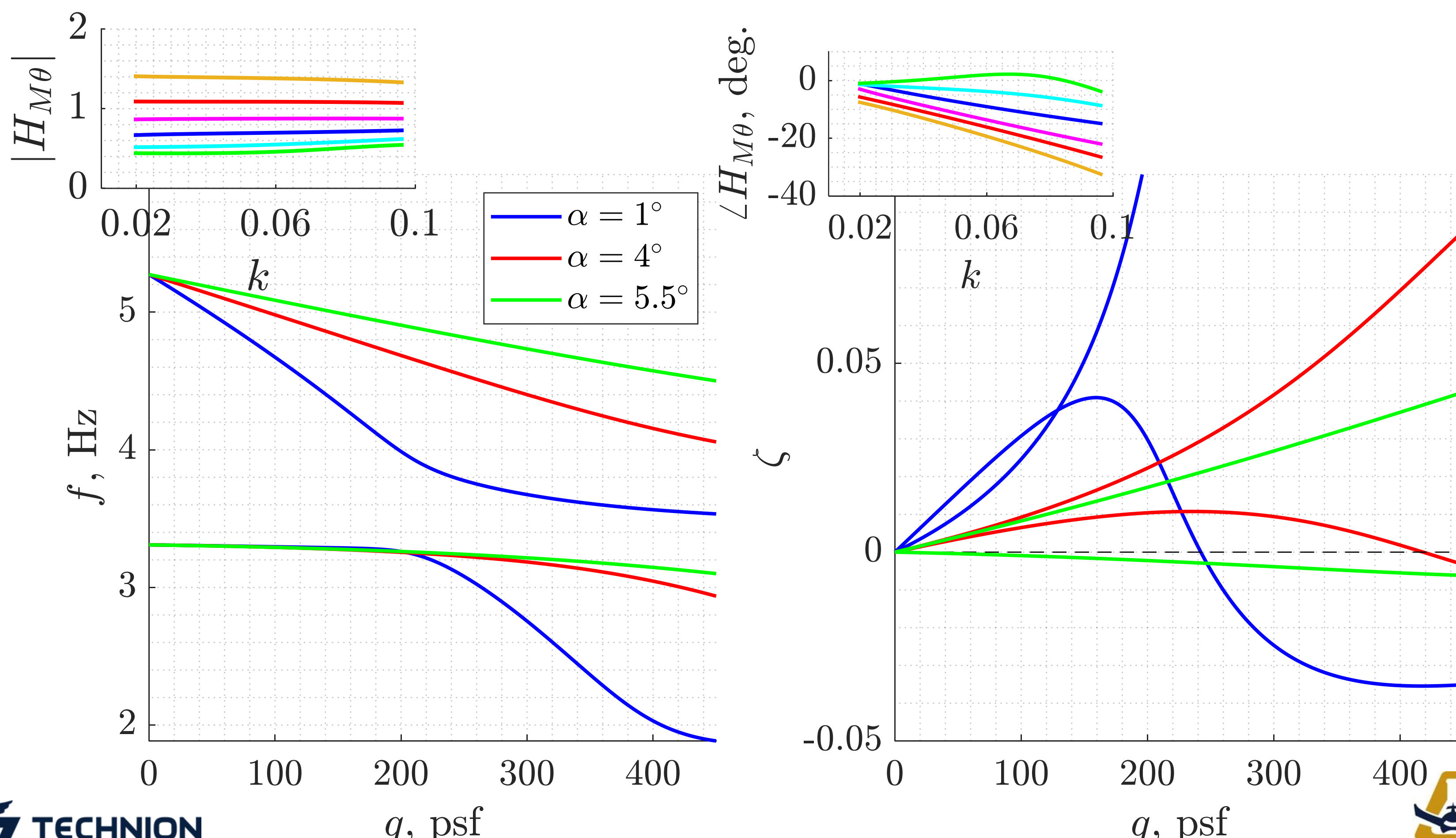
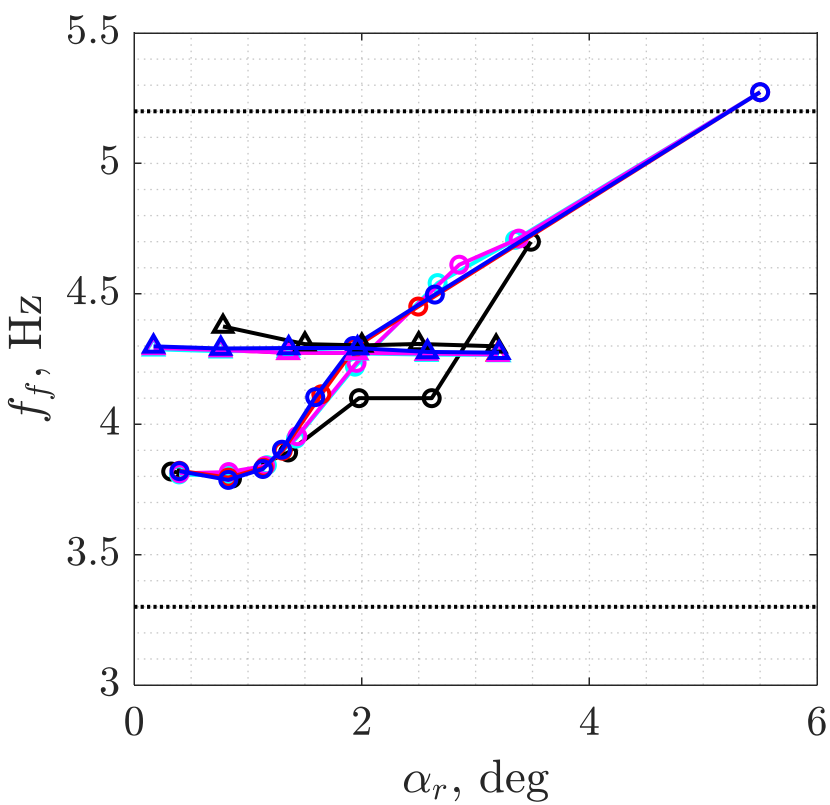
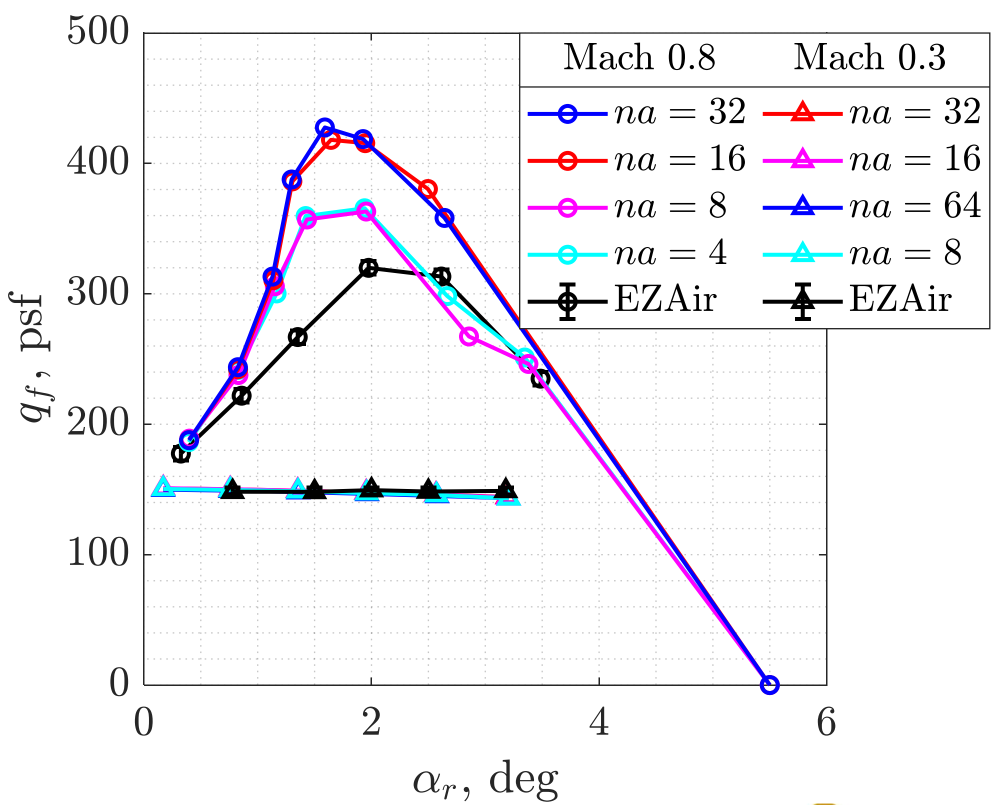


Flutter Computation

- ROM flutter results





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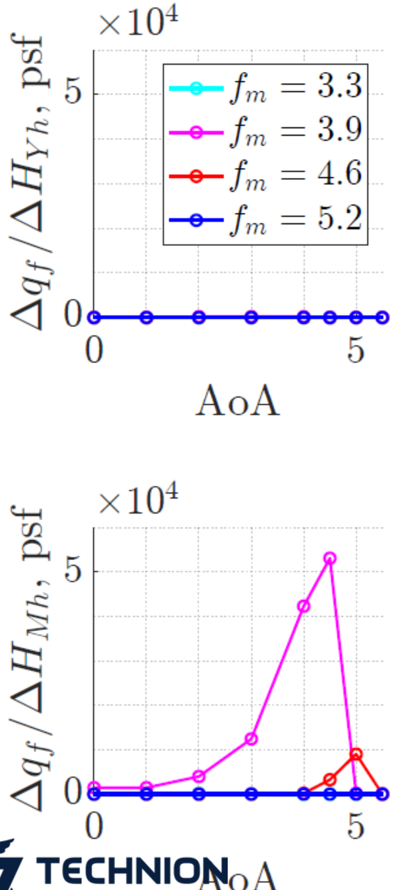
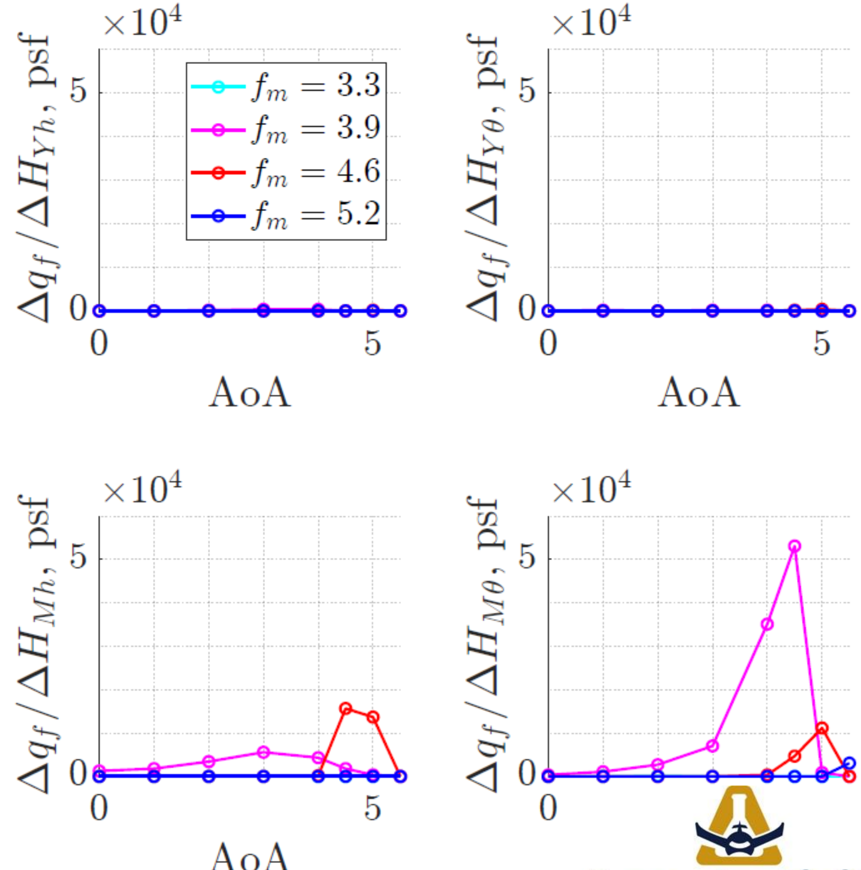
Flutter Sensitivity Analysis

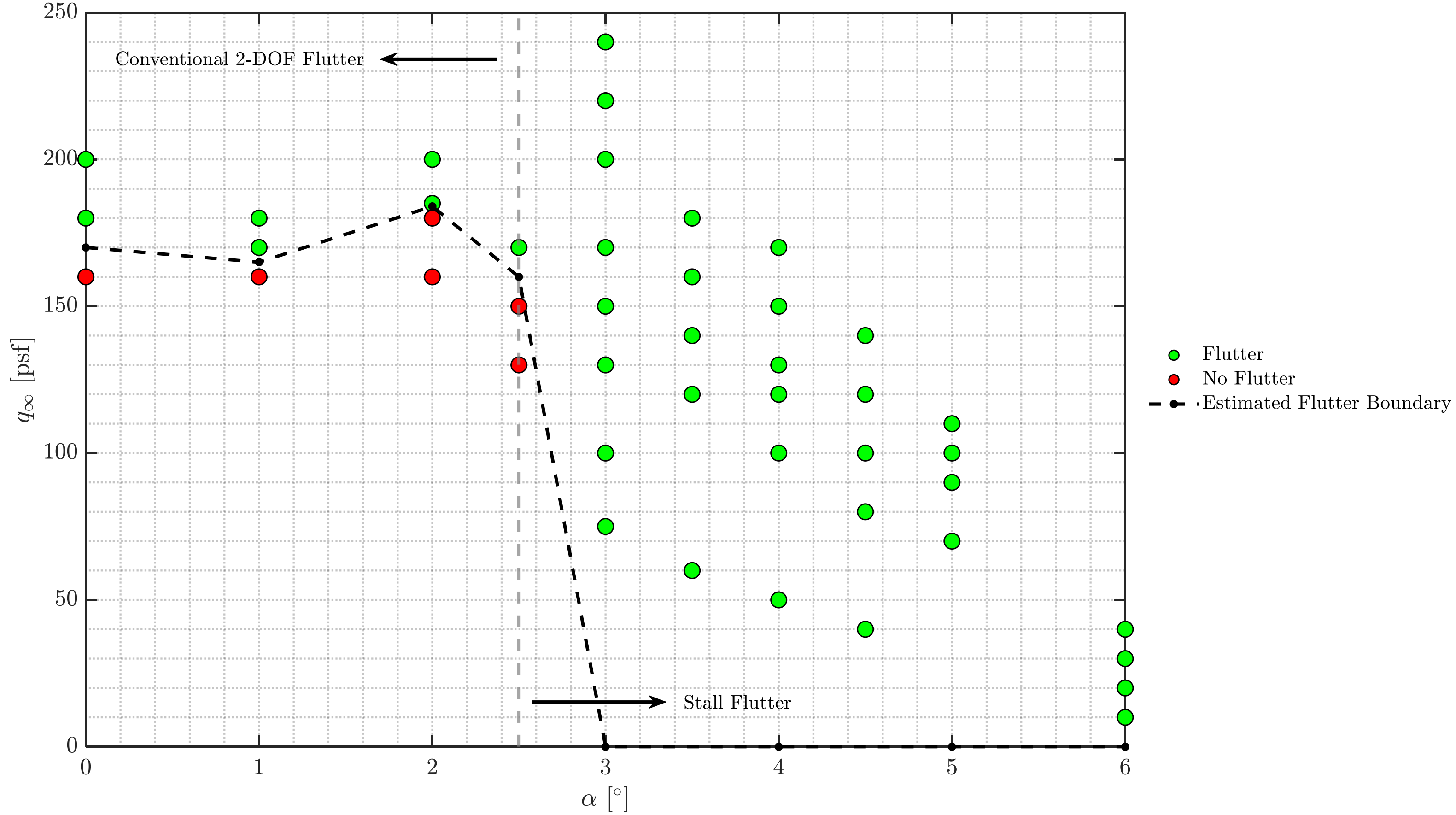
Real Perturbation



Imaginary Perturbation



3D BSCW Results Overview



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Conclusion

- MOARX modeling provides accurate and efficient identification of **linearized aerodynamic models**
  - Agreement with direct harmonic simulations and with time evolution of aerodynamic response even in transonic detached conditions
- Accurate flutter prediction in **subsonic and attached-transonic flows**
  - High sensitivity in presence of flow separation
- Sudden drop in flutter dynamic pressure and switch to stall mechanism is evident in 3D and 2D aerodynamics
- Sensitivity of flutter conditions to aerodynamic model is increased significantly with AoA

Thank you!

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