ECERTA Project

Exploiting an Aerodynamic Hierarchy for Searching Large Parameter Spaces for Aeroelastic Instabilities

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http://cfd4aircraft.com/

Research Sponsor

MARIE CURIE ACTIONS

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Overview

- Introduction
- Framework for Aeroelastic Stability Analysis
- Application
- Coordinated Sampling
- Exploiting the Model Hierarchy
- Summary & Outlook

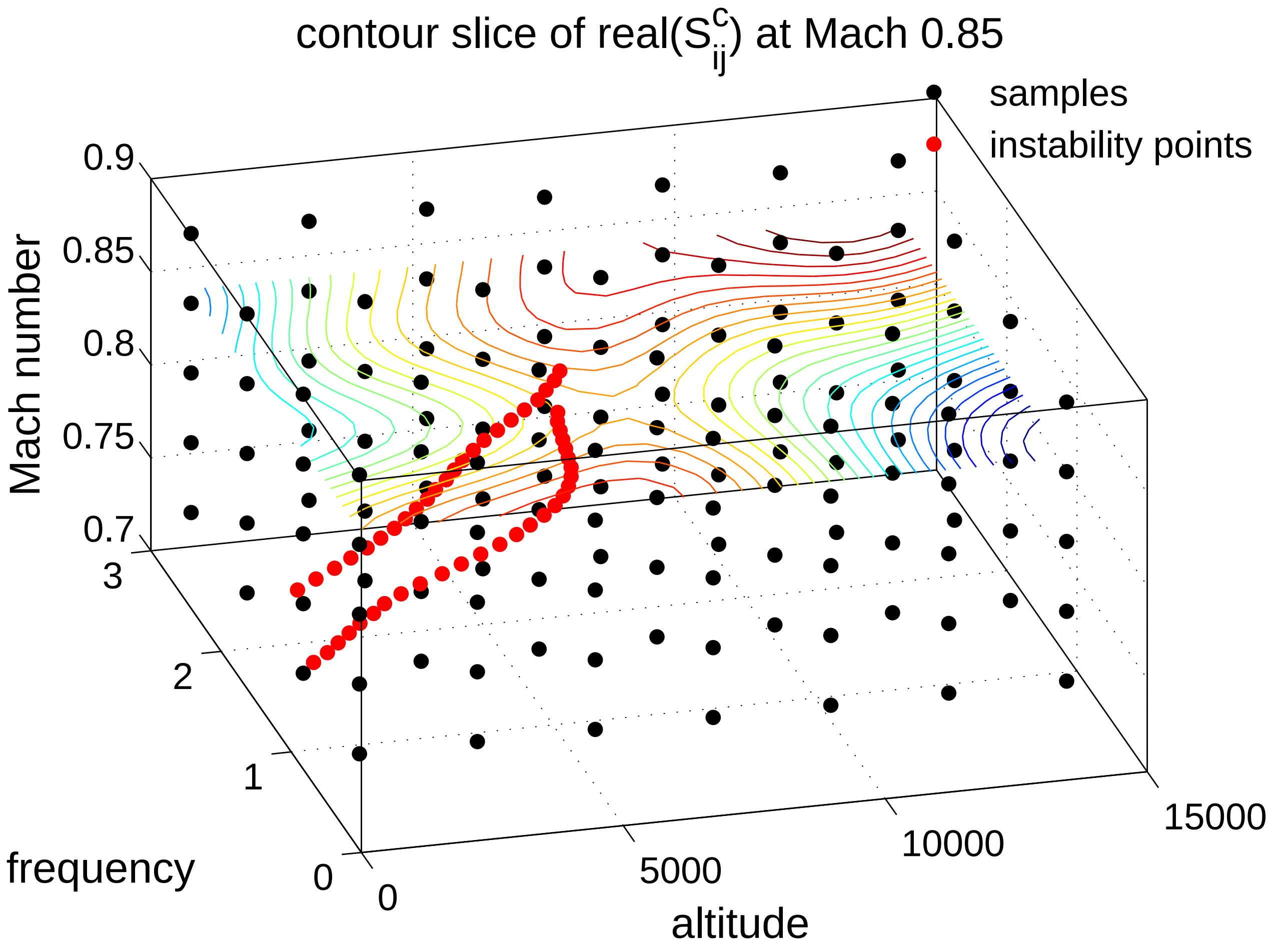
Introduction

Introduction

- ECERTA — **E**nabling **Cert**ification by **A**nalysis
- Doublet–Lattice Method (DLM)
  - single most important tool for production flutter analysis
  - transonic limitations and corrections
- Nonlinear aerodynamic modelling
- Requirement to deal with high dimensional parameterised problems

Introduction

- MDO wing configuration



Introduction

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- ECERTA — **E**nabling **Cert**ification by **A**nalysis
- Doublet–Lattice Method (DLM)
  - single most important tool for production flutter analysis
  - transonic limitations and corrections
- Nonlinear aerodynamic modelling
- Requirement to deal with high dimensional parameterised problems
- Objectives
  - general method for model updating using nonlinear modelling and experiments
  - general method for searching large parameter spaces for instability

Framework for Aeroelastic Stability Analysis

Flow Models

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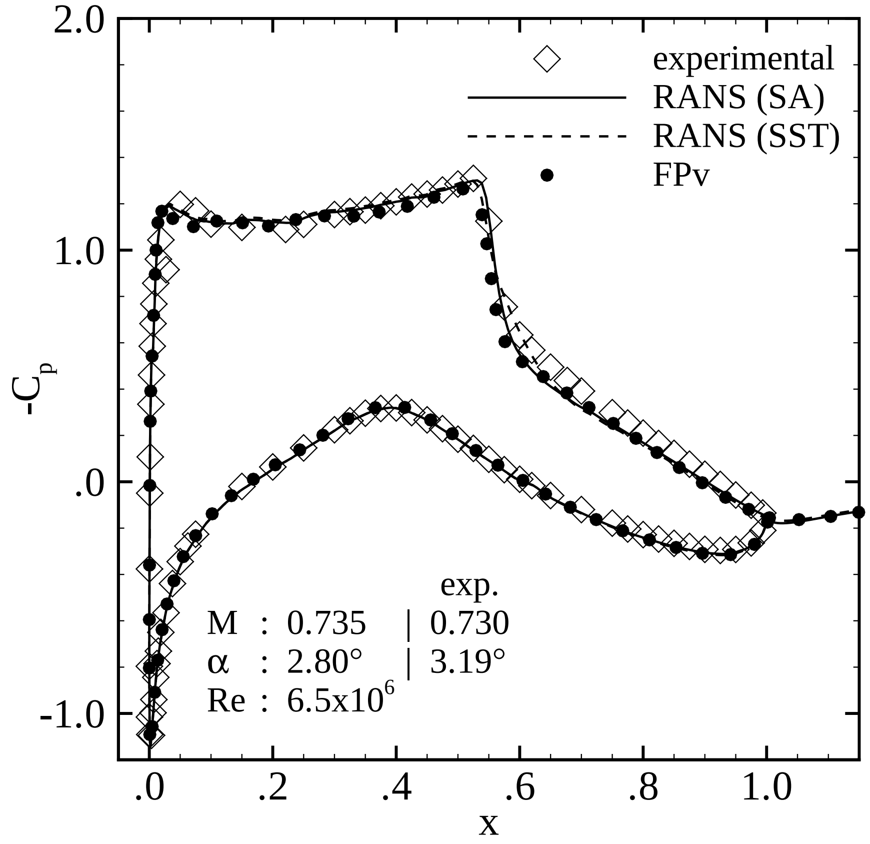
- Hierarchy of flow models was needed
  - Euler and RANS equations
    ⇒ established research code*
    - fully implicit, block-structured, cell-centred, finite-volume scheme
    - 2nd order spatial/temporal discretisation
  - FP equations and viscous correction
    ⇒ newly developed research code
    - unstructured, vertex-based, finite-volume scheme applying Newton's method
    - 2nd order spatial/temporal discretisation



RAE 2822 aerofoil case**

*) Badcock et al, Progr Aero Sci 36, 2000

**) Cook et al, AGARD AR 138, 1979

Schur Complement Formulation

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- Schur complement formulation*

$$\left(S(\lambda) - \lambda I\right) \boldsymbol{p}_s = 0$$

with
$$S(\lambda) = A_{ss} - A_{sf} \left(A_{ff} - \lambda I\right)^{-1} A_{fs}$$
$$= A_{ss} + S^c(\lambda)$$

- modelling aspects: aerodynamics' influence stripped free
- main tasks of stability analysis: *accurate* and *cheap* evaluation of interaction term

*) Badcock et al, AIAA-2008-1820
Badcock et al, AIAAJ, 48 (6), 2010

Approximating the Schur Interaction Matrix

- Interaction term S^c depends on
  - frequency/damping
  - steady state solution (Mach number, incidence, altitude, structural parameters)
- Evaluating S^c will become too expensive
- Instead: form cheap surrogate model
  - two main tasks
    - sample the parameter space of interest
    - reconstruct elements of S^c by interpolation, e.g. kriging or ANN
  - any tool for sampling and interpolation is possible
  - stability analysis becomes very cheap with approximation model

$$S(\lambda) \approx A_{ss} + \widehat{S}^c(\omega)$$

Generating the Schur Interaction Matrix

- Frequency domain
  - n linear solves using $A_{fs} = [A_{f\eta}, A_{f\dot{\eta}}]$

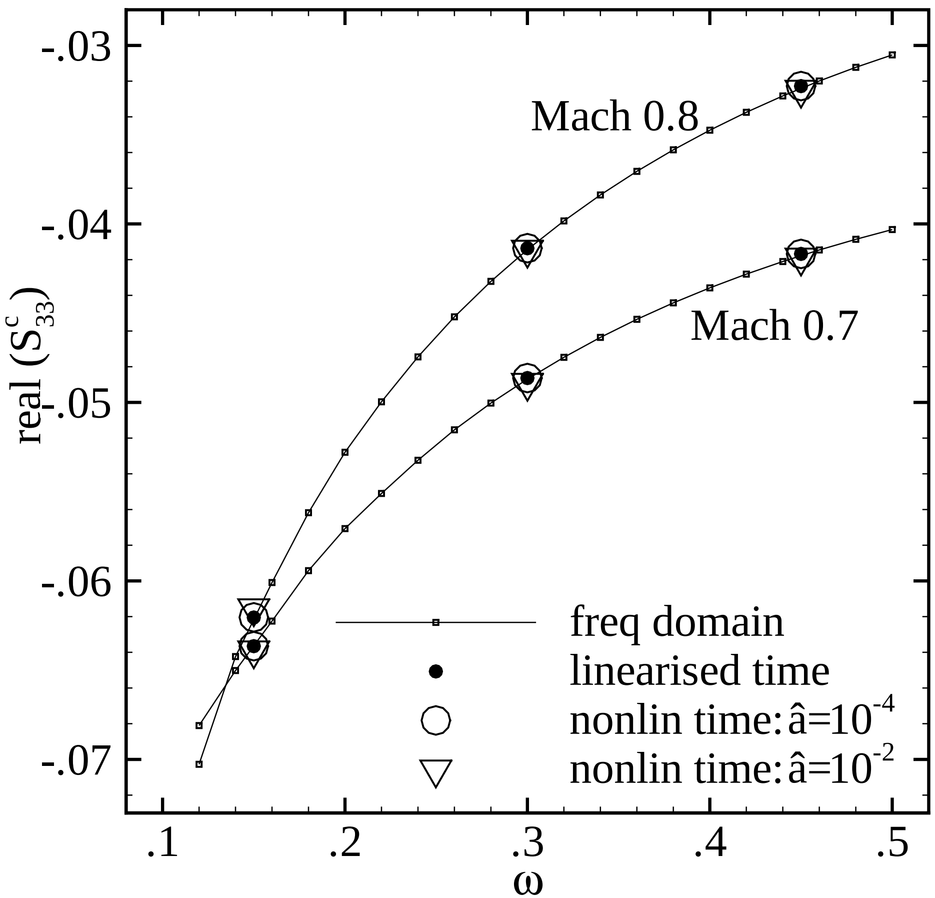
$$S^c = -A_{sf} \left\langle (A_{ff} - i\omega I)^{-1} (A_{f\eta} + i\omega A_{f\dot{\eta}}) \right\rangle$$

  - Implemented in TAU using LFD solver

- Time domain
  - Fourier decompose GAF following forced motion in $\boldsymbol{\eta}$

$$\Phi^T \boldsymbol{f} = Q(\omega)\, \boldsymbol{\eta}$$

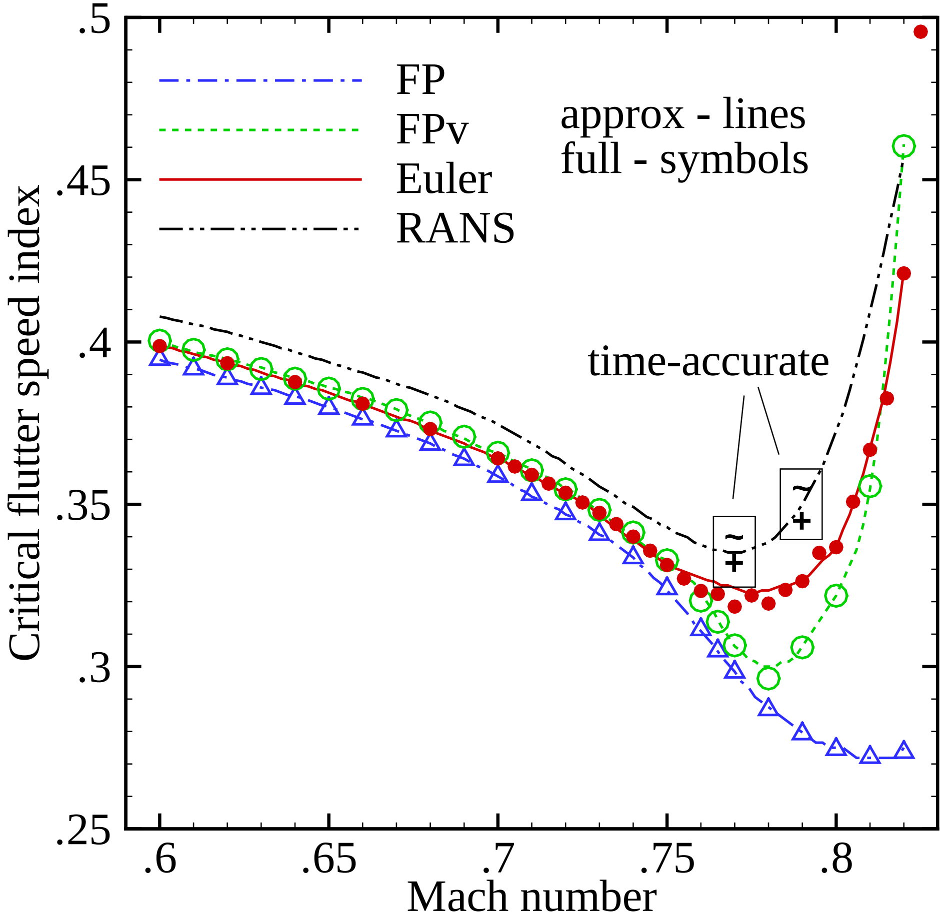
  - it can be shown that $Q^c(\omega) \approx S^c(\omega)$



Applying the Approximation Model

Applying the Approximation Model

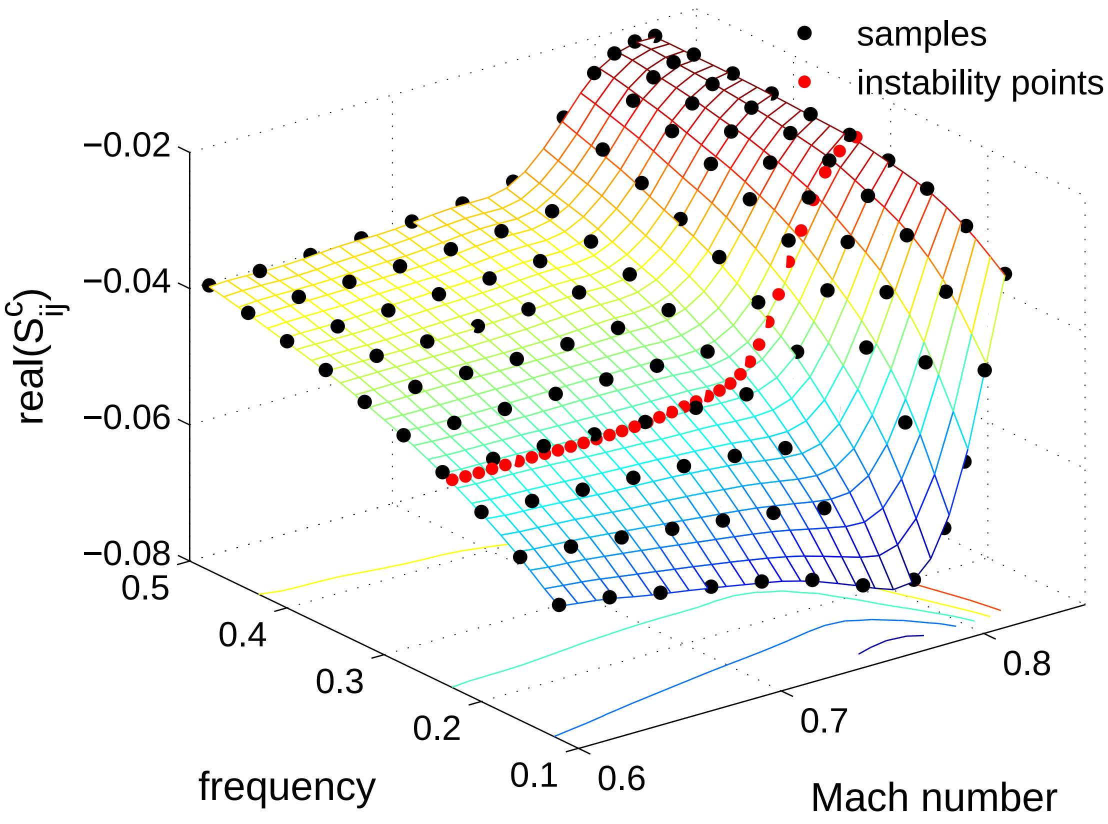
- Stability analysis of NACA 0012 “heavy case” configuration*



*) Badcock et al, AIAAJ, 42 (5), 2004

Response Surfaces for Model Hierarchy

- Full potential



Response Surfaces for Model Hierarchy

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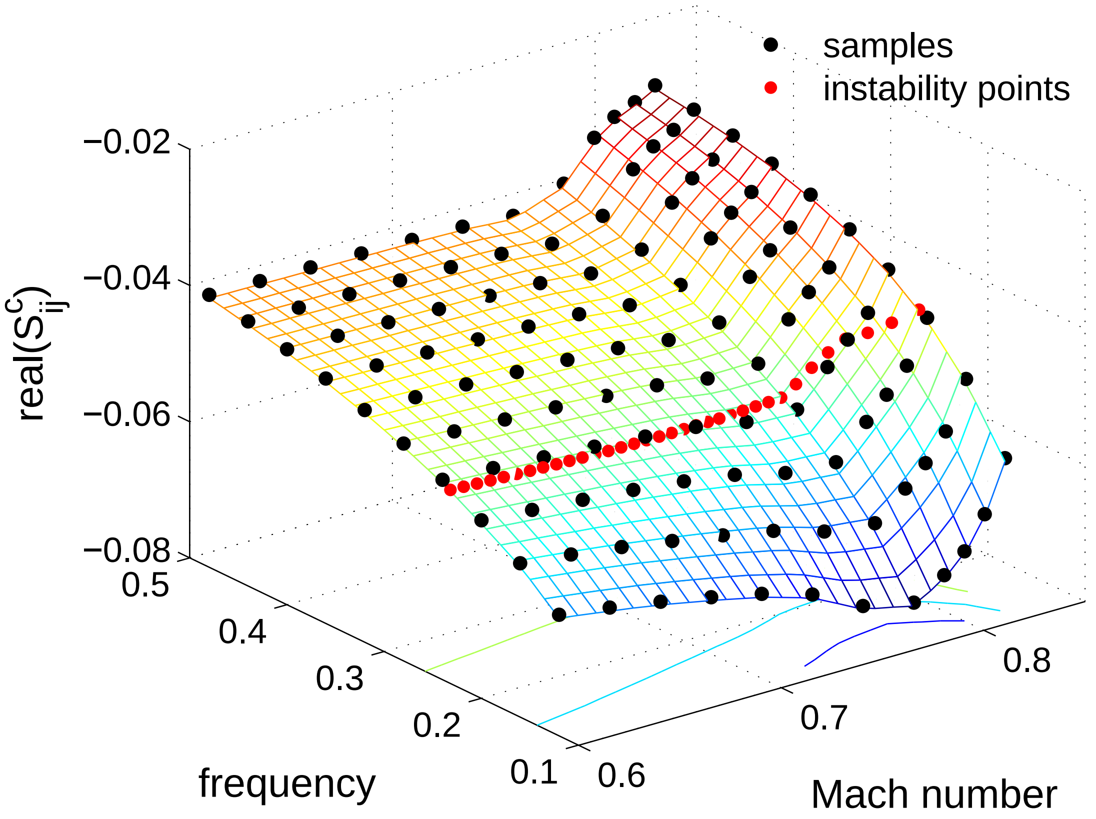
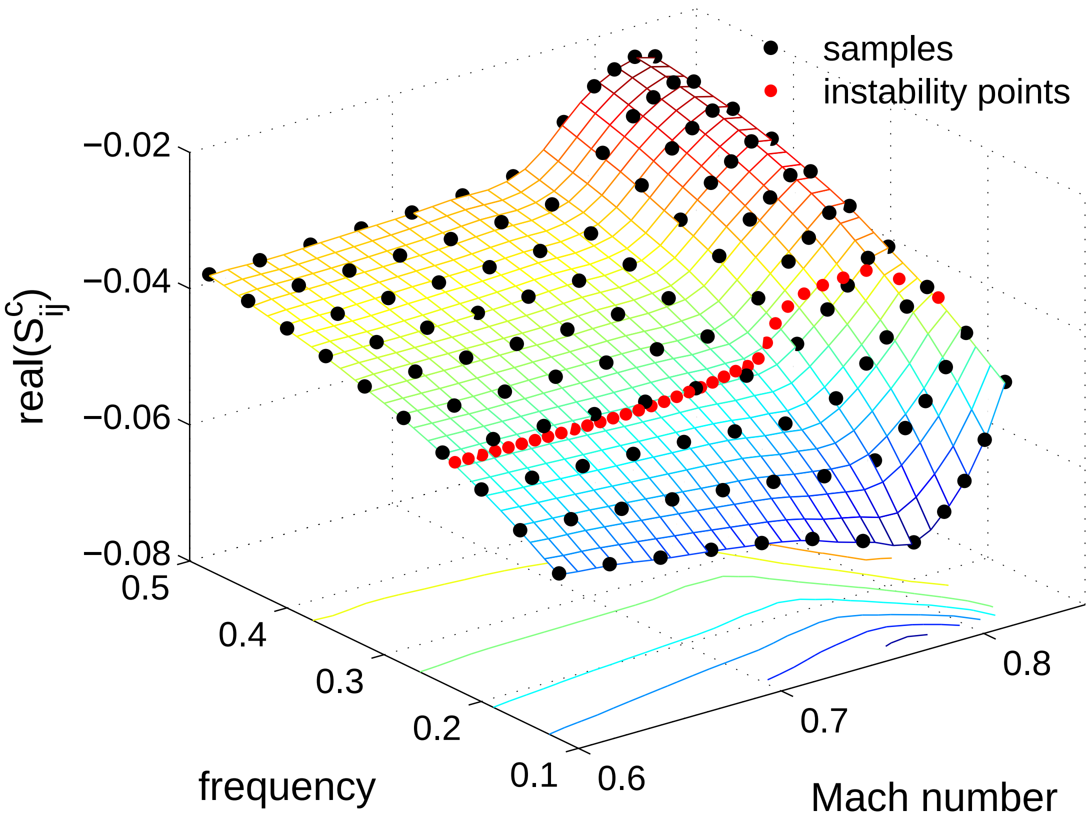
- Euler



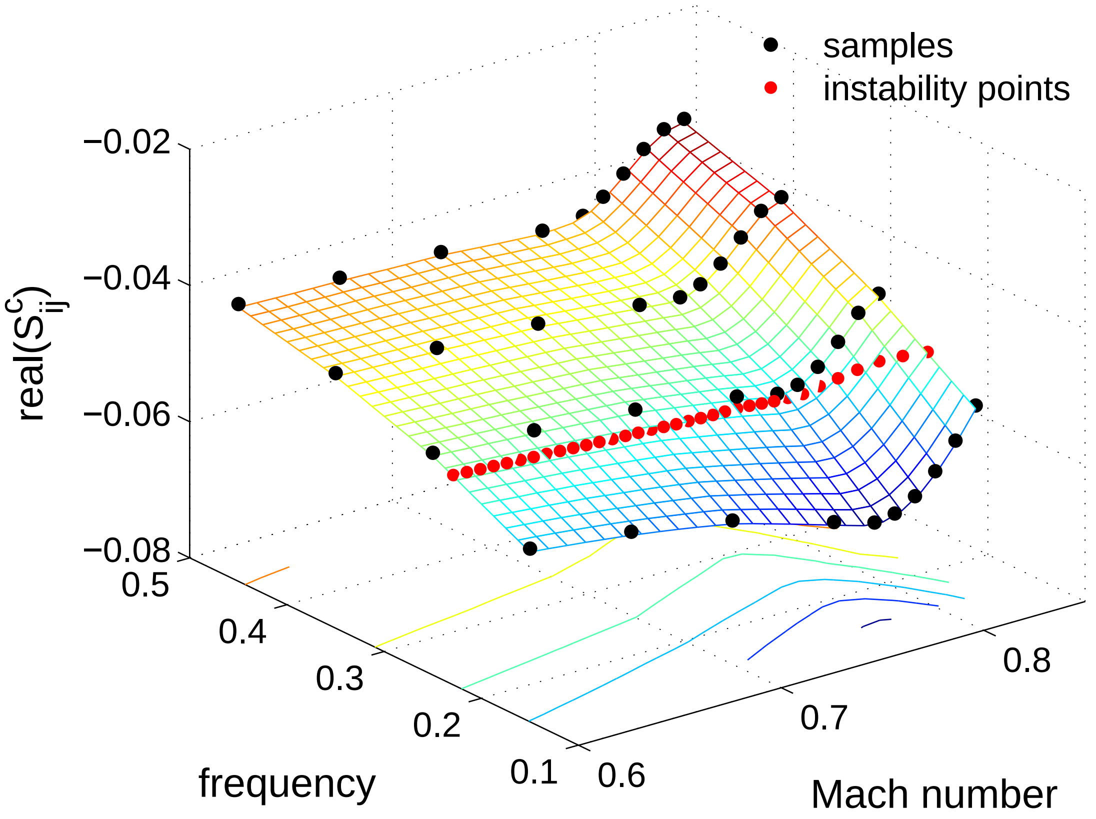
Response Surfaces for Model Hierarchy

- Full potential viscous



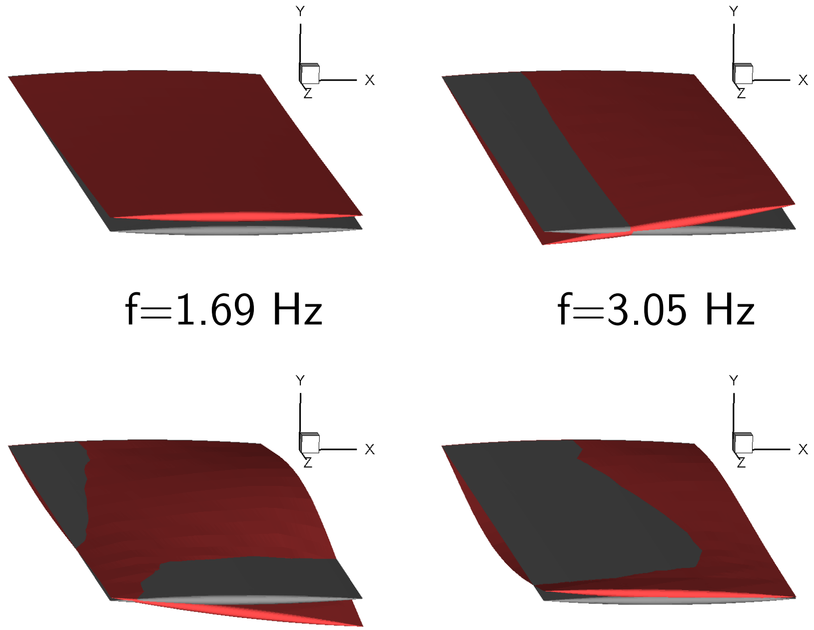
Response Surfaces for Model Hierarchy

- RANS



Applying the Approximation Model

- Stability analysis of symmetric Goland wing configurations



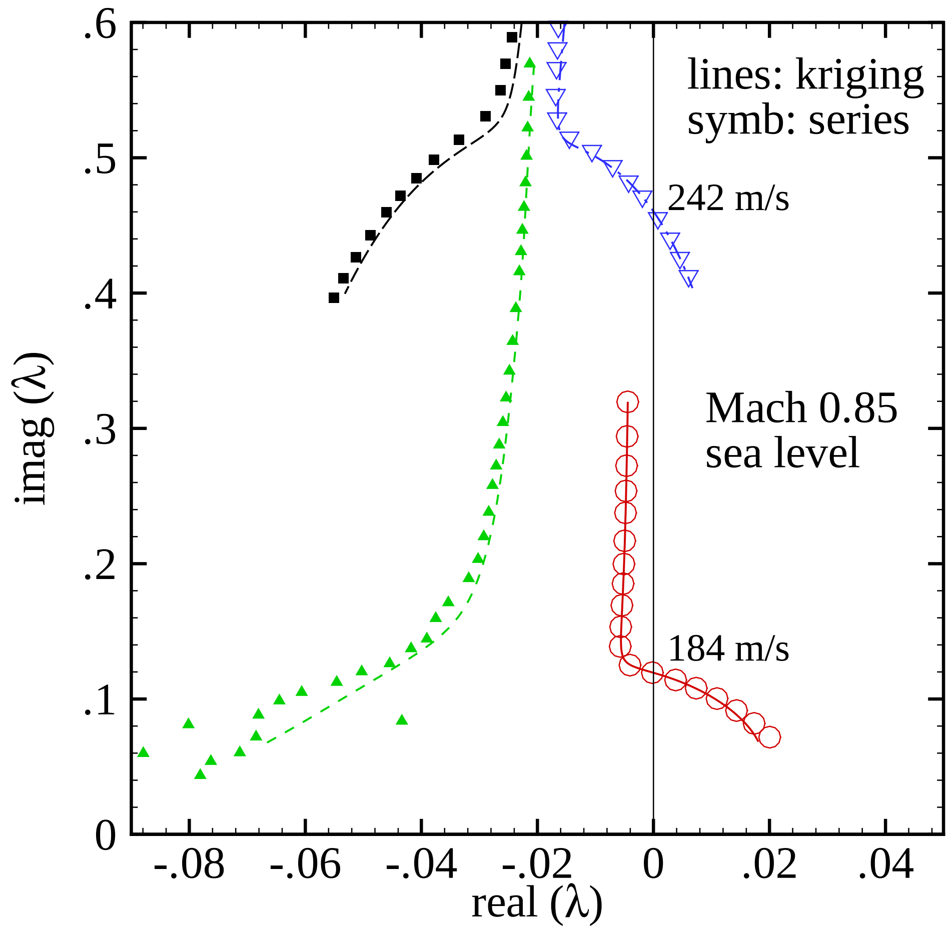
f=1.69 Hz

f=3.05 Hz

f=9.17 Hz

f=10.8 Hz

Mode shapes of wing/store configuration



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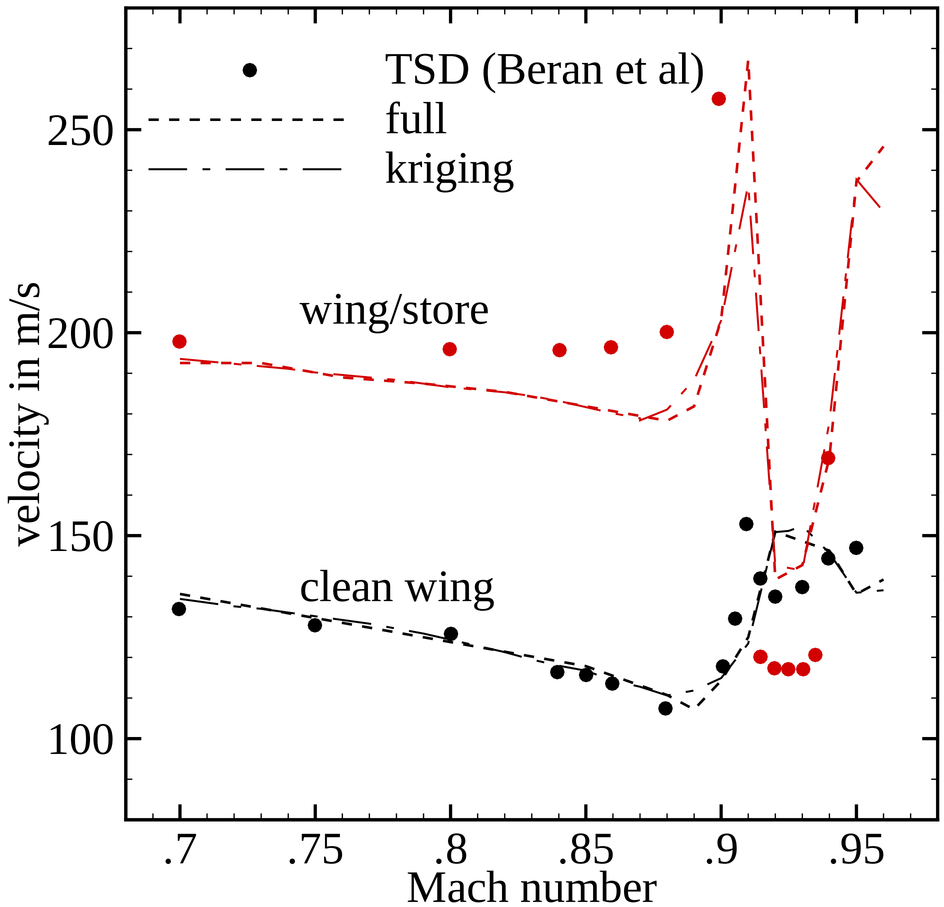
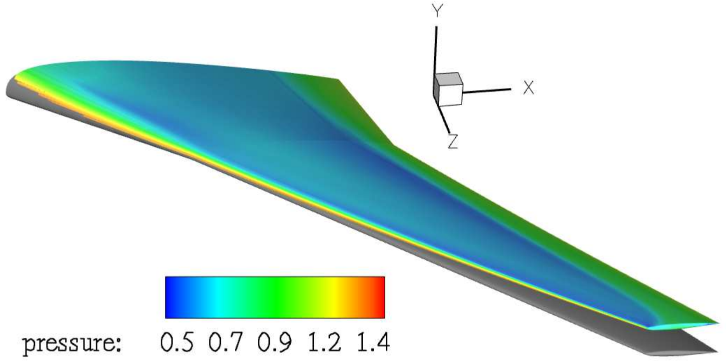
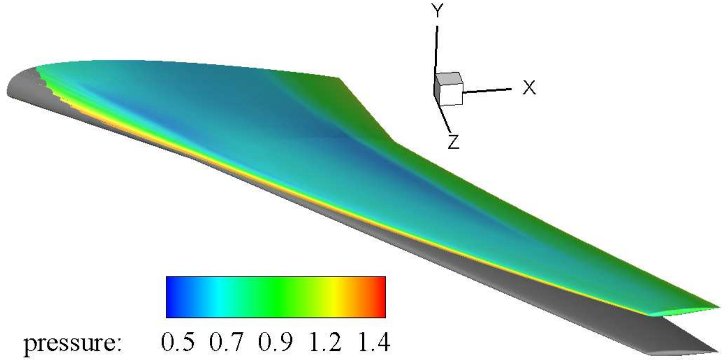


Applying the Approximation Model

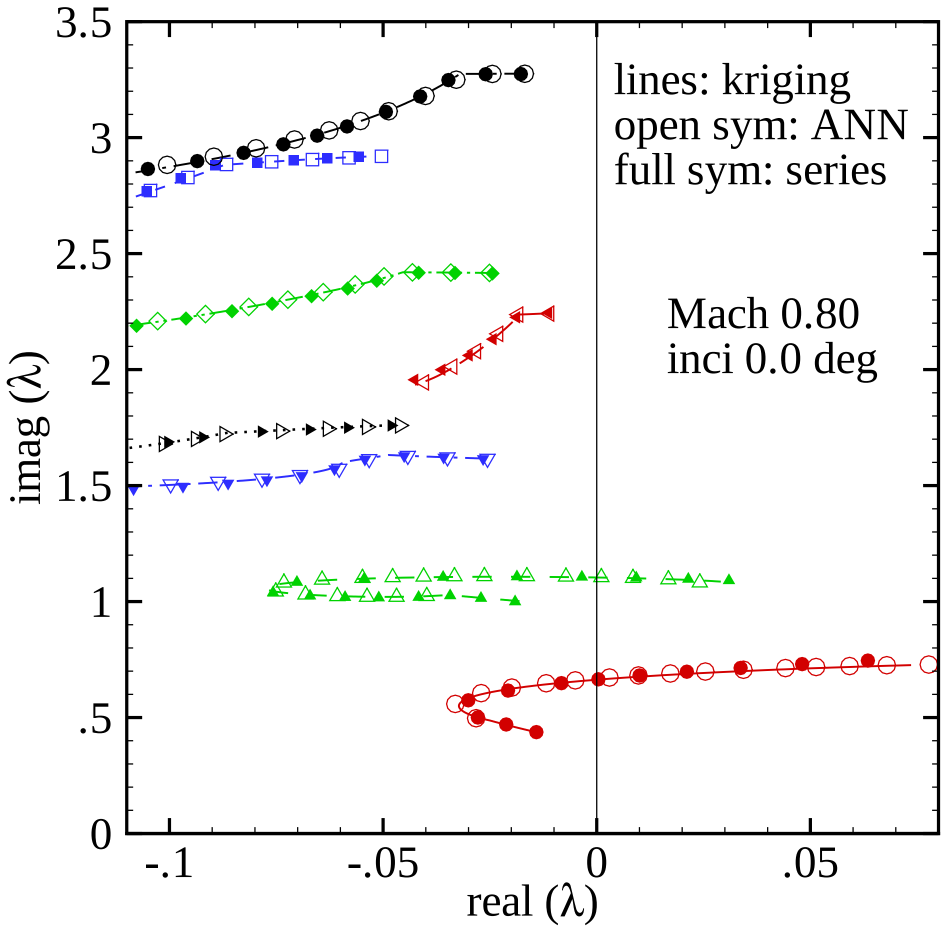
➢ Stability analysis of MDO wing configuration – aerostatic effects



flexible wing 15 km



flexible wing 9 km



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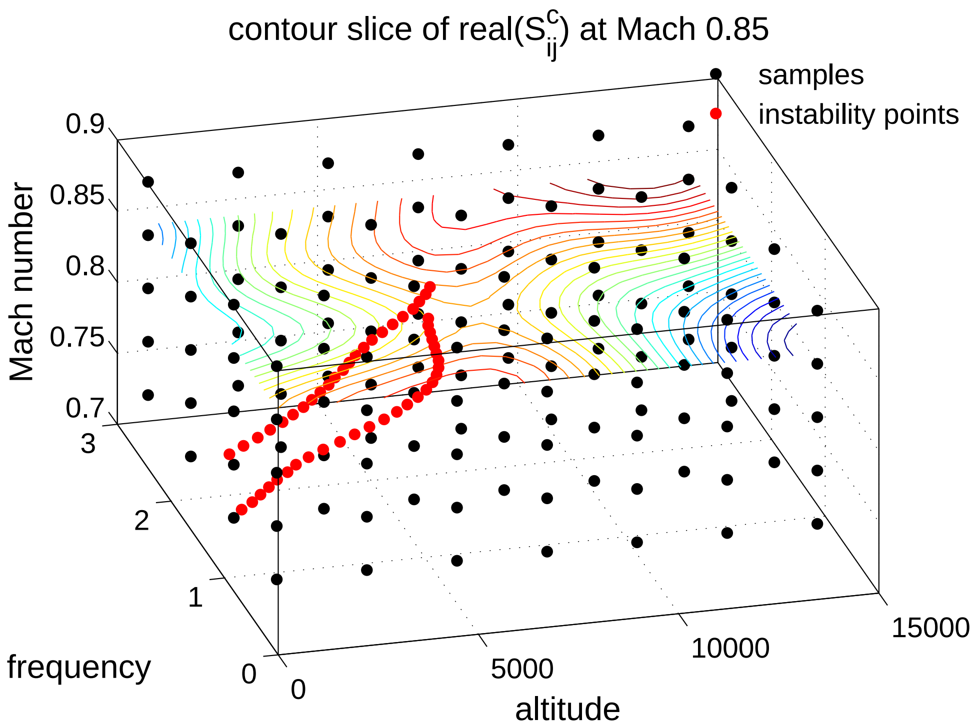

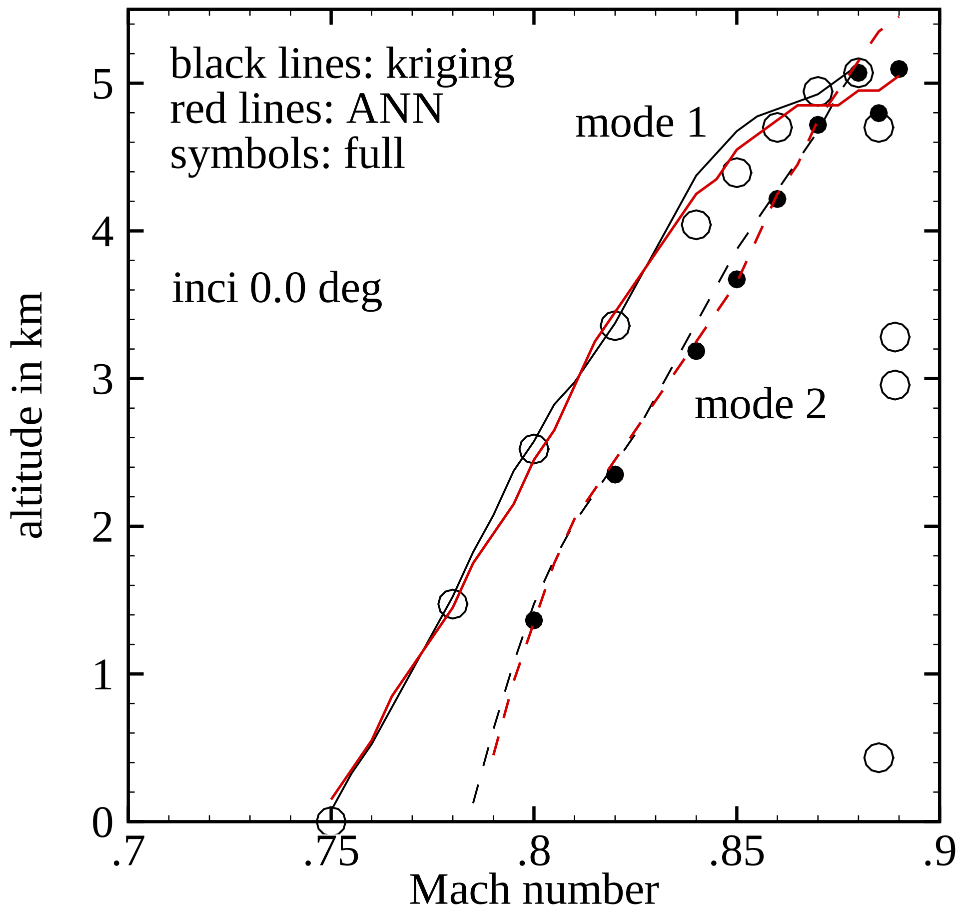

Applying the Approximation Model

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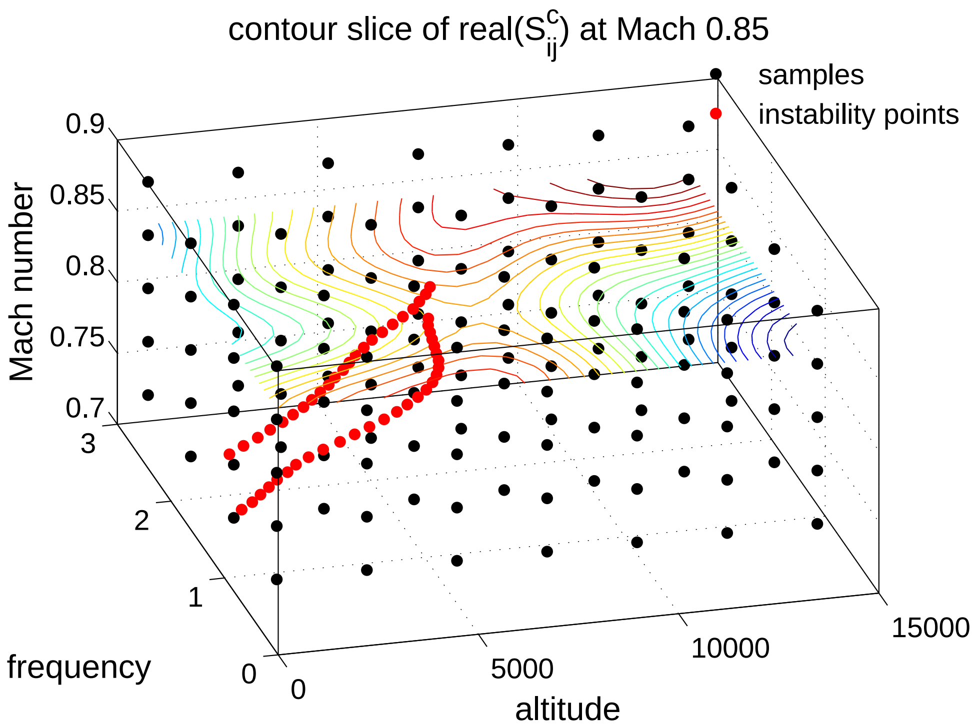
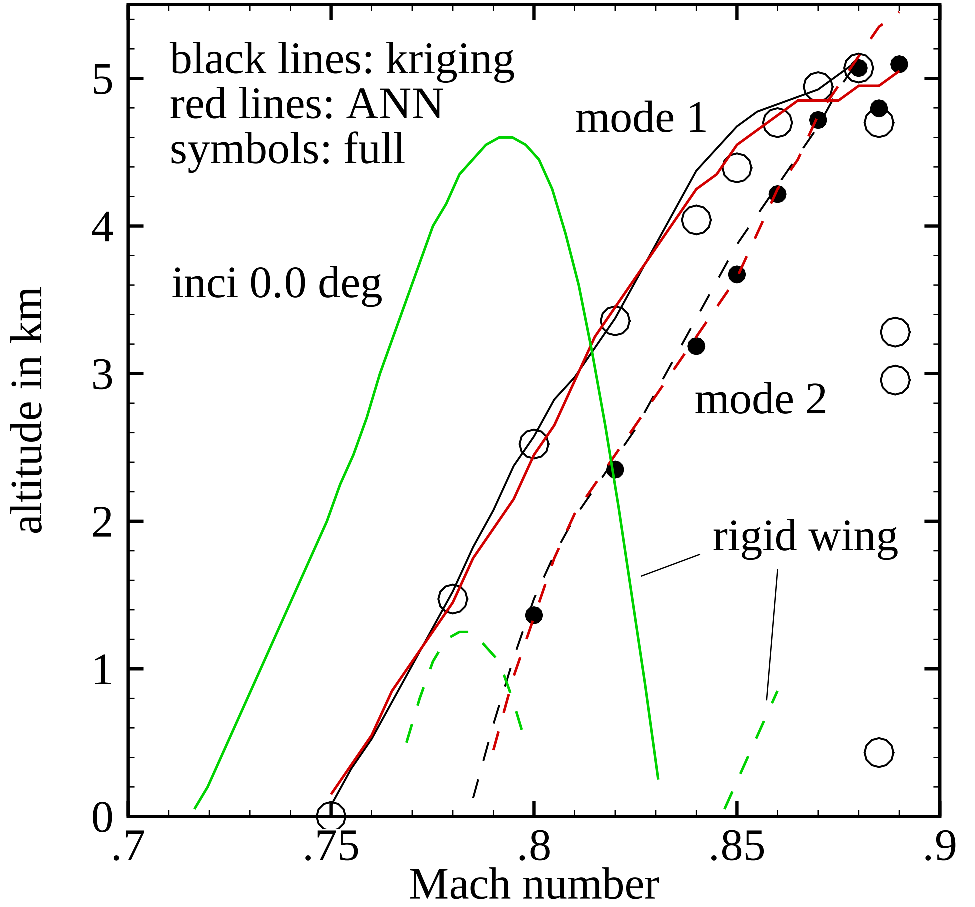
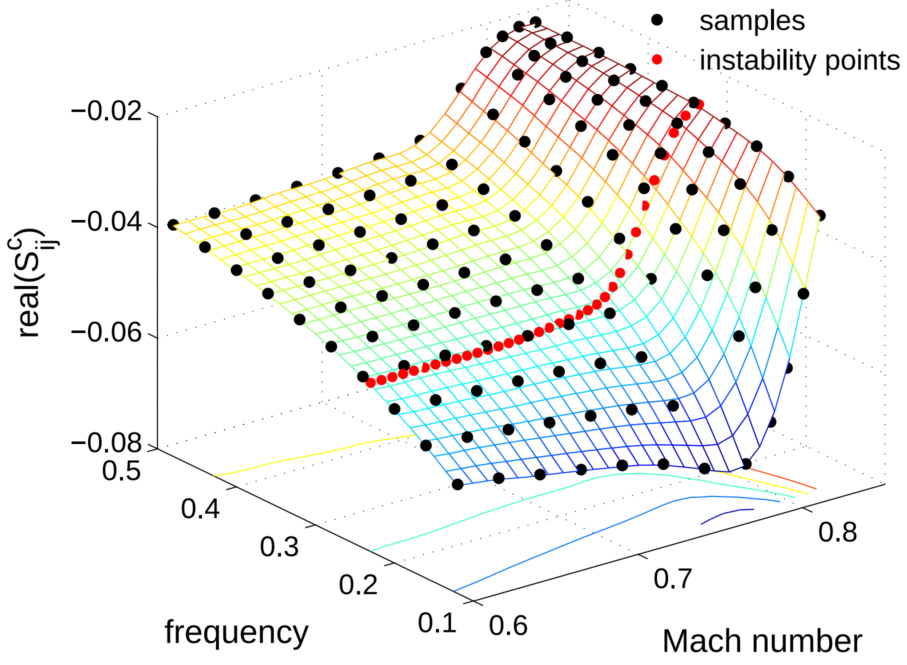


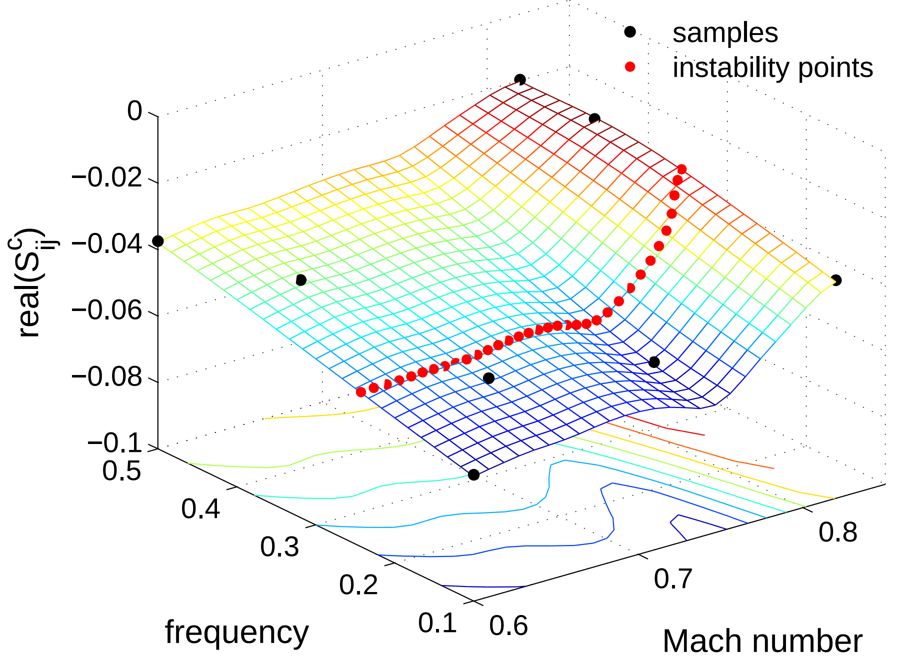


Coordinated Sampling

How to place samples smartly?



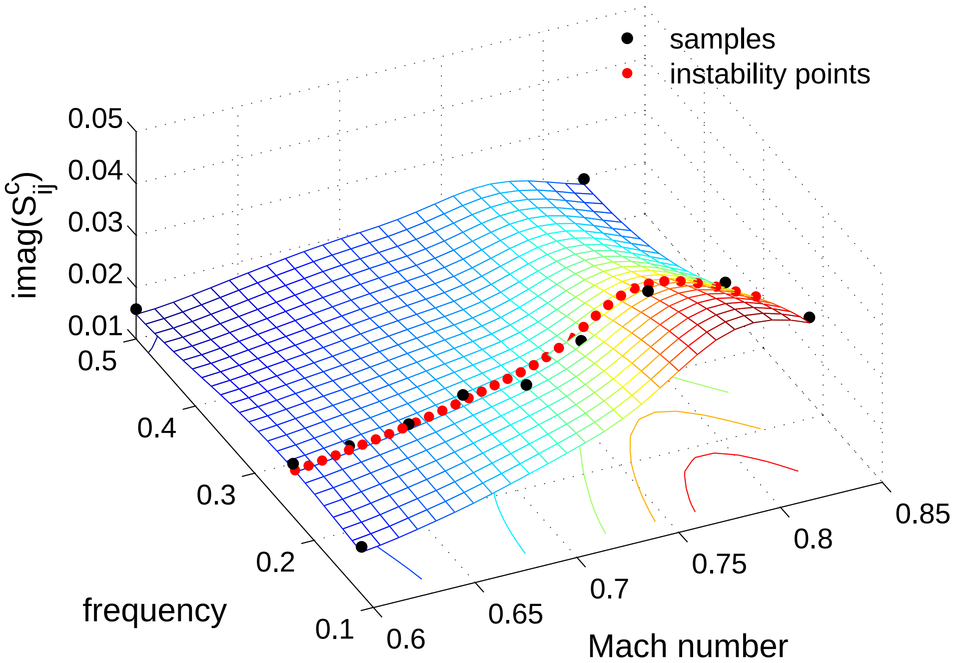
Brute force grid sampling



Latin hypercube sampling

Coordinated Sampling

- Risk–based sampling for blind search: NACA 0012 aerofoil



- Span initial search space
- Iterate on 3 steps
- Advantage of sample selection
  - prediction supported
  - kriging model improved

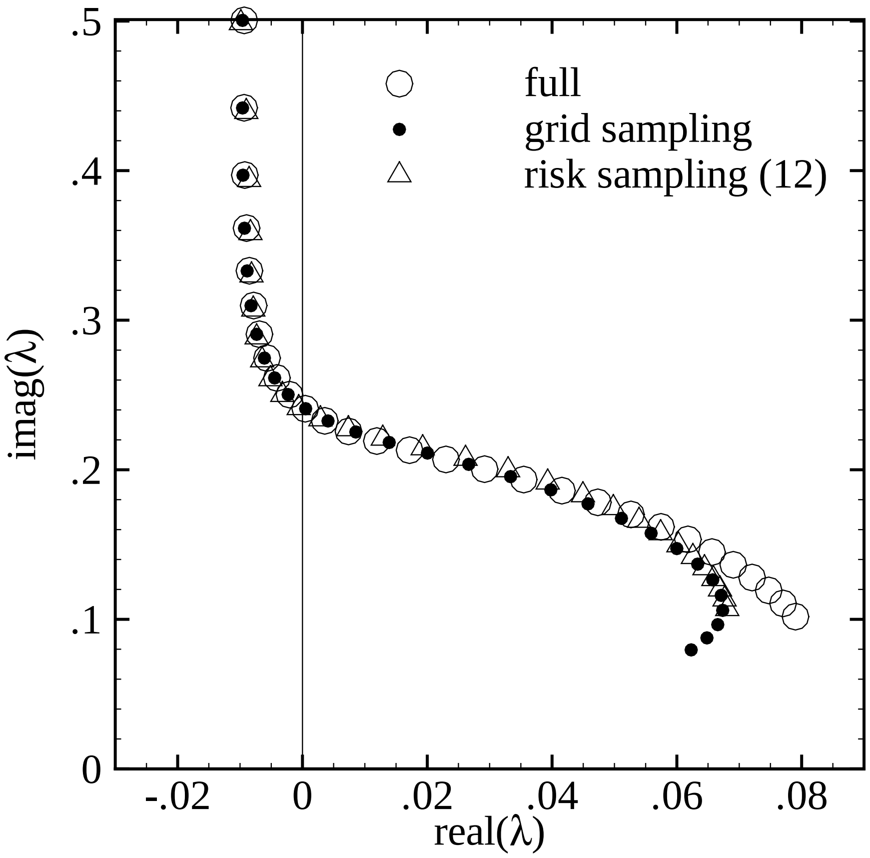
fully automated search

Coordinated Sampling

≻ Risk–based sampling for blind search: NACA 0012 aerofoil

- No globally accurate interaction matrix
  ⇒ good enough approximation

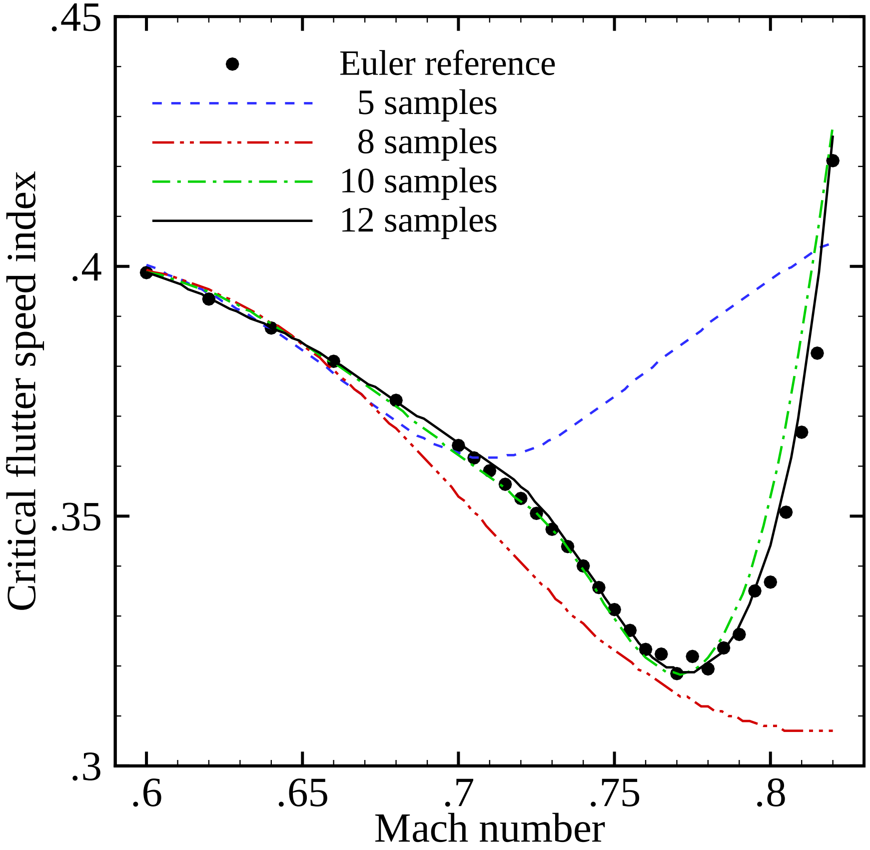
$$S(\lambda) \approx A_{ss} + \widehat{S}^c(\omega)$$



Coordinated Sampling

- Risk–based sampling for blind search: NACA 0012 aerofoil

- Issue of cost
  Euler simulation with 60k DOF
  - kriging:
    12 samples: cost of 6 steady state solves
  - full model: (using series expansion)
    1 Mach number: cost of 4 steady state solves
  - time domain:
    1 cycle of motion per (M, V) takes
    > 20 steady state solves



Coordinated Sampling

≻ Expected improvement sampling to locate most critical condition

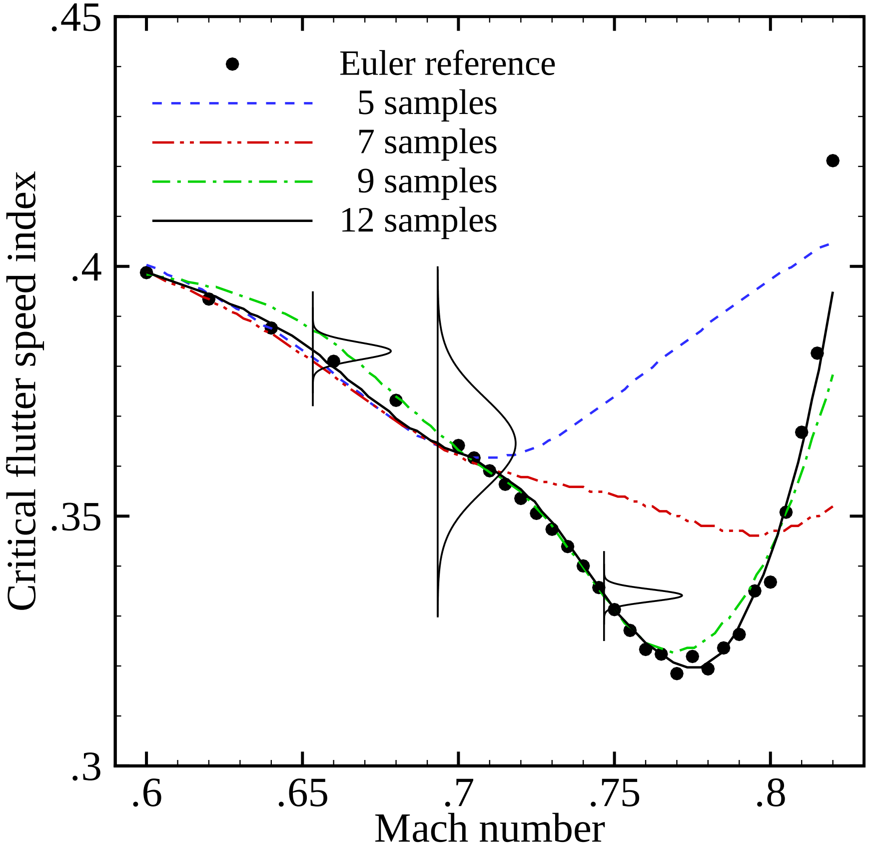
- Run stability analysis based on mean prediction
- Expand interaction term about mean

$$S(\lambda) \approx A_{ss} + \widehat{S}^c(\omega)$$

with

$$\widehat{S}^c(\omega) = \mathcal{N}\left(\widehat{S}^c(\omega_0), \varphi^2(\omega_0)\right) + \frac{\partial \widehat{S}^c}{\partial \omega_0}(\omega - \omega_0)$$

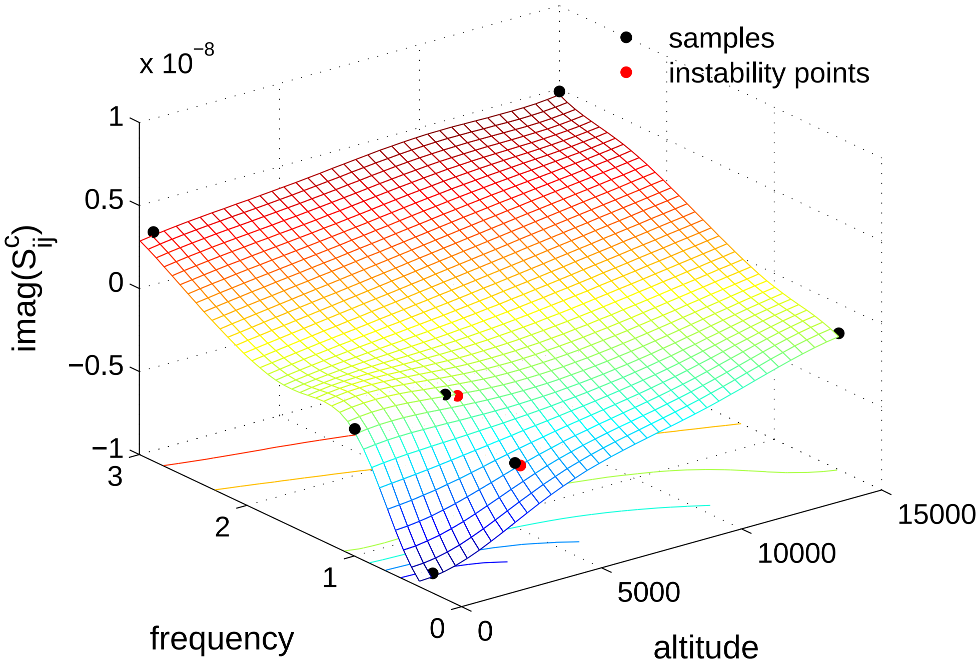
- Run Monte Carlo simulation
- Place new sample according to expected improvement function* for critical flutter speed index

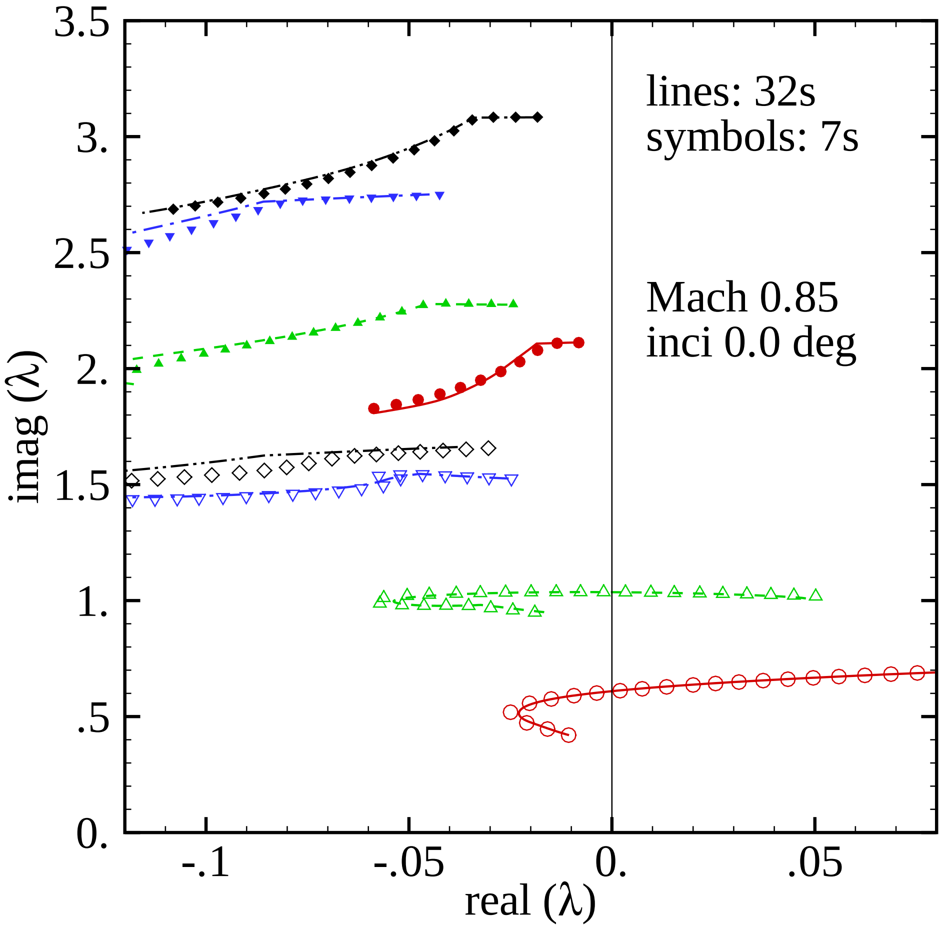


*) Jones et al, J Gobal Optim, 13, 1998

Coordinated Sampling

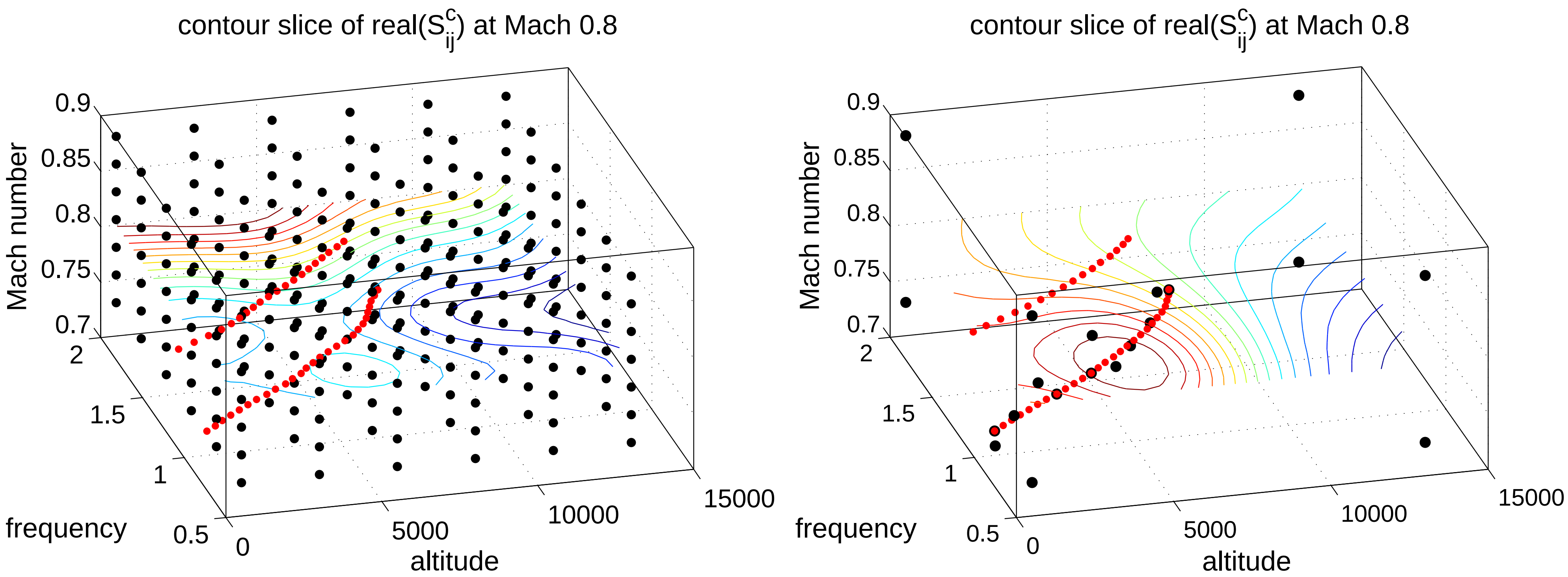
- 2D risk–based sampling for blind search: MDO wing





Coordinated Sampling

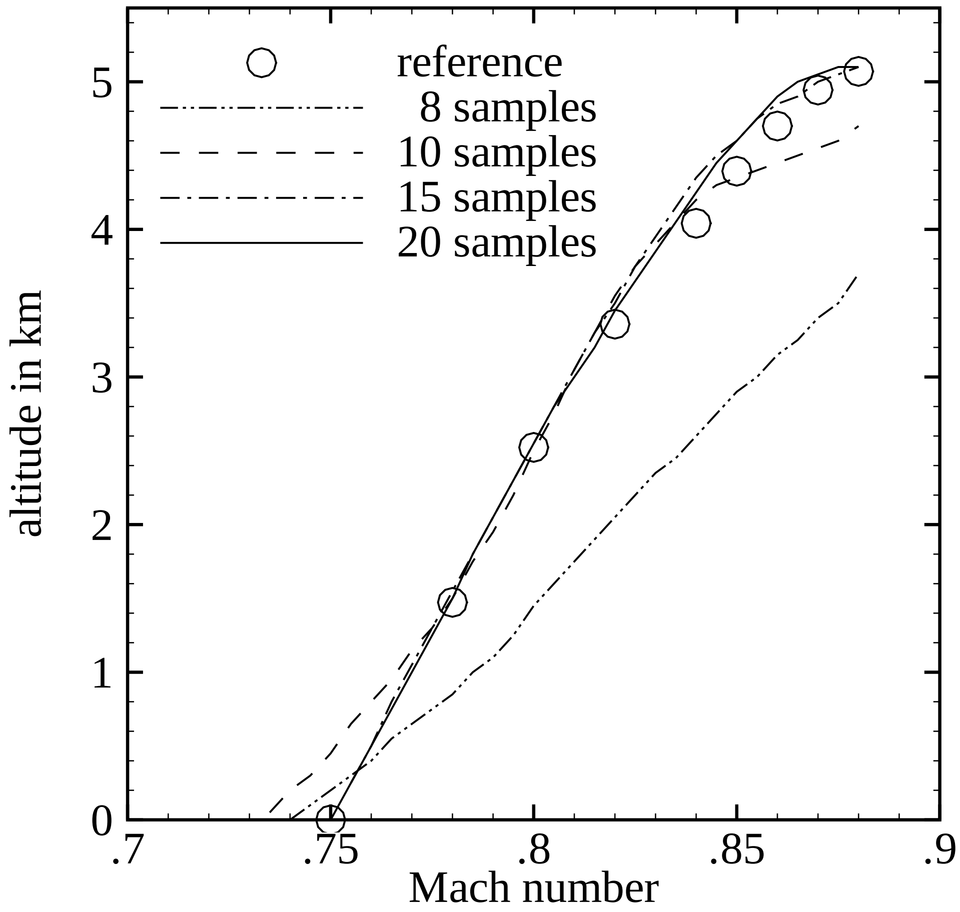
- 3D risk–based sampling for blind search: MDO wing

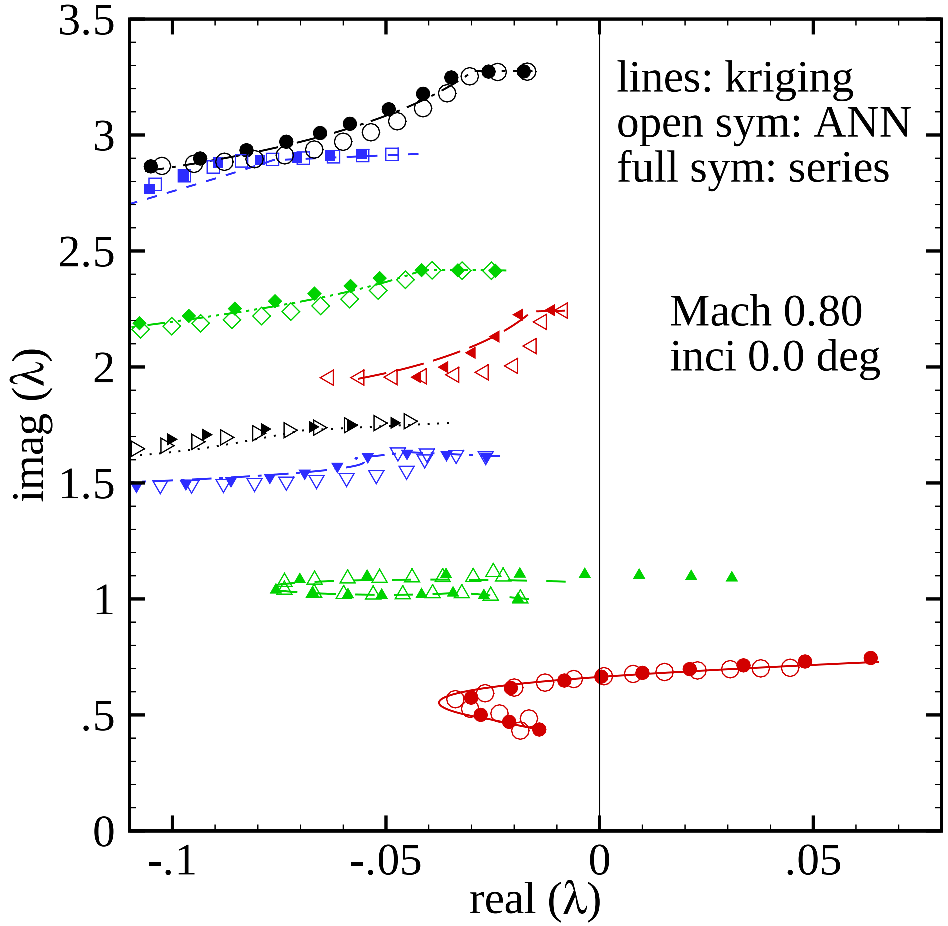


cost reduction by factor of 20!

Coordinated Sampling

- 3D risk–based sampling for blind search: MDO wing

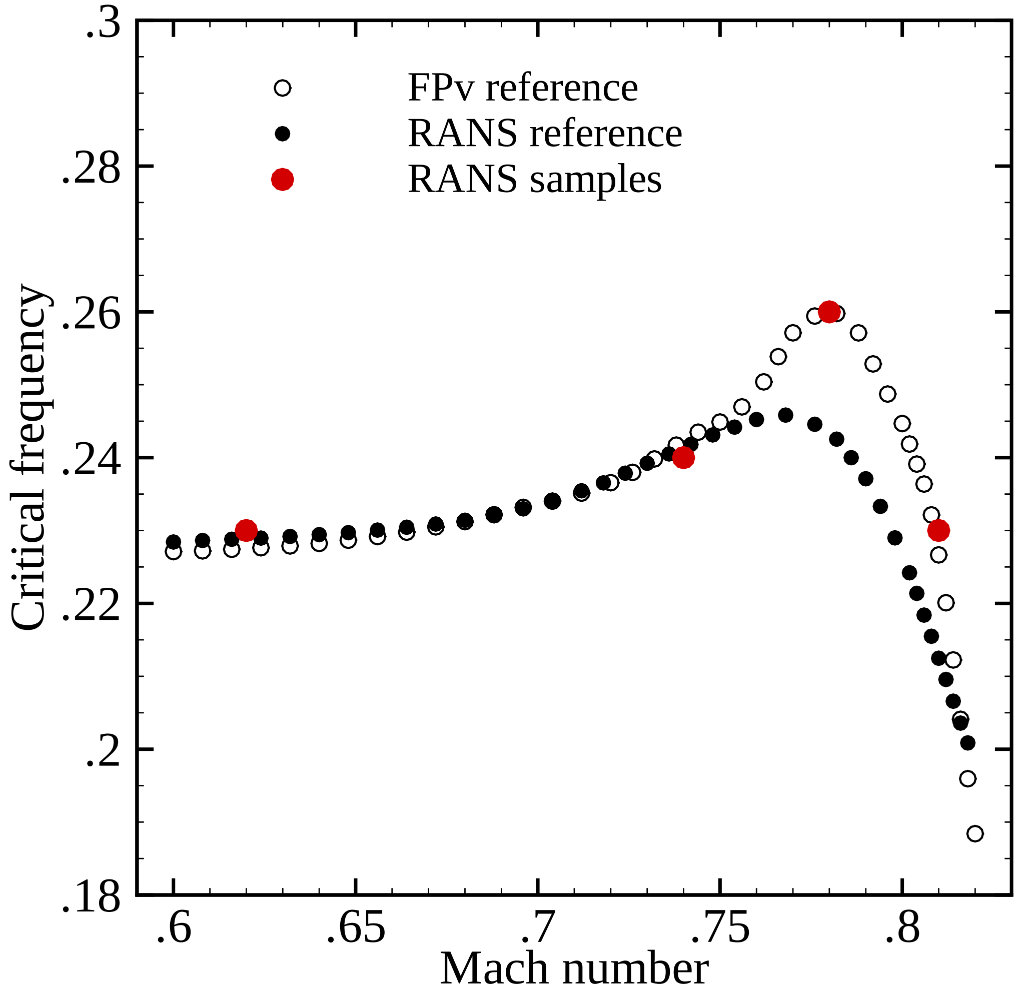




Exploiting the Model Hierarchy

Exploiting the Model Hierarchy

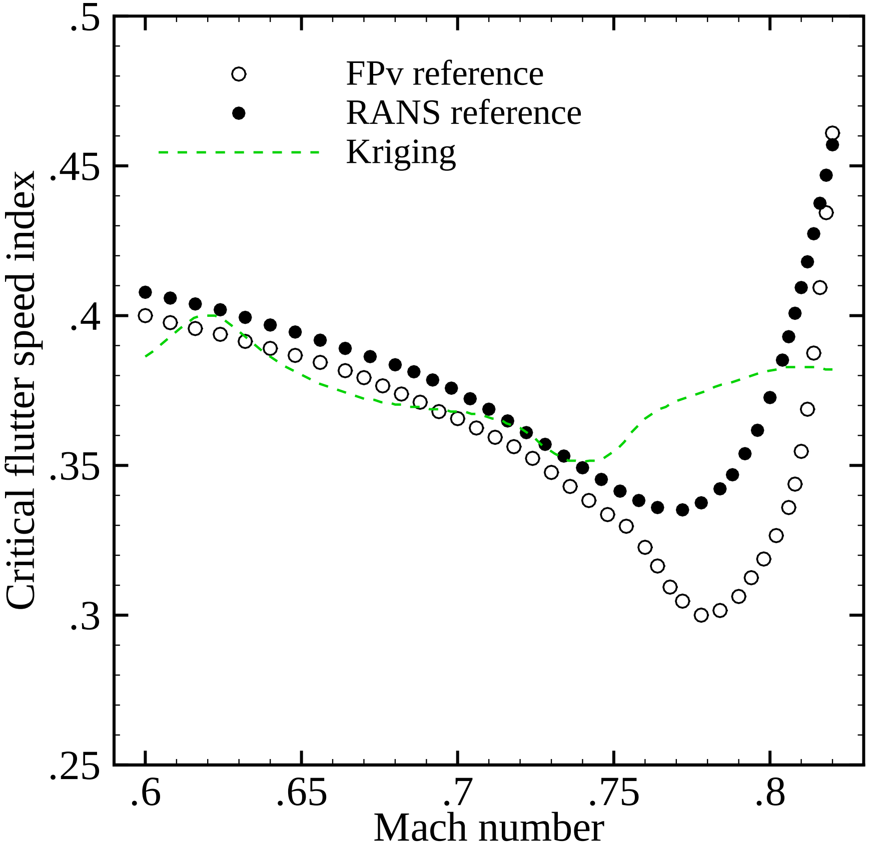
- Place expensive RANS samples according to cheap FPv prediction



Exploiting the Model Hierarchy

≻ 3 steps taken

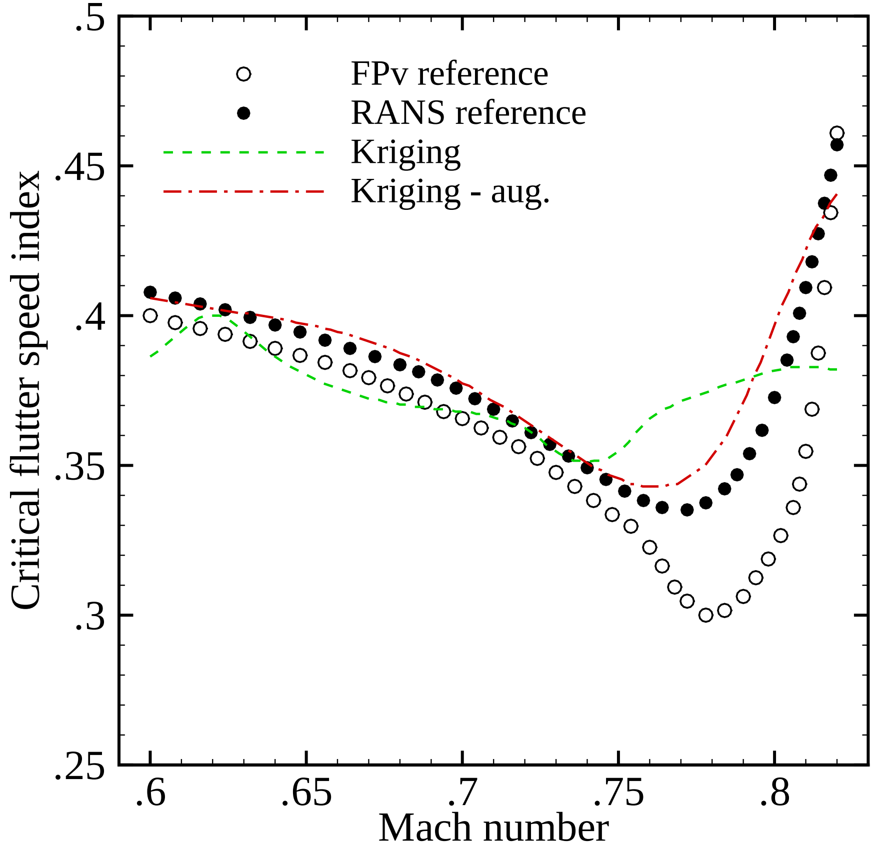
- Use kriging model based on RANS samples



Exploiting the Model Hierarchy

≻ 3 steps taken

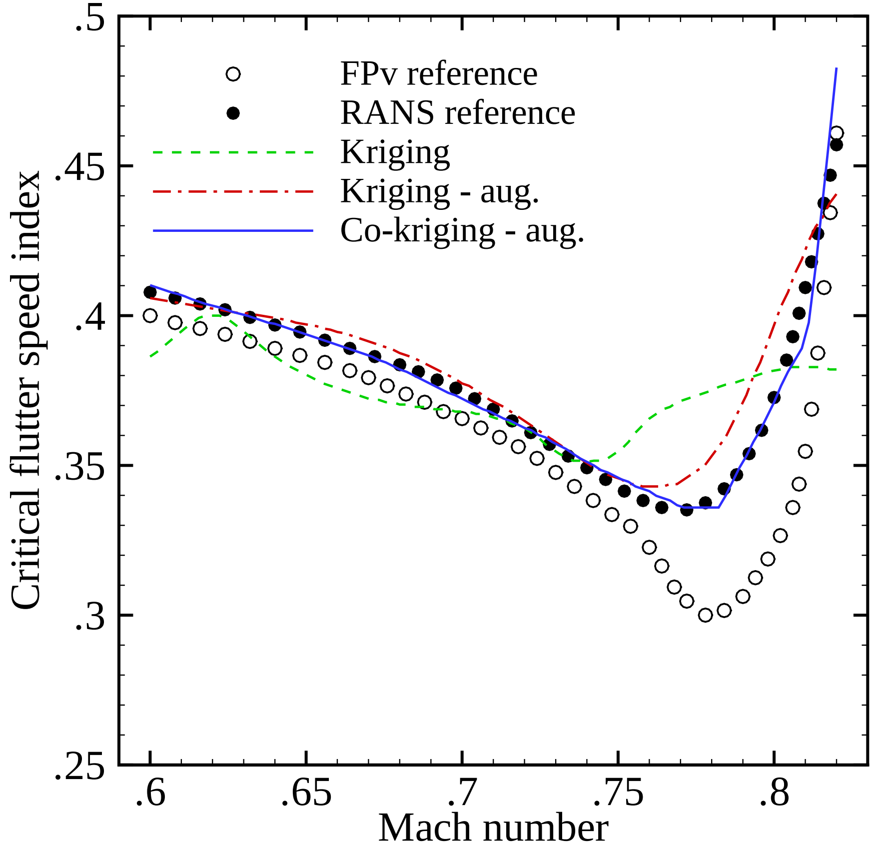
- Use kriging model based on RANS samples
- Augment RANS samples by FPv corner samples



Exploiting the Model Hierarchy

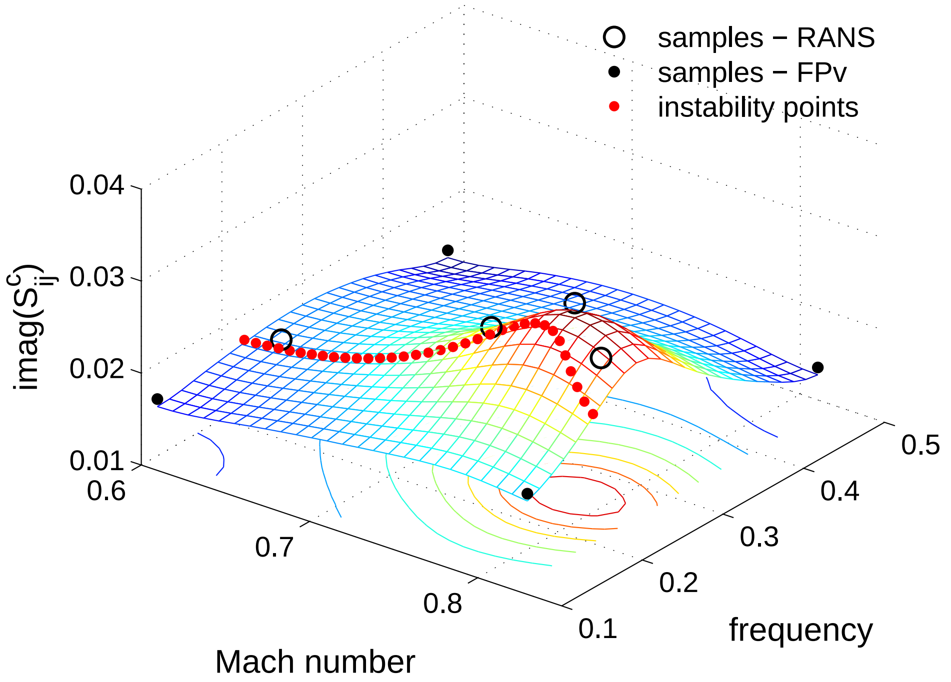
≻ 3 steps taken

- Use kriging model based on RANS samples
- Augment RANS samples by FPv corner samples
- Expand RANS input parameter space by FPv response

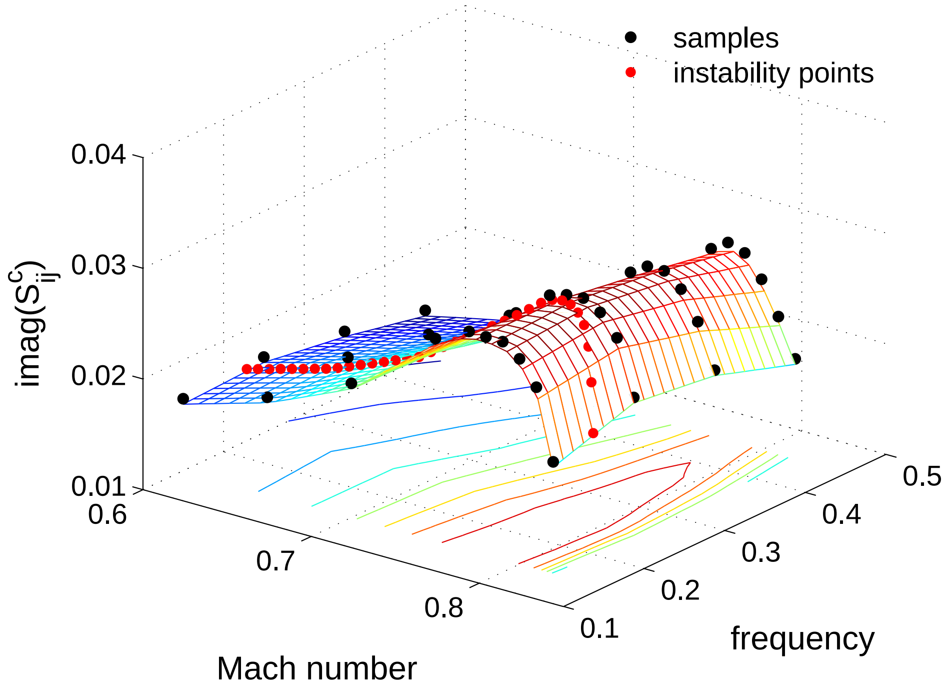


Exploiting the Model Hierarchy

- Co-kriging: FPv samples provide trend information for RANS



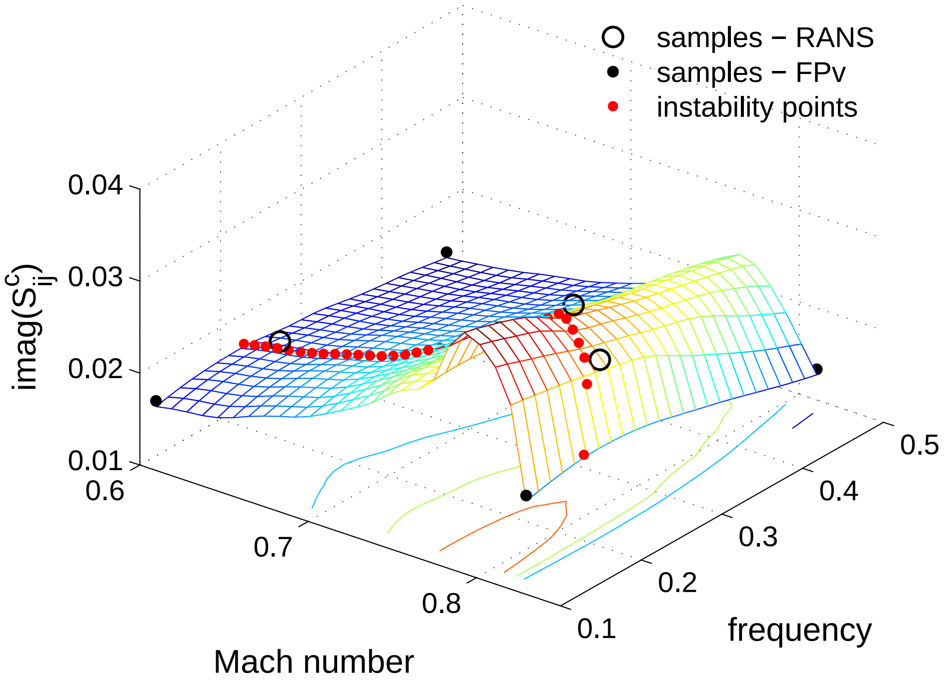
Augmented kriging



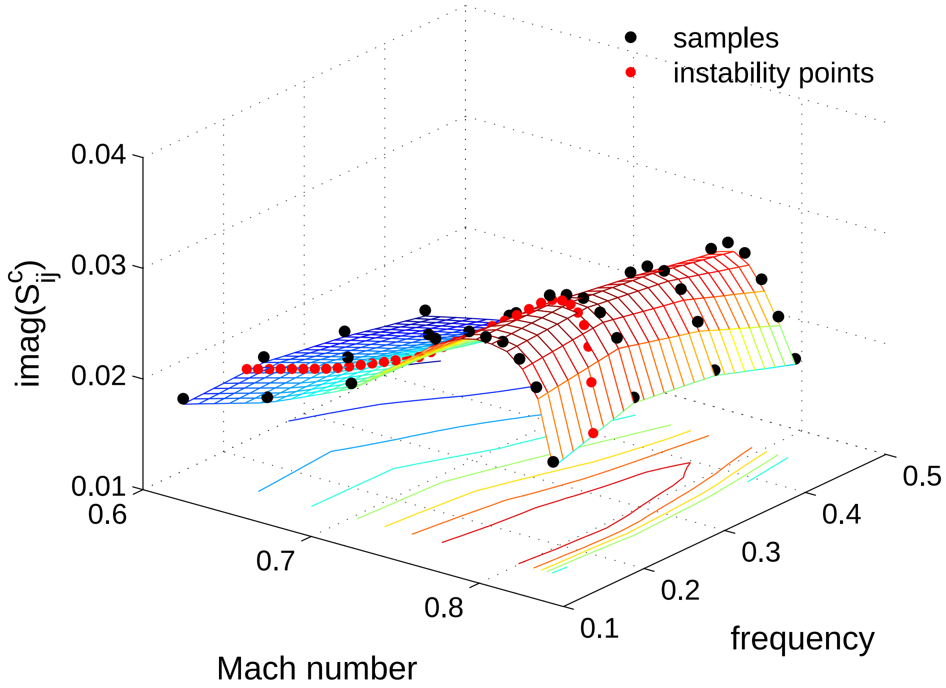
Reference surface

Exploiting the Model Hierarchy

- Co-kriging: FPv samples provide trend information for RANS



Augmented co-kriging



Reference surface

Summary & Outlook

Summary & Outlook

- ≻ Approach presented for blind search aeroelastic stability analysis
  - based on modified structural eigenvalue problem
  - sampling & reconstruction of fluid interaction term
  - very competitive results at lower cost

- ≻ Risk–based sampling and models of variable fidelity

- ≻ Address how aerodynamic modelling uncertainty enters problem
- ≻ Address model updating/correction with experimental data

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