MUSAF II Colloquium, Toulouse, France

Aeroelasticity of Turbomachines

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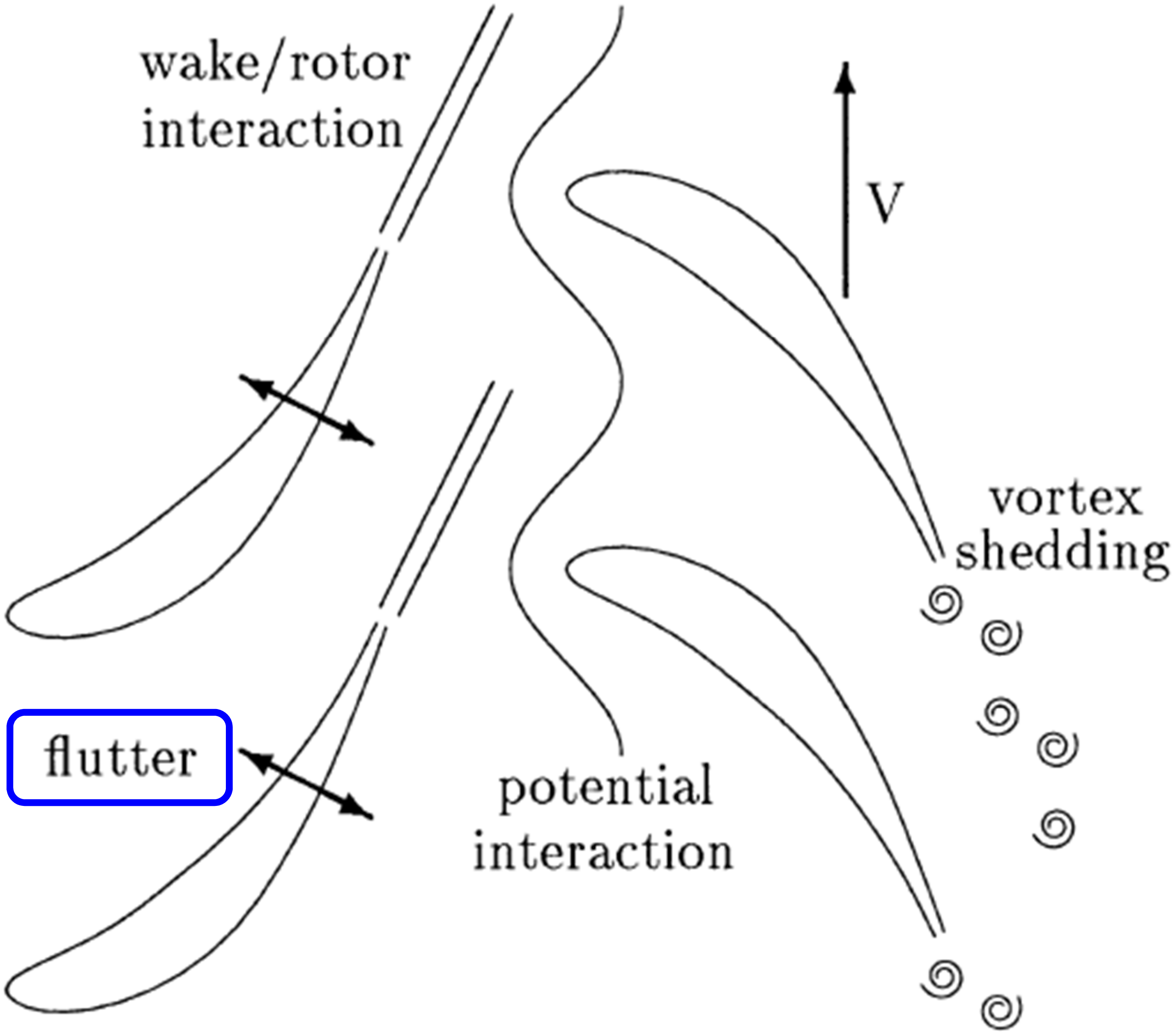


(Giles, 1991)

Content of Today‘s Talk

- „Crash course” in turbomachinery flutter
- How well are we presently doing in predicting flutter?
- How can we validate our flutter prediction tools?

Motivation

- The accurate and reliable prediction of flutter is of paramount interest to turbomachinery manufacturers
  - Increased accuracy and reliability of predictions allow pushing limits further such as to make turbomachines „greener“

- There is a clear context between the greening potential of new turbomachine generations and aeroelastic phenomena
  - More efficient engines come along with less components, more aggressive operating conditions and consequently greater aerodynamic loading
  - In case of stationary turbomachines, greening is much related to operational flexibility
  - Both aspects can lead to aeroelastic phenomena

A ”Crash Course” in Turbomachinery Flutter

General Aspects of Flutter

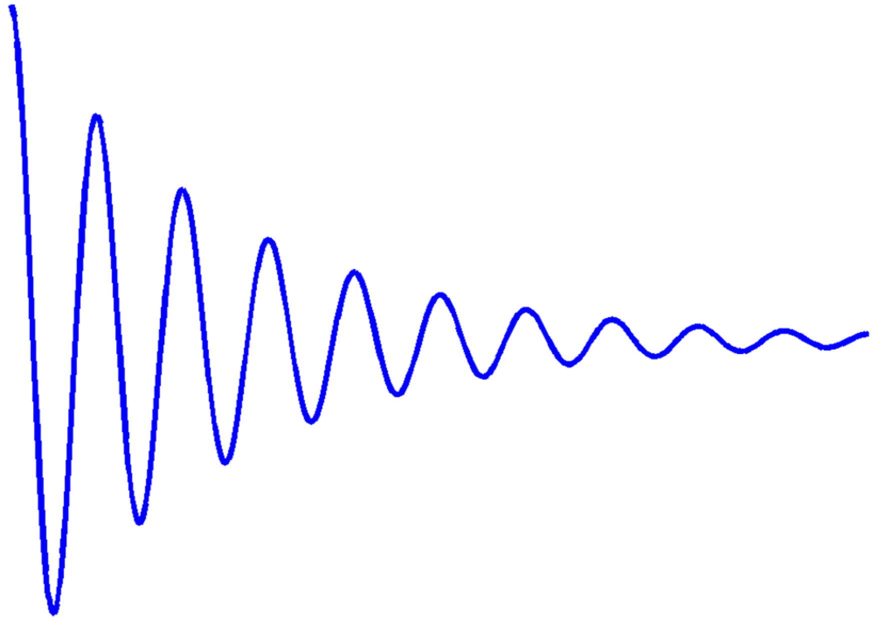
- Flutter is a self-excited and self-sustained vibration phenomenon

  - The vibration starts by itself if the fluid-structure coupled system becomes unstable

  - Unless we provide proper damping, vibration amplitudes rapidly escalate

Vibration scenarios

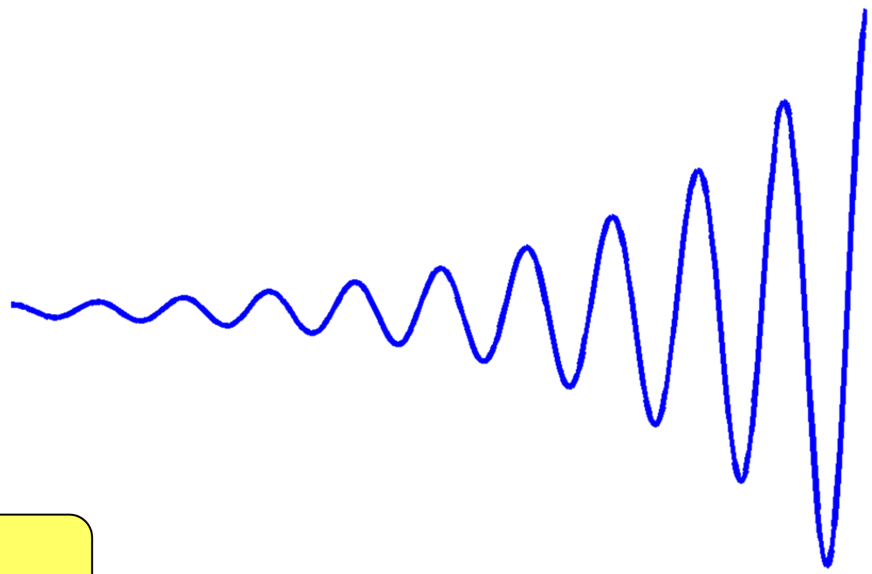
- Positively damped
  - Preferred



No flutter

Vibration scenarios

- Self-excited (negatively damped)
  - Must be avoided

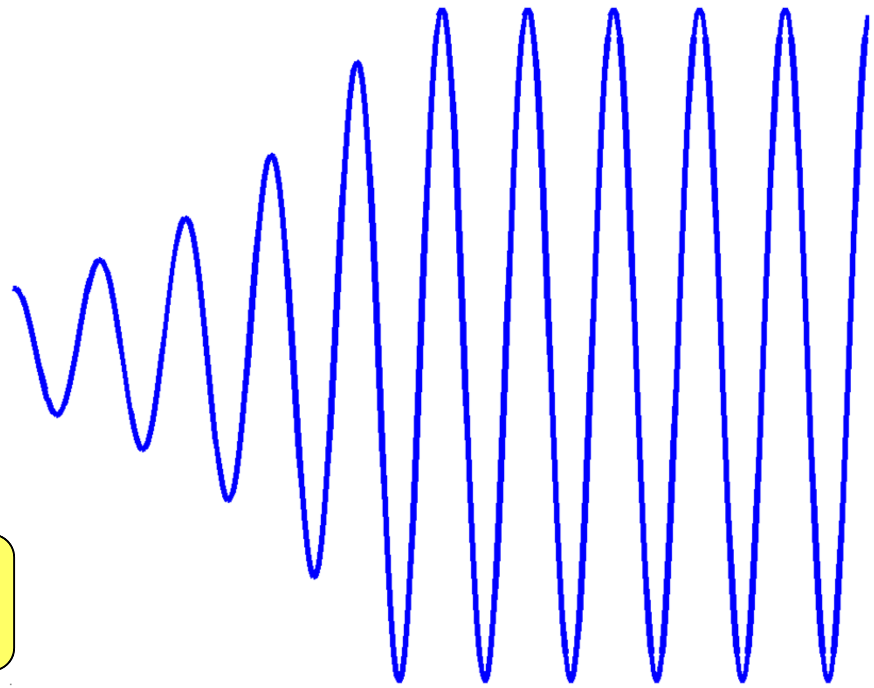


Flutter

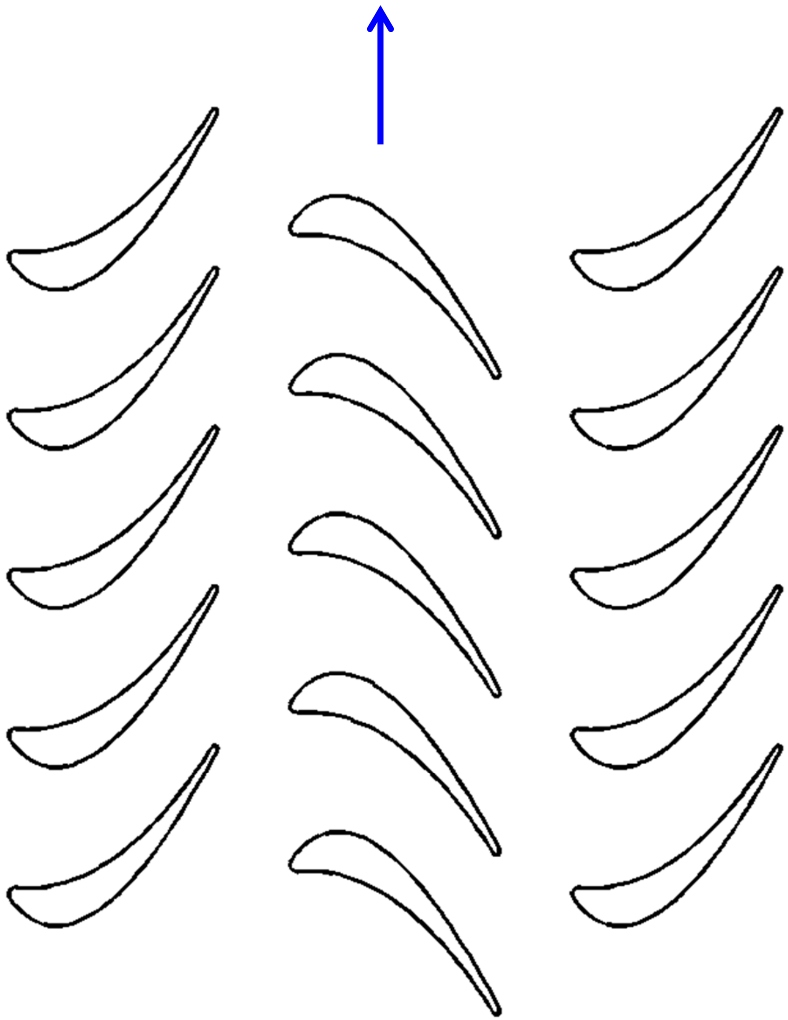
Vibration scenarios

- Self-excited, attaining Limit Cycle Oscillations (LCO)
  - Can be tolerated

Flutter



What Happens if Blades Vibrate?



What Happens if Blades Vibrate?

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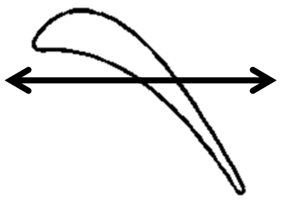
Structure and fluid

$$m\ddot{x} + c\dot{x} + kx = F(t)$$

Structural part

Aerodynamic part

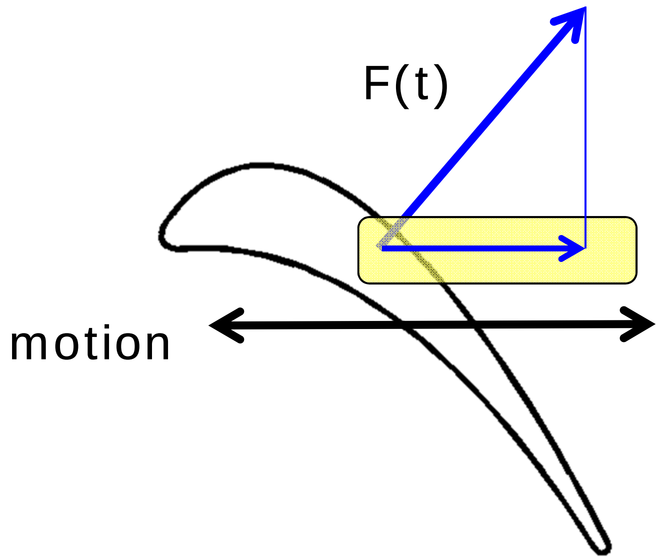
motion



x: deformation coordinate
→ modal coordinate

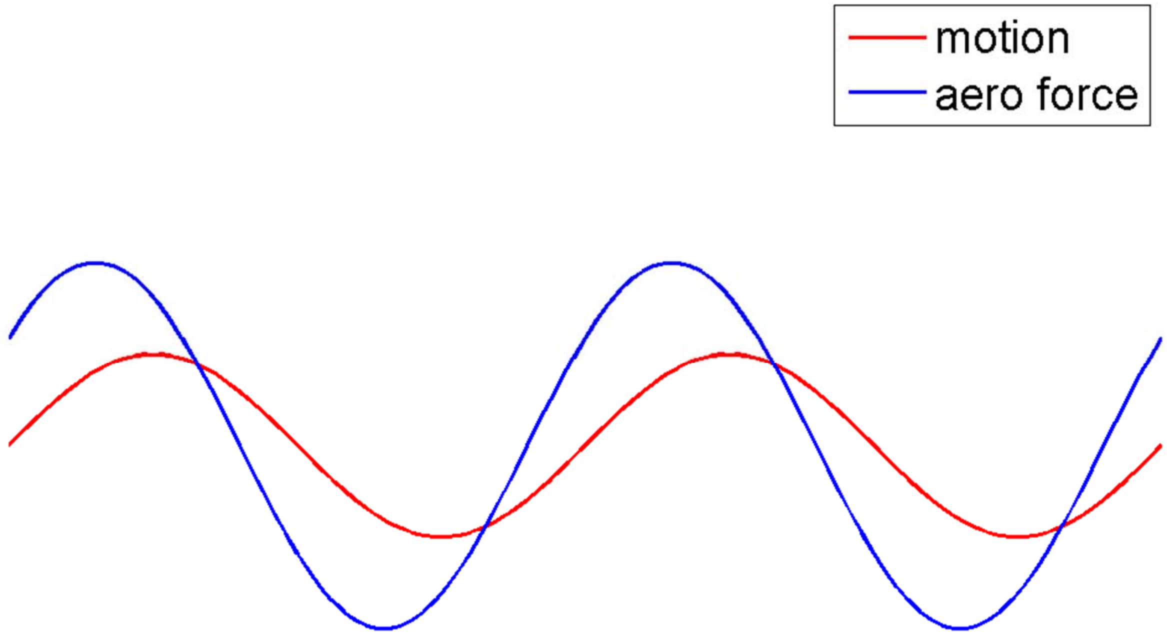
F(t) : aerodynamic force

What about F(t)?



- F(t) is due to flow and the motion of the blade
- F(t) has an arbitrary direction
  - But it is only the component in direction of the mode that matters
- F(t) is most probably not in phase with the motion

Aerodynamic Force F(t)



- It is the out-of-phase component that gives us the aerodynamic damping

  - Of importance: the mode, the magnitude and the phase of the unsteady aerodynamics

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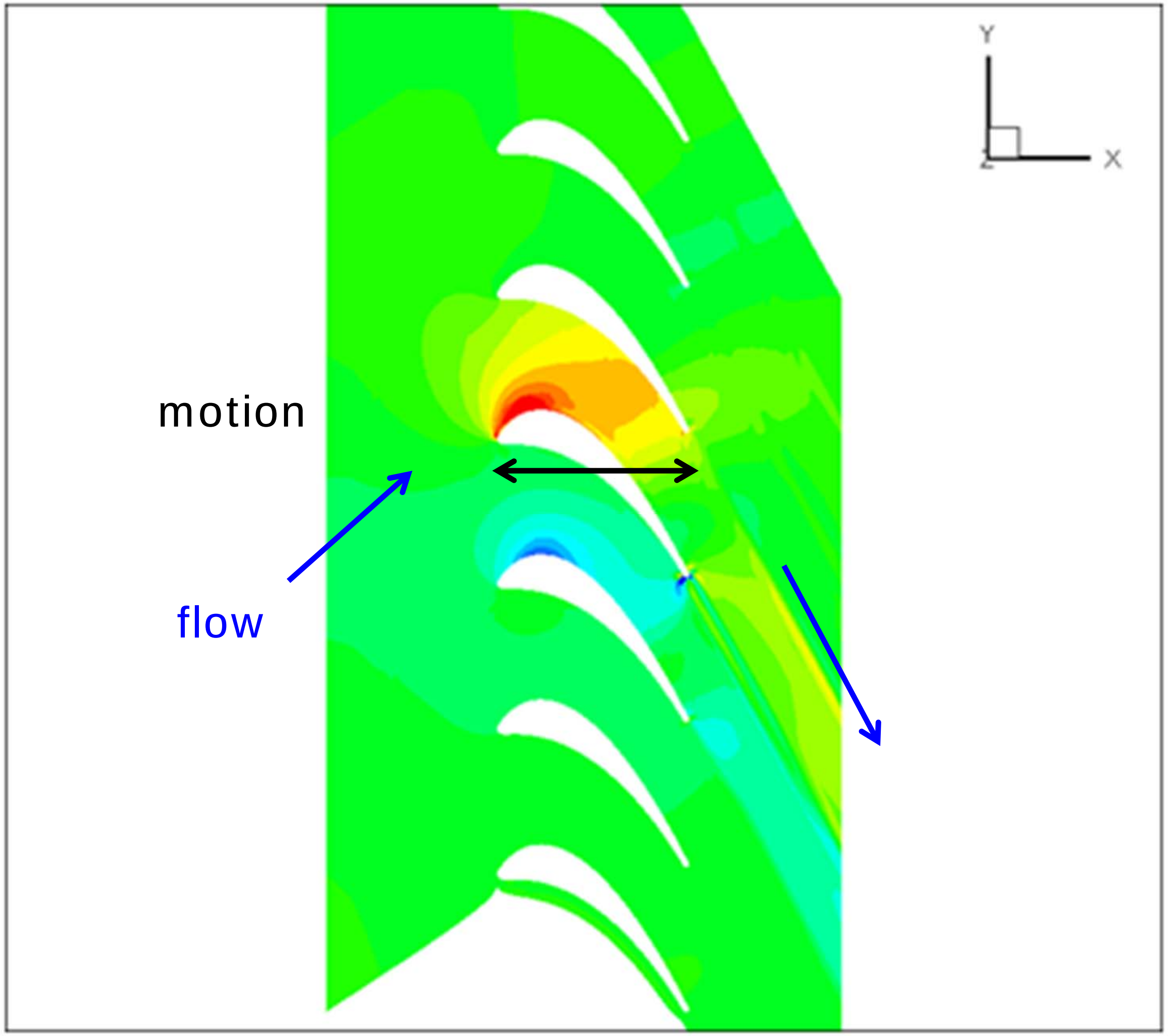
Blade Row Aeroelasticity

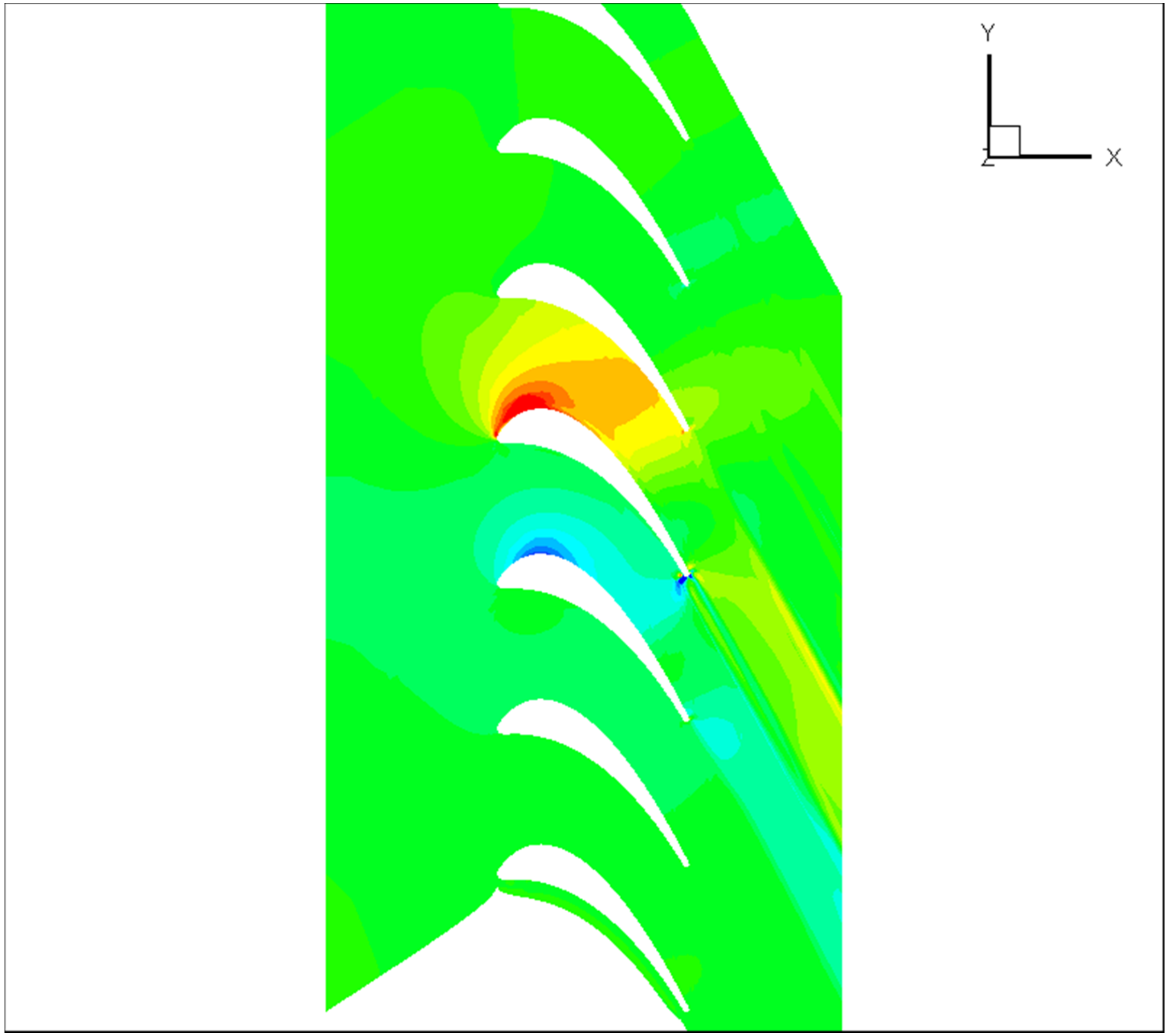
Figure shows pressure perturbation

Single blade oscillating

→ Aerodynamic influence

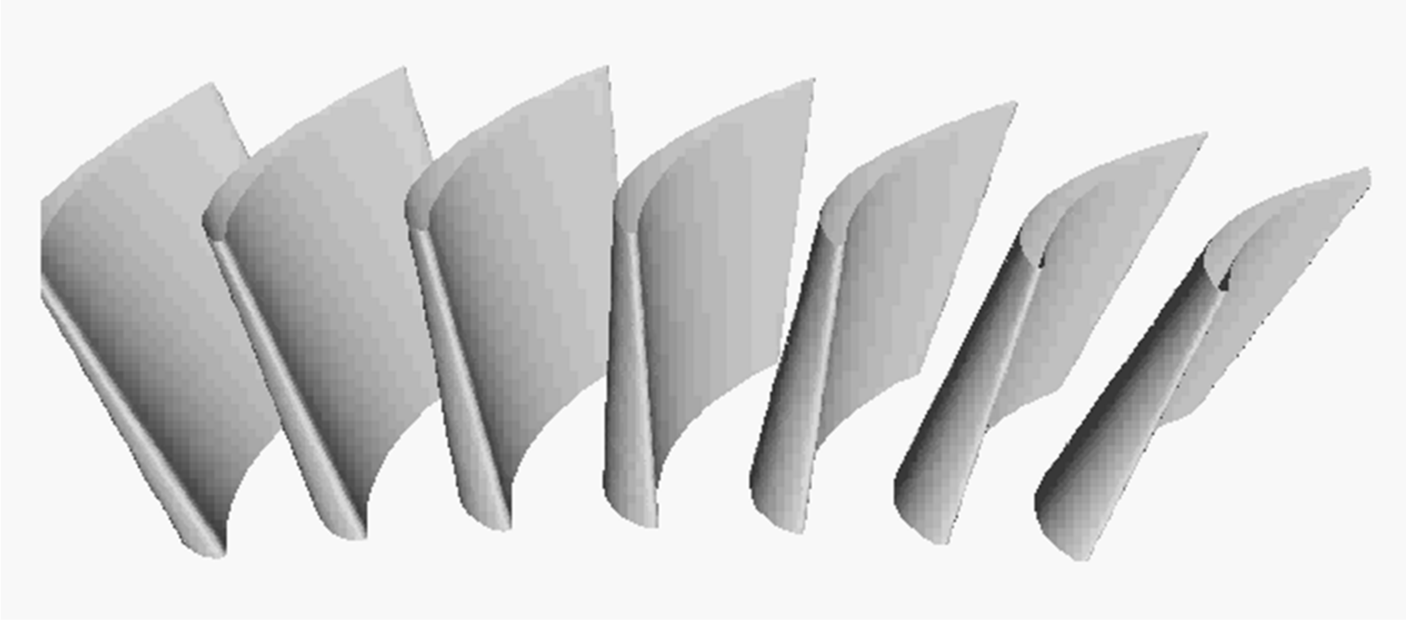


Blade Row Aeroelasticity



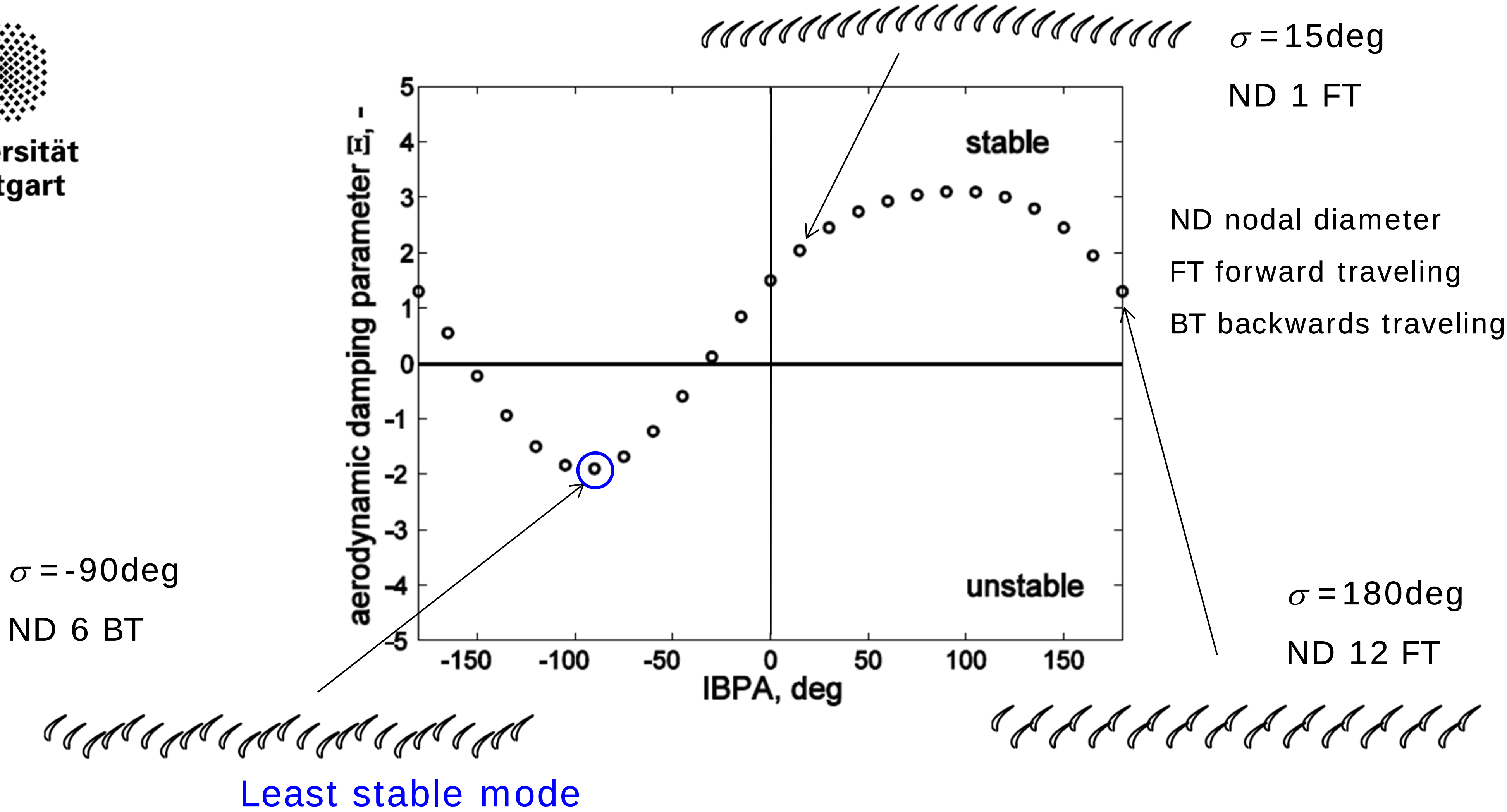
Traveling Wave Mode Stability

- In a blade row, in which all blades oscillate, the influence of the individual blades is superimposed



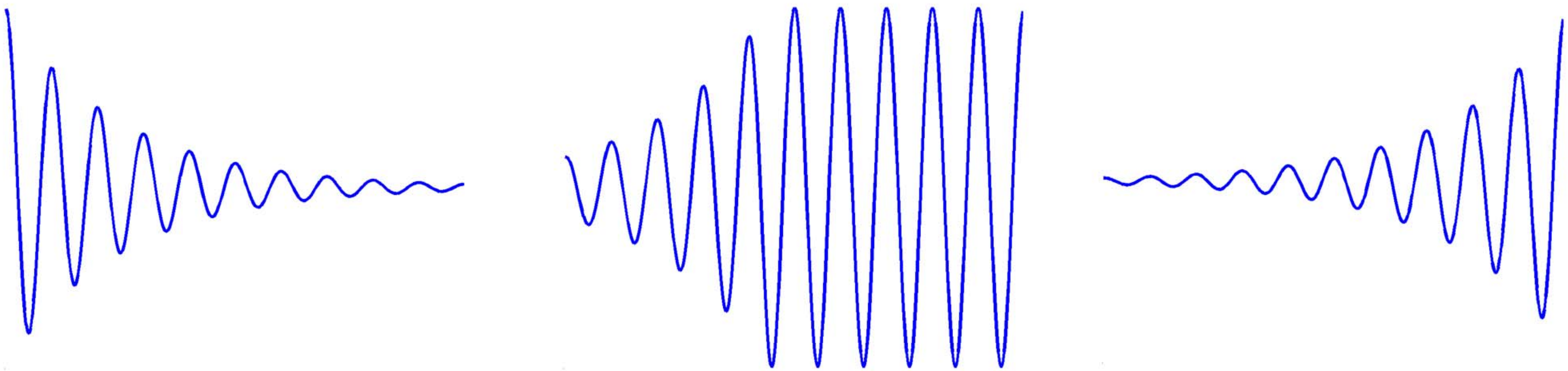
→ Linear superposition $$\hat{c}_{p}{}^{m,\sigma}_{A,twm}(x,y) = \sum_{n=-\frac{N}{2}}^{n=+\frac{N}{2}} \hat{c}_{p}{}^{n,m}_{A,ic}(x,y) \cdot e^{-i\sigma \cdot n}$$

Aeroelastic Stability Curve



Aerolasticity „Crash Course“ Essentials

- Predicting flutter is about ...
  - Predicting the aerodynamic damping for different vibration modes (mode direction, nodal diameter pattern)
  - Putting the aerodynamic damping against the structural damping at these modes
  - Evaluating the resulting type of vibration



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How well are we presently doing in predicting flutter?

Blind-Test Prediction Accuracy

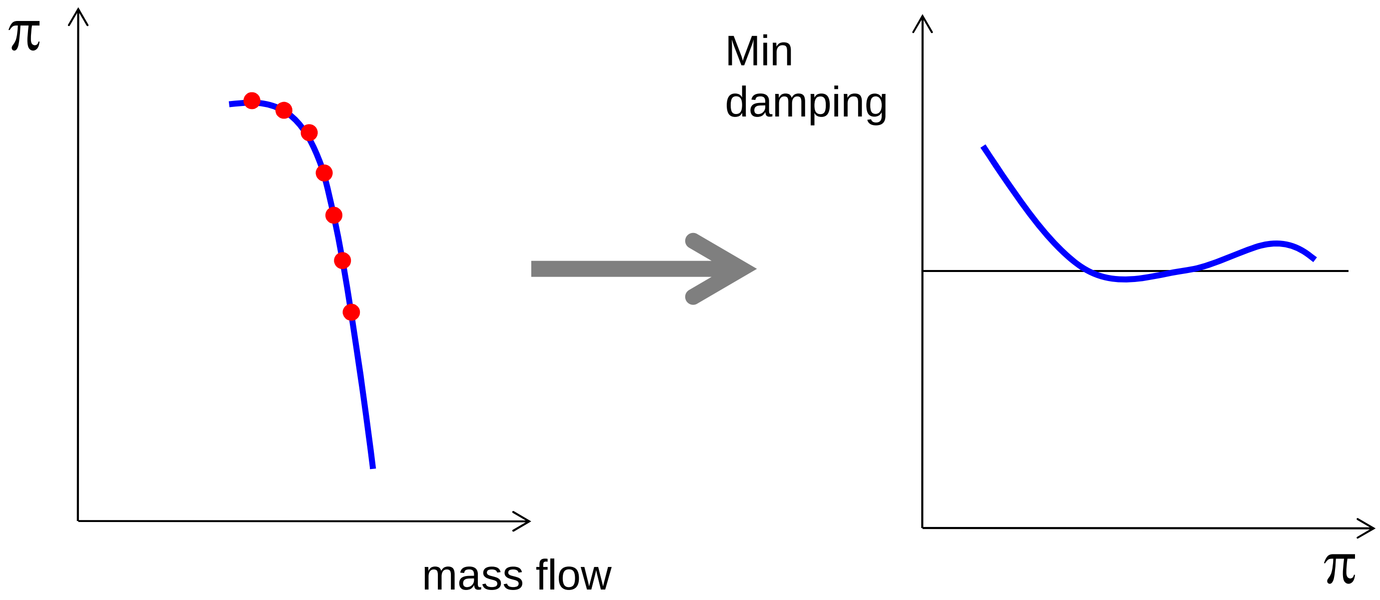
- The results shown below have been obtained in the EU FP7 collaborative Research Project FUTURE (Flutter-free Turbomachinery Blades)

- They have been obtained as blind-test predictions
  - In other words, test data were first available at a much later stage

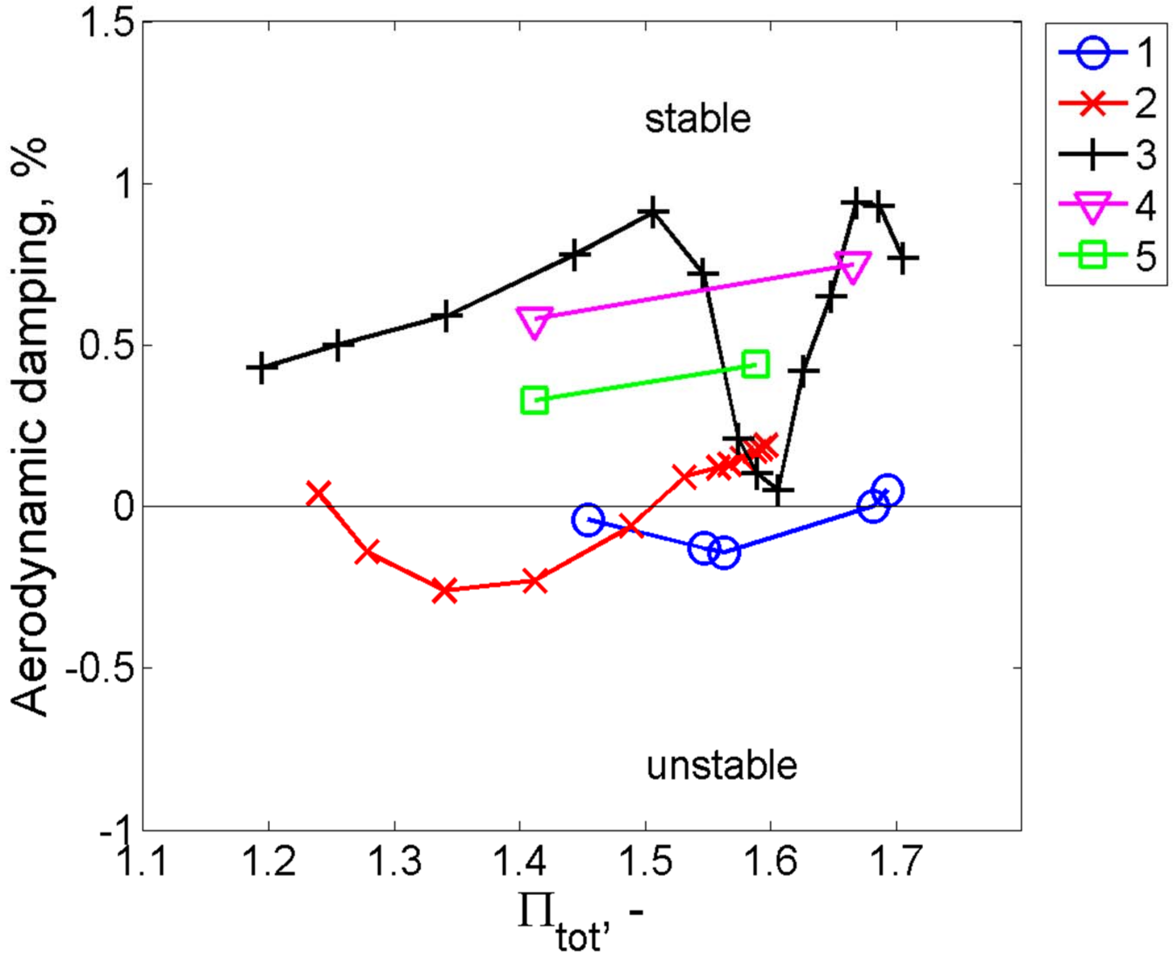
- Test case
  - Transonic compressor, blisk type, 1 ½ stage
  - Well-defined geometry and boundary conditions have been provided to several partners

Flutter Prediction Accuracy Test Case

- Predict the minimum aerodynamic damping of the transonic compressor test case at various operating points on a speedline

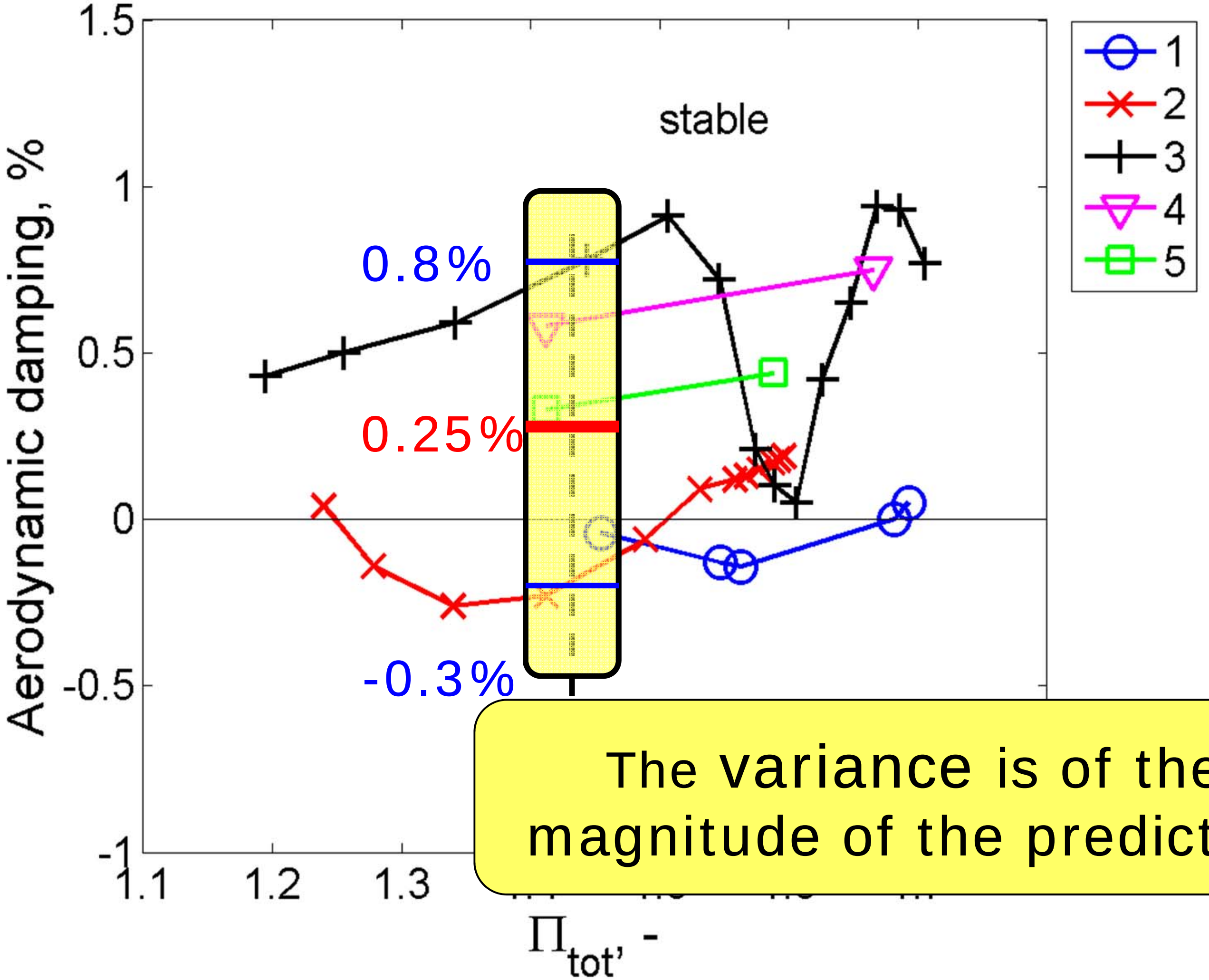


Comparison of Predicted Aero Damping



Ref: FUTURE Project

Analysis Aero Damping Predictions



The variance is of the order of magnitude of the predicted damping

Ref: FUTURE Project

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How can we validate our flutter prediction tools?

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Validation of Flutter Prediction Tools

- The validation must be performed on relevant test cases, on which high quality experimental data are available

- Ideally, the validation is carried out at various levels of complexity
  - Rotating rig tests: near-engine environment, total damping measurements, expensive and complex
  - Stationary cascade test: well-controlled conditions but real conditions are only assimilated, aero damping measurements, detailed, simpler and more affordable

The FUTURE Project

- The FUTURE project was a collaborative research project that has been carried out within the EU FP7 framework during 2008-2013
  - 25 partners from industry, academia and research institutes
  - Lead by KTH (Prof. T. Fransson and Doc. D. Vogt)
  - Total budget 10.6M€

- The goal of the project was to set-up new and relevant test cases in turbomachinery aeroelasticity and to validate state-of-the-art flutter prediction tools against these
  - Derivation of best practice guidelines for flutter analyses and testing

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FUTURE Project Consortium

Lead (Fransson, Vogt)

Industry

- VOLVO AERO
- MTU Aero Engines
- ALSTOM
- Avio propulsione aerospaziale
- CERFACS
- SIEMENS
- ITP GRUPO Industria de Turbo Propulsores, S.A.
- Techspace Aero Groupe SAFRAN
- Rolls-Royce
- PCA ENGINEERS Engineering Consultants
- Snecma Groupe SAFRAN
- Turbomeca SAFRAN Group

Research Institutes

- DLR
- CSIR our future through science
- CTA Centro de Tecnologías Aeronáuticas Aeronautikako Teknologien Zentroa
- ONERA

Academia

- KTH VETENSKAP OCH KONST ROYAL INSTITUTE OF TECHNOLOGY
- STVDIORVM UNIVERSITAS FLORENTINA
- POLITECNICO DI TORINO 1859 - 1906
- EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
- UNIVERSITEIT STELLENBOSCH UNIVERSITY
- CENTRALE LYON
- Imperial College London
- UNIVERSIDAD POLITÉCNICA MADRID
- TECHNISCHE UNIVERSITÄT DARMSTADT

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FUTURE Project Concept

- Two main streaks of new validation test cases
  - Transonic compressor
  - High subsonic aero Low-Pressure Turbine (LPT)

- Interconnected experiments
  - Non-rotating cascade tests, controlled blade oscillation
  - Rotating tests, multi-blade row, free and forced oscillation
  - Mechanical characterizations of components (blisk, bladed disks)

- Numerical analyses performed by several partners

FUTURE Transonic Compressor Tests

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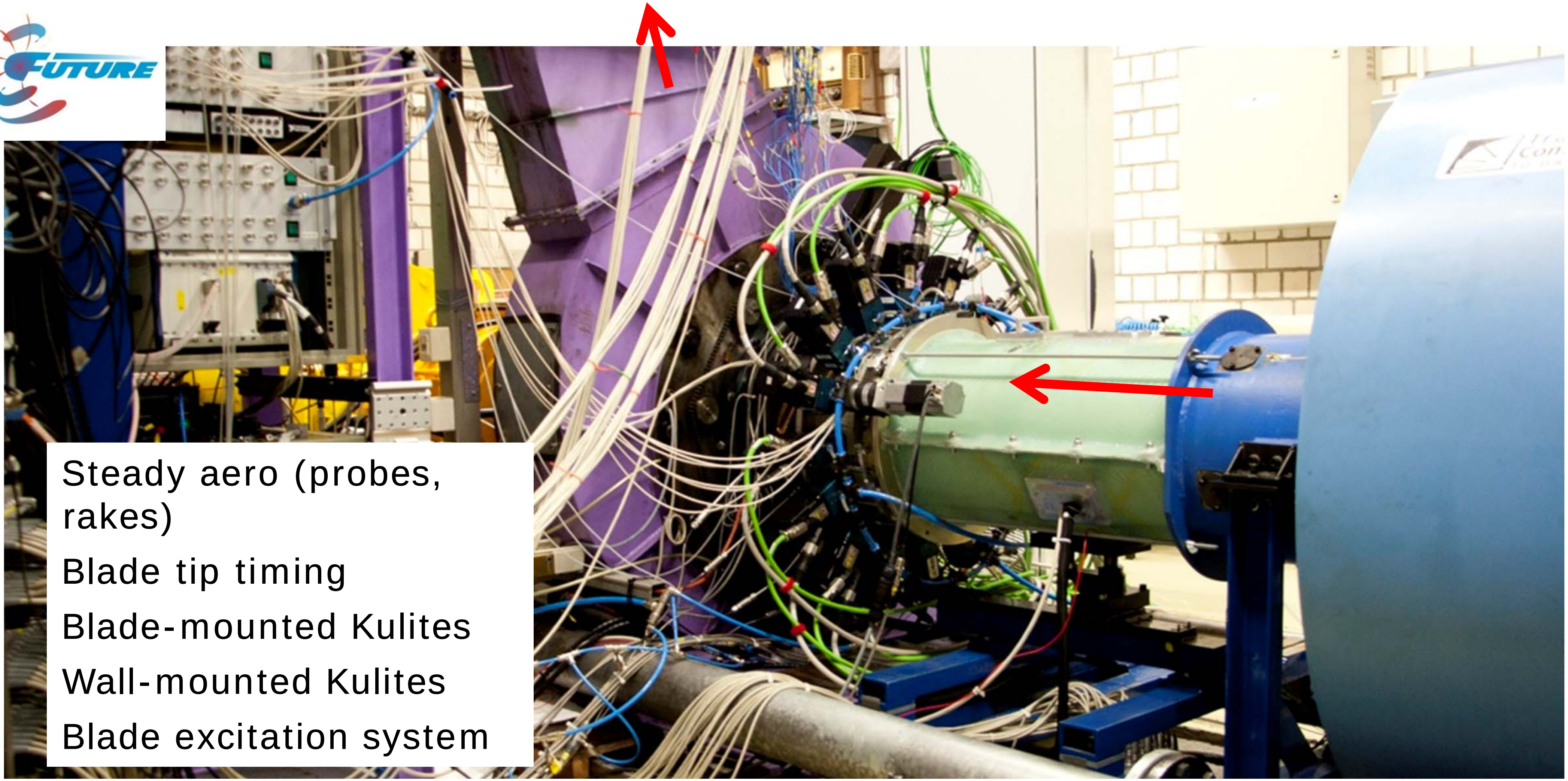
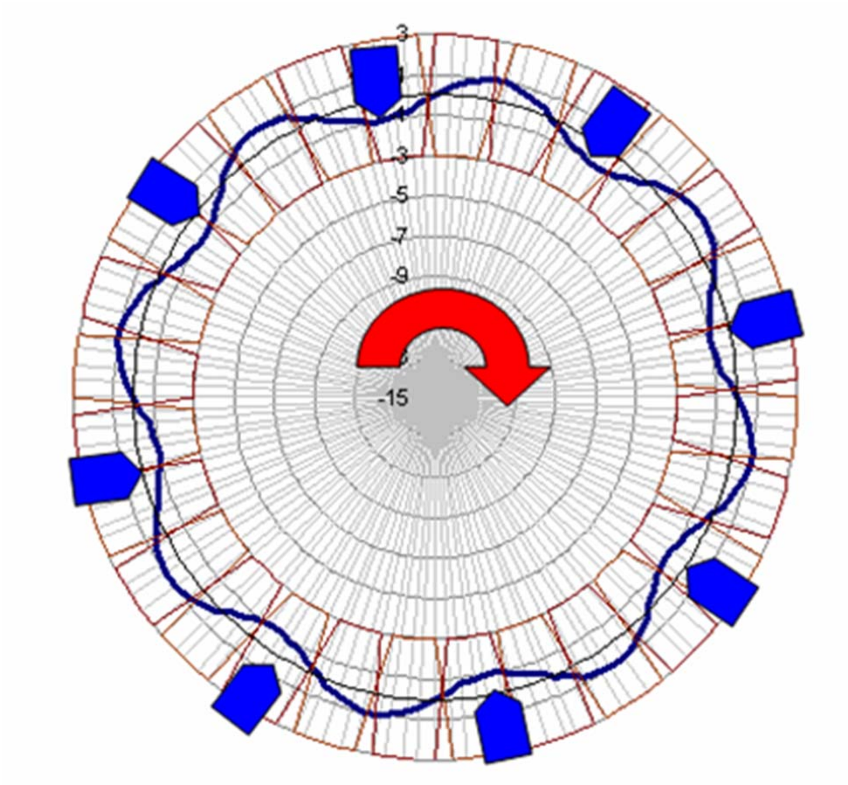


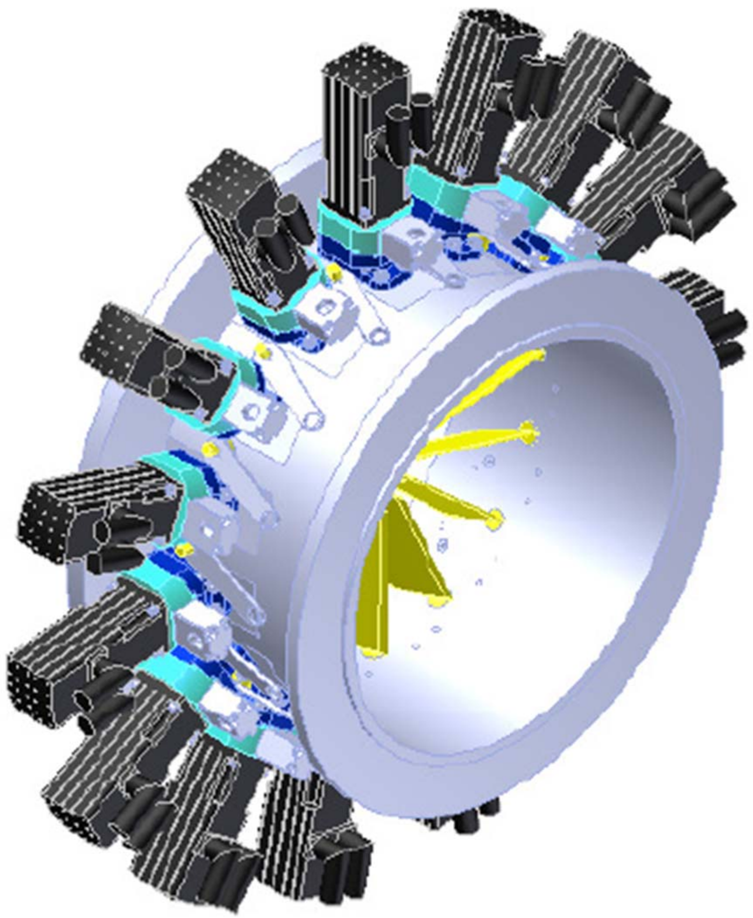
- Steady aero (probes, rakes)
- Blade tip timing
- Blade-mounted Kulites
- Wall-mounted Kulites
- Blade excitation system

Transonic compressor rig at TUD Darmstadt, Germany

FUTURE Compressor Excitation System



Rotating excitation pattern (ND)



Air jet exciter ring

FUTURE Results and Findings

- Results and findings from the FUTURE project have among others been (and will be) published at the following events:

  - ISUAAAT 2009, 2012
  - IFASD 2011
  - Aero Days 2011
  - ETC 2011, 2013
  - AIAA Symposium 2013
  - ASME TE 2014

Summary

- A brief introduction into aeroelasticity of turbomachines with the focus on flutter has been given
  - In order to predict flutter, the aerodynamic and the structural damping needs to be assessed for a variety of modes
- By means of a blind test case, it has been demonstrated that the accuracy of predicting aerodynamic damping in turbomachines is not within single digits %
  - Validation of flutter prediction codes on new and relevant test cases is therefore of great importance
  - Acquiring relevant test data is extremely challenging
- Having accurate and reliable flutter prediction tools opens up for exploring the greening potential of next generations of turbomachines

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Thank you for your attention