Detecting damage via aerodynamic quantities on an aeroelastic structure

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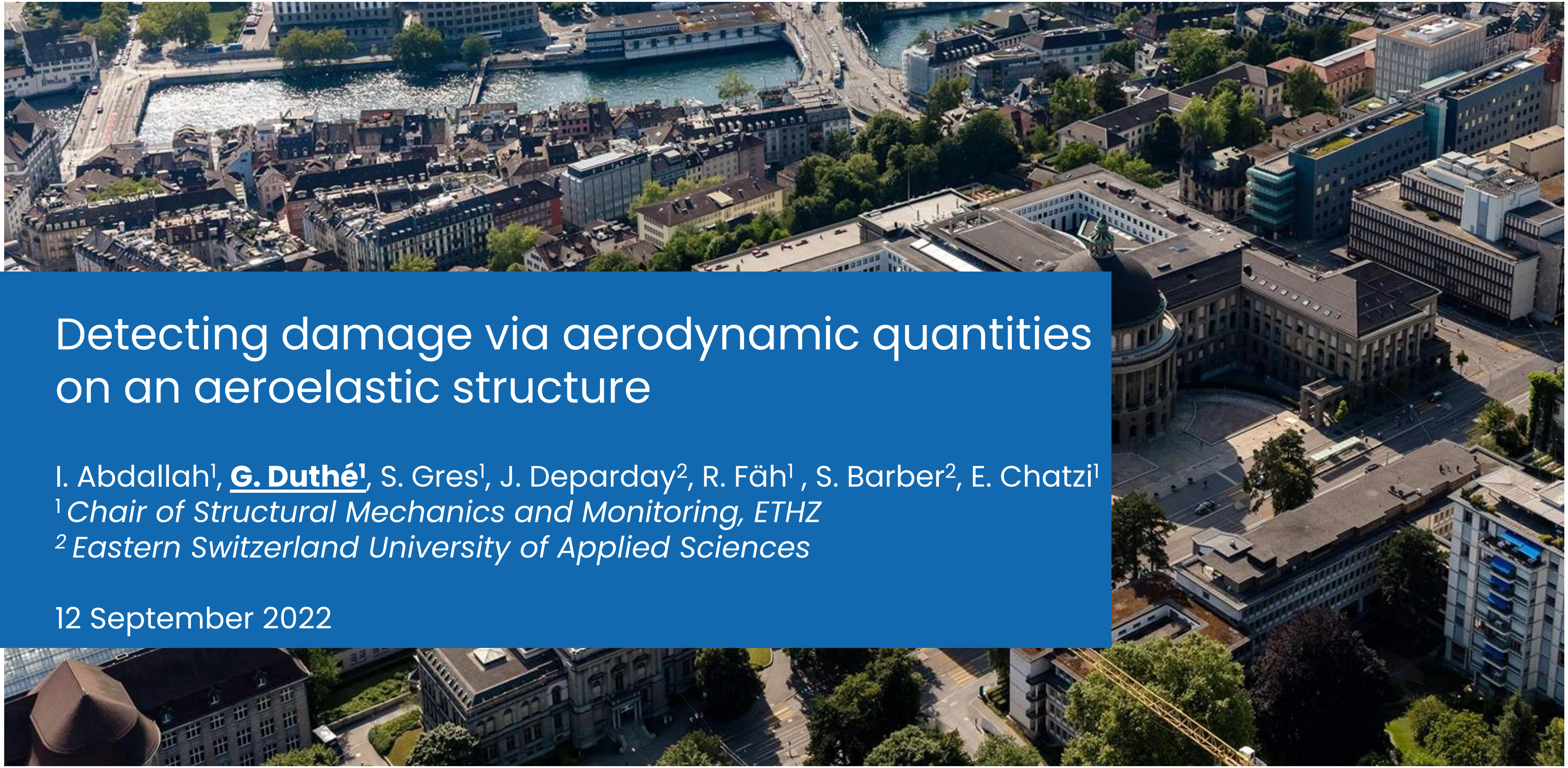
187087 - AeroSense: a novel MEMS-based surface pressure and acoustic IoT measurement system for wind turbines (SNF)

ETH zürich

Institute of Structural Engineering



Detecting damage via aerodynamic quantities on an aeroelastic structure

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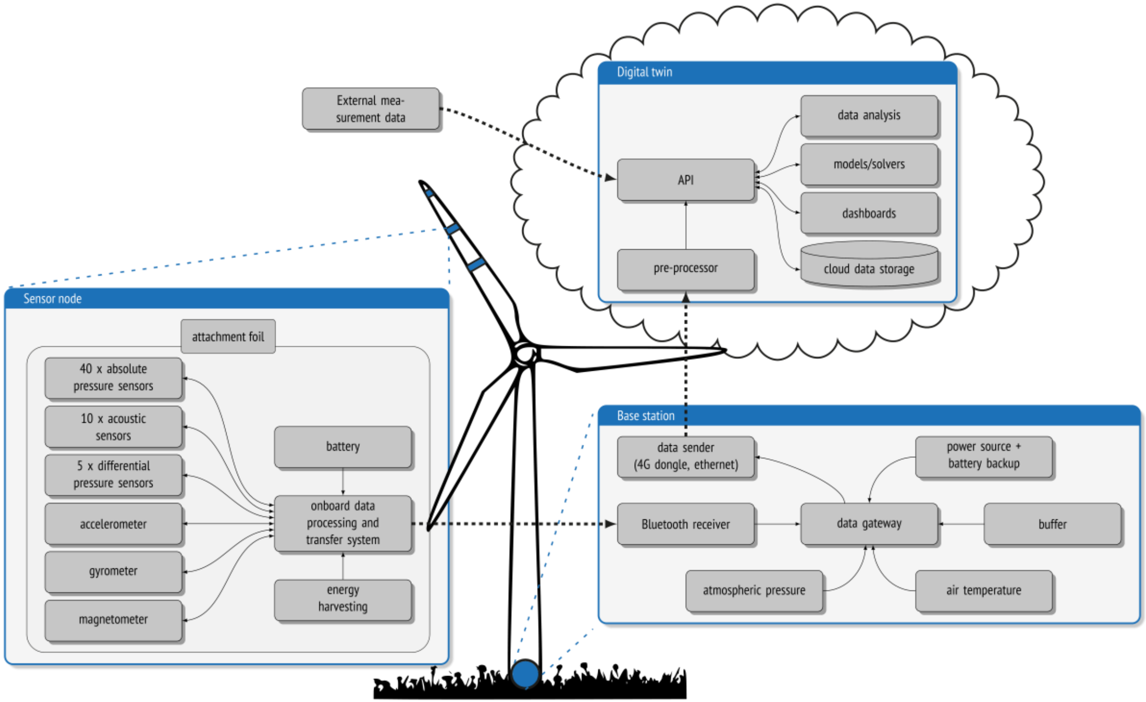
12 September 2022

Agenda

1. Problem statement and background
2. Methods: how to detect damage from aerodynamic pressure?
3. Wind tunnel tests & results
4. Numerical aero-elastic model & results
5. Unsteady 2D FSI of a heaving/twisting airfoil

Background: Aerosense research project

Project goal: develop a MEMS-based surface pressure and acoustic smart measurement system for wind turbine blades.



Use cases:

- **Operators**: blade surface/structural damage detection, and performance optimization.
- **OEMs:** Improve aero-acoustic design tools & 3D field aerodynamics.

Scope:

- 3 years May 2020 – April 2023
- Funding from SNF/Innouisse BRIDGE programme

Partners:

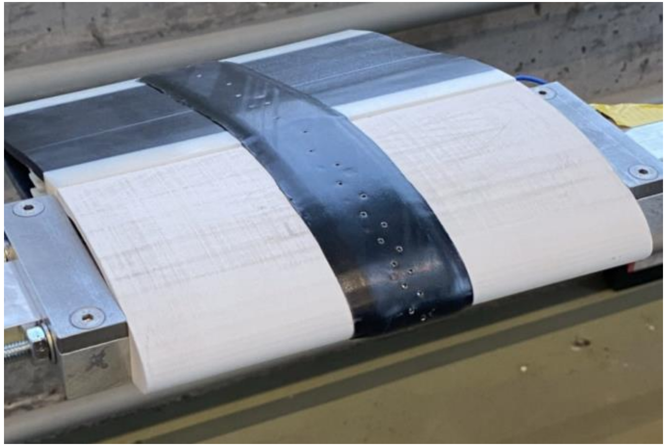
- Eastern Switzerland University of Applied Sciences
- ETH Zurich, Chair of Structural Mechanics and Monitoring
- ETH Zurich, Center for Project-Based Learning
- Octue (UK)

Advisory Board:

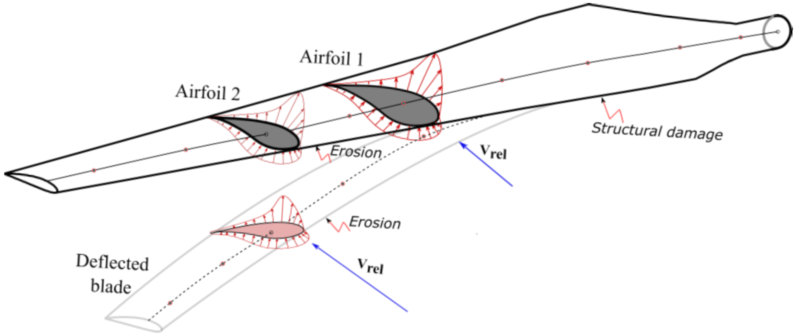
- RES, EKZ Renewables, Enercon, GE (LM), Brüel&Kjaer, Fraunhofer IWES, ECN, DTU, TU Delft.

Problem

Research question:
Can sectional aerodynamic pressure over an airfoil be used to detect structural damage, e.g. _cracks_, on an aeroelastic structure, e.g. _wind turbine blade_?



Classical approaches:
Use vibration and/or strain-based methods for damage detection



Methods

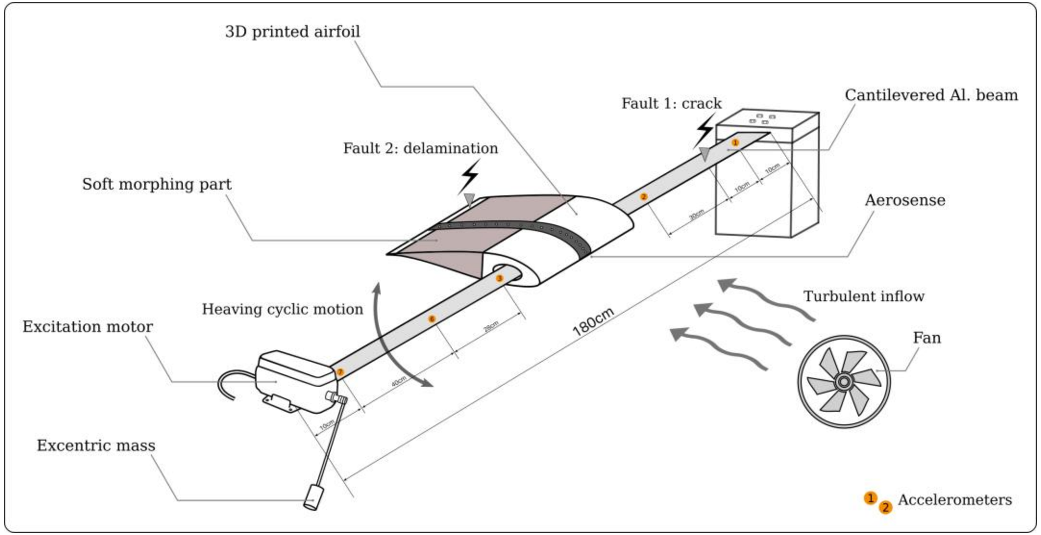
Various exploratory physical and numerical experimentation to answer the research question:

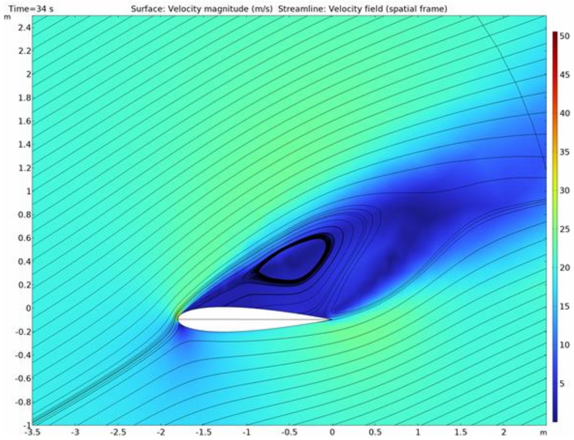
1. "ad-hoc" Wind tunnel experiments
   i. *Classical damage detection via vibration time series*
   ii. *Spectral-POD of aerodynamic pressure time series*

2. Numerical aero-elastic model: time marching linear beam elements FEM coupled to an aerodynamic model

3. Unsteady 2D FSI in COMSOL

Schematic of the experimental setup

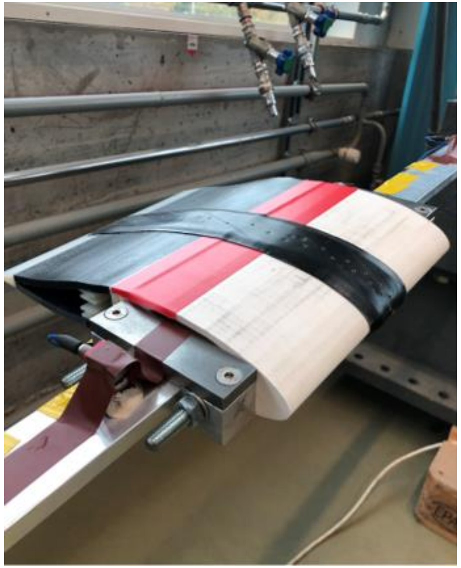


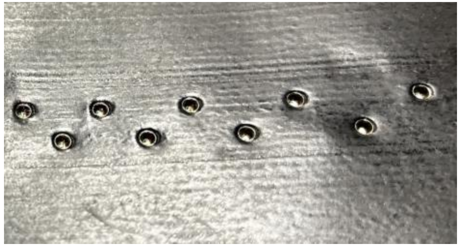
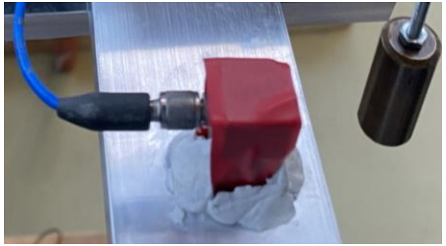


“Wind tunnel” experiments

Setup:
- 1.8m Long slender Aluminium beam
- A 3D printed airfoil section
- Rotating imbalanced mass at the tip for period load input
- A fan is used in front of the setup as a source of wind loading
- Damage is introduced on both the beam and the 3D printed airfoil section

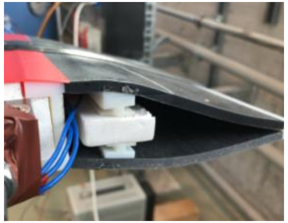
Measurements:
- 40 barometers sampled at 100Hz
- 5 x 1D PCB Accelerometers distributed along the span of the blade (2kHz)

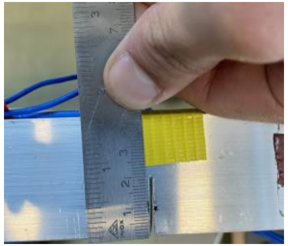


“Wind tunnel” experiments

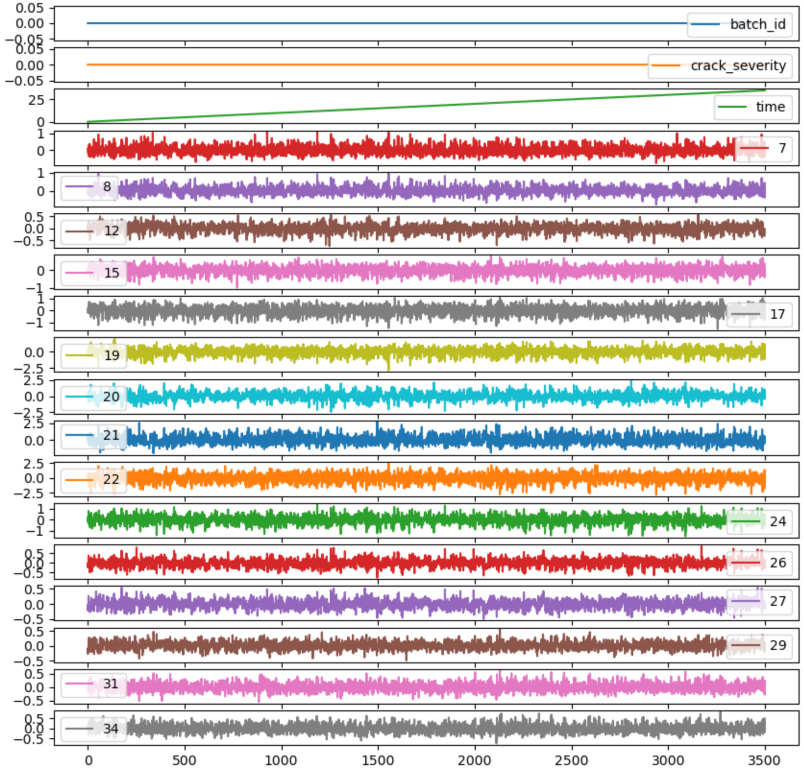
Experiment id	Heaving freq. [Hz]	Mean wind speed [m/s]	Health state
1	1.5	13	Healthy
2	1.5	13	Healthy
3	1.5	13	Beam not cracked, airfoil morphed
4	1.5	13	Beam not cracked, airfoil morphed
5	1.5	13	5mm beam crack
6	1.5	13	5mm beam crack
7	1.5	13	15mm beam crack
8	1.5	13	15mm beam crack, airfoil TE cracked
9	1.5	13	15mm beam crack, airfoil TE cracked
10	1.5	13	20mm beam crack, airfoil TE cracked





Experiments: aerodynamic pressure signals

Raw pressure signals from select baros



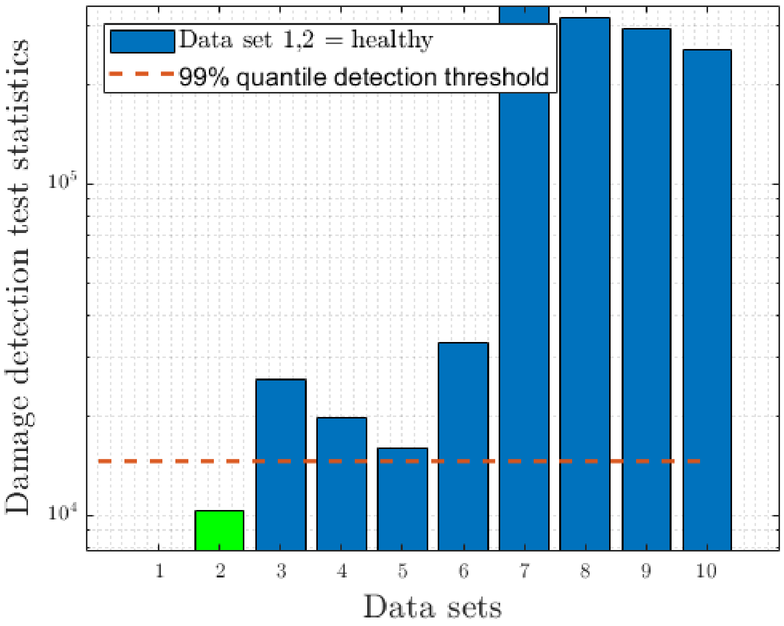
Experiments: Vibration based damage detection

Method

Hankel matrix normalization for damage detection robust (invariant) to excitation changes.

Damage detection residual is achieved using the difference of the Hankel matrices in the reference state and the excitation normalized Hankel matrix in the tested, potentially damaged state.

For the decision about the condition of the system, the proposed residual is evaluated in a hypothesis test, which follows a χ^2 distribution.



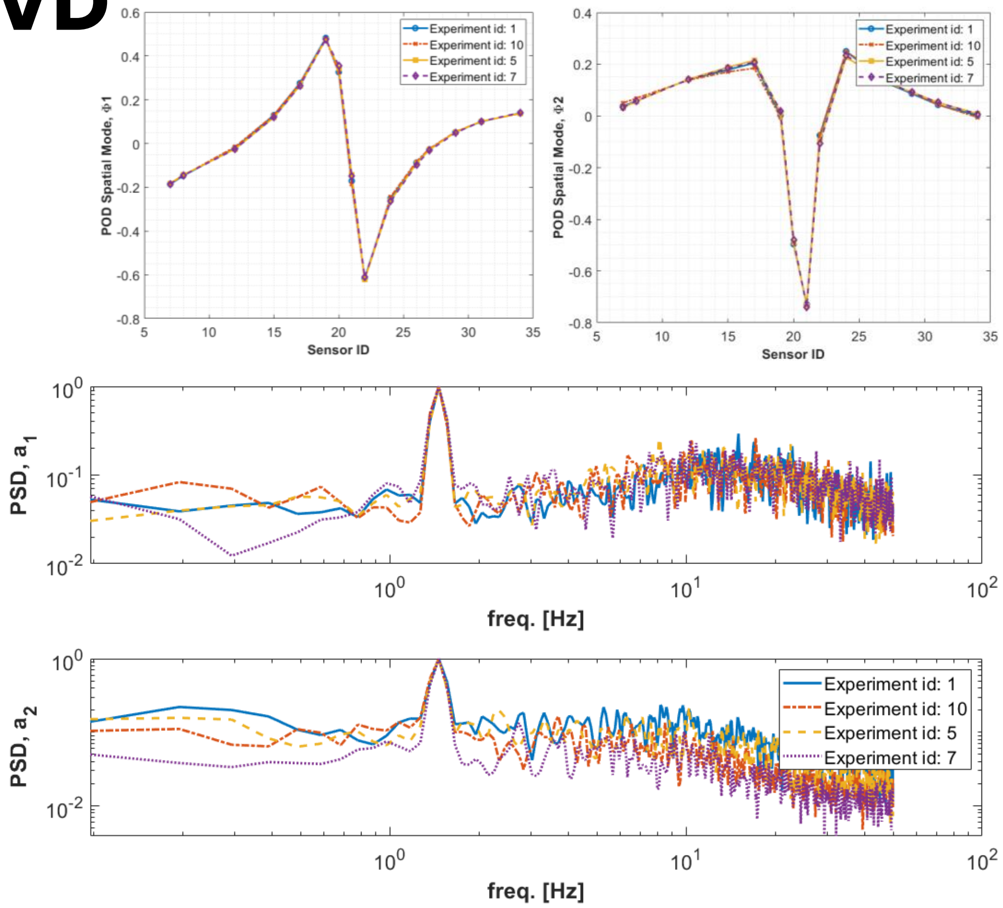
S. Greś, K.E. Tatsis, V. Dertimanis, E. Chatzi, *Hankel matrix-based Denoising for Statistical Damage Diagnosis,* Proceedings of IOMAC 2022

Experiments: POD/SVD of aero pressure

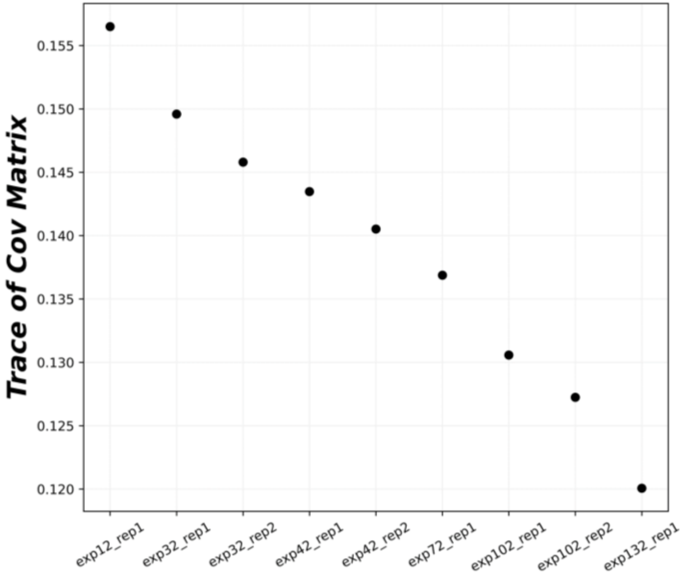
POD Decomposes the pressure snapshots as follows:

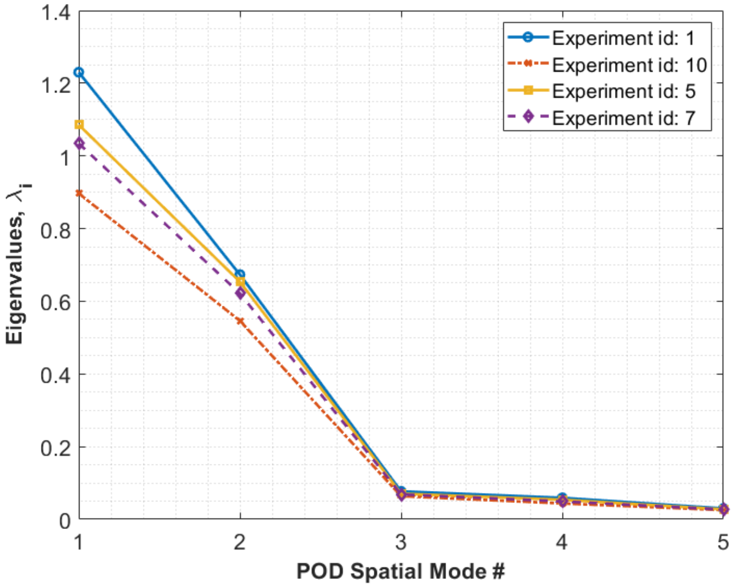
$$u(x,t) = \sum_{i=1}^{N_m} \Phi_i(x) a_i(t)$$

No effects were observed on the spatial modes nor temporal modes as structural damage progresses!!



Experiments: POD/SVD of aero pressure





- Trace of the pressure measurements covariance matrix & Eigenvalues drop as the size of the crack increases.
- Drop in Trace & Eigenvalues indicates a drop in the total variation amongst the pressure signals as the damage severity increases.

Experiments: discussion

- More repetitions per damage class to draw statistically significant conclusions.

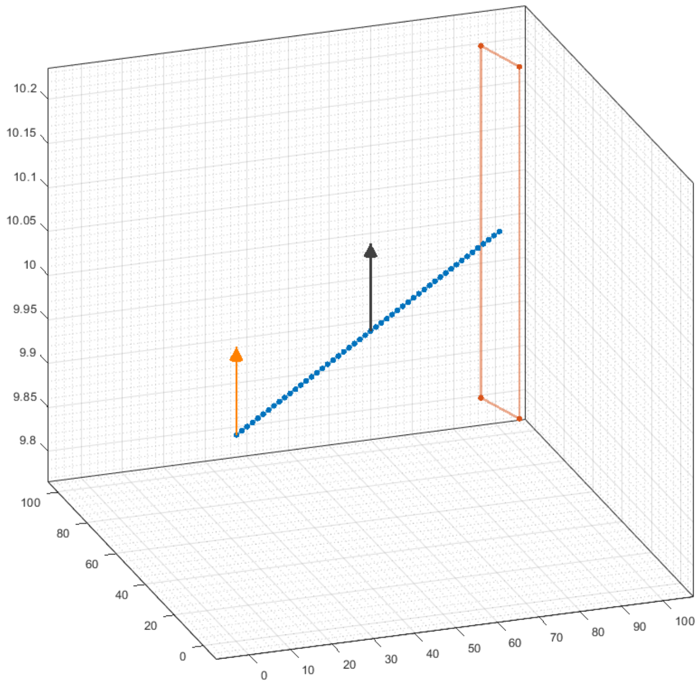
- Possible sources of errors:
  - X Change in the input load conditions, i.e. not repeatable
  - X Change in the ambient conditions during the experiment
  - X Drift in the Aerosense Baros measurements
  - X Drift in the experimental setup:
    - *e.g. Clamping of beam getting loose over time*
    - *e.g. Changed "something" in the setup as we introduced the cracks*

- New and improved experimental setup

Numerical aero-elastic model

Model:

- Numerical model representation of the experimental setup
- Linear beam FEM, coupled to an unsteady BEM aerodynamic model (+dynamic stall).
- Newmark integration scheme for linear time invariant system to solve the system of equations.
- Continuous mass and stiff., in addition to lumped mass at the tip and mid-section.



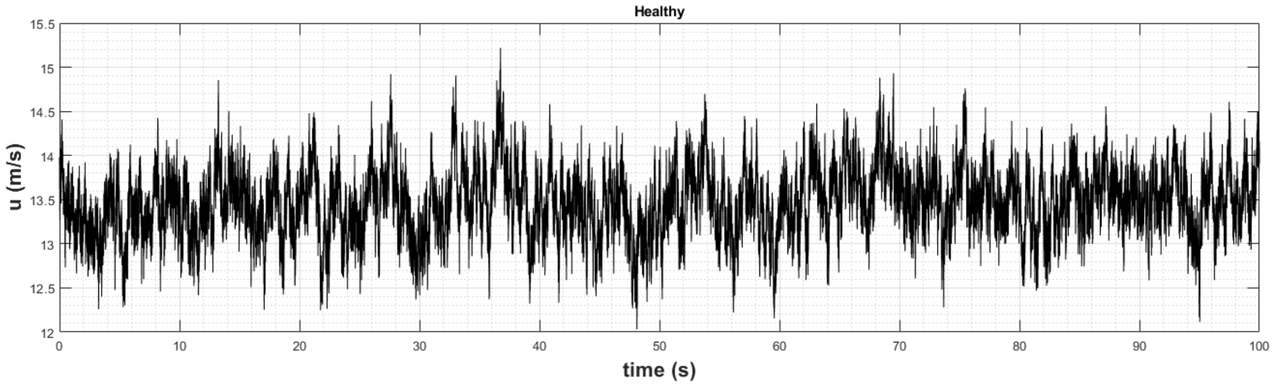
Objectives:

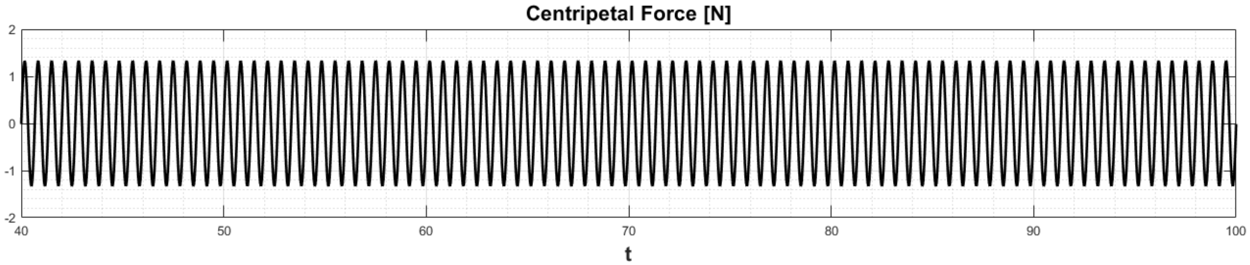
1. Perform numerical experiments: observe the aerodynamic data as the damage severity is increased.
2. Damage severity → {Healthy, 15%, 35%, 50%} reduction in beam root stiffness.

Numerical aero-elastic model

Model input time series

Wind speed, periodic centrifugal forces

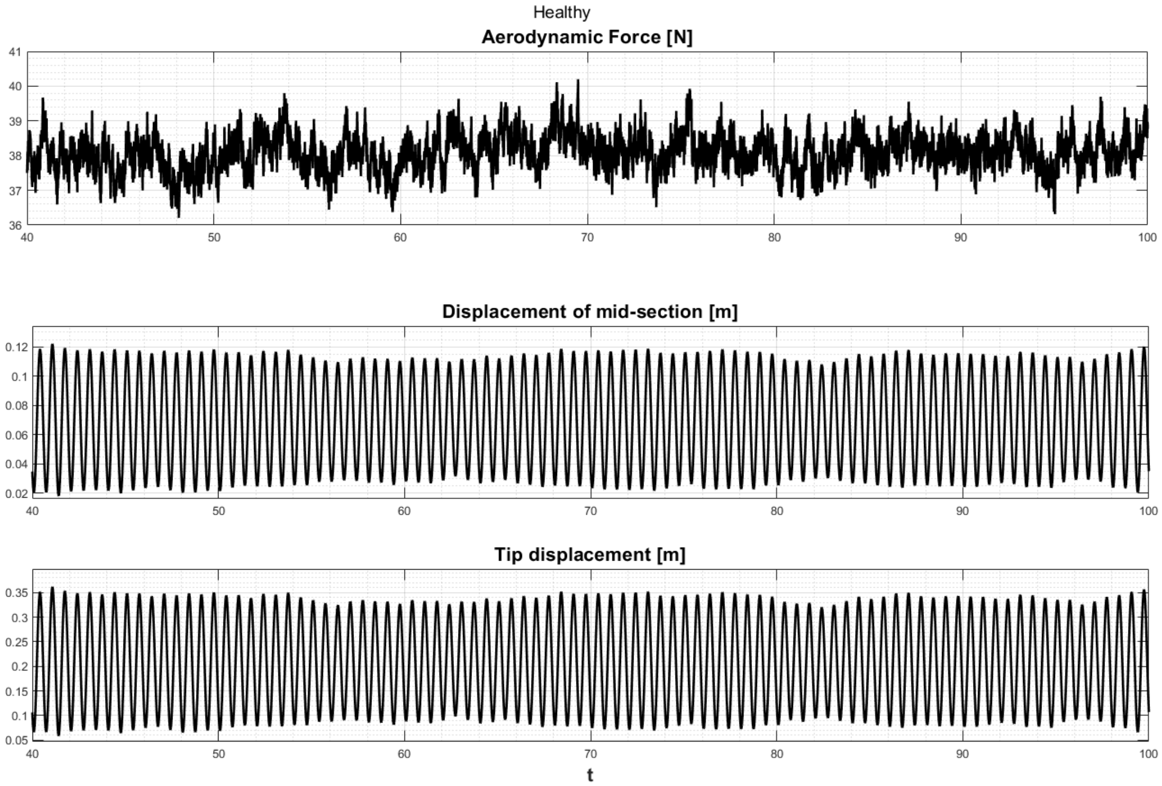




Numerical aero-elastic model

Model output time series

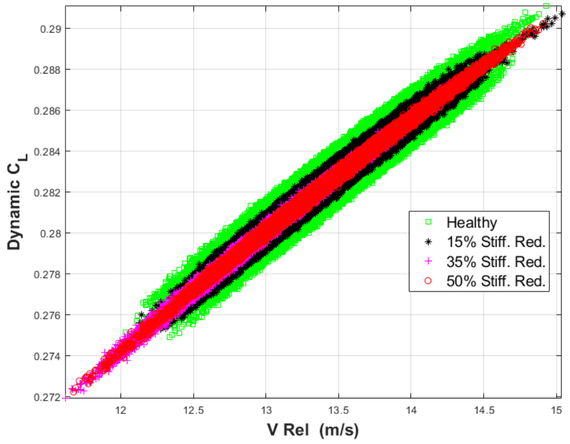
aerodynamic force,
beam mid-section and
tip displacement

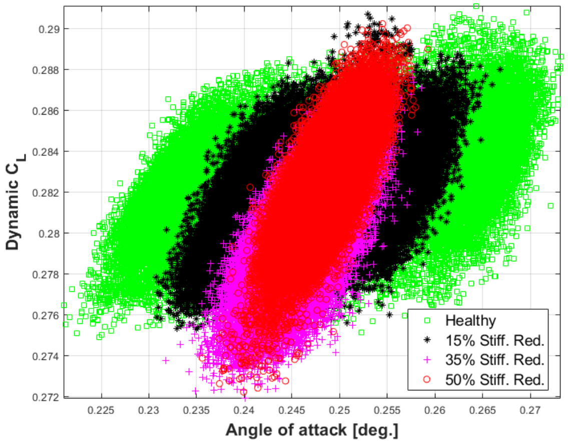


Numerical aero-elastic model

Dynamic lift vs angle of attack or relative wind speed at the airfoil section

With increasing damage magnitude, we observe a reduction in the CL scatter/range.





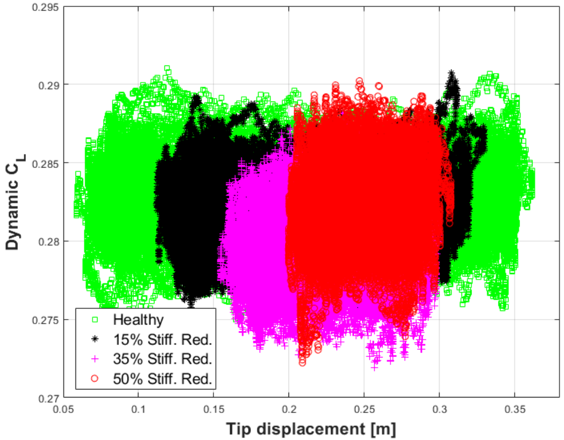
Numerical aero-elastic model

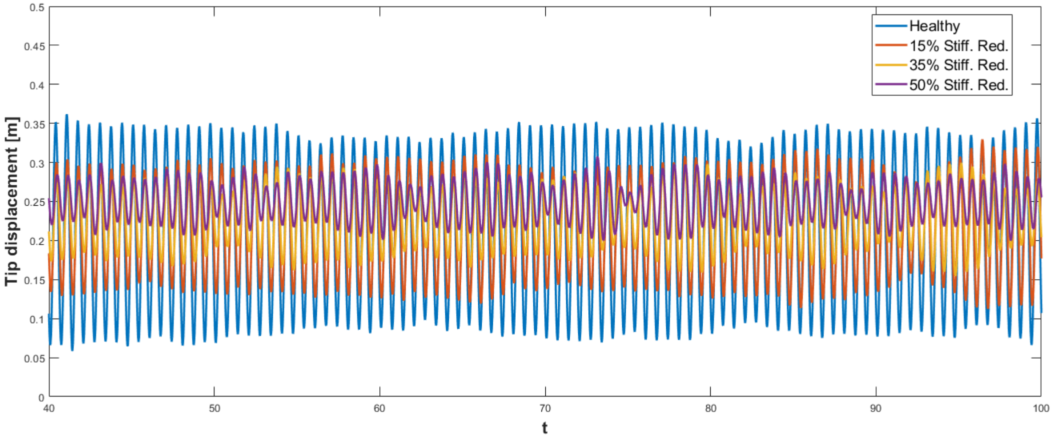
Dynamic lift vs displacements

With increasing crack size (lower stiffness) in the beam root, we see a reduction in the mid and tip section displacements scatter/range.

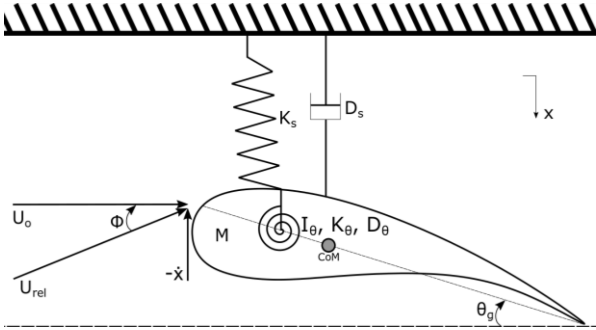
Interpretation

Positive z-axis points down →Higher stiffness reduction (larger crack) results in the beam sagging further under its own static weight, resulting in higher mean displacement but lower displacement scatter/range.





Unsteady 2D FSI in COMSOL



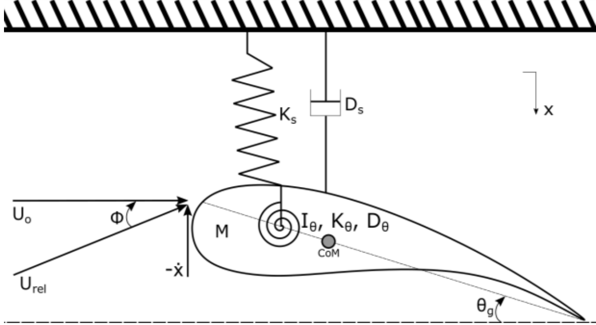
Model:

- Fully coupled FSI model of a heaving and pitching 2D airfoil section
- URANS
- $K - \omega - SST$ turbulence model

Objectives:

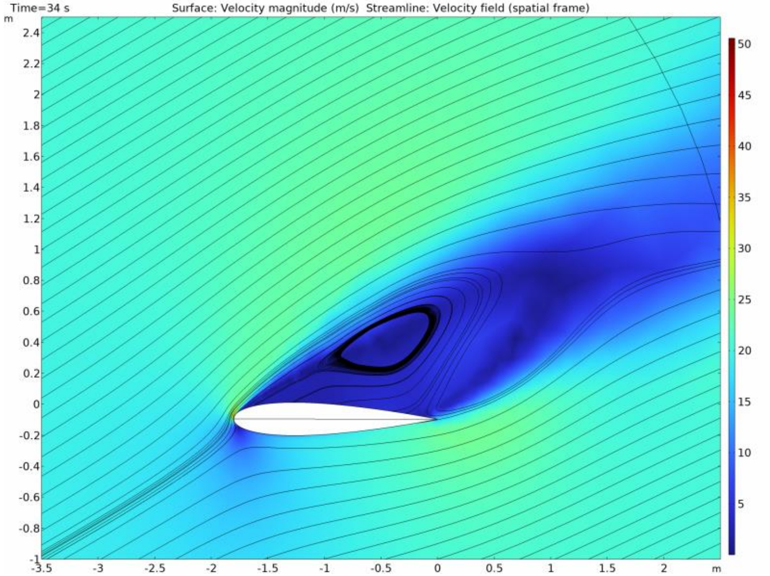
1. Perform numerical experiments: observe the aerodynamic data as the damage severity is increased.
2. Damage severity → {Healthy, 5%} reduction in heaving and pitching stiffness.

2D FSI in Comsol

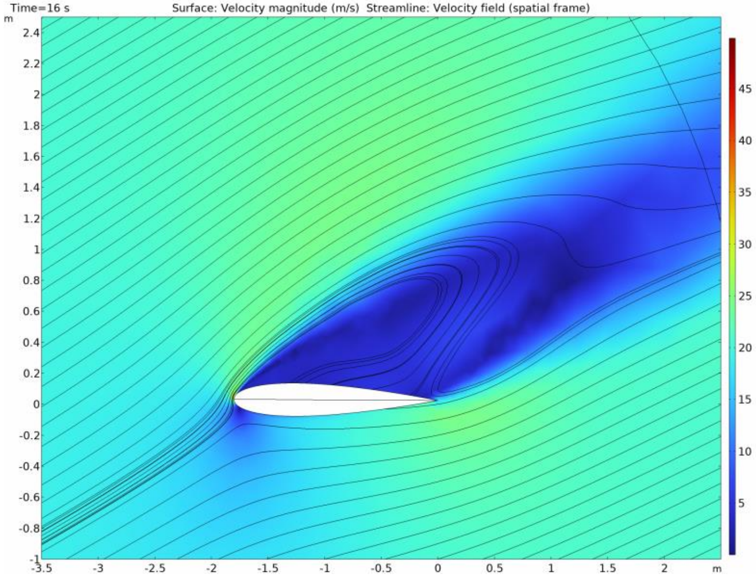


(Healthy)

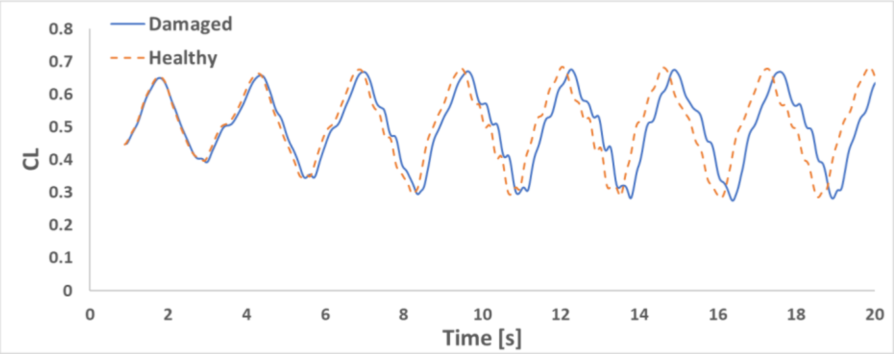
M=70kg, Ks = 578N/m

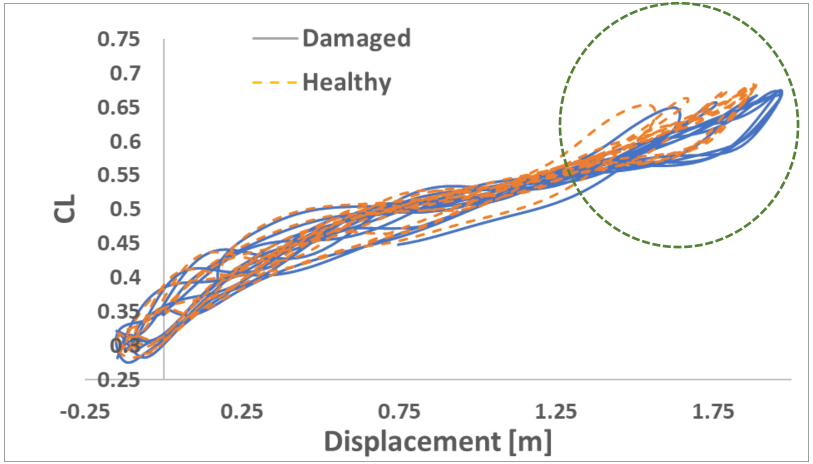


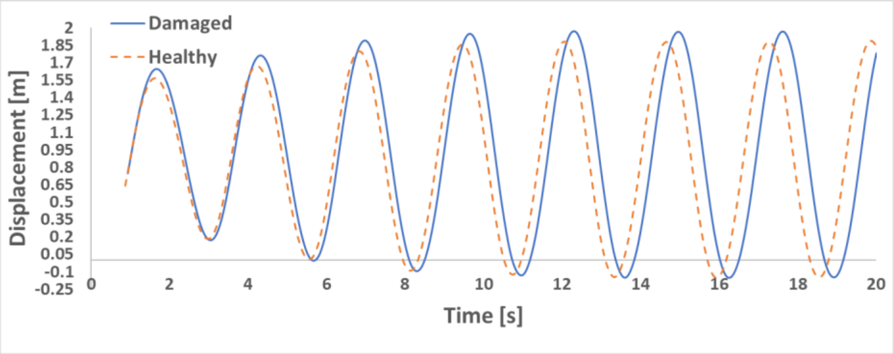
M=70kg, Ks = 550N/m

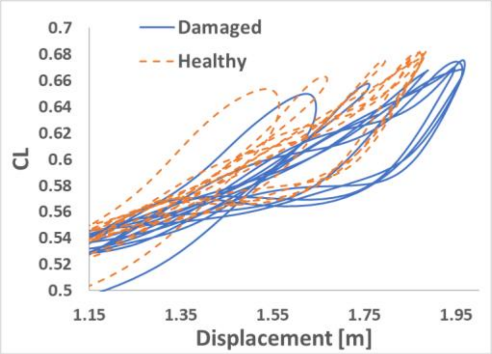


2D FSI in Comsol









Shallower hysteresis in healthy state

Conclusions and outlook

Research question:
Can sectional aerodynamic pressure over an airfoil be used to detect structural damage on an aeroelastic structure?

Various exploratory physical experimentation and numerical modeling

1. Wind tunnel experiments
2. Numerical aero-elastic model
3. Unsteady 2D FSI in COMSOL

Improvements
Optimize barometers selection for inference

Add more physics to the aeroelastic and FSI models

Develop further analysis methods based on POD, DMD or NNM-VAE

Initial results indicate that we can detect structural damage from aerodynamic pressure!

Acknowledgements

BRIDGE Discovery Program of the Swiss National Science Foundation and Innosuisse, project number 40B2 - 0 187087

FNSNF BRIDGE

Innosuisse

Research partners:

OST

CENTER FOR PROJECT-BASED LEARNING

Octue

Aventa AG

Appendix: outlook of analysis methods

- Nonlinear normal modes (with VAE) for damage detection, DOI: 10.1007/s11012-016-0453-8

- Modal decomposition approaches:
  - ❑ Proper Orthogonal Decomposition (POD)
  - ❑ Balanced POD

- Dynamic Mode Decomposition (DMD)
- Physics informed Dynamic Mode Decomposition (DMD):
  - ❑ https://youtu.be/lx-msllg1kU
  - ❑ https://github.com/baddoo/piDMD

- CAE-DMD:
  - ❑ https://github.com/Israr-r/CAE-DMD
  - ❑ https://www.sciencedirect.com/science/article/pii/S107731422100182X

- Aero damping and Xdot-CL phase delay as damage propagates, DOI: 10.1016/j.jfluidstructs.2020.103111

- Vinuesa, R., Brunton, S.L. Enhancing computational fluid dynamics with machine learning. *Nat Comput Sci* **2**, 358–366 (2022):
  - ❑ https://doi.org/10.1038/s43588-022-00264-7
  - ❑ https://youtu.be/i-_1RY6EBI0

- CNN-based autoencoders for modal decomposition: https://www.sciencedirect.com/science/article/pii/S0957417422004535