DLRK 2022

Active vibration suppression of wind tunnel models using piezoelectric materials

Anna Altkuckatz

DLRK 2022
DEUTSCHER LUFT- UND RAUMFAHRTKONGRESS
27. - 29. SEPTEMBER 2022 – DRESDEN
„Luft- und Raumfahrt - gemeinsam forschen und nachhaltig gestalten"
DGLR
FH AACHEN UNIVERSITY OF APPLIED SCIENCES
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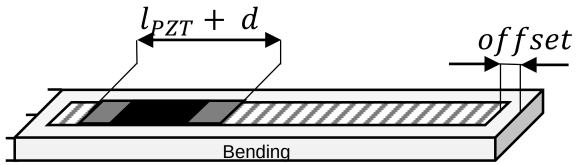
Institute of
Aeroelasticity

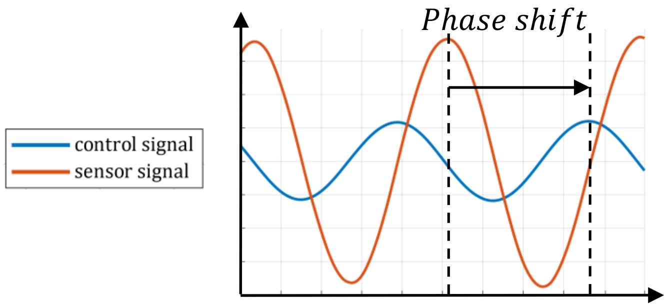
Investigation goals

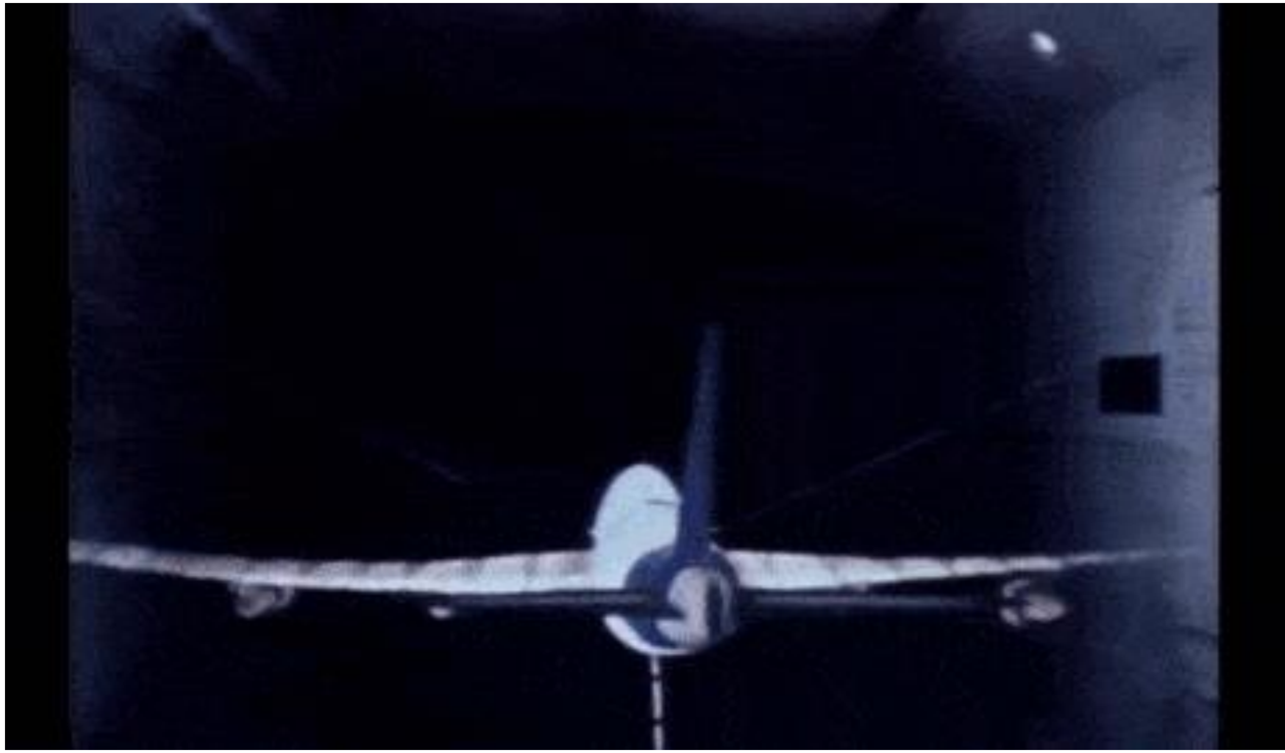
Is it possible to damp vibrations due to flutter with PZTs?

What is the optimal position & size of the PZTs?



Which control signal is required?





https://personal.lse.ac.uk/ROBERT49/ebooks/PhilSciAdventures/lecture12.html

Agenda

- Investigation goals
- Foundations
- Methodology
- Validation of the methodology
- Application of the methodology
- Summary and Future application ideas

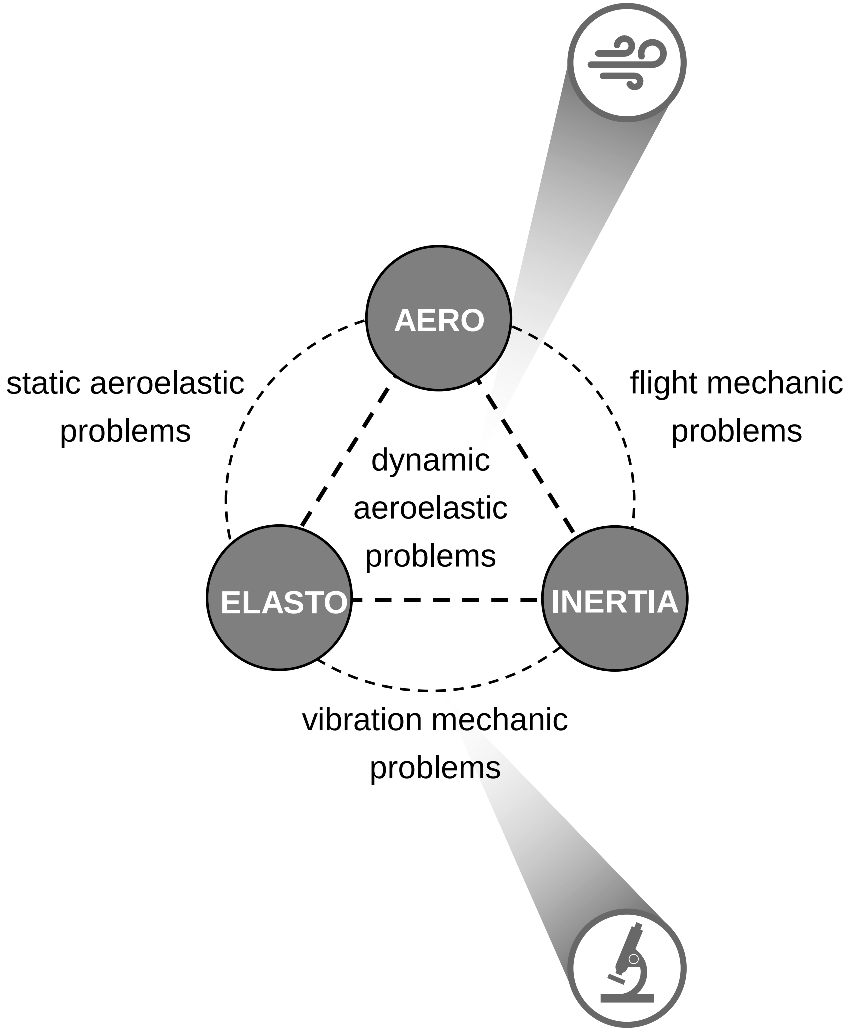
Agenda

Foundations

Aeroelasitc problem

- Aeroelastic triangle of forces

Application of the methodology



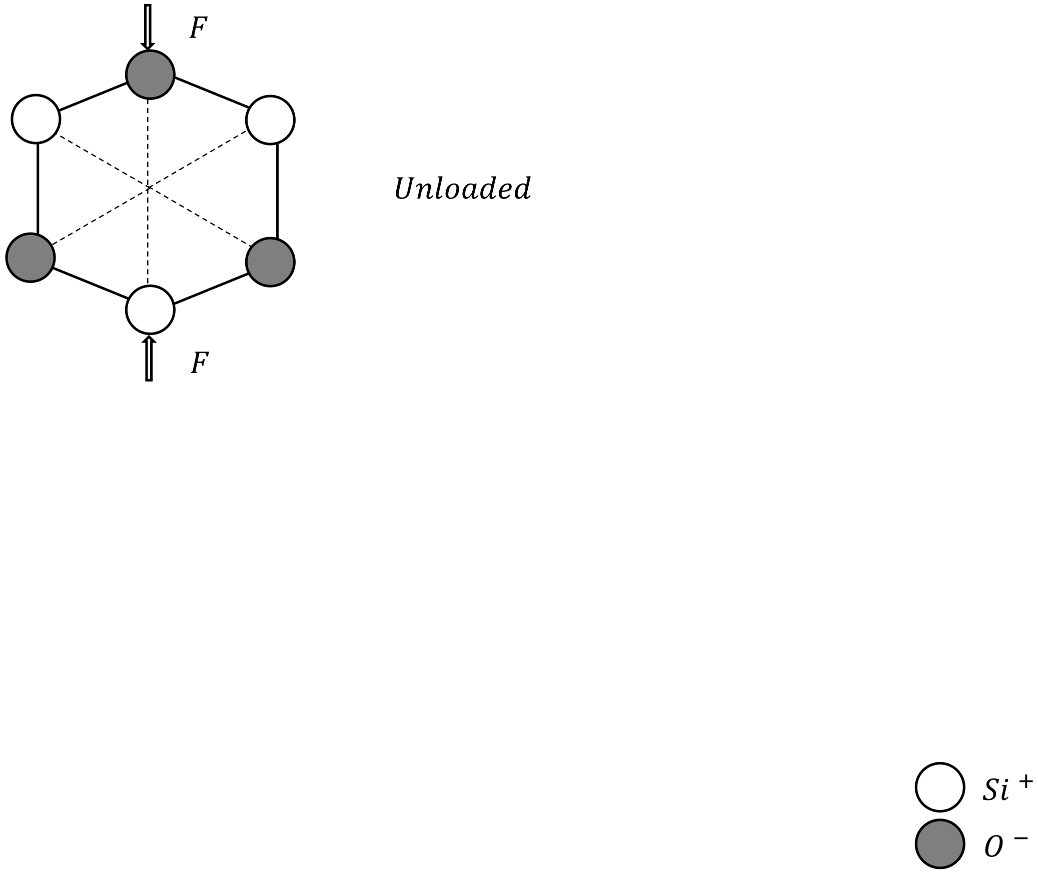
Validation of the methodology

Foundations

Aeroelasitc problem

- Aeroelastic triangle of forces

Piezoelectric materials



Foundations

Aeroelasitc problem

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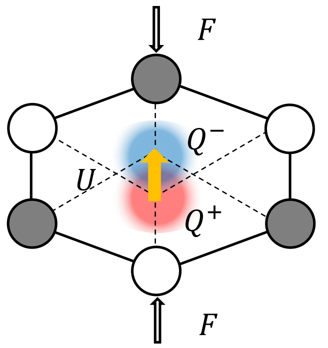
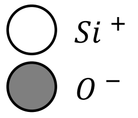


Pressure load



Foundations

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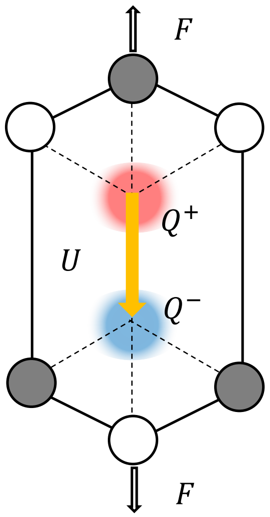
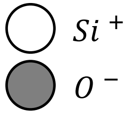
- Aeroelastic triangle of forces

Piezoelectric materials



Tensile load

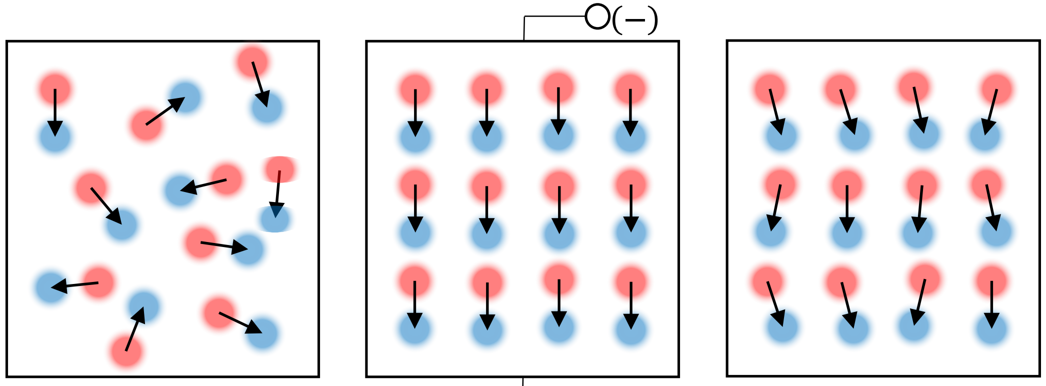


Foundations

Aeroelasitc problem

- Aeroelastic triangle of forces

Piezoelectric materials



$(a)\ Nonpolarity$ $(b)\ while\ Poling$ $(c)\ after\ Poling$

Si^{+}

O^{-}

Foundations

Aeroelasitc problem

- Aeroelastic triangle of forces

Piezoelectric materials

- Direct piezoelectric effect
- Inverse piezoelectric effect

Direct piezoelectric effect:
Sensor

$$P = d * T = e * S$$

Inverse piezoelectric effect:
Actuator

$$S = d * E$$

$P \coloneqq polarisation$
$d, e \coloneqq piezoelectric\ coefficients$
$T \coloneqq mechanical\ stress$
$E \coloneqq electric\ field\ strength$
$S \coloneqq deformation$

Foundations

Aeroelasitc problem

- Aeroelastic triangle of forces

Piezoelectric materials

- Direct piezoelectric effect
- Inverse piezoelectric effect
- Coupled equations

$$P = d * T = e * S$$

$$S = d * E$$

→

$$S = s^E * T + d^t * E$$

$$D = d * T + \epsilon * E$$

$\epsilon \coloneqq permittivity$

$s^E \coloneqq inverse\ of\ stiffness$

D $\coloneqq electric\ displacement\ field$

$superscript\ "t" \coloneqq transposition$

$P \coloneqq polarisation$

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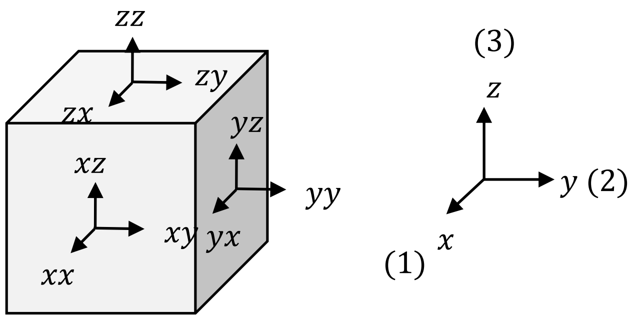
Methodology



Modelling of structure

$$S = s^E T + d^t E$$

$$D = dT + \epsilon E$$

$$\begin{Bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{Bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} & 0 & 0 & 0 \\ s_{21} & s_{22} & s_{23} & 0 & 0 & 0 \\ s_{31} & s_{32} & s_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66} \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{Bmatrix}$$

$\epsilon :=$ *permittivity*

$s^E :=$ *inverse of stiffness*

D $:=$ *electric displacement field*

superscript "t" $:=$ *transposition*

$P :=$ *polarisation*

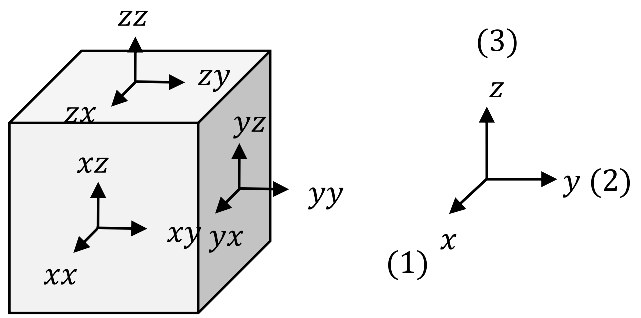
$d, e :=$ *piezoelectric coefficients*

$T :=$ *mechanical stress*

$E :=$ *electric field strength*

$S :=$ *deformation* (dimensionless)

Methodology



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$$S = s^E T + d^t E$$
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$$\begin{Bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ \hline D_1 \\ D_2 \\ D_3 \end{Bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} & 0 & 0 & 0 & 0 & 0 & d_{31} \\ s_{21} & s_{22} & s_{23} & 0 & 0 & 0 & 0 & 0 & d_{32} \\ s_{31} & s_{32} & s_{33} & 0 & 0 & 0 & 0 & 0 & d_{33} \\ 0 & 0 & 0 & s_{44} & 0 & 0 & 0 & d_{24} & 0 \\ 0 & 0 & 0 & 0 & s_{55} & 0 & d_{15} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{15} & 0 & \epsilon_{11} & 0 & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 & 0 & \epsilon_{22} & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 & 0 & 0 & \epsilon_{33} \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ \hline E_1 \\ E_2 \\ E_3 \end{Bmatrix}$$

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Methodology

Modelling of structure

$$S = s^E T + d^t E$$

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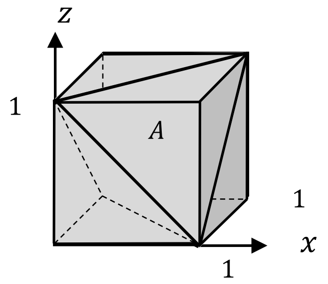
Setting up and solving PDEs



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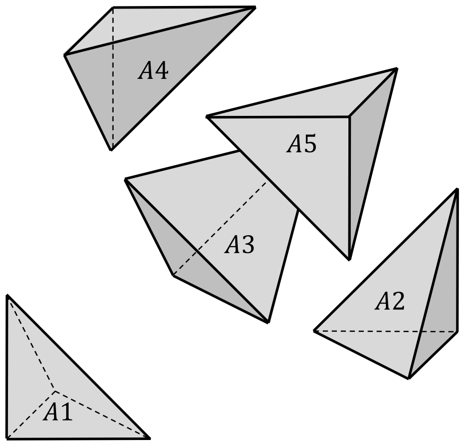

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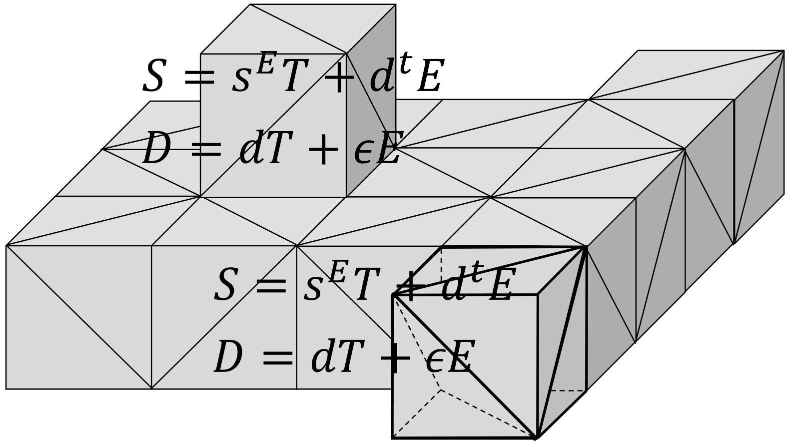

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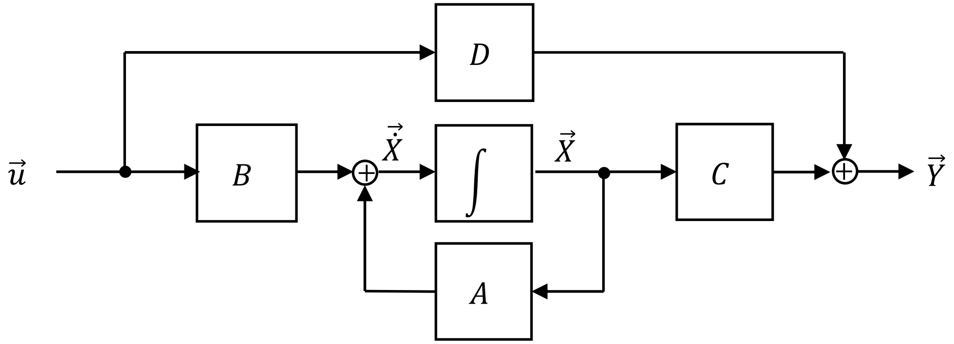
Setting up and solving PDEs

State-space representation of FEM model

$$[M]_{gen}\{\ddot{q}\} + [D]_{gen}\{\dot{q}\} + [C]_{gen}\{q\} = \{F\}_{gen} + p\{Q_{1V}\}_{gen}$$

$$\{\dot{X}\} = [A]\{X\} + [B]\{u\}$$

$$\{Y\} = [C]\{X\} + [D]\{u\}$$



$m_{ij} \coloneqq [M]_{gen} = [\phi]^t[M][\phi]$ *generalized mass matrix*
$c_{ij} \coloneqq [C]_{gen} = [\phi]^t[C][\phi]$ *generalized stiffness matrix*
$d_{ij} \coloneqq [D]_{gen} = [\phi]^t[D][\phi]$ *generalized damping matrix*
$\{F\}_{gen} = [\phi]^t\{F\}$ *generalized force vector*

Methodology

Modelling of structure

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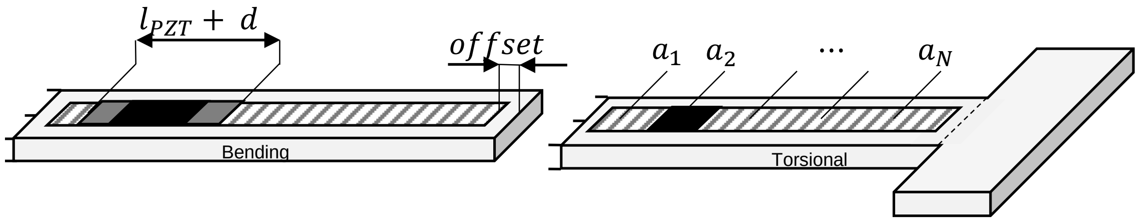
Setting up and solving PDEs

State-space representation of FEM model

Position optimization

- Two different bending beams for position optimization analysis



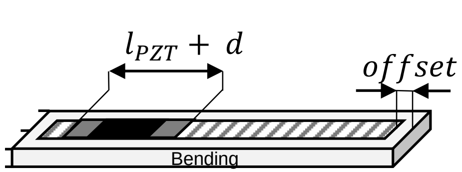
$a \coloneqq position\ PZT$

$l_{PZT} \coloneqq length\ PZT$

$d \coloneqq PZT\ growth\ rate$

$N \coloneqq number\ of\ positions$

Methodology



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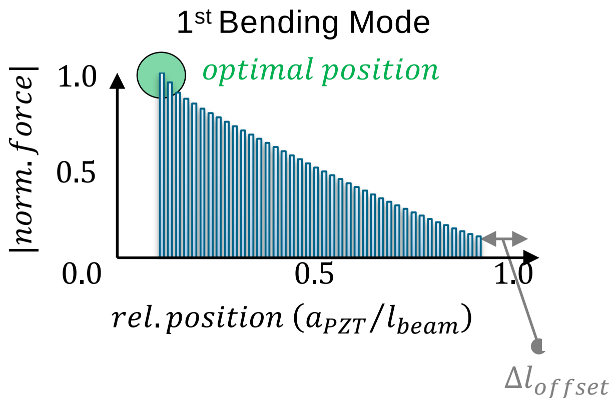


$l_{PZT_{min}} = l_{PZT}$

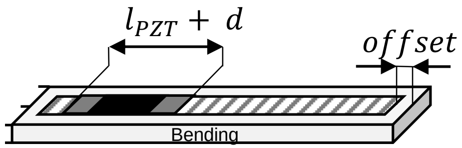
$N = 40;$

$\Delta l_{offset} = offset + \frac{l_{PZT_{min}}}{2}$

$a_{start} = \Delta l_{offset}$

$a_{end} = l_{beam} - \Delta l_{offset}$

Methodology



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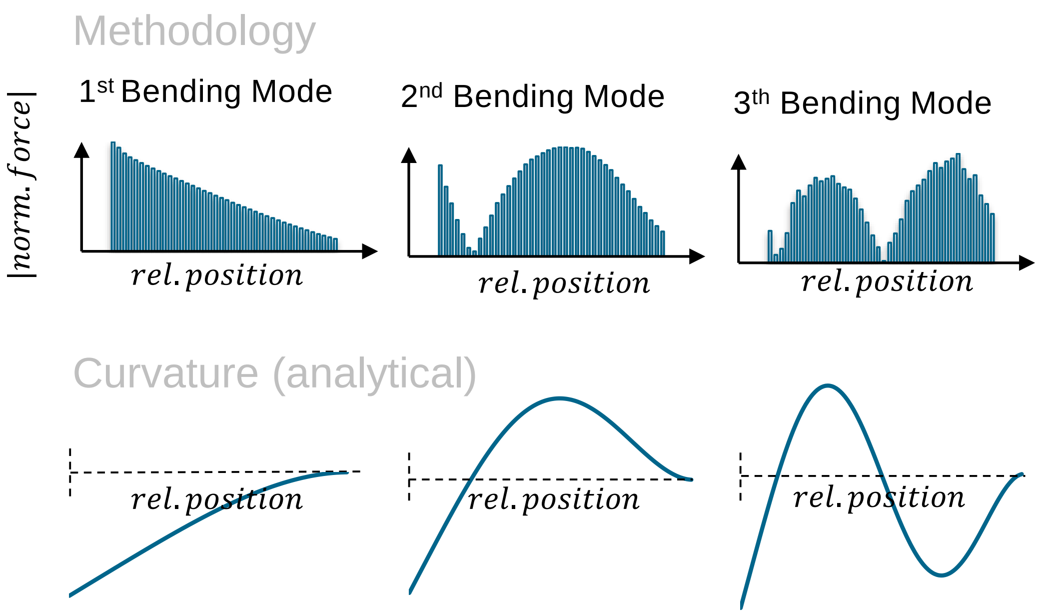

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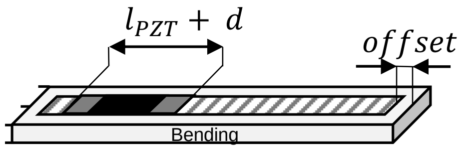

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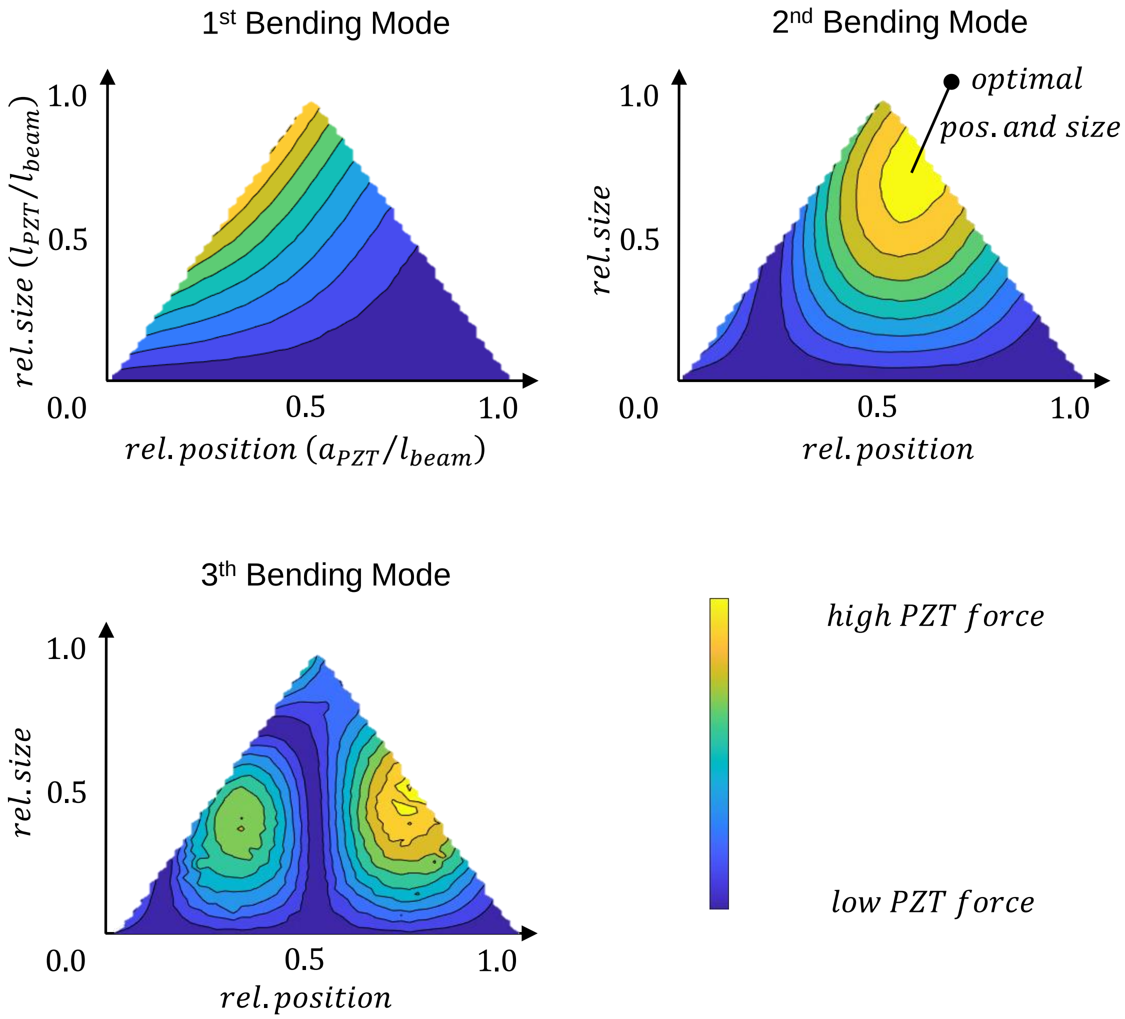

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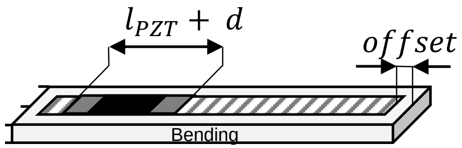

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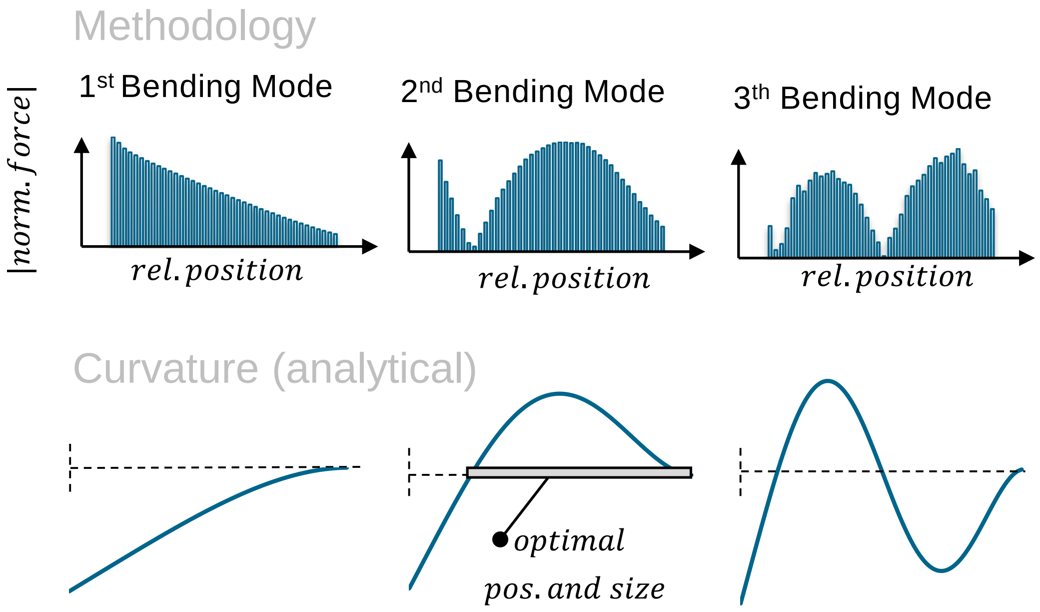

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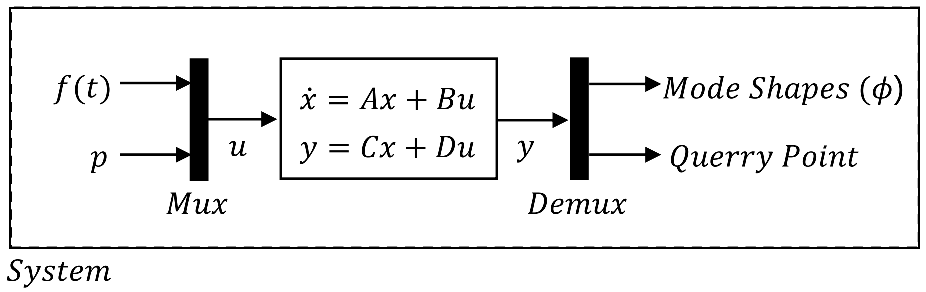
Design of control system using SIMULINK



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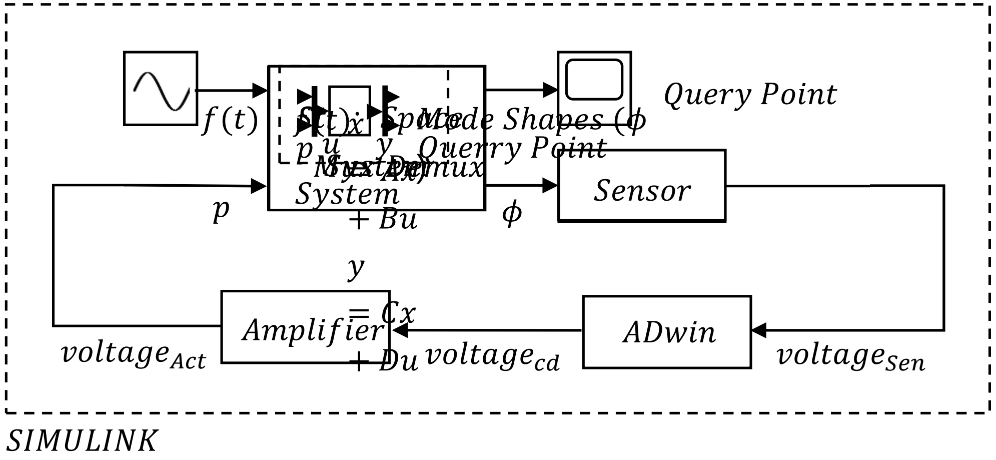

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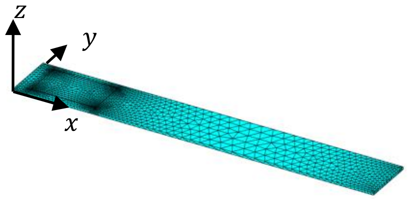
- Methodology
- **Validation of the methodology**
- Application of the methodology
- Summary and Future application ideas

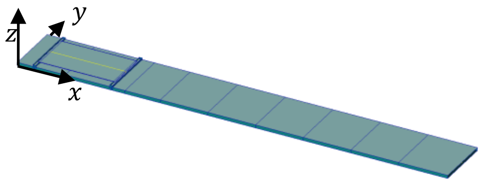
Validation of the methodology

Validation of structure

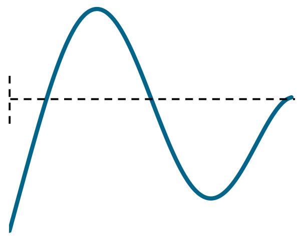
Methodology



Nastran



Analytical

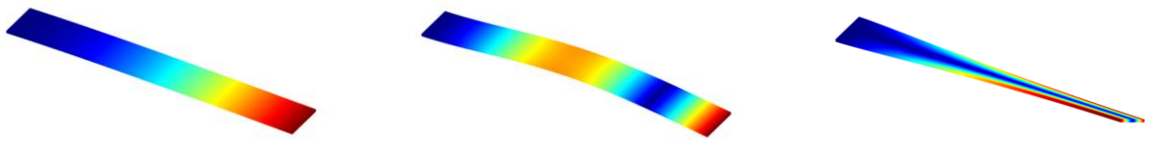


Validation of the methodology

Validation of structure

Frequency	Methodology	Nastran	Analytical
$f_{e_1}\ [Hz]$	21.50	21.73	21.00
$f_{e_2}\ [Hz]$	132.56	130.33	131.50
$f_{e_3}\ [Hz]$	290.45	–	–

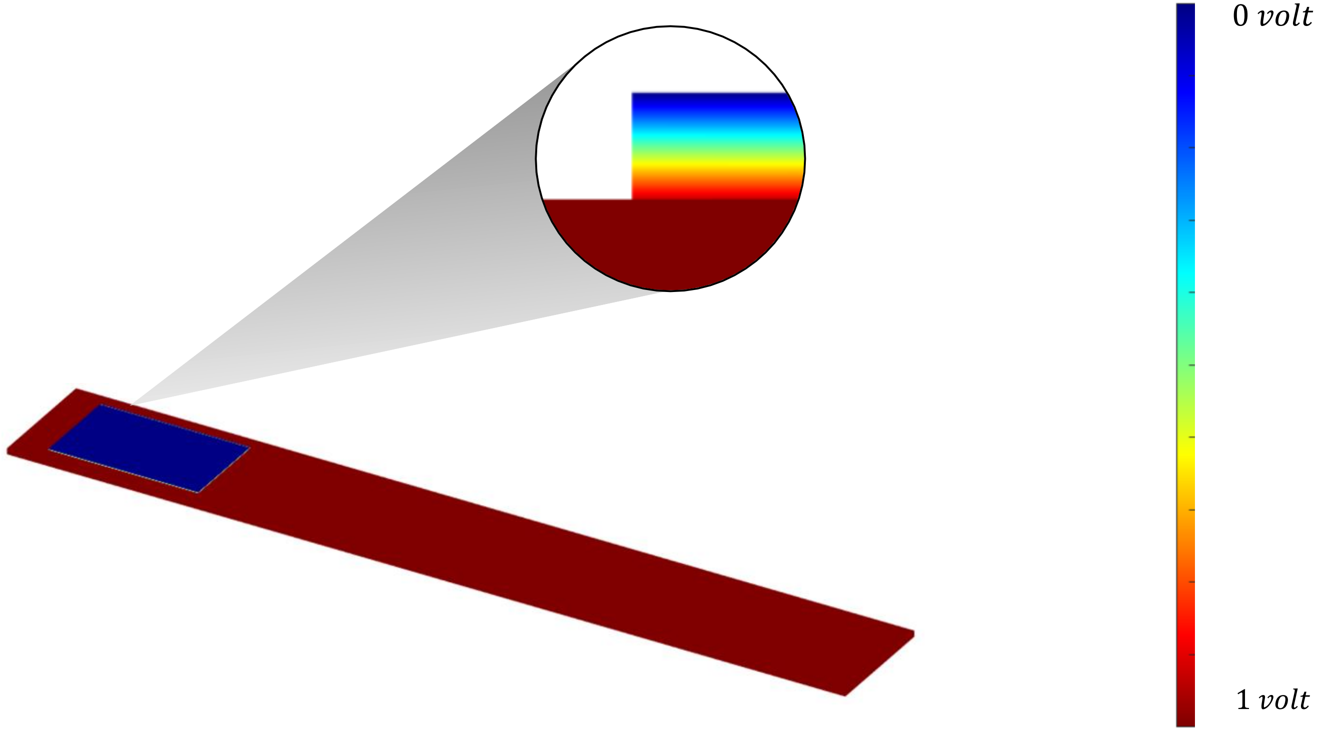
$1^{st}\,Eigenmode\ (bending)$ $2^{nd}\,Eigenmode\ (bending)$ $3^{rd}\,Eigenmode\ (torsional)$



Validation of the methodology

Validation of structure

Validation of piezo effect



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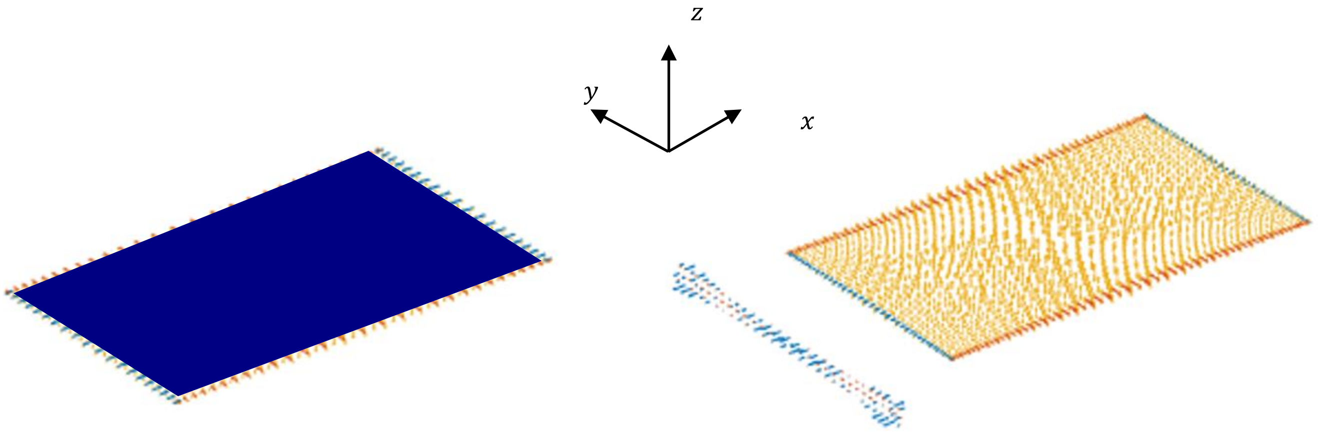
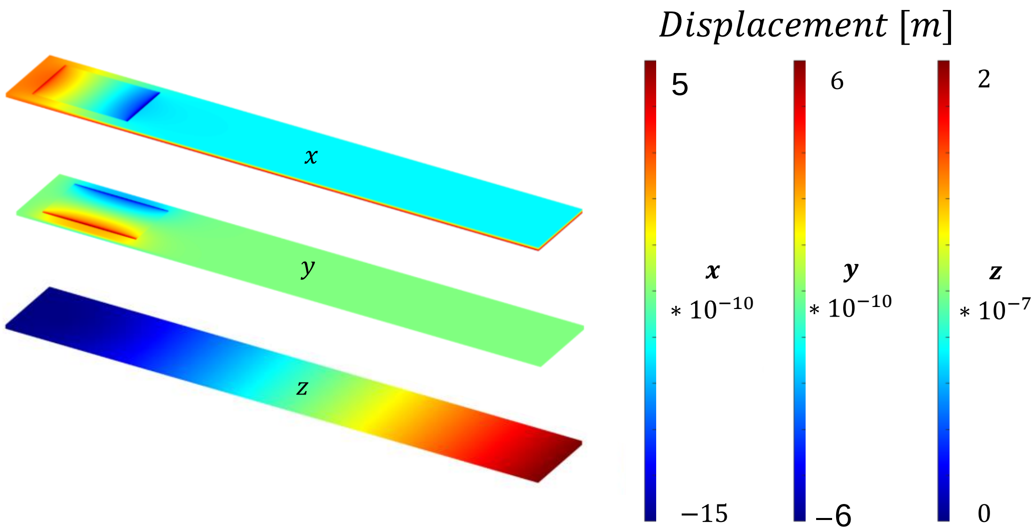


PZT forces   *total system forces*



direction i	$\sum_i F_n$ [N]
x	$3.62 * 10^{-6}$
y	$1.42 * 10^{-6}$
z	-12.38

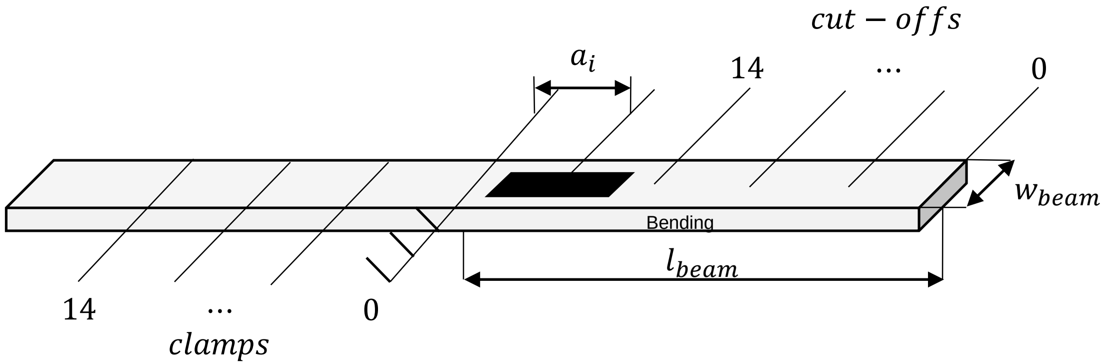
x − direction forces
y − direction forces
z − direction forces

Validation of the methodology

Validation of structure

Validation of piezo effect

Validation of position optimization



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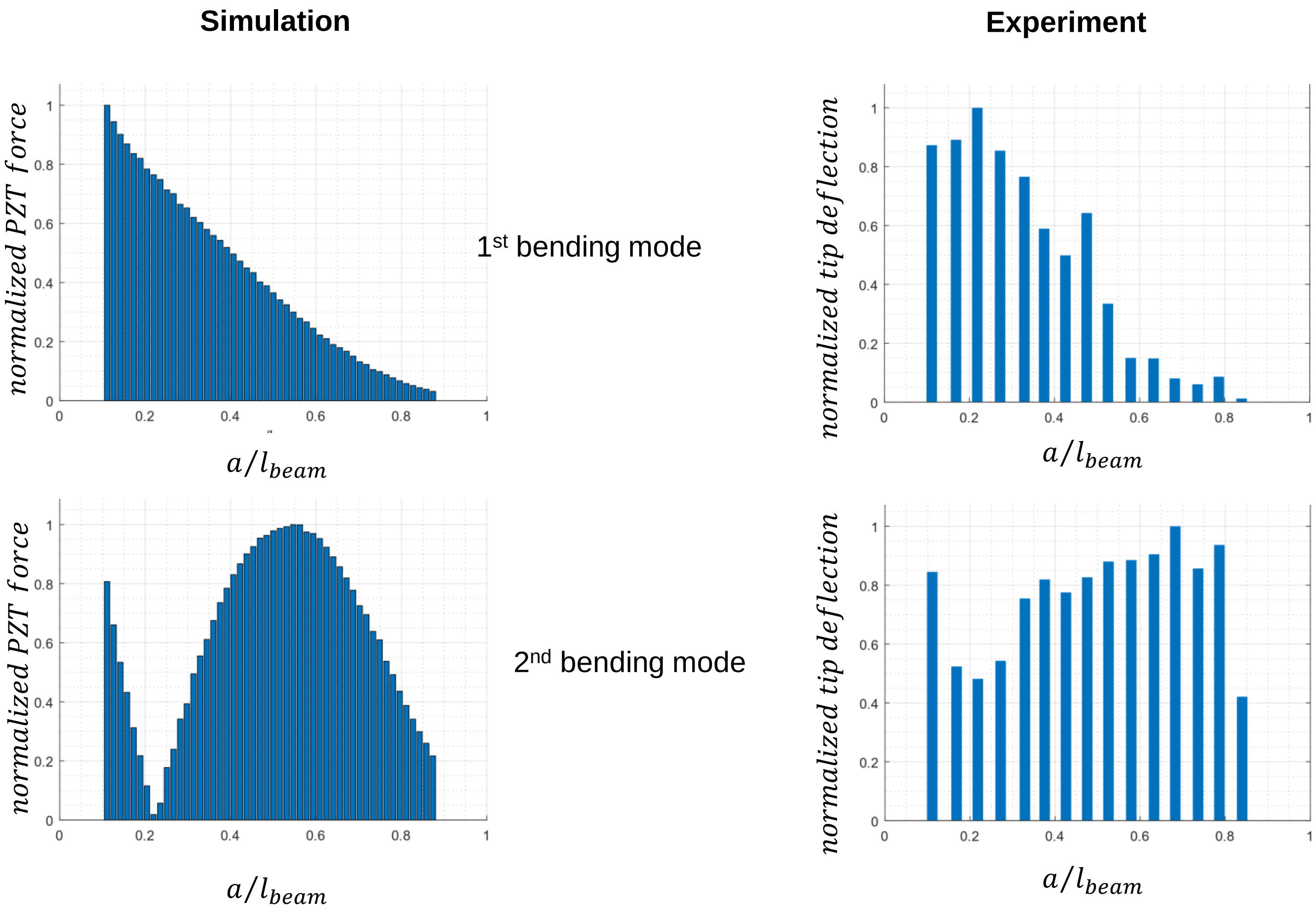

Validation of the methodology

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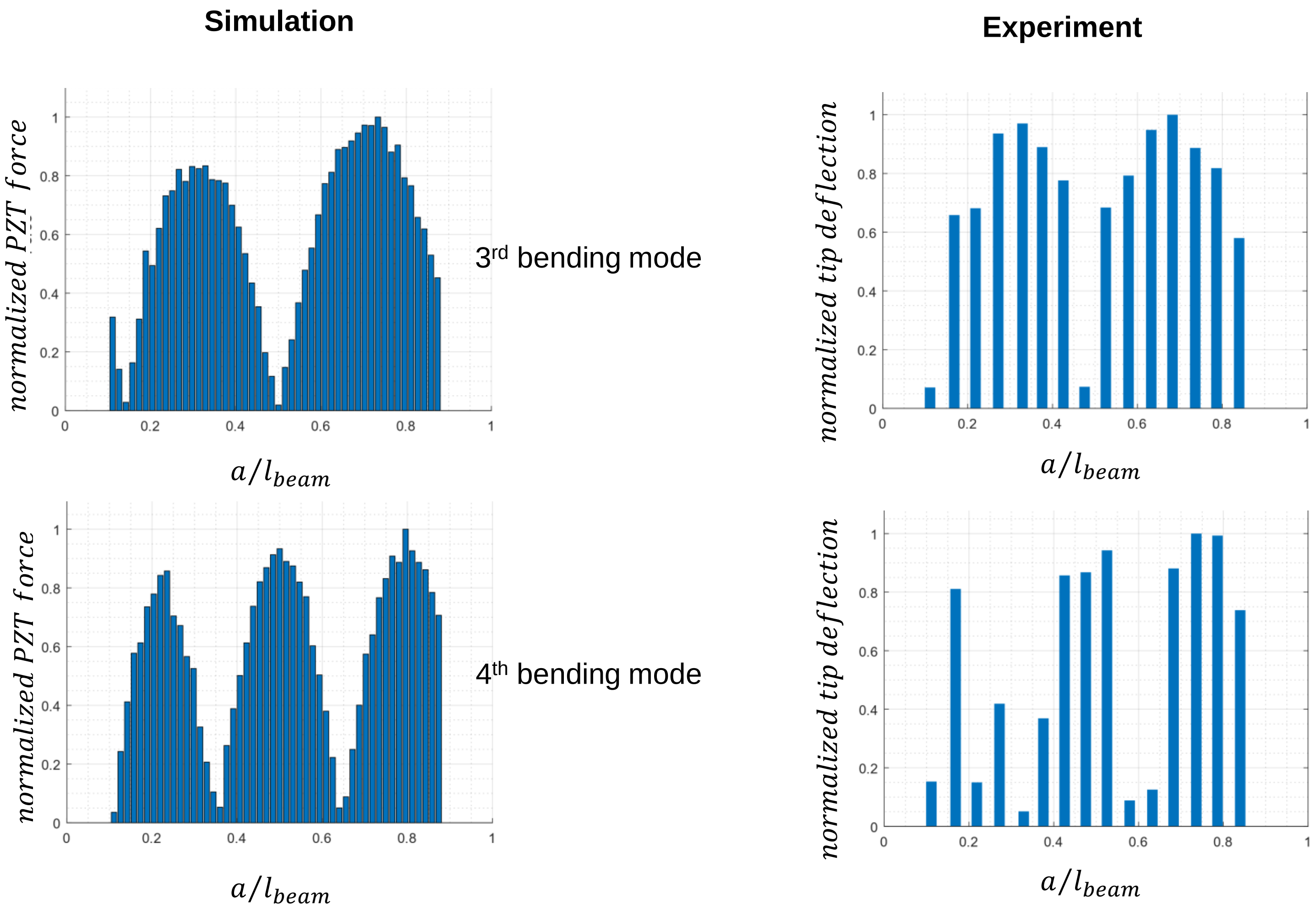

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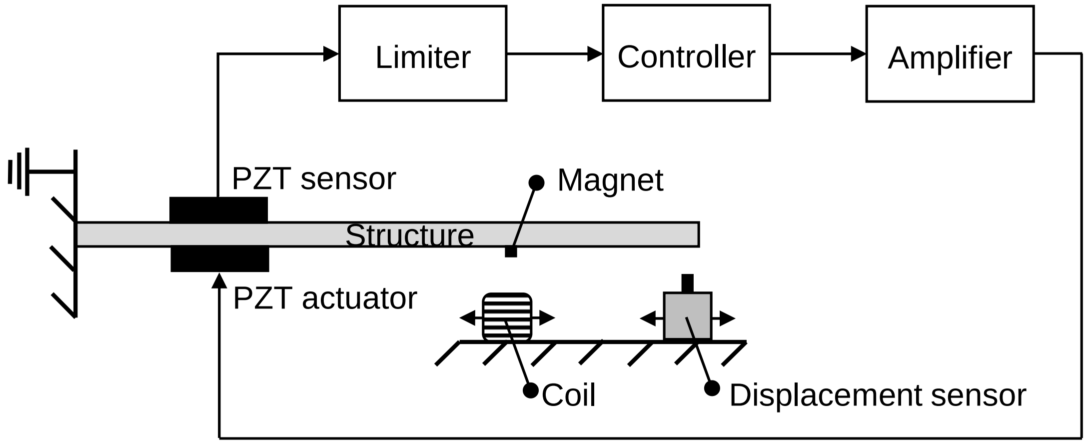
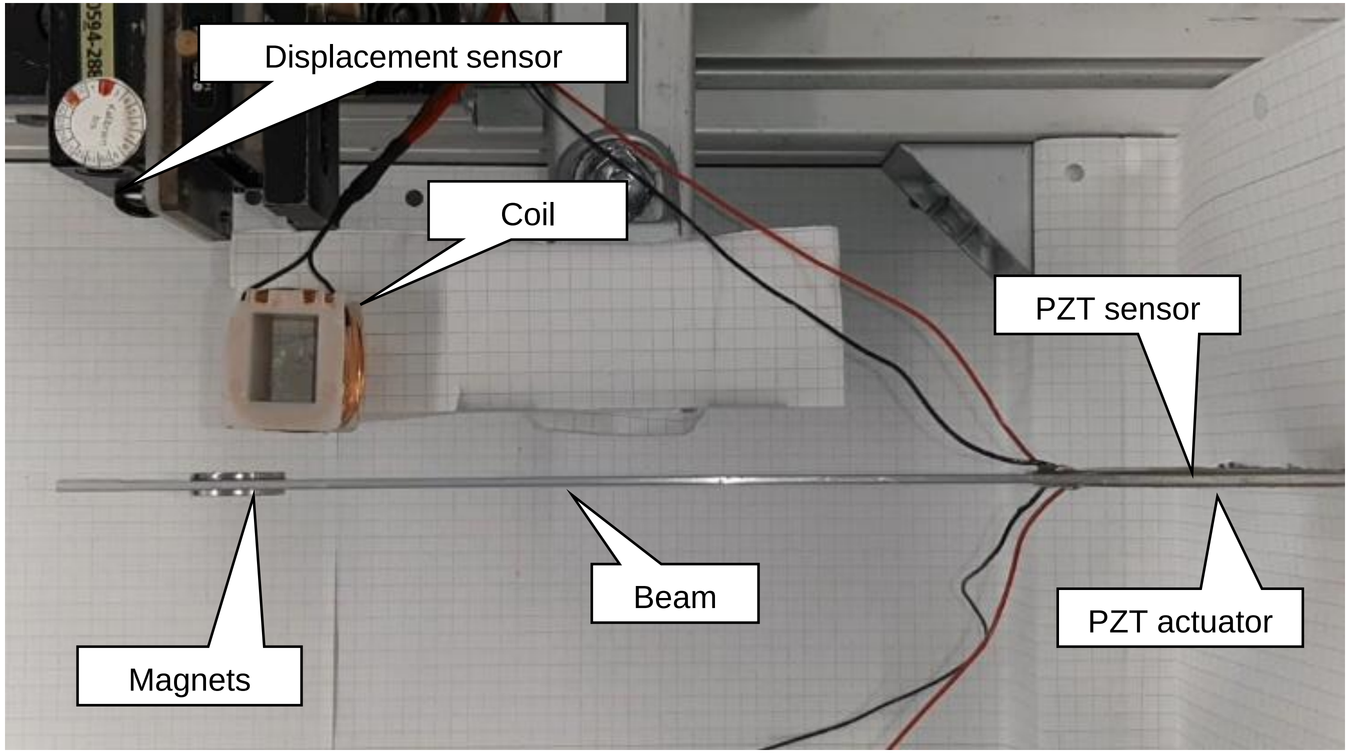
Application of the methodology

Test Setup



Application of the methodology

Test Setup



Application of the methodology

Test Setup

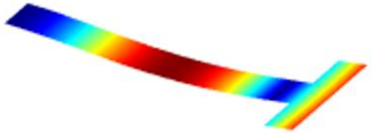
Pre- Windtunnel tests

1st Mode (bending)

$f_1 = 4.22$ Hz

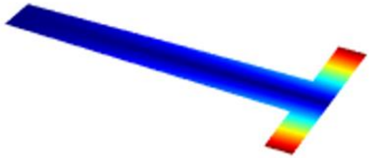
2nd Mode (bending)

$f_2 = 29.29$ Hz



3rd Mode (torsional)

$f_3 = 30.01$ Hz

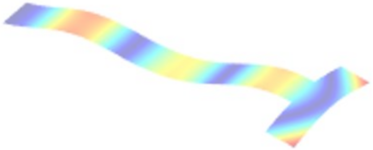


4th Mode (bending)

$f_4 = 91.37$ Hz

5th Mode (bending)

$f_5 = 181.42$ Hz



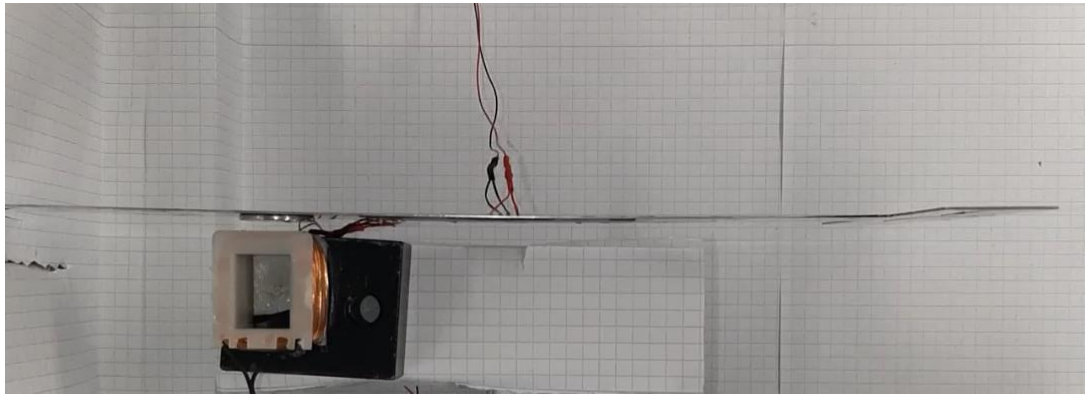
6th Mode (torsional)

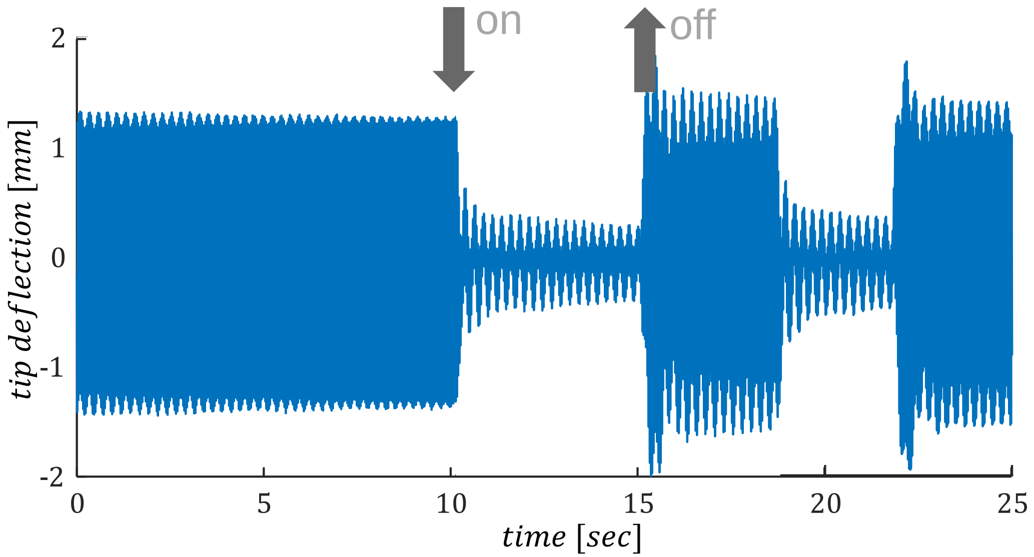
$f_6 = 188.20$ Hz

Application of the methodology

Test Setup

Pre- Windtunnel tests





Application of the methodology

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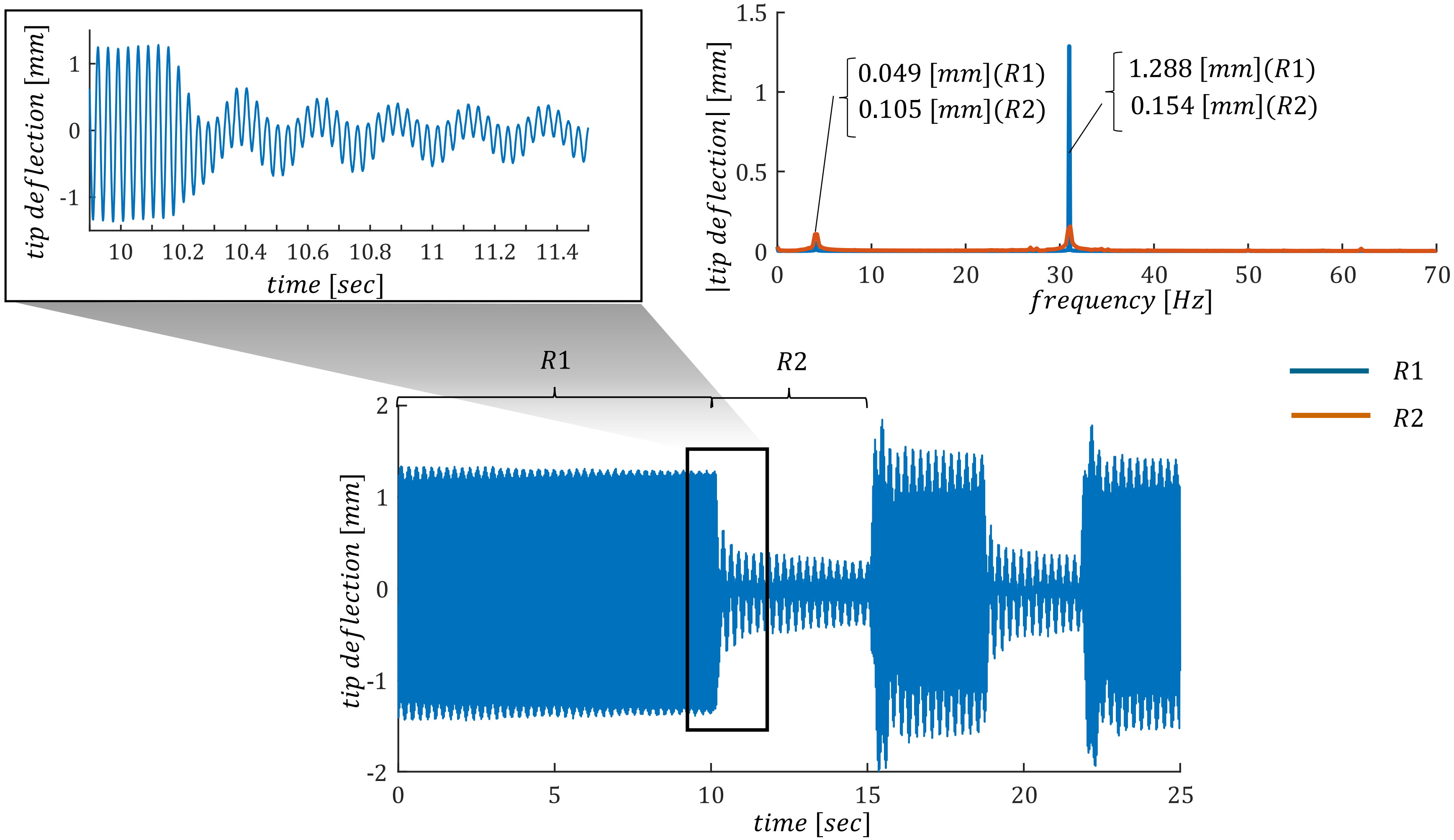
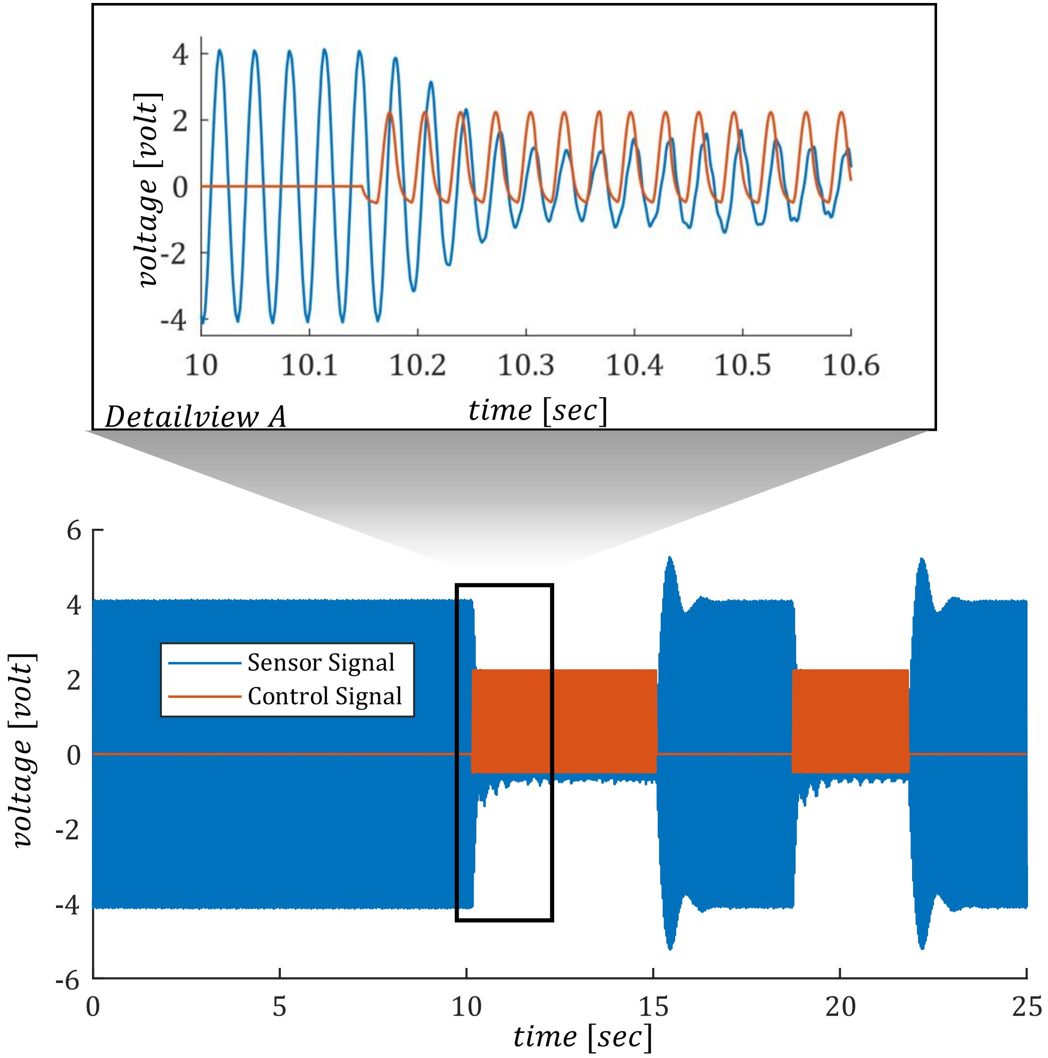


Application of the methodology

Test Setup

Pre- Windtunnel tests

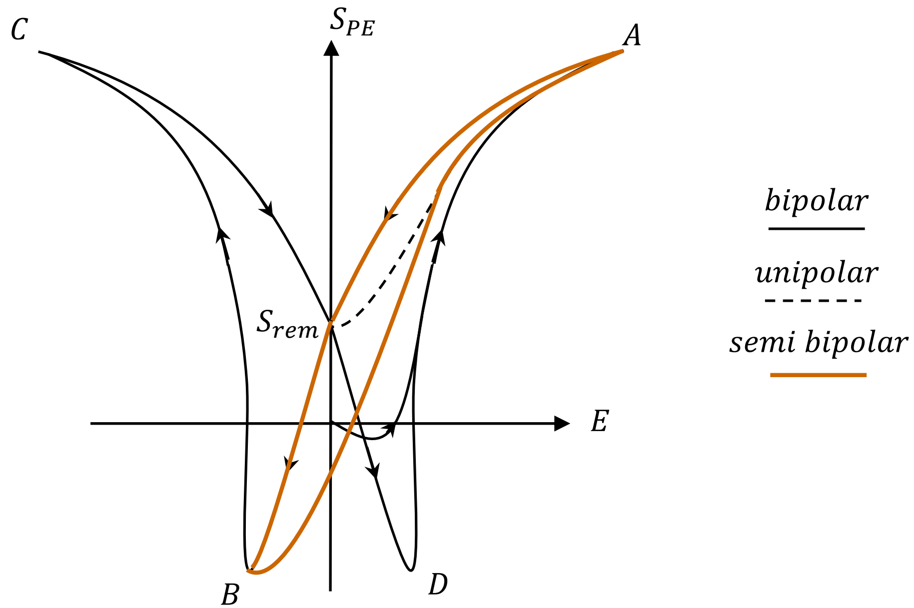


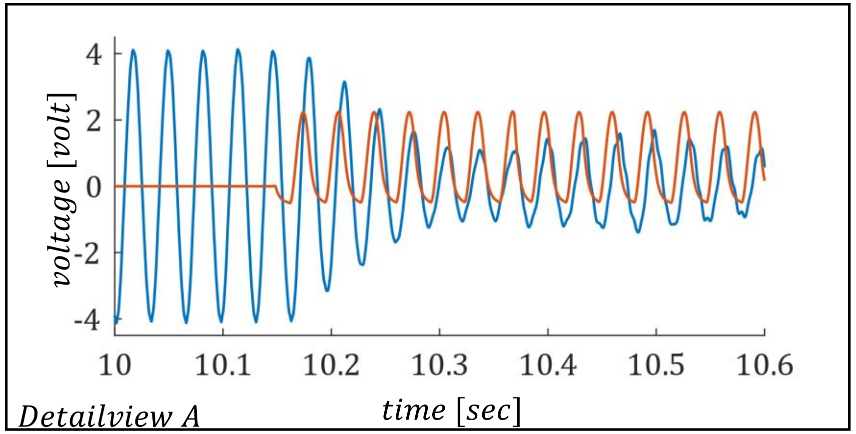
$+2kV/mm$
$-0.5kV/mm$

Application of the methodology

Test Setup

Pre- Windtunnel tests



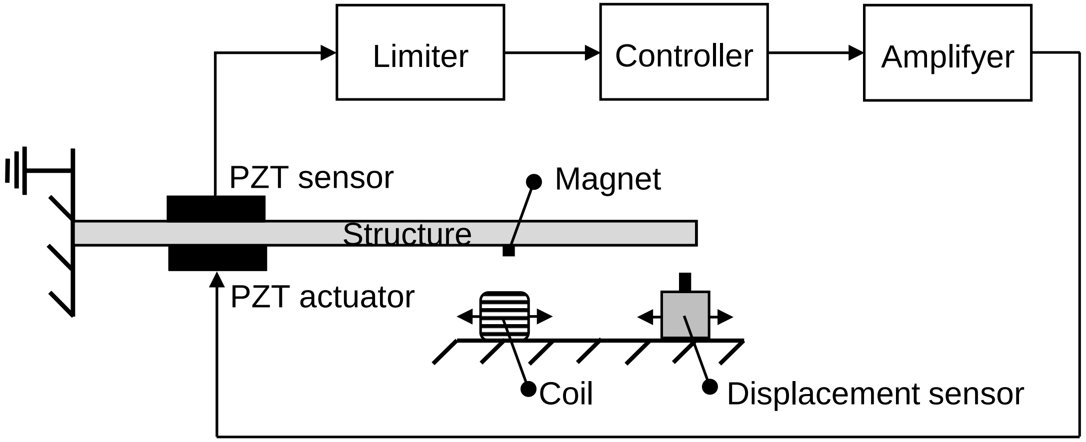


Application of the methodology

Test Setup

Pre- Windtunnel tests

Windtunnel test

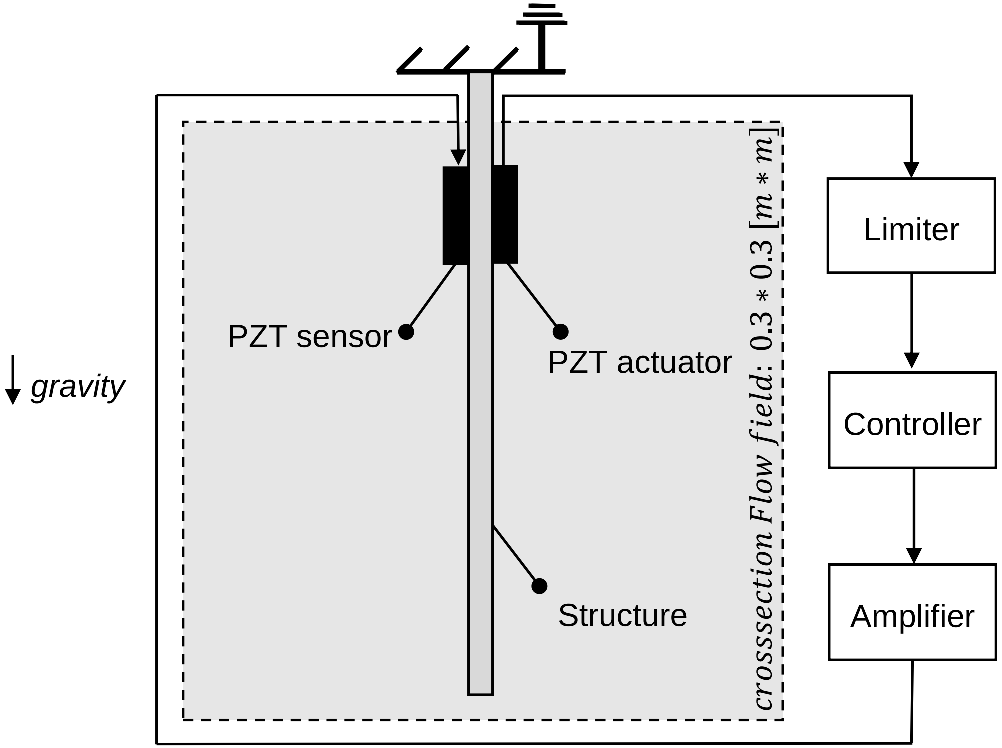


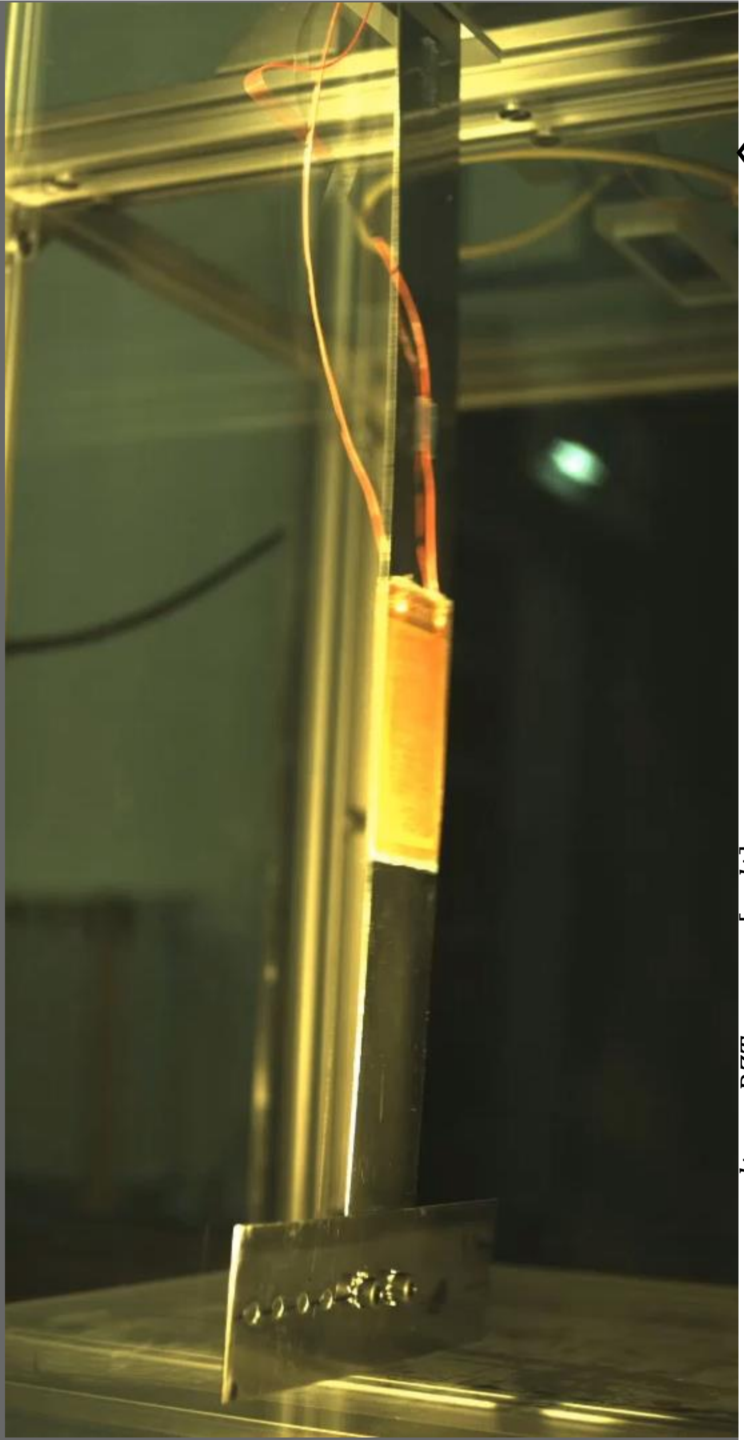
Application of the methodology

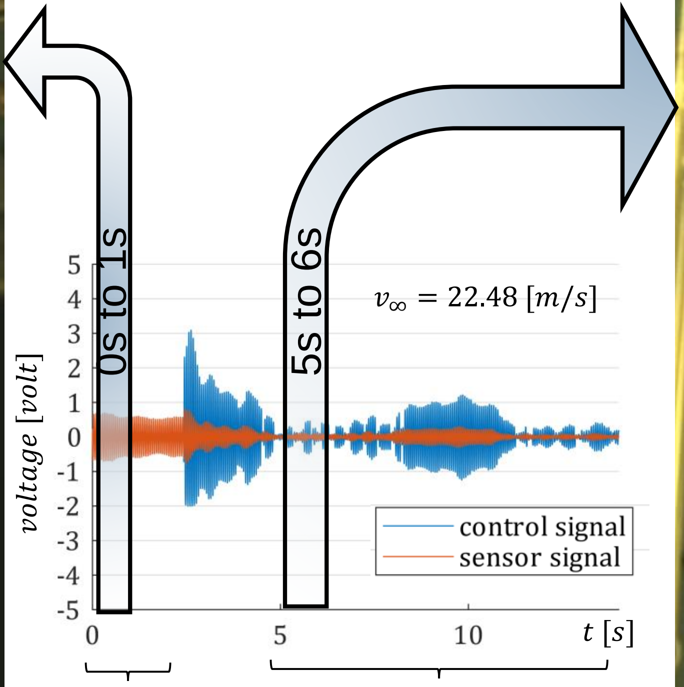
Test Setup

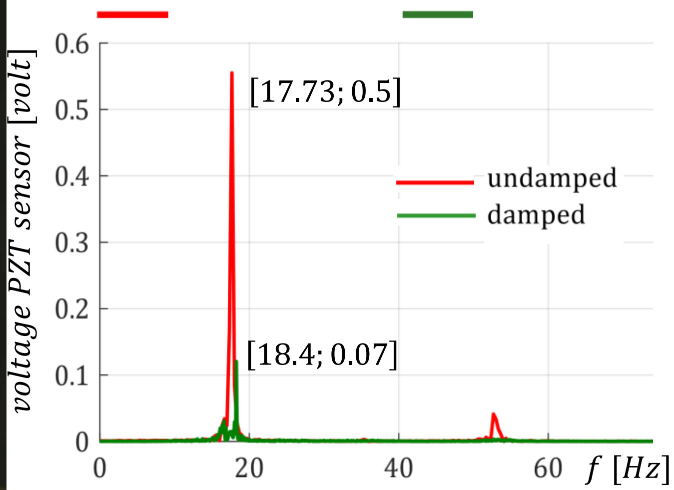
Pre- Windtunnel tests

Windtunnel test

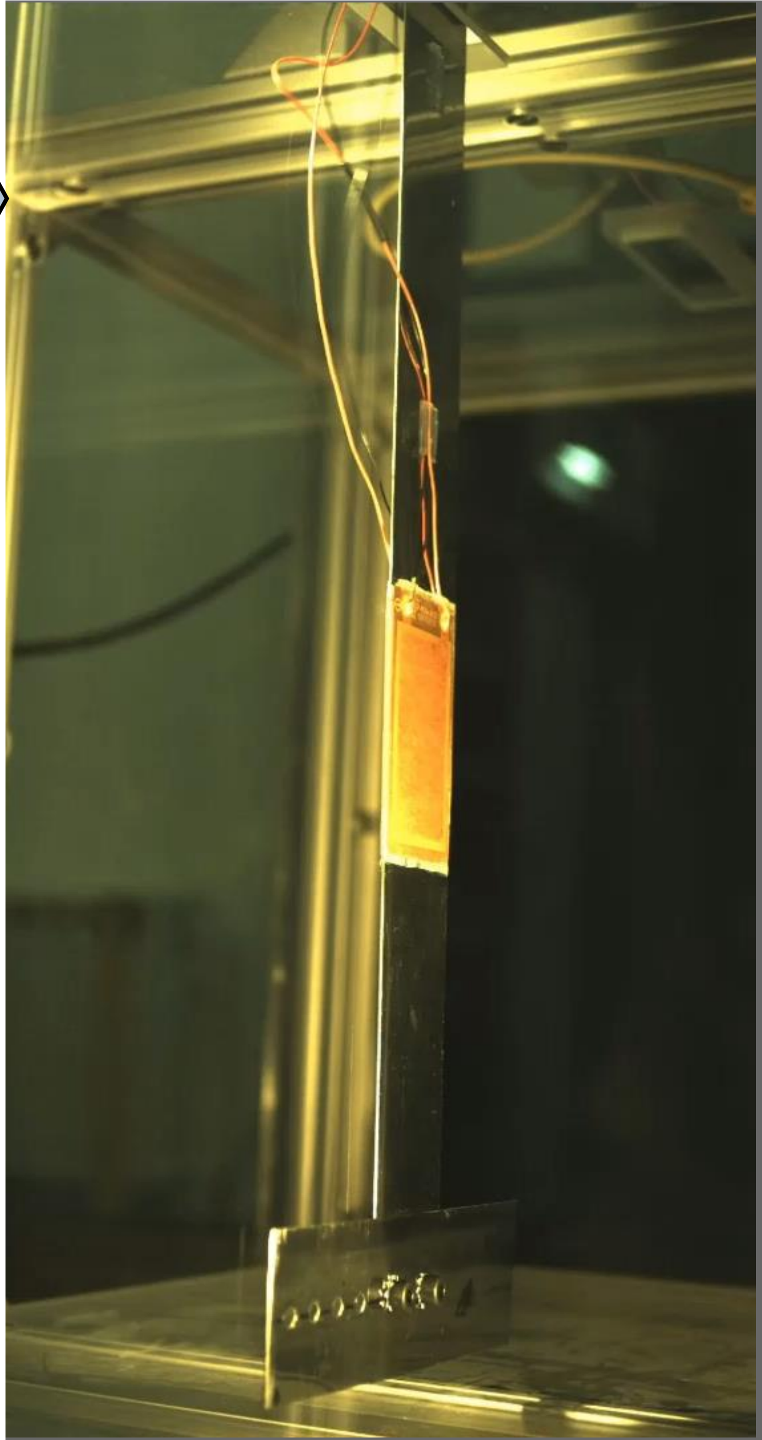





0s to 1s
5s to 6s
$v_\infty = 22.48\ [m/s]$
voltage [volt]
control signal
sensor signal
t [s]
0
5
10


voltage PZT sensor [volt]
[17.73; 0.5]
[18.4; 0.07]
undamped
damped
f [Hz]

$$time * 0.06$$



Agenda

Investigation goals

Foundations

Methodology

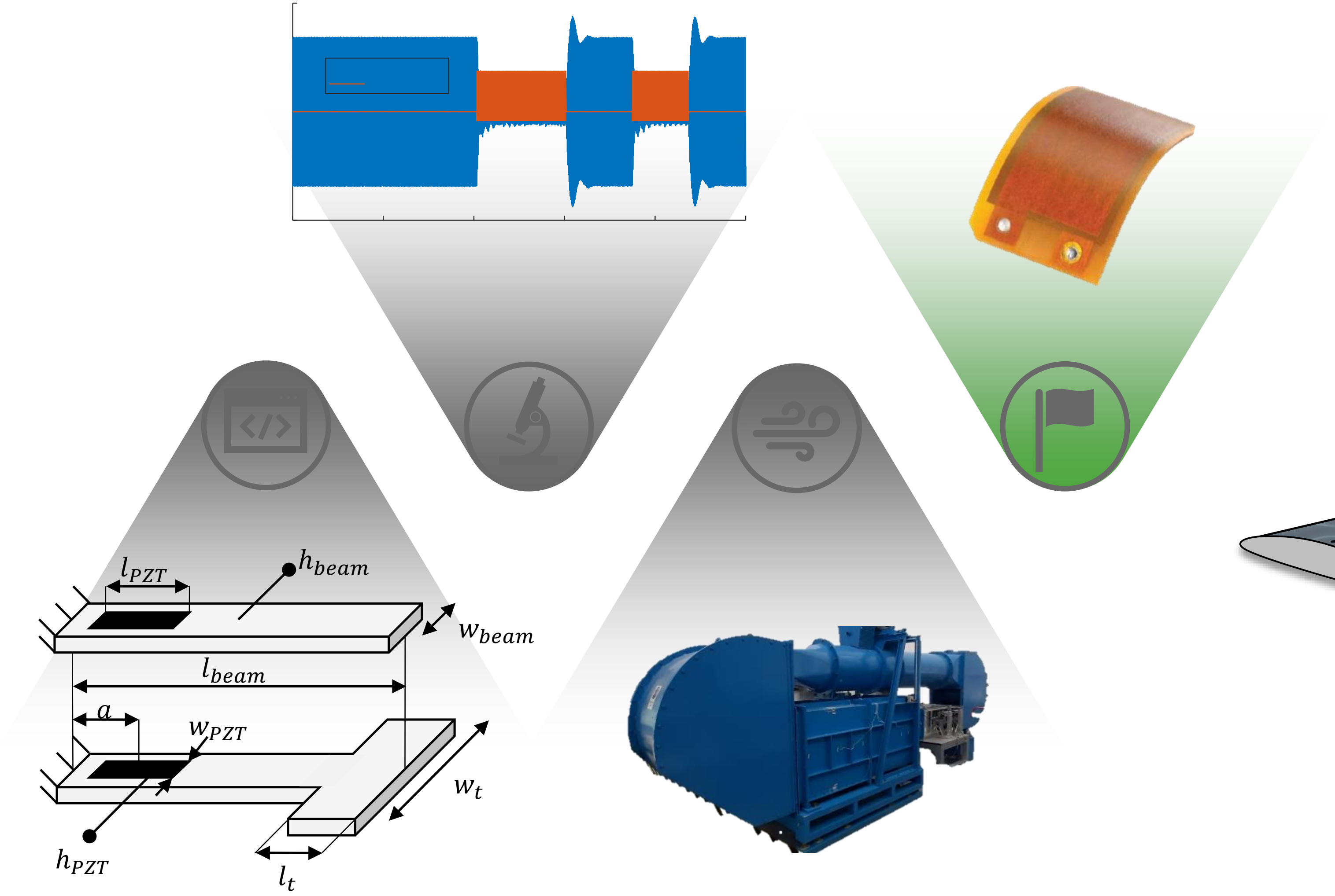
Validation of the methodology

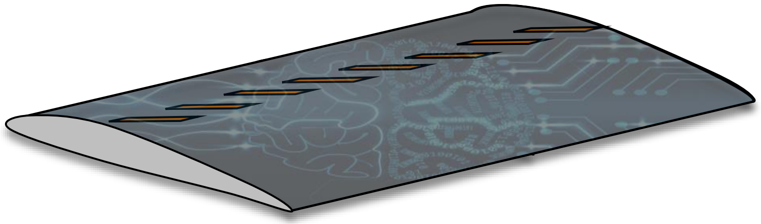
Application of the methodology

Summary and Future application ideas

Summary and Future application ideas

DLR





Thank you for your attention!

IABG

DLRK 2022
DEUTSCHER LUFT- UND RAUMFAHRTKONGRESS
DGLR 27. - 29. SEPTEMBER 2022 – DRESDEN
„Luft- und Raumfahrt - gemeinsam forschen und nachhaltig gestalten“

FH AACHEN UNIVERSITY OF APPLIED SCIENCES

DLR Institute of Aeroelasticity

Questions ?

AE @ LinkedIn

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