AePW-3
High Speed Working Group
RC-19 Wind Tunnel

2024 Updates

Aeroelasticity Laboratory | Duke University

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Motivation For Our Work

- To provide the highest possible fidelity in the computational model at an affordable cost; orders of magnitude reduction in cost compared to traditional CFD/CSD methods
- To explore a wide range of relevant parameters including M_∞, Re, static pressure differential, thermal stresses and structural boundary conditions, both out of plane and in plane.
- To correlate computational results with experimental results and assess the sensitivity of these results to uncertainties in key parameters

Increasing the complexity in the solution

Individual Studies

1. FEM study on the in-plane boundary support (β_{BC}) sensibility ✓
2. Validation/correlation of the temperature distribution over the panel and the Heat Equation (HE) implementation ✓

Exploratory Study

1. Explore a range of p_c, ΔT, β_{BC} (based on the previous step) ✓
2. Euler w/o walls vs. RANS w/ walls *(On going)*
3. Sensibility to the linear heat flux in the HE for the shock case *(On going)*
4. Implementation of the HE in the aeroelastic solver

Target study

1. Specific sets of of p_c, ΔT, β_{BC} (longer time-marching solutions)
2. Selected case for the aerodynamics and heat flux computation

How can we improve the fidelity of the computational model

How sensitive is our aeroelastic to this configuration for a "wide" range of parameters?

Final correlation with wind tunnel data → longer time marching solutions and more complex implementations (aerodynamic, thermal, …)

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Computational Method

Nonlinear Aeroelastic Model

$$\underbrace{M_{m,n}\ddot{q}_n(t) + C_{m,n}\dot{q}_n(t) + G^{(2)}_{m,n}q_n(t)}_{\text{Linear plate model}} + \underbrace{D^{(2)}_{m,n,r,p}q_n(t)q_r(t)q_p(t)}_{\text{NL structural stiffness}} + \underbrace{Q^{Aero}_{m,n}}_{\text{Aero}}$$

$$-\underbrace{L^{c}_{n,m}P_n(t)}_{\text{Cavity coupling}} + \underbrace{Q^{static}_{m}}_{\text{Static pressure differential}} = 0$$

Static pressure differential sensitivity ($\Delta p = p_\infty - p_c$)

In-plane Boundary sensitivity + Thermal Buckling (ΔT)

Acoustic Modes don't play a significant effect in the panel dynamic response (for the RC-19 model)

Unsteady Aerodynamics Model

- Linear Piston Theory
- Full Potential Aerodynamics
- Dynamically Linearized Time-domain Approach
    - Euler
    - Navier-Stokes (RANS)

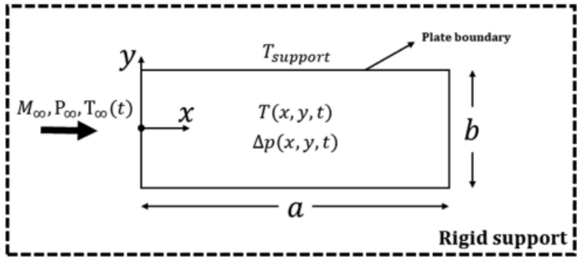

Fig. 1 Plate top view with freestream flow, static pressure differential, and support and plate temperatures.

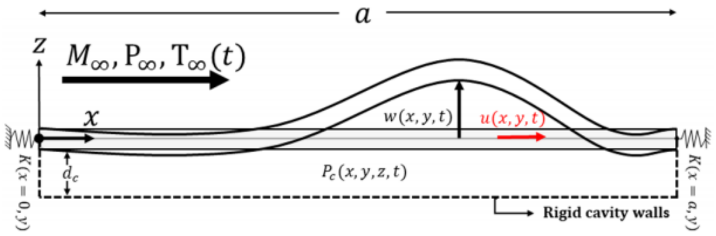

Fig. 2 Side view of plate, freestream flow, cavity, and in-plane edge stiffness $K(x = [0,a], y)$; and cross section at $-b/2 < y < +b/2$.

Freydin and Dowell. AIAA(2020)

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Summary

- A range of aerodynamic models has been considered including piston theory, full potential flow, Euler flow and RANS with and without shock impingement.
- For the RC-19 configuration the **results are particularly sensitive to the pressure differential, thermal stress** (which leads to buckling) **and the in-plane as well as out of plane boundary support conditions** for the plate.
- A **finite element model** of the plate and its support structure allows the **determination of the effective in-plane support boundary condition.**
  - This information could also be obtained from an experiment to measure the change in natural frequencies due to a pressure differential.
- **Results for flutter and LCO** of the RC-19 experiment **are not particularly sensitive to the aerodynamic model**, with the key exception that the heating of the plate is due to the aerodynamic flow.
  - The thermal field needs to be determined by a RANS model or from experiment. Piston theory, potential flow theory and Euler flow all give similar results, but all require some auxiliary modeling of the heating due to the aerodynamic flow (e.g. Eckert model).
- Flutter and LCO results do become sensitive to M_∞ and other flow parameters in the low supersonic, transonic range and the results from the various aerodynamic models may vary substantially.

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Outline

Individual Studies

1. FEM study on the in-plane boundary support (β_{BC}) sensibility
2. Validation/correlation of the temperature distribution over the panel and the Heat Equation (HE) implementation

Exploratory Study

1. Explore a range of p_c, ΔT, β_{BC} (based on the previous step)
2. Euler w/o walls vs. RANS w/ walls
3. Sensibility to the linear heat flux in the HE for the shock case
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Target study

1. Specific sets of of p_c, ΔT, β_{BC} (longer time-marching solutions)
2. Selected case for the aerodynamics and heat flux computation

- Computation of natural frequences of a plate with changes in a Δp using a FEM of the plate and its support structure
  - This allows the determination of the effective in plane support spring stiffness for the plate.
- Correlation between the Heat Equation implementation and experimental data
- LCO correlation results
  - No-shock configuration (review from AePw3)
  - 4° shock wedge configuration using Euler and RANS models (preliminary results)

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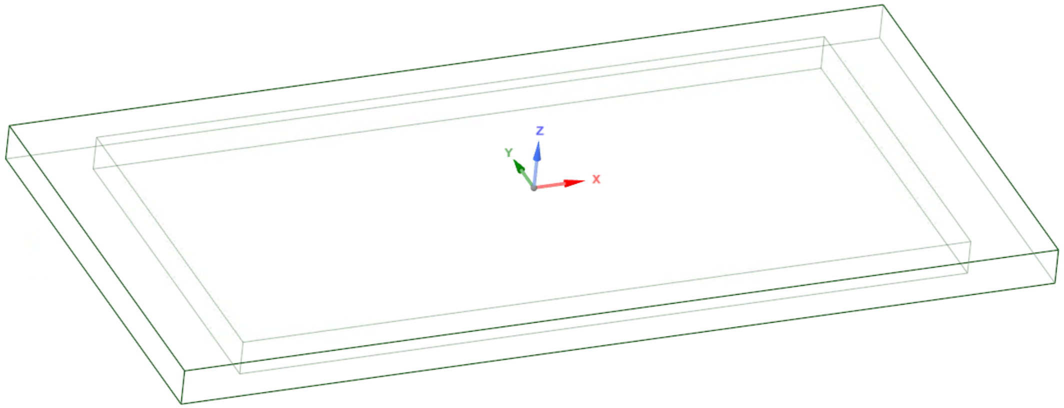
FEM study on the β_{BC} sensibility

$$\beta_{BC} \equiv \frac{K_{BC}a}{Eh}$$

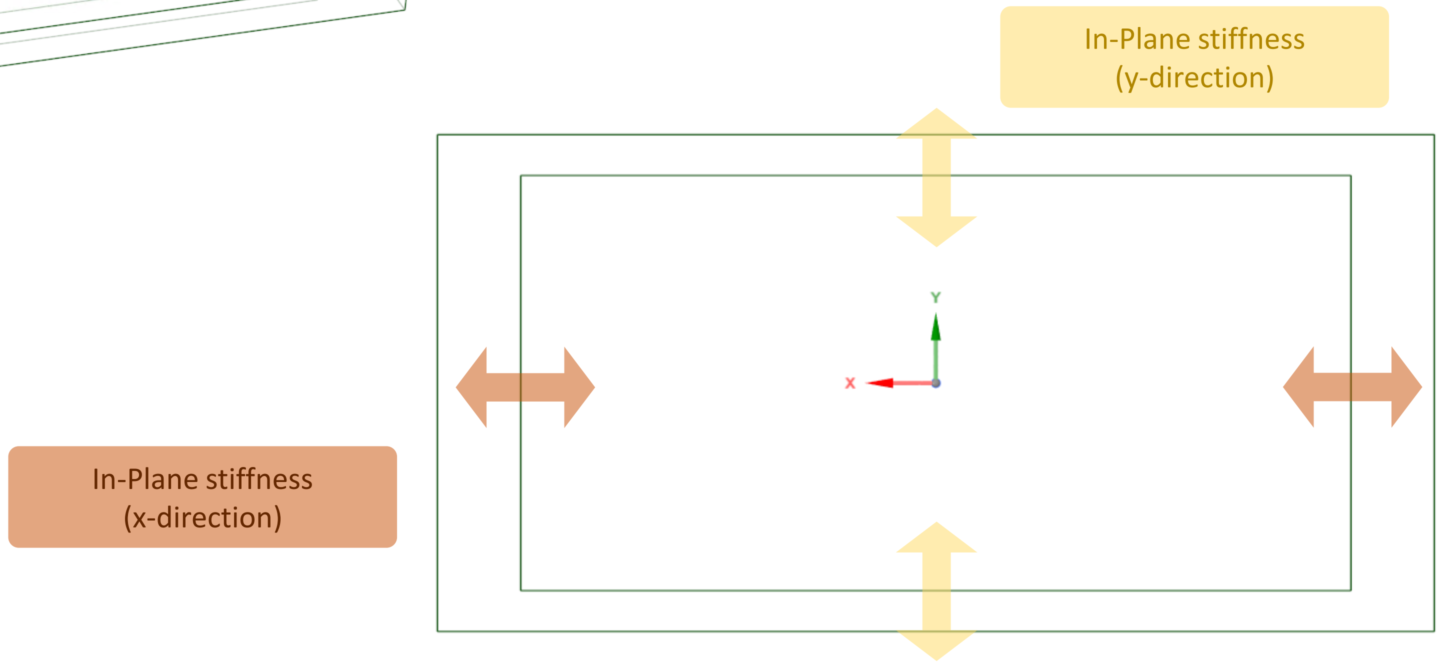
Individual Studies

Exploratory Study

Target Study



0.305×0.152×0.0127 m block of AISI 4140 alloy steel with a machined pocket, leaving the thin panel (elastic structure)



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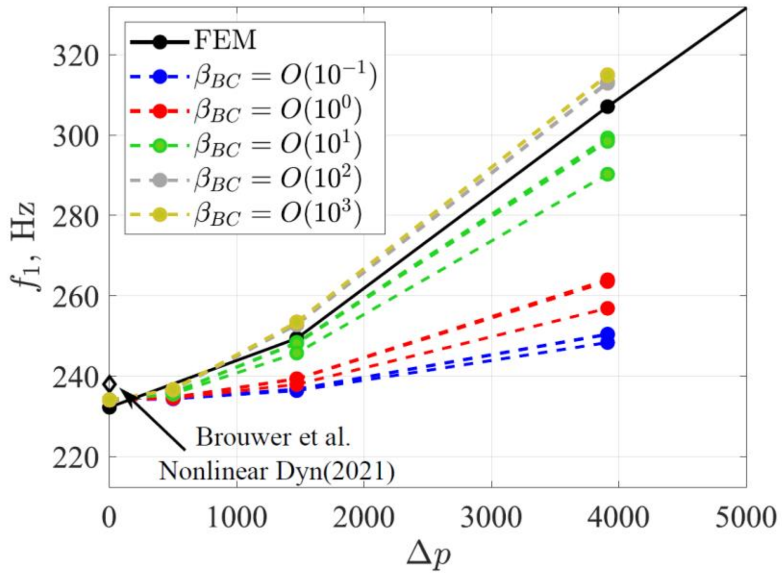
Δp *vs.* Natural Frequency: FEM *vs.* Aeroelastic Code

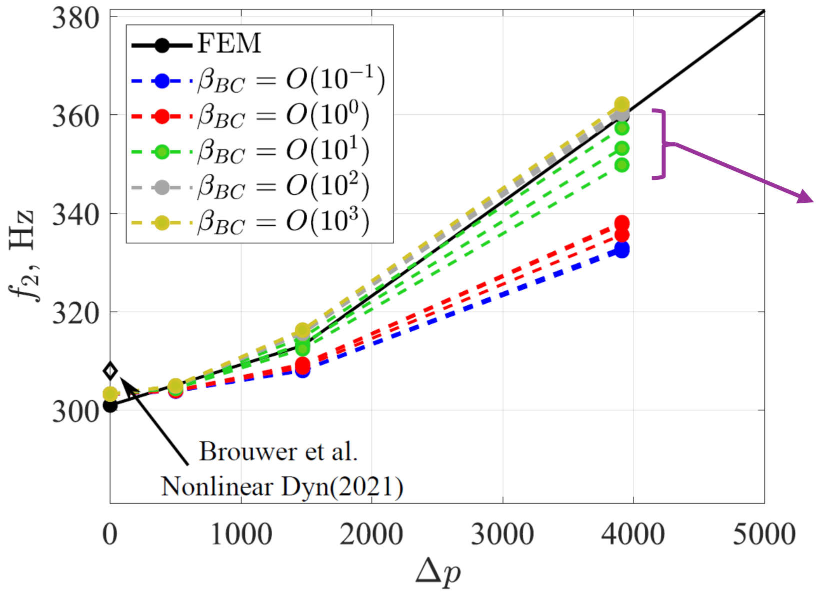
$\Delta T = 0$
$U_\infty = 0$

Individual Studies

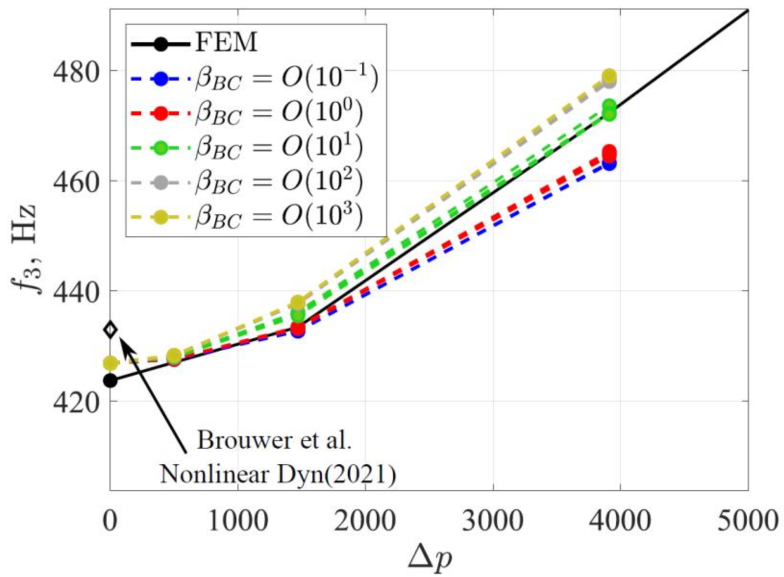
Exploratory Study

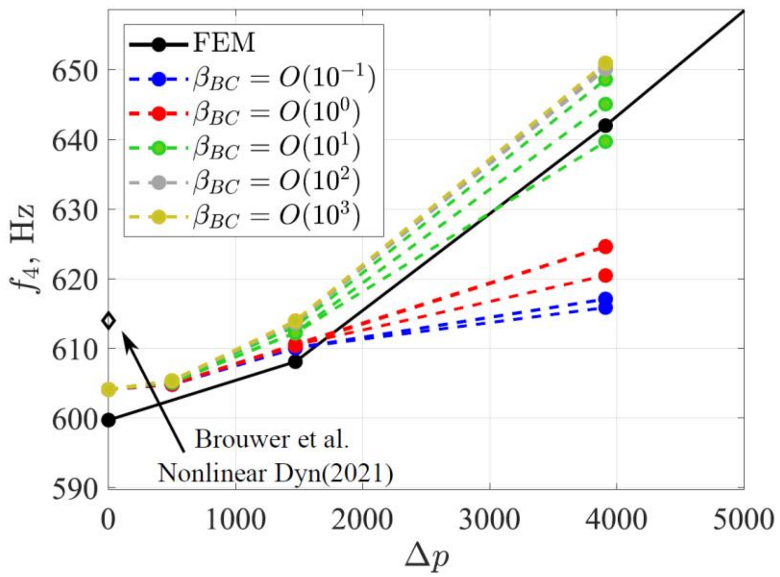
Target Study





Plots include results for the symmetric ($\beta_{BC,x} = \beta_{BC,y}$)and asymmetric ($\beta_{BC,x} \neq \beta_{BC,y}$) in-plane stiffness, but they are roughly the same in all cases





Expected range for the RC-19 conf. :

$O(10^1) < \beta_{BC} < O(10^2)$

Heat Equation (HE) Implementation

$$\underbrace{M_{m,n}\ddot{q}_n(t) + C_{m,n}\dot{q}_n(t) + G^{(1)}_{m,n}q_n(t)}_{\text{Linear plate model}} + \underbrace{D^{(2)}_{m,n,r,p}q_n(t)q_r(t)q_p(t)}_{\text{NL structural stiffness}} + \underbrace{G^{(3)}_{m,n,r}q_n(t)T_r(t)}_{\text{Thermal coupling}} + \underbrace{Q^{Aero}_{m,n} + Q^{static}_{m}}_{\text{Pressure terms}} = 0$$

$$\underbrace{M^H_{m,n}\dot{T}_n(t) + K^H_{m,n}T_n(t)}_{\text{Thermal inertia and stiffness}} + \underbrace{+Q^0_m + Q^q_{m,n}q_n(t) + Q^{\dot{q}}_{m,n}\dot{q}_n(t) + Q^{T_q}_{m,n}T_n(t)}_{\text{Coupled linear aerodynamic heating}} = 0$$

- The ΔT measured by the thermocouple is slightly smaller than the mid-plate temperature
- The HE implementation overpredicts the mid-plate temperature by $< 5K$

Individual Studies

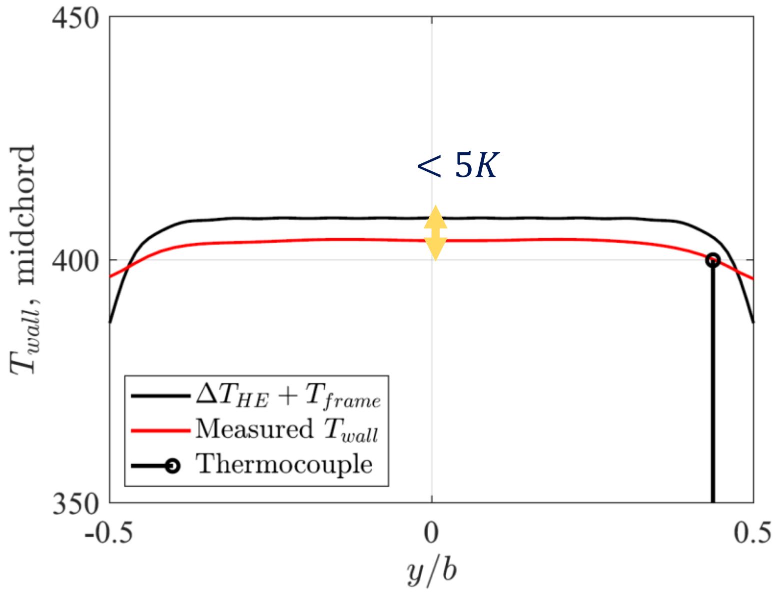
Exploratory Study

Target Study

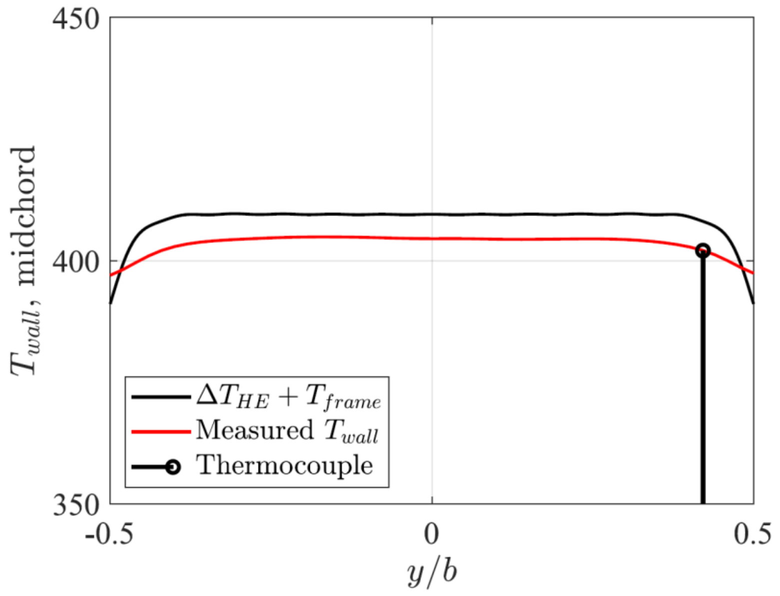
Wind Tunnel Setup

Parameter	Value
M_∞	1.92
p_0	$\approx$ 346 kPa
T_0	$\approx$ 420 K
$\Delta \boldsymbol{p}$	0

No shock



4° Wedge Shock



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Different setup from the workshock case!

Heat Equation (HE) Implementation

$$\underbrace{M_{m,n}\ddot{q}_n(t) + C_{m,n}\dot{q}_n(t) + G^{(1)}_{m,n}q_n(t)}_{\text{Linear plate model}} + \underbrace{D^{(2)}_{m,n,r,p}q_n(t)q_r(t)q_p(t)}_{\text{NL structural stiffness}} + \underbrace{G^{(3)}_{m,n,r}q_n(t)T_r(t)}_{\text{Thermal coupling}} + \underbrace{Q^{Aero}_{m,n} + Q^{static}_{m}}_{\text{Pressure terms}} = 0$$

$$\underbrace{M^H_{m,n}\dot{T}_n(t) + K^H_{m,n}T_n(t)}_{\text{Thermal inertia and stiffness}} + \underbrace{+Q^0_m + Q^q_{m,n}q_n(t) + Q^{\dot{q}}_{m,n}\dot{q}_n(t) + Q^{T_q}_{m,n}T_n(t)}_{\text{Coupled linear aerodynamic heating}} = 0$$

The HE implementation overpredicts the temperature at and after the shock location for the shock case (chord-wise)

Individual Studies

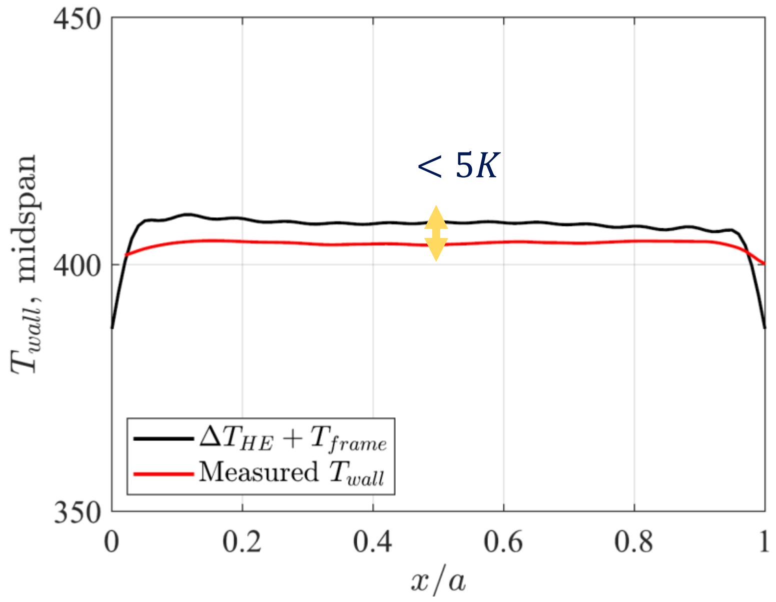
Exploratory Study

Target Study

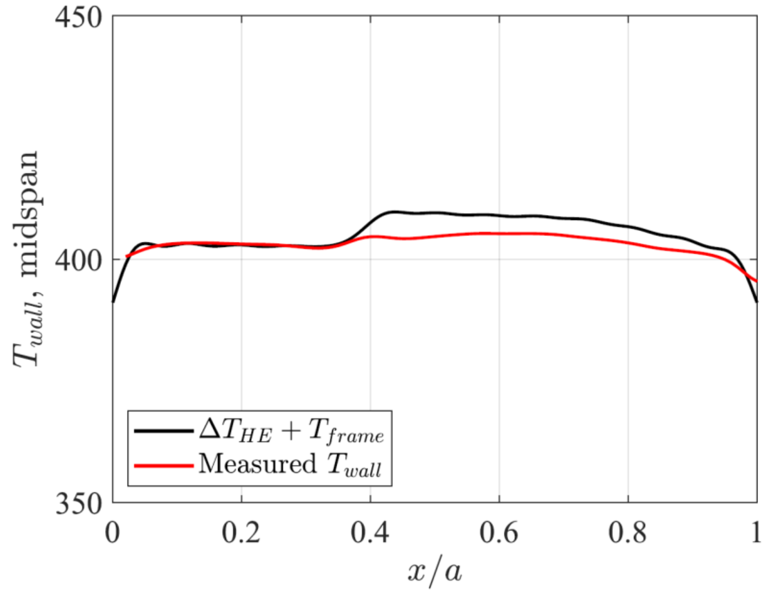
Wind Tunnel Setup

Parameter	**Value**
M_∞	1.92
p_0	≈ 346 kPa
T_0	≈ 420 K
Δp	0

No shock



4° Wedge Shock



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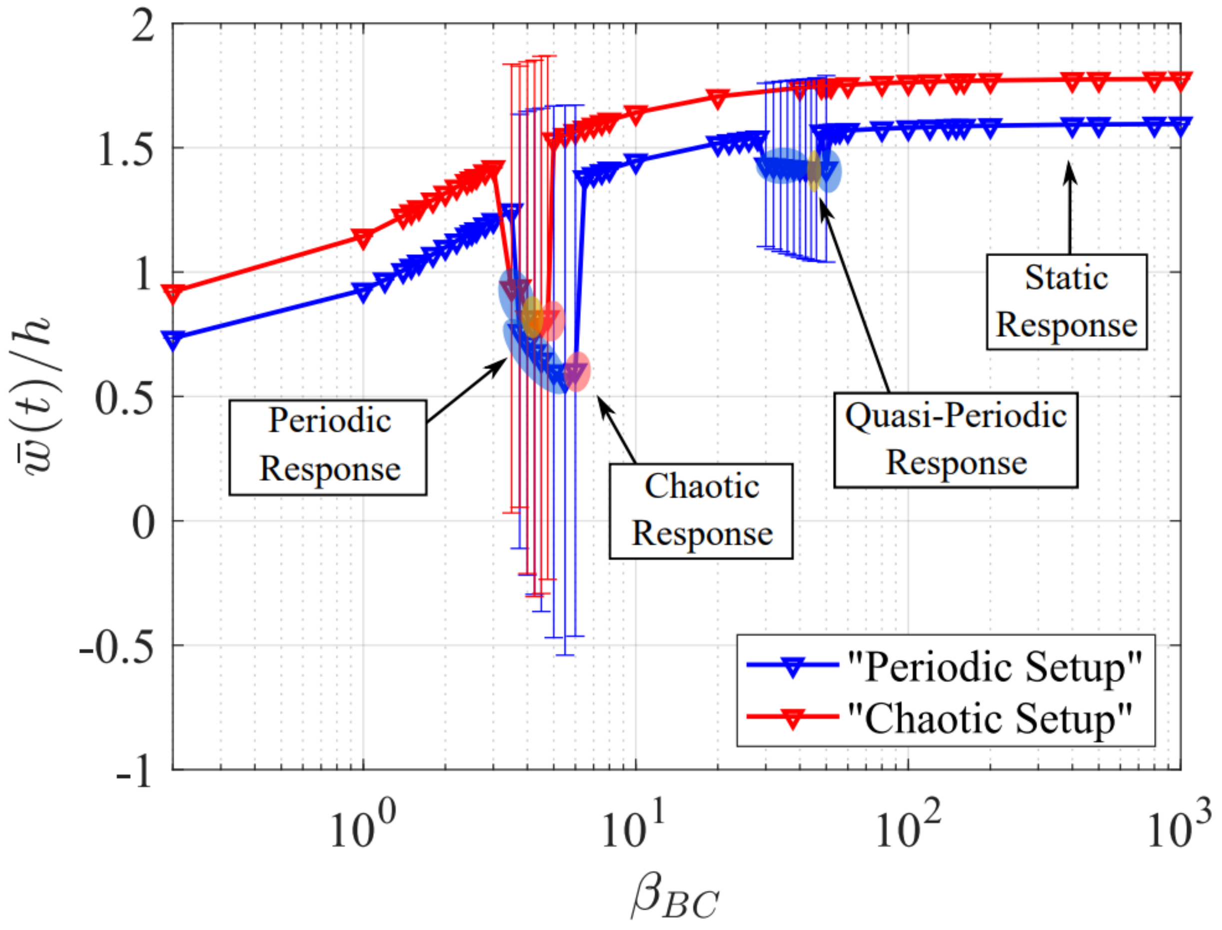
Different setup from the workshock case!

Review from the AePW3: No-shock case

Effect of In Plane Boundary Stiffness on Panel Response

Individual Studies
Exploratory Study
Target Study



Periodic Parameters		Chaotic Parameters	
Δp (kPa)	3.91	Δp (kPa)	5.01
ΔT (K)	12.8	ΔT (K)	14.7

β_{BC} can be determined from a ground vibration test of Finite Element Modeling of panel + its boundary support

$$\beta_{BC} \equiv \frac{K_{BC}a}{Eh}$$

Piccolo Serafim et al. JFS(2023)

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Correlation with Measurement: “Periodic” LCO

Periodic Parameters	
Δp (kPa)	3.91
ΔT (K)	12.8

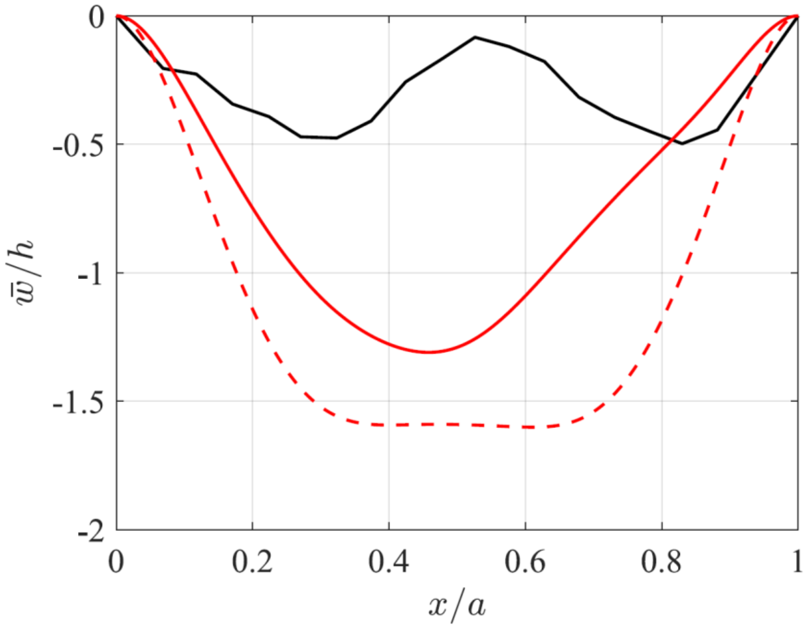
Aerodynamic Model: Piston Theory, $M_\infty = 1.94$, no wind tunnel walls

Individual Studies

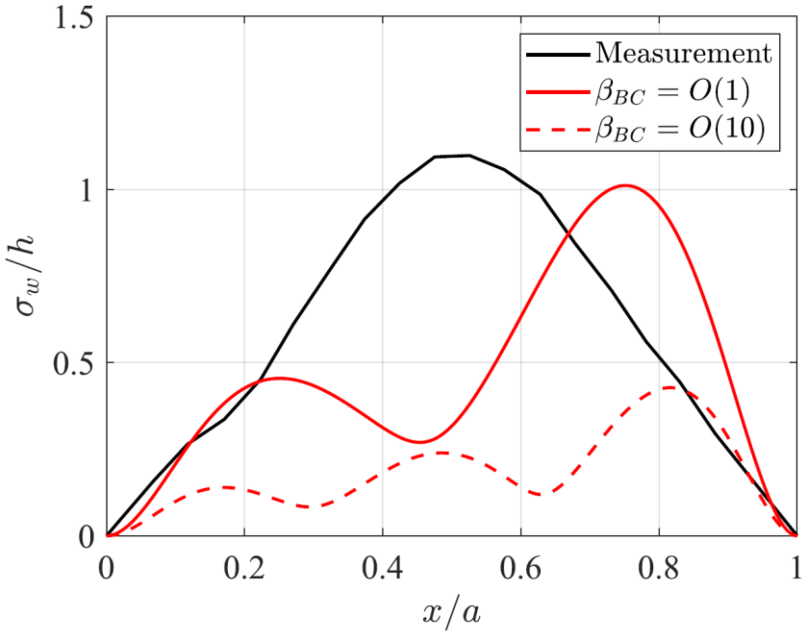
Exploratory Study

Target Study

Mean deformation



Standard Deviation



Bigger β_{BC} leads to bigger static deformation, and smaller LCO amplitude

The enforced Δp is the main reason for the big difference in the mean deformation between experiment and computational results

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Correlation with Measurement : "Chaotic" LCO

Chaotic Parameters	
Δp (kPa)	5.01
ΔT (K)	14.7

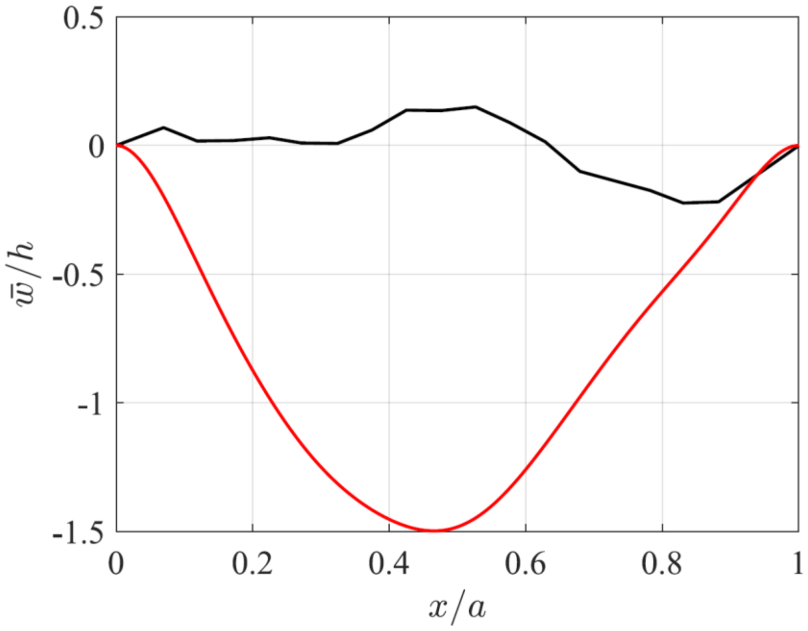
Aerodynamic Model: Piston Theory, $M_\infty = 1.94$, no wind tunnel walls

Individual Studies

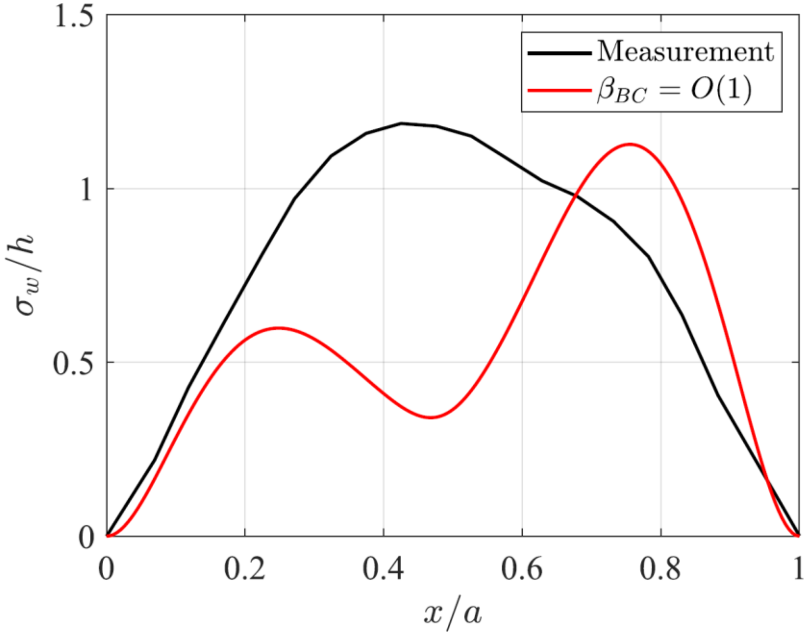
Exploratory Study

Target Study

Mean deformation



Standard Deviation



LCO was only found for $\beta_{BC} = O(1)$

Again, the enforced Δp is the main reason for the big difference in the mean deformation between experiment and computational results

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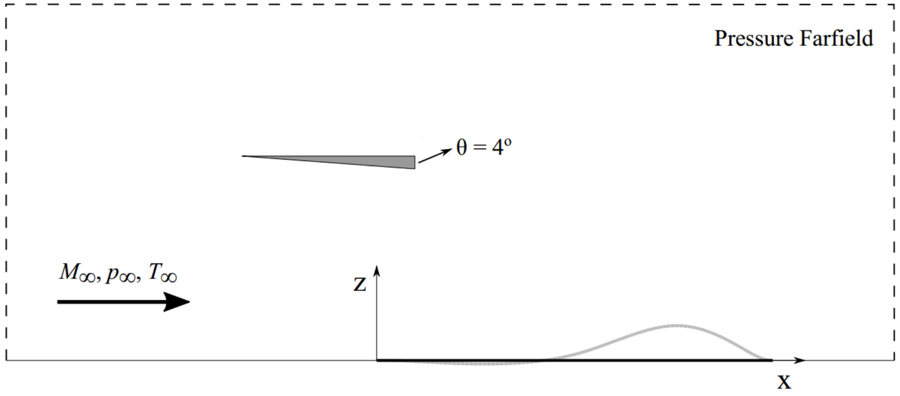
Shock Impingement Case: Correlation with experimental data

Preliminary Results

Individual Studies

Exploratory Study

Target Study

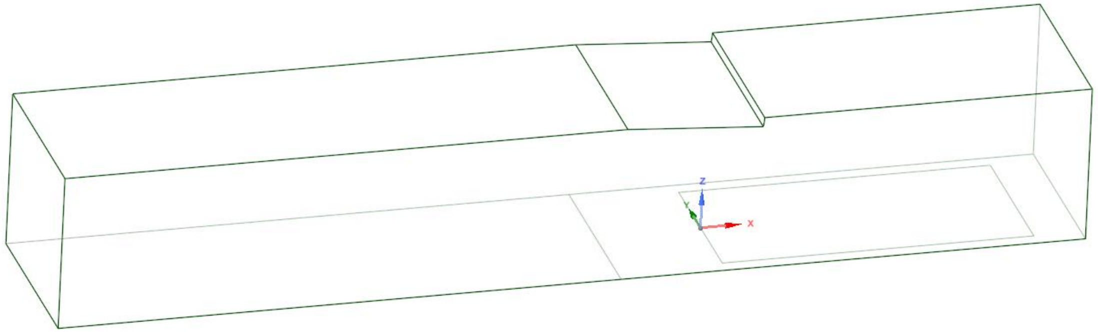


Aerodynamic Model: Euler/DLTA (Dynamically Linearized Time-Domain Approach)

- ~~**Wind Tunnel walls**~~
- In-Plane boundary stiffness
- $\boldsymbol{M_\infty = 2.0}$ **on the wall**
- ΔT between panel and frame
- Δp between fluid and acoustic cavity

Aerodynamic Model: RANS/DLTA (Dynamically Linearized Time-Domain Approach)

- **Wind Tunnel walls**
- In-Plane boundary stiffness
- $\boldsymbol{M_\infty = 1.92}$ **on the wall**
- ΔT between panel and frame
- Δp between fluid and acoustic cavity



SST $k-\omega$
$y^+ = 5$
$\delta_{LE} \approx$ 8mm (Wind Tunnel: $\delta_{LE} \approx$ 8.6mm)
$\delta_{LE}/a \approx 0.03$ (Wind Tunnel: $\delta_{LE}/a \approx 0.033$)

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Aeroelastic solution for a range of p_c, ΔT, and β_{BC}

Exploratory parameters

$\beta_{BC} = [0.1, 1000]$ → we're computing the solution at this stage for a wider range of in-plane stiffness, although we have an "expected range" for this parameter predicted by the FEM study.

$\Delta T = 15$ K → considers the small increase in temperature between the thermocouple location ($\Delta T = 13.3$ K) and the mid-plate

$\Delta T = 20$ K → considers the overshoot from the HE solution

Uniform Distribution for ΔT

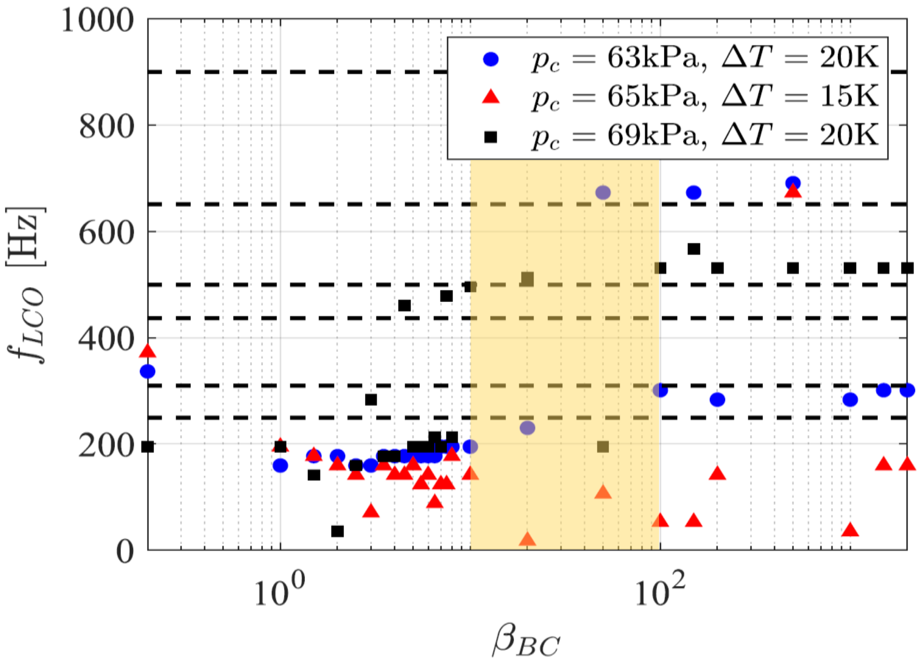
$p_c = 69$ kPa → the same as the wind tunnel setup

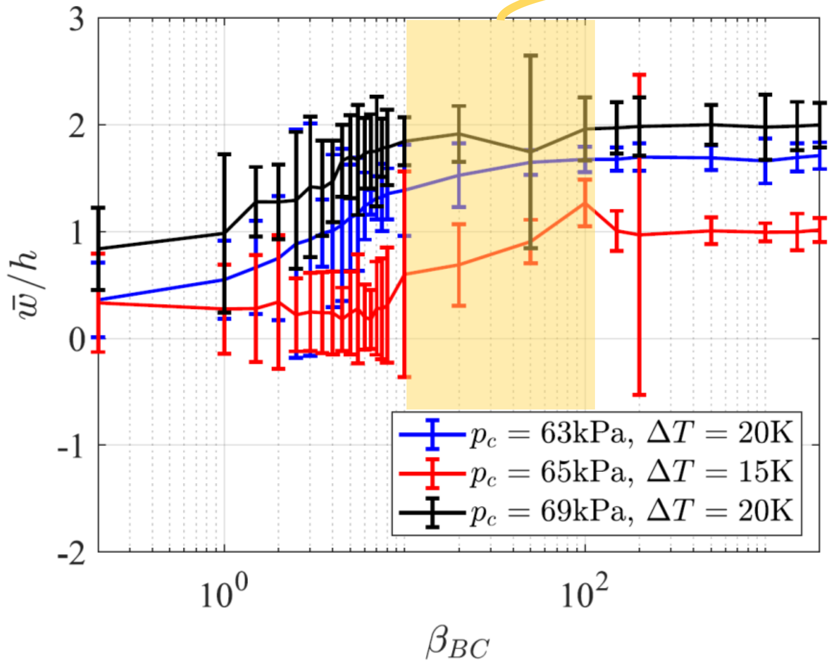
$p_c = 63$ and 65 kPa → considers a smaller cavity pressure to assess the LCO behavior after the shock location

Individual Studies

Exploratory Study

Target Study





β_{BC} range from the FEM study

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Aeroelastic solution for a range of p_c, ΔT, and β_{BC}

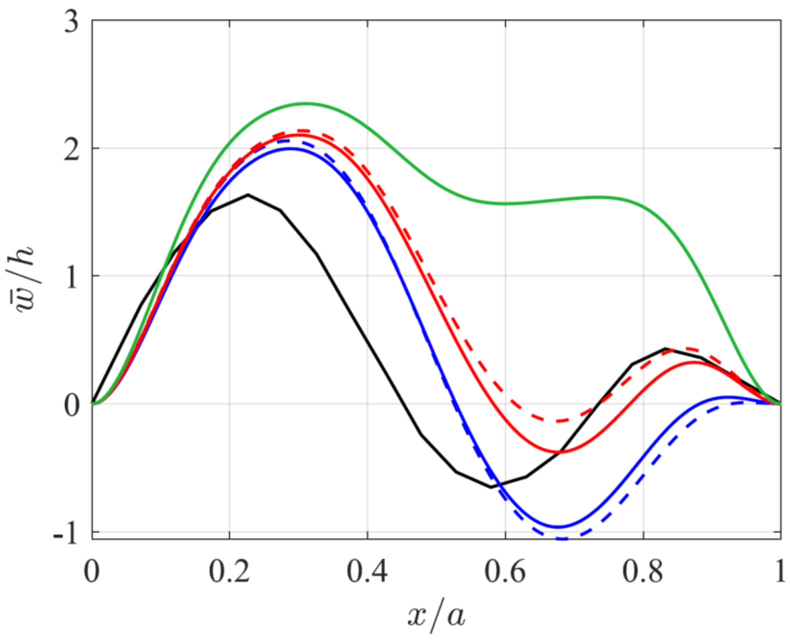
Aerodynamic Model: Euler/DLTA, $M_\infty = 2.0$, no wind tunnel walls

Individual Studies

Exploratory Study

Target Study

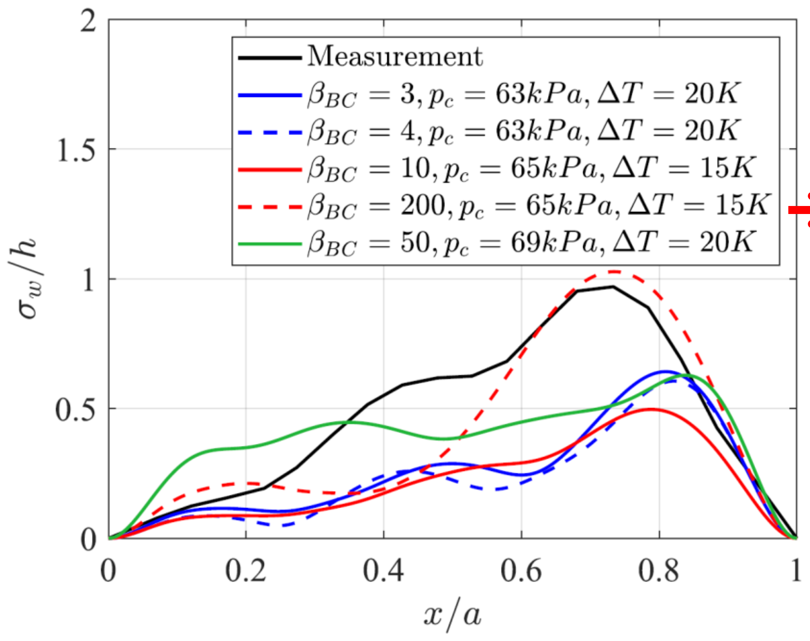
Mean deformation



Bigger ΔT leads to bigger mean deformation in the post shock region

$p_c = 69$ kPa keeps all oscillations above the y-axis line

Standard Deviation



Very chaotic LCO

LCO after the shock location more sensitive to the smaller ΔT conf.

$p_c = 69$ kPa leads to a “first mode-shape” deformation

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Next Steps

Individual Studies

1. FEM study on the in-plane boundary support (β_{BC}) sensibility
2. Validation/correlation of the temperature distribution over the panel and the Heat Equation (HE) implementation

Exploratory Study

1. Explore a range of p_c, ΔT, β_{BC} (based on the previous step)
2. Euler w/o walls vs. RANS w/ walls
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4. Implementation of the HE in the aeroelastic solver

Target study

1. Specific sets of of p_c, ΔT, β_{BC} (longer time-marching solutions)
2. Selected case for the aerodynamics and heat flux computation

- Implement the DLTA (Euler or RANS) to the no-shock configuration and correlate with measurements
- Implement the aeroelastic solver coupled with the Heat Equation.
- "Target study"

Additional step:

8° shock wedge configuration: assess the modal convergence and the (potential) fluid instability after the wedge body

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