Correlation of Mathematical Model with AFRL RC-19 Aerothermoelastic Experiment Including an Impinging Shock

AIAA AVIATION Forum 2025

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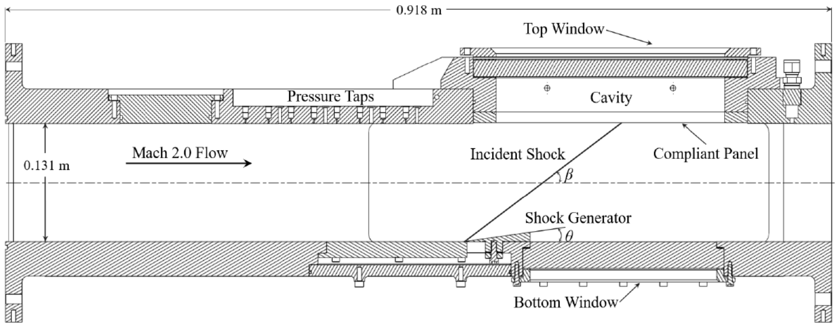
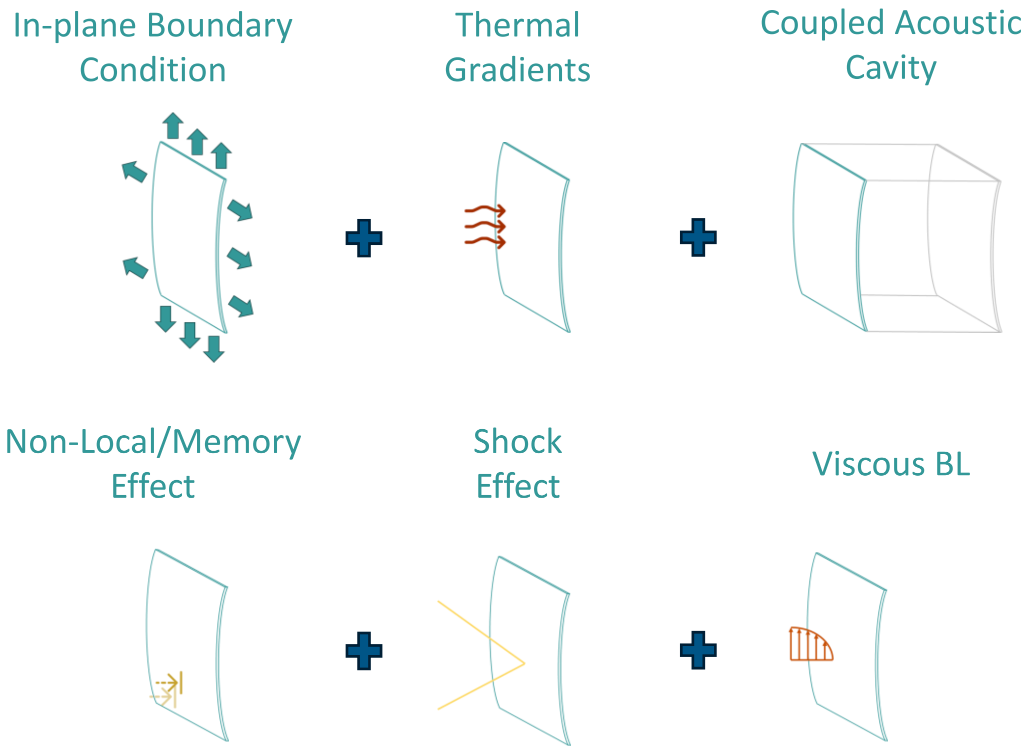
Motivation for this Work

- 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**



Brouwer et al. AIAAJ (2021)



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Mathematical/Computational Modeling

Nonlinear Aeroelastic Solver

Set Boundary Conditions

- p_C fixed
- ΔT fixed
- ICs
- Flow parameters

Compute Structural Matrices

- Geometrical dimensions
- β_{BC} varying per run

Compute Aerodynamic Matrices

- Numerical Methods (ROM): Dynamically Linearized Time-domain Approach

Solve ODE in terms of the generalized coord.

$$\underbrace{M_{mn}\ddot{q}_n(t) + C_{mn}\dot{q}_n(t) + G^{(2)}_{mn}q_n(t)}_{\text{Linear plate model}} + \underbrace{D^{(2)}_{mnrp}q_n(t)q_r(t)q_p(t)}_{\text{NL structural stiffness}} + \underbrace{Q^{Aero}_m}_{\text{Aero}} + \underbrace{Q^{static}_m}_{\text{Static pressure differential}} = 0$$

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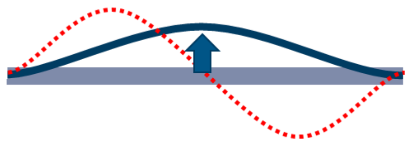
ROM to include unsteady aerodynamics into the aeroelastic solution

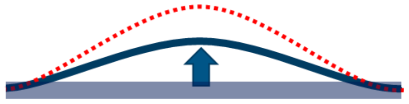
Step change in the CFD domain for each ψ_{mn} …

… in the panel deformation:



1^{st} set of CFD runs

… in the velocity of the panel deformation:



2^{nd} set of CFD runs

… to obtain a pressure field (output) from a known deformation (input)

$$Q_{mn}^{CFD}(t) = \iint \frac{\Delta p_m(x,y,t)}{\rho_\infty U_\infty^2} \psi_n(x,y)dxdy$$

Work the other way around to obtain the A_{mn}, B_{mn}, and $E_{mn}(t)$ using the input/output relationship

$$Q_{mn}^{CFD}(t) = q_m(t)A_{mn} + \dot{q}_m(t)B_{mn} + \int_0^t q_m(\tau)E_{mn}(t-\tau)d\tau$$

Once A_{mn}, B_{mn}, and $E_{mn}(t)$ are obtained, we can reconstruct the Generalized Aerodynamic Force inside the Aeroelastic Solver for any arbitrary panel deformation ($q_m(t)$, $\dot{q}_m(t)$)

$$Q_{mn}(t) = q_m(t)A_{mn} + \dot{q}_m(t)B_{mn} + \int_0^t q_m(\tau)E_{mn}(t-\tau)d\tau$$

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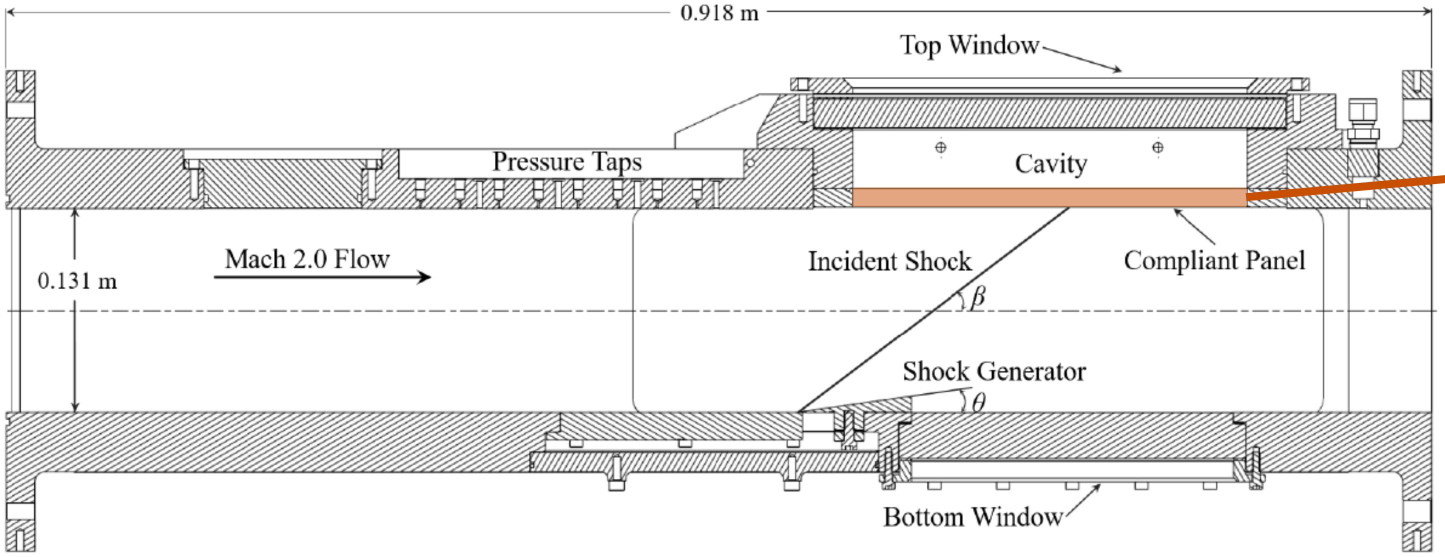
Experimental Study Case: AFRL/SD RC-19 Wind Tunnel Section

Additional Considerations: In-plane boundary condition



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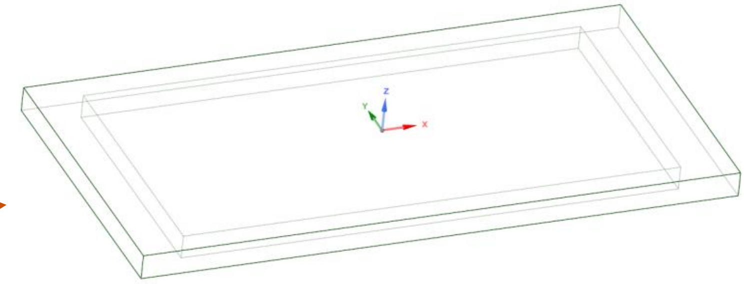

Nonlinear structural behavior

In-plane boundary stiffness

"allowing the panel to deform at the edges as a reaction to the fixed support"

In-plane boundary stiffness

Nondimensional in-plane boundary stiffness

$$\beta_{BC} \equiv \frac{K_{BC}\,a}{E\,h}$$

Panel length

Panel thickness

$\beta_{BC} \approx 0$: Free edge displacement

$\beta_{BC} \gg 0$: No edge displacement

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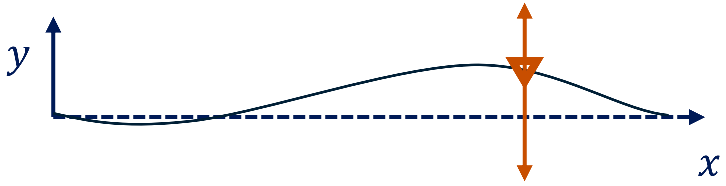
Experimental Study Case: AFRL/SD RC-19 Wind Tunnel Section

Additional Considerations: In-plane boundary condition

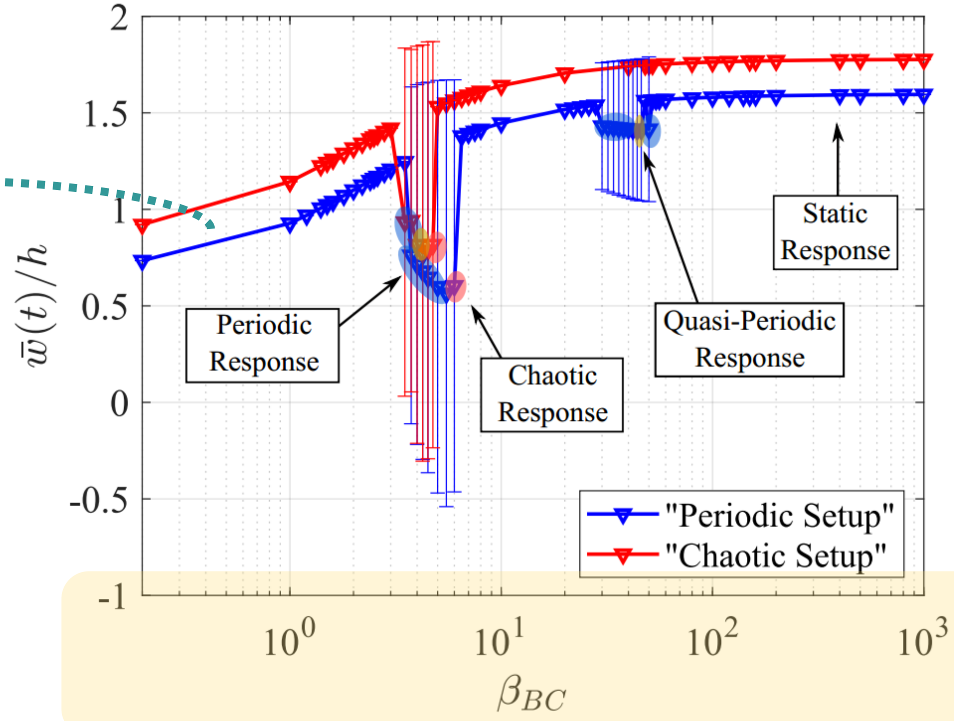
Results are presented as a function of the β_{BC}, which is a **structural** parameter

For example:

Mean and STD of the panel deformation at ¾ of the panel length using Linear Piston Theory as the aerodynamic model



Mean & SDT deformation



Piccolo Serafim et al. JFS (2023)

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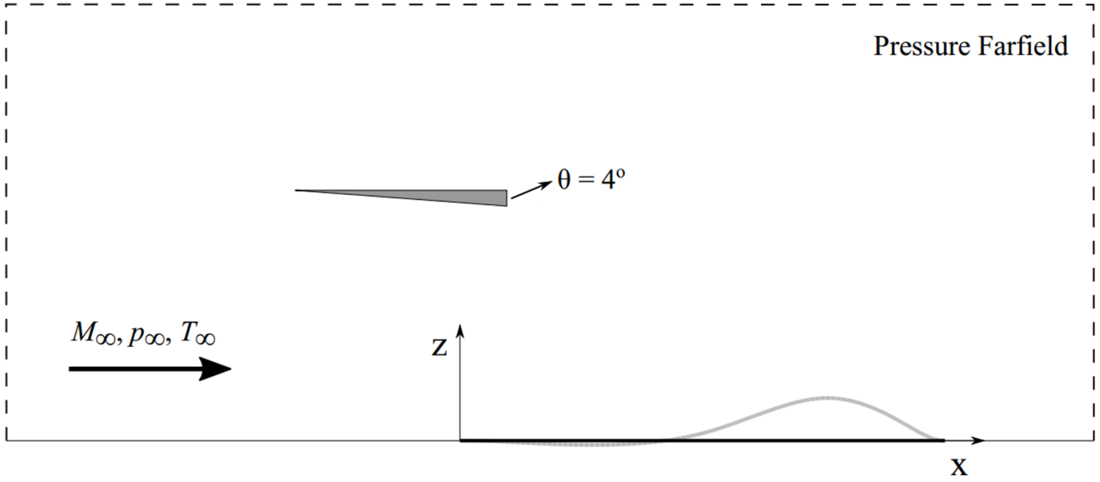
DLTA with a Shock Impingement

$\theta = 4^{\circ}$ wedge shock configuration

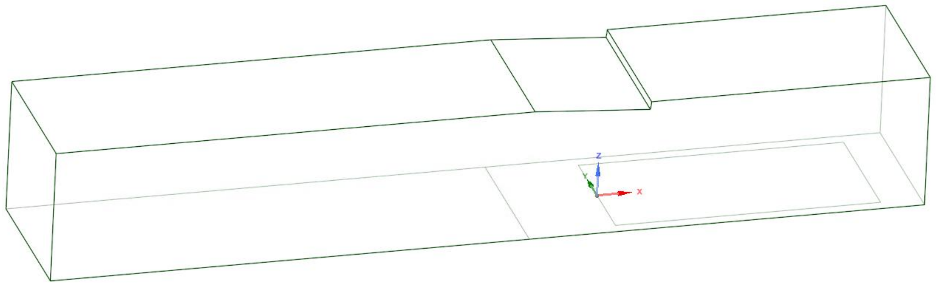
Aerodynamic Model: Euler (unsteady)/DLTA

(Dynamically Linearized Time-Domain Approach)



Aerodynamic Model: RANS (unsteady)/DLTA

(Dynamically Linearized Time-Domain Approach)



In-Plane boundary stiffness sensitivity

$M_{\infty} = 2.0$

ΔT between panel and frame

Δp between fluid and acoustic cavity

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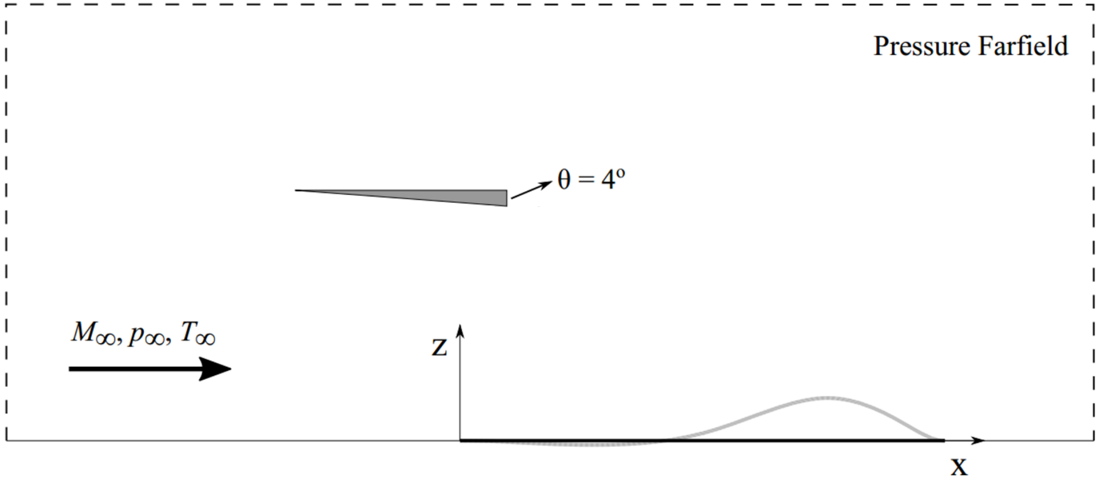

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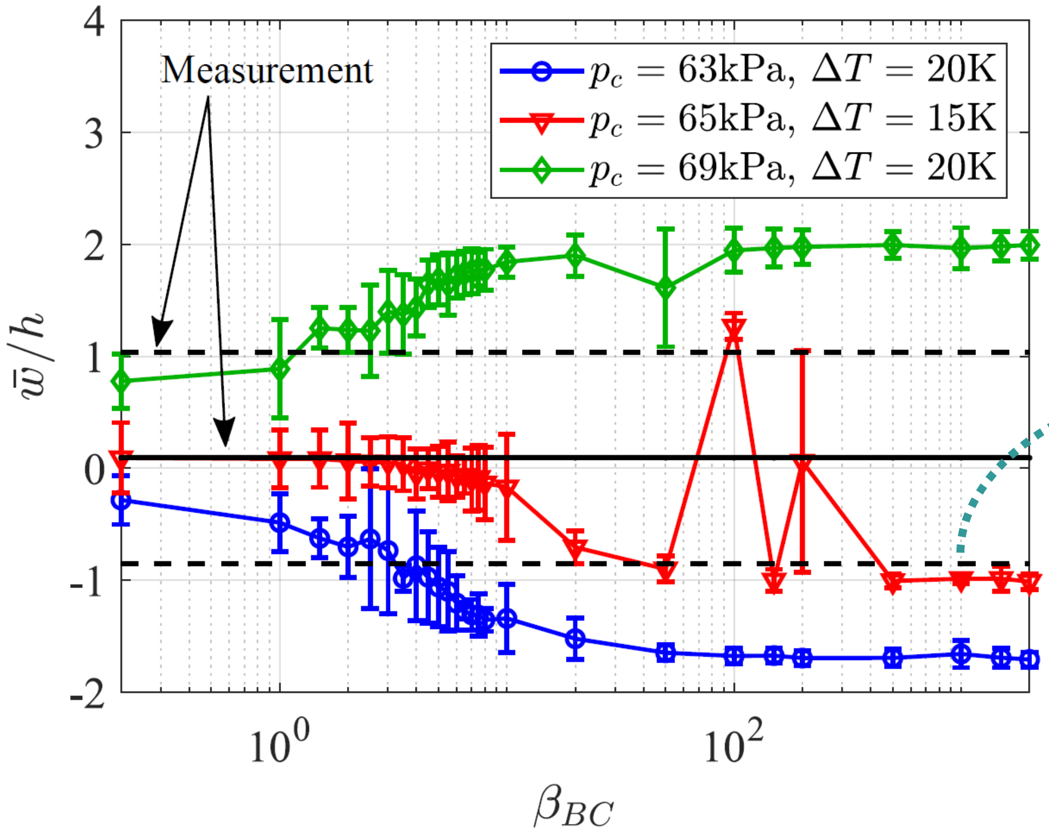
DLTA with an Inviscid Shock Impingement

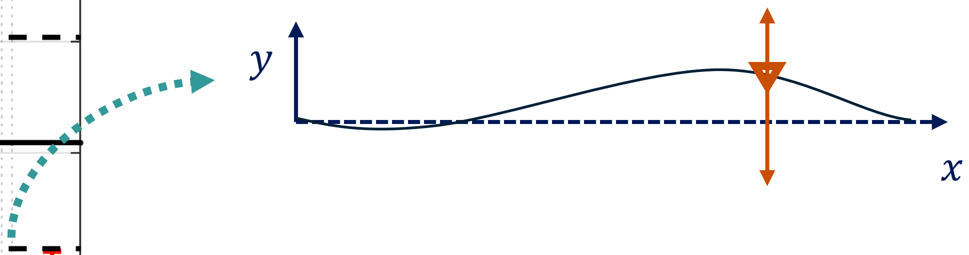
$\theta = 4^{\circ}$ wedge shock configuration

Wind Tunnel Setting

p_c (kPa)	ΔT (K)
68.9	13.3

Mean & SDT deformation
(at ¾ of the panel length)





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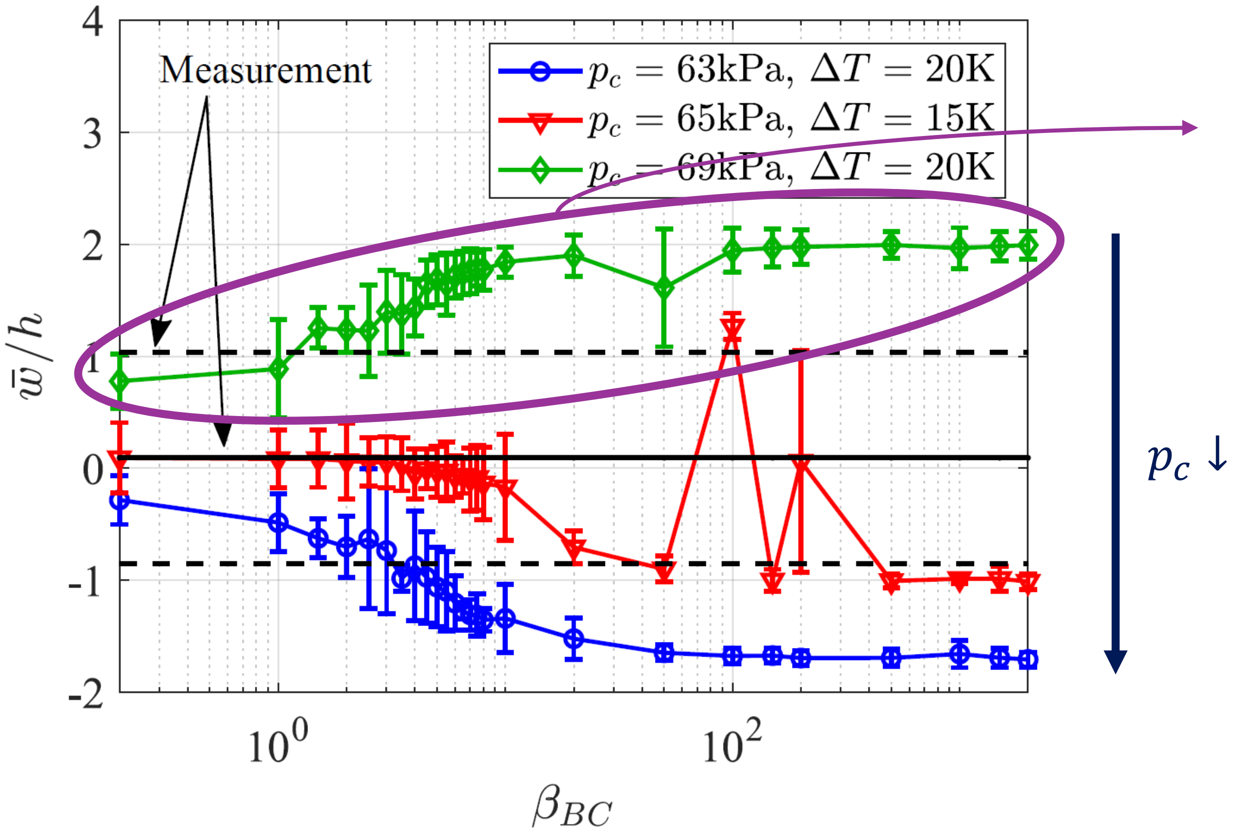

Similar to the wind tunnel setting

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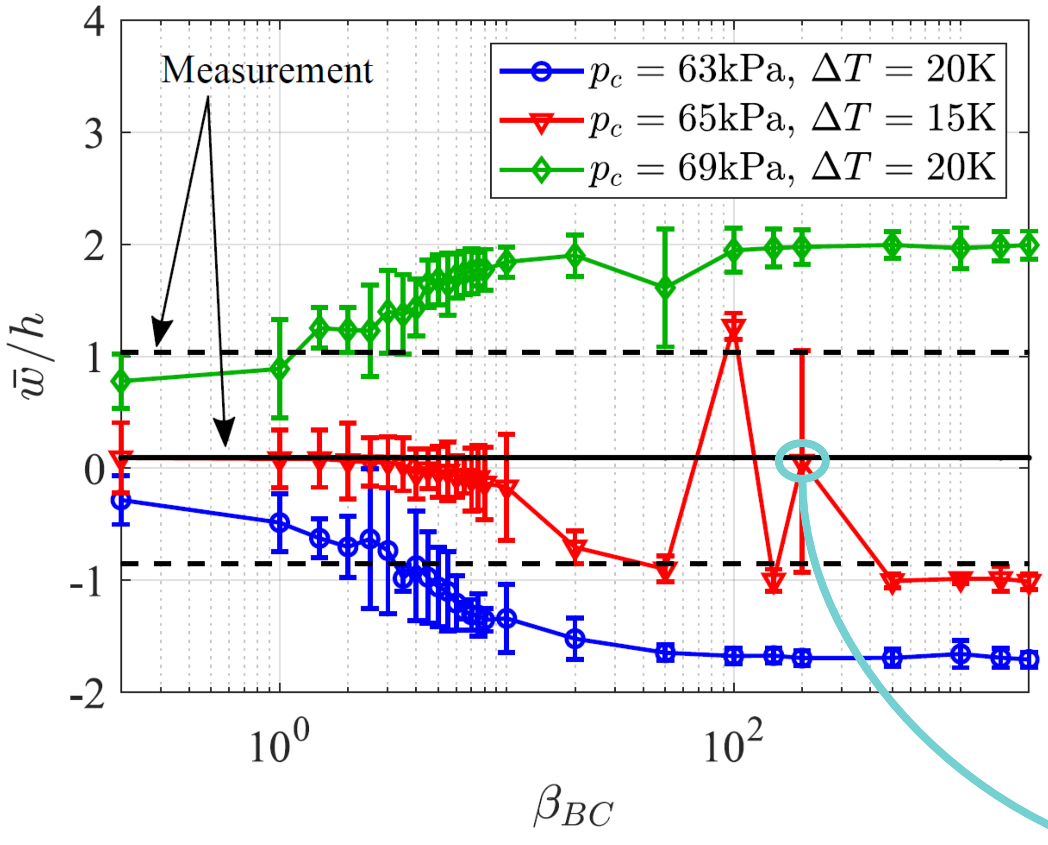
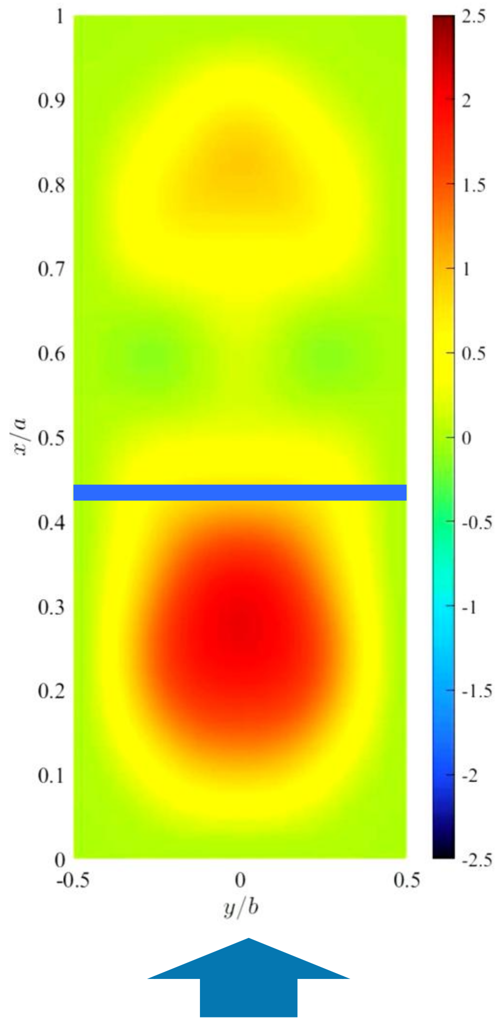
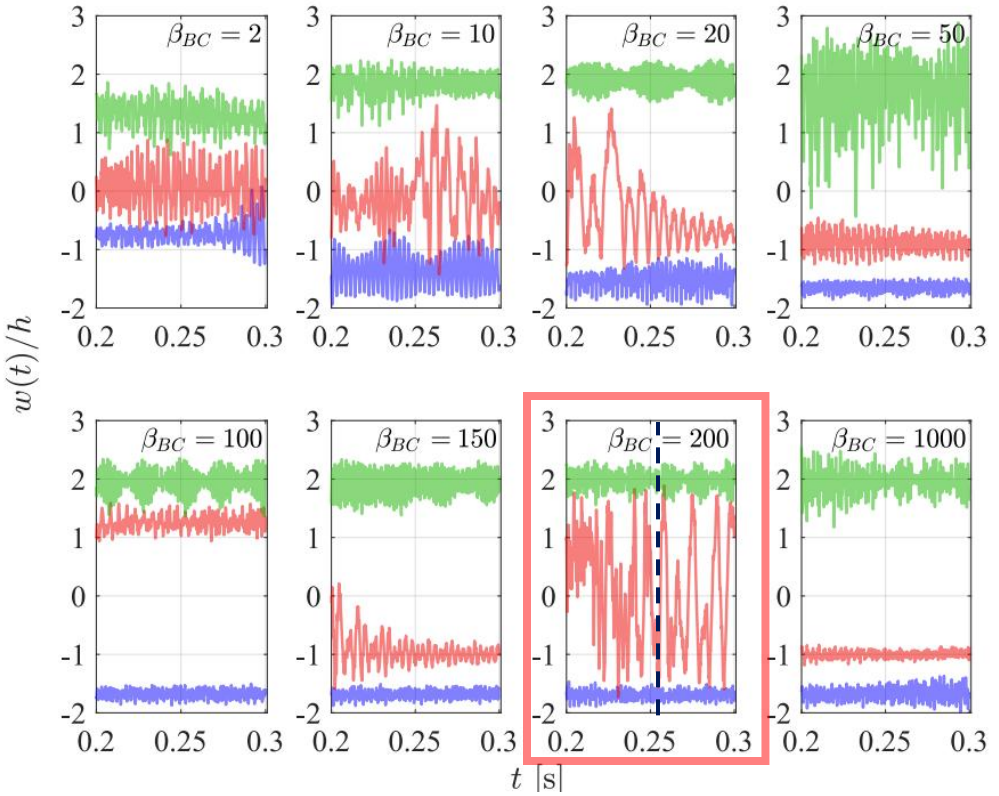




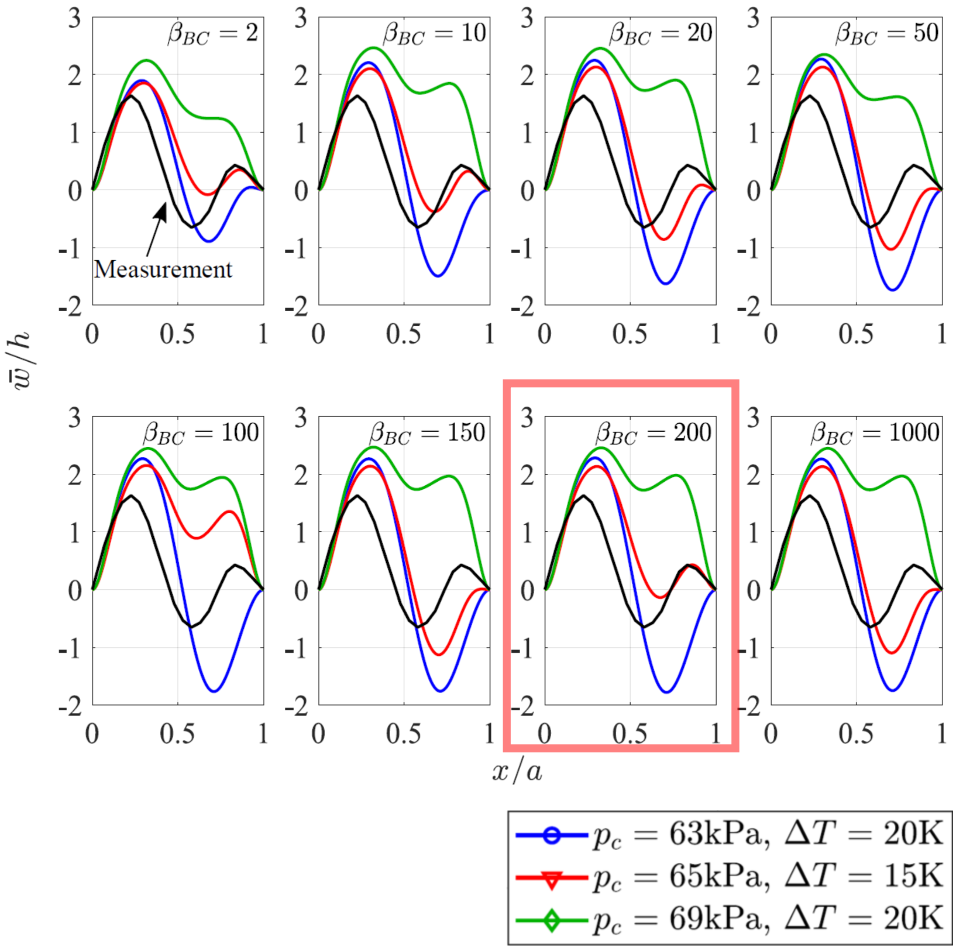
Flow Field

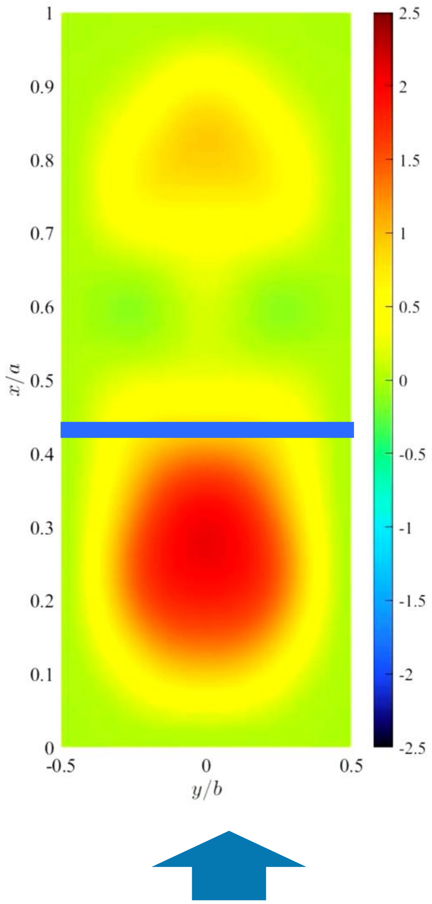
DLTA with an Inviscid Shock Impingement

Deformation in time
(at ¾ of the panel length)



Mean deformation





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Aerodynamic Model: RANS (unsteady)/DLTA

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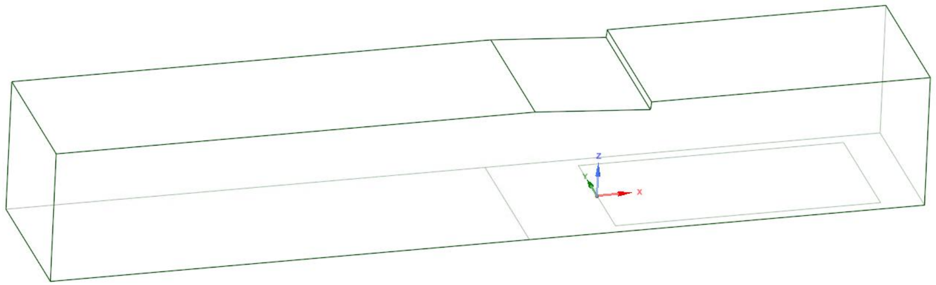

In-Plane boundary stiffness sensitivity

$M_\infty = 2.0$

ΔT between panel and frame

Δp between fluid and acoustic cavity

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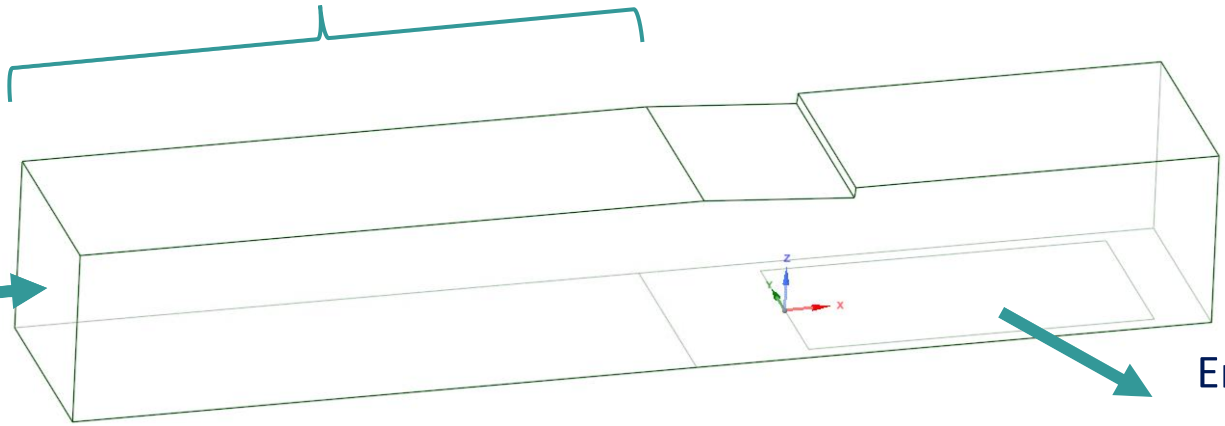
DLTA with a Shock Impingement

$\theta = 4^{\circ}$ wedge shock configuration: CFD setup

SST $k - \omega$
$y^{+} = 5$ and 1
$\delta_{LE} \approx$ 8mm (Wind Tunnel: $\delta_{LE} \approx$ 8.6mm)
$\delta_{LE}/a \approx 0.03$ (Wind Tunnel: $\delta_{LE}/a \approx 0.033$)

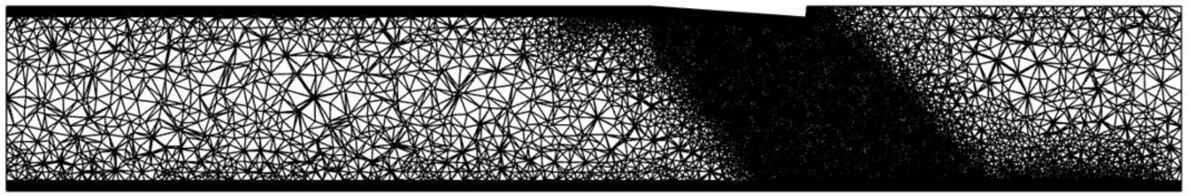
Distance between the end of the nozzle and the elastic panel

Inlet BC
$M_{\infty} = 2.0$



Outlet BC

Enforced motion only on the “elastic panel”



Inflation layer on the lower and upper (pre-wedge/wedge) walls

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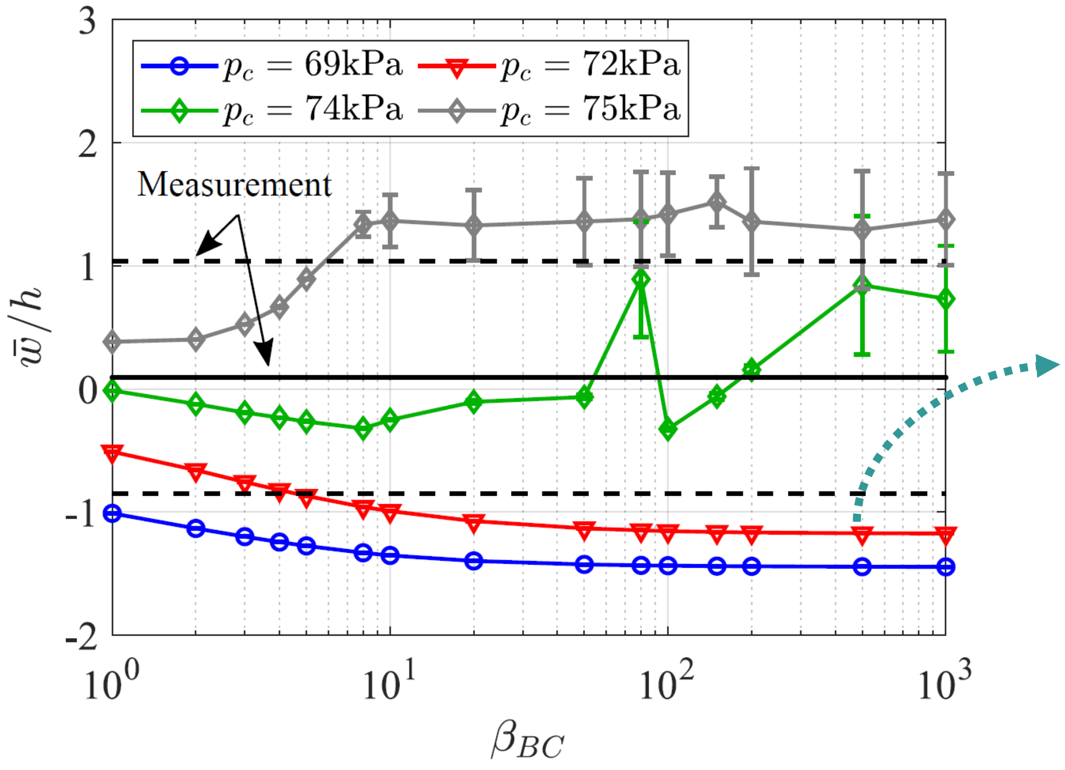
DLTA with a Viscous Shock Impingement

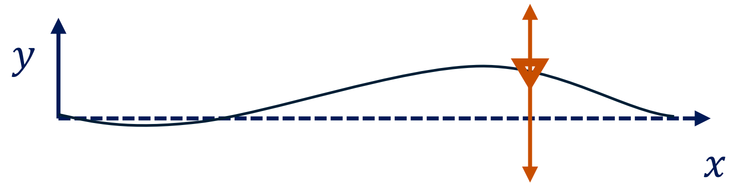
$\theta = 4^{\circ}$ wedge shock configuration

$\Delta T = 15$ K
$y^{+} = 1$

Mean & SDT deformation

(at ¾ of the panel length)





Wind Tunnel Setting

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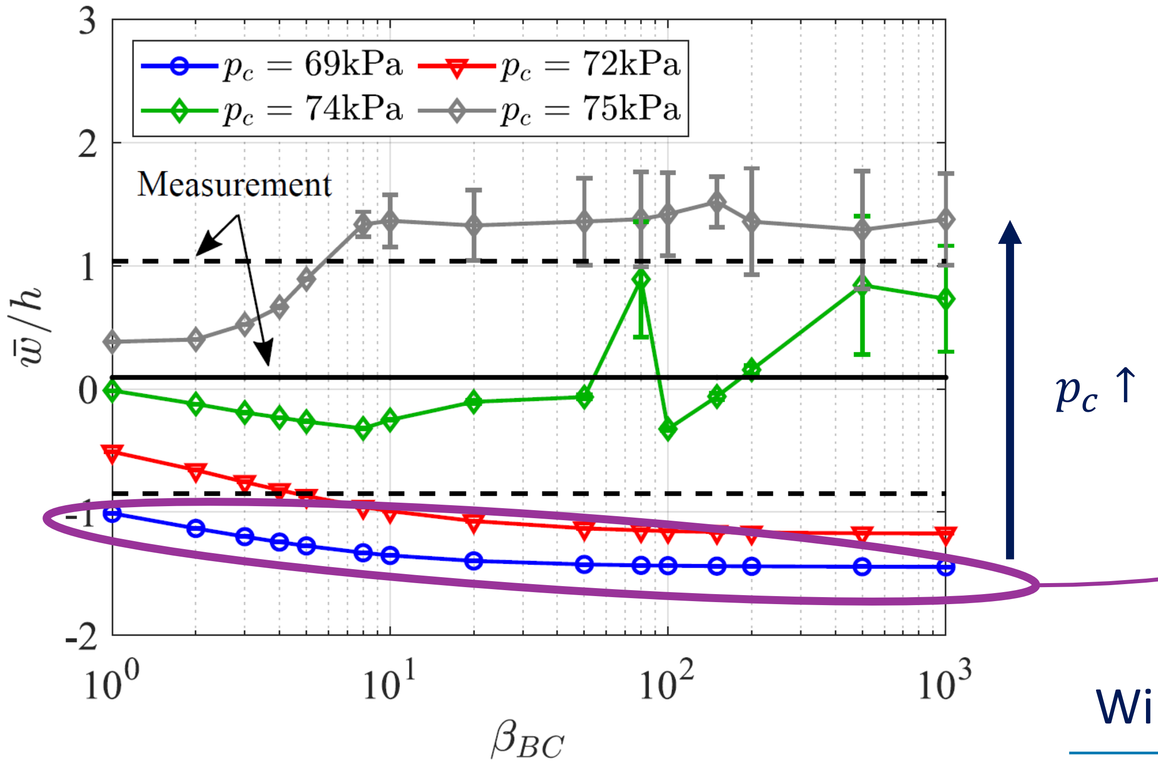

Similar to the wind tunnel setting

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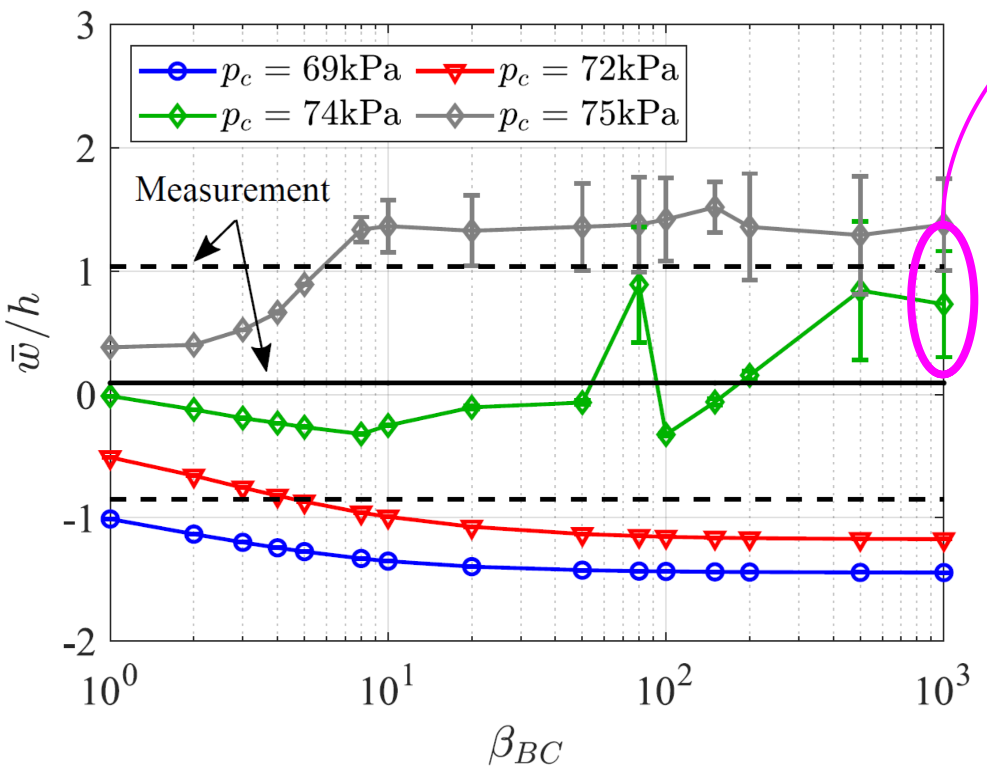

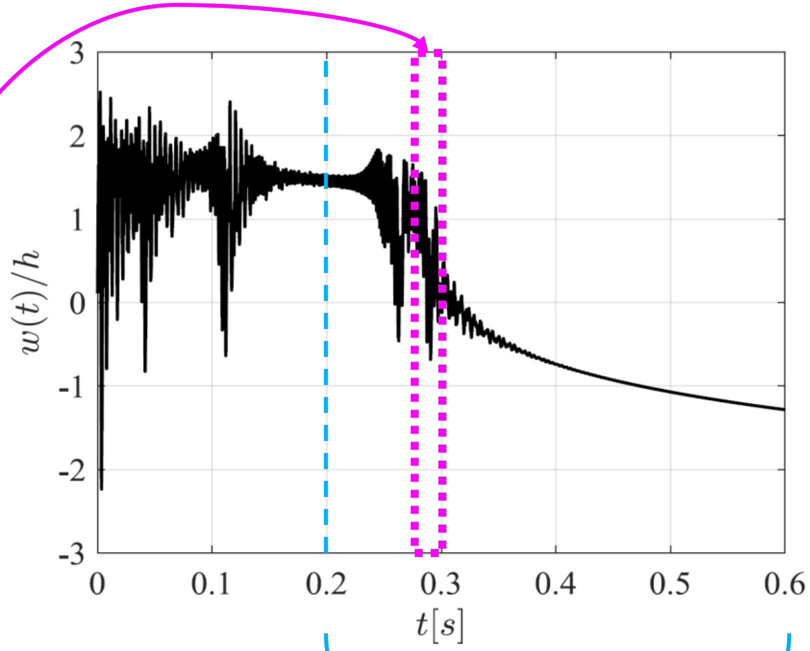

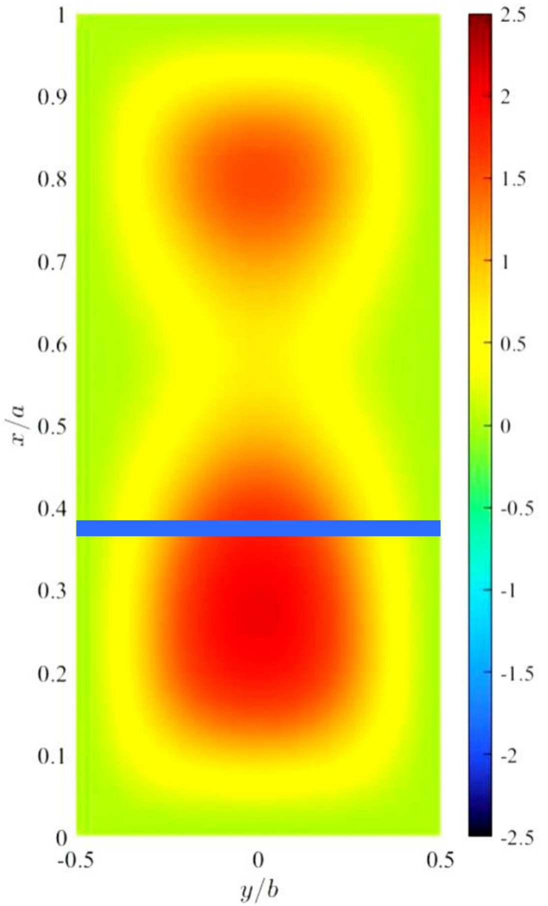

Wind Tunnel Setting

p_c (kPa)	ΔT (K)
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Flow Field

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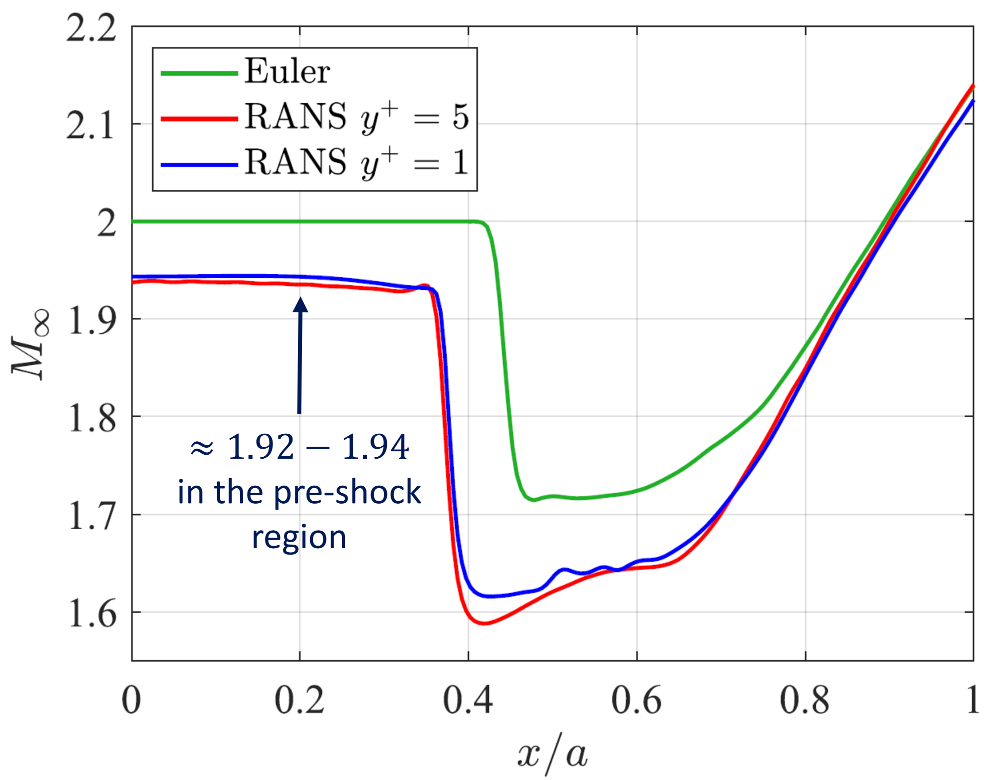
Shock Impingement Aerodynamic Properties

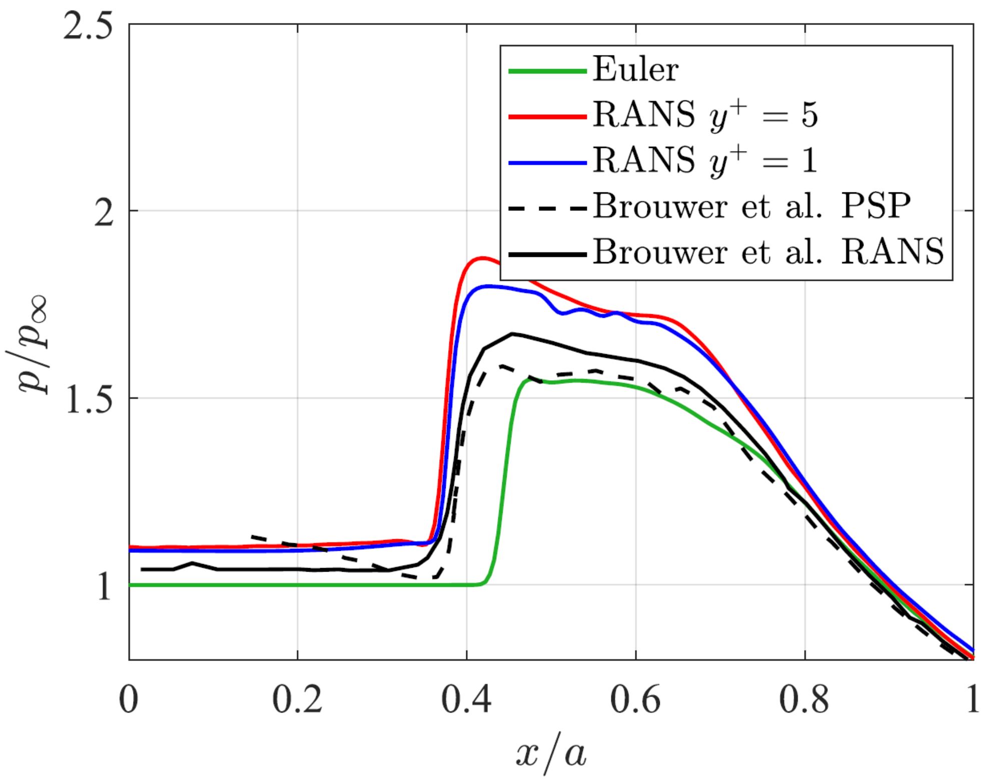
Steady Solution

Local Mach number



Flow more likely to cause structural instability

Static pressure

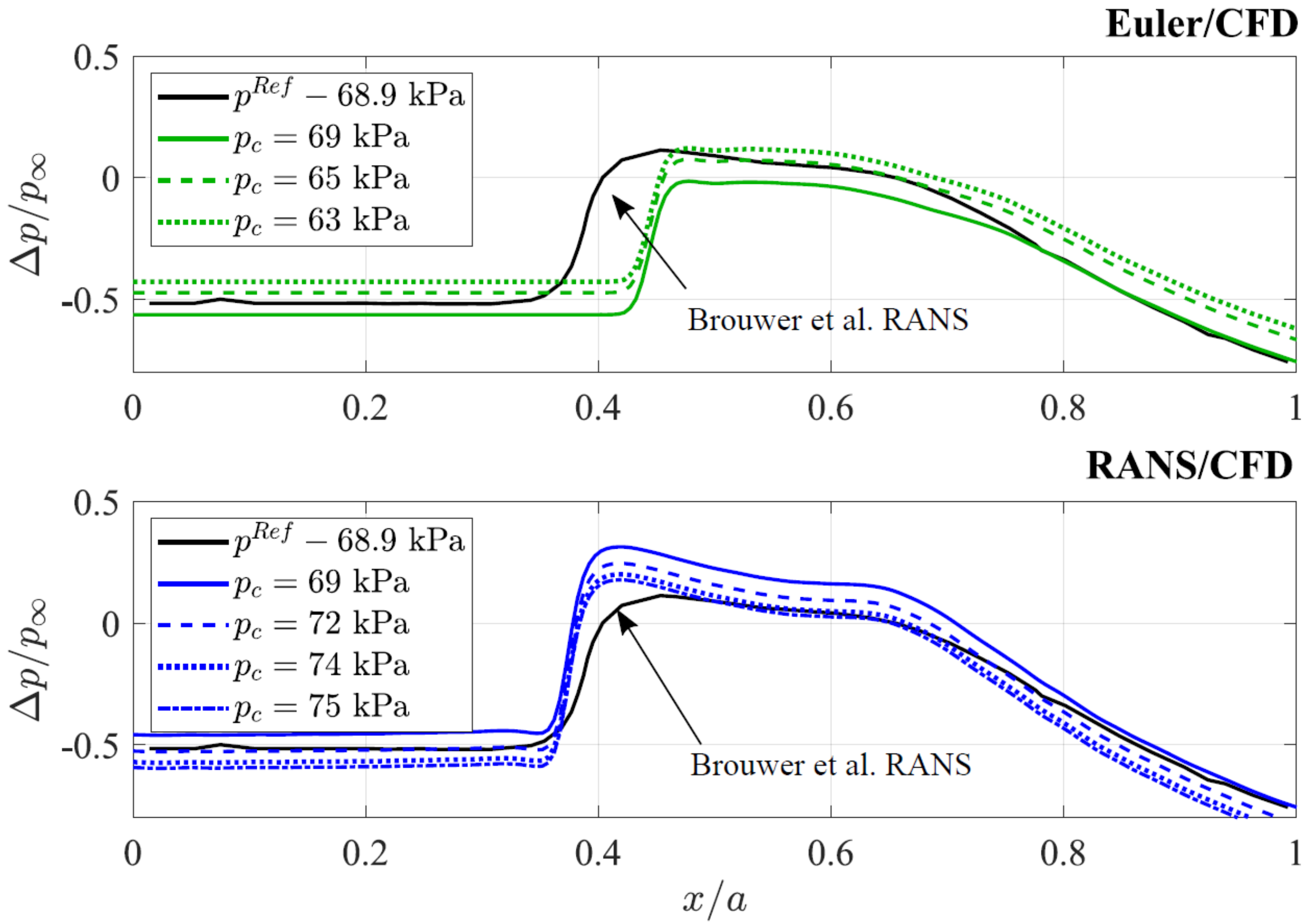


Panel stiffened by the Δp effect

Shock Impingement Aerodynamic Properties

Steady Solution

Static pressure differential



Panel stiffened by the Δp effect

Conclusion

- A range of aerodynamic models has been considered including Linear Piston Theory and Full Potential Flow for the no-shock case, and Euler and RANS/DLTA for the shock impingement case.
- 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.
- **Results for flutter and LCO of the RC-19 experiment are not particularly sensitive to the aerodynamic model**, with the key exception that when using the DLTA/CFD method, the steady solution for the shock location/magnitude can present indirect implications in the LCO prediction.

The computational models agree with the observations from experiments **on the essentials of the physical phenomena** e.g. buckling, flutter and limit cycle oscillations.

There is broad quantitative agreement between computations and experiments, given the sensitivity of the results to a wide range of parameters**.**

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