AePW-3
High Speed Working Group
RC-19 no impingement shock case

Aeroelasticity Laboratory | Duke University

Luisa Piccolo Serafim, Earl Dowell

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Summary

- For the experimental configuration considered → the flutter/LCO results are sensitive to Δp, ΔT, and in-plane boundary conditions.

- For different combinations of Δp and ΔT considered to date → there are different intervals for β_{BC} where flutter/LCO is found

- For the no-shock impingement case → piston theory, full potential flow models present very similar results. The same similarity is seen for the static deformation if using the Euler aerodynamic model, but the β_{BC} values at which LCO occurs differ

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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:

$$Q^{static}_m = \int_0^b \int_0^a \frac{[p_\infty(x,y) - p_{cavity}(x,y)]}{\rho_\infty U^2_\infty}\psi_n(x,y)dxdy$$

where

$$w(x,y,t) = \sum_n q_n(t)\psi_n(x,y)$$ → Linear eigenmodes

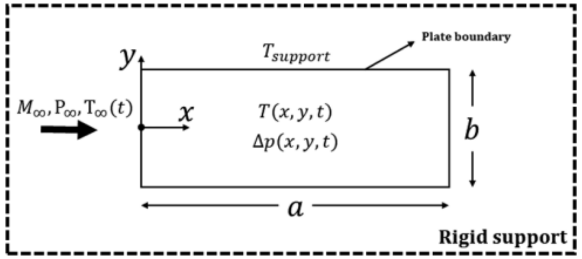

Fig. 1 Plate top view with freestream flow, static pressure differential, and support and plate temperatures.

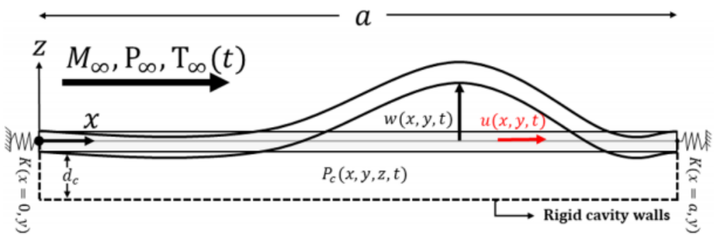

Fig. 2 Side view of plate, freestream flow, cavity, and in-plane edge stiffness $K(x = [0,a], y)$; and cross section at $-b/2 < y < +b/2$.

Freydin and Dowell. AIAA(2020)

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Effect of In Plane Boundary Stiffness on Panel Response

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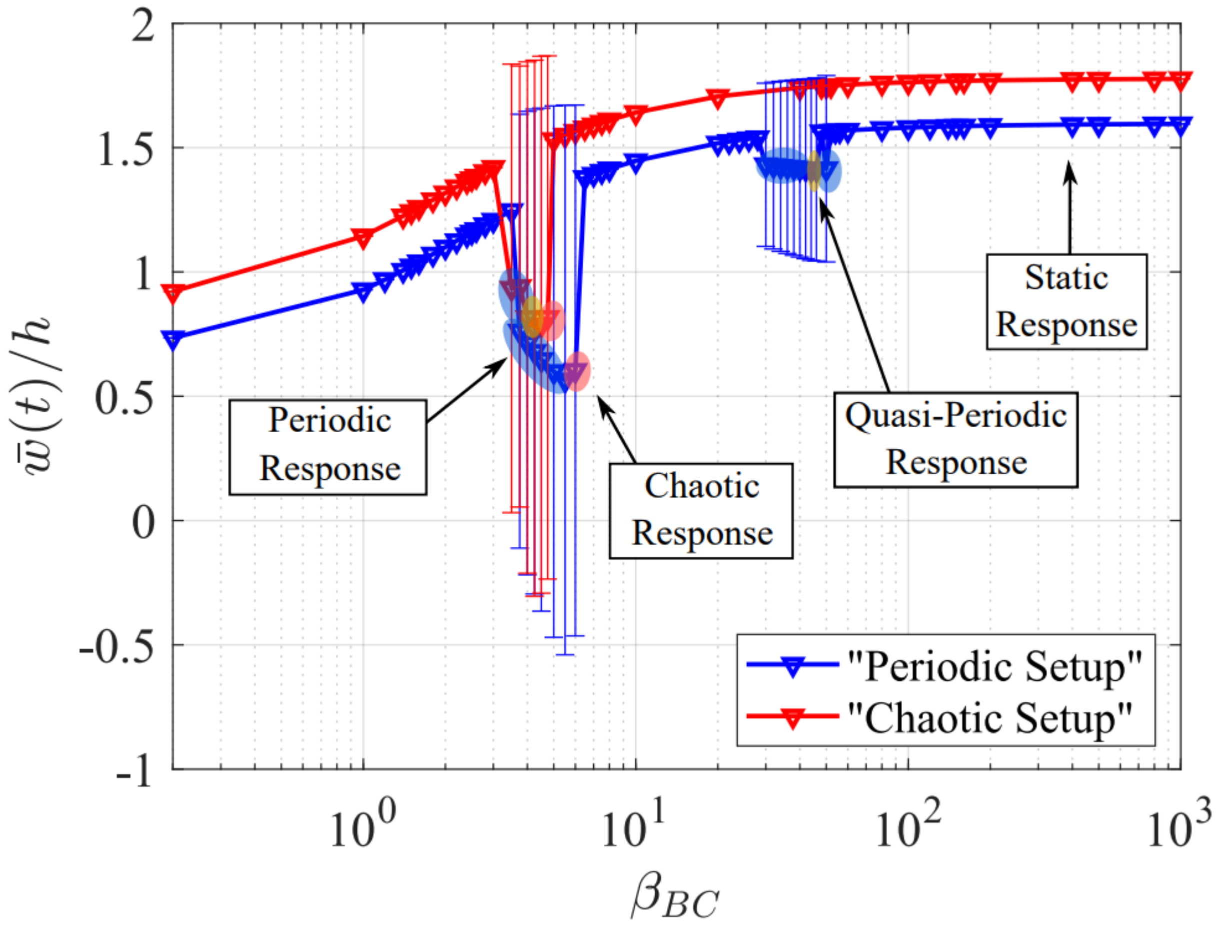

Periodic Parameters		Chaotic Parameters	
Δp (kPa)	-3.91	Δp (kPa)	-5.01
ΔT (K)	12.8	ΔT (K)	14.7

β_{BC} can be determined from a ground vibration test

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

$$M_\infty = 1.94$$

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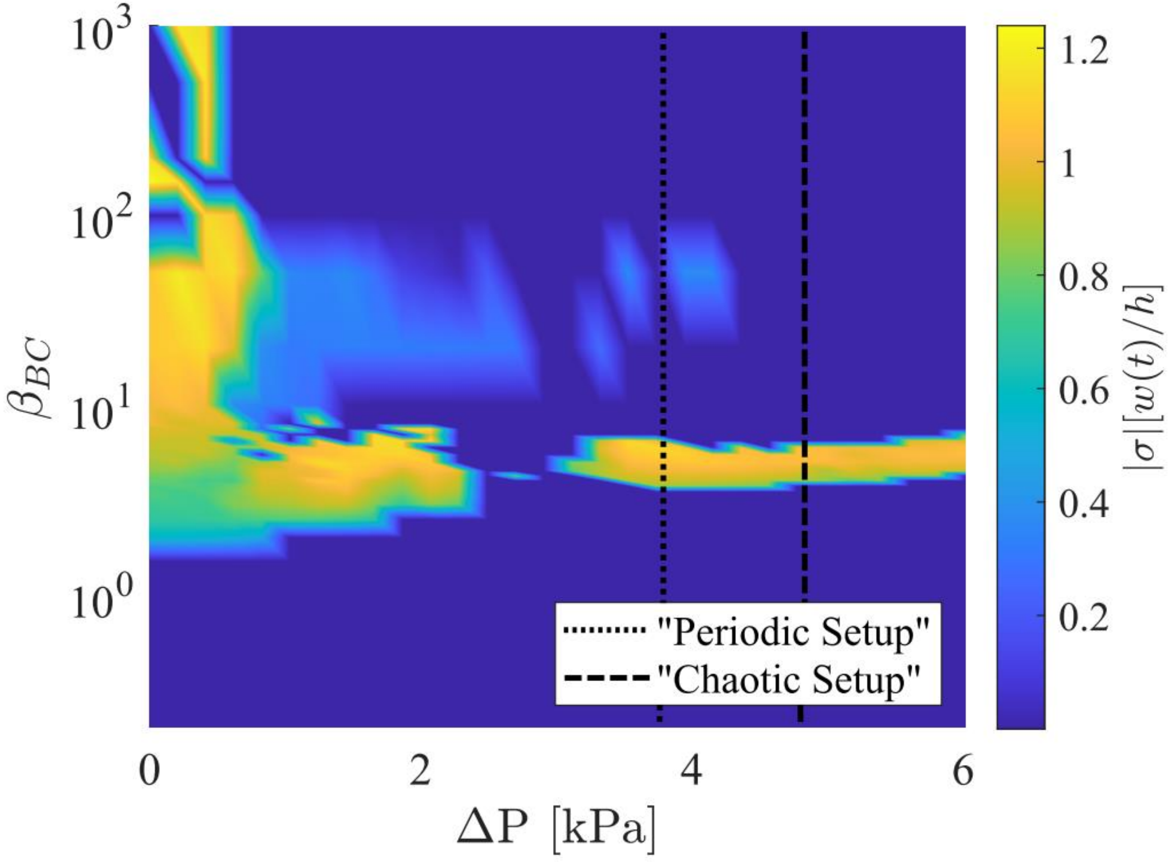
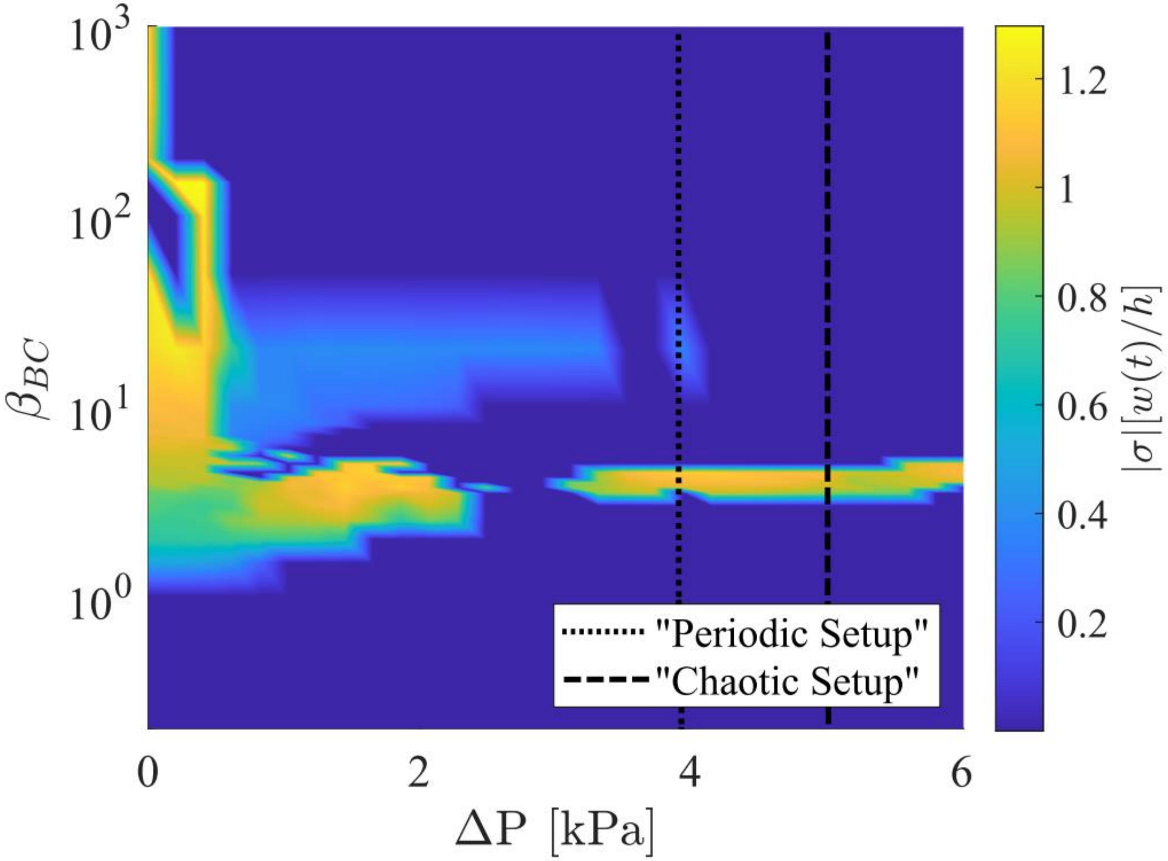
Piccolo Serafim et al. JFS(2023)

Effect of In Plane Boundary Stiffness on Panel Response

Flutter critical boundary - Δp *vs.* β_{BC}



ΔT from "Periodic Setup"



ΔT from "Chaotic Setup"

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ΔT and Δp sensibility

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	$\Delta p = 0$	**Nominal Δp (Periodic/Chaotic)**	**Δp from Diamond-Shock Profile**	**Δp from Exp. Data**
$\Delta T = 0$	-	Steady Deformation	Steady Deformation	LCO (All range of β_{BC})
Nominal ΔT (Periodic/Chaotic)	LCO (All range of β_{BC})	LCO (Limited range of β_{BC})	LCO (Limited range of β_{BC})	-
ΔT from Heat Equation	LCO (All range of β_{BC})	Steady Deformation	LCO (All range of β_{BC})	LCO (All range of β_{BC})

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	$\Delta p = 0$	Nominal Δp (Periodic/Chaotic)	Δp from Diamond-Shock Profile	Δp from Exp. Data
$\Delta T = 0$	-	Steady Deformation	Steady Deformation	LCO (All range of β_{BC})
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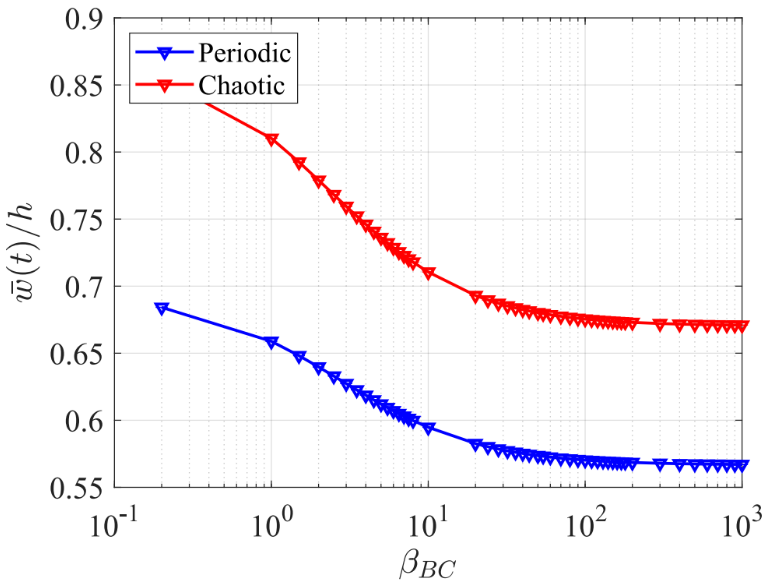
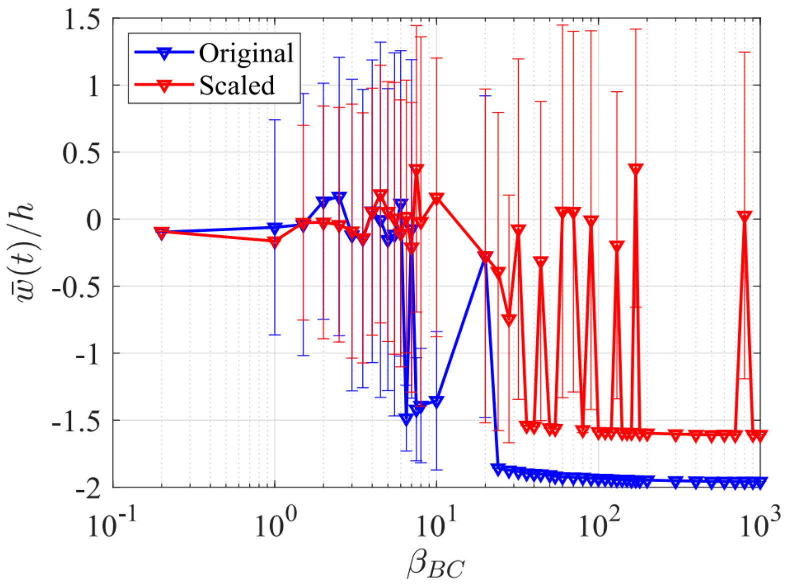
ΔT from Heat Equation	LCO (All range of β_{BC})	Steady Deformation	LCO (All range of β_{BC})	LCO (All range of β_{BC})





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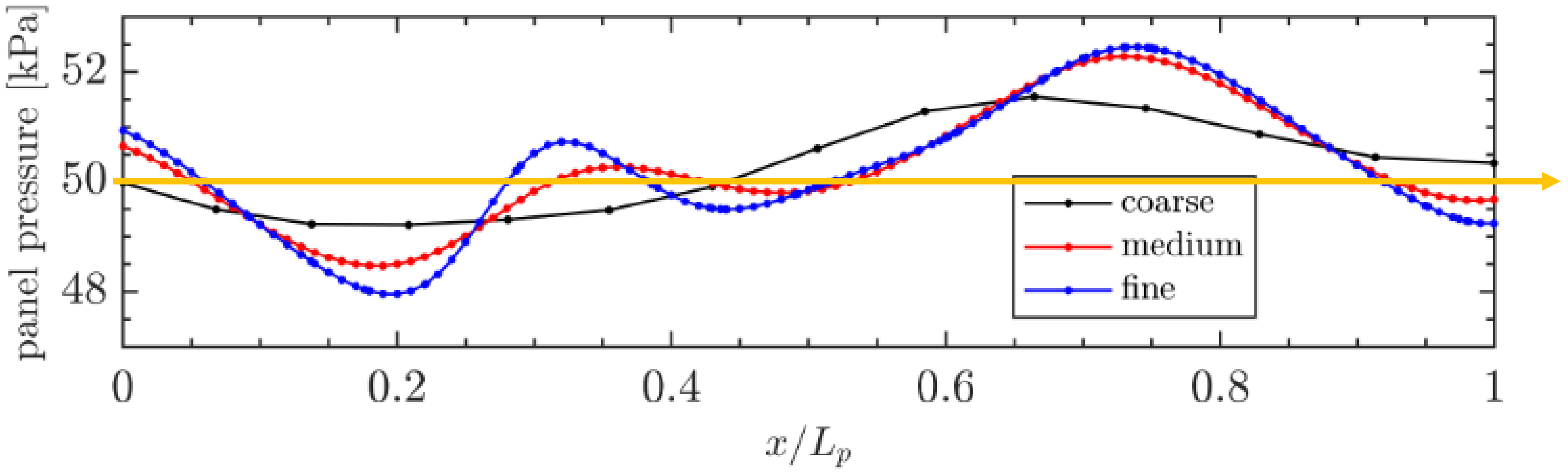
CASE I: Nominal ΔT (Periodic/Chaotic) *vs.* Δp from Diamond-Shock Profile



Average static pressure over the panel around $50\ kPa$

Pressure on the wall data from a CFD steady flow computation courtesy of Bret Stanford

Parameters considered in this analysis:

Uniform Δp distribution **only** on the y-direction

$$M_\infty = 1.92$$

$$p_\infty = 50.139\ kPa$$

$$\Delta T = 13\ K$$

To match the mean static pressure on the panel by using isentropic relations:

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Pressure profile on the wall into the PT matrices

$$Q_{m,n}(t) = q_m(t)S_{m,n} + \dot{q}_m(t)D_{m,n}$$

$$S_{m,n} = \frac{1}{M_\infty}\int_0^a \int_{-\frac{b}{2}}^{\frac{b}{2}} \gamma p_{wall}(x,y) M_{dist}(x,y) \frac{\partial \psi_m(x,y)}{\partial x} \psi_n(x,y) dydx$$

$$D_{m,n} = \frac{1}{M_\infty U_\infty}\int_0^a \int_{-b/2}^{b/2} p_{wall}(x,y) \sqrt{\left(\frac{\gamma}{R_{air}T_0}\right)\left[1+\left(\frac{\gamma-1}{2}\right)M_{dist}^2(x,y)\right]}\, \psi_m(x,y)\, \psi_n(x,y) dydx$$

where

$$M_{dist}(x,y) = \sqrt{\left[\left(\frac{p_{wall}(x,y)}{p_0}\right)^{-(\gamma-1)/\gamma}\right]\frac{2}{\gamma-1}} \quad \text{and} \quad p_{wall}(x,y) = p_{diamond-shock}(x,y)$$

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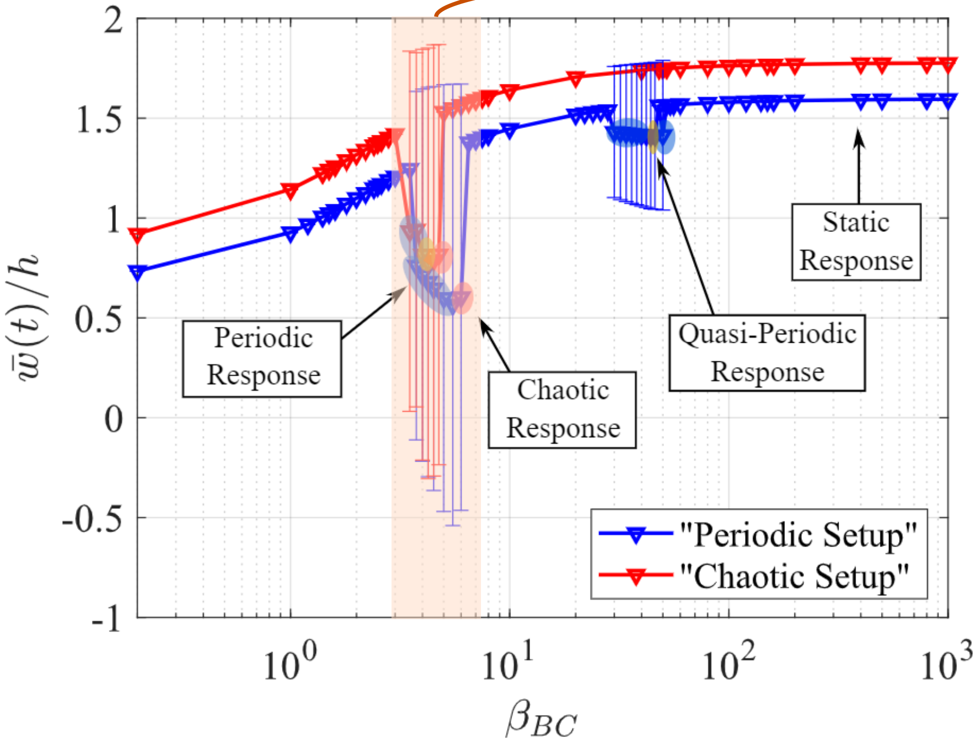
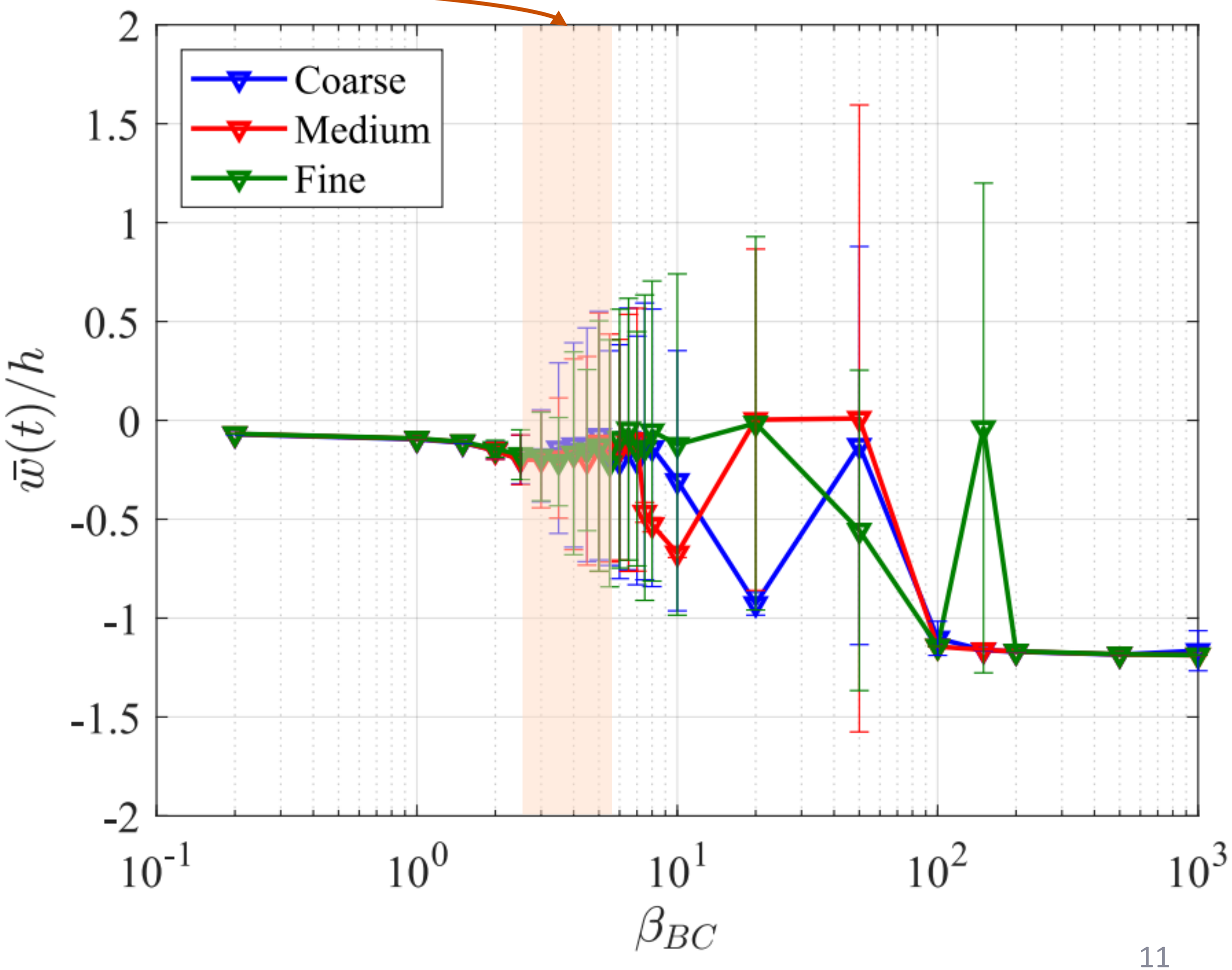
Effect of In Plane Boundary Stiffness on Panel Response

Enforcing Δp as Brouwer et al. (2020) in the Q_m^{static} definition

Using $\Delta p = p_{diamond-shock}(x,y) - p_{cavity}(x,y)$ in the Q_m^{static} definition AND the PT matrices



Piccolo Serafim et al. JFS(2023)



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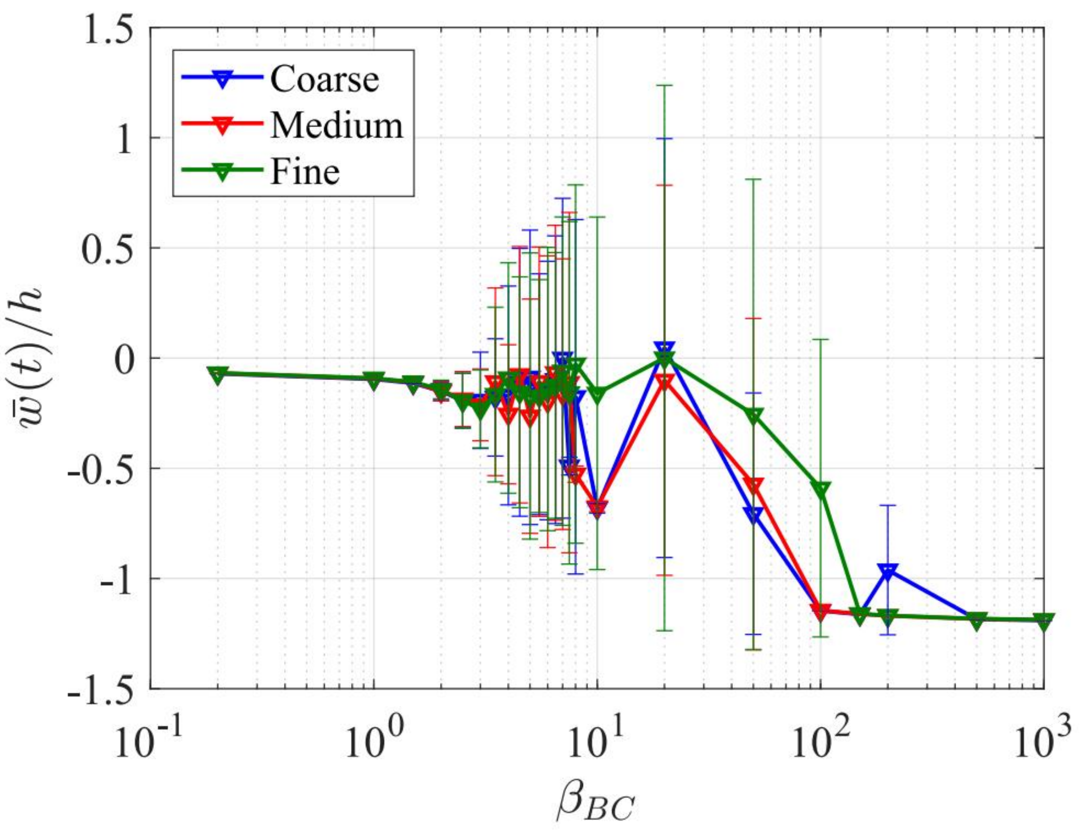
$$\beta_{BC} \equiv \frac{K_{BC}a}{Eh}$$

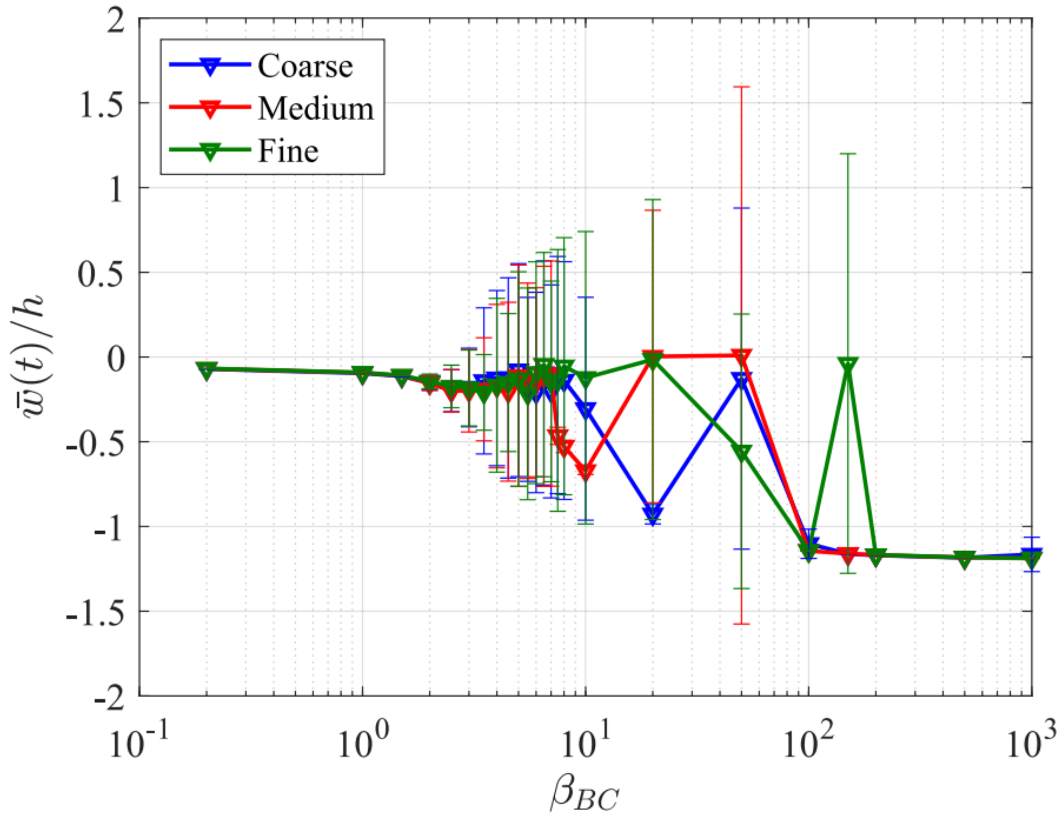
CASE I: Nominal ΔT (Periodic/Chaotic) *vs.* Δp from Diamond-Shock Profile

Effect of In Plane Boundary Stiffness on Panel Response

Using $\Delta p = p_{diamond-shock}(x, y) - p_{cavity}(x, y)$ in the Q_m^{static} definition



Using $\Delta p = p_{diamond-shock}(x, y) - p_{cavity}(x, y)$ in the Q_m^{static} definition AND the PT matrices



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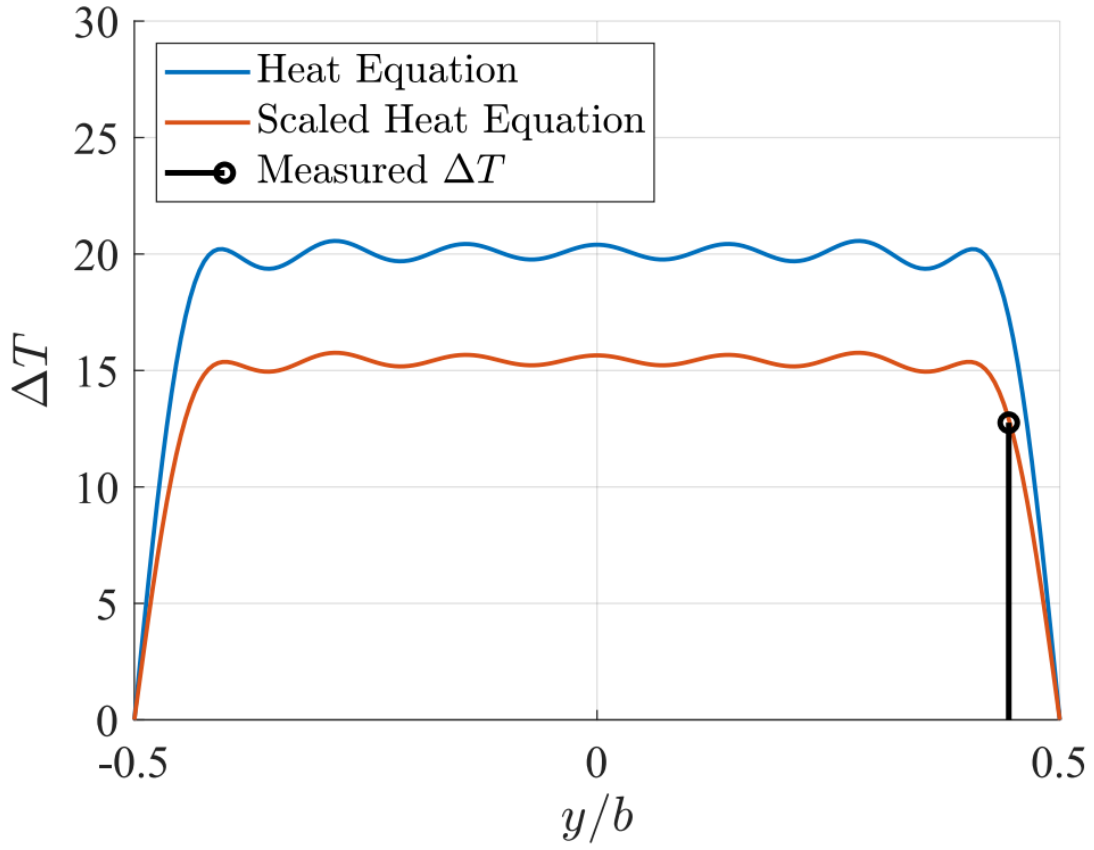
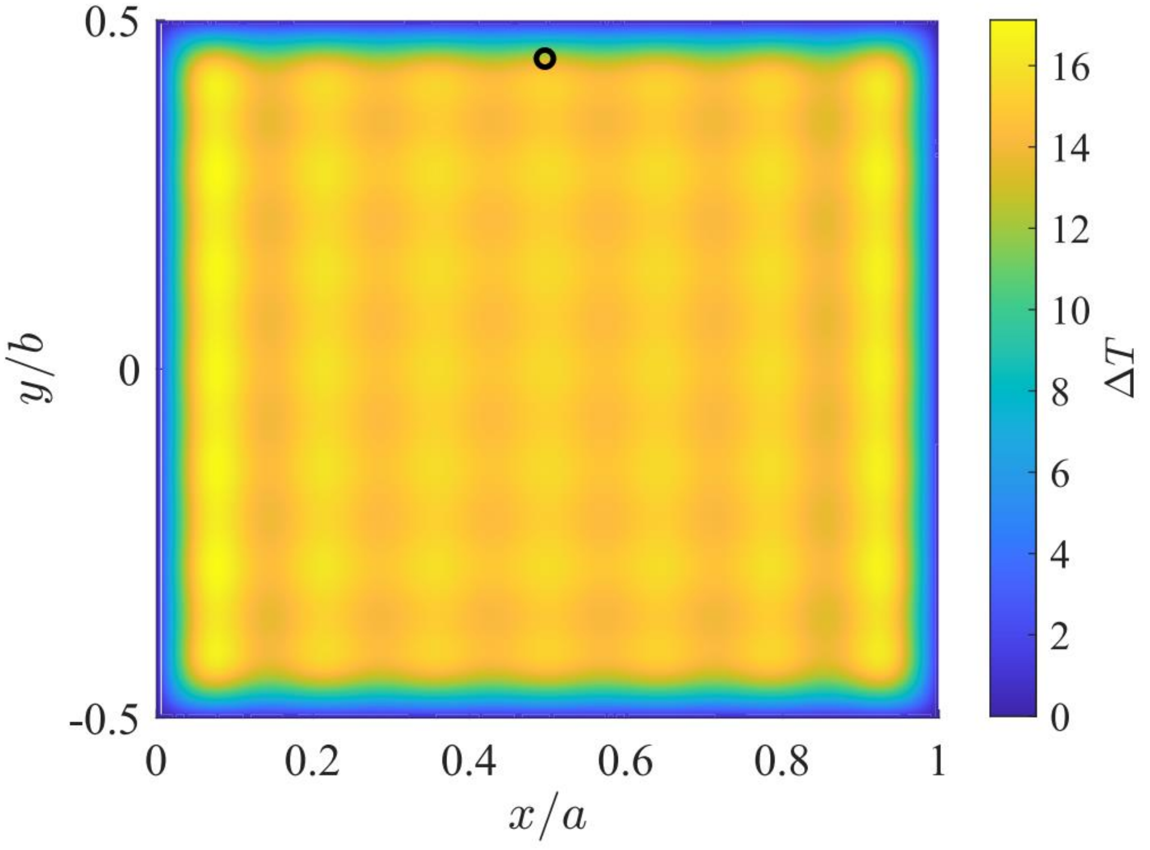
ΔT distribution from heat equation





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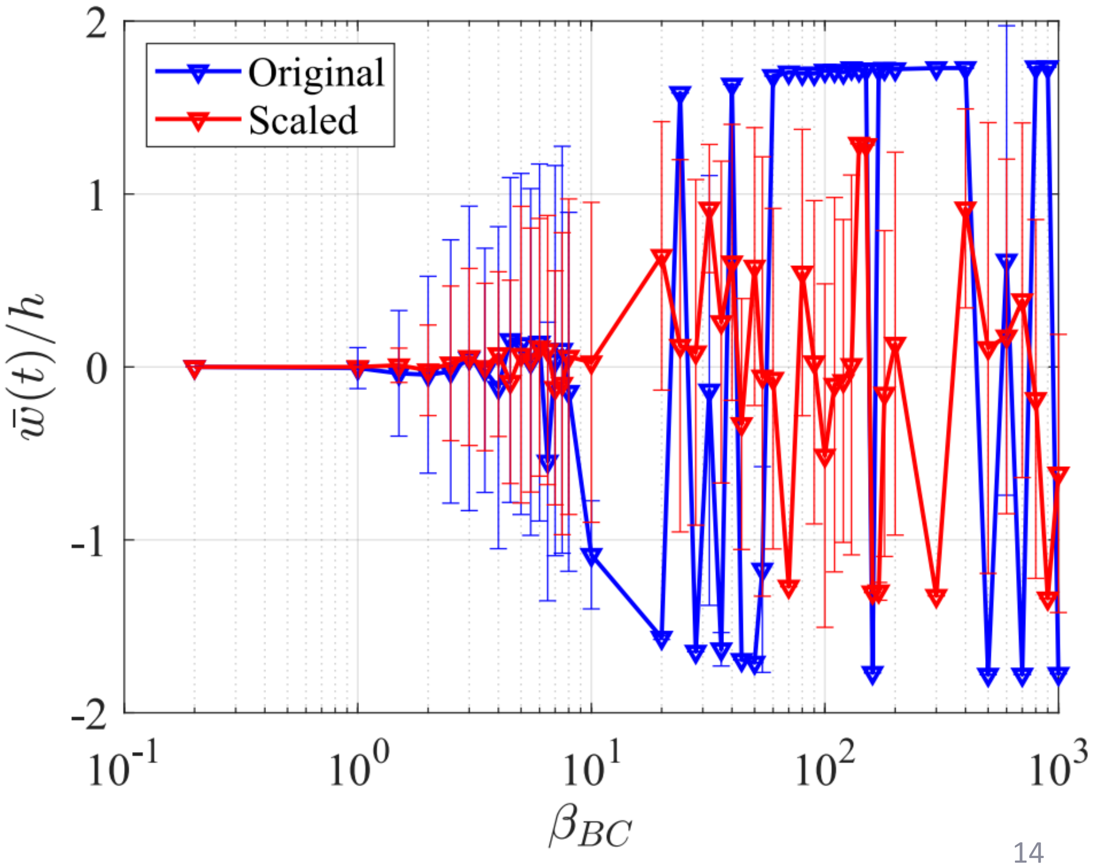
$\Delta p = 0$, ΔT from heat equation

$$\underbrace{M_{m,n}\ddot{q}_n(t) + C_{m,n}\dot{q}_n(t) + G^{(1)}_{m,n}q_n(t)}_{\text{Linear plate model}} + \underbrace{D^{(2)}_{m,n,r,p}q_n(t)q_r(t)q_p(t)}_{\text{NL structural stiffness}}$$

$$\underbrace{+G^{(3)}_{m,n,r}q_n(t)T_r(t)}_{\text{Thermal coupling}} + \underbrace{Q^{Aero}_{m,n} + Q^{static}_{m}}_{\text{Pressure terms}} = 0$$

$$\underbrace{M^H_{m,n}\dot{T}_n(t) + K^H_{m,n}T_n(t)}_{\text{Thermal inertia and stiffness}} +$$

$$\underbrace{+Q^0_m + Q^q_{m,n}q_n(t) + Q^{\dot{q}}_{m,n}\dot{q}_n(t) + Q^{T_q}_{m,n}T_n(t)}_{\text{Coupled linear aerodynamic heating}} = 0$$



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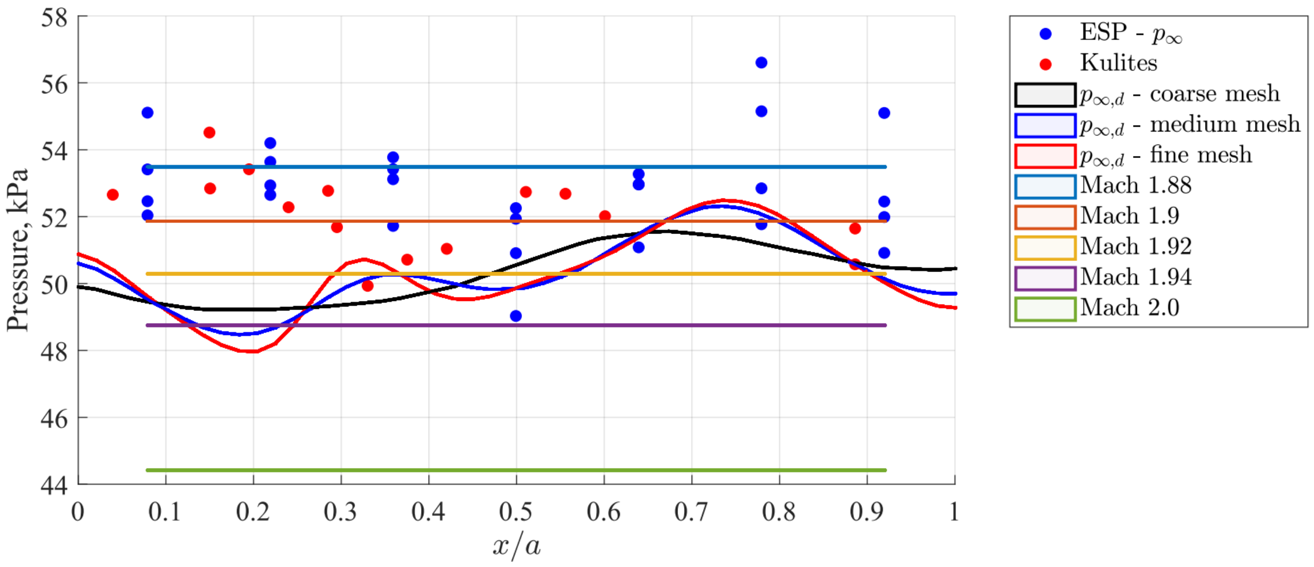
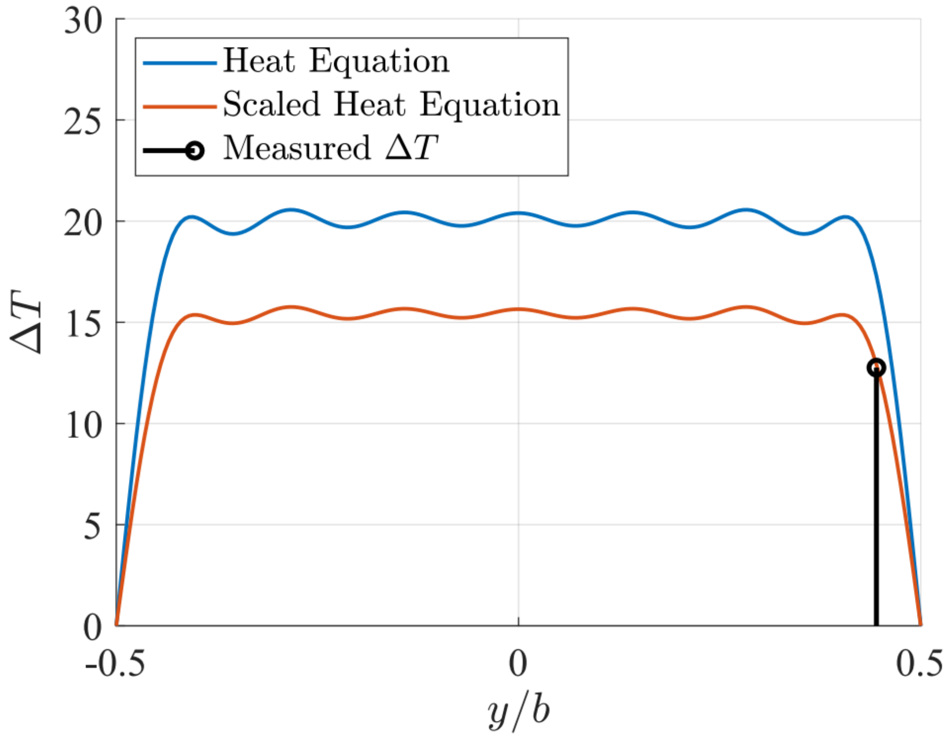
Δp from Experimental Data, ΔT from heat equation



Pressure on the wall data from a CFD steady flow computation courtesy of Bret Stanford + measured pressure distribution on the panel wall



Question

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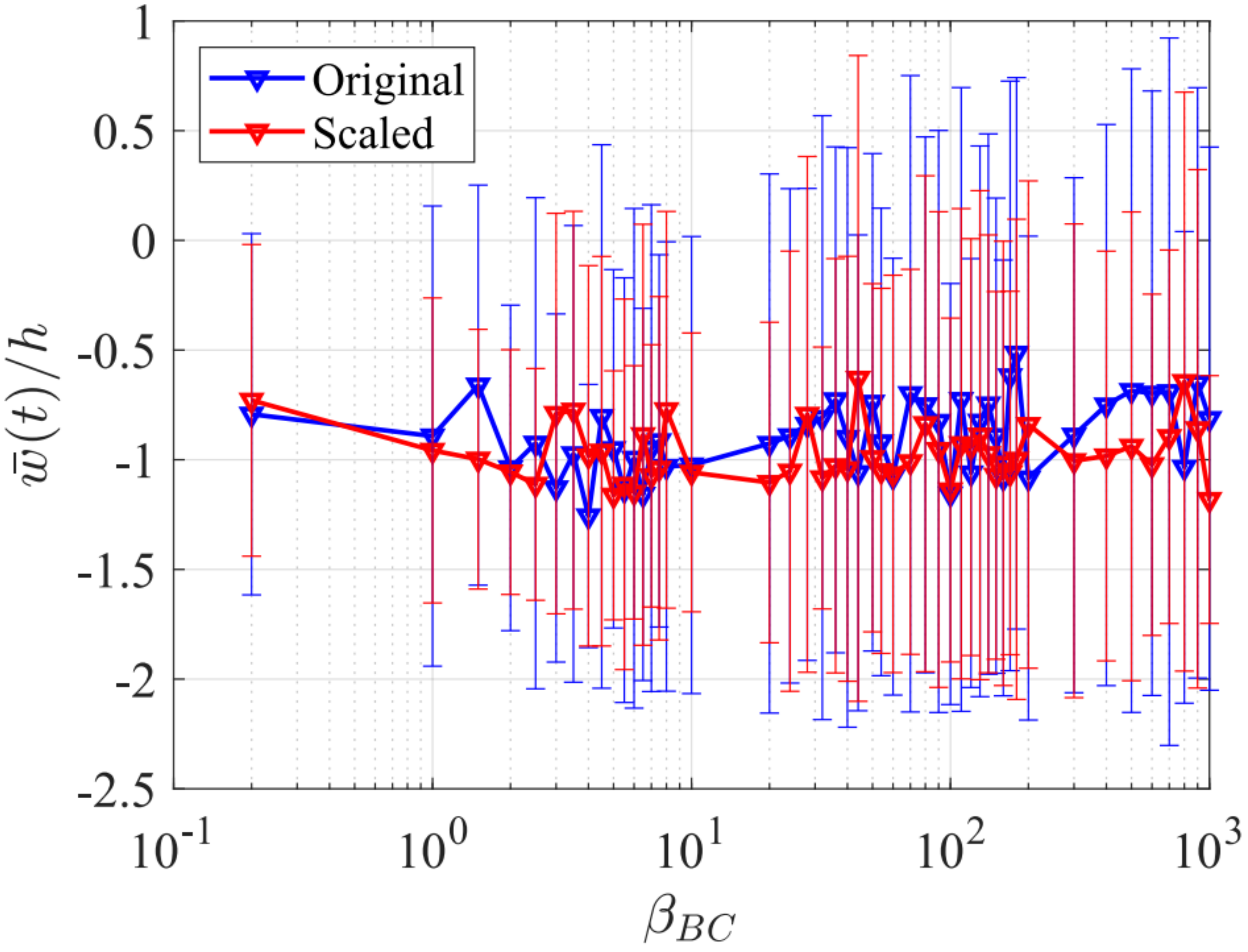
Δp from Experimental Data, ΔT from heat equation



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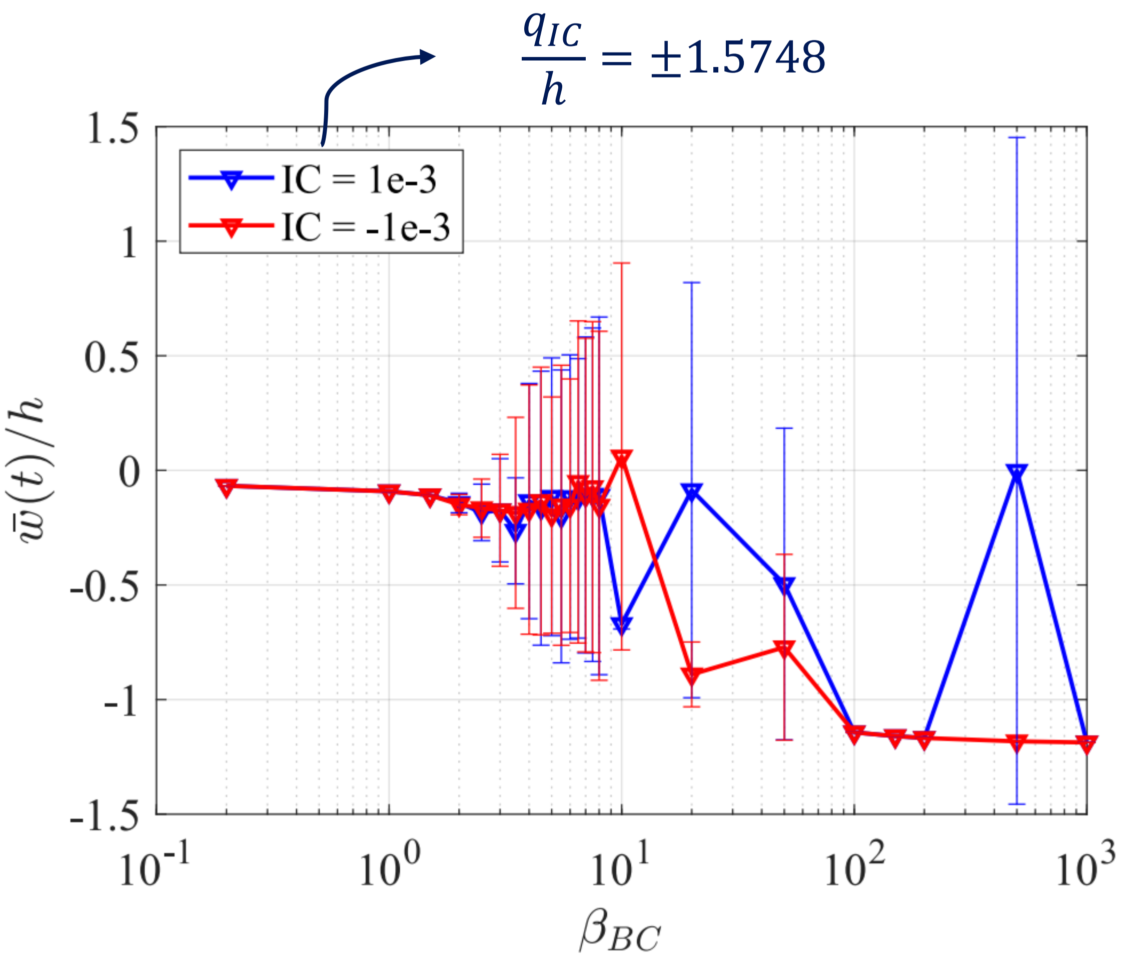
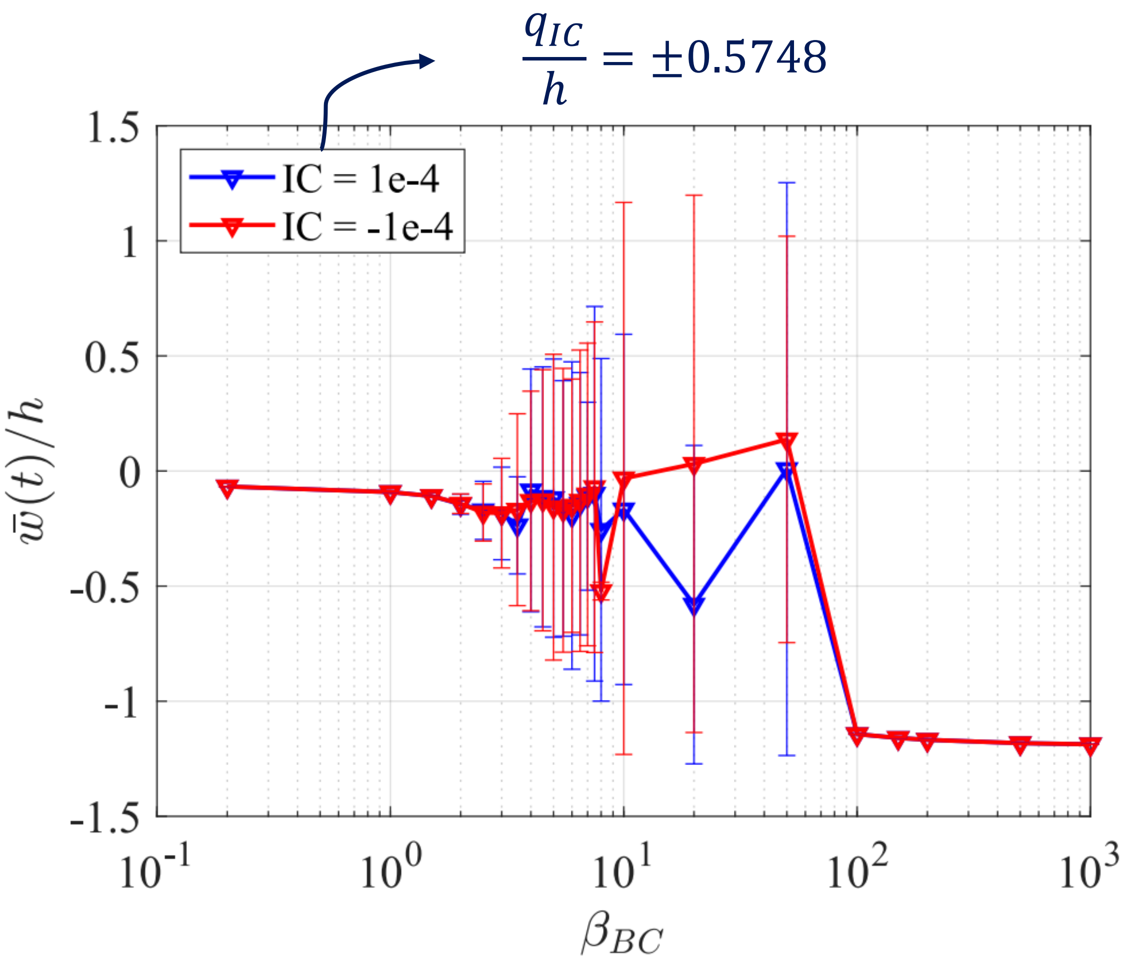
IC sensibility

Using the “diamond shock-profile” with different IC’s





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IC=Initial Conditions

Different Aerodynamic Models

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Aerodynamic Models

Linear Piston Theory

$$Q_n(t) = q_m(t)S_{m,n} + \dot{q}_m(t)D_{m,n}$$

Potential Flow Aerodynamics

$$Q_n(t) = q_m(t)S_{m,n} + \dot{q}_m(t)D_{m,n} + \int_0^t q_m(\tau)H_{m,n}(t-\tau)d\tau + \int_0^t \dot{q}_m(\tau)I_{m,n}(t-\tau)d\tau$$

Analytical Solutions

Euler/CFD → RANS/CFD

$$Q_n^{CFD}(t) = q_m(t)A_{m,n} + \dot{q}_m(t)B_{m,n} + \int_0^t q_m(\tau)E_{m,n}(t-\tau)d\tau$$

Based on CFD solution

Allows for shock impingement analysis ← Based on CFD solution

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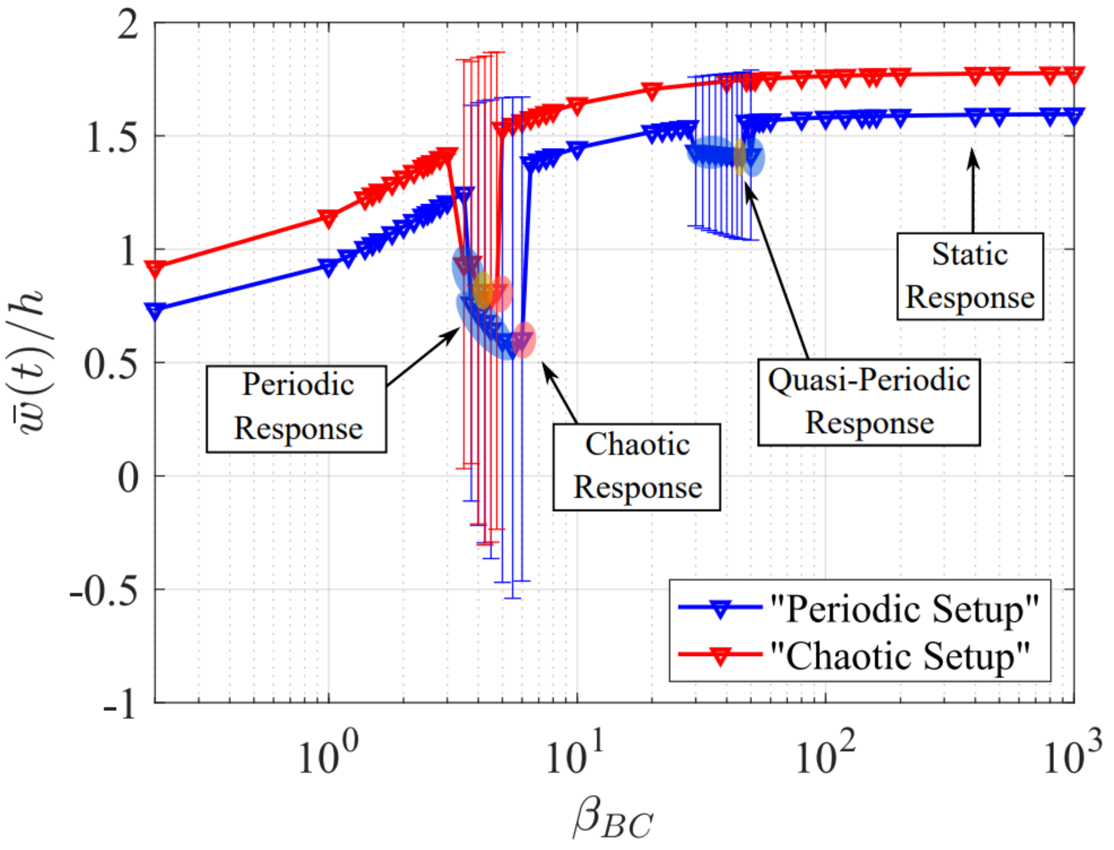
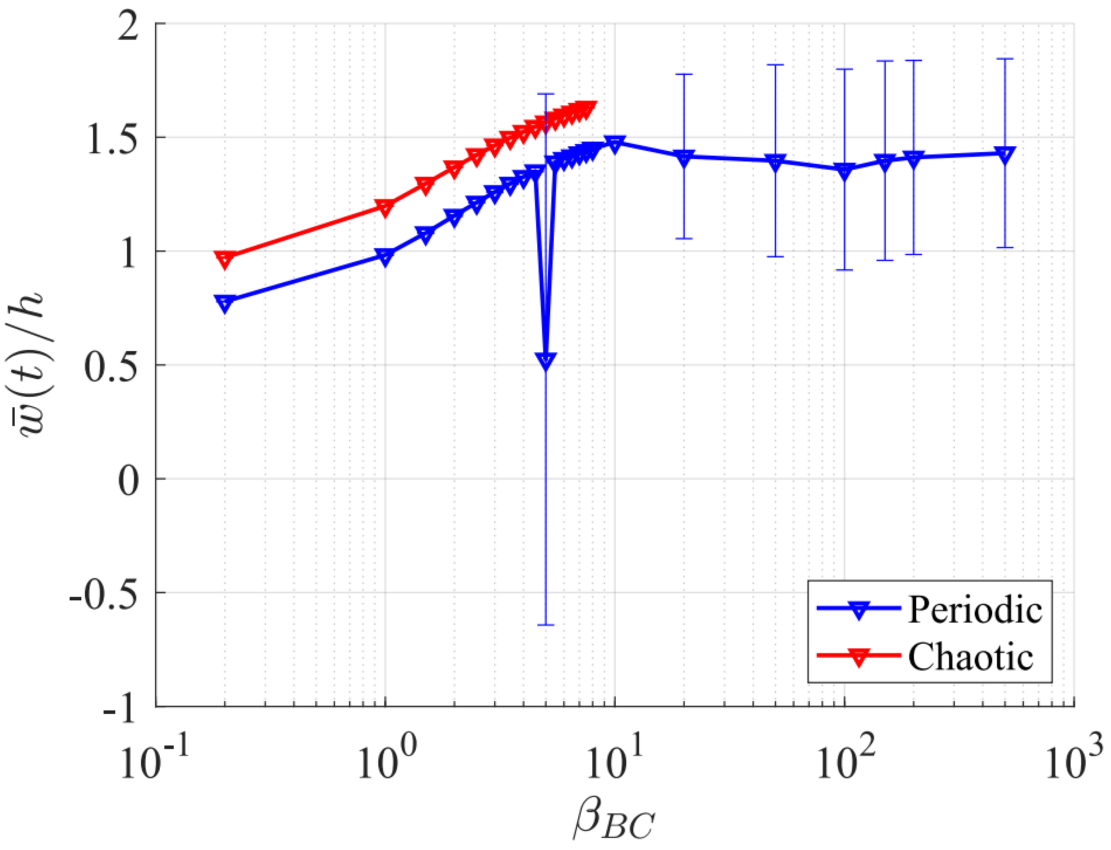
Preliminary results using Euler/CFD – Ansys Fluent

Using Piston Theory



Using Euler/CFD – work in progress



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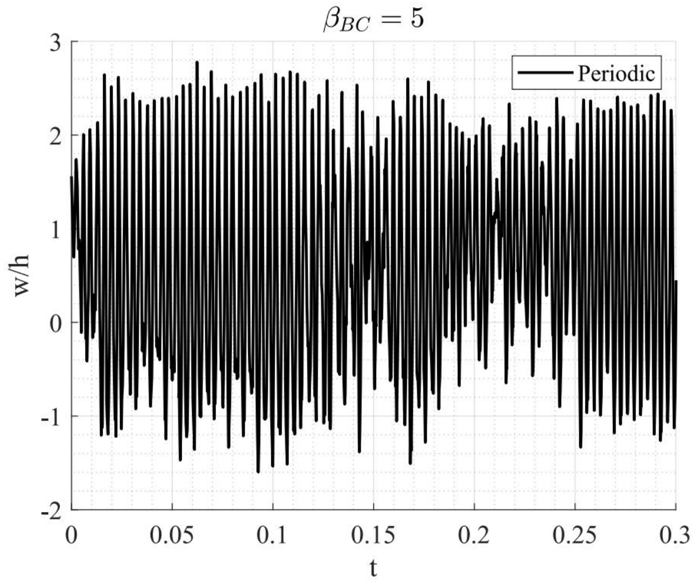
Preliminary results using Euler/CFD – Ansys Fluent



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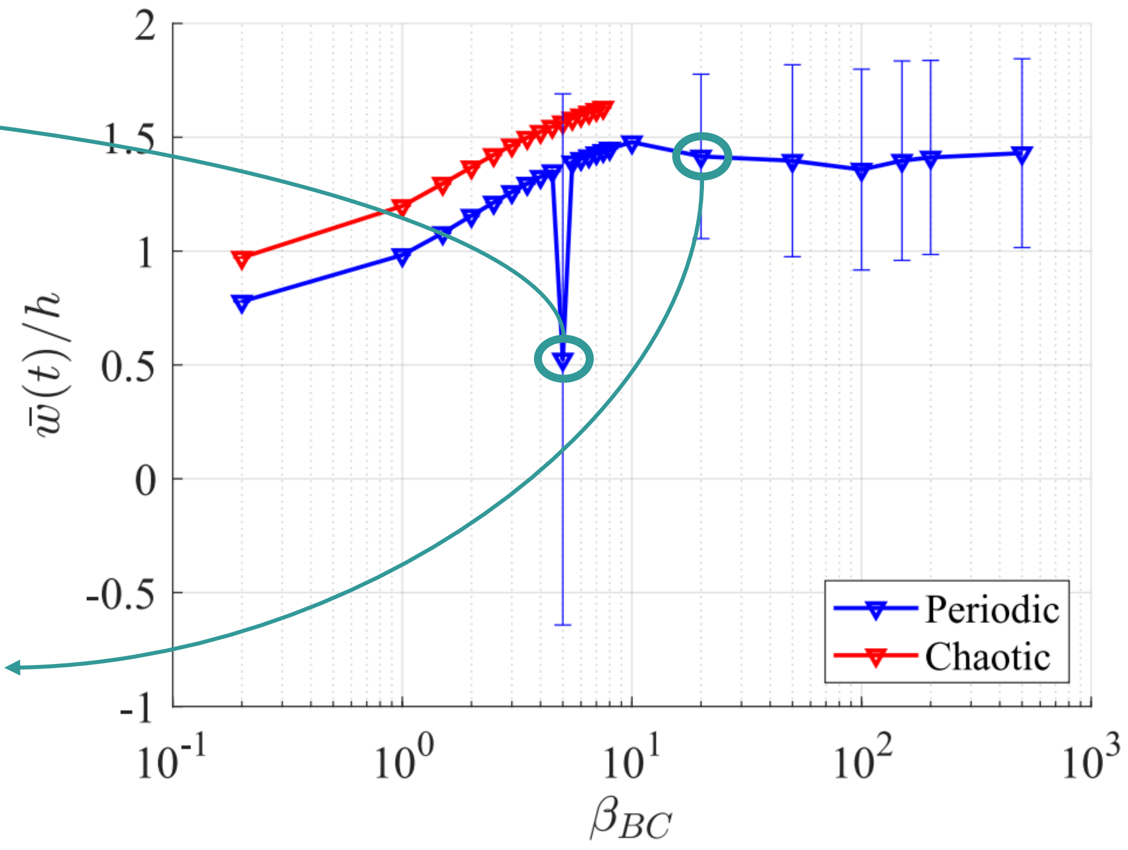

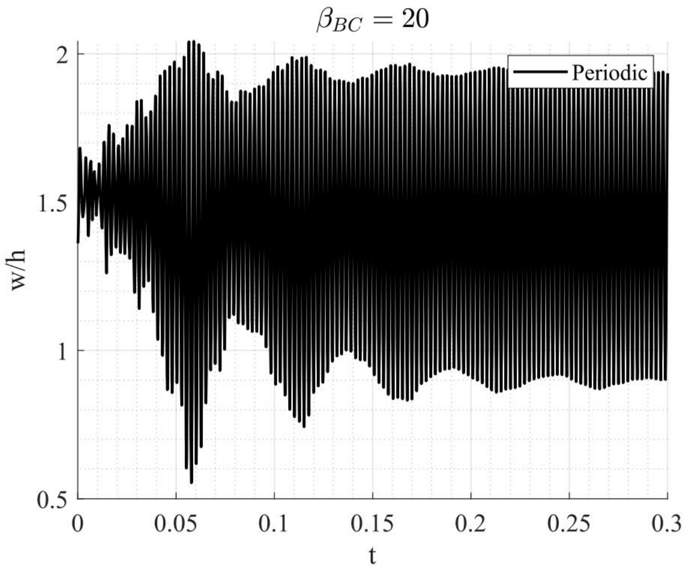

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Approx. Run time for each Aero. Model

Aerodynamic Case	Analytical Solution	CFD	CFD Run time/mode	LCO run time/β_{BC}		Pros	Cons
				Local Computer	Cluster		
Piston Theory	X	-	-	< day	A couple of hours	Really fast	Local No shock case Inviscid
Potential Flow	X	-	-	~1 day*	< 1 day*	Non-local Relative fast	No shock case Inviscid
Euler/CFD	-	X	~1-2 days	-	< day	Shock case Potential for RANS	Takes more time to run
RANS/CFD	-	X	~3-4 days	-	-	Shock case Viscosity effects	Takes more time to run

Work in progress

* if the influence matrices are not previously saved

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4° Shock Wedge

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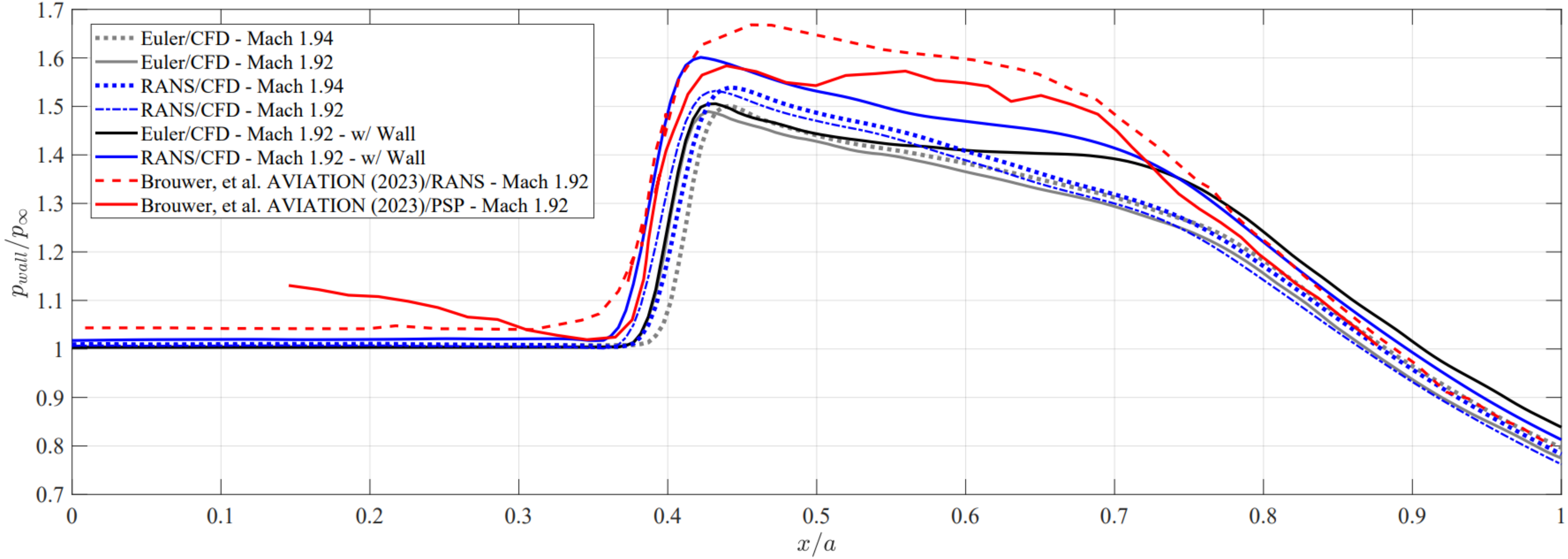
p_∞ comparison



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Summary

- For the experimental configuration considered → the flutter/LCO results are sensitive to Δp, ΔT, and in-plane boundary conditions.
- For different combinations of Δp and ΔT considered to date → there are different intervals for β_{BC} where flutter/LCO is found
- For the no-shock impingement case → piston theory, full potential flow models present very similar results. The same similarity is seen for the static deformation if using the Euler aerodynamic model, but the β_{BC} values at which LCO occurs differ

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Back-Up Slides

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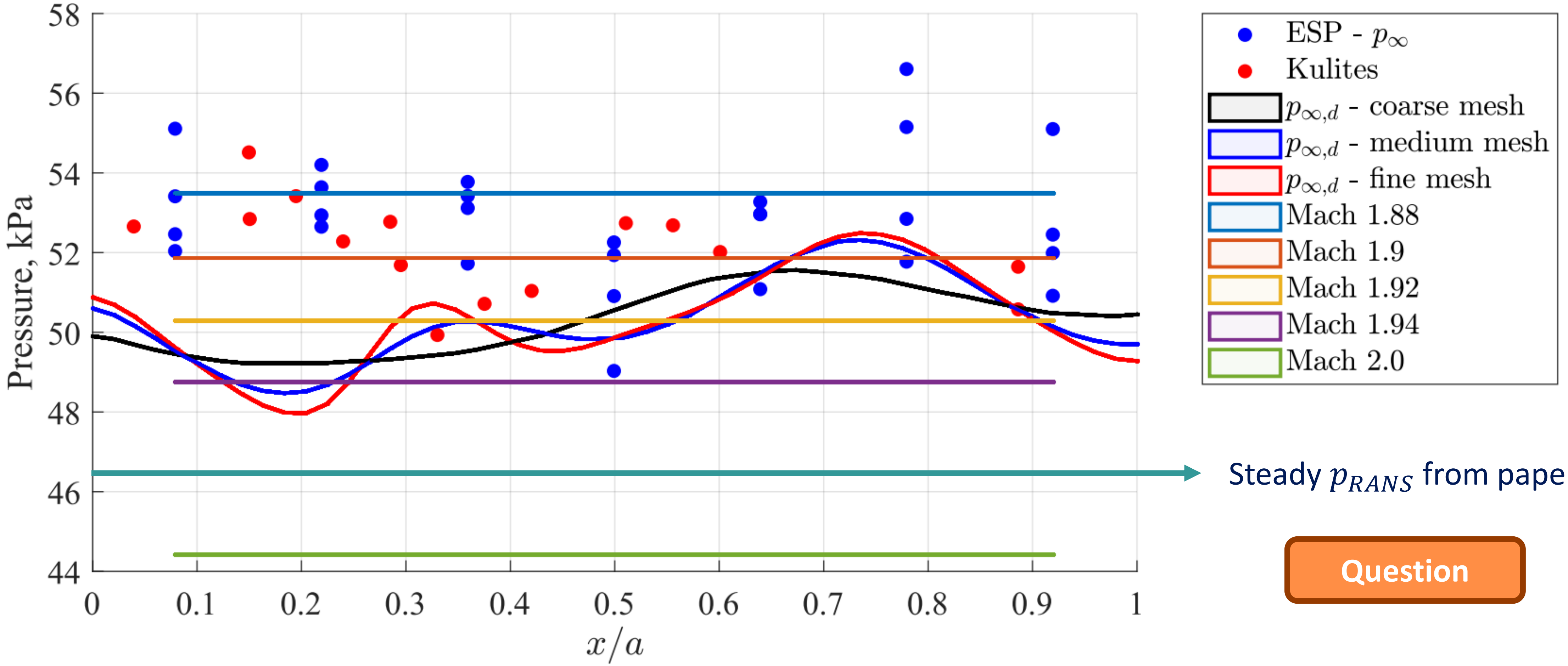
New data: p_∞ on the wall



Steady p_{RANS} from paper

Question

New delta p data from a CFD steady flow computation courtesy of Bret Stanford
+ measured pressure distribution on the panel wall

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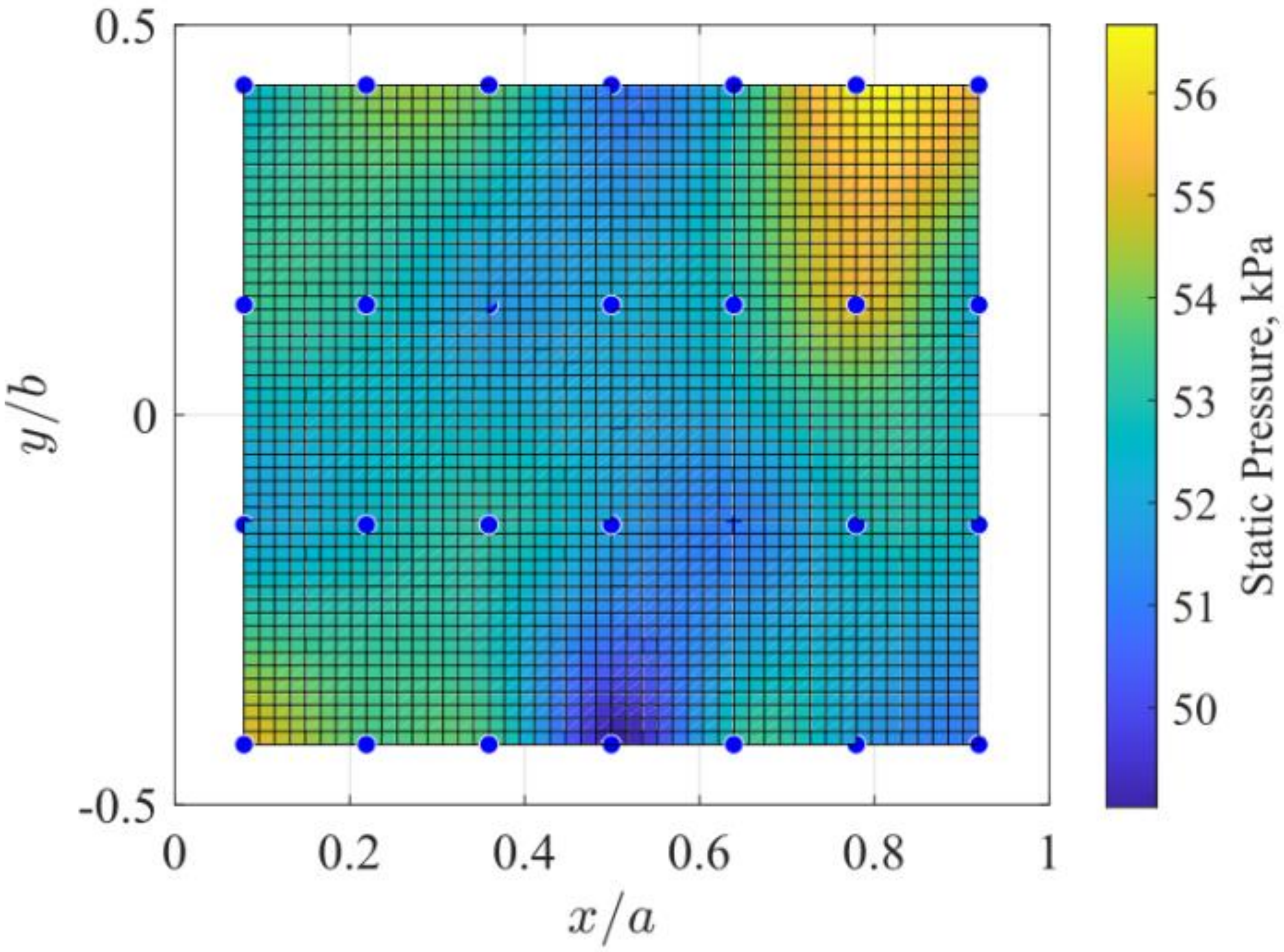
New data: p_∞ on the wall



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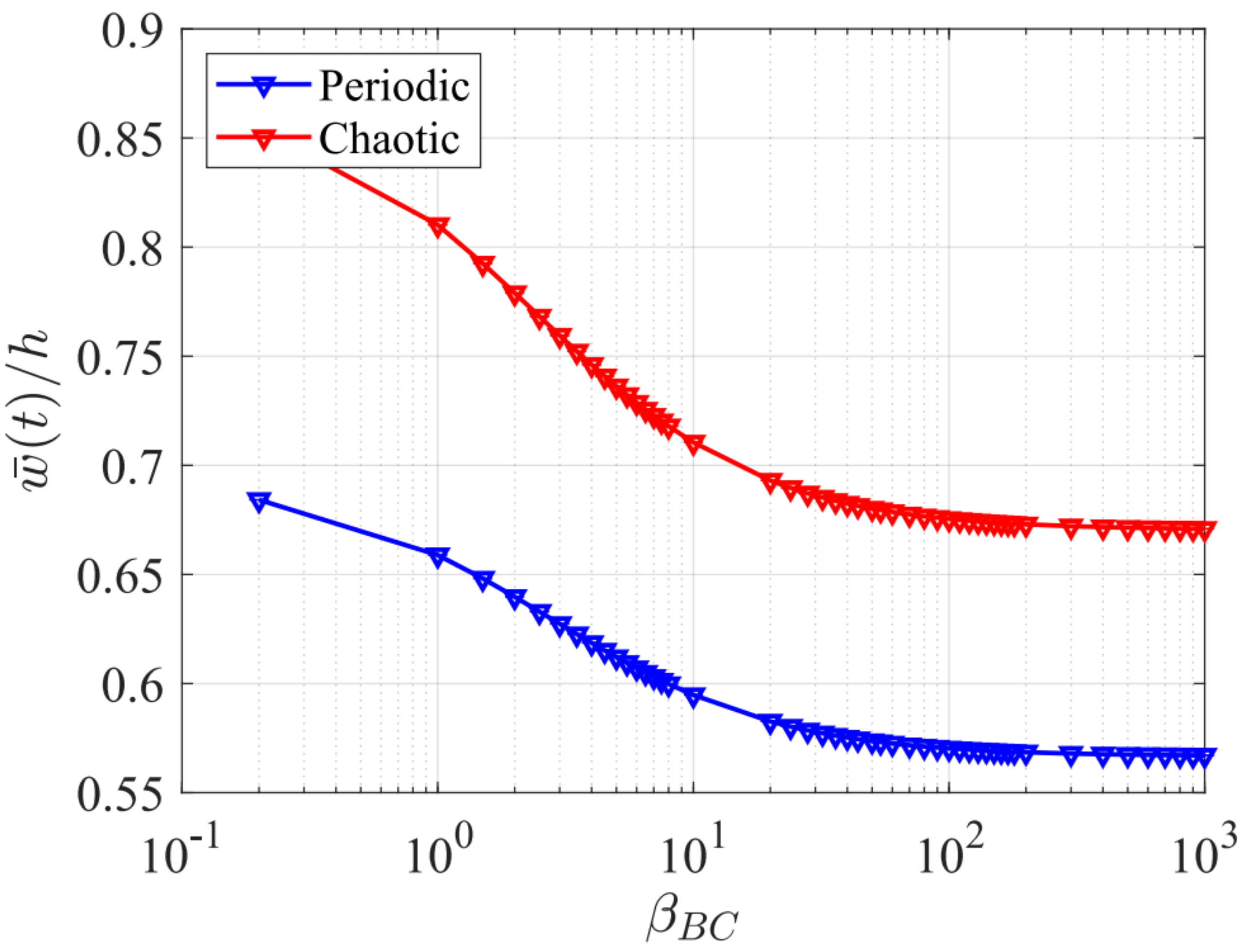
$\Delta T = 0$, nominal periodic and chaotic Δp

Periodic Parameters		Chaotic Parameters	
Δp (kPa)	3.91	Δp (kPa)	5.01

Uniform Δp distribution (x- and y- directions)



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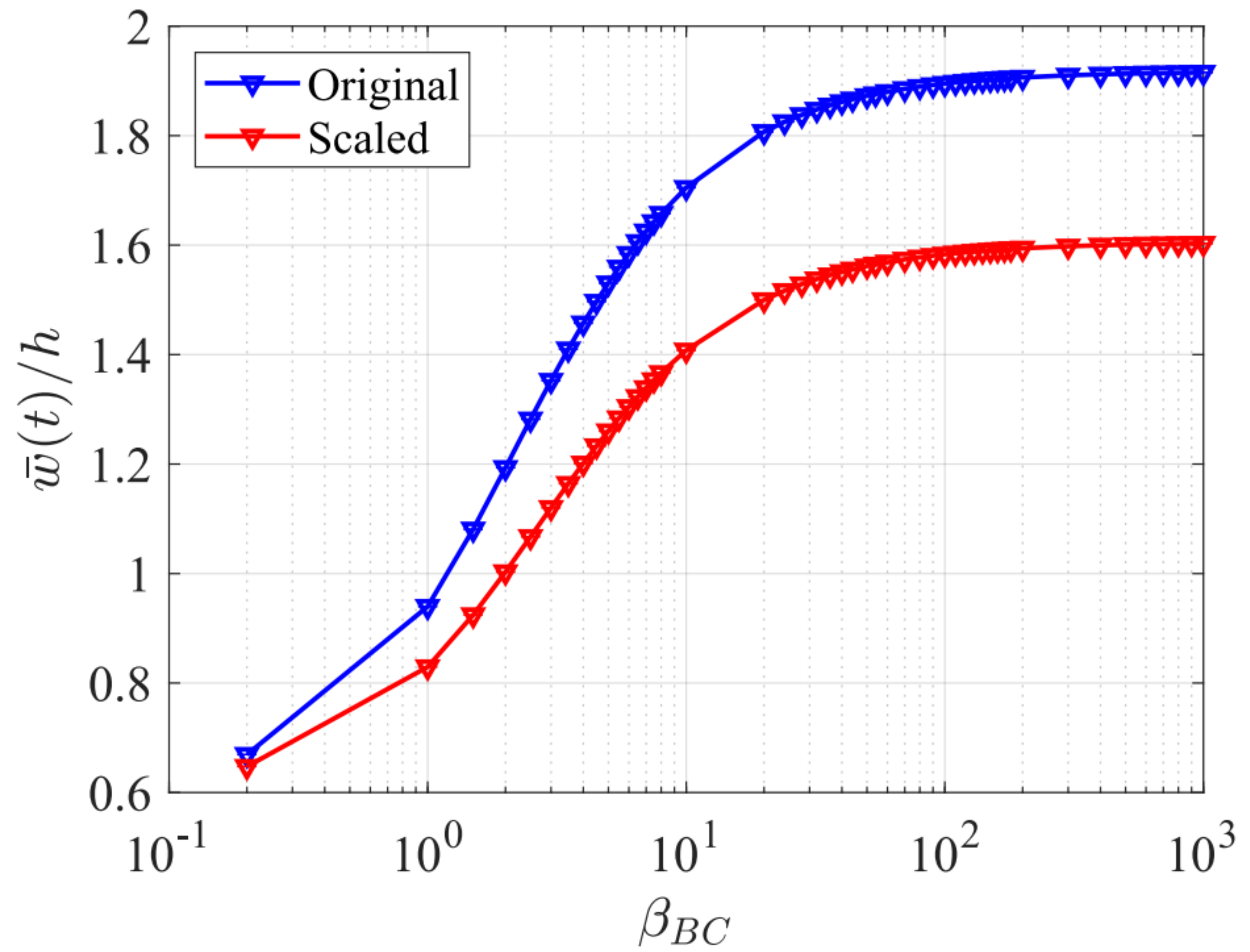
Nominal Δp, ΔT from heat equation



Δp from Periodic Setup (the same behavior was seen using the Chaotic Setup values)

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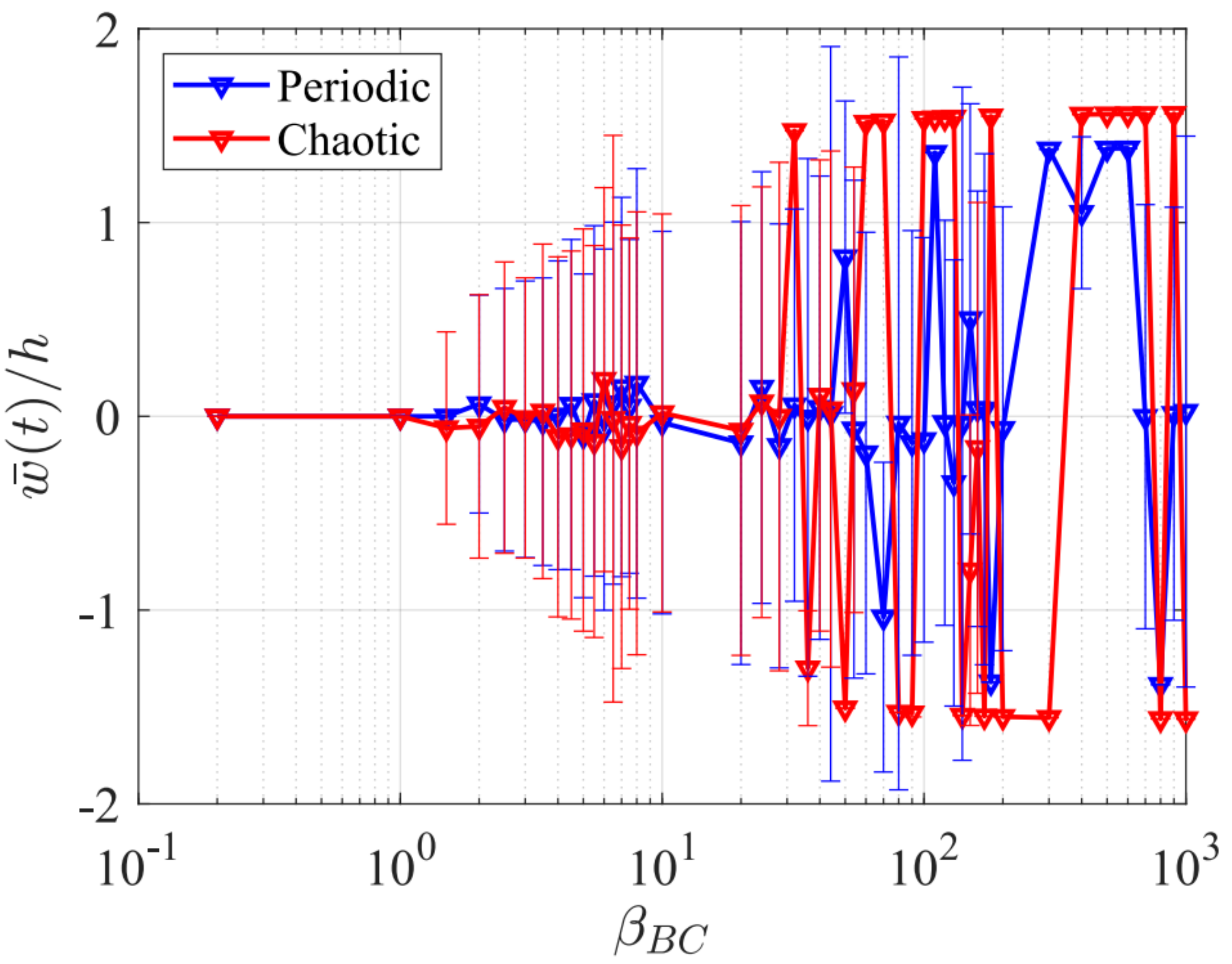
$\Delta p = 0$, nominal periodic and chaotic ΔT

Periodic Parameters		Chaotic Parameters	
ΔT (K)	12.8	ΔT (K)	14.7



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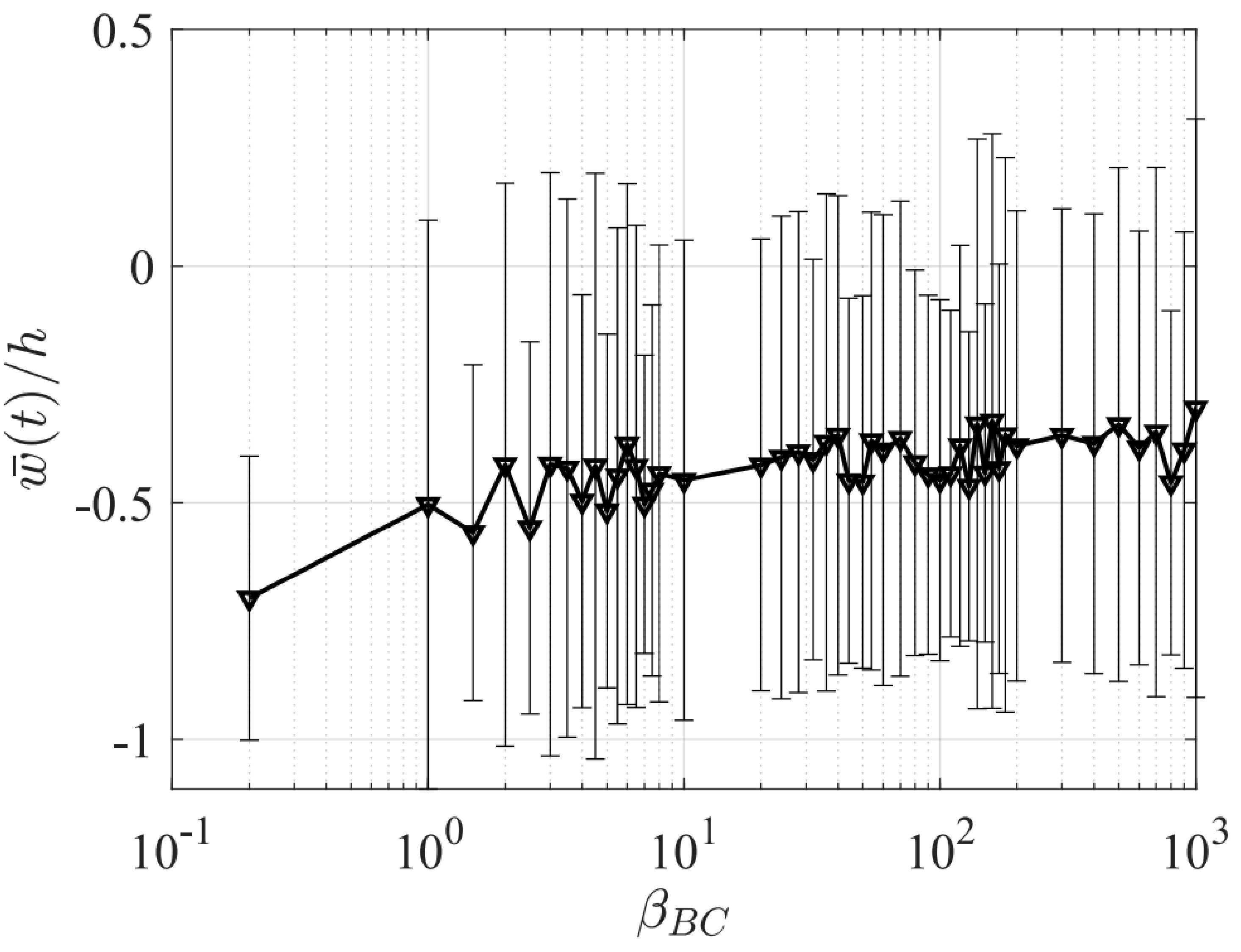
$\Delta T = 0$, Δp from measurement

$M_\infty = 1.92$

$p_c = 50.139\ kPa$

Pressure distribution on the PT and static pressure terms



Nonuniform span-wide p_∞ leads to oscillatory response for the wide range of β_{BC}, for $\Delta T = 0$

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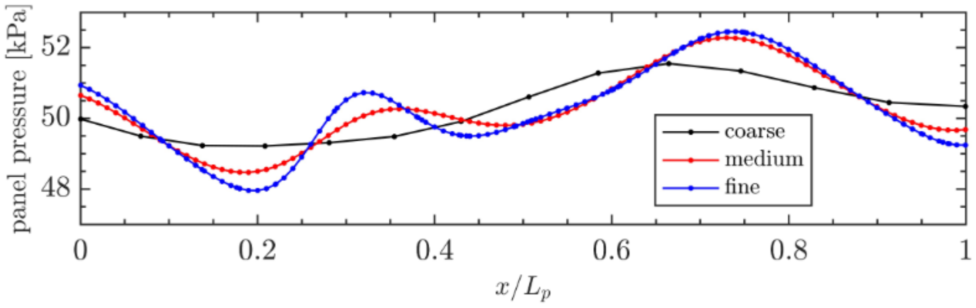
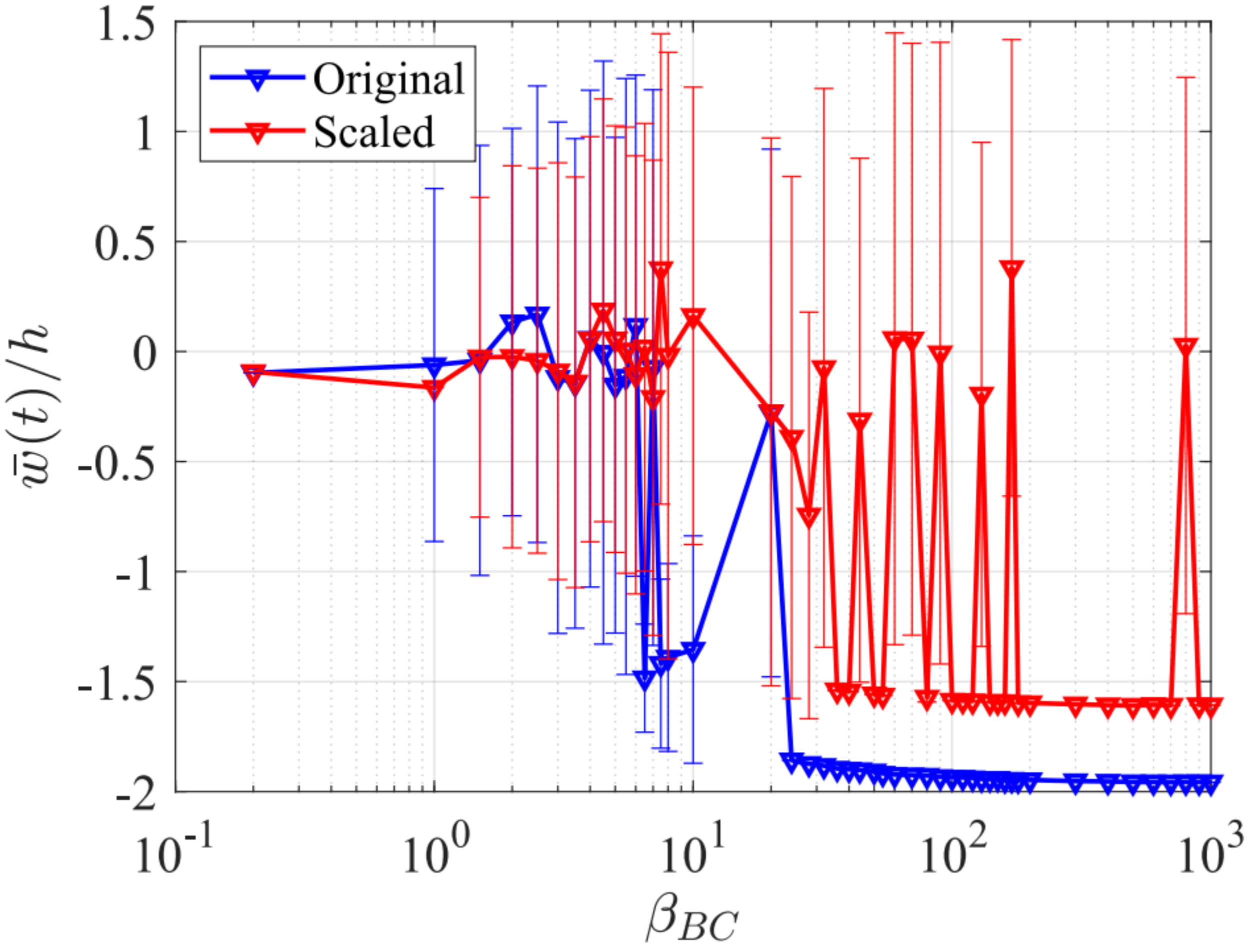
Δp from the Diamond Shock-Profile, ΔT from heat equation

Stanford and Chwalowski. Presentation at the AePW(2023)





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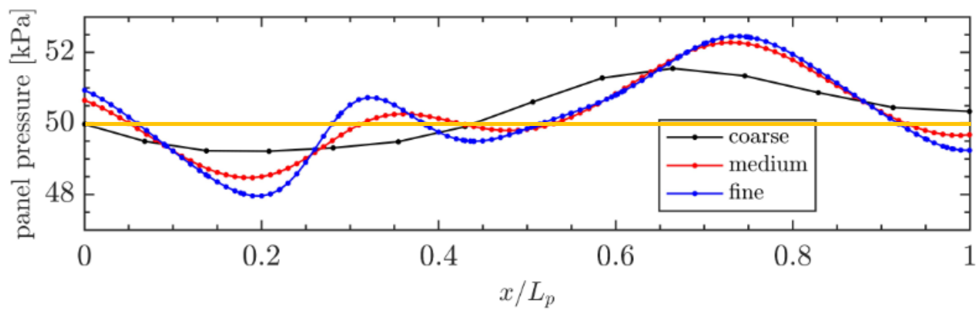
$\Delta T = 0$, Δp from "diamond shock"

Pressure on the wall data from a CFD steady flow computation courtesy of Bret Stanford

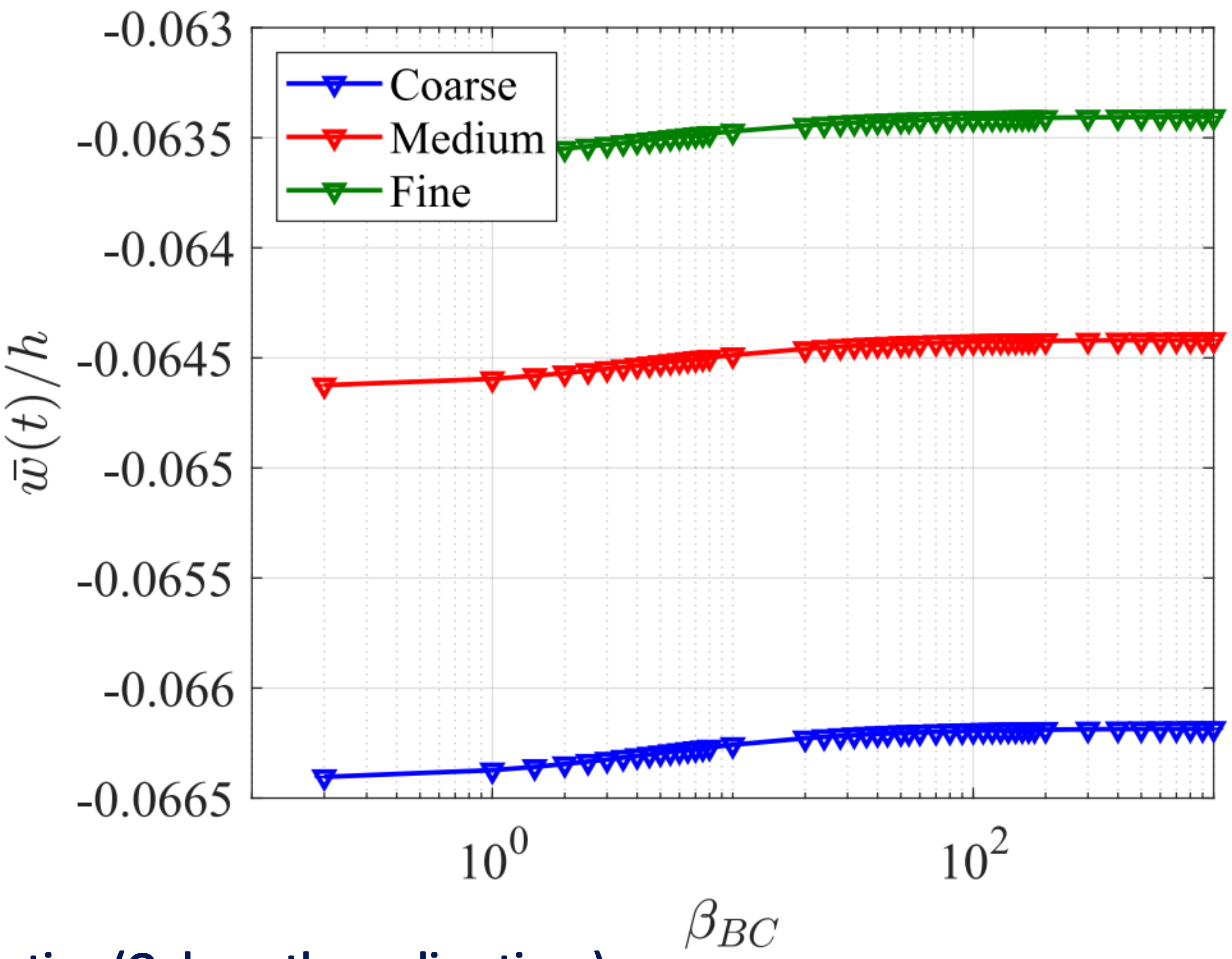


Average static pressure over the panel around 50 kPa

$$M_\infty = 1.92$$

$$p_\infty = 50.139\ kPa$$

$$\Delta T = 13\ K$$



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<u>**Uniform Δp distribution (Only on the y- directions)**</u>

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