Aeroelastic Prediction Workshop

High Speed Working Group Overview and Results

Bret Stanford
NASA
DPW-8/AePW-4, Aviation 2026

Participant Presentations

- Duke – ROMs (Luisa Piccolo Serafim)
- NASA – CFD + FE (Bret Standford)
- AFRL – ROMs (Kirk Brouwer)
- Cadence – RANS + FE (Rodrigo Gutierrez)

Model Benchmarking Overview

- **Three cases selected for comparison**
  1. Periodic oscillations without SBLI
  2. Chaotic oscillations without SBLI
  3. Periodic oscillations induced by an attached SBLI

- **For each case, the following comparisons with experiments are made:**
  - Thin panel frequencies
  - Rigid baseline unheated flow conditions (i.e. surface pressure and boundary layer thickness)
  - Heated flow operating conditions (participants allowed/encouraged to alter conditions to predict desired responses)
  - Structural response:
    - X-T plots of deformation time history (visual comparison only)
    - Mean and standard deviation *(σ)* of deformation
    - Amplitudes and PSD at location of maximum dynamics (½ -chord for Cases 1& 2, ¾-chord for Case 3)

Predicted Structural Frequencies

Mode Number		Exp	Percent Error (%)				
			AFRL	Duke	NASA	Cadence	DLR
	(1,1)	242	1.65	3.31	8.60	0.00	1.57
	(1,2)	302	1.99	0.33	11.4	3.64	2.12
	(1,3)	418	3.59	2.15	10.6	5.26	3.78
	(1,4)	593	3.54	1.86	7.87	4.89	3.46
	(2,1)	618	0.32	1.46	4.23	1.78	0.32
	(2,2)	679	1.33	0.29	4.55	2.80	1.43
	(2,3)	771	4.54	2.98	6.69	6.10	4.64

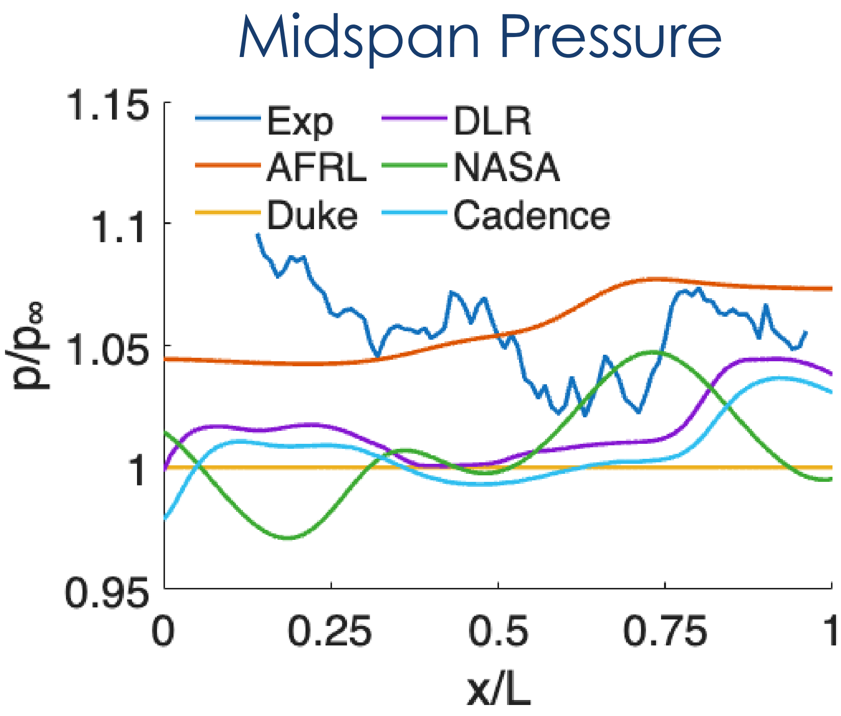
All participants reasonably predicted frequencies for the first 7 natural modes with most errors < 10%

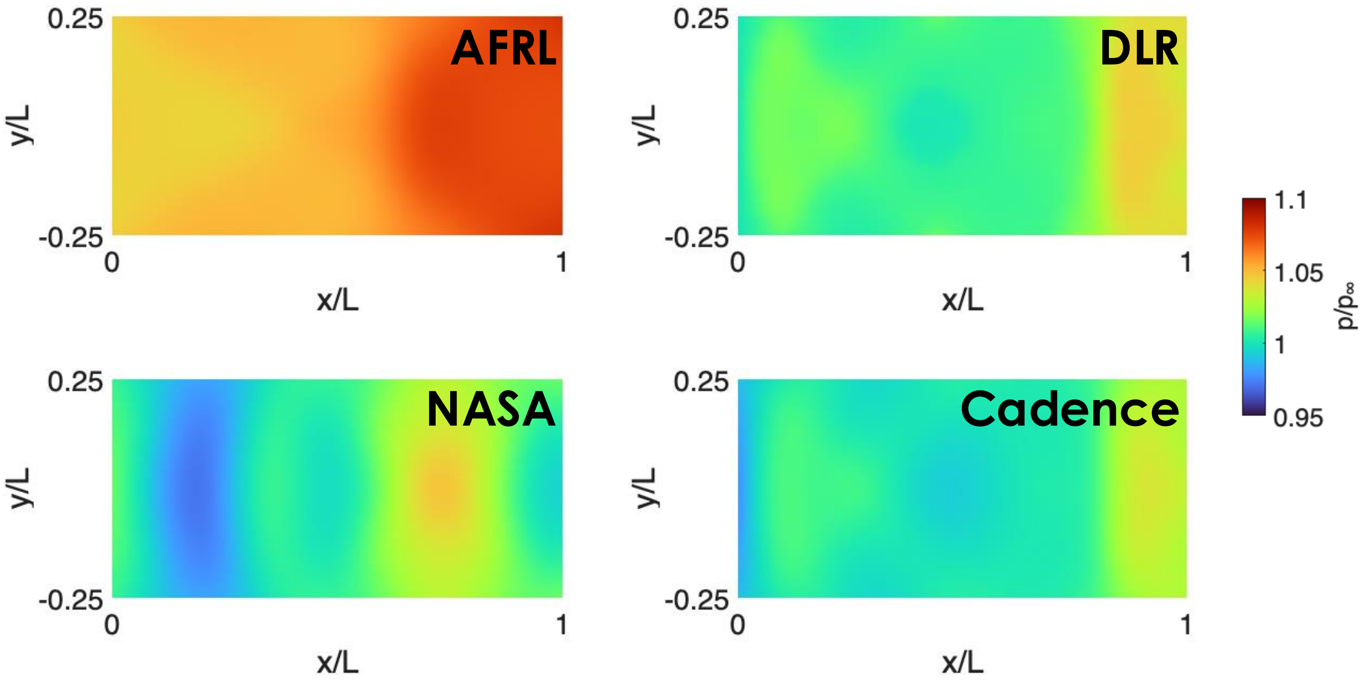
Predicted Boundary Layer Thickness (BLT)

	Percent Error (%)				
Exp (mm)	AFRL	Duke	NASA	DLR	Cadence
8.60	0.00	- / 6.98	52.3	38.3	16.3

- **Notes:**
  - – Duke's simulations assume CPT for Cases 1 & 2 → BLT not applicable
  - – AFRL's RANS simulations use semi-empirical formulations at inflow to enforce BLT
  - – Modeling nozzle + test section yields increased errors relative to enforcing inflow BC
  - – Need improved characterization of inflow TBL from experiments when initializing CFD

Predicted Surface Pressure (Cases 1 & 2)



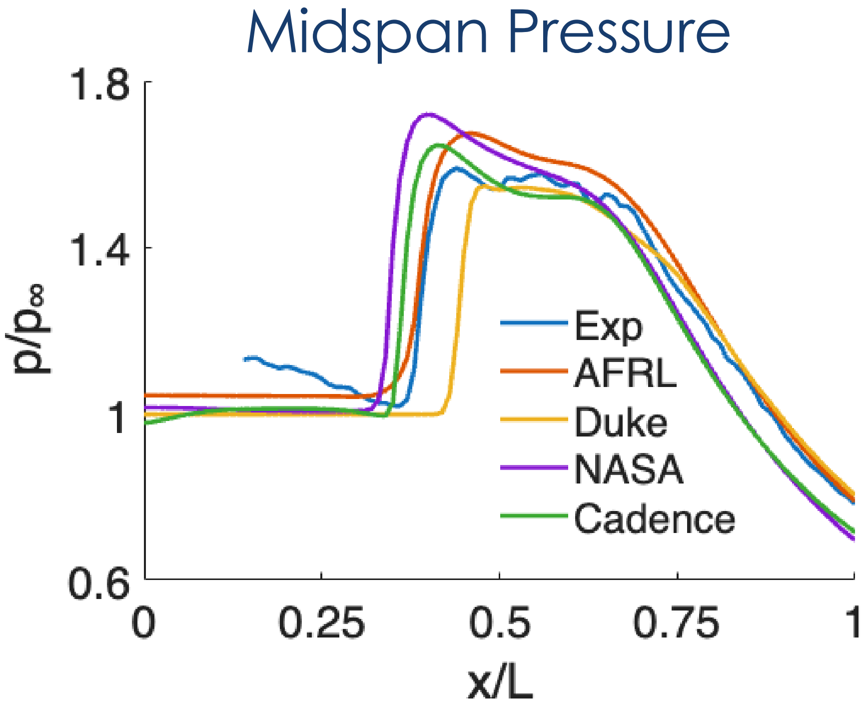


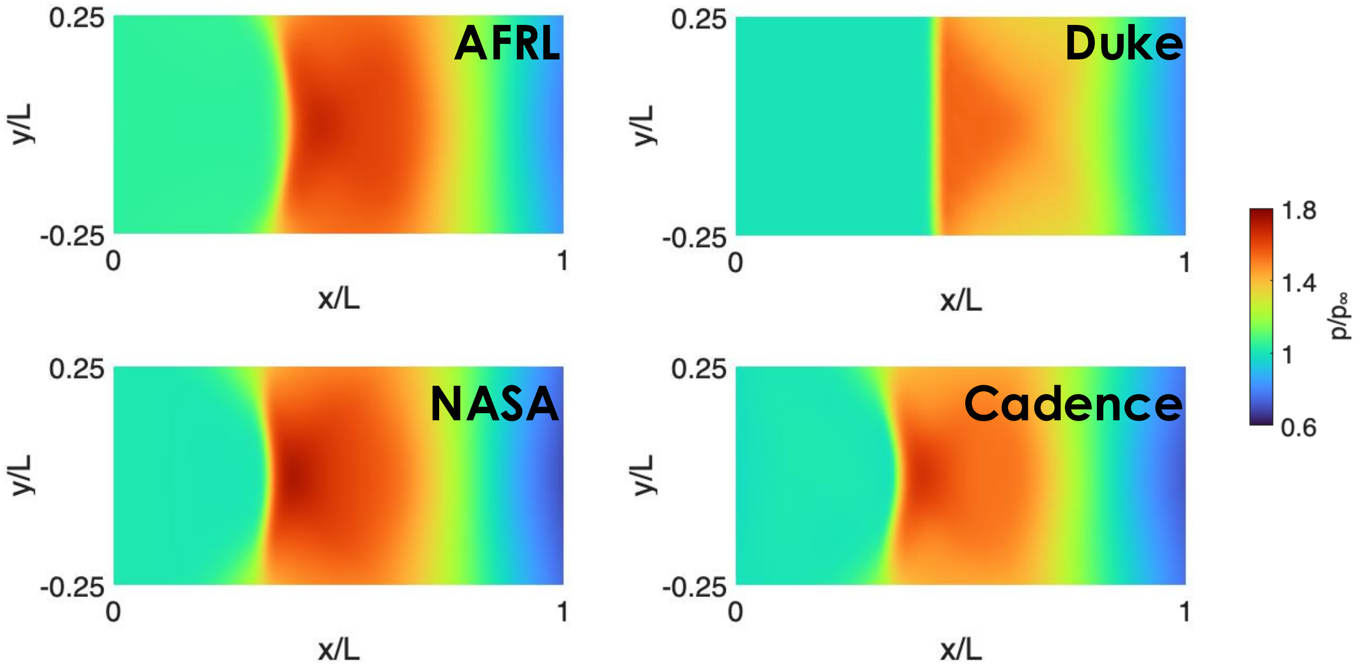
Normalized RMS Error (%) Relative to PSP

AFRL	Duke	DLR	NASA	Cadence
3.14	4.37	3.15	4.28	3.79

- **Streamwise undulations due to reflection of compression waves in test section**
- **Duke's simulations assume CPT ($p = p_\infty$)**
- **Good agreement in terms of magnitude**

Predicted Surface Pressure (Cases 3)





Normalized RMS Error (%) Relative to PSP

AFRL	Duke	NASA	Cadence
5.00	18.4	15.9	7.96

- **Location of shock-induced pressure gradient is critical for AE predictions**
- **Modeling sidewalls is critical**
- **Good agreement in terms of magnitude**

Case 1: Periodic Oscillations without SBLI

Operating Conditions Case 1

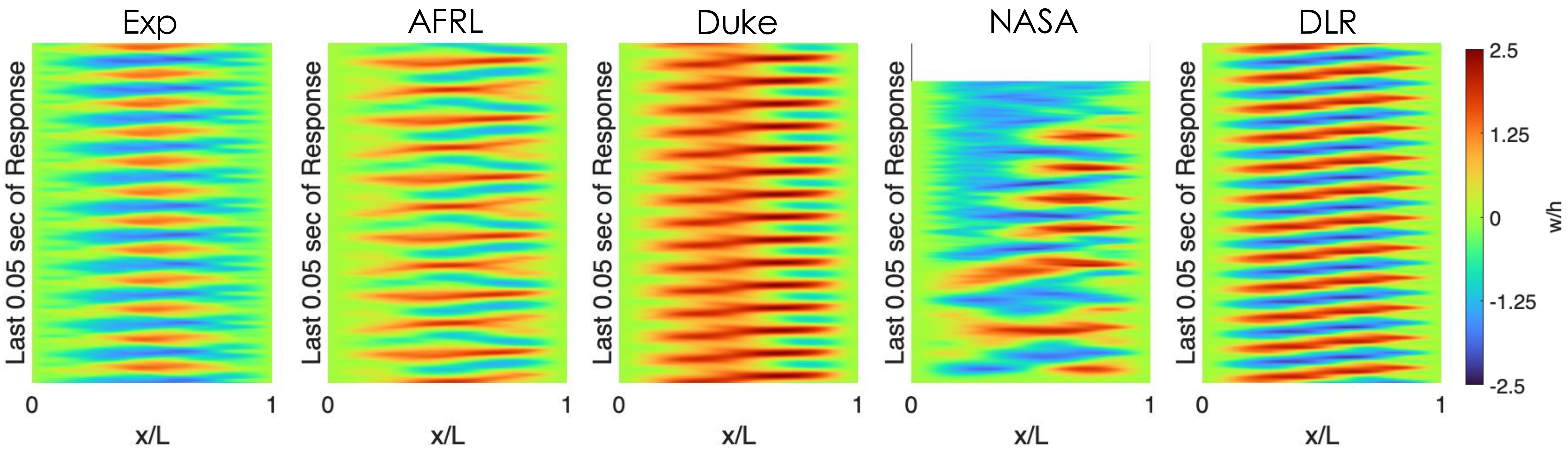
	Exp	AFRL	Duke	NASA	Cadence	DLR
p_c (kPa)	50.4	52.7	52.7	50.4	50.4	50.6
ΔT (K)	12.8	7.1	12.8	12.8	N/A	12.8

BC stiffness modeled ($\beta_{BC} = 5$)

ΔT not included in initial model

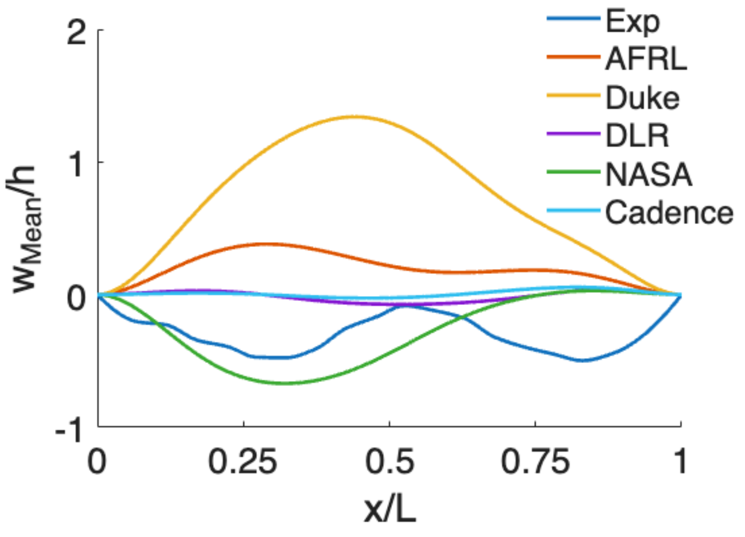
	Percent Error (%)				
	AFRL	Duke	NASA	Cadence	DLR
p_c (kPa)	4.50	4.43	0.00	0.00	0.34
ΔT (K)	44.6	0.00	0.00	N/A	0.00

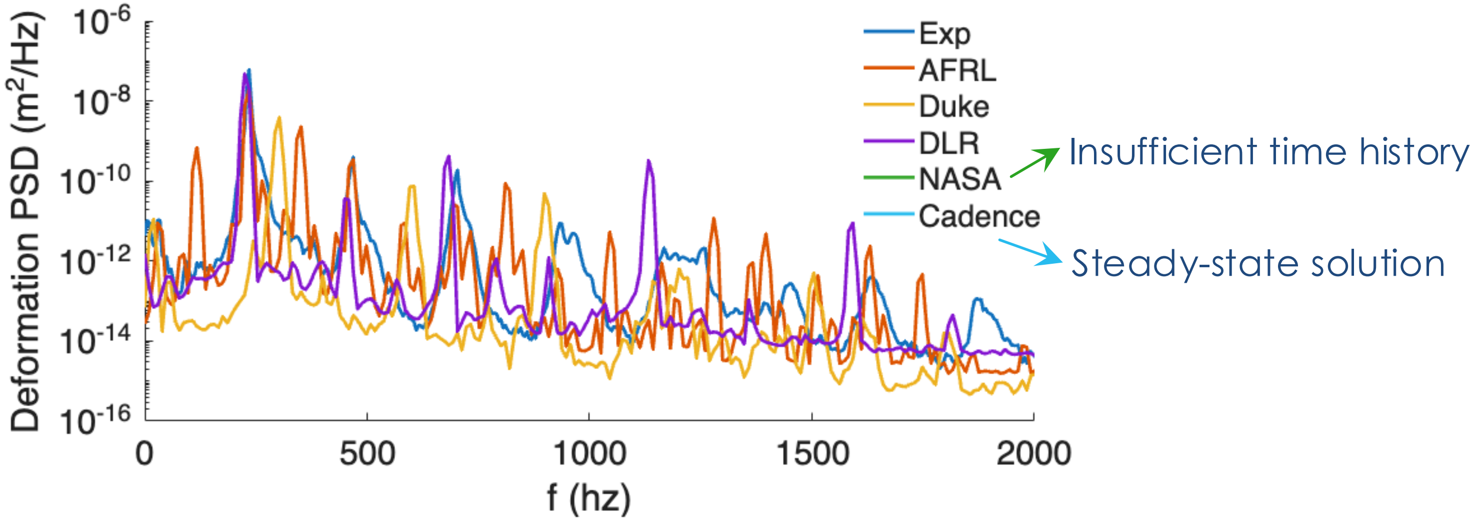
Specific Results for Case 1

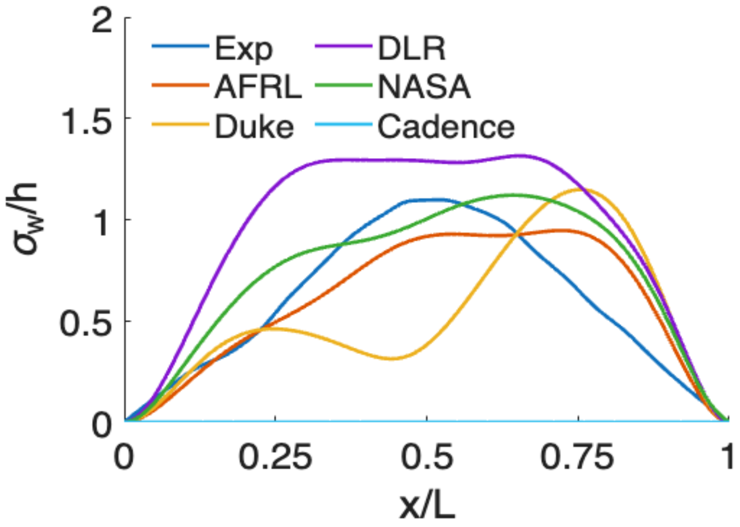


- **Cadence simulations not shown because data only extracted at ¼, ½, & ¾ chord locations and simulations appeared to converge to steady-state**
- **NASA simulations only conducted for ~0.04 sec**

Specific Results for Case 1







	Normalized RMS Error (%)				
	AFRL	**Duke**	**NASA**	**DLR**	**Cadence**
w_{Mean}	164	340	84.5	99.4	104
σ_w	23.7	57.0	30.0	55.1	N/A
Amplitude	7.98	63.8	66.5	12.9	N/A

Case 2: Chaotic Oscillations without SBLI

Operating Conditions Case 2

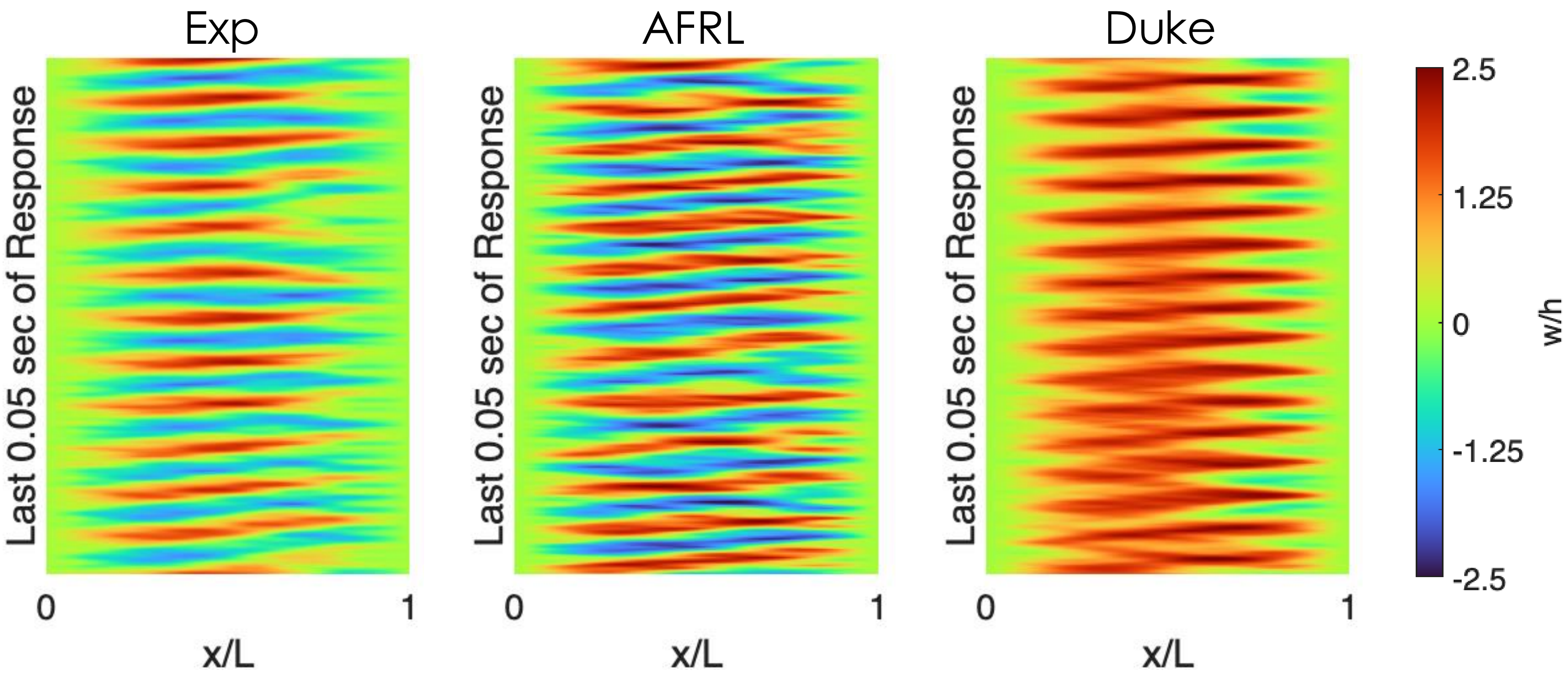
	Exp	AFRL	Duke	Cadence
p_c (kPa)	51.5	51.1	53.6	51.5
ΔT (K)	14.7	13.6	14.7	N/A

BC stiffness modeled ($\beta_{BC} = 4.5$)

ΔT not included in initial model

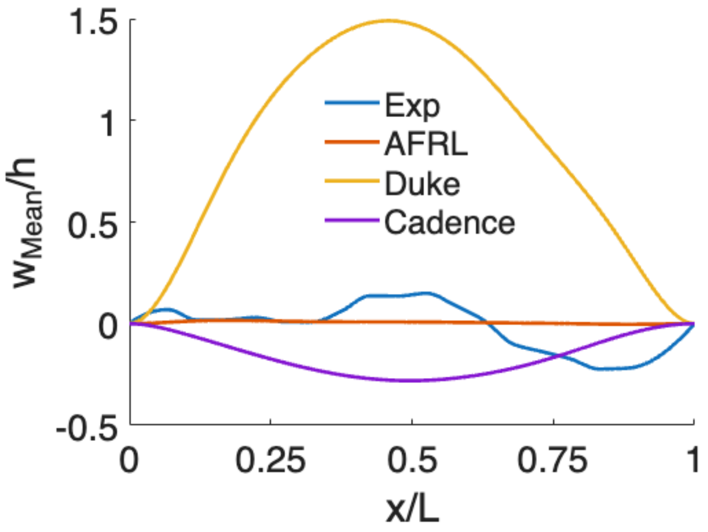
	Percent Error (%)		
	AFRL	Duke	Cadence
p_c (kPa)	0.76	4.13	0.00
ΔT (K)	7.73	0.00	N/A

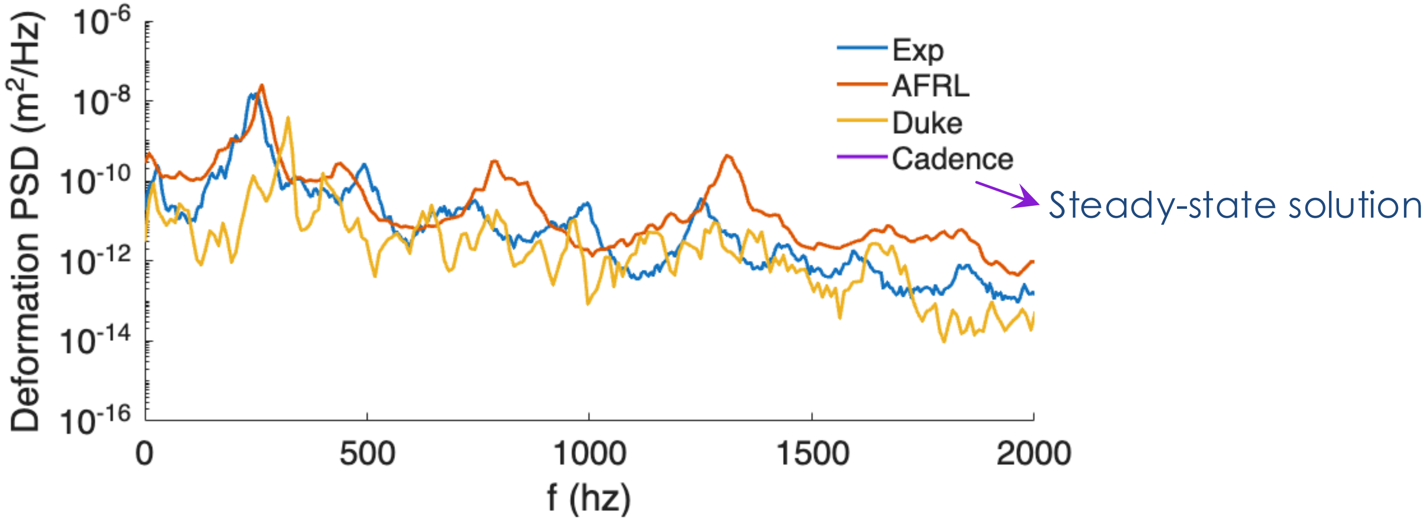
Specific Results for Case 2

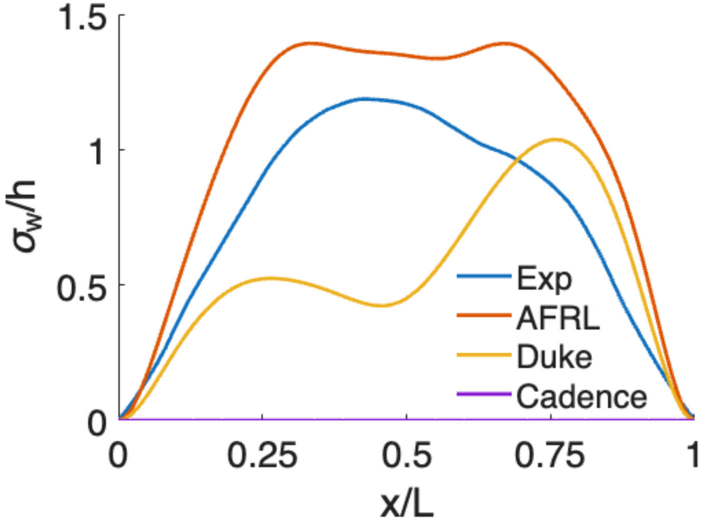


- **Cadence simulations not shown because data only extracted at ¼, ½, & ¾ chord locations and simulations appeared to converge to steady-state**
- **NASA simulations not conducted for this case**
- **DLR still working on simulations for this case**

Specific Results for Case 2







	Normalized RMS Error (%)		
	AFRL	**Duke**	**Cadence**
w_{Mean}	97.5	856	200
σ_w	34.7	47.4	N/A
Amplitude	3.60	64.7	N/A

Case 3: Periodic Oscillations with Attached SBLI

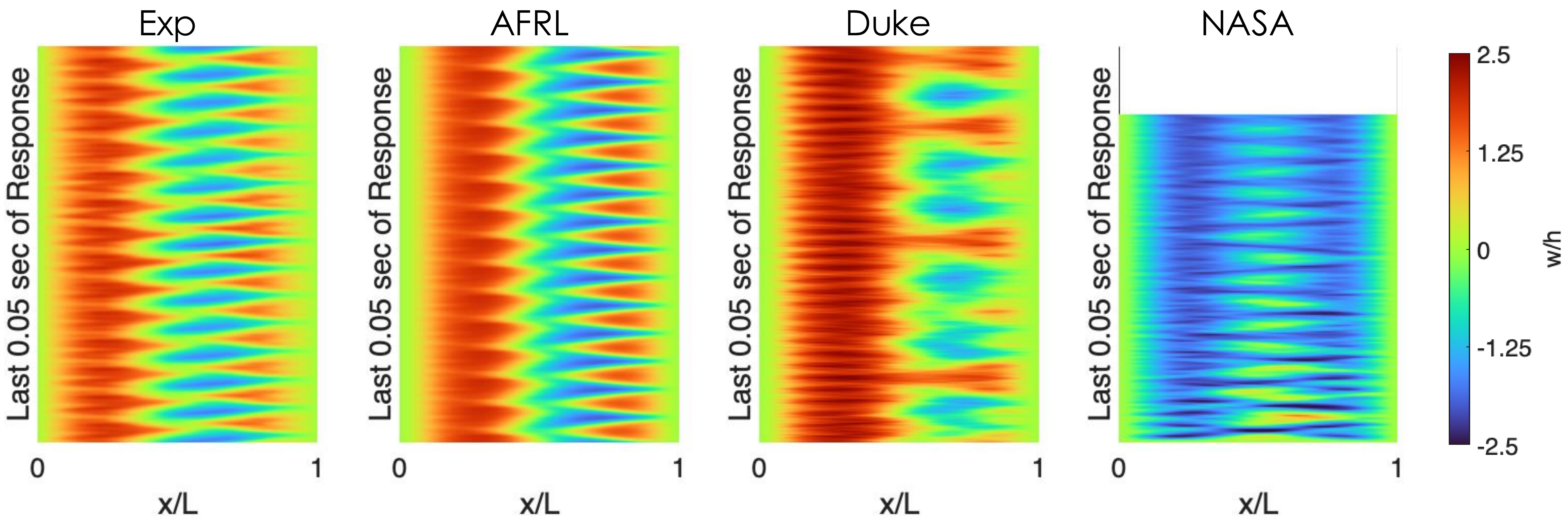
Operating Conditions Case 3

	Exp	AFRL	Duke	NASA	Cadence
p_c (kPa)	68.9	68.1	65	68.9	68.9
ΔT (K)	13.4	11.1	15	13.4	13.4

BC stiffness
modeled (β_{BC} = 5)

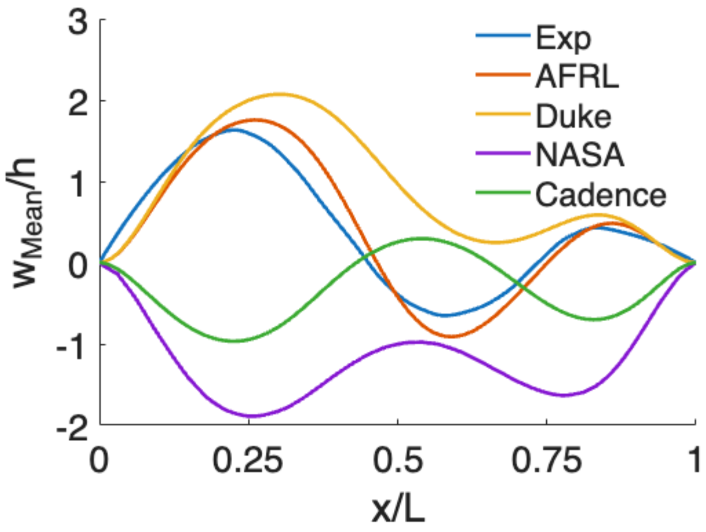
	Percent Error (%)			
	AFRL	Duke	NASA	Cadence
p_c (kPa)	1.13	5.63	0.00	0.00
ΔT (K)	17.3	11.7	0.00	0.00

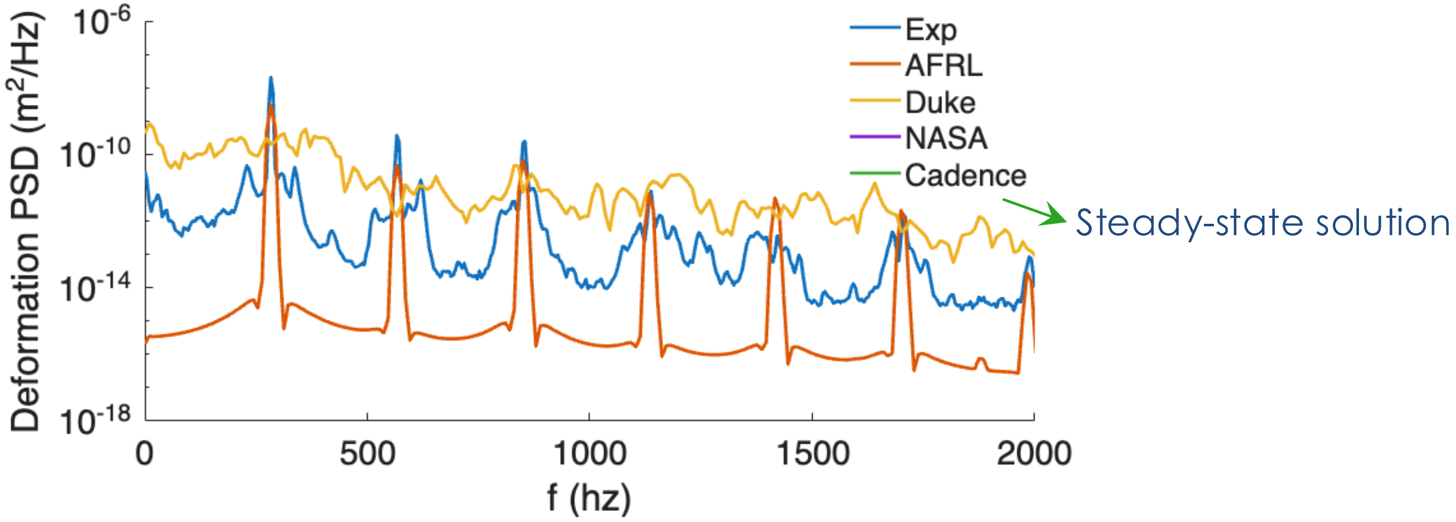
Specific Results for Case 3

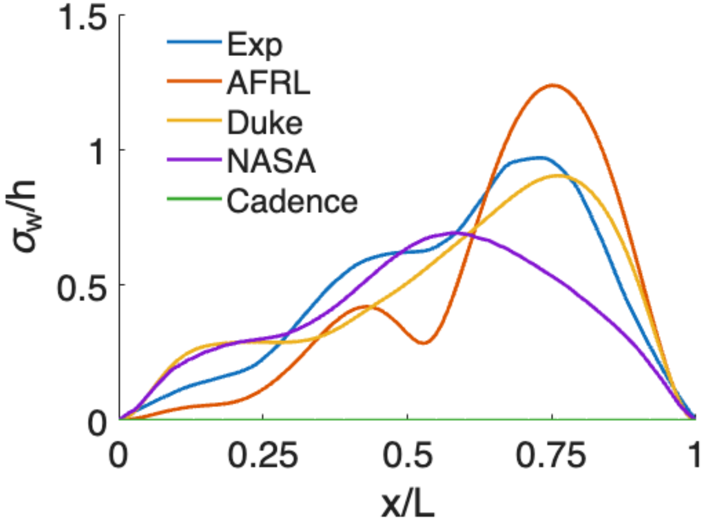


- **Cadence simulations not shown because data only extracted at ¼, ½, & ¾ chord locations and simulations appeared to converge to steady-state**
- **NASA simulations only conducted for ~0.03 sec**
- **DLR didn't compute solutions for this condition**

Specific Results for Case 3







	Normalized RMS Error (%)			
	AFRL	**Duke**	**NASA**	**Cadence**
w_{Mean}	26.3	90.5	235	160
σ_w	34.0	19.3	31.7	N/A
Amplitude	9.89	27.0	84.2	N/A

Findings & Takeaways: Computational Models

- **Low fidelity toolsets (Enriched piston & potential flow theories + structural ROMs) offer good balance of efficiency and predictive accuracy**
  - Accurately predict instability onset, but do not always capture post-threshold response
  - Computational efficiency enables exploration of vast parameter space and more detailed mapping of instability boundaries
  - Generally, require less data from experiments to setup/initialize

- **High-fidelity simulations (CFD + FEA)**
  - Require additional data to setup/initialize (e.g., CFD – inflow BC, nozzle/test section geometry)
  - Significant computational burden restricts study of:
    - Long-duration time histories (concern for aeroelastic simulations with transient behavior)
    - Entire parameter space – complicates comparison with experiments given input parameter uncertainty
  - Introduction of higher fidelity models may move solution further away from experiments
  - Higher fidelity likely needed for complex SBLI cases

- **Limited use of data-driven multi-fidelity methods to tackle these challenge problems**

Findings & Takeaways: Feedback for Experiments

- **Temperature field characterization, especially for buckled panels**
  - Simulated response is very sensitive to assumed thermal solution
  - A single measurement of temperature differential may neglect gradients near panel boundaries or those due to SBLI

- **Improved characterization of experimental setup:**
  - Structural boundary conditions after test article installation
  - Test section inflow conditions and/or boundary layer profiles

- **Improved baseline (no structural deformation) flow characterization for fluid model validation**

Questions?