AFRL

FSI/FTSI DEVELOPMENTS AT THE AFRL STRUCTURAL SCIENCES CENTER

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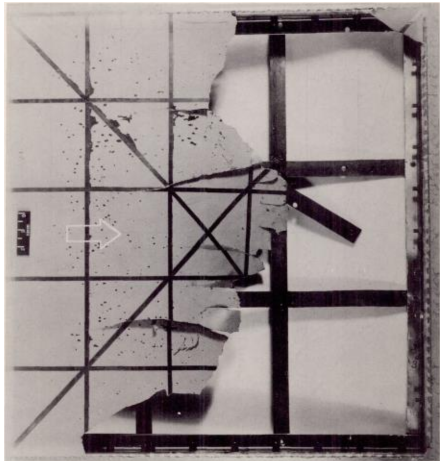
Background & Motivation – Local FTSI

- Extreme, complex loading in high-speed environments (transition, turbulence, separation, **SBLI**, **3D-effects**) combined with flight-weight structures necessitates aeroelastic/aerothermoelastic considerations

- Limited full-field calibration/validation data which includes post-flutter response
  - Several ongoing FSI experiments with SBLI *[**AFRL-SSC**; Willems, Daub, and Gülhan (DLR); Austin (CalTech); Bruce (ICL); Narayanaswamy (NCSU); Bodony (UIUC) and Laurence (UMD); Neely (UNSW), Buttsworth (USQ), and Jahn (UQ); Alvi, Kumar, and Shoele (FAMU-FSU); Clemens (UT Austin)]*
  - Studies typically restricted to:
    - Canonical structures to study phenomena → **Extension to built-up/realistic structures**
    - 2-D SBLIs → **Extension to realistic 3-D geometries**
  - Also, **difficult to perform parameter sweeps due to cost/resource limits**

- Computationally efficient low/multi-fidelity models must play a role but there are **open questions regarding accuracy bounds**



Panel failure during flutter [Dixon, 1962]

Pylon Rip due to SBLI

Perspectives on Local FTSI Research Needs

Research need: Experimental FTSI datasets for computational model development

High-quality FTSI data

- Pretest characterization of machined article (modal, thermal buckling & thickness)
- Boundary conditions (structural, thermal & fluid)
- Spatiotemporal loading (pressure & thermal)
- Full-field response (deformation, temp. & pressure)

Computational Model Development

- Individual-discipline model fidelity (empirical, theoretical, & FEM/CFD)
- Accuracy limits & missing physics
- Required coupling strategy
- Parametric sensitivities & uncertainty quantification

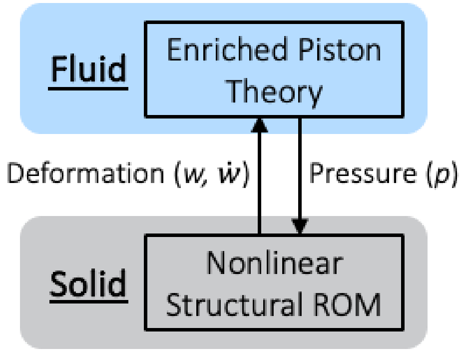
SSC Role: Utilize unique test facilities to design & carry out component-level FTSI experiments

- Explore new & improved existing measurements to better characterize response/environment
- Design test articles to observe excessive structural behavior/limit-states
- Provide well-characterized datasets to broader community
- ***Develop simulation methods to capture FTSI for reusable high-speed vehicles***

Deep Dive:

RC-19 Aeroelastic Computations

Companion Computations



$$p = p_l\left\{1 + c_{l,1}\frac{v_n}{a_l} + c_{l,2}\left(\frac{v_n}{a_l}\right)^2 + c_{l,3}\left(\frac{v_n}{a_l}\right)^3\right\}$$

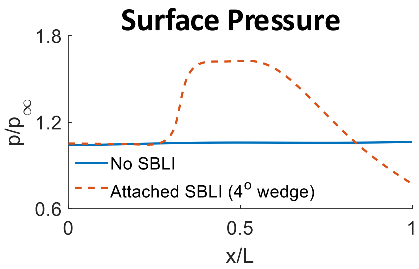
$$v_n = \frac{\partial w}{\partial t} + u_l\left\{\frac{\partial w}{\partial x}\right\}$$

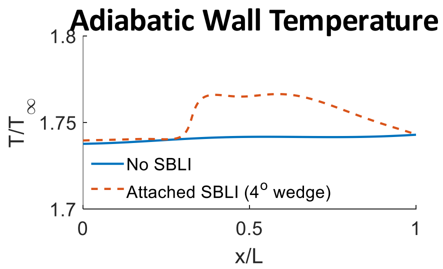
p_l - Local Pressure
a_l - Local speed of sound
u_l - Local velocity
c_l - Local coefficients
w - Surface position

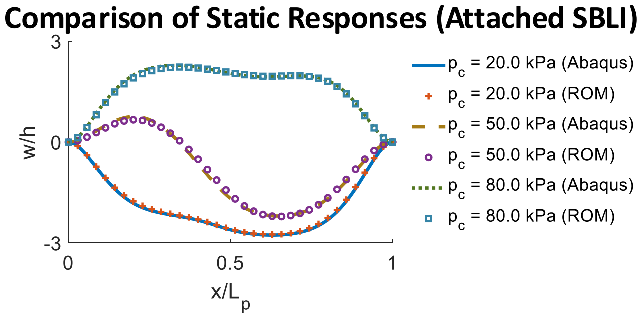
$$M\ddot{\eta} + D\dot{\eta} + \left(K^{(1)} - K^{(Therm.)}\right)\eta + K^{(2)}\eta\eta + K^{(3)}\eta\eta\eta = F^{(Aero.)} + F^{(Therm.)}$$

M - Mass matrix
D - Damping matrix
K - Stiffness matrices
F - Load vectors
η - Modal weight

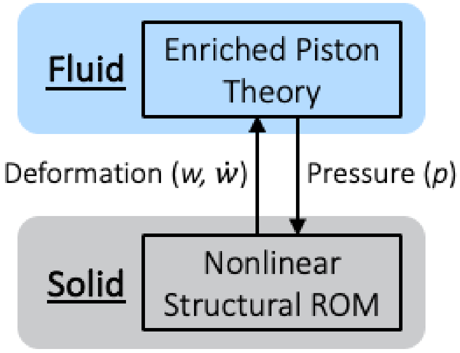
- **Fluid:** Second-order enriched piston theory
  - Local conditions from RANS over flat, rigid plate
  - Reasonable agreement for attached SBLI
    [Brouwer and McNamara, 2018]
  - Turbulent boundary layer fluctuations not modeled
- **Structure:** Nonlinear reduced-order model (ROM)
  - Applicable to a broad range of structures
  - Constructed using up to 18 modes
  - Thermal mode: Adiabatic wall temperature used to define distribution where the mean is shifted to match ΔT_{Avg}







Companion Computations



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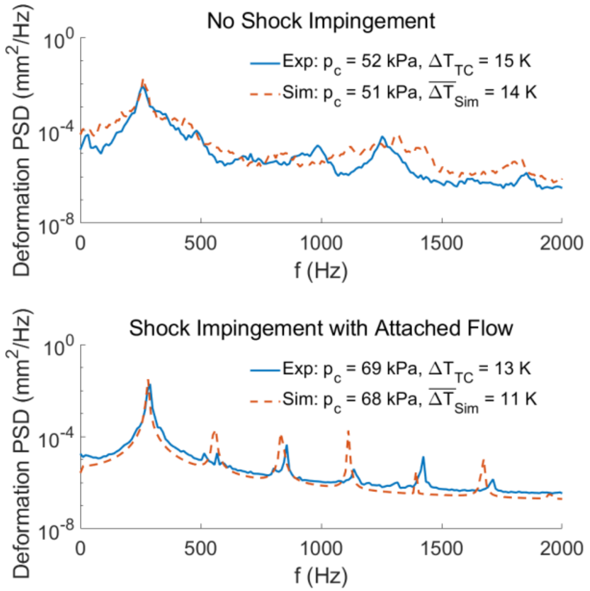
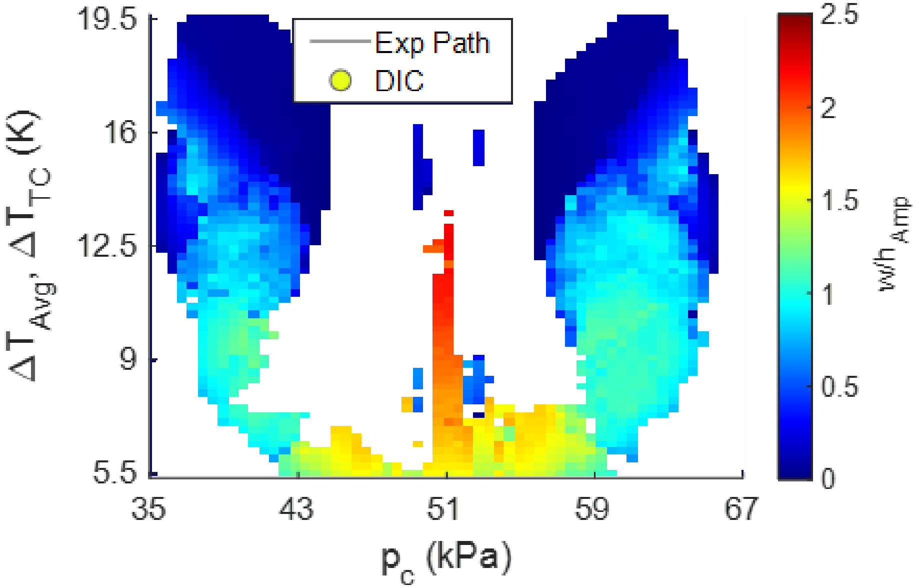
- Computationally efficient reduced-order simulation framework enables study of *O*(min.) time histories
- Computations capture measured dynamic behavior for attached flows:
  - Cross-well chaos of a buckled panel without SBLI
  - Shock-excited limit cycle oscillations
- Poor performance for separated SBLI conditions due to errors in modeling unsteady flow physics



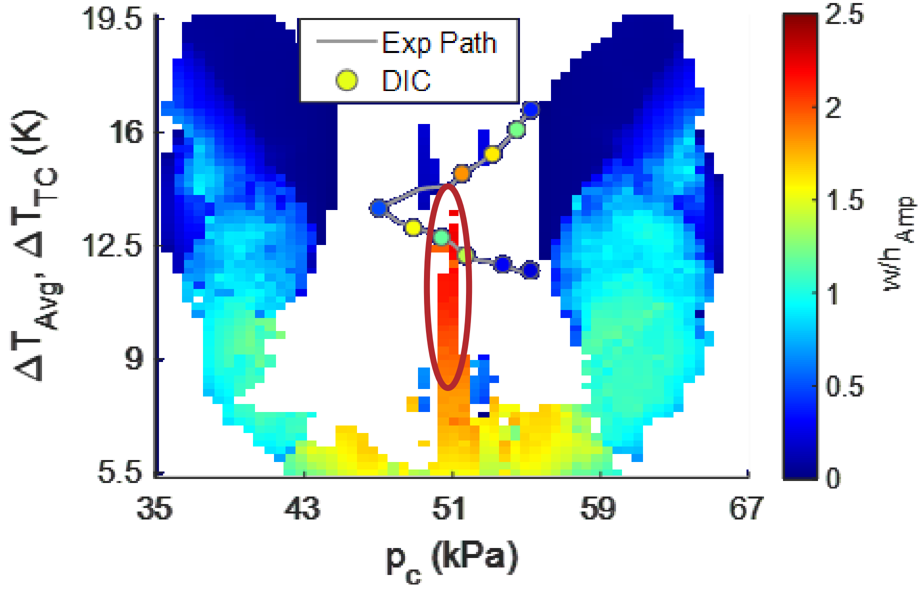
*Data extracted at ¾-chord

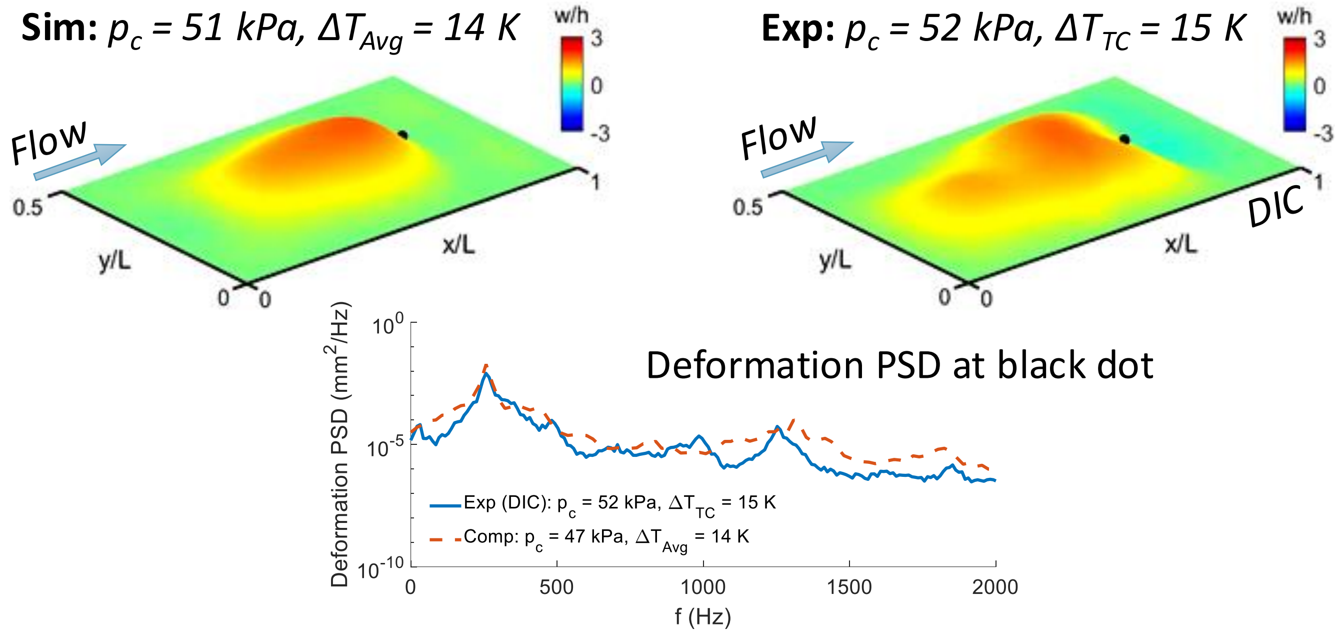
Model Evaluation: System Response Maps



- System response maps used to explore the impact of p_c and ΔT
  - Embarrassingly parallel process to construct maps since each pixel represents a single, independent simulation
  - Neglects path-dependency (likely important in experiments) → **Exploring this effect is a focus of ongoing work**
- Several parameter combinations produced static responses (white spaces)
  - Current aeroelastic framework neglects turbulent boundary layer (TBL) pressure fluctuations
  - Predicted response is expected to recover the small-amplitude forcing if acoustic loads are included (**Ongoing**)

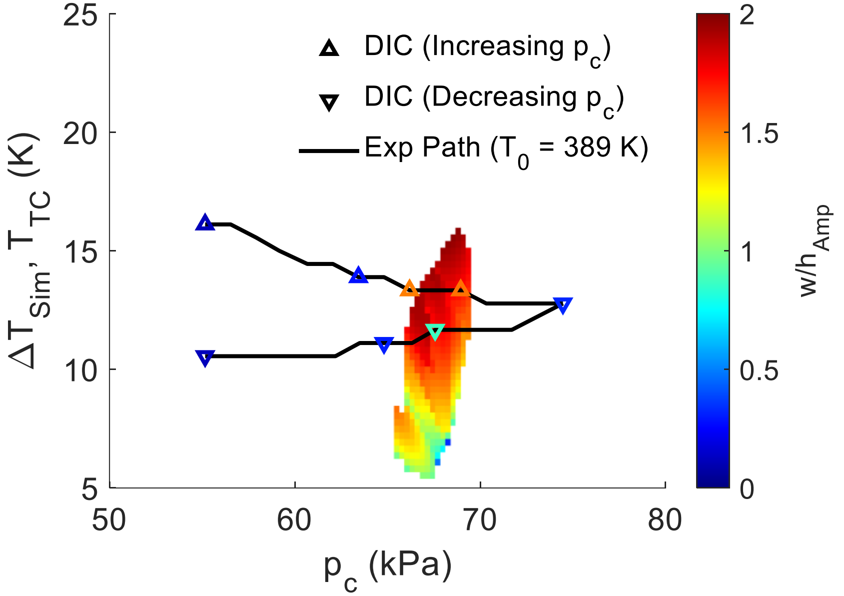
Model Evaluation Without SBLI

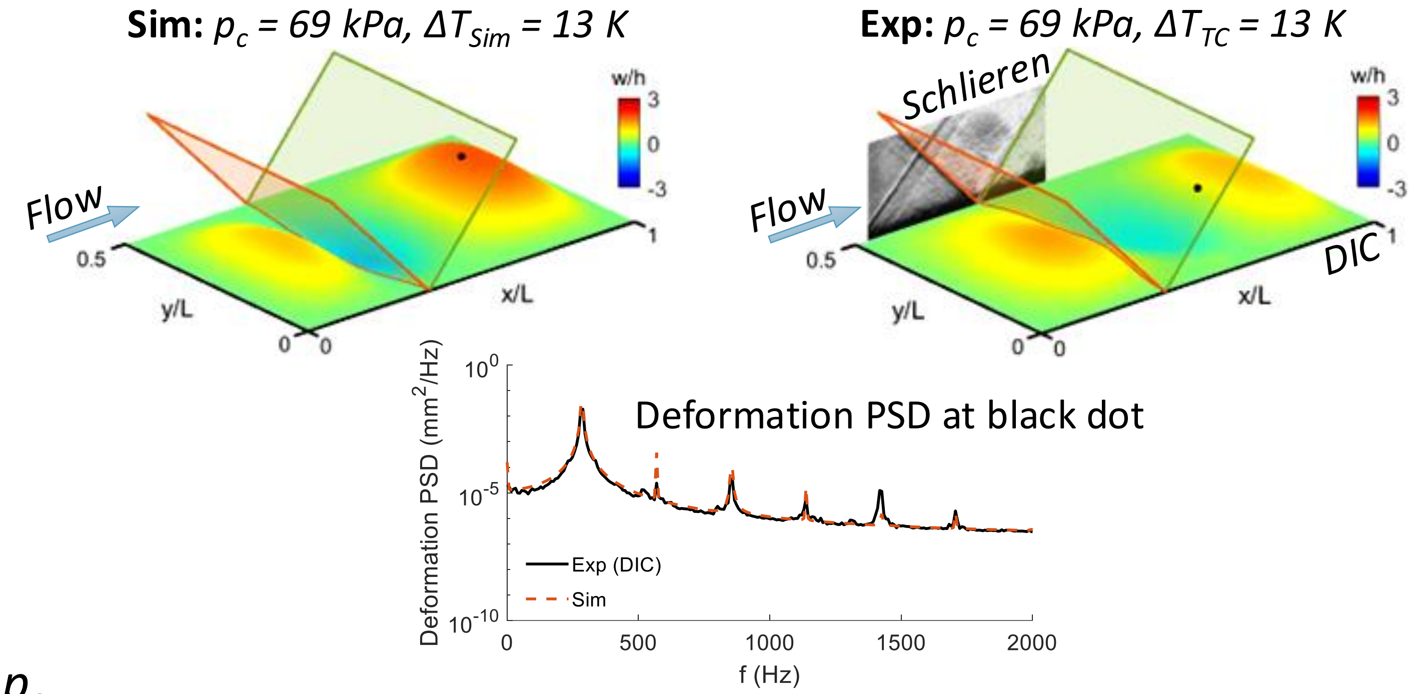




- Complex system response centered about p_c = 47 kPa ($\Delta p \approx 0$)
  - Panel is buckled since $\Delta T_{Critical}$ is 5.6 K → co-existing equilibria can lead to large-amplitude cross-well chaos
  - Two distinct regions of single-well oscillations with lower amplitudes as $|\Delta p|$ increases
- Simulations reasonably capture trend in amplitude for p_c = 47 kPa ($\Delta p \approx 0$)
  - Good agreement in dominant frequency (~260 Hz), but simulations overestimate amplitude
  - Differences in estimated and actual distribution of ΔT likely a leading source of error

Model Evaluation With Unswept, Attached SBLI





- Flutter boundary not symmetric about p_c
- Simulations approximately capture flutter boundary but tend to overestimate post-flutter amplitude
- Post-flutter response:
  - Majority of predicted dynamics occur over back half of panel, consistent with experiments
  - Excellent agreement in terms of frequency
  - Simulations overestimate panel dynamics near the leading and trailing edges

Computational Modeling Conclusions and Future Directions

Accomplishments:

- Computationally efficient simulations require ~30 min. on a processor for 1 min. of response
- Computations capture instability boundaries and measured post-threshold behavior for attached flow conditions
    - Cross-well and post-flutter motions for buckled panel without SBLI
    - LCO response for attached SBLI without shock sweep
    - Good agreement in frequency content, particularly for shock-induced LCOs
    - Errors due to uncertainty in ΔT distribution (Needs to be addressed using full-field temperature measurements)

Ongoing work & Future Directions:

- Identify sources of uncertainty (ΔT, acoustic loads, structural parameters, etc.)
- Exercise validated reduced-order/multi-fidelity ATE models to identify/bound parameters that govern instabilities
- Push computations/experiments to more complex loading environments and structures
    - When and why do the predictions fail?
    - Effect of separated SBLI and swept shocks on dynamic instabilities