Oral presentation | Fluid-structure interaction

Fluid-structure interaction-III

Mon. Jul 15, 2024 4:30 PM - 6:30 PM Room A

[3-A-04] Data-Driven Fluid-Structure Interaction with Fully-Partitioned Method and Deep Koopman Model

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Keywords: Fluid-structure interaction, Koopman, Data-driven approach

Data-Driven Fluid-Structure Interaction with Fully-Partitioned Method and Deep Koopman Model

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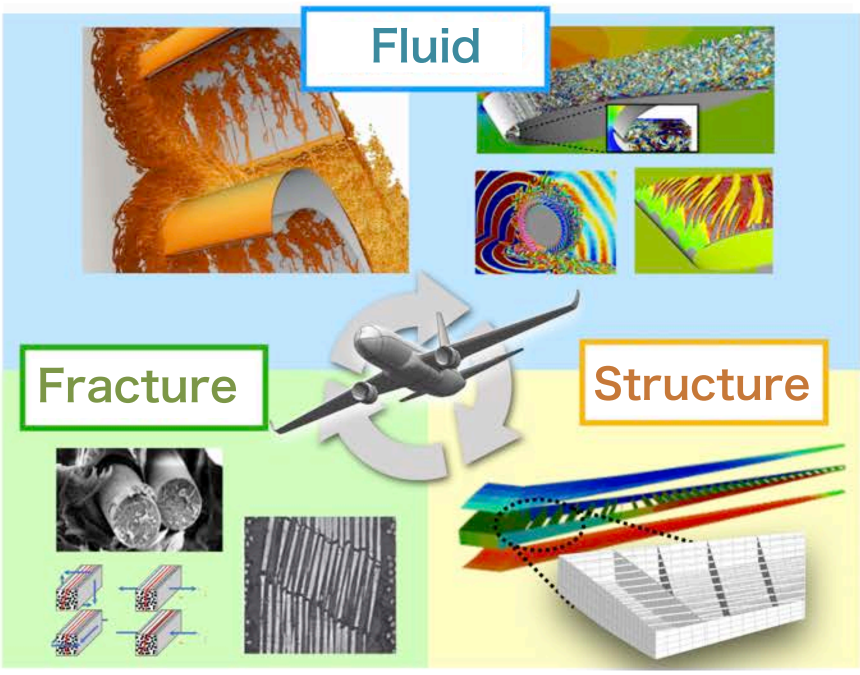
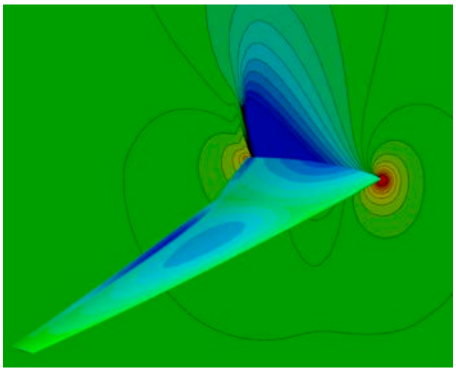
Freddie D. Witherden (Texas A&M University)
Yu Kawano (Hiroshima University)

Green Innovation for Global Aviation



Aerodynamic design? Structural design?

Aerodynamic shape optimization

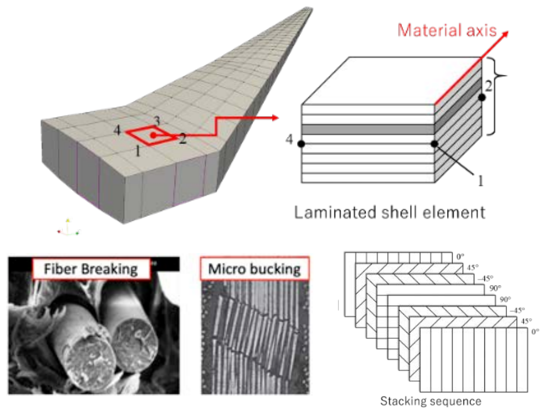


Fluid dynamics

Aerodynamic load

Structural deformation

Structural sizing (optimization) based on *margin of safety* (M.S.)



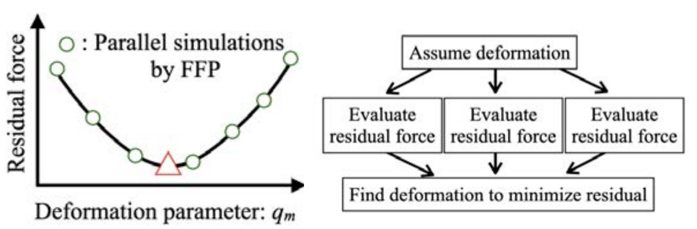
Solid mechanics, Fracture
Material Science

Digitalization of integrated design process with multi-physics simulation

Contents

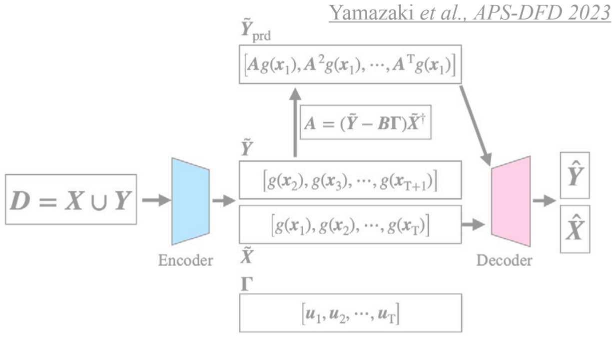
Residual minimization for static FSI

Abe *et al., JSCM, 48, 6 (2022)*



Data-driven dynamic FSI

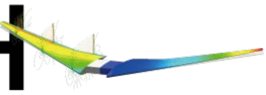
Yamazaki *et al., APS-DFD 2023*



Digital engineering in aircraft design 5

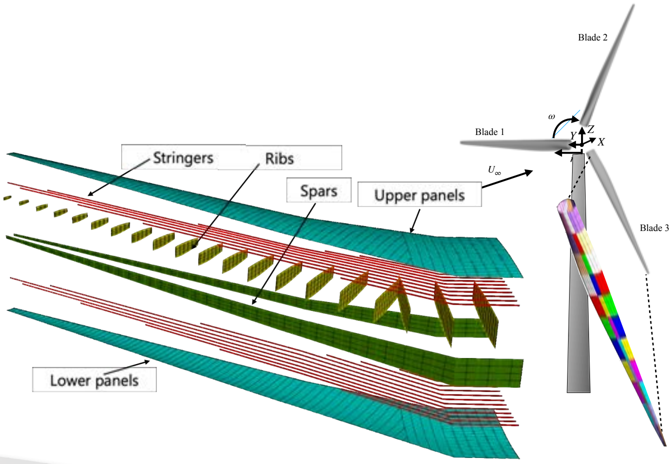
Aircraft design simulator

DASH



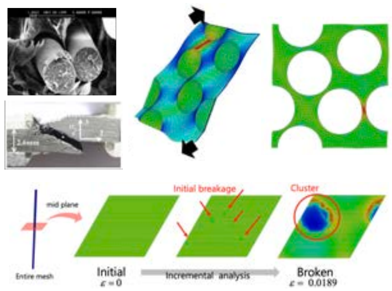
Digital Aircraft Design tool of Tohoku University

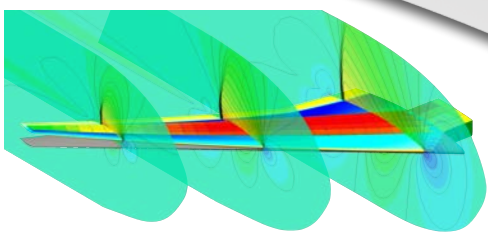
Date, Abe, *et al.*, *J. Aero. Sci. Tech.* 2022
Abe, *et al.*, CM3-ECCOMAS (invited, 2023)



Microscale analysis for composite material
$[\mu\mathrm{m} - \mathrm{mm}]$

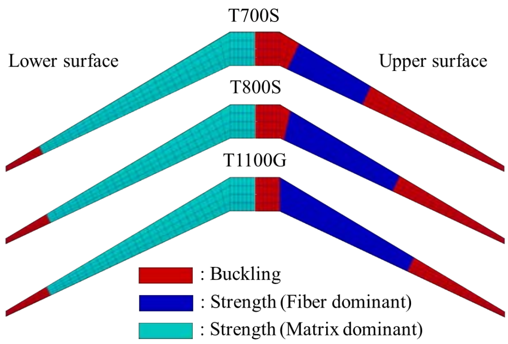
Macroscale aeroelastic / design analysis $[\mathrm{m}]$

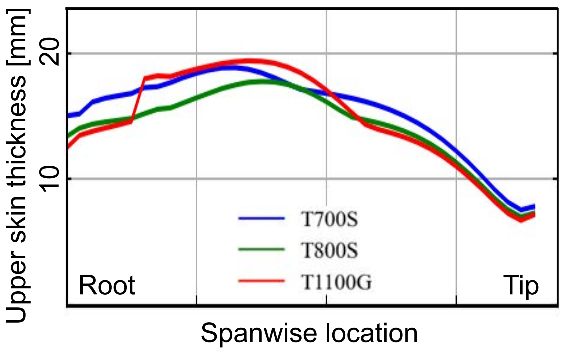




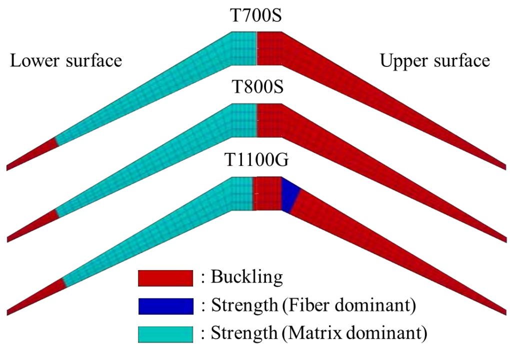
Aerostructural design in equilibrium condition 6

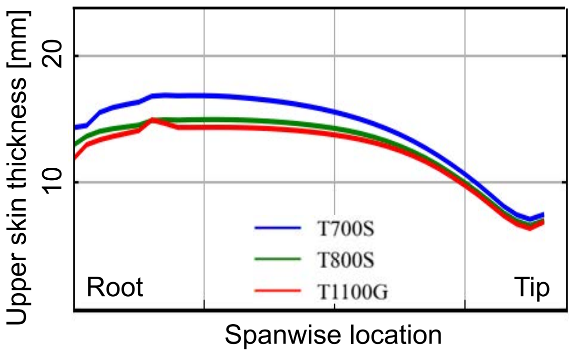
One-way (CFD → CSD)





Two-way (CFD ⇄ CSD)





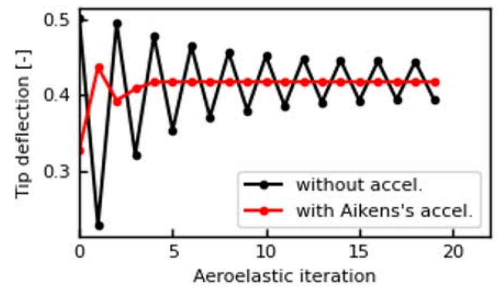
- Failure mode cannot be accurately captured by one-way coupled analysis

Challenges in high-fidelity FSI for aircraft design 7

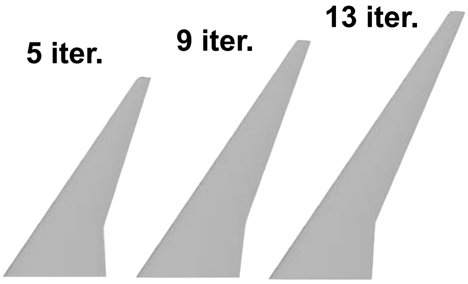
Sequential iteration

✓ 5 - 20 times aeroelastic iteration

✓ 50 - 200 times structural-sizing iter.

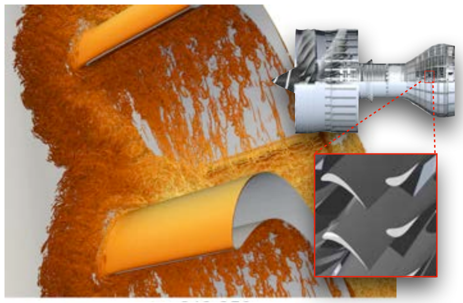


✓ High-aspect-ratio wing requires larger iter.



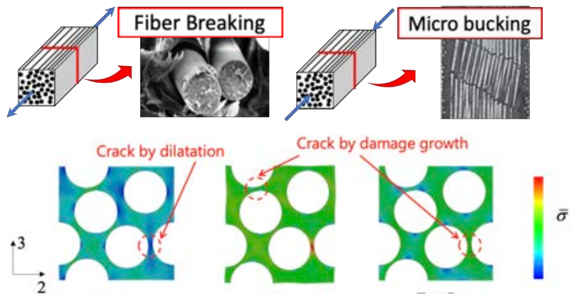
High-fidelity models

✓ CFD at real high-load conditions



A.S. Iyer, Y. Abe *et al.*, *C&F,* **226**, 104989, (2021)

✓ CSD with damage propagation



Conventional iterative method for static FSI 8

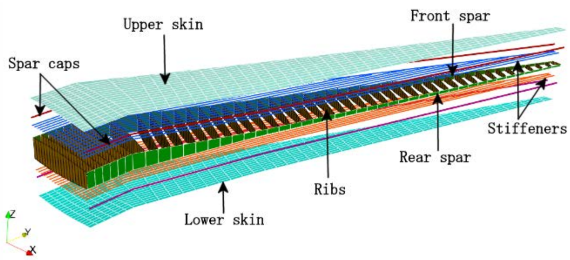
▶ Structural deformation in equilibrium condition

$$\boldsymbol{\lambda}_S(\boldsymbol{u}_S) - \boldsymbol{f}_S(\boldsymbol{u}_S) = 0 \qquad (\boldsymbol{u}_S : \text{displacement})$$

Internal force

$$\boldsymbol{\lambda}_S = \underline{\mathcal{S}^*}(\boldsymbol{u}_S)$$

Structural solver

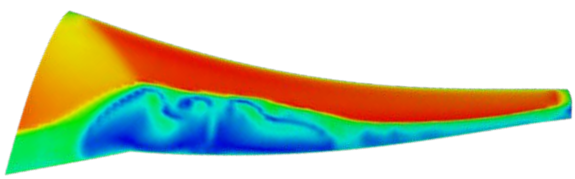


External force

$$\boldsymbol{f}_S = \boldsymbol{T}^T \underline{\mathcal{A}}(\boldsymbol{x}^{(0)}_{\mathrm{Av}}, \underline{\boldsymbol{T}}\boldsymbol{u}_S)$$

Flow solver

Transformation matrix



Residual minimization approach in static FSI

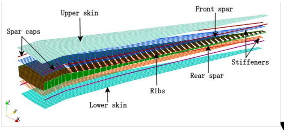
Force-based fully partitioned (**FFP**)

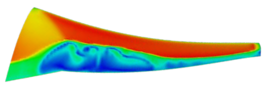
Simultaneously evaluate

Assume deformation: $\boldsymbol{u}_\mathrm{S}^{(1)}$

Structural solver **Flow solver**

$\boldsymbol{\lambda}_\mathrm{S} = \mathcal{S}^*(\boldsymbol{u}_\mathrm{S}^{(1)})$ $\boldsymbol{f}_\mathrm{S} = \boldsymbol{T}^T \mathcal{A}(\boldsymbol{x}_\mathrm{Av}^{(0)}, \boldsymbol{T}\boldsymbol{u}_\mathrm{S}^{(1)})$



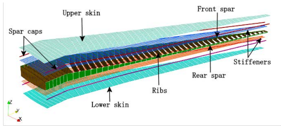


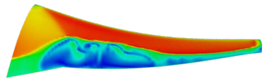
Residual force: $\boldsymbol{\lambda}_\mathrm{S} - \boldsymbol{f}_\mathrm{S} = R(\boldsymbol{u}_\mathrm{S}^{(1)})$

Assume deformation: $\boldsymbol{u}_\mathrm{S}^{(2)}$

Structural solver **Flow solver**

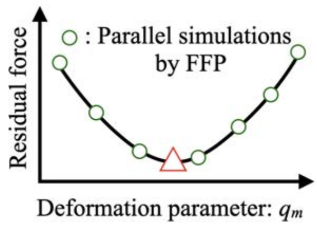
$\boldsymbol{\lambda}_\mathrm{S} = \mathcal{S}^*(\boldsymbol{u}_\mathrm{S}^{(2)})$ $\boldsymbol{f}_\mathrm{S} = \boldsymbol{T}^T \mathcal{A}(\boldsymbol{x}_\mathrm{Av}^{(0)}, \boldsymbol{T}\boldsymbol{u}_\mathrm{S}^{(2)})$





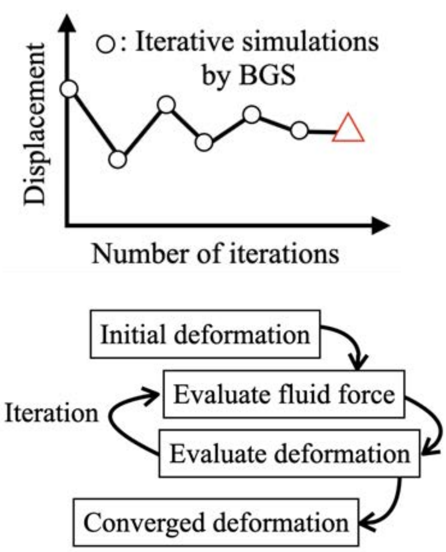
Residual force: $\boldsymbol{\lambda}_\mathrm{S} - \boldsymbol{f}_\mathrm{S} = R(\boldsymbol{u}_\mathrm{S}^{(2)})$

- ✓ Response surface of the residual force: $R(\boldsymbol{u}_\mathrm{S})$
- ✓ Find the deformation minimizing $R(\boldsymbol{u}_\mathrm{S})$

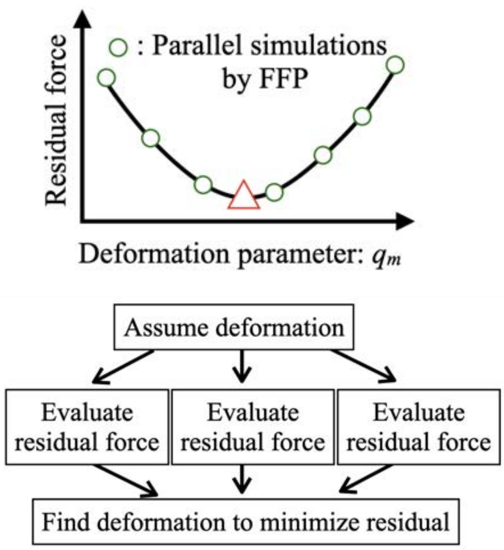


Residual minimization approach in static FSI

Nonlinear Block Gauss-Seidel (**BGS**)

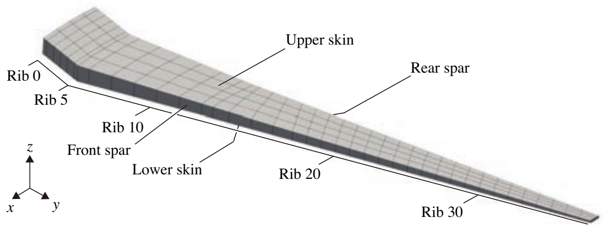


Force-based fully partitioned (**FFP**)



Residual minimization approach in static FSI

▶ Leading edge deformation of CFRP wing



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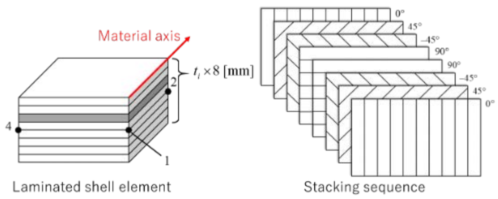
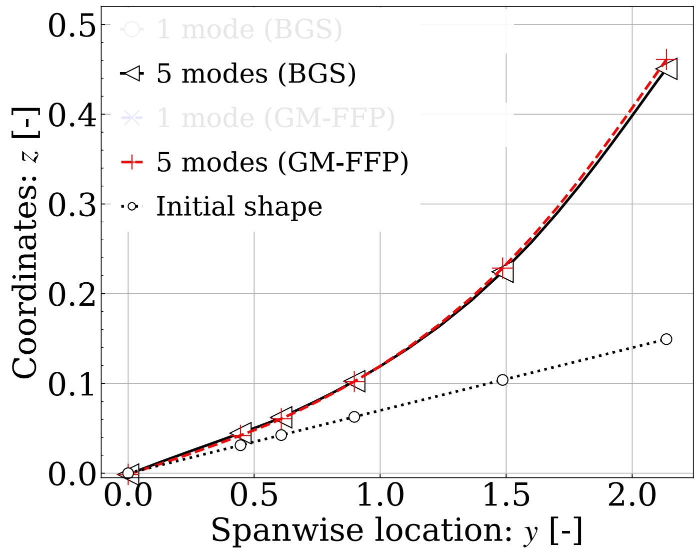




✓ GM-FFP is ***highly parallelizable*** in iterative direction.

=> It becomes faster if the iteration of BGS is large.

BGS v.s. GM-FFP (AoA = 0 deg.)

▶ Elapsed time with CPU (4 cores for 1 simulation)

Method	Cores	Elapsed time
BGS (1 mode, 4 iter.)	4	302.9 sec.
BGS (5 modes, 6 iter.)	4	459.1 sec.
GM-FFP (1 mode)	20	74.69 sec.
GM-FFP (5 modes)	20	373.44 sec.

approx. 4 times speed-up

✓ GM-FFP is parallelizable in iterative direction.

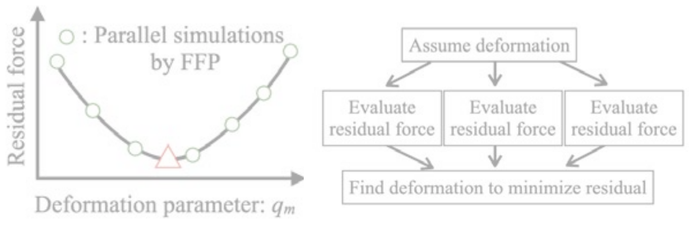
=> It becomes faster if the iteration of BGS is large.

Contents

14

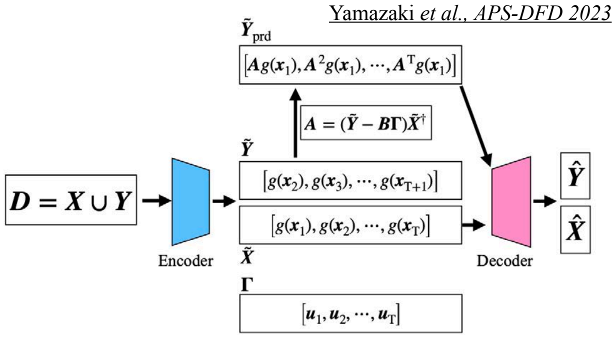
Residual minimization for static FSI

Abe *et al., JSCM, 48, 6 (2022)*



Data-driven dynamic FSI

Yamazaki *et al., APS-DFD 2023*

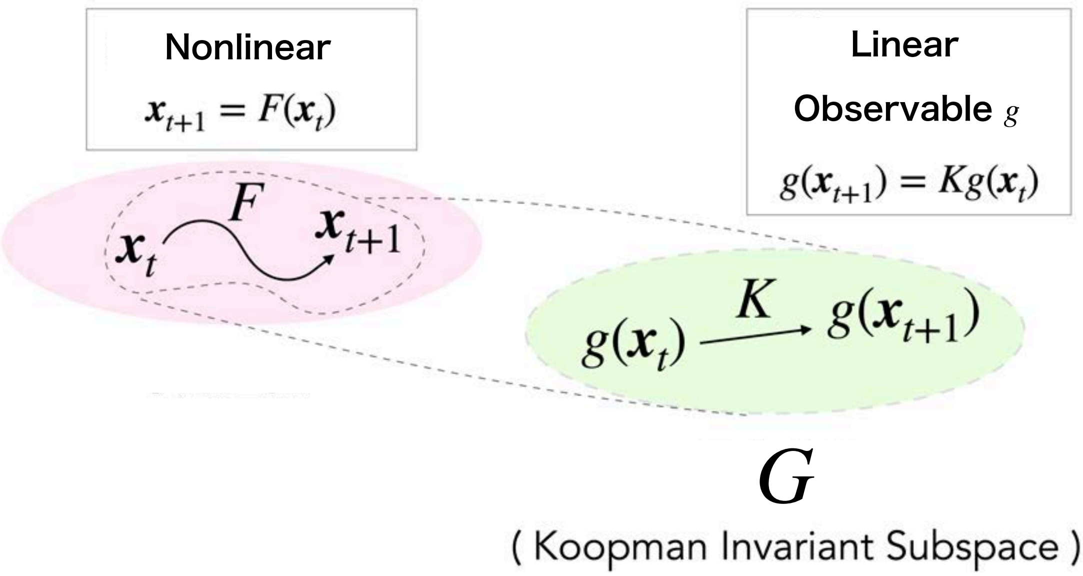


Deep Koopman dynamical model

15

Morton *et al., NeurIPS* 2018; Takeishi *et al., NeurIPS* 2017

$$x_{t+1} = F(x_t) \longrightarrow g(x_{t+1}) = g(F(x_t)) = \mathcal{K}\, g(x_t)$$



Deep Koopman dynamical model

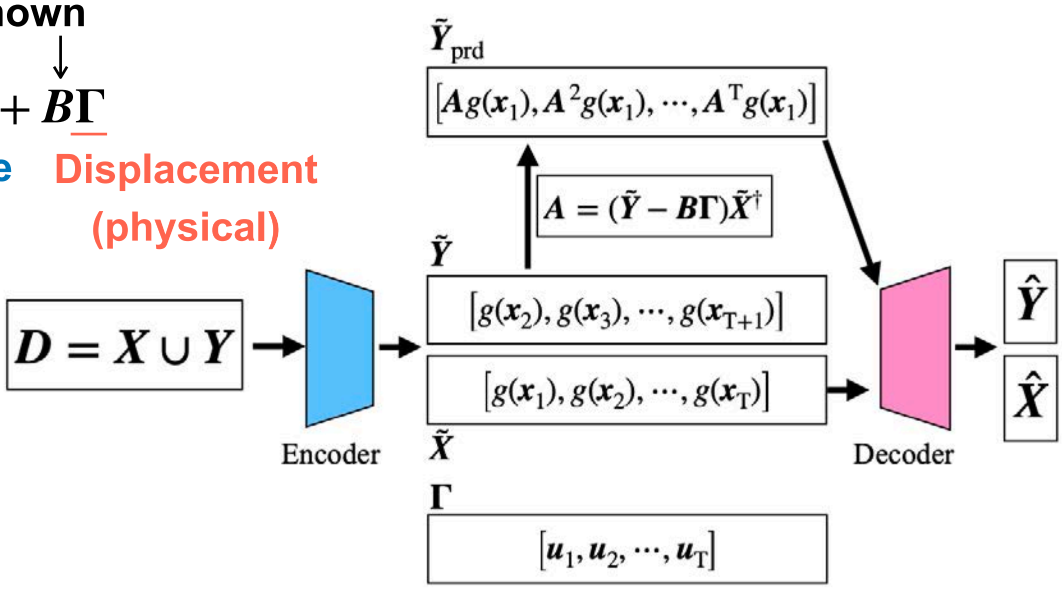
Morton *et al.*, *NeurIPS* 2018; Takeishi *et al.*, *NeurIPS* 2017

$$x_{t+1} = F(x_t) \longrightarrow g(x_{t+1}) = g(F(x_t)) = \mathcal{K}\, g(x_t)$$

Unknown

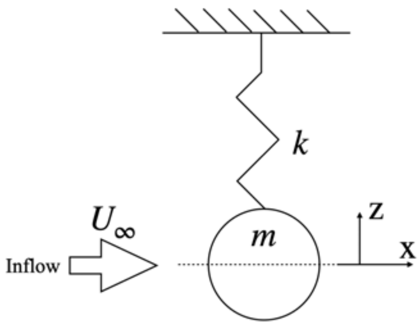
$$\tilde{Y} = A\tilde{X} + B\Gamma$$

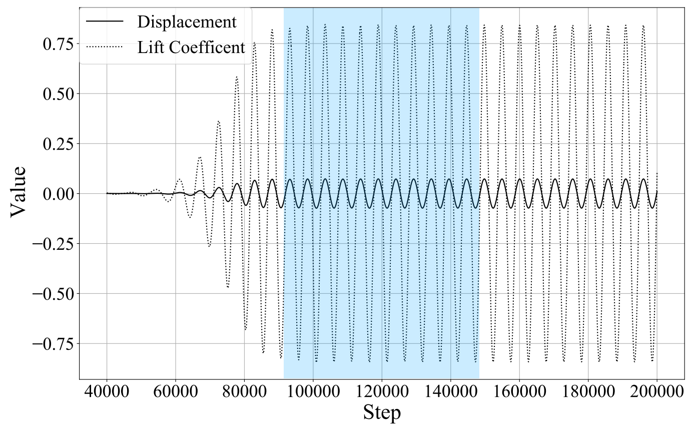
Flow state (latent) — **Displacement (physical)**



Deep Koopman dynamical model

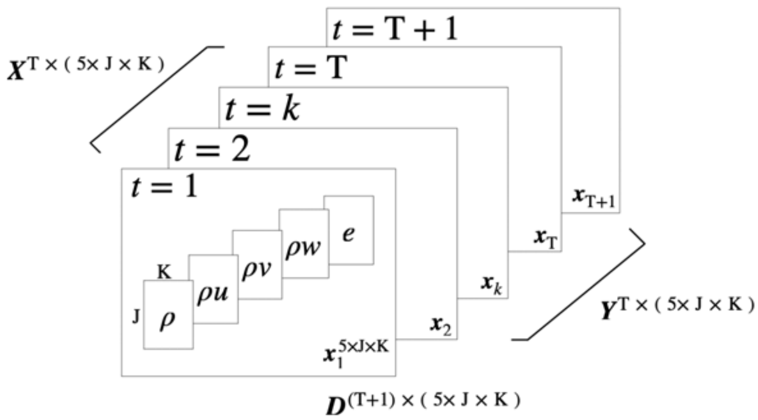
- **Flow around cylinder**





- **Flow variables: X, Y**

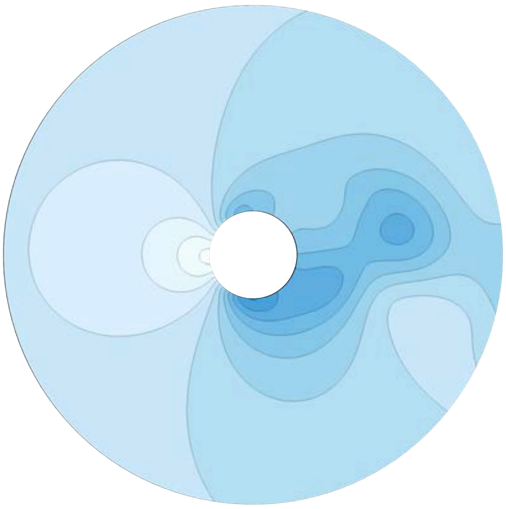
  input: $u = [z, \ddot{z}]^T$

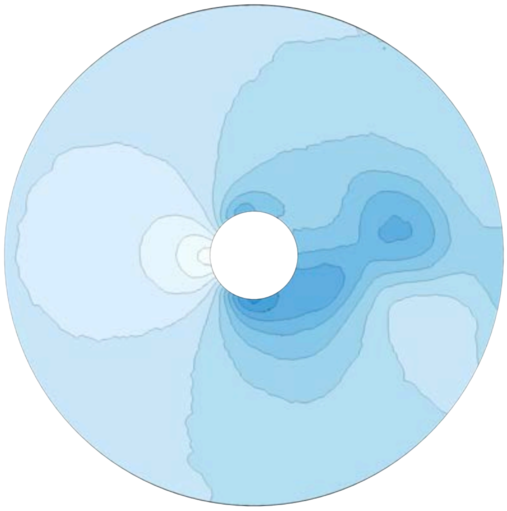


Deep Koopman dynamical model

Original (pressure field)

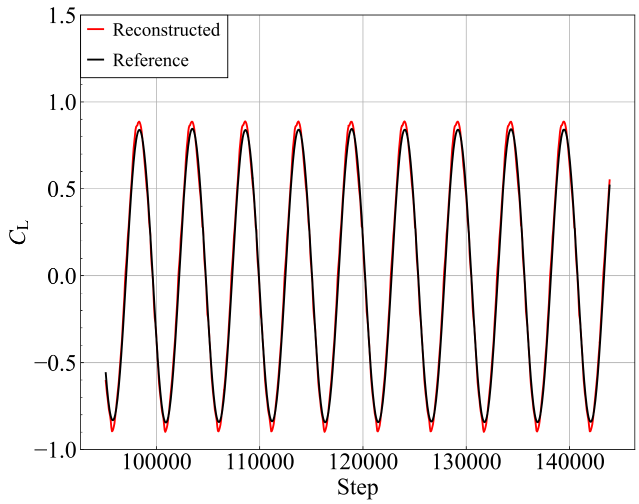
Reconstructed



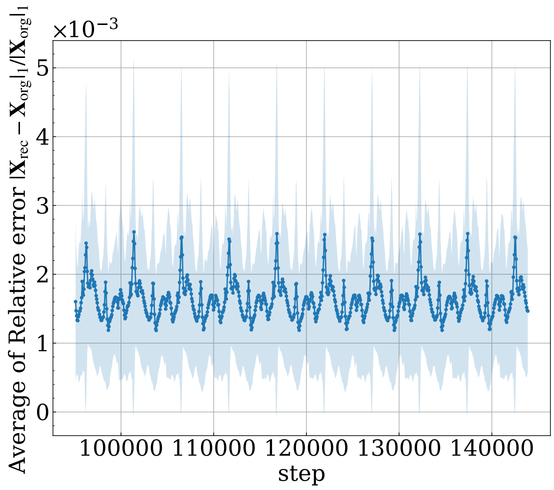


Deep Koopman dynamical model

- **Lift force history**



- **Relative error** (loss function)



Dynamic FSI

Farhat and Lesoinne *CMAME* (2000)
Barcelos *et al*., *CMAME* (2006)

- Iteration at fixed time

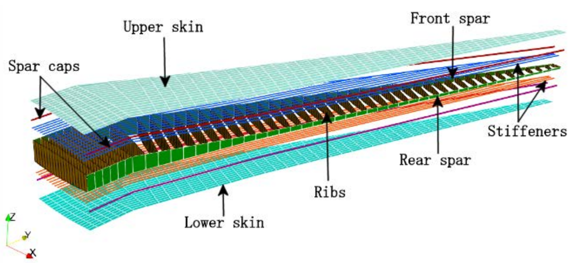
$$\boldsymbol{\lambda}(\boldsymbol{u}) - \boldsymbol{f}(\boldsymbol{u}) = 0$$

($\boldsymbol{u}$: displacement)

Internal force

$\boldsymbol{\lambda} = S(\boldsymbol{u})$

Structural solver



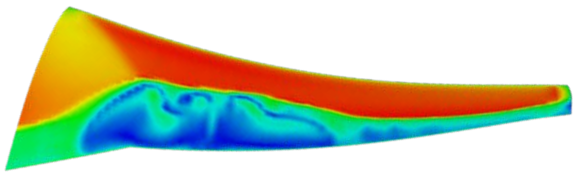
t_n

t_{n+1}

External force

$\boldsymbol{f} = A(\boldsymbol{u})$

Flow solver



Dynamic FSI

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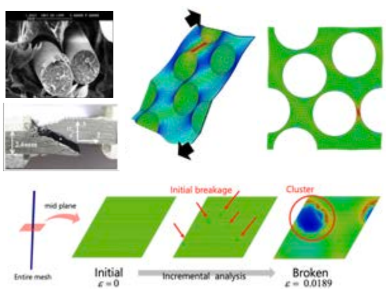
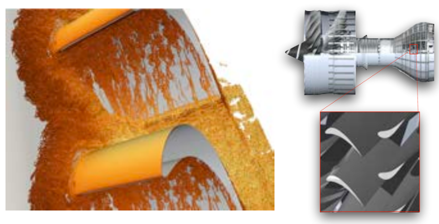


t_n

t_{n+1}

External force

$\boldsymbol{f} = A(\boldsymbol{u})$

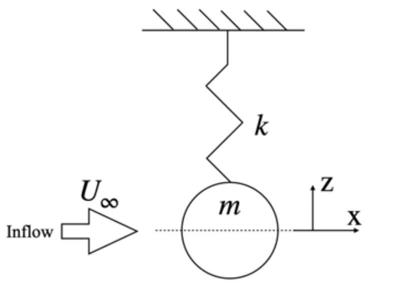


High-fidelity simulations in each physics?

- Large number of degrees of freedom in space
- Communications between “big” solvers at each time step

Proof of concept (preliminary…)

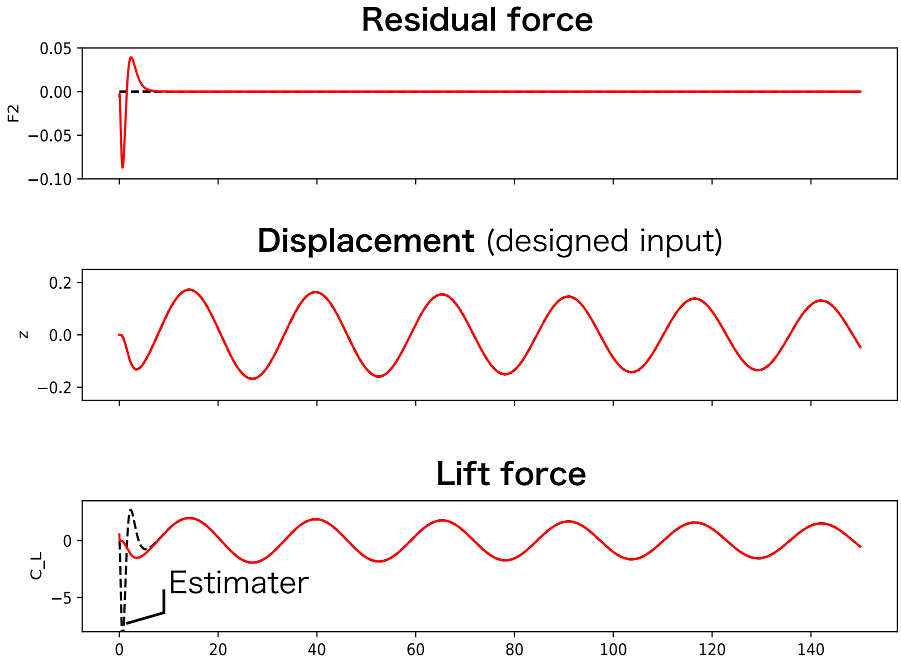
- **Observer-based control design** (DMDc-based flow dynamics)



$$\frac{\mathrm{d}}{\mathrm{d}t}\underbrace{\begin{bmatrix}\hat{C}_L\\ \hat{C}_D\\ \hat{u}_2\\ \hat{\dot{u}}_2\end{bmatrix}}_{\xi} = (\boldsymbol{A}+\boldsymbol{L}\boldsymbol{C})\underbrace{\begin{bmatrix}\hat{C}_L\\ \hat{C}_D\\ \hat{u}_2\\ \hat{\dot{u}}_2\end{bmatrix}}_{\xi} - \underbrace{\boldsymbol{L}}_{4\times 1}\boldsymbol{y} + \boldsymbol{B}\boldsymbol{F}.$$

Estimater

Design parameter



Residual force can be replaced by simulation results

Conclusions

Data-driven FSI approach was proposed with

- **Residual force minimization**
- **Deep Koopman dynamical model**

- Parallelization of computing residuals for FSI solution was introduced
- Deep autoencoder was applied in the Koopman dynamical model

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