2022-2023 Performance Report of Tohoku University Students' Projects
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Project for real-time control of flow field using sparse processing PIV and plasma actuators

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Backgrounds1 - PA -

[1] https://www.ana.co.jp/ja/jp/domestic/departure/inflight/seatmap/
[2] https://global.nissannews.com/ja-JP/releases/231010-01-j

□Various fluid machines

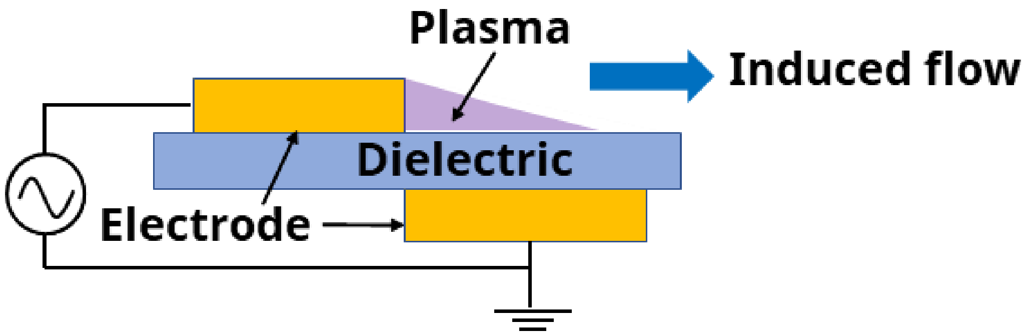
- Airplanes, drones, automobiles, windmills…
  - ➢Expectations for performance improvement in <u>active</u> flow control


[1]


[2]

□Plasma actuator (PA) (Corke *et al*., 2007, Fujii, 2014)

- Induced flow by plasma



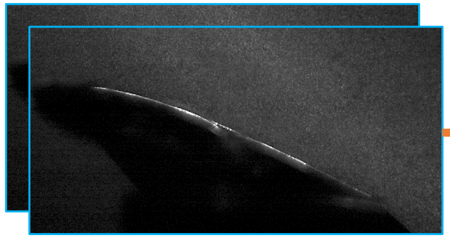
- Optimal control input depends on airflow conditions

➡ **<u>Feedback control according to flow field is important</u>**

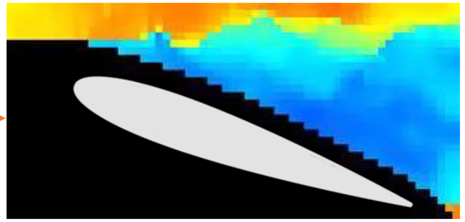
Background2 – SPPIV -

□How to measure the current flow with high accuracy?

- Particle image velocimetry (**PIV**)
- The flow field data is huge

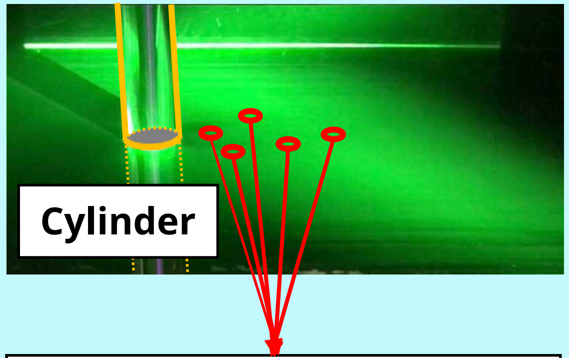


Calculate particle movement



□Sparse Processing PIV (**SPPIV**) (Kanda *et al.*, 2021, 2022)

- Estimating the overall state with information from a sparse points (= sensors)
- Estimate $\boldsymbol{z}$ (the "intensity" of the spatial structure known in advance)

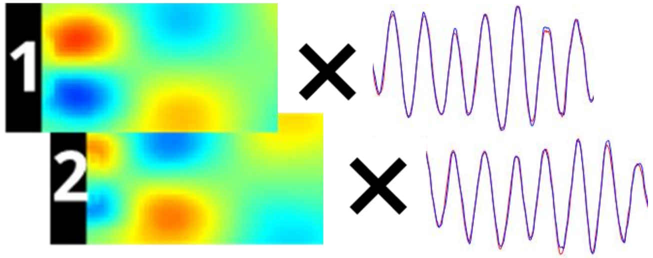


PIV on sparse points

Model

Use information from training data to predict the next flow

Correction



spatial structure "**modes**"

$\boldsymbol{z}$

Objectives

Construct a real-time feedback control system using SPPIV and PA and evaluate the estimation performance and control effect

Target
Kármán vortex suppression

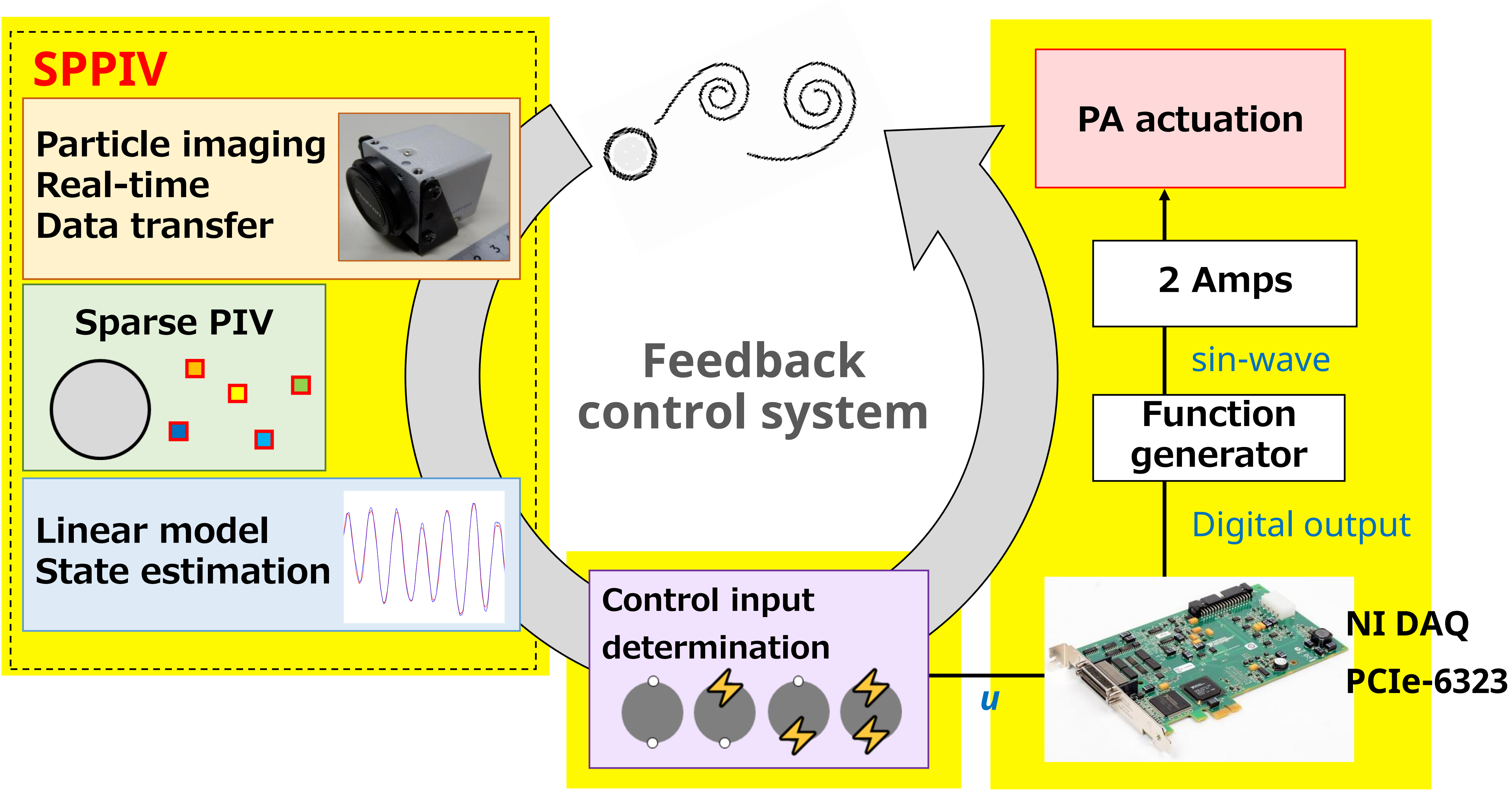
□Construct binary control rules by turning PA ON/OFF

- One-point predictive control
- Advanced control (control in section)

□Feedback control in wind tunnel testing

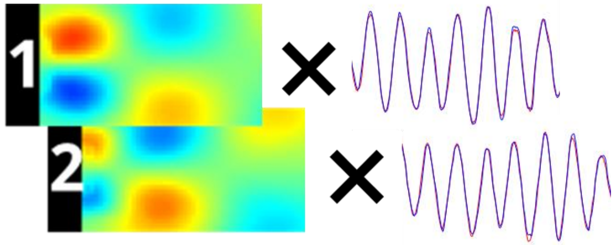
- Evaluation of control effect by focusing on symmetry of flow velocity field

Feedback Control System



Feedback Control Methods

□Construction of feedback control rules



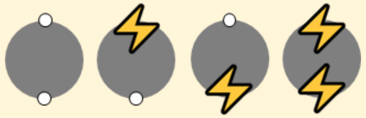
$\boldsymbol{z}$ → attenuate intensity of <u>antisymmetric</u> modes → Symmetric flow (weak Kármán vortex)

➢Control law 1

One-point Predictive Control

- Predict $\boldsymbol{z}_{k+L}$ of each $\boldsymbol{u}_k$
- **Consider the next one step**

Calculation for all patterns



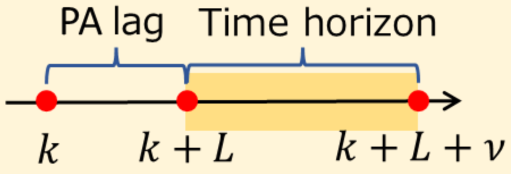
$$\underset{\boldsymbol{u}}{\operatorname{argmin}} \|\boldsymbol{z}\|_2$$

➢Control law 2

Advanced control (Ikeda *et al.*, 2017)

- **Consider the interval** between ν steps

$$\left(\boldsymbol{v} = \left[\boldsymbol{u}_k{}^{\mathrm{T}}\ \boldsymbol{u}_{k+1}{}^{\mathrm{T}} \cdots \boldsymbol{u}_{k+\nu-1}{}^{\mathrm{T}}\right]^{\mathrm{T}}\right)$$



- Solve the optimization problem

$$\underset{\boldsymbol{v}}{\operatorname{argmin}} \left(\|\boldsymbol{z}_{k+L+\nu}\|_2 + \boxed{\text{binarize}}\right)$$

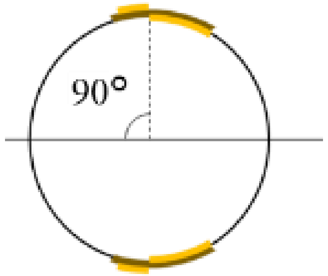
Experiment Setup

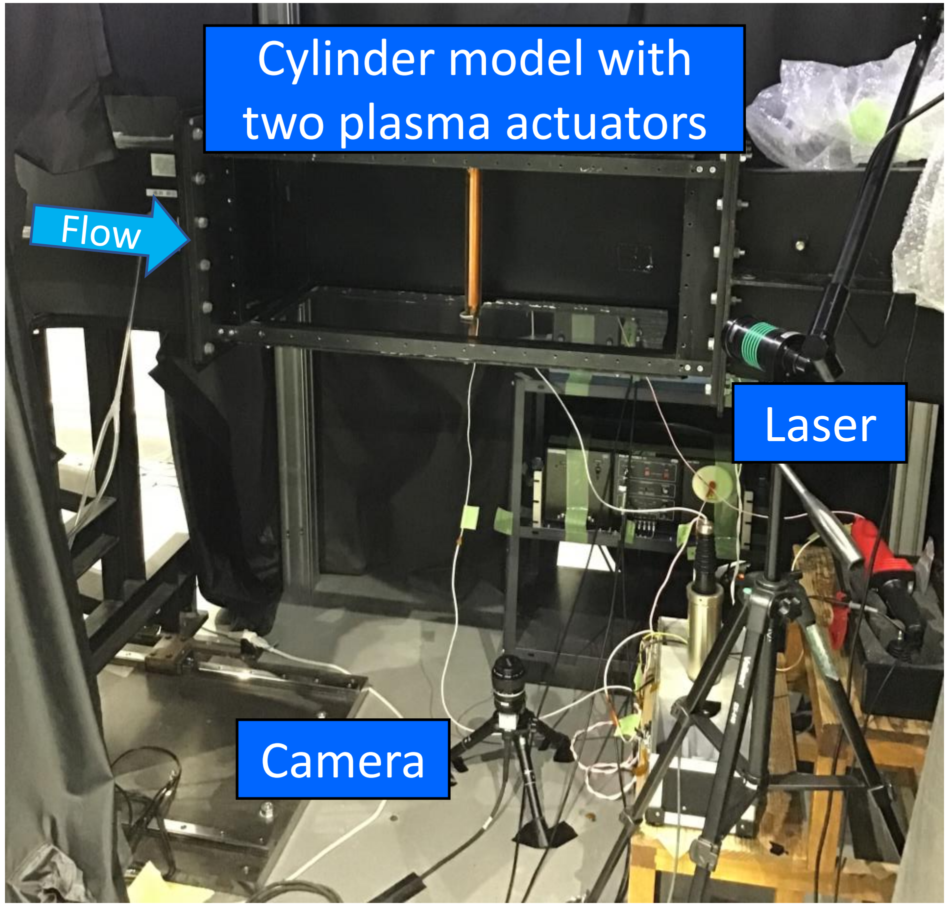
□ Test equipment

- Wind tunnel : Tohoku-University Basic Aerodynamic Research Wind Tunnel (T-BART)
- Camera : IDP-Express R2000 (Photron)
- Airfoil section : Cylinder model (*d* = 30mm)

□ Test condition

- Flow speed : 5 m/s
- Sampling rate : 4000 Hz
- *Re* : 1.1×10^4





□ Plasma actuator

- waveforms : 8kVpp, 10000Hz sin-wave
- Switching ON/OFF
  <u>for training data</u> : <u>**100Hz random**</u>

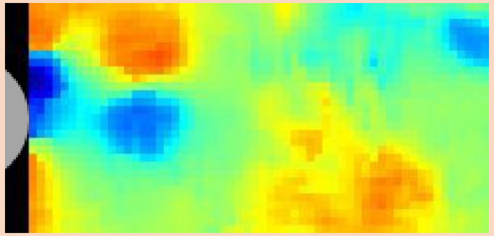
□ Analysis

- Estimation modes *r* : 2
- Number of sensors *p* : 2, 5, 10
- Parameters of l_1 opt. : ν = 40 (Time horizon), α = 0.5 (weight parameter)

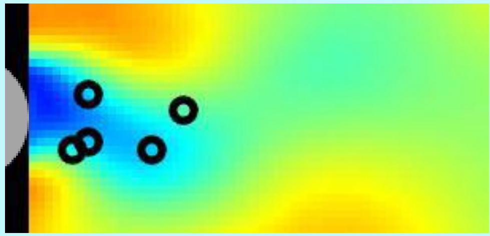
Visualization of Training Data / Error

◻ Velocity field (*x*-direction)

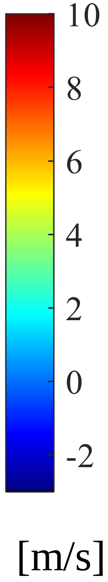
Original PIV data



SPPIV estimation

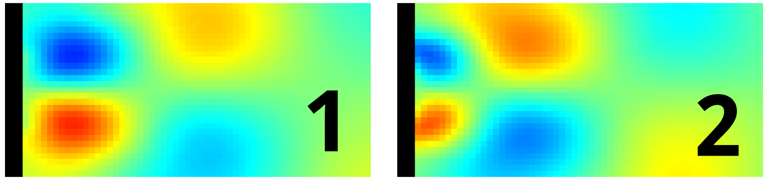


leading 2 mode estimation (r = 2)
5 sparse sensors (p = 5)



- Tracks large structures well
- Expects upper 2 modes to be sufficient for control

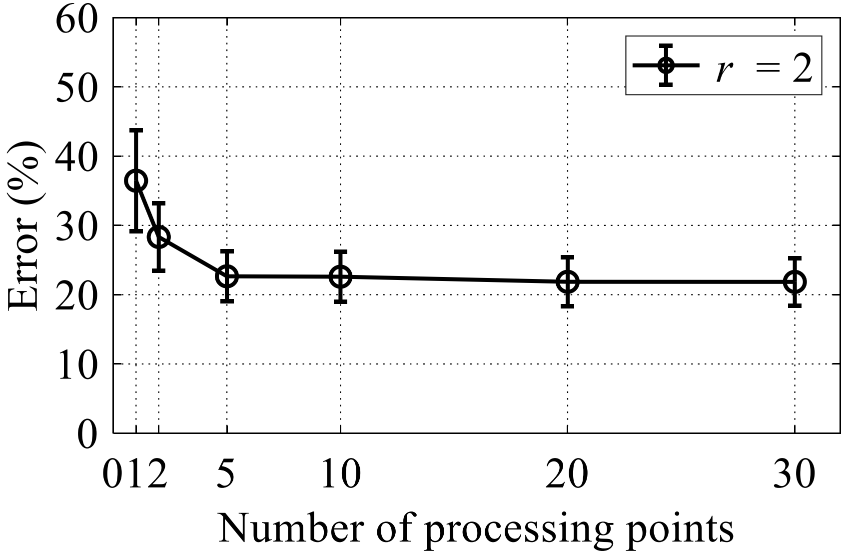
◻ Spatial modes for reconstruction



Leading two modes represent **>50%** (Energy-based)

- Two modes represent the periodic movements

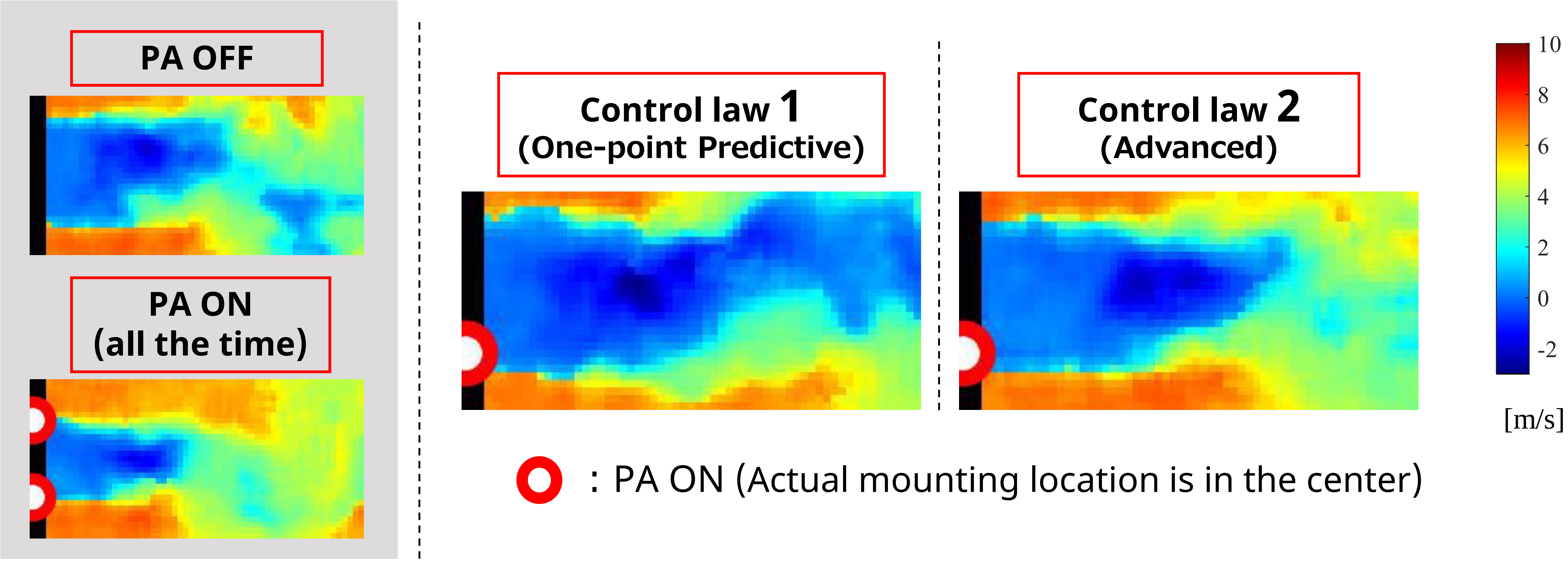
◻ Estimation error



- High accuracy
- 5 sensors are enough

Visualization of Feedback Control Results

□ Velocity field in x-direction (PIV was repeated for all pixels of flow field)

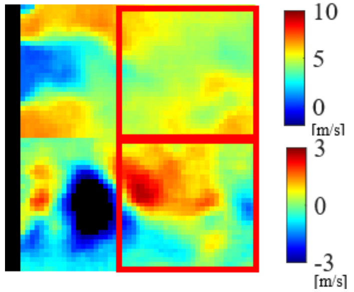


- The large-scale structure was disturbed by switching PA ON/OFF
- Time period when Karman vortex is suppressed exists (not continuous)
- **Control law 2** uses two PAs discharging at the same time

Control Effectiveness / Processing Time

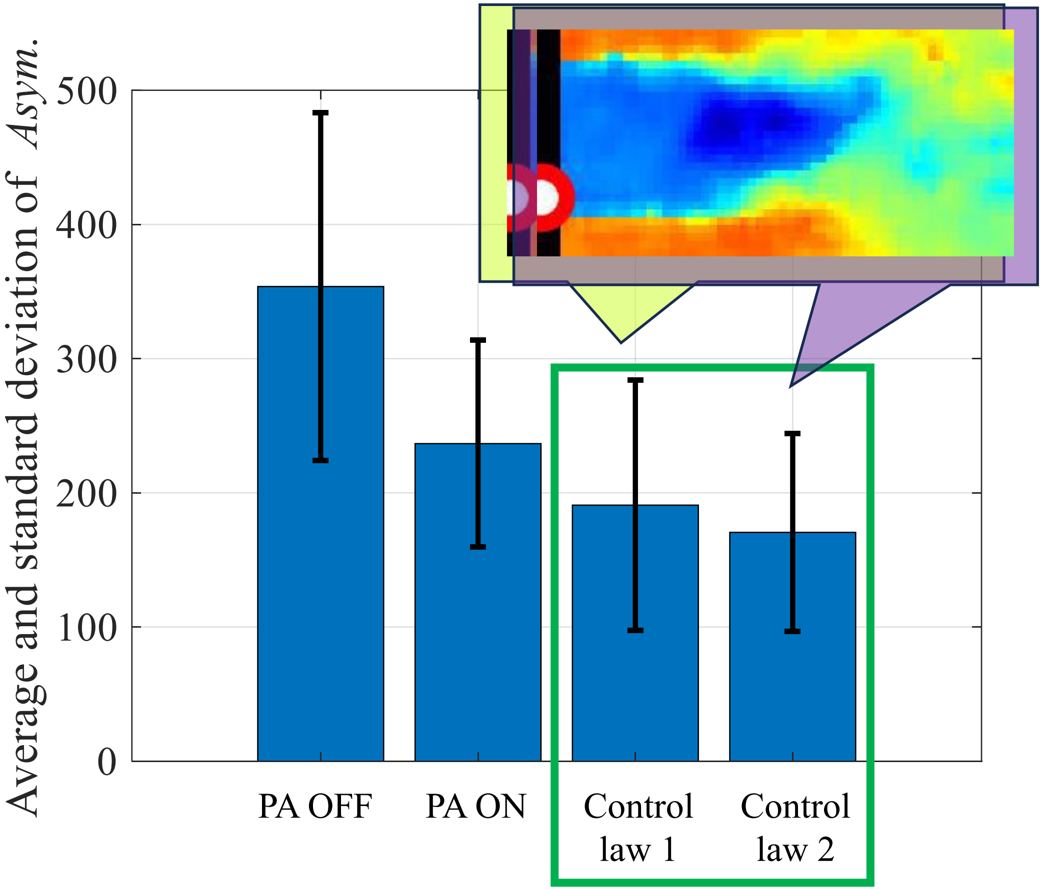
□Evaluation of control effectiveness

- Evaluated by asymmetry of the flow field



$$Asym. = \sum \left(\boxed{u} \text{(difference)}^2 + \boxed{v} \text{(sum)}^2 \right)$$

- Certain control effect confirmed
- **Law 2** : More stable with small variance
  →Due to time horizon



□ Processing time by step (5 sensors, average)

	Law **1**	Law **2**
SPPIV + determine ***u***	**60** μs	**97** μs

- Short enough for a sample rate of 500 μs
- Law **2** : ADMM enables high-speed iterative calculations

*Alternating Direction Method of Multipliers

Conclusions

Constructed a real-time feedback control system using SPPIV and PA and evaluated the estimation performance and control effect

◻ Results

- Real-time feedback control is achieved through wind tunnel testing
- It is found that control by time horizon considerations is better

◻ Future works (for my master’s degree)

- Parameter tuning for feedback control data
- Improving training data construction process