Project for real-time control of flow field using sparse processing PIV and plasma actuators

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Various fluid machines
- Airplanes, drones, automobiles, windmills...
  ➢ Expectations for performance improvement in active flow control

Plasma actuator (PA) (Corke et al., 2007, Fujii, 2014)
- Induced flow by plasma

- Optimal control input depends on airflow conditions

Feedback control according to flow field is important
How to measure the current flow with high accuracy?

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

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

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

Model

Use information from training data to predict the next flow

Correction

spatial structure “modes”$Z$
4 Objectives

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

Target
Kármán vortex suppression

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

**SPPIV**
- Particle imaging
- Real-time
- Data transfer

**Sparse PIV**
- Linear model
- State estimation

**Feedback control system**

**PA actuation**
- 2 Amps
- sin-wave
- Function generator
- Digital output

**Control input determination**

**NI DAQ**
- PCIe-6323
Construction of feedback control rules

Control law 1

One-point Predictive Control

- Predict $z_{k+L}$ of each $u_k$
- Consider the next one step

Calculation for all patterns

\[
\arg\min_u \|z\|_2
\]

Control law 2

Advanced control (Ikeda et al., 2017)

- Consider the interval between $\nu$ steps

\[
v = [u^T_k \ u^T_{k+1} \ \cdots \ u^T_{k+\nu-1}]^T
\]

- Solve the optimization problem

\[
\arg\min_v (\|z_{k+L+\nu}\|_2 + \text{binarize})
\]

attenuate intensity of antisymmetric modes

Symmetric flow (weak Kármán vortex)
Experiment Setup

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

- **Test condition**
  - Flow speed: 5 m/s
  - Sampling rate: 4000 Hz
  - \(Re\): \(1.1 \times 10^4\)

- **Plasma actuator**
  - Waveforms: 8kVpp, 10000Hz sin-wave
  - Switching ON/OFF for training data: 100Hz random

- **Analysis**
  - Estimation modes \(r\): 2
  - Number of sensors \(p\): 2, 5, 10
  - Parameters of \(l_1\) opt.: \(\nu = 40\) (Time horizon), \(\alpha = 0.5\) (weight parameter)
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
    \[ \text{Asym.} = \sum \left( \frac{\text{difference}}{\text{sum}} \right)^2 \]
  - Certain control effect confirmed
  - **Law 2**: More stable with small variance
    \[ \rightarrow \text{Due to time horizon} \]

- **Processing time by step (5 sensors, average)**

<table>
<thead>
<tr>
<th></th>
<th>Law 1</th>
<th>Law 2</th>
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<tbody>
<tr>
<td><strong>SPPIV + determine</strong> ( u )</td>
<td>60 ( \mu s )</td>
<td>97 ( \mu s )</td>
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- Short enough for a sample rate of 500 \( \mu s \)
- **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