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Estimating Pitching Airfoil Kinematics Using Convolutional Neural Networks

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Introduction

- Rapid motion in aerial vehicles can cause substantial wake fluctuations

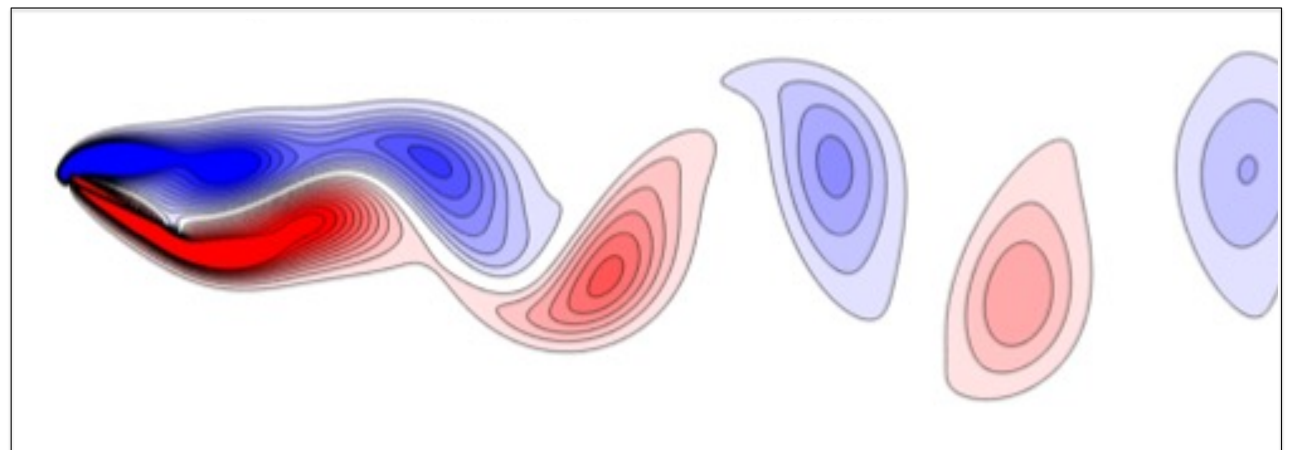


figure - Vorticity field in the wake of a pitching airfoil

- The affected wake behind the airfoil becomes very unsteady, which makes the control of any system that within or influenced by the wake challenging.
- Requires understanding of unsteady aerodynamics!
- It is also important to understand the unsteady aerodynamics quickly, for systems that require fast feedback for control.
- Therefore, it will be very powerful if one can determine the kinematics of a pitching airfoil from a single snapshot of the velocity field, in a small window downstream of the airfoil.
- Convolutional neural network (CNN) models have advantages in modeling complex, high-dimensional flows with inherent nonlinearity due to the model-free nature and usage of nonlinear activation functions.

Use CNN to:

1. Analyze unsteady aerodynamics

2. Predict airfoil kinematics

Aim of Study

1. Predict the airfoil pitching frequency and the base angle of attack from limited instantaneous velocity field measurements downstream of the airfoil.
2. Explore the effect of decreasing input image size on prediction in two different ways.

Method

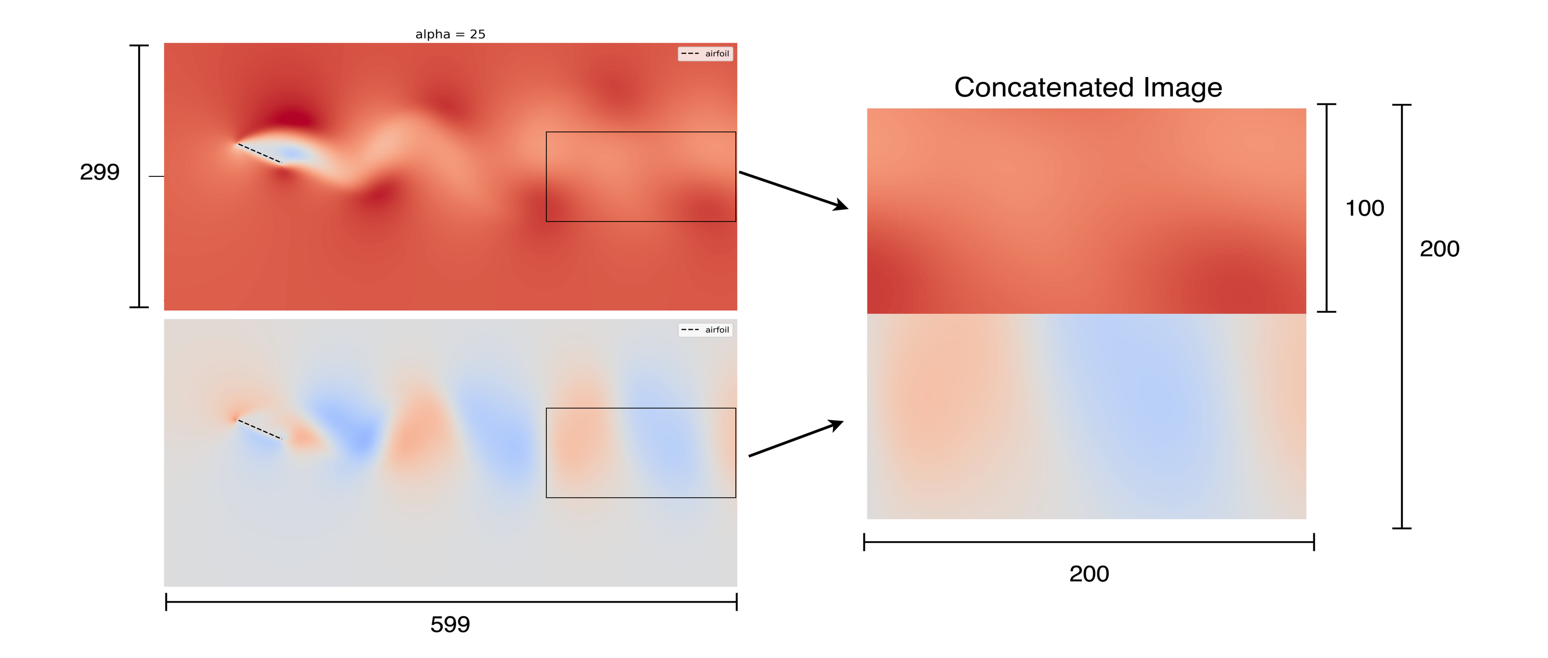
- Database from Towne et al., "A Database for Reduced-Complexity Modeling of Fluid Flows", *AIAA Journal* 2023. (DNS, Re = 100.)
- Airfoil Kinematics : $\alpha(t) = \alpha_0 - \alpha_p \sin(2\pi f_p t)$

α_0 : *Base angle of attack*
f_p : *dimensionless frequency* $\left({}^{fc}/{}_{U_\infty}\right)$
f : *pitching frequency*
c : *chord length*
U_∞: *freestream velocity*

- Tested on α_0 : $25°$, $30°$, f_p : $0.05, 0.1, 0.2, 0.25, 0.3, 0.35, 0.4, 0.5$

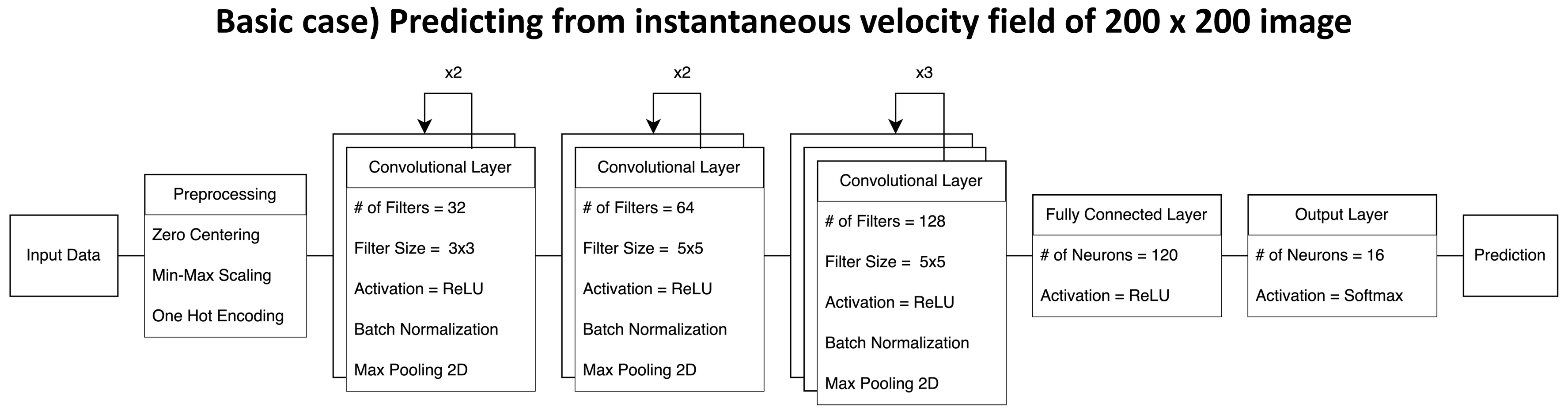
  → 16 categories corresponding to combination of α_0 & f_p

- Making input image :

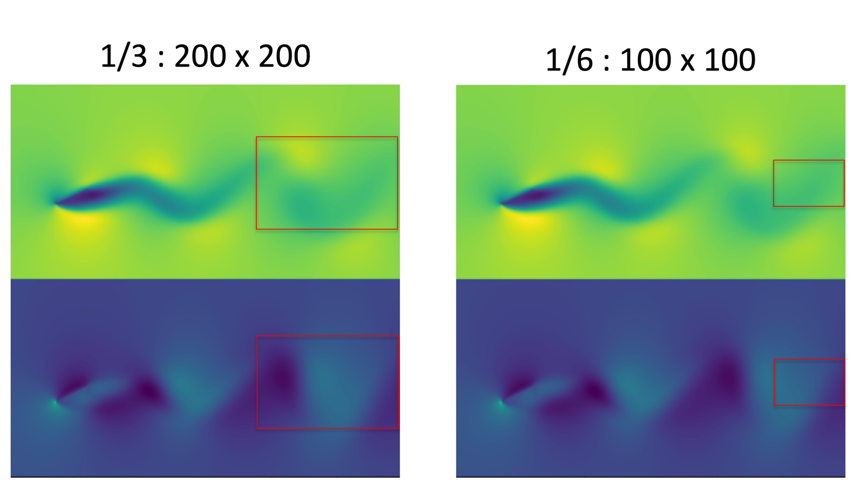


Taken UX & UY velocity from downstream and concatenated vertically.

Basic case) Predicting from instantaneous velocity field of 200 x 200 image

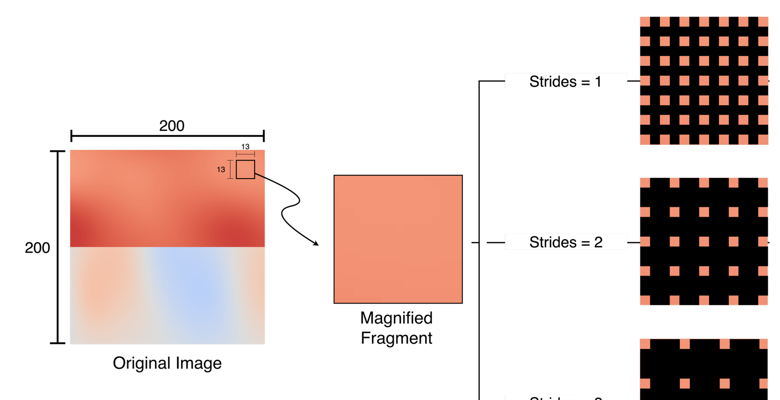


Test 1) Reducing the size of window



Ratio: 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9, 1/10, 1/11, 1/12, 1/13, 1/14, 1/15
(edge length 200, 150, 120, 100, 86, 76, 66, 60, 54, 50, 46, 42, 40)

Test 2) Simple downsampling of image.

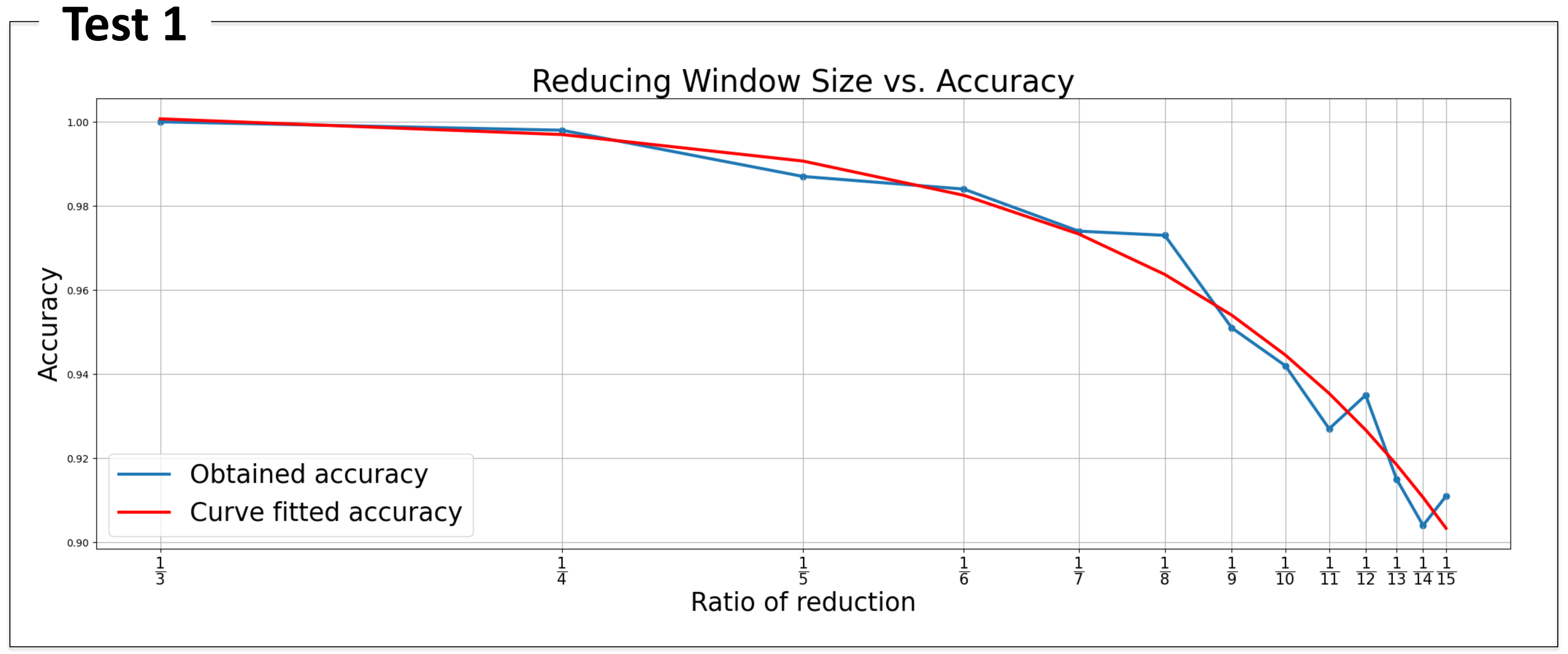


Base Ratio	Strides	Edge Length
1/3	1	100
1/3	2	66
1/3	3	50
1/3	4	40
1/4	1	76
1/4	2	50
1/5	1	60
1/5	2	40
1/6	1	54
1/7	1	42

Used images from test 1 of ratio 1/3, 1/4, 1/5, 1/6, and 1/7 and gave strides.

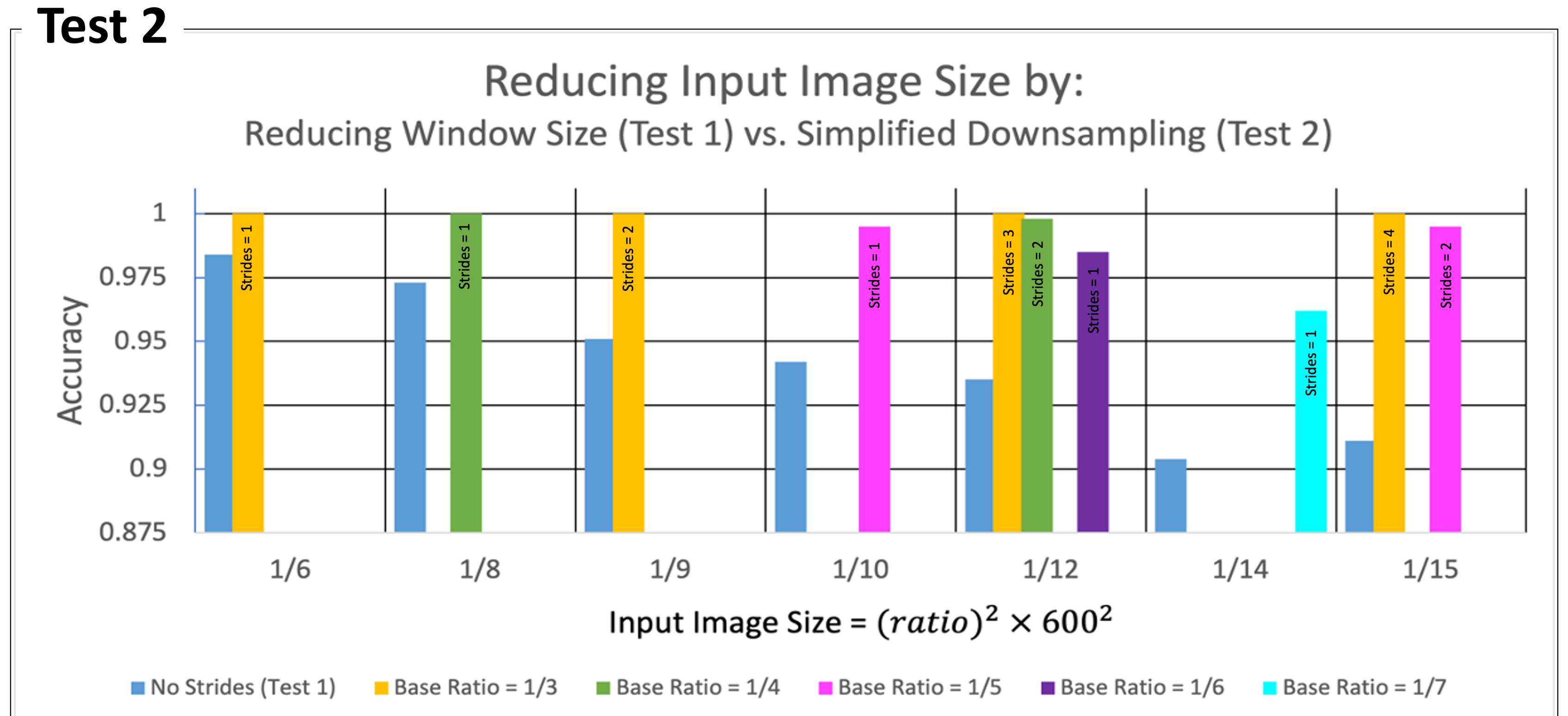
Result

Test 1



- The prediction from ratio 1/3, which is 200 x 200 image had 100% accuracy.
- Accuracy dropped exponentially. $(accuracy = 1 - 0.3e^{-16.2 * ratio\ of\ reduction})$
- Even in ratio 1/15 (25 times smaller input pixel number compared to ratio 1/3), the accuracy remained over 90%.

Test 2



- With same input image size, downsampling from a wider window performed much better compared to having smaller sensing area with densely collected velocity.

Conclusion

- The pitching frequency and base angle of attack can be estimated from a single snapshot of data with high accuracy even with substantial reduction of window size or downsampling of image.
- When comparing two methods, downsampling conserves the prediction accuracy of airfoil kinematics at higher level.