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A report on

Two-Dimensional Vortex Shedding Behind an Airfoil Using a Soap Film Tunnel with a Control Cylinder and POD analysis

Submitted By

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Acknowledgment

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Abstract

Abstract

This study investigates the two-dimensional (2D) wake transition behind a NACA 0012airfoil and NACA 0020 placed in a vertically mounted soap film tunnel. A passive flow control technique, in the form of a small control cylinder, is introduced upstream or downstream of the airfoil to modulate wake behavior. The soap film, acting as a quasi-2D medium, allows direct visualization of vortex structures and wake transitions under controlled flow conditions. High-resolution images are analyzed using Proper Orthogonal Decomposition (POD) to extract dominant spatial modes and identify coherent vortex structures. The experiment demonstrates the effectiveness of a control cylinder in suppressing or altering vortex shedding, providing insight into passive flow control in low Reynolds number regimes.

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Introduction

The soap film experiment is a widely used technique to investigate two-dimensional (2D) fluid dynamics in a controlled and visually accessible environment. Due to its extremely thin structure, a soap film can approximate the behavior of an incompressible, inviscid 2D fluid, making it an excellent medium for studying phenomena such as vortex shedding, wake transitions, flow instabilities, and turbulence.

In this experiment, we utilized a soap film tunnel to observe the flow behavior around streamlined body, such as an airfoil with a control cylinder. The motion of the film is driven by external flow, and its interaction with inserted objects produces visible flow patterns due to variations in film thickness. These variations, when illuminated properly, allow flow structures to be captured through high-speed photography or video.

We recorded the flow using a camera in manual mode to ensure consistent exposure, focus, and frame rate. The images and video data were then analyzed using MATLAB to extract velocity fields and perform Proper Orthogonal Decomposition (POD), helping to identify coherent structures and dominant flow modes. This method provides deeper insight into the flow dynamics that are otherwise difficult to capture in traditional fluid experiments.

Overall, the soap film experiment serves as a cost-effective, high-resolution method to visualize and analyze two-dimensional fluid behavior, bridging experimental observations with computational analysis.

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Literature Review

The phenomenon of vortex shedding behind airfoils in low-Reynolds-number flows has been extensively studied due to its importance in flow stability, aerodynamic performance, and control applications. Particularly, soap film tunnels have emerged as effective tools to visualize and analyze two-dimensional flow fields under controlled conditions.

2D WAKE TRANSITION OF A NACA0012 AIRFOIL INSOAPFILM, (By Harish Wathore, Kamal Poddar, & Alakesh C Mandal∗)

- Wake Behavior and Vortex Modes:
  - At low angles of attack, alternating vortex shedding (Mode 2a) was observed.
  - With increasing α, the flow transitioned into an alternating vortex-pair shedding mode (Mode 3).
  - At Re ~5000 and α ≥ 18°, a new chaotic alternating vortex shedding mode (Mode 2b) was observed — not previously reported in literature.
- Strouhal Number (St):
  - St generally decreases with increasing angle of attack.
  - At higher α (≥16°), St increases again at Re ~5000 due to intense suction and increased vortex shedding frequency.
- Velocity Profiles:
  - The wake deflects toward the pressure or suction side depending on α and Re.
  - As Re increases, transitions between wake modes occur earlier, at lower angles of attack.
  - RMS of velocity fluctuations showed asymmetry and dual peaks indicating different vortex structures.
- Drag Coefficient (Cd):

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- Drag is lower at higher Reynolds number.
- A sudden increase in Cd was observed at transition points ($\alpha = 8°$ for Re ~3000 and $\alpha = 4°$ for Re ~5000), corresponding to the switch from Mode 2a to Mode 3.

Finding from Organized Modes and the Three-Dimensional Transition to Turbulence in the Incompressible Flow Around a NACA0012 Wing(by Authors: Y. Hoarau, M. Braza, Y. Ventikos, D. Faghani, and G. Tzabiras)

1.Flow Regime and Conditions

- Geometry: NACA0012 airfoil at 20° angle of attack.
- Reynolds number range: 800 to 10,000.
- Flow is incompressible and massively separated.

2. Transition Mechanisms Identified

- **Von Kármán Mode**: Regular vortex shedding starts around Re = 450 and remains dominant up to Re ≈ 1600.
- **Period-Doubling**: Nonlinear bifurcation behavior begins near Re = 800 and becomes more complex as Re increases, leading to chaotic behavior.
- **Shear-Layer Instability**: Appears beyond Re = 2000, driven by a forced Kelvin–Helmholtz instability; produces high-frequency vortices.

3. Wavelength and Frequency Scaling

- Shear-layer wavelength decreases with Reynolds number:
- $\lambda sl \propto Re-0.44$
- Frequency ratio (shear layer to von Kármán) increases with Re:
- $fsl/fVK \propto Re0.43$

Together, these studies build the foundation for analyzing wake dynamics using soap film experiments and POD, especially in the presence of passive flow control strategies.

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1.Experimental Setup

The experiment was conducted using a vertically mounted soap film tunnel designed for 2D flow visualization. Two different NACA airfoils — **NACA 0012** and **NACA 0020** — were tested under various geometric configurations.

A small **control cylinder** was used as a passive flow control element to investigate its effect on wake transition. The distance between the airfoil, divergence section, and the cylinder was systematically varied, and observations were made at **two angles of attack**: 0° and 5°.

The setup includes:

- A soap film channel formed between two vertical strings, connected to a soap solution reservoir at the top and drainage at the bottom.
- A flow inducer system driven by gravity, which produces a steady flow of soap film between the strings.
- The airfoil model was carefully inserted into the film to minimize film disturbance and simulate 2D flow past the body.
- A high-resolution DSLR camera (Nikon d850) was mounted in front of the film to capture flow patterns. Camera settin gs were configured manually to ensure optimal contrast and focus on interference fringes and vortex structures.
- Proper illumination was ensured using diffuse white light placed orthogonally to the camera to enhance the visibility of flow features in the thin soap film.

1.1 Instrument / Equipment

1. Soap Film Apparatus
2. Soap Solution Reservoir
3. NACA 0012and NACA 0020 Airfoils
4. Nikon D850 DSLR camera

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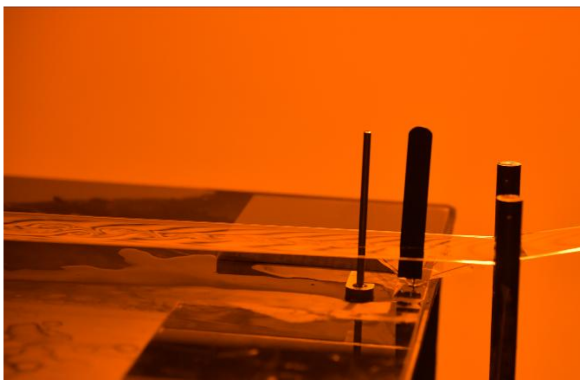
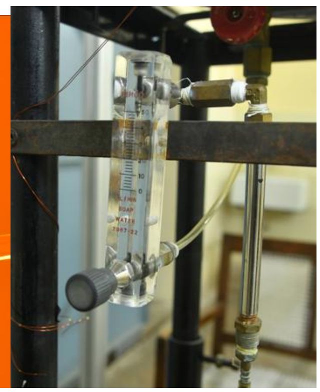
1.1 Instrument / Equipment

5. Tripod Stand
6. Water-Detergent Mix
7. MATLAB Software
8. 55W GE Low-Pressure Sodium Vapor Lamp)

1.2 Airfoils Geometry

Parameter	Airfoil 1 (NACA 0012)	Airfoil 1 (NACA 0020)
Type	NACA 0012	NACA 0020
Thickness	1.8	3.52
Chord Length	16 mm	18mm
Maximum Thickness %	11.25%	19.56%

Observational Conditions

Trial	Airfoil	Angle (°)	Distance from	Distance Airfoil to

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			Divergence (cm)	Cylinder (cm)
1	NACA 0020	**0**	**6**	**2**
2	NACA 0020	**5**	**6**	**3.5**
3	NACA 0012	**0**	**6**	**2.5**
4	NACA 0012	**5**	**10**	**2**

Each configuration was recorded separately using a fixed-position DSLR camera. The angle was adjusted by tilting the airfoil within the plane of the film, simulating attack angle conditions without disturbing the film integrity.

Reynold's Number Calculation

• Volume Collected of the solution = 56 ml = 56×10^{-6} m³

• Time of collection, t = 2.5 min = 150 s

• Density of the fluid, ρ = 1008 kg/m³ (for 2% glycerin

solution)

• Cross-sectional area of flow, $A = \pi \times 10^{-6}$ m² (circular pipe of 1 mm radius)= $3.1416\times10{-6}m^2$

• Dynamic viscosity, $\mu \approx 1.155 \times 10^{-3}$ Pa·s

• Kinematic viscosity, $\nu = \mu / \rho = 1.155 \times 10^{-3} / 1008 = 1.146 \times 10^{-6}$ m²/s

Step 1: Mass Flow Rate

• $\dot{m} = (\rho\times V)/t= 3.7632 \times 10^{-4}$ kg/s

Step 2: Velocity of Flow

• $V = \dot{m} /(\rho \times A)= 0.119$ m/s ;Step 3:

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Reynolds Number $Re = (V \times D)/\nu = 1031$

2 .Methodology

2.1 Airfoil Placement

- The airfoils (NACA 0020 and 0012) were inserted one at a time into the soap film between the two vertical wires.
- In each trial, the airfoil was placed at a fixed distance from the divergence section (where flow enters the channel).
- A control cylinder was positioned relative to the airfoil at a defined downstream distance
- Two flow conditions were tested for each airfoil:
    - 0° angle of attack (airfoil aligned with flow)
    - 5° angle of attack (airfoil tilted slightly upward

2.1.1 Image Capture

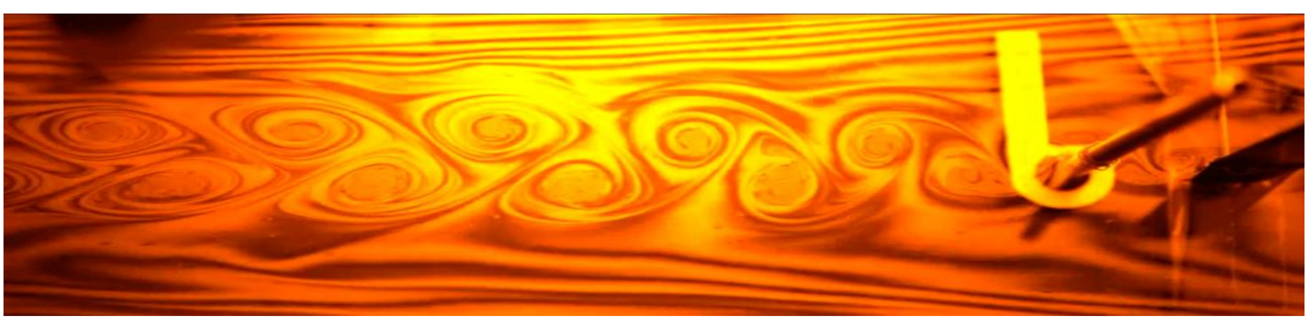

Fig-1 : 2.5 cm distance 0 degree angle (NACA 0012)

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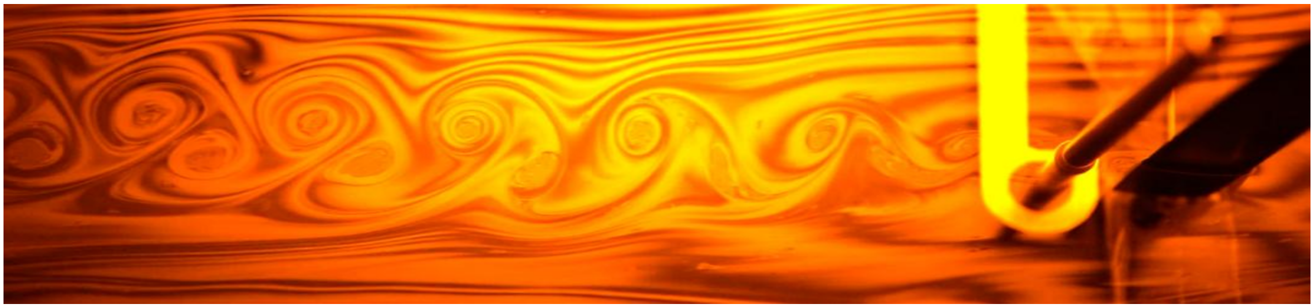

Fig-2 : 2 cm distance 5 degree angle (NACA 0012)

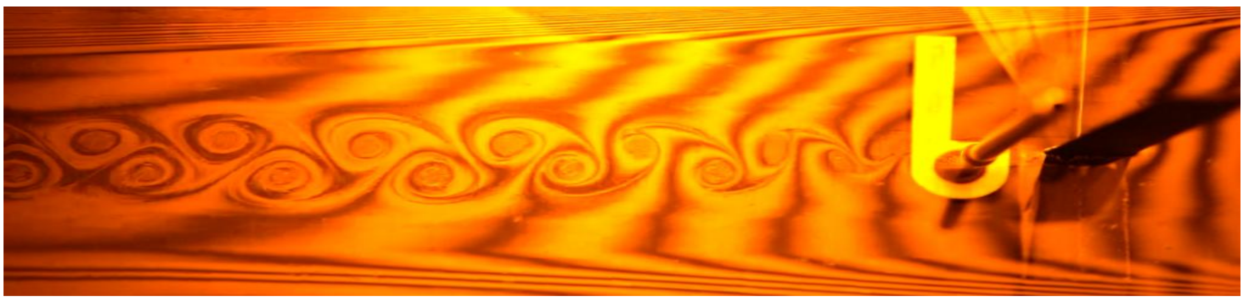

Fig-3 : 2 cm distance 5 degree angle (NACA 0020)

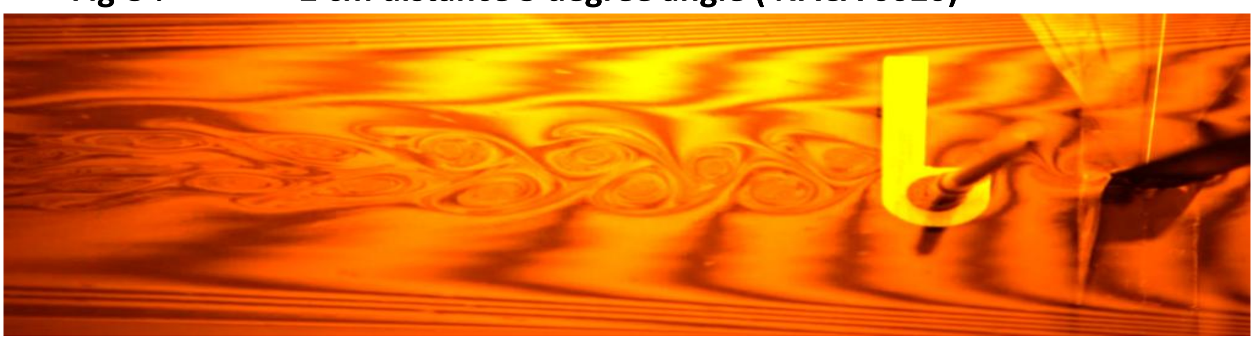

Fig-4 : 3.5 cm distance 5 degree angle (NACA 0020)

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3.Post-processing

3 .1 Contour Plot

A contour plot is a 2D plot that shows curves of constant values (like height, pressure, temperature, or velocity) in a spatial field

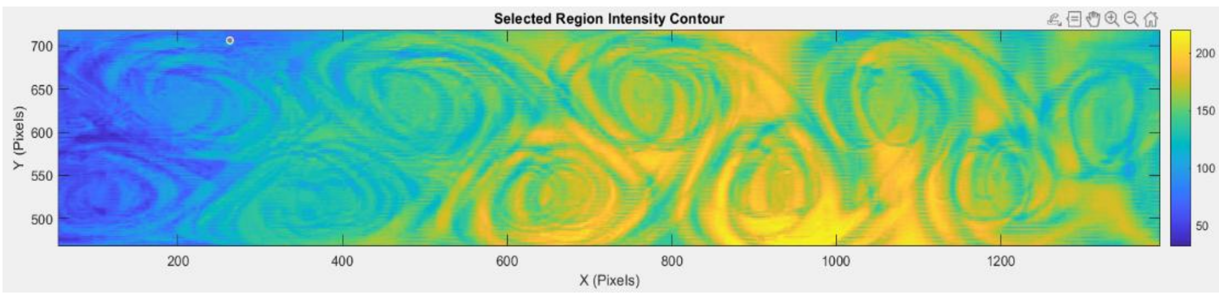

Fig-5 : 2.5 cm distance 0 degree angle (NACA 0012)

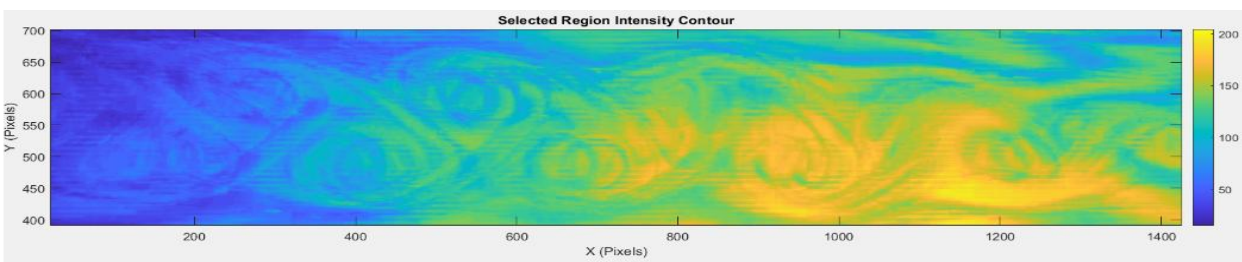

Fig-6 : 2 cm distance 5 degree angle (NACA 0012)

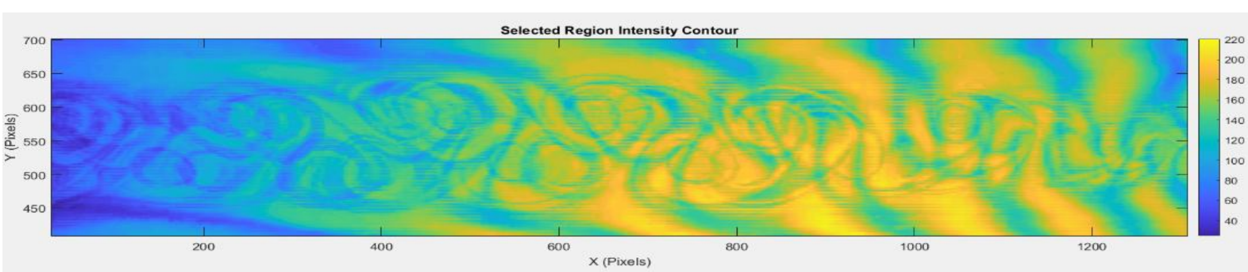

Fig-7 : 2 cm distance 5 degree angle (NACA 0020)

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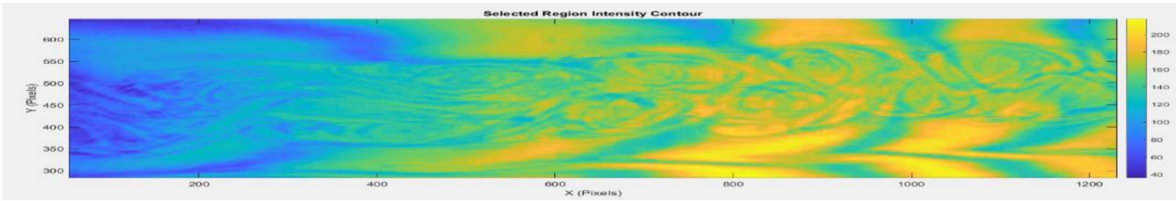

Fig-8 : 3.5 cm distance 5 degree angle (NACA 0020)

3.2 Apply Welch's Method

The Welch Method is a technique for estimating the Power Spectral Density (PSD) of a signal, which tells you how the power of a signal is distributed over frequency.

It improves upon the basic periodogram method by reducing noise and variance in the PSD estimate.

Purpose:

To provide a **smooth and reliable** estimate of a signal's **frequency content** using averaging of multiple FFTs.

Steps of Welch Method:

1. Segment the signal into overlapping sections.
2. Window each segment to reduce spectral leakage.
3. Compute the FFT of each windowed segment.
4. Compute the periodogram (magnitude squared of the FFT) for each segment.
5. Average all the periodograms to get the final PSD estimate.

window_size = 512;

noverlap = 100;

nfft = 512;

Welch Power Spectral Density Estimate

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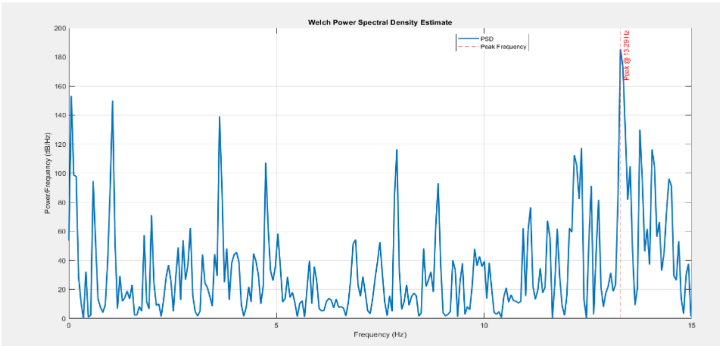

Fig-9

Dominant Frequency: 13.2875 Hz

Corresponding Amplitude: 13.6126 (intensity units)

Sampling Frequency of the data is: 29.9700

Coordinates of the selected point: (x = 601, y = 517)

3.3 Proper Orthogonal Decomposition (POD)

input:

Time series of spatial fields (e.g., velocity components u(x,y,t),v(x,y,t))

Steps:

- Stack the data into a matrix:
  X=[x1,x2,…,xN]
- Subtract the mean to get fluctuations:
  $X'=X-\bar{X}$
- Perform Singular Value Decomposition (SVD):
  $X'=\Phi\Sigma V^T$

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Output:

- Φ: spatial modes
- Σ: diagonal matrix of singular values (related to energy)
- V: temporal coefficients

Energy:

- Each mode's energy: $\lambda_i = \sigma_i^2$
- Energy % = $(\lambda_i / \sum \lambda) \times 100$
- 3.3.1 Top 5 POD Spatial Modes from experiment

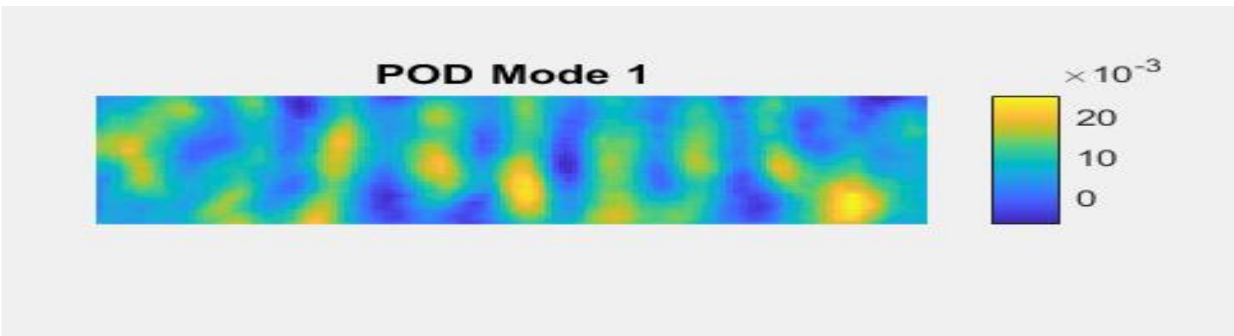
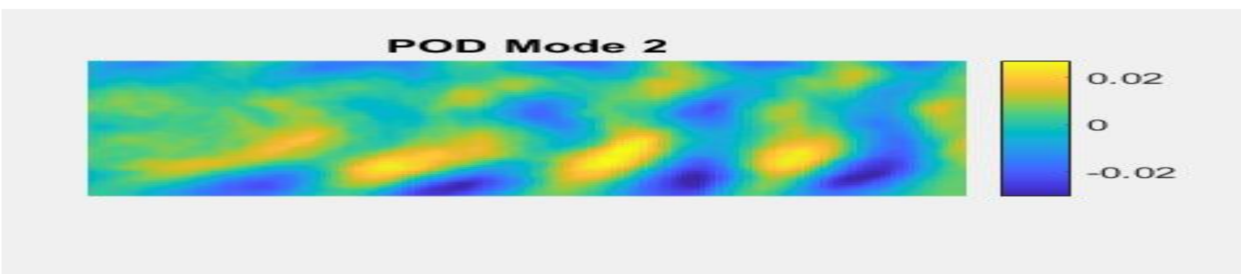
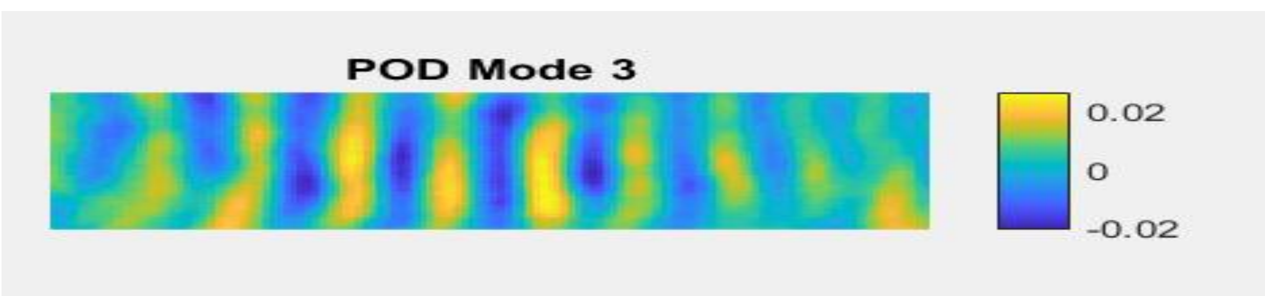


Fig-10





Plot of Enargy vs modes from experiment

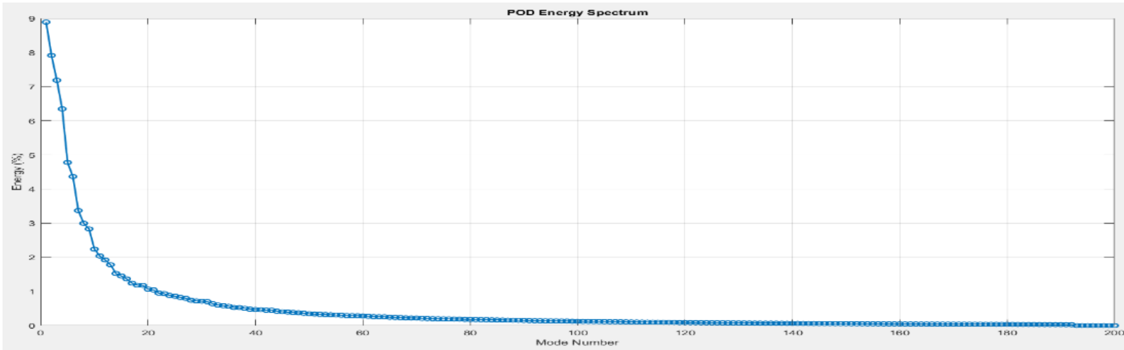


Fig-12

3.3.2 POD Modes of x direction and y direction velocity fluctuated (U_fluct) from experiment

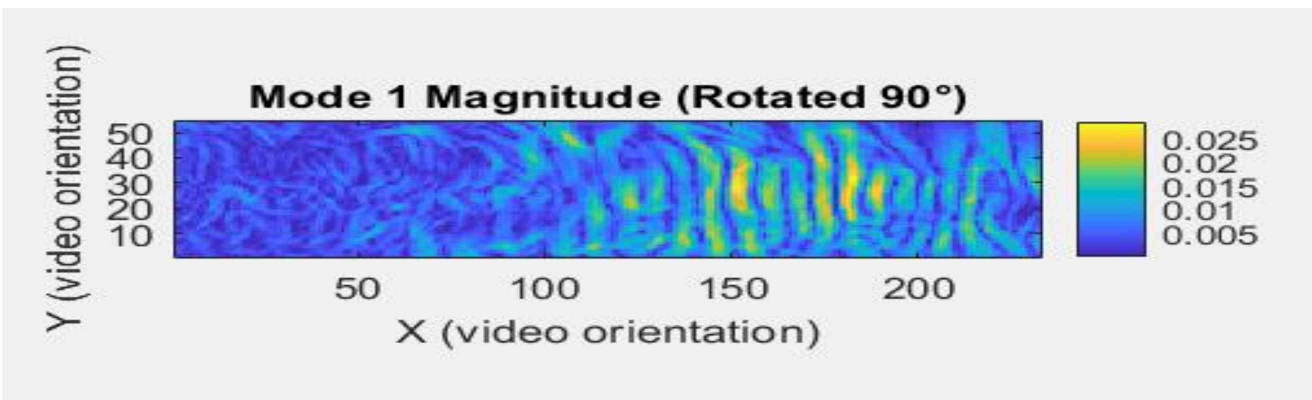


Fig-13

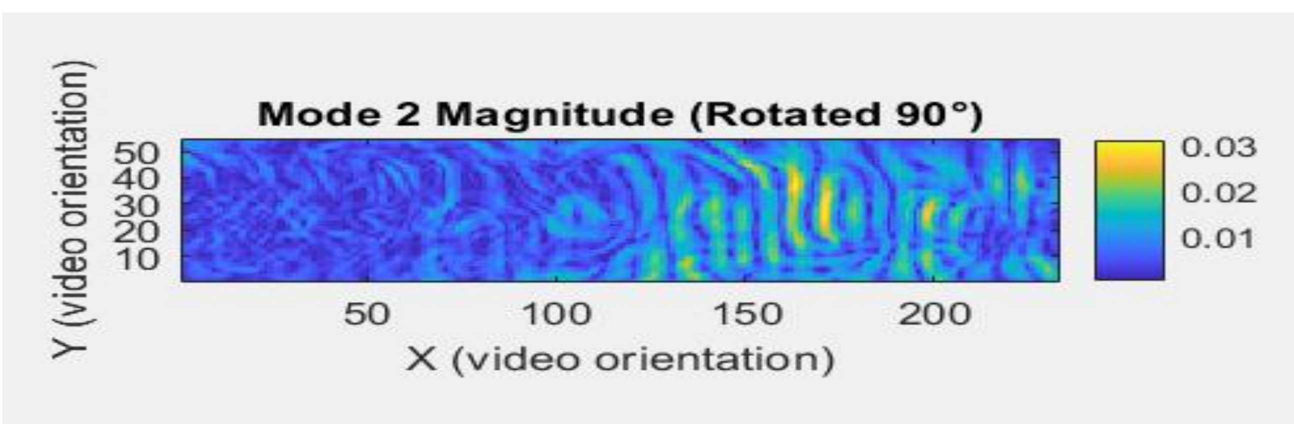


Fig-14

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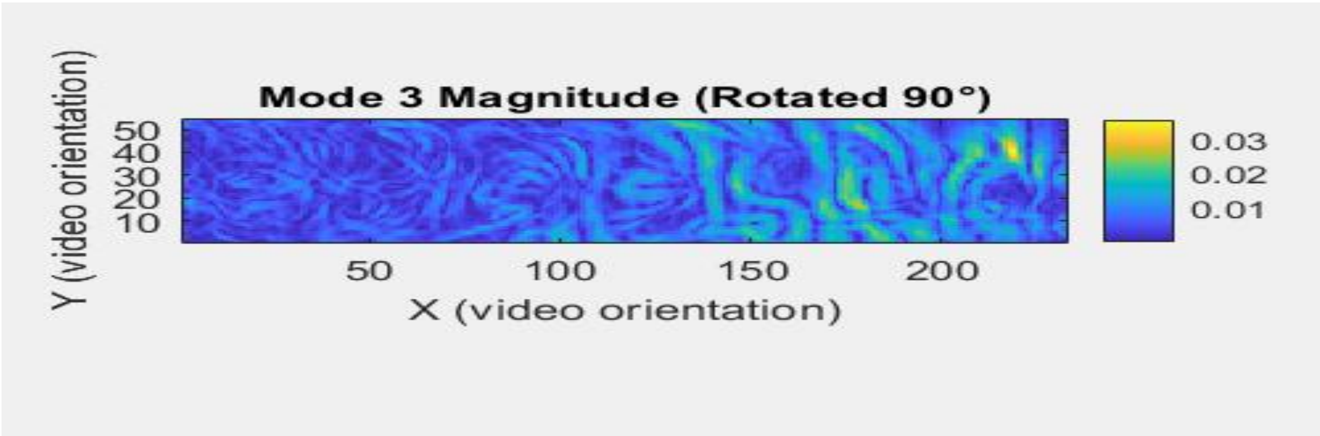

Fig-15

Plot of Enargy vs modes

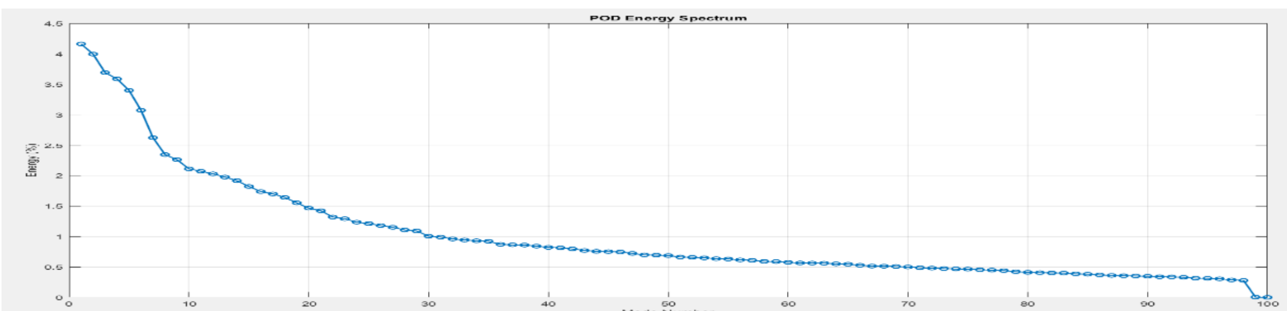

Fig-16

3.3.4 Reconstruct flow field using top 10 modes from experiment

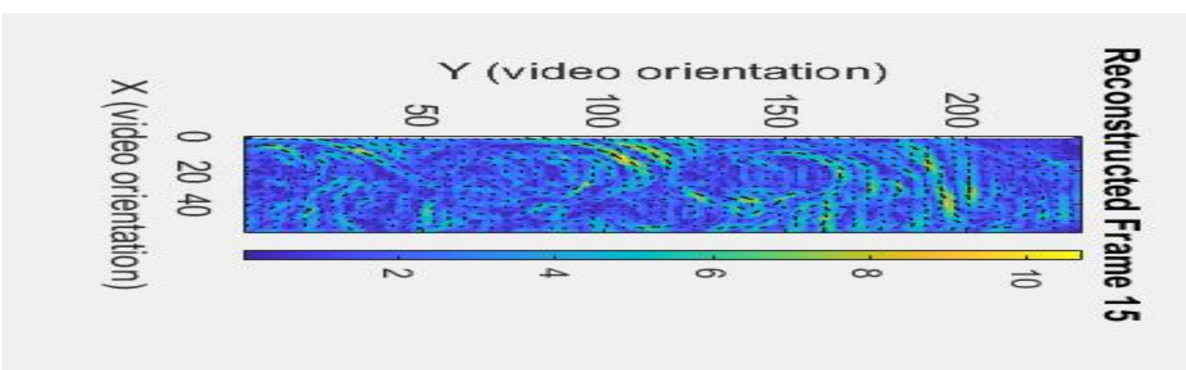

Fig-17

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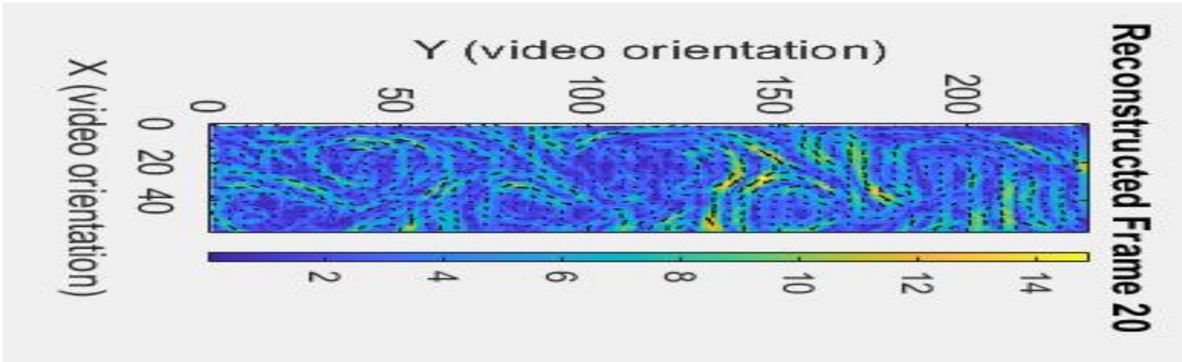

Fig-18

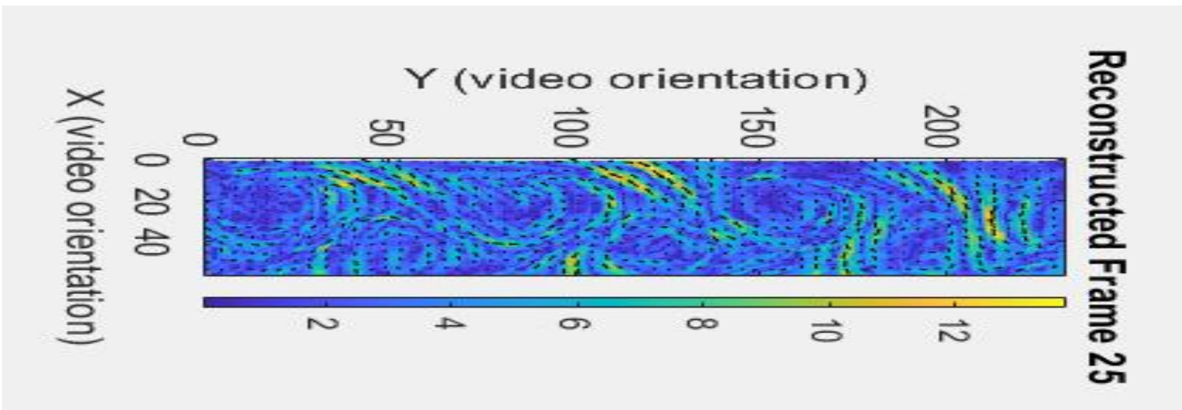

Fig-19

3.3.5 Top 5 POD Spatial Modes from data

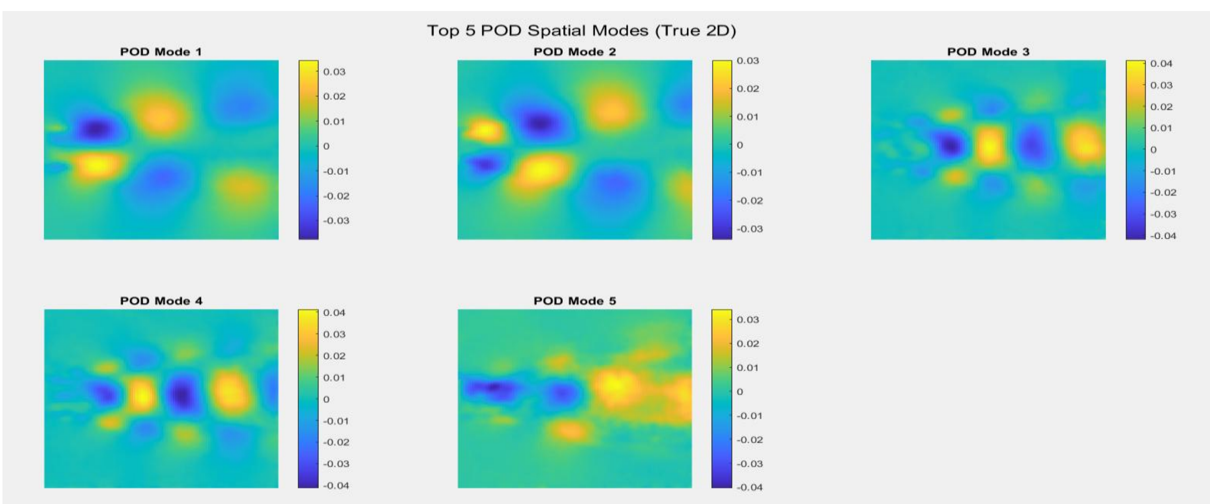

Fig-20

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Plot of Enargy vs modes

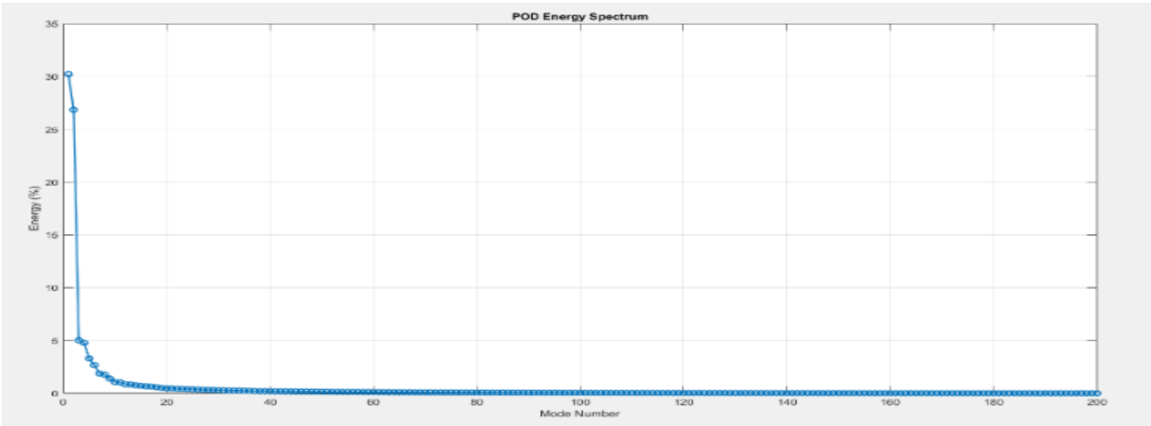

Fig-21

3.3.6 POD Modes of x direction and y direction velocity fluctuated (U_fluct) from data

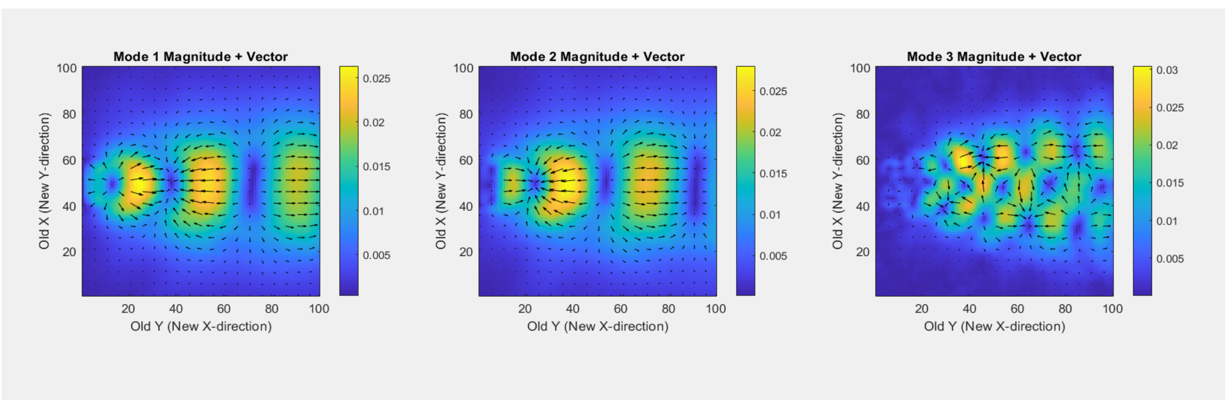

Fig-22

3.3.7 Reconstruct flow field using top 10 modes

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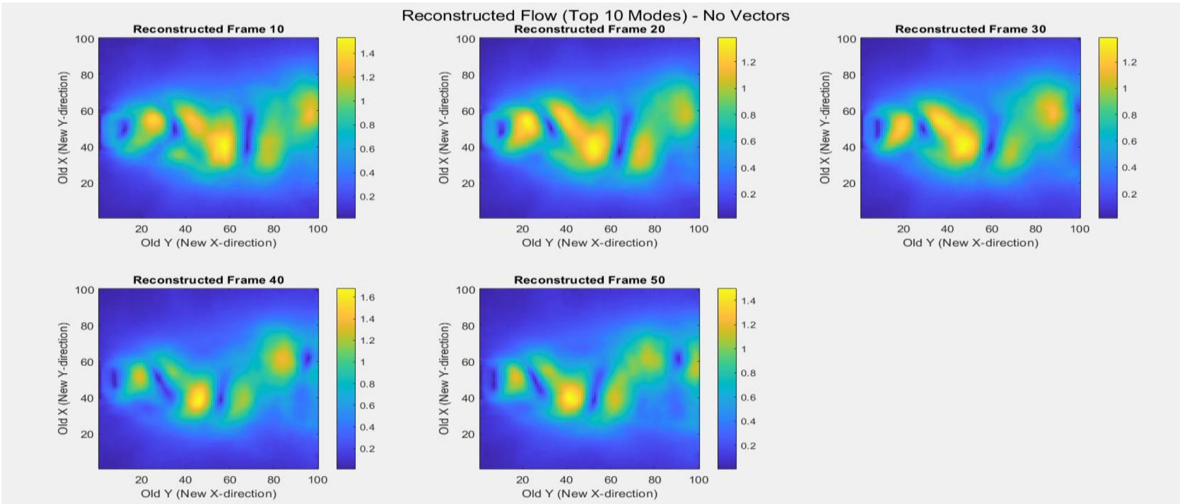

Fig-23

Plot of Enargy vs modes

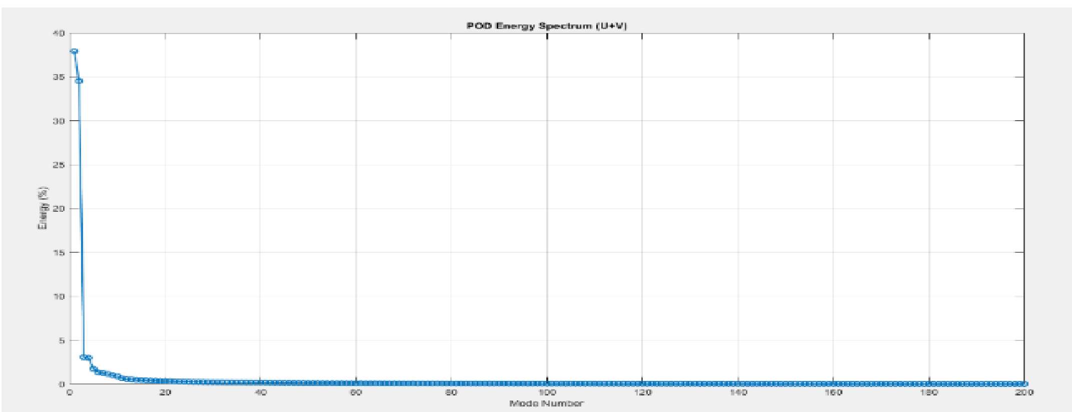

Fig-24

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4. Results and Discussion

In this study, we investigated the effect of placing a control cylinder behind an airfoil at various distances to assess the reduction in wake vorticity. The primary goal was to determine the optimal positioning of the control cylinder to minimize vortex formation in the airfoil's wake.

We tested four different spacing configurations between the airfoil and the control cylinder: **2 cm**, **2.5 cm**, **3.5 cm**, and **5 cm**. The control cylinder was positioned centrally within the wake region in each case to directly interact with the shedding vortices.

The results demonstrated that **as the distance between the airfoil and the control cylinder decreased**, the **vorticity in the wake was significantly reduced**. This effect was most prominent when the control cylinder was placed **at 2 cm**, which is closer to the region of vortex formation. In this configuration, the cylinder interacted more directly with the initial roll-up of the vortices, leading to maximum vorticity attenuation. Conversely, at larger distances (e.g., 5 cm), the reduction in vorticity was less pronounced, as the vortices had more space to develop before encountering the cylinder.

This indicates that **to achieve maximum vorticity suppression, the control cylinder should be placed as close as possible to the vortex formation region**, without interfering with the boundary layer of the airfoil itself. The optimal distance for this specific setup was found to be **2 cm**, where the control effect was strongest.These findings support the use of passive flow control elements cylinders to manage wake dynamics and potentially reduce drag and noise in aerodynamic applications.

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5.Conclusion

The Welch's Method analysis revealed a clear dominant frequency at 13.2875 Hz with a corresponding amplitude of 13.6126 intensity units, indicating a strong periodic component in the signal. This suggests the presence of a consistent oscillatory behavior at this frequency, which may be critical to understanding the underlying physical phenomena at the analyzed location (x = 601, y = 517).

The experimental analysis demonstrated that placing a control cylinder in the wake of an airfoil can effectively reduce vorticity, especially when the cylinder is positioned close to the trailing edge. Among the tested configurations, the **2 cm distance** between the airfoil and the control cylinder showed the **maximum reduction in wake vorticity**, indicating that early interaction with the forming vortex structures significantly suppresses their strength.

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6.References

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