2nd International Forum on Aerospace and Aeronautics

17th December, 2022, online

Liutex Validation by Experiments

Virtual Short Course

Liutex and Third Generation of Vortex Definition and Identification

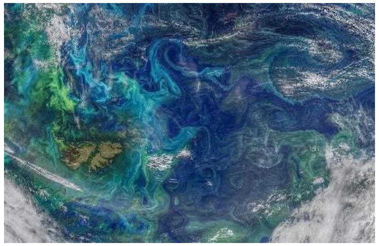
Dr. Xiangrui DONG, Prof. Dr. Xiaoshu CAI

School of Energy and Power Engineering

University of Shanghai for Science and Technology

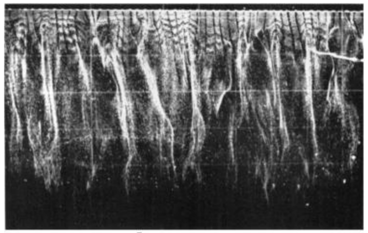
Introduction

Turbulence

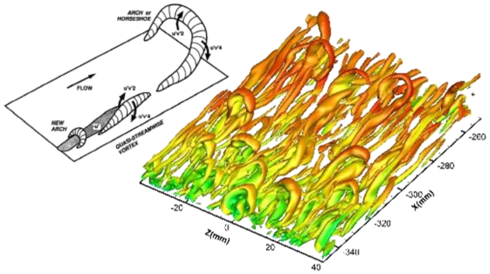


Turbulent boundary layer

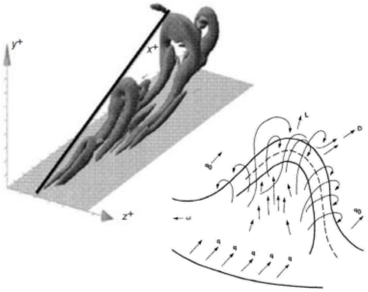
Coherent motions



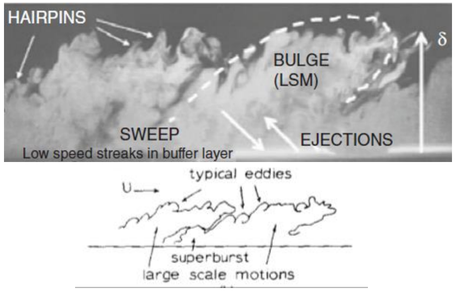
High-/ low-speed streaks



Quasi-sreamwise vortices



Hairpin & hairpin vortex packets

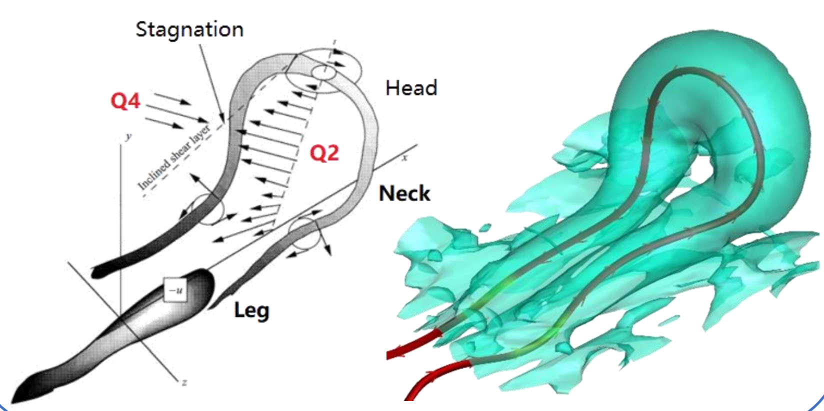


Large-scale motion

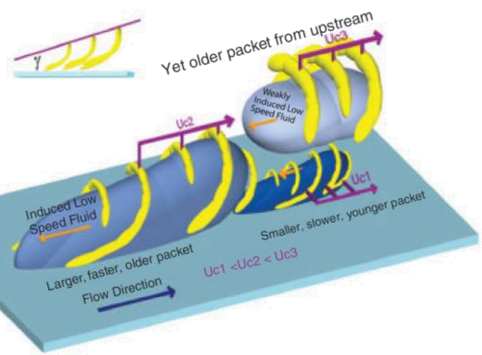
Coherent structures make a significant contribution to the time averaged statistics of the flow.

Introduction

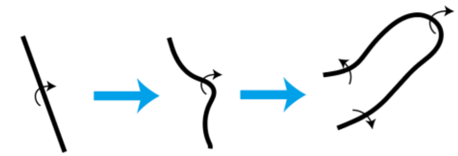
Single hairpin model



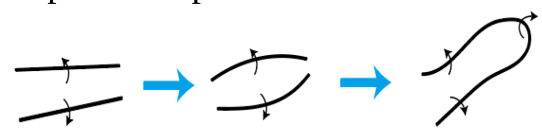
Hairpin packet model



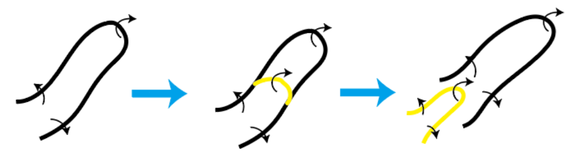
Generation mechanism



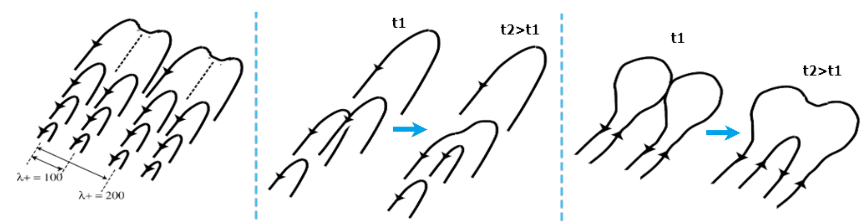
1. Developed from perturbation wave



2. Quasi-streamwise vortex developed into hairpin



3. Auto generation hairpins (Secondary /Tertiary)



4. Interaction between hairpins &hairpin packets

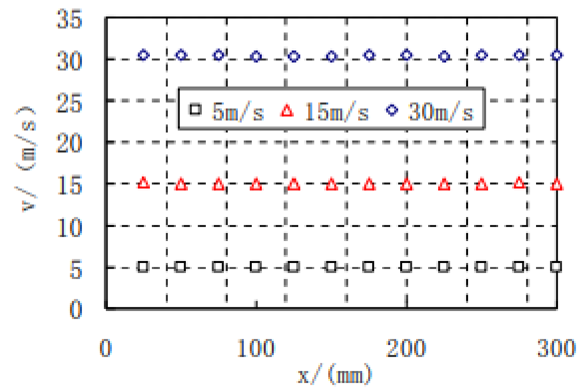
New ideas on vortex generation and self-maintenance mechanism in turbulent boundary layer ?

Introduction

Flow field measuring method

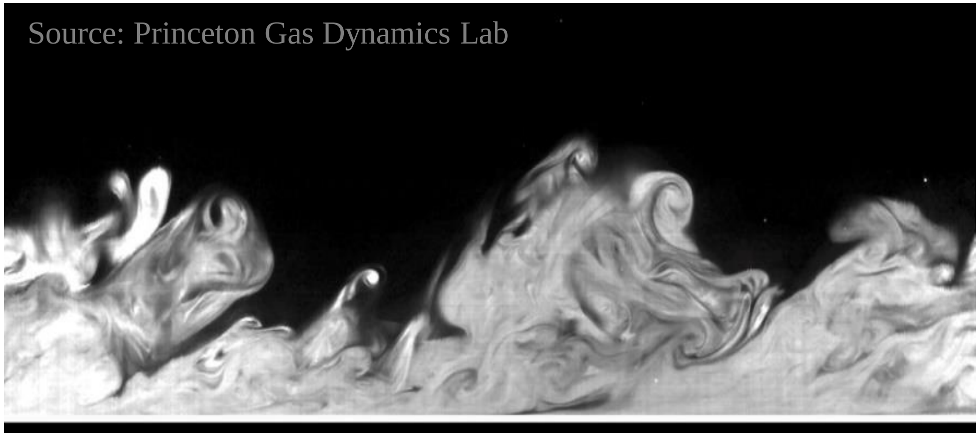
Measurements

- Hot-Wire (Film) Anemometer (HWFA)
- Laser Doppler Velocimetry (LDV)
- Tracer particle flow visualization technology
  - smoke
  - hydrogen bubble
  - dye
  - etc.
- Single-Frame and Long-Exposure (SFLE)
- Particle Image Velocimetry (PIV)
  - 2D PIV
  - Tomographic PIV
  - Holographic PIV
  - etc.
- Particle Tracking Velocimetry (PIV)
- Particle Streak Velocimetry (PSV)



velocity distribution without probe in flow

Source: L. Cui et al.

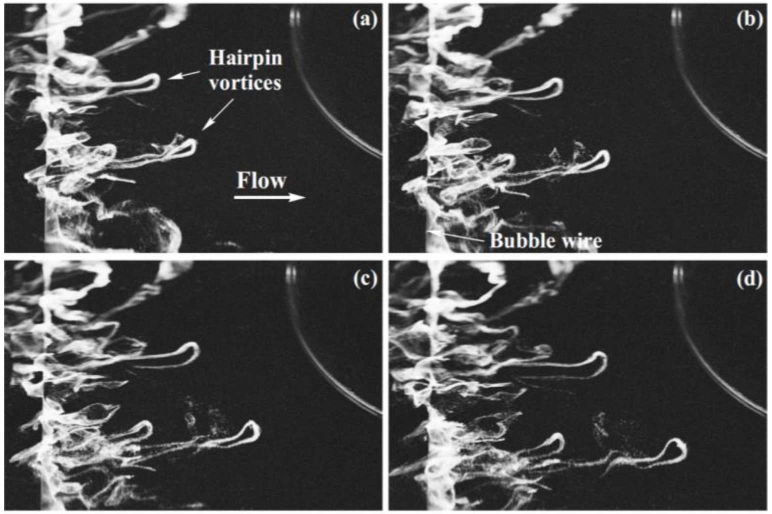


Introduction

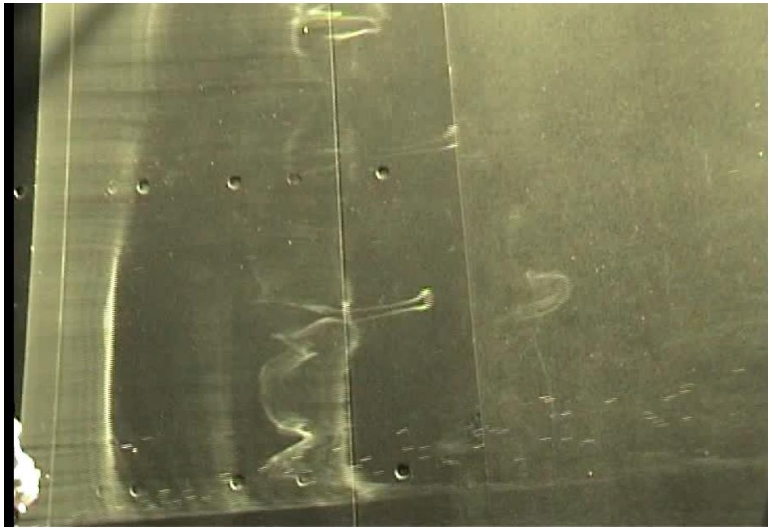
Flow field measuring method

Measurements

- Hot-Wire (Film) Anemometer (HWFA)
- Laser Doppler Velocimetry (LDV)
- Tracer particle flow visualization technology
  - smoke
  - hydrogen bubble
  - dye
  - etc.
- Single-Frame and Long-Exposure (SFLE)
- Particle Image Velocimetry (PIV)
  - 2D PIV
  - Tomographic PIV
  - Holographic PIV
  - etc.
- Particle Tracking Velocimetry (PIV)
- Particle Streak Velocimetry (PSV)



Source: D. R. sabatino et al.

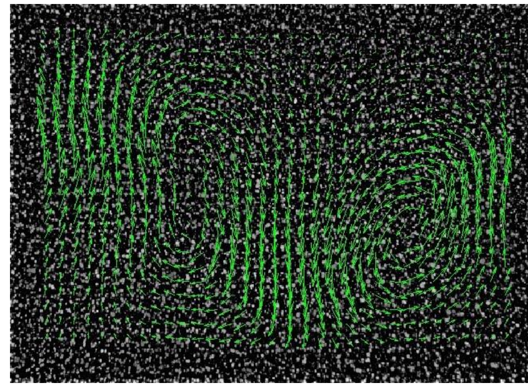


Introduction

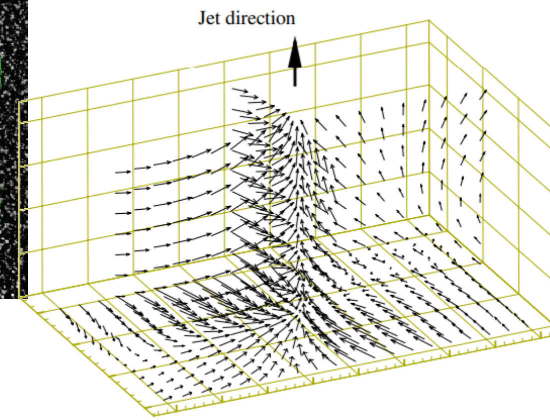
Flow field measuring method

Measurements

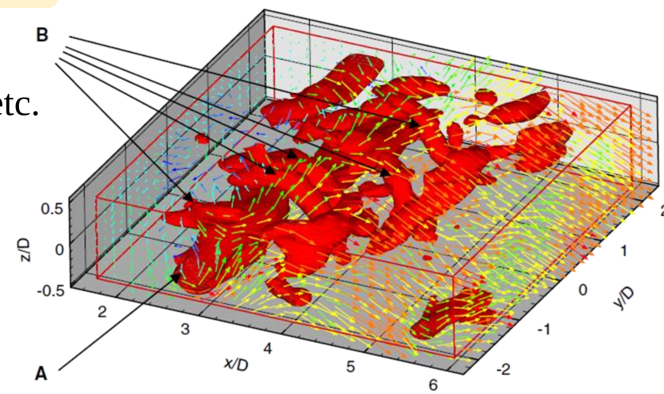
- Hot-Wire (Film) Anemometer (HWFA)
- Laser Doppler Velocimetry (LDV)
- Tracer particle flow visualization technology
  - smoke
  - hydrogen bubble
  - dye
  - etc.
- Single-Frame and Long-Exposure (SFLE)
- Particle Image Velocimetry (PIV)
  - 2D PIV
  - Tomographic PIV
  - Holographic PIV
  - etc.
- Particle Tracking Velocimetry (PTV)
- Particle Streak Velocimetry (PSV)



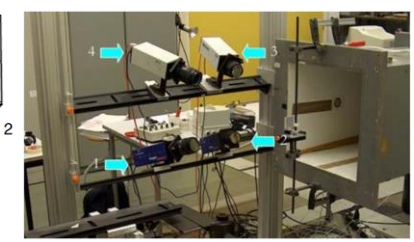
Source: Ariadacapo

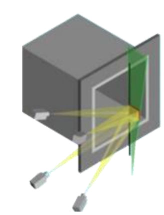


Source: H. Meng, et al.



Source: G. E. Elsinga, et al.





Introduction

Flow field measuring method

Measurements

- Hot-Wire (Film) Anemometer (HWFA)
- Laser Doppler Velocimetry (LDV)
- Tracer particle flow visualization technology
  - hydrogen bubble, smoke, dye, etc.
- Single-Frame and Long-Exposure (SFLE)
- Particle Image Velocimetry (PIV)
  - 2D PIV, Holographic PIV, Tomographic PIV, etc.

methods	globality	contactless	qualitative	quantitative	instantaneity
HWFA	×	×	×	√	-
LDV	×	√	×	√	-
flow visualization	√	√	√	×	-
SFLE	√	√	×	√	**low**
PIV	√	√	×	√	**high**

➤ Our work

- Moving-Single-Frame and Long-Exposure (MSFLE)
- Moving-Particle Image Velocimetry (MPIV)

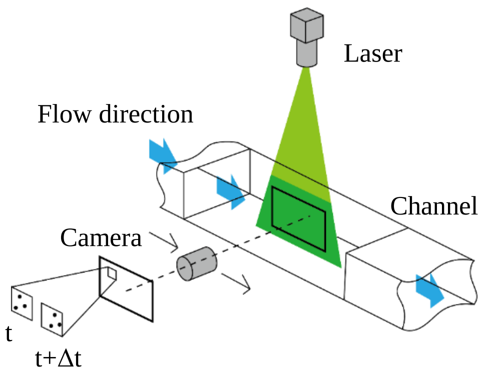
M-SFLE	√	√	√	√	**low**
M-PIV	√	√	×	√	**high**

✔ Interaction between coherent structures； ✔ Vortex generation and evolution

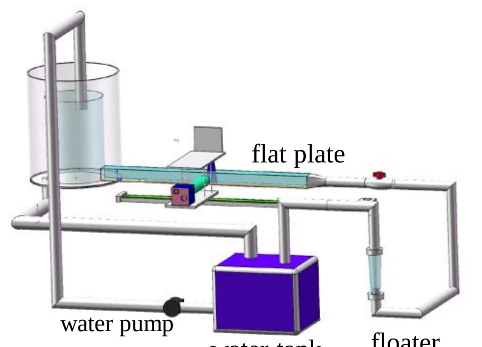
✔ Non-contact； ✔ Globality； ✔ Qualitative； ✔ Quantitative (high accuracy)

Measuring system & Equipment

Measuring system

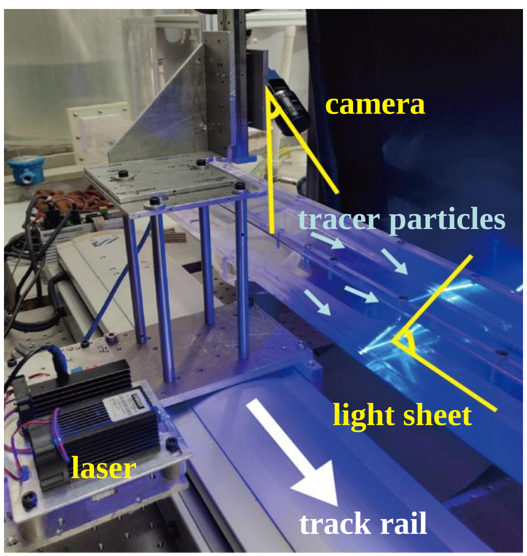


Circulating water tunnel

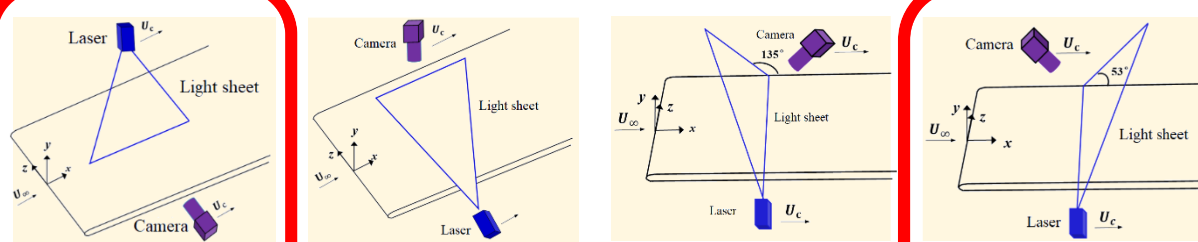


Item	SFLE	PIV
Tracer particle	PSP（5um）	PMM（10μm）
Exposure time	100~200ms	0.5ms~5ms
Laser	Wavelength 450nm, Power 4W	
XIMEA camera	Pixel size 4.8um, Resolution 1280×1024	
Lens	M = 0.14	M = 0.13
Tunnel parameters	Cross area = 80×80mm x = 400mm ~ 1300mm δ =10mm ~ 20mm, Re_θ = 97~194	
Flow condition	Moving speed 80~100 mm/s Flow rate 1.6 m^3/h	

Experimental setup



Light sheet arrangement



(a) Streamwise-wall normal direction

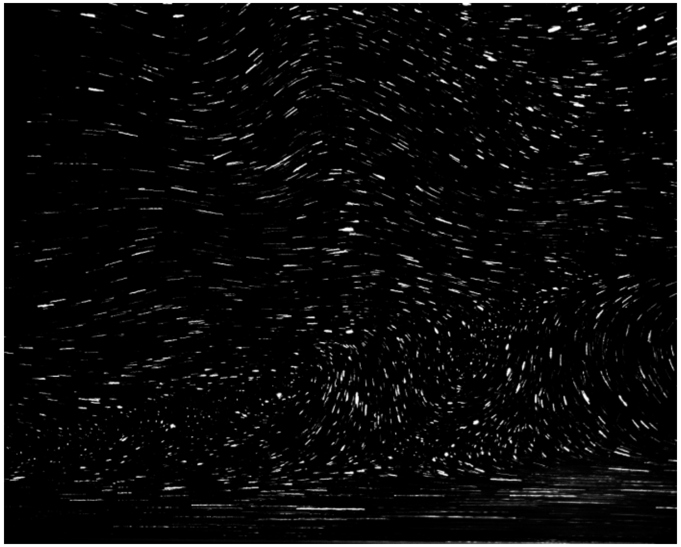
(b) Streamwise-spanwise direction

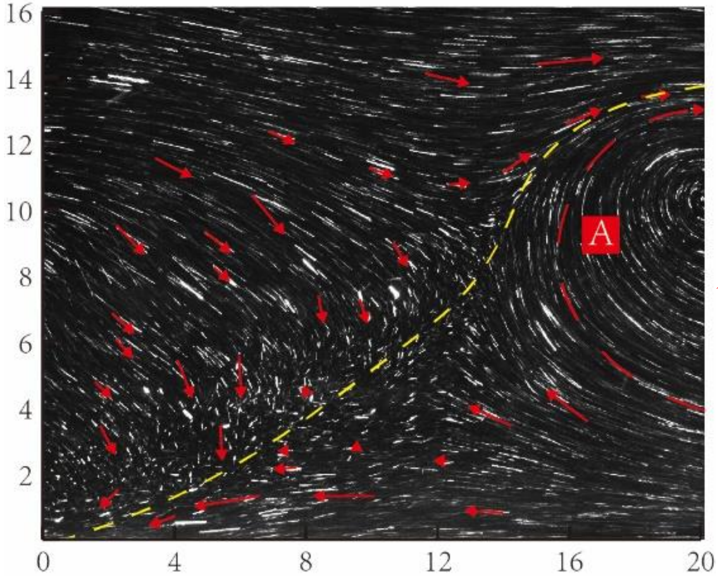
(c) Inclined to the flow direction (angle of inclination is set as 135°)

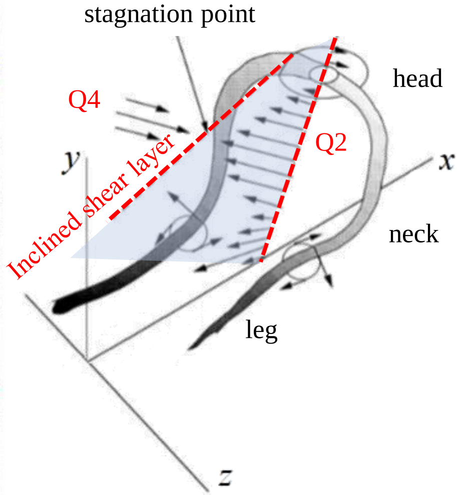
(d) Inclined to the flow direction (angle of inclination is set as 53°)

1. Identification & quantification of vortex generation

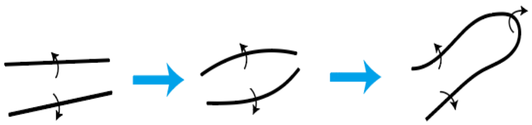
- **Trajectory tracking of a hairpin head generation by Moving-SFLE**

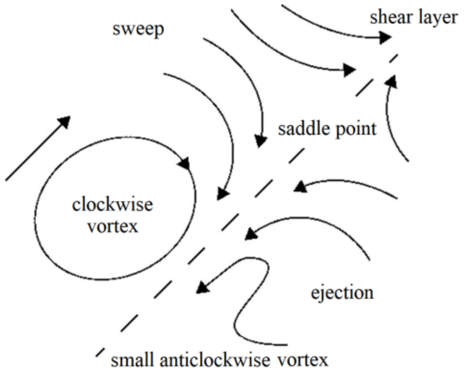






($U^* = 0.9$ exposure time 100 ms and the frame rate 9.995 fps)

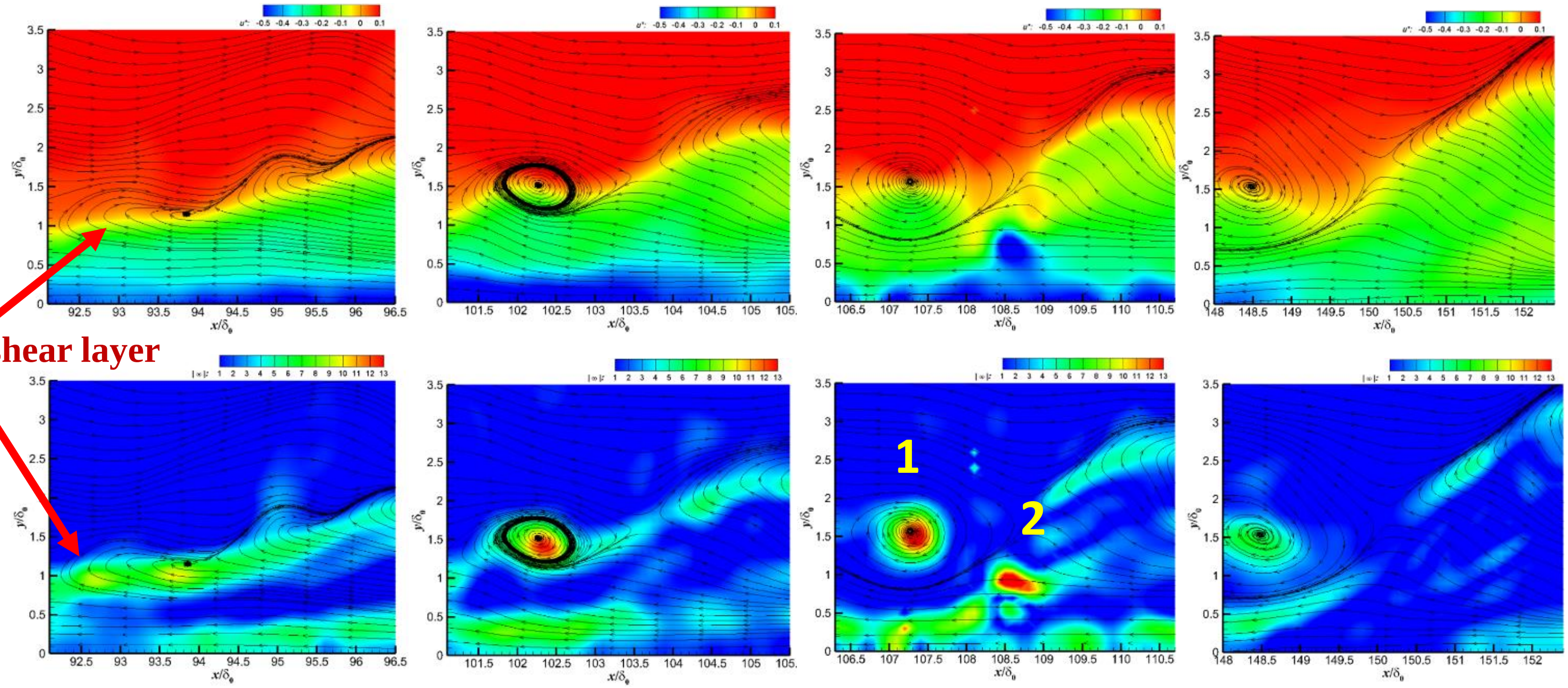




➢ **Strong Q2 and Q4 events induce the spanwise shear to connect the streamwise vortices in downstream and then develop into a hairpin vortex.**

1. Identification & quantification of vortex generation

- **Spatio-temporal evolution of a hairpin head generation by Moving-PIV**



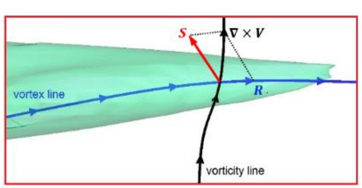
(a) $t^* = 0$ (b) $t^* = 10.2$ (c) $t^* = 16.1$ (d) $t^* = 28.6$

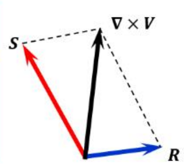
Process of vortex generation and evolution by u (up), $|\omega|$ (bottom)

➢ **Vortex identification by Liutex** → **A new definition of fluid rigid rotation**

Basic idea : Vorticity decomposition $\nabla \times \vec{V} = \vec{R} + \vec{S}$

$$\begin{cases} \vec{R} = R \cdot \vec{r} \qquad \nabla\vec{V} \cdot \vec{r} = \lambda_r \vec{r} \\ R = \vec{\omega} \cdot \vec{r} - \sqrt{(\vec{\omega} \cdot \vec{r})^2 - 4\lambda_{ci}^2} \end{cases}$$





- Strength R: It is determined in the plane normal to the direction of the real eigenvector.
- Direction $\vec{r}$: The real eigenvector of the velocity gradient tensor $\nabla\vec{V}$.

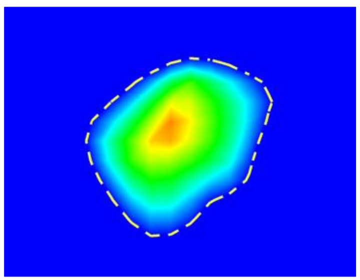
1. Identification & quantification of vortex generation

Spatio-temporal evolution of a hairpin head generation by Moving-PIV

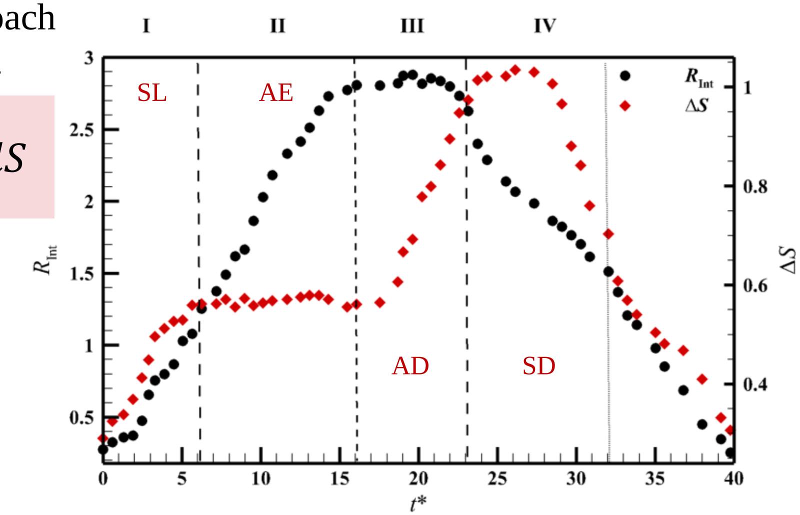
Quantitative statistics based on Liutex integration

- Proposed a statistical approach for 2D/3D experimental data.

$$R_{\text{Int}} = \int_{\Delta S} R dS, S = \int_{\Delta S} \frac{R}{|R|} dS$$

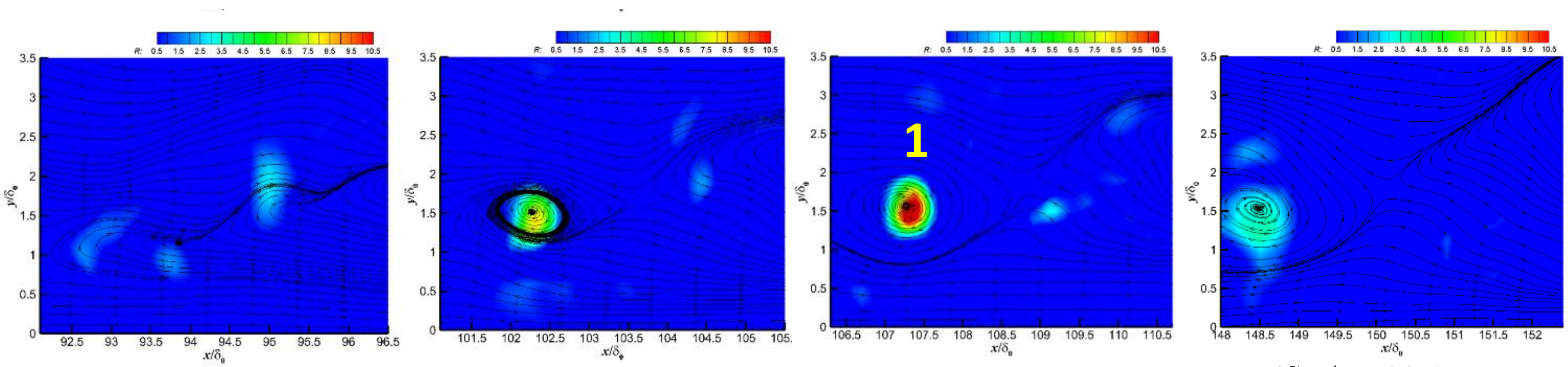


R_{Int} is Liutex integral
ΔS is the area where R > 0



Temporal distributions of R_{Int} and ΔS during the whole process of vortex generation and evolution

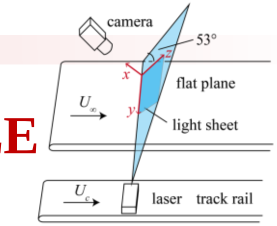
I synchronous linear segment (SL)
II absolute enhancement segment (AE)
III absolute diffusion segment (AD)
IV skewing dissipation segment (SD)



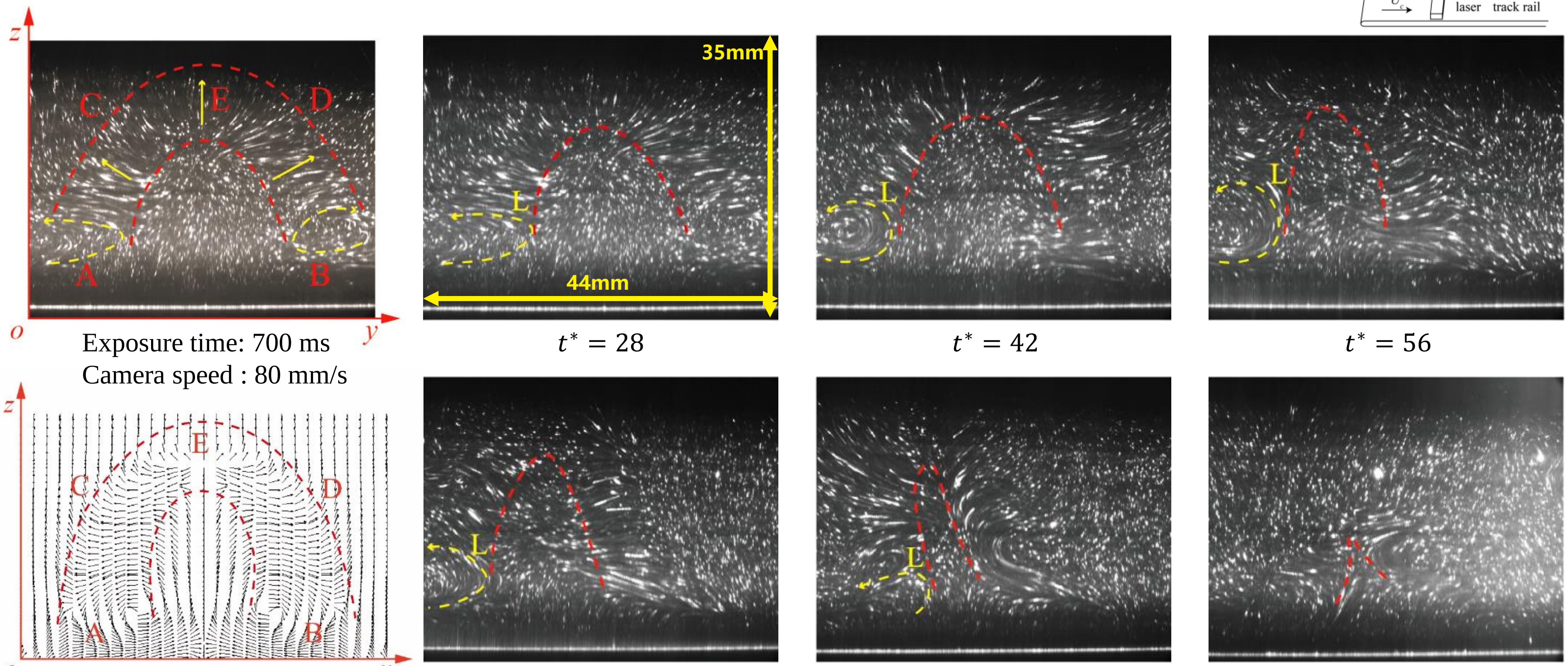
(a) $t^* = 0$ (b) $t^* = 10.2$ (c) $t^* = 16.1$ (d) $t^* = 28.6$

Process of vortex generation and evolution by u (up), $|\omega|$ (center) and R (bottom)

1. Identification & quantification of vortex generation

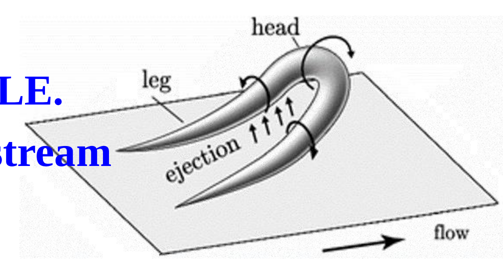


- **Trajectory tracking of a whole hairpin structure by Moving-SFLE**



Hairpin vortex simulated by DNS

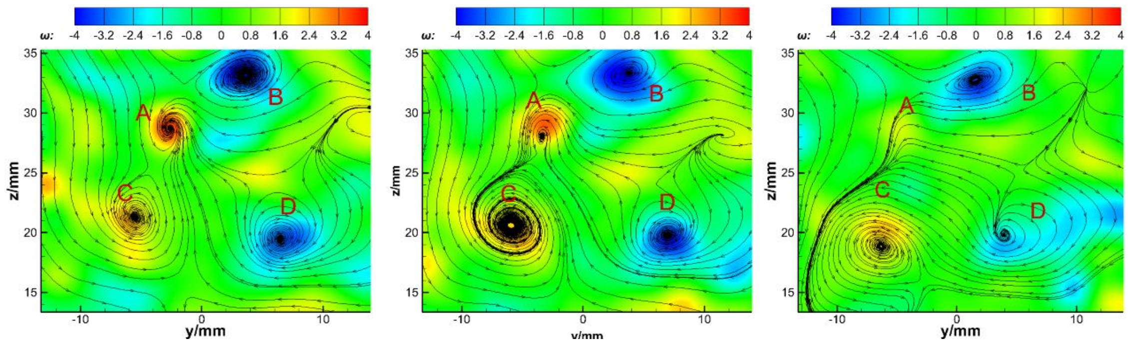
- ➢ **A complete hairpin containing head, neck and legs is captured by MSFLE.**
- ➢ **Spanwise asymmetry is the result of asymmetric secondary and downstream hairpin vortices generated from the initial symmetric vortex structure.**



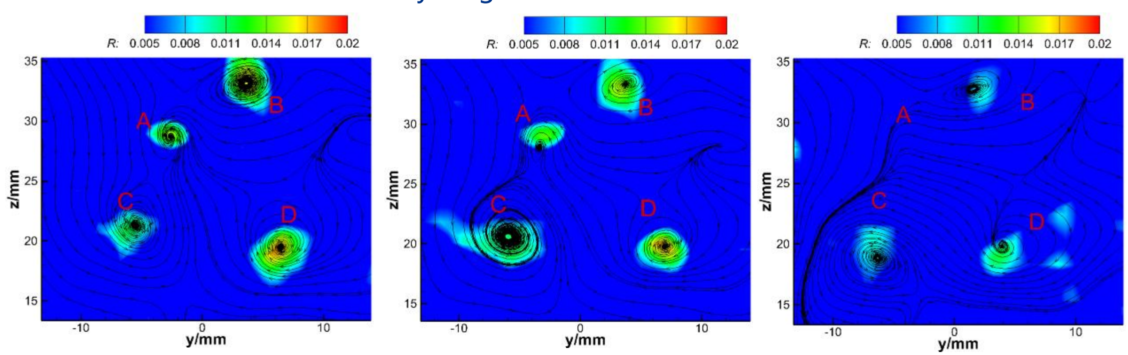
1. Identification & quantification of vortex generation

- **Spatio-temporal evolution of a whole hairpin structure by Moving-PIV**

53° between light and plate

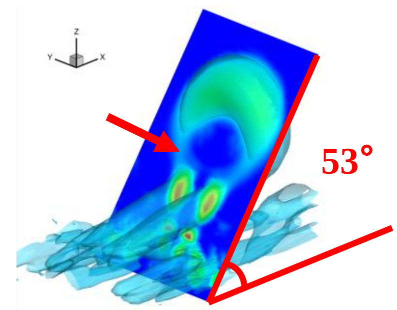


Vorticity magnitude contour and streamlines



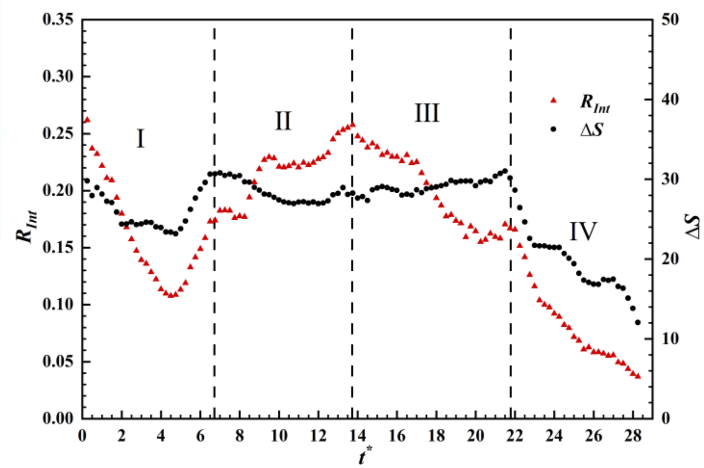
53° Liutex magnitude contour and streamlines

(a) $t^* = 14.7$ (b) $t^* = 16.1$ (c) $t^* = 20.7$



$R = 0.1$ iso-surface of hairpin vortex by DNS data

synchronous enhancement | absolute enhancement | absolute dissipation | synchronous dissipation



2. Mechanism of regeneration & self-maintenance

A. Hairpin regeneration induced by interaction between hairpins & packets

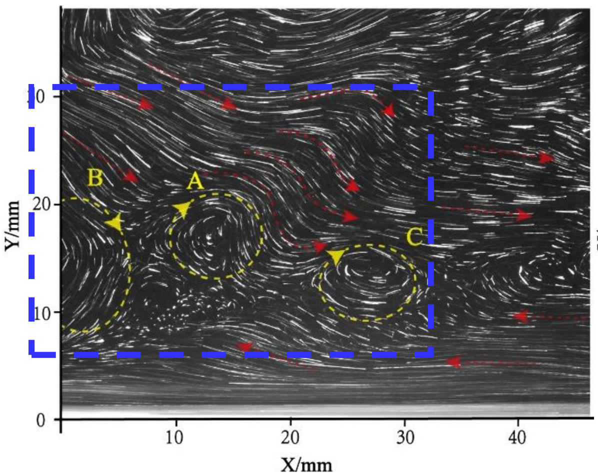


Fig.(a) $t^* = 26.7$

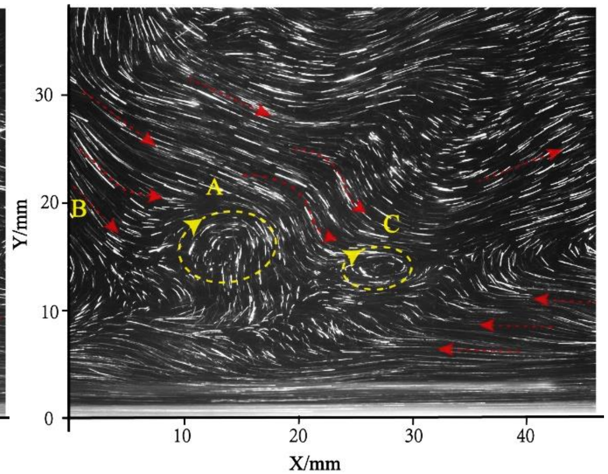
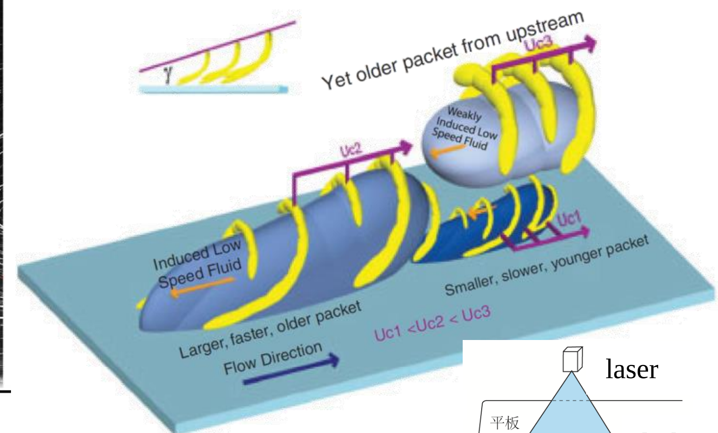
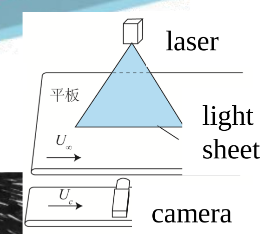


Fig.(b) $t^* = 30.1$





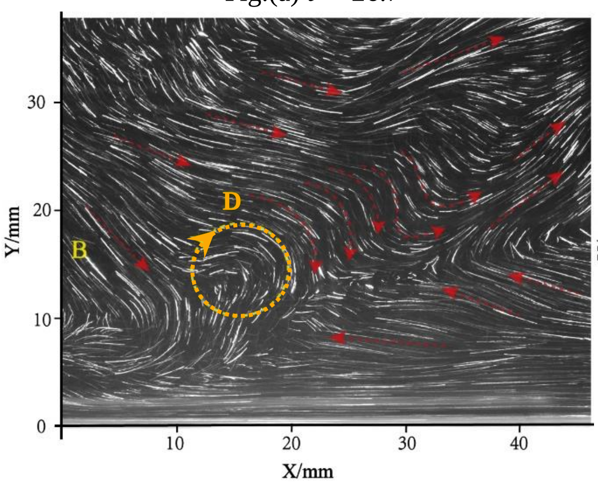


Fig.(c) $t^* = 33.4$

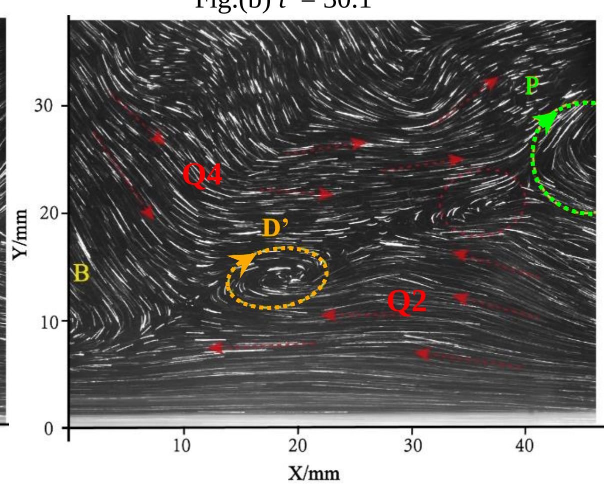
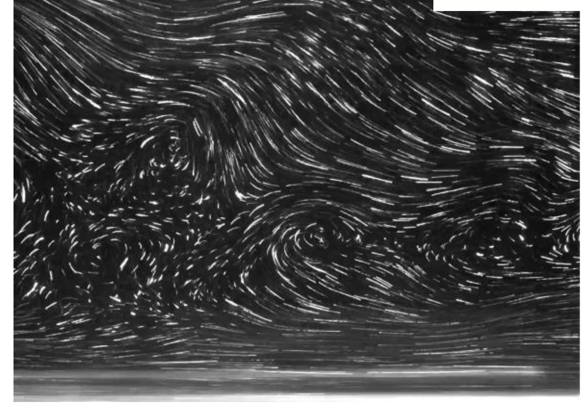


Fig.(d) $t^* = 40.1$



➢ **Spanwise shear instability caused by the collision between the hairpin vortex packets**

2. Mechanism of regeneration & self-maintenance

- **B. Auto generation hairpins (the young generation induced by the old)**

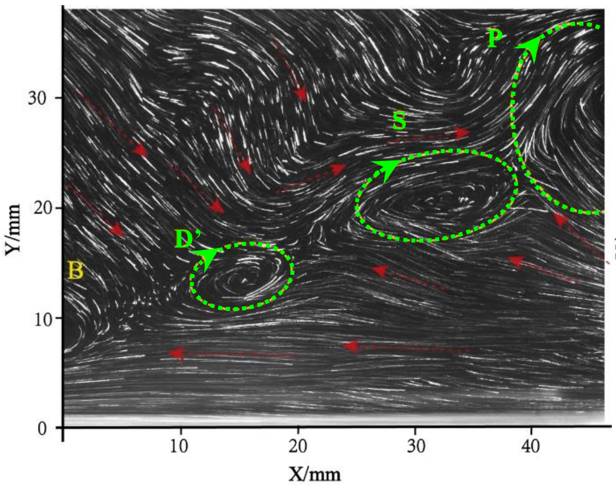


Fig.(a) $t^* = 43.4$

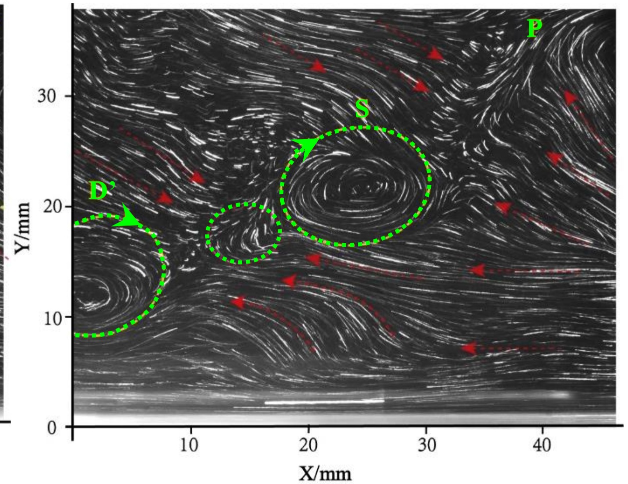


Fig.(b) $t^* = 50.1$

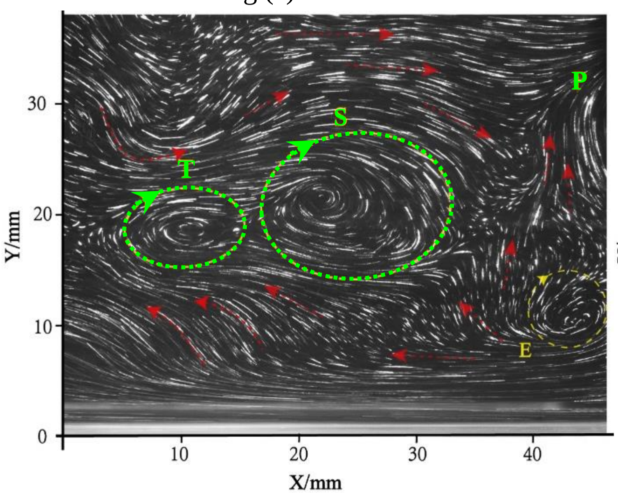


Fig.(c) $t^* = 58.5$

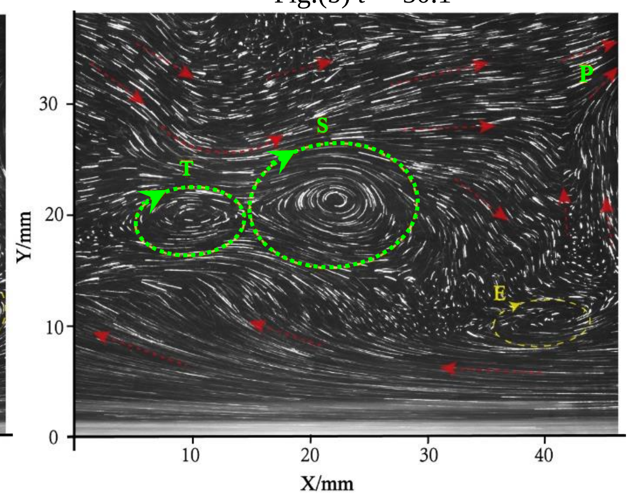
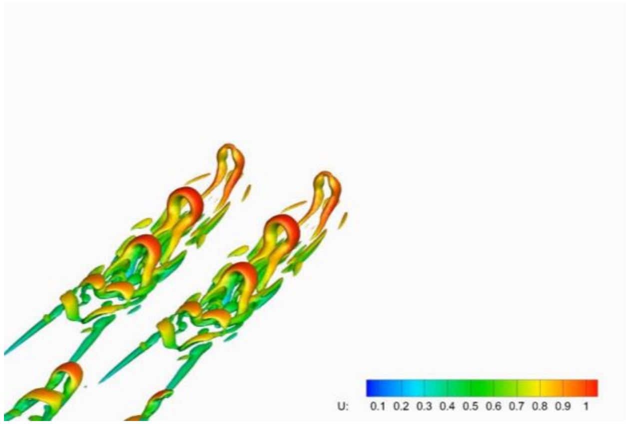
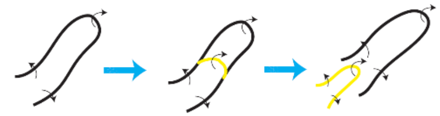


Fig.(d) $t^* = 63.5$





P (Primary hairpin)
S (Secondary hairpin)
T (Tertiary hairpin)

$t^* = 43.4$: Secondary hairpin S appears;
$t^* = 50.1$: S sheds from P;
$t^* = 58.5$: Tertiary hairpin T generates;
$t^* = 63.5$: A new vortex comes out under P.

2. Mechanism of regeneration & self-maintenance

B. Auto generation hairpins (the young generation induced by the old)

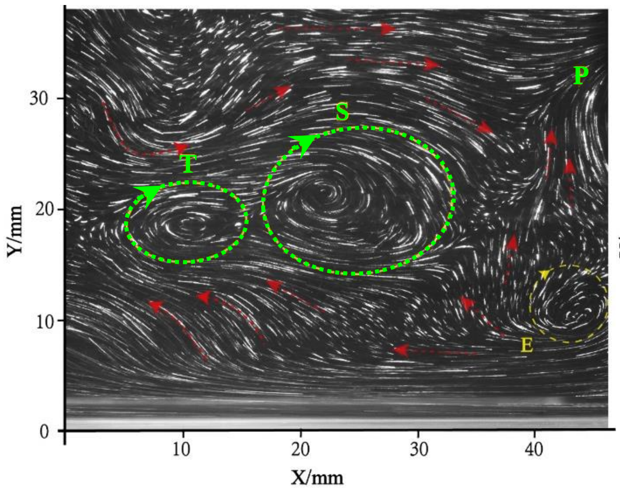


Fig.(c) $t^* = 58.5$

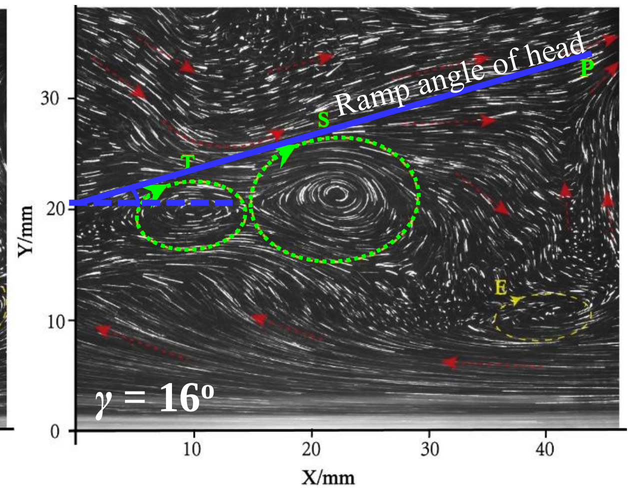
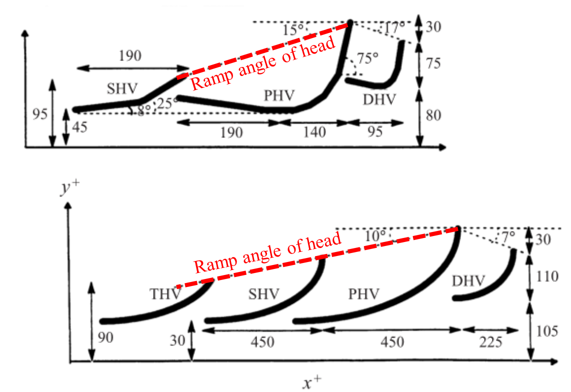
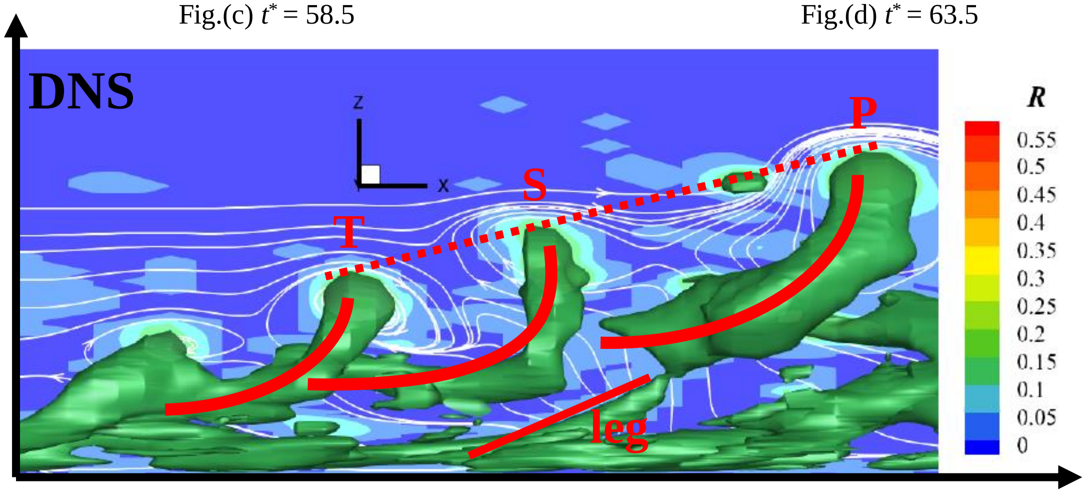


Fig.(d) $t^* = 63.5$

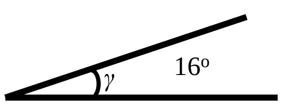
t^+≈120/300



Zhou, J., Adrian, R. J., Balachandar, S. & Kendall, T. M. 1999 Mechanisms for generating coherent packets of hairpin vortices in channel flow. J. Fluid Mech. 387, 353–396



Ramp angle of head

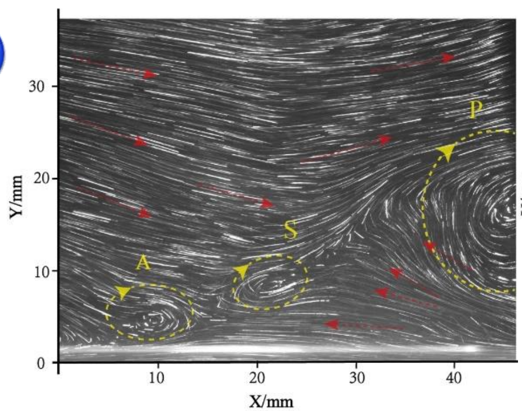


10°~20°

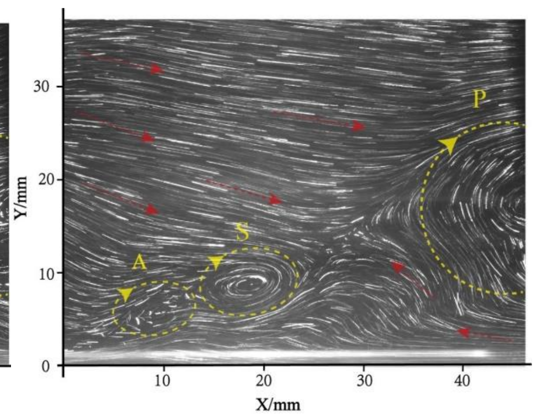
- **The self-induced motion is pointed up and backward, resulting in further generation of hairpin vortex. The ramp angle is the fundamental characteristics of the linear growth of hairpins.**

2. Mechanism of regeneration & self-maintenance

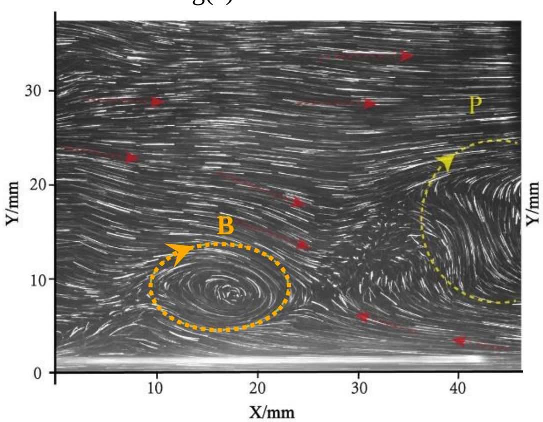
● C. Merging of hairpin vortices in a packet



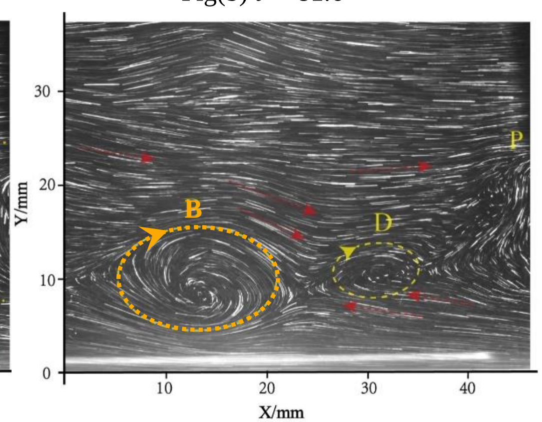
Fig(a) $t^* = 76.8$



Fig(b) $t^* = 81.6$



Fig(c) $t^* = 86.4$



Fig(d) $t^* = 92.8$

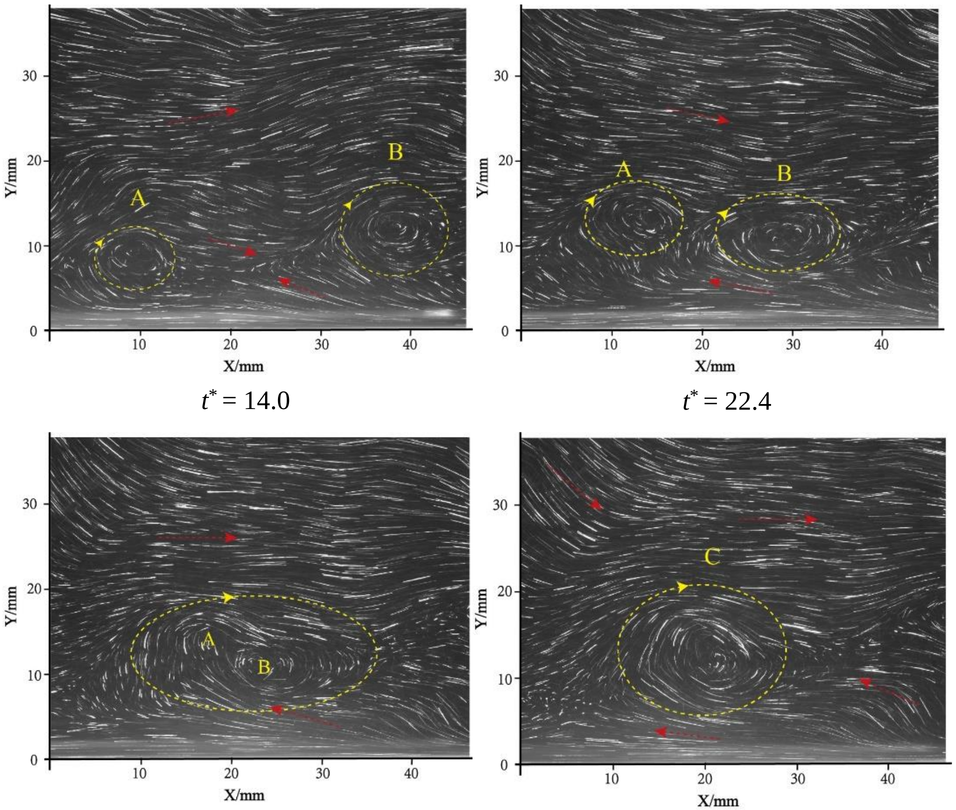
$t^* = 76.8$: Secondary hairpin S appears;
$t^* = 81.6$: A approaches S;
$t^* = 86.4$: A and S merge into B;
$t^* = 92.8$: A new vortex D comes out under the shear layer.

How to determine the energy interchange during the merging process?

➢ **Hairpin vortices in a packet may merge into a new hairpin vortex once their distance is close enough.**

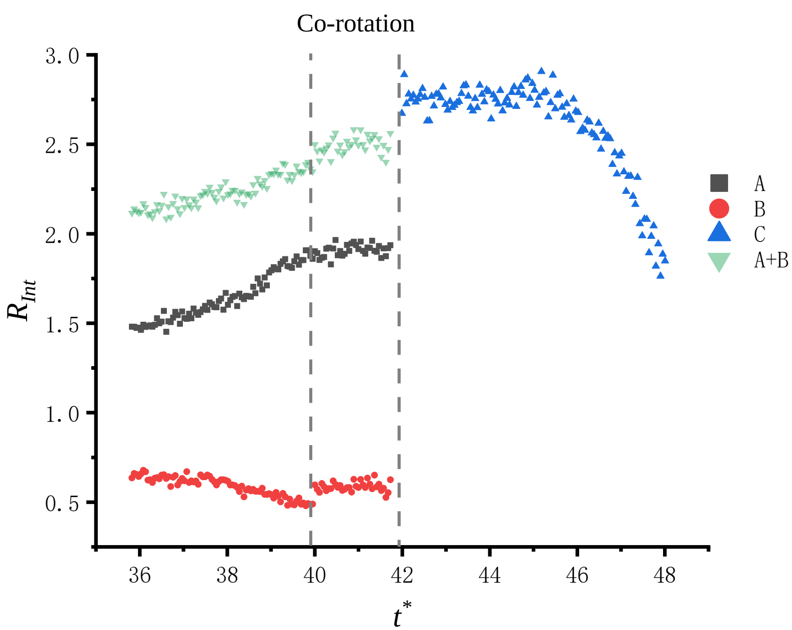
2. Mechanism of regeneration & self-maintenance

- **C. Merging of hairpin vortices in a packet**



Images captured by Moving-SFLE

Statistics analysis by Liutex integral method

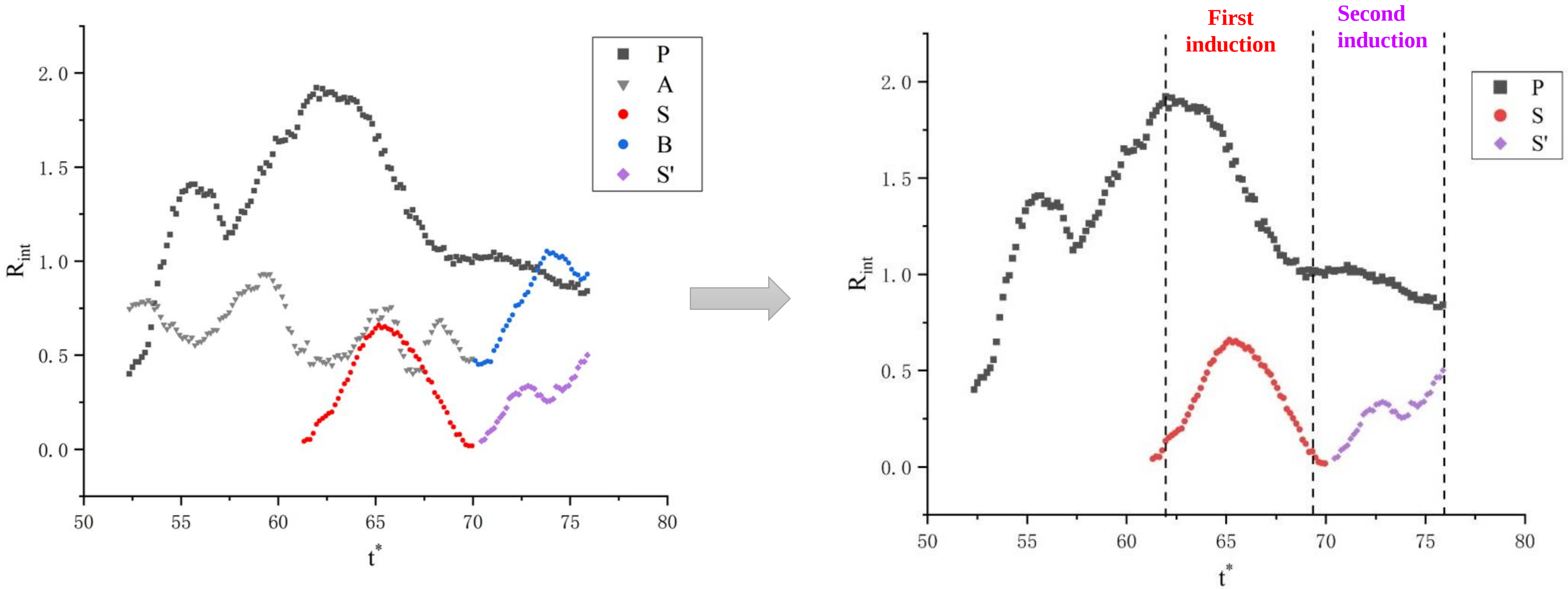


The rotation strength R_{int} changes with time

➢ **The vortex structure with less strength will be entrained into the vortex structure with greater strength. The strength of a newly generated vortex is about the sum of the two (A+B).**

2. Mechanism of regeneration & self-maintenance

- **Turbulence self-sustaining theory based on the mechanism of mother and child hairpin vortices**



- **A parent hairpin vortex with sufficient intensity may induce multiple generations of hairpin vortices, or may induce secondary hairpin vortices continuously.**

- **The primary hairpin vortices will induce a new generation hairpin vortex in its growth period, and contribute energy and increase the rotation intensity through decaying themselves. This cycle continues to maintain the development of turbulence.**

Conclusion

- **The Liutex integral is proposed for statistical analysis of the evolution of vortex intensity and size.**

- **Three mechanisms of the hairpin vortex regeneration:**
  - **A. Hairpin regeneration induced by interaction between hairpins & packets**
  - **B. Auto generation hairpins (the young generation induced by the old)**
  - **C. Merging of hairpin vortices in the packets**

- **Turbulence self-sustaining mechanism in boundary layer:**
  - **Based on the mechanism of mother and child hairpin vortices**

Thanks！