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UNSTEADY SEPARATION PROCESS AND VORTICITY BALANCE ON UNSTEADY AIRFOILS

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ABSTRACT

Low momentum fluid erupts at the unsteady separation region and forms a local shear layer at the viscous-inviscid interface. At the shear layer, the vorticity lumps into a vortex and protrudes into the inviscid region. This process initiates the separation process. The response of airfoils in unsteady free stream was investigated based on this vortex generation and convection concept. This approach enabled us to understand the complicated unsteady aerodynamics from a fundamental point of view.

INTRODUCTION

Unsteady separation is an important feature of many flows. For example, when an airfoil undergoes maneuvering, the lift and drag experience very large variations from the steady state values. The unsteady separation from the leading edge produces coherent vortical structures which can greatly alter the surface loading on the wing (McCrosky, 1982). The separation process and the formation of the vortices can be very different for various operating conditions. On a 2D airfoil, there is no effective vorticity convection mechanism. The separating vortices therefore can not hold on to the chord and are convected by the mean flow. Shih (1988) found that the time needed for the vortex moving along the chord is an important time scale in determining the aerodynamic properties. On a small aspect ratio delta wing, vorticity can be transported along the cores of the leading edge separation vortices. The vortices can be stationary on the wing. Therefore, there is no vortex convection time scale. In this paper, the measured lift of airfoils in an unsteady free stream will be presented and will be interpreted by the vorticity balance concept (Reynolds and Carr, 1985).

1. UNSTEADY SEPARATION MECHANISM

It has been experimentally shown that shear stress vanishes at an interior point away from the wall for both upstream moving separation (Shih, 1988) and downstream moving

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separation (Didden and Ho, 1985). These cases were illustrated in figures 1a and 1b. The data validated the MRS criterion and showed many important aspects of unsteady separation pointed out by Van Dommelen and Shen (1982). Erruption of the boundary layer fluid and the formation of a local shear layer with an inflection point (figure 2) was found to be generic to unsteady separation.

When an external disturbance induces an unsteady adverse pressure gradient (figure 3), the fluid particles near the wall decelerates. Low momentum fluid errupts from the wall region. A local shear layer forms at the boundary of the inviscid and viscous zones. Velocity profile of the local shear layer has an inflectional point between the point $\partial u/\partial y = 0$ near the wall and $\partial u/\partial y = 0$ at free stream. This shear layer is inviscidly unstable and extracts energy from the mean flow.

2. UNSTEADY WATER CHANNEL

Experiments on unsteady airfoils were performed in an unsteady water tunnel (figure 4). The tunnel was operated under constant head. Therefore, the free stream speed was determined by the resistance provided by the exit gate. This arrangement made the tunnel extremely versatile and simple to operate. The opening area of the exit gate was controlled by a computer-driven stepping motor. The free stream velocity was varied as a function of time in many different types of waveforms. The lift was measured by load cells while the velocity field was measured by laser Doppler velocimetry.

3. ATTACHED UNSTEADY FLOW AROUND 2D AIRFOIL

When the flow on the 2D airfoil was attached, the vorticity convection was balanced by a part of the vorticity diffusion. Hence, the convected vorticity did not play a role in the dynamics. The lift was determined by the rest of the vorticity diffused from the surface. Since there was no intrinsic time scale of the vorticity balance, the lift curves of the attached flow was only scaled by the free stream velocity time scale. Based upon the vorticity balance we can show that the local circulation is scaled with the velocity at the edge of the boundary layer.

4. SEPARATED UNSTEADY FLOW AROUND 2D AIRFOIL

During the separated phase, the vorticity measurement indicated that the vorticity diffused from the surface is negligible compared with that shed from the leading edge. In other words, the flow was controlled by the vorticity convection instead of the vorticity diffusion. The vorticity originating from the leading edge rolled up into a vortex which produced high suction on the wing. When this lift generating vortex moved from leading edge to trailing edge, the lift of the unsteady airfoil was much higher than that of the steady one. The lift dropped significantly after the lift generating vortex left the chord. Therefore, the ratio between the vortex convection time scale and external perturbation time scale dictates the lift curve of the airfoil.

5. AN AIRFOIL WITH $C_L > 10$

How to obtain high lift coefficient in the post stall region is the goal of supermaneuverability research. The fundamental understanding of the time scale and the vorticity balance on the separated airfoil mentioned in the above section enabled us to achieve this purpose. We placed a NACA 0012 airfoil at an angle of attack of 20° which is in the static stall region. The reduced frequency was chosen such that a large coherent vortex can be trapped on the chord for an appreciable portion, say 40%, of the cycle. We then obtained a lift coefficient larger than ten. This is shown in figure 5.

ACKNOWLEDGMENT

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Shih, C., 1988, "Unsteady Aerodynamics of a Stationary Airfoil in a Periodically Varying Free Steam", USC Ph.D. Thesis.

Van Dommelen, L. L. and Shen, S. F., 1982, The genesis of separation. In *Numerical and Physical Aspects of Aerodynamic Flows* (ed. T. Cebeci), pp. 293–311, Springer.

Upstream moving separation

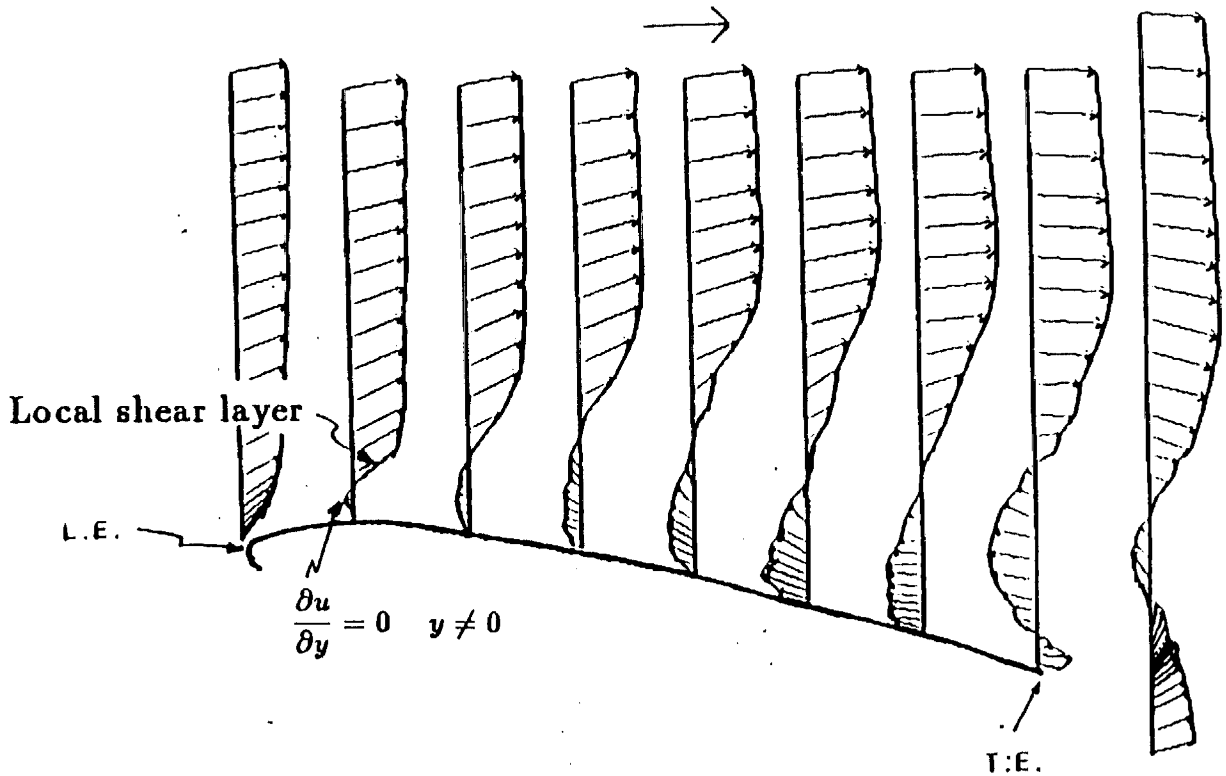


Figure 1a: Upstream moving separation (Shih, 1988).

Downstream moving separation

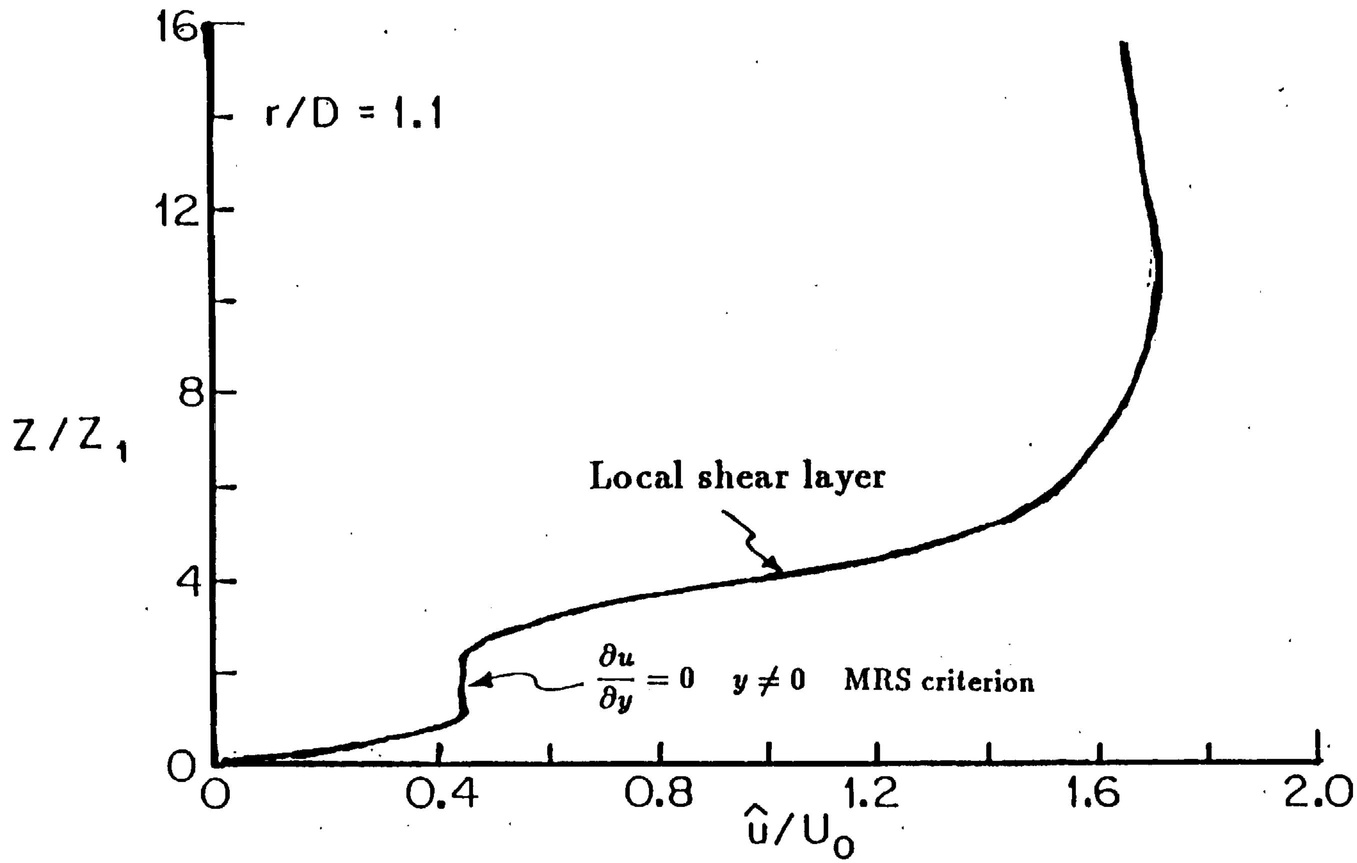


Figure 1b: Downstream moving separation (Didden and Ho, 1985).

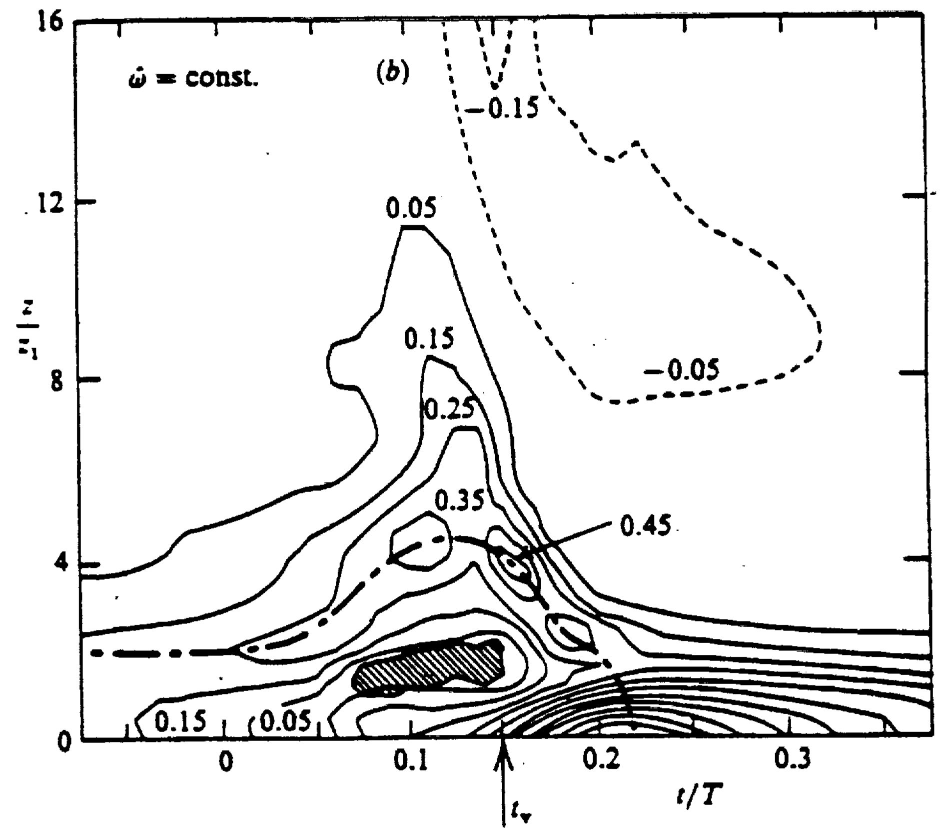


Figure 2: Secondary vortex ejection in vortex induced separation (Didden and Ho, 1985).

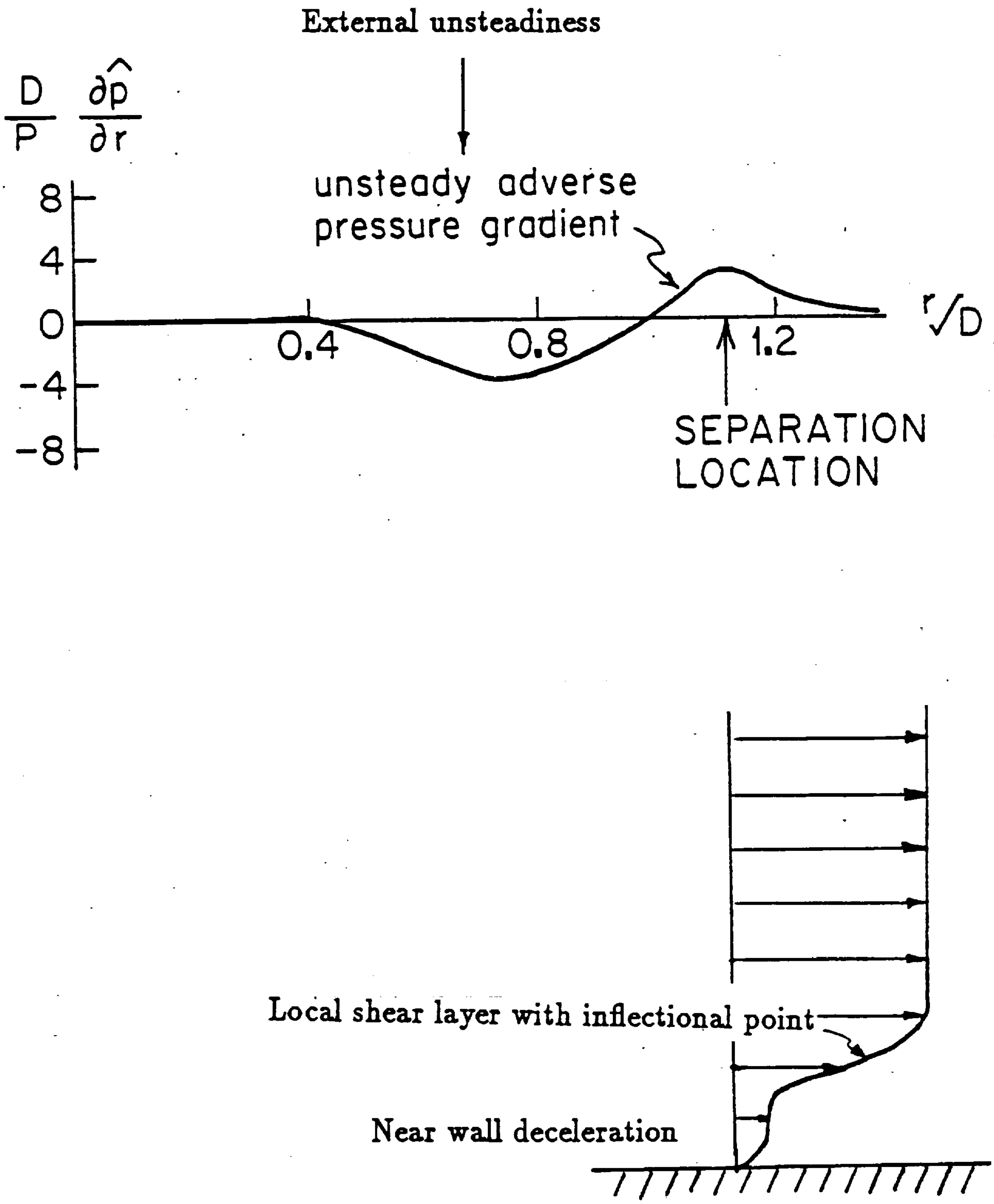


Figure 3: Unsteady separation mechanism.

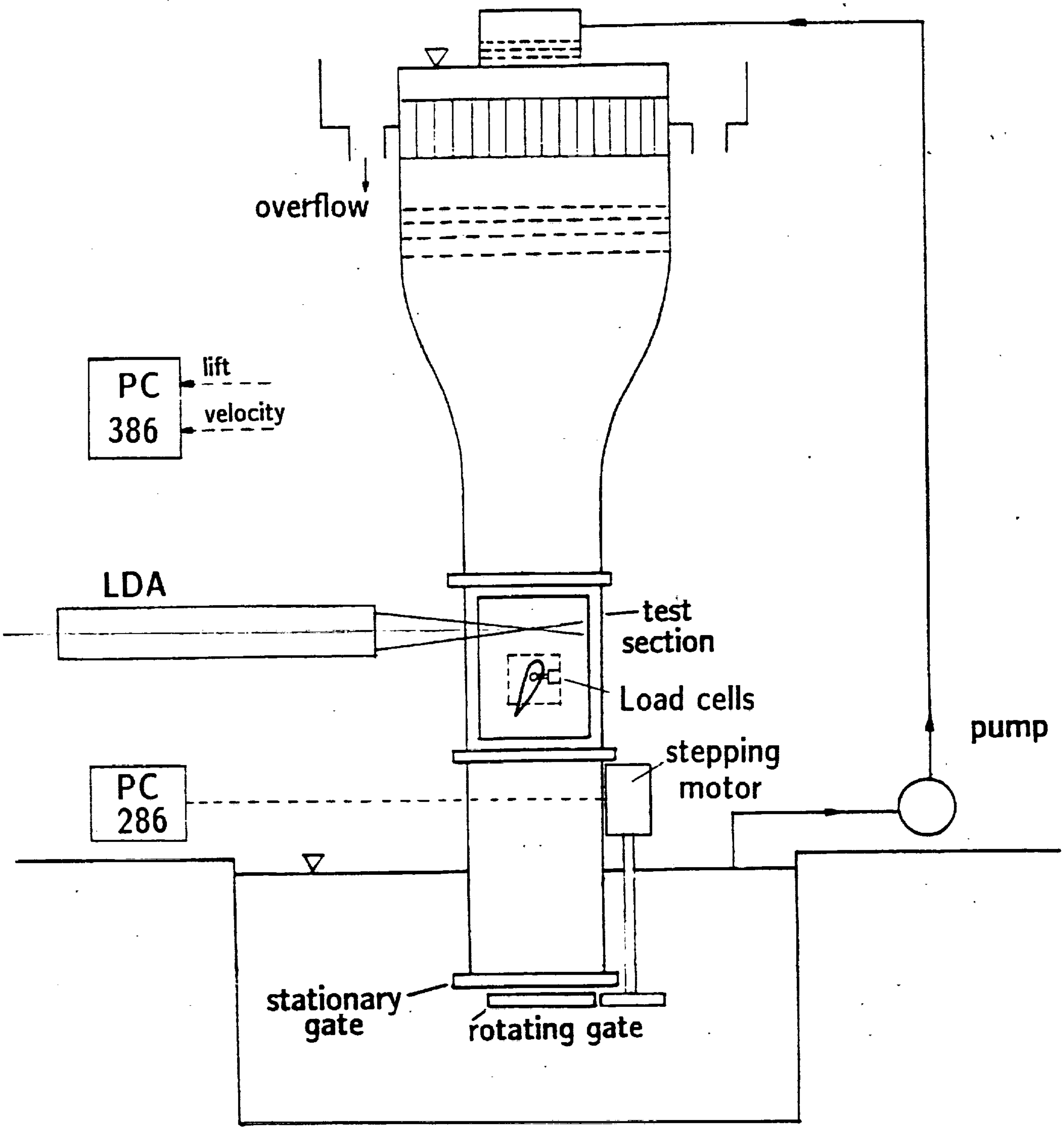


Figure 4: Unsteady water channel.

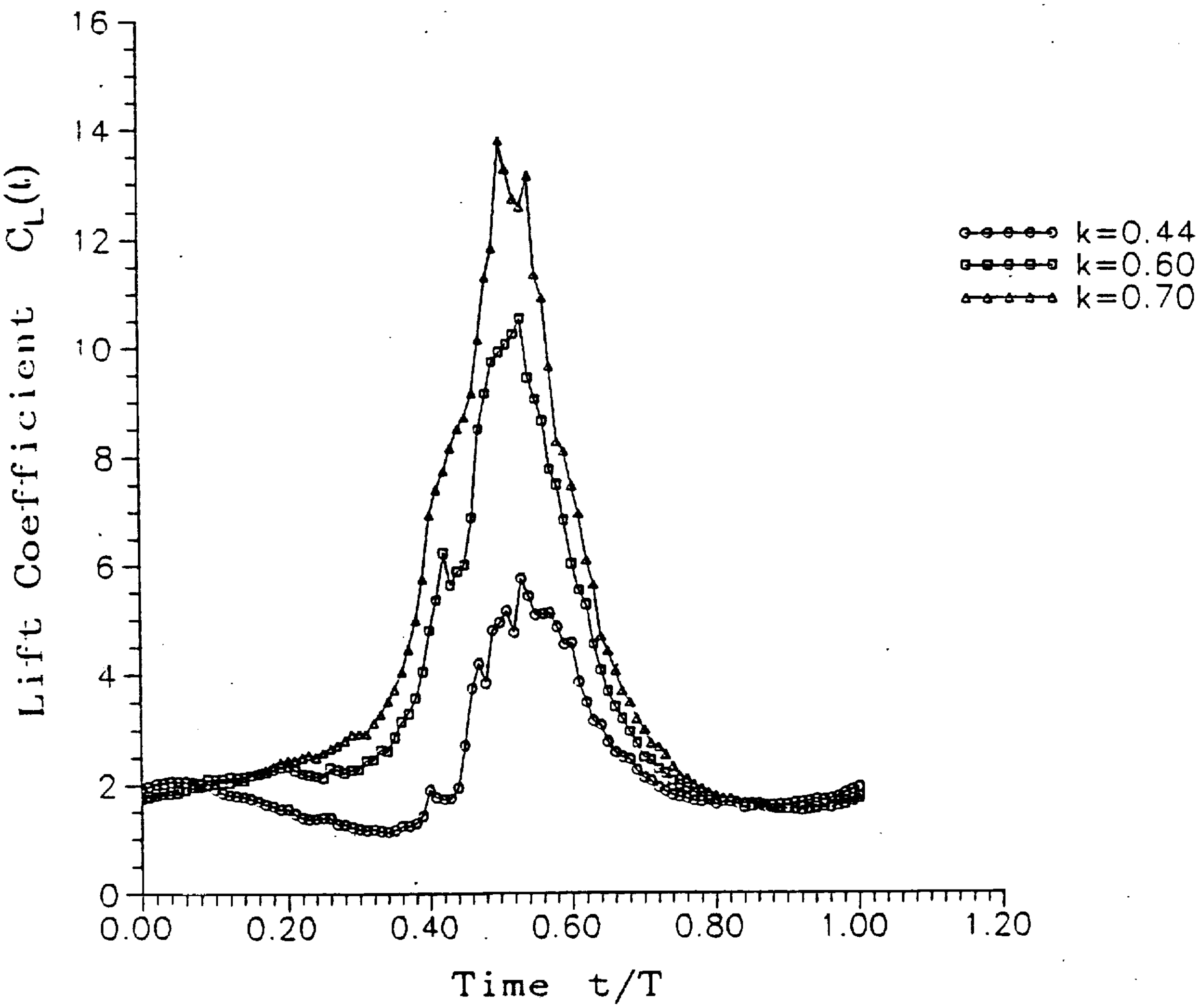


Figure 5: Variation of phase-averaged lift coefficient over a cycle for NACA 0012 at $\alpha=20^{\circ}$.

OUTLINE

- Vorticity Balance of Attached flow

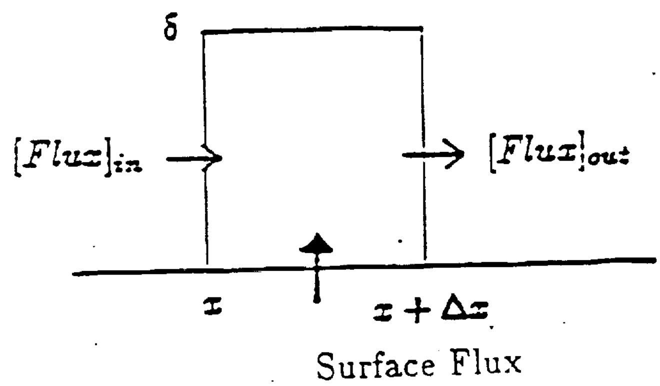
- Unsteady Separation Mechanism
  - Downstream moving separation
  - Upstream moving separation
  - 2-D separation ?

- Vorticity Balance of Separated flow

- Unsteady Lift of Post-Stall 2-D Wing
  - Optimum frequency
  - $C_L > 10$

- Unsteady Lift of 3-D Wing
  - Small aspect ratio delta wing
  - Large aspect ratio delta wing

ATTACHED FLOW



- Increasing Convection

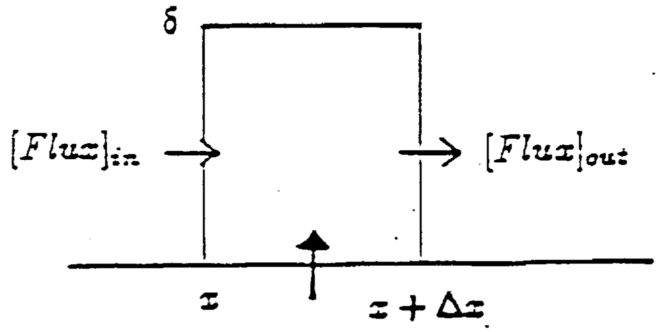
$$\left[\int_0^\delta U\Omega dy\right]_{in} - \left[\int_0^\delta U\Omega dy\right]_{out} = \left[\int_0^\delta U\frac{\partial U}{\partial y}dy\right]_{in} - \left[\int_0^\delta U\frac{\partial U}{\partial y}dy\right]_{out}$$
$$= \left[\frac{1}{2}U_e^2(x) - \frac{1}{2}U_e^2(x+\Delta x)\right]$$

- Vorticity Flux from the Surface

$$-\int_x^{x+\Delta x} \nu\frac{d\omega}{dy}dx = -\int_x^{x+\Delta x} \frac{1}{\rho}\frac{\partial P}{\partial x}dx$$
$$= \int_x^{x+\Delta x} \frac{\partial U_e}{\partial t}dx + \int_x^{x+\Delta x} U_e\frac{\partial U_e}{\partial x}dx$$
$$= \int_x^{x+\Delta x} \frac{\partial U_e}{\partial t}dx + \left[\frac{1}{2}U_e^2(x+\Delta x) - \frac{1}{2}U_e^2(x)\right]$$

- Surface Flux Dominates the Flow

ATTACHED FLOW



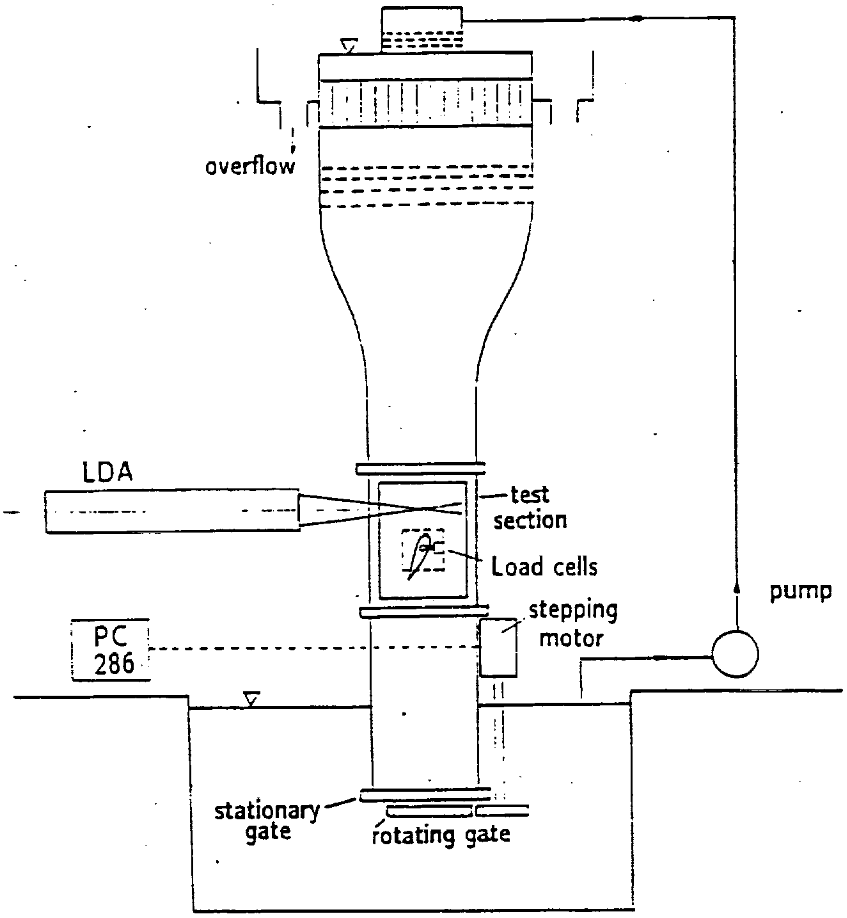
Surface Flux

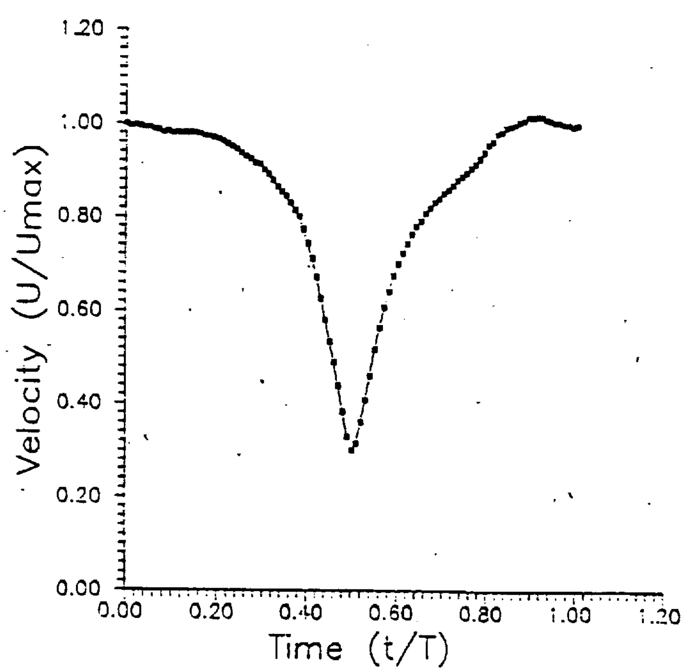
⊙ Net Vorticity (Circulation) Accumulation

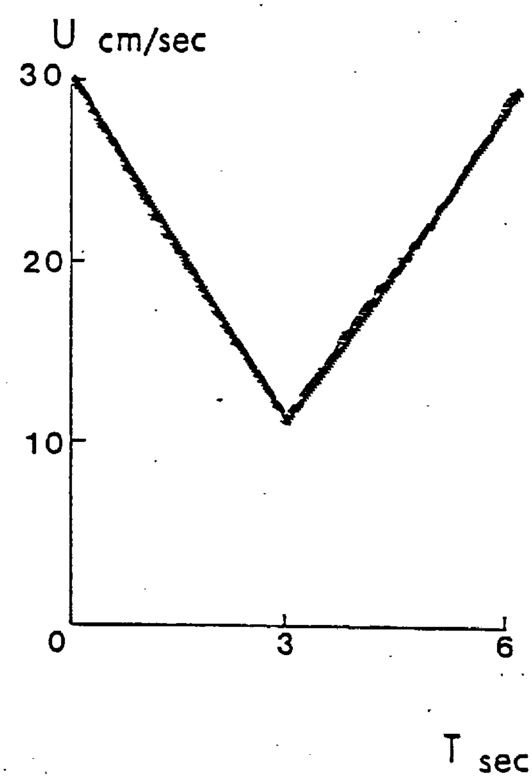
$$\frac{\partial \Gamma}{\partial t} = \int_{x}^{x+\Delta x} \frac{\partial U_e}{\partial t} dx$$

⊙ Circulation Scale

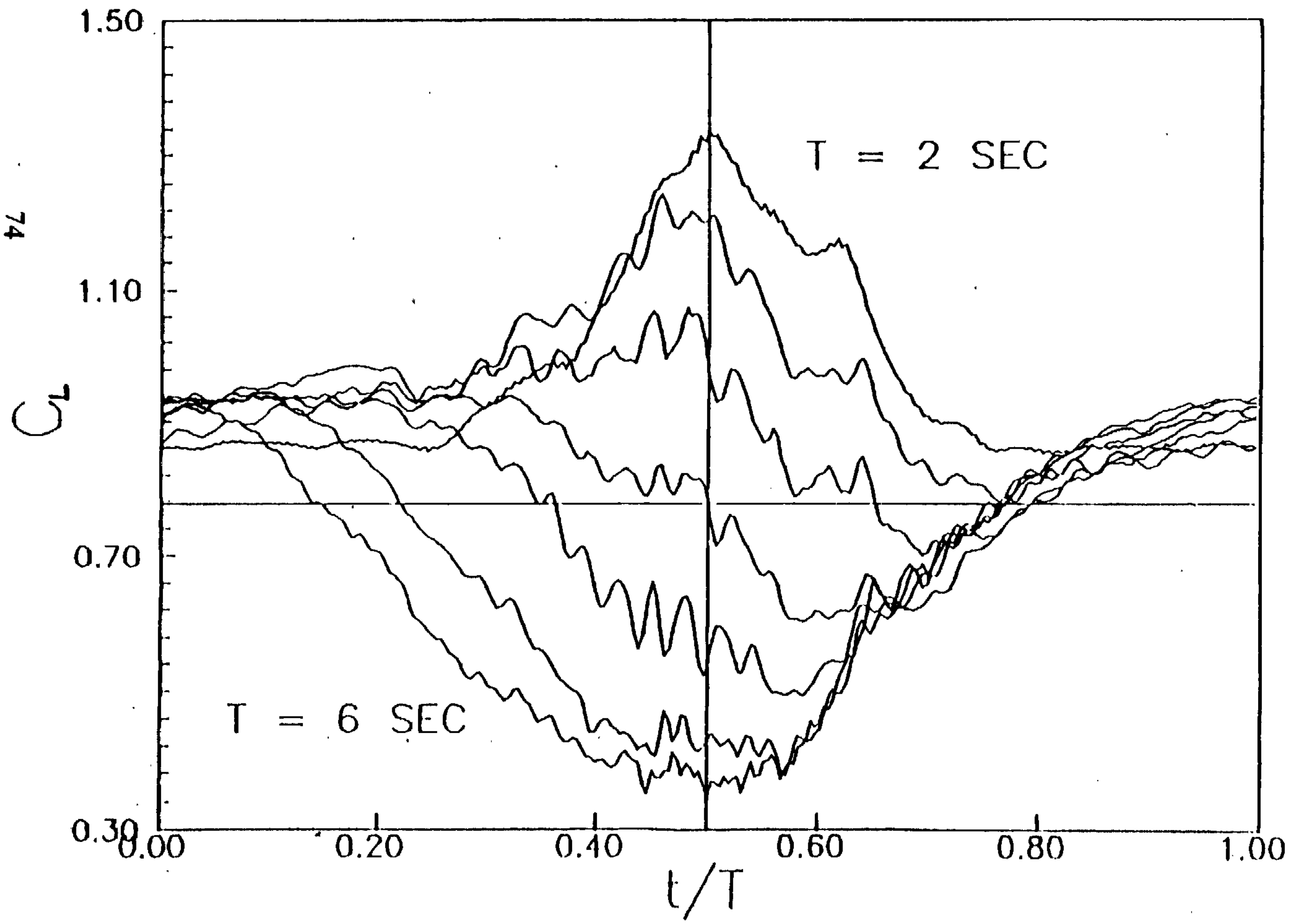
$$\Gamma = \int\int \Omega dx dy = \int_{x}^{x+\Delta x} \int_{0}^{\delta} \frac{\partial U}{\partial y} dy dx$$
$$= \int_{x}^{x+\Delta x} U_e dx$$


overflow
LDA
test section
Load cells
pump
stepping motor
PC 286
stationary gate
rotating gate

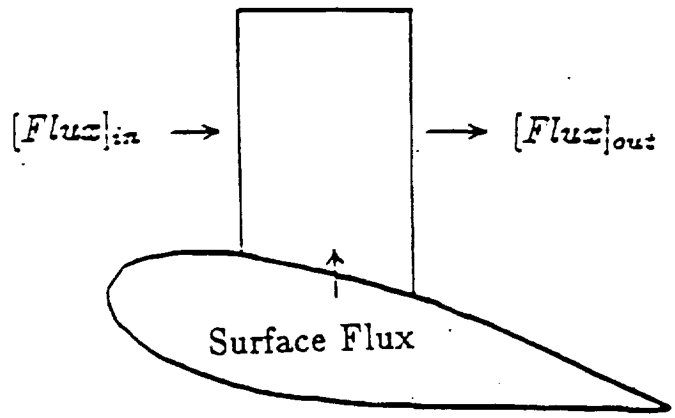

Velocity (U/Umax)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00 0.20 0.40 0.60 0.80 1.00 1.20
Time (t/T)


U cm/sec
30
20
10
0
3
6
T sec

- Curves Collapse for Attached Flow
- Single Time Scale



Regional Balance of Phase-Averaged Vorticity



$$\frac{\partial <\Gamma>}{\partial t} = \left[\int <u\omega> dy\right]_{in} - \left[\int <u\omega> dy\right]_{out} - \left[\int \nu \frac{d<\omega>}{dy} dx\right]_s$$

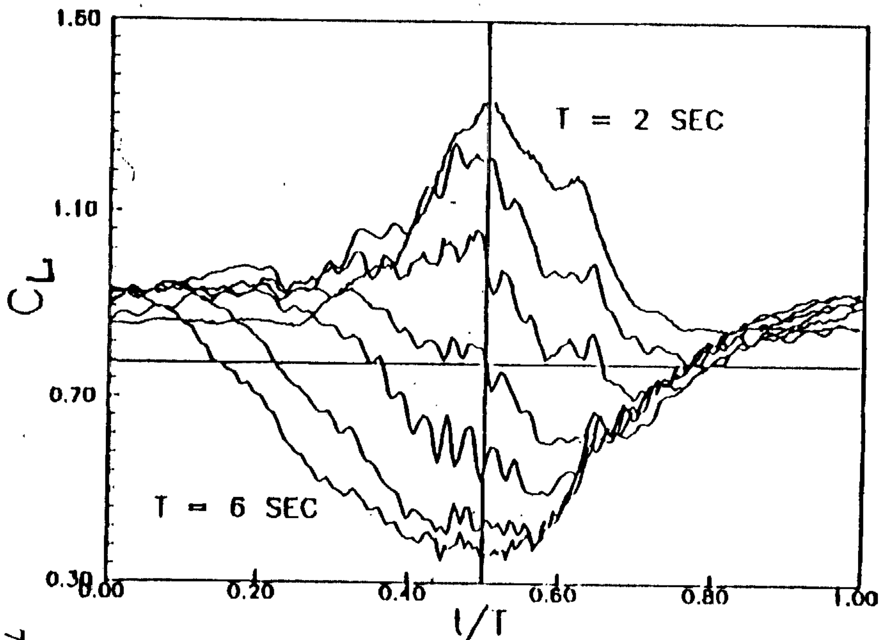
$$<u\omega> \;=\; U\Omega + \frac{\partial}{\partial x} <u'v'> - \frac{1}{2}\frac{\partial}{\partial y} <u'^2 - v'^2>$$

$$<u\omega> \;\approx\; U\Omega$$

$$\frac{\partial <\Gamma>}{\partial t} \approx \left[\; U\Omega \;\right]_{in} - \left[\; U\Omega \;\right]_{out} - \left[\int \nu \frac{d<\omega>}{dy} dx\right]_s$$

$$\approx \left[\; U\Omega \;\right]_{in} - \left[\; U\Omega \;\right]_{out}$$

— for separated flow except at L.E.

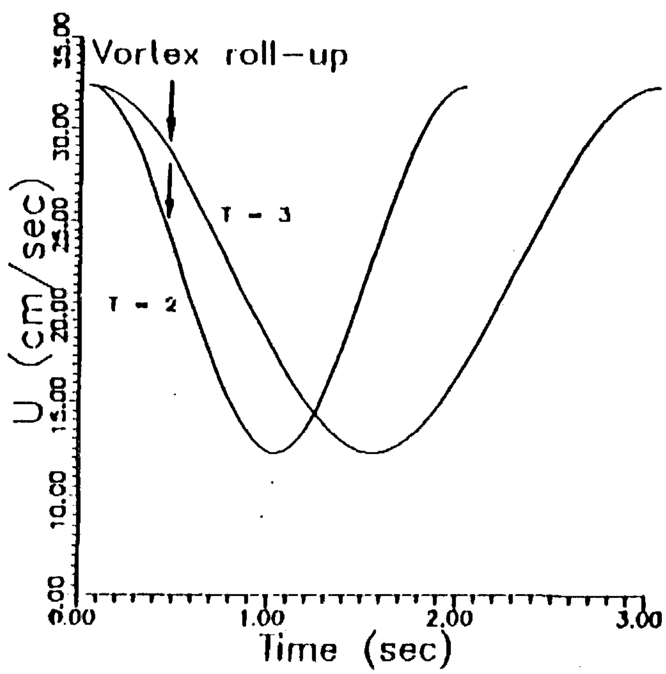


Two Time scales

- $[t_r]_{T=3} \quad \sim \quad [t_r]_{T=2}$
- $[U(t)]_{T=3} \quad > \quad [U(t)]_{T=2}$

  $[t_c]_{T=3} \quad < \quad [t_c]_{T=2}$

  $[\frac{t_c}{T}]_{T=3} \quad << \quad [\frac{t_c}{T}]_{T=2}$



$$C_L = \frac{Lift}{\frac{1}{2}\rho U^2}$$

$U \quad \downarrow$

$C_L \quad \uparrow$

CONCLUSIONS

- Unsteady Separation
  - $\frac{\partial u}{\partial y} = 0 \quad y = \infty$

    Local shear layer $\longrightarrow$ separation vortex

    $\frac{\partial u}{\partial y} = 0$ Near wall $\longleftarrow$ MRS criterion
  - Separation pattern $\longrightarrow$ 3-D
- Vorticity Balance of 2-D Wing
  - Attached flow

    vorticity diffusion

    single time scale
  - Separated flow

    vorticity convection

    multiple time scales
- Unsteady C_L of Post-Stall 2-D Wing
  - $K_{\text{optimum}} \approx 1$
  - $C_L > 10$
- Unsteady C_L of 3-D Wing
  - Attached L.E. Vortices

    single time scale
  - Convected L. E. vortices

    separated 2-D wing