On the three-dimensional evolution of an initially two-dimensional vortex dipole in shallow water

Julie ALBAGNAC

Supervisors:
Pierre BRANCHER,
Olivier EIFF

Collaborators:
Laurent LACAZE,
Frédéric Y. MOULIN.

Institut de Mécanique des Fluides de Toulouse
Waves, Turbulence and Environment Group
Motivation

- Vortex dipole
- Shallow water configuration:
  - depth (H) < horizontal length scale (L)
- Rip currents, estuaries...
- Effects:
  - resuspension
  - transport and mixing
  - (pollutants, nutriments, temperature...)

Rip currents, Rosarita Beach, Baja California, Mexico, October 1956
[Photography : D.L. Inman.]

Outflow of an estuary
Previous studies

- Numerous studies of vortex dipoles in deep continuously stratified flows.
  - Horizontal layering of elongated vortex dipoles (Billant & Chomaz 2000,)
- Turbulence collapse in a shallow water layer (Sous et al. 2004).
  - Dissipation of turbulent structures
  - Generation of a quasi-two-dimensional vortex dipole
  - Observation of a spanwise vortex at the front of the vortex dipole

3D turbulence → Shallow water → Q2D dipole → ? → Spanwise vortex

Origin and dynamics of this secondary structure?
Experimental set-up

- Creation of controlled, laminar and reproducible two-dimensional dipoles

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth $h$ (cm)</td>
<td>0.5-4.5</td>
</tr>
<tr>
<td>Flaps closure time $T_c$ (s)</td>
<td>5-25</td>
</tr>
<tr>
<td>Dipole diameter $D_0$ (cm)</td>
<td>10</td>
</tr>
<tr>
<td>Kinematic viscosity $\nu$ (cm$^2$/s)</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Reynolds number $Re$</td>
<td>1-280</td>
</tr>
<tr>
<td>Confinement number $C$</td>
<td>0.05-0.75</td>
</tr>
</tbody>
</table>

- $Re = \frac{T_a D_0}{h^2/\nu U_{adv}} = \frac{h^2}{\nu T_c}$

- $C = h/D_0$
PIV Measurements

- **Measurement equipment**
  - Nd-YAG 30mJ laser BIG SKY *ultra twin*.
  - 1280 px × 1024 px 12-bit CCD camera PCO *sensicam*.

- **Processing**
  - Spatial correlation technique with peak-locking reduction algorithms (Fincham and Spedding (1997) and Fincham and Delerce (2000)).
  - Mesh resolution:
    - In horizontal plane: 1.36 mm
    - In vertical plane: 1 mm
Existence of a spanwise vortex

- **Horizontal structure**
  - Vertical vorticity field $\omega_z$ and streamlines in the moving reference frame

$t = 2s$

$t = 16s$

$t = 0s$: end of the flap closure

$(U_{adv}=1.25 \text{ cm/s}, \text{Re}=174, C=0.6)$
Existence of a spanwise vortex

- **Vertical structure**
  - Quasi-parallel flow
  - Attached spanwise vortex
  - Detached spanwise vortex
  - Vorticity tongue
Existence of a spanwise vortex

- **Vertical structure**

  - **X**: Quasi-parallel flow
  - **+**: Attached spanwise vortex
  - **O**: Detached spanwise vortex
  - **☐**: Vorticity tongue

---

**Case 1**: \((U_{adv}=1.25 \text{ cm/s}, \text{Re}=56, C=0.3)\)

**Case 2**: \((U_{adv}=1.25 \text{ cm/s}, \text{Re}=174, C=0.6)\)

**Case 3**: \((U_{adv}=0.75 \text{ cm/s}, \text{Re}=107, C=0.6)\)
Evolution of the detached spanwise vortex

Spanwise vorticity field in the plane $y=0$

$t = 3.5s$

$t = 15s$

$t = 18s$

$t = 21s$

$t = 23.5s$

$t = 26.5s$

$t = 35s$

$t = 61s$

(U_{adv}=1.25 \text{ cm/s}, Re=174, C=0.6)
# Generation of the detached spanwise vortex

- Advection of the vortex pair on a solid surface $\rightarrow$ generation of a boundary layer
  - Spanwise component of vorticity $\omega_y$

- Vorticity equation in the vertical symmetry plane for simplicity :
  \[
  \frac{\partial \omega_y}{\partial t} = -u \frac{\partial \omega_y}{\partial x} - v \frac{\partial \omega_y}{\partial y} - w \frac{\partial \omega_y}{\partial z} + \omega_y \frac{\partial v}{\partial y} + \nu \nabla^2 \omega_y
  \]
  
  - If $\frac{\partial v}{\partial y} > 0$, the vorticity is amplified and concentrated

- Stretching induced by the dipole

- Iso contours of stretching $\frac{\partial v}{\partial y}$ (colors) and iso contours of spanwise vorticity (solid lines) in the vertical symmetry plane
Evolution of the detached spanwise vortex

Case 1: \( (U_{adv}=1.25 \text{ cm/s}, \ Re=56, \ C=0.3) \)

Case 2: \( (U_{adv}=1.25 \text{ cm/s}, \ Re=174, \ C=0.6) \)

Case 3: \( (U_{adv}=0.75 \text{ cm/s}, \ Re=107, \ C=0.6) \)

VD: Vortex Dipole
SV: Spanwise Vortex
Spatio-temporal diagram of the bed shear

\[ \frac{\partial u}{\partial z} \] in the plane \( y=0 \) for the case 2 (\( U_{adv}=1.25 \text{ cm/s}, Re=174, C=0.6 \))

△ Dipole position

△ Spanwise vortex position

\( t < 15\text{s} : \)

\[ \frac{\partial u}{\partial z} > 0 \]

\( t > 15\text{s} : \)

\[ \frac{\partial u}{\partial z} > 0, \frac{\partial u}{\partial z} < 0 \]
A recent scanning PIV technique developed by IMFT, USC and MétéoFrance.

- A high frequency pulsed laser (2x20 mJ at 1000 Hz)
- A high frequency camera synchronized with the laser (CMOS camera 5600Hz at 1024x1024 pix)
- A motor to move the laser sheet very quickly (25xg, 10m/s)

About 200 horizontal planes to describe a 30mm deep volume
Visualization of a 3D scanning vortex dipole
Conclusion and perspectives

- 4 different regimes for dipole evolution:
  - Quasi parallel flow: $Re < Re_c$
  - Attached spanwise vortex: $Re_c$
  - Detached spanwise vortex: $Re > Re_c$, $C < C_c$
  - Vorticity tongue: $C > C_c$

- Detached spanwise vortex evolution:
  - Development of the boundary layer below the dipole
  - Growth of a spanwise vorticity patch at the front of the dipole which rises to the free surface
  - Translation of the detached vortex

- Creation of bed shear of opposite direction due to the detached spanwise vortex

- Characterization of the 3D structure and its evolution by 3D-3C scanning PIV measurements
Spatio-temporal diagram of the mean vertical velocity

Vertical velocity $w$ in the plane $y=0$ for the case 2 ($U_{adv}=1.25 \text{ cm/s}$, $Re=174$, $C=0.6$)

- $\blacktriangle$ Dipole position
- $\triangle$ Spanwise vortex position
Spatio-temporal diagram of the parietal shear

Legend:

- Dipole position
- Spanwise vortex position
3D-3C scanning PIV experimental set-up
Traitement des mesures PIV