Separation in three-dimensional steady flow

Part 3: TOPOLOGY OF SOME REMARKABLE THREE-DIMENSIONAL FLOWS
Separation on a blunt body

H. Werlé. © Onera
Separation on a blunt body
Two-vortex structure. Skin friction line pattern

Seen from above

Separation line of detachment
Attachment line

Wind tunnel S2Ch. © Onera
Separation on a blunt body
Two-vortex structure. Skin friction line pattern

Wind tunnel S2Ch. © Onera
Separation on a blunt body
Two-vortex structure. Skin friction line pattern

Close up on the body rear part

Attachment line
Detachment lines
Focus

Wind tunnel S2Ch. © Onera
Separation on a blunted body
Two-vortex structure. Skin friction line pattern

Details at the nose
Pressure side developed
Separation on a blunt body
Two-vortex structure. Skin friction line pattern

Details at the nose

Pressure side developed
Separation on a blunted body. Skin friction line pattern with two foci. Formation of tornado like vortices
Separation on a blunt body. Structure with two tornado like vortices. First detachment surface.
Separation on a blunt body. Structure with two tornado like vortices. Second detachment surface.
Separation on a blunt body. Structure with two tornado like vortices. Third detachment surface.
Separation on a blunt body
Assembling of the detachment surfaces
Flow past a delta wing at incidence
Separation on a delta wing at incidence
One-vortex system

Starting of the primary detachment surface at the wing apex

Skin friction line pattern on the suction side
Separation on a delta wing at incidence
One-vortex system

Windward side

Skin friction line pattern

Leeside

Starting of the primary detachment surface
Field projected in a plane normal to the wing surface

What is seen as two vortices are in fact the traces of the horseshoe vortex forming at the wing apex
Vortices over a delta wing with a sweep angle of 70°
Separation on a delta wing at incidence
One-vortex system. Other organisation

Skin friction line pattern

Field projected in a plane normal to the wing surface
Vortices over the Concorde wing

H. Werlé. © Onera
Vortices over a Concorde type wing. Cut by a downstream vertical plane.
Separation on a delta wing at incidence
Two-vortex system

Skin friction line pattern on the wing leeside

Flow in the vicinity of the wing apex
Separation on a delta wing at incidence
Two-vortex system

With cusp points

Variant with distinct points
Separation on a delta wing at incidence
Two-vortex system

Water tunnel visualization

Field projected in a plane normal to the wing surface
Separation on a delta wing at incidence
Two-vortex system
Separation on a delta wing at incidence
Two-vortex system with limit circle

Field projected in a plane normal to the wing surface
Wake vortex of a classical wing
Wake vortex of an isolated classical wing. Skin friction line pattern

**Leading edge region**

**Pressure side**

**Suction side**
Due to the overpressure on the pressure side, the flow is pushed by the pressure difference and tends to stream on the suction side.
Vorticity (entropy) produced in the boundary layers is concentrated in the two tip vortices.
Formation of a wing tip vortex

Focus origin of the vortex

H. Werlé. © Onera
Wake vortex of a wing with control surfaces
Skin friction line pattern on the suction side
Wake vortex of a wing with control surfaces
Vortices emitted by tips of wing and control surfaces
Wake vortex of a wing with control surfaces
Field projected in a downstream plane
Separation on a delta wing at very low Reynolds number

Vortices emanate from foci distinct from the wing apex

H. Werlé. © Onera
Separation on a slender body
Separation on a space launcher ogive

Starting of tornado like vortices
Separation on a blunted slender body
Separation with two tornado like vortices. Skin friction line pattern.
Separation on a blunted slender body
Separation with two tornado like vortices. Detachment surfaces
Detachment on a missile ogive with flat faces
Separation with four tornado like vortices
Separation on a sharp slender body

Skin friction line pattern

Details near the apex

View from above
(body surface developed)

Side view
Separation on a sharp slender body

Two-vortex system

Field projected in a plane normal to the body axis
Separation on a sharp slender body
Separation on a sharp slender body

Three-vortex system

Field projected in a plane normal to the body axis
Separation on a sharp slender body in a Mach 2 flow
Laser sheet visualization
Separation on a sharp slender body

Existence of a limit circle

Field projected in a plane normal to the body axis
Side force

Asymmetric configuration and side force

Interaction between the two vortices may lead to a loss of symmetry for the system. This occurs in a well defined range of angle of incidence. Asymmetry entails existence of a side force.

Field projected in a plane normal to the body axis.
Separation on a sharp slender body
Symmetrical and asymmetrical configurations
Separation induced by a blunt obstacle
Separation induced by a blunt obstacle
Skin friction line pattern

One-vortex system
Separation induced by a blunt obstacle
Flow in the symmetry plane

One-vortex system
Separation induced by a blunt obstacle
Detachment surface

One-vortex system
Separation induced by a blunt obstacle
Skin friction line pattern

Three-vortex system
Separation induced by a blunt obstacle
Detachment surface

Three-vortex system
Separation induced by a blunt obstacle
Flow in the symmetry plane

Four-vortex system
Separation induced by a blunt obstacle
Field in a downstream vertical plane

Two tornado like vortex system

Impact regions: pressure and heat transfer peaks
Separation induced by a blunt obstacle
Flow in the symmetry plane. Variant

Structure with one detachment
Separation induced by a blunt obstacle
Flow in the symmetry plane. Variant

Structure with two detachments
Separation induced by a blunt obstacle
Flow in the symmetry plane. Variants

Attachment at the obstacle foot

Detachment on the obstacle
Detachment induced by an obstacle in supersonic flow
Detachment induced by an obstacle in supersonic flow
Skin friction line pattern on the horizontal floor
Detachment induced by an obstacle in supersonic flow
Skin friction line pattern on the obstacle

Impact of the shear layer
Separation induced by a blunt obstacle
Flow in the vertical symmetry flow
Separation induced by a blunt obstacle
Detachment surfaces forming on the obstacle
Separation on a blunt obstacle
The various detachment surfaces
Separation induced by a protuberance

H. Werlé. © Onera
Separation induced by a protuberance in supersonic flow
Surface flow visualisation

- Shadow of the separation shock
- Primary separation line
- Attachment line
- Shadow of the front shock

Sedney & Kitchens
Separation induced by a protuberance

Skin friction line pattern on the flat plane
Separation induced by a protuberance
Skin friction line pattern on the protuberance
Separation induced by a protuberance
Rear tornado like vortices

The tornado like vortices are entrained by the main flow

Completely immersed protuberance
Configuration with a free surface

Separation induced by a protuberance
Rear tornado like vortices
Separation induced by a protuberance
The detachment surfaces
Separation induced by a protuberance
Field projected in a downstream vertical plane