Separation in three-dimensional steady flow

PART 4 : TWO-DIMENSIONAL SEPARATION REVISITED

WITH THE THREE-DIMENSIONAL CONCEPTS

OR A CASE APPARENTLY SIMPLE!

ONERA

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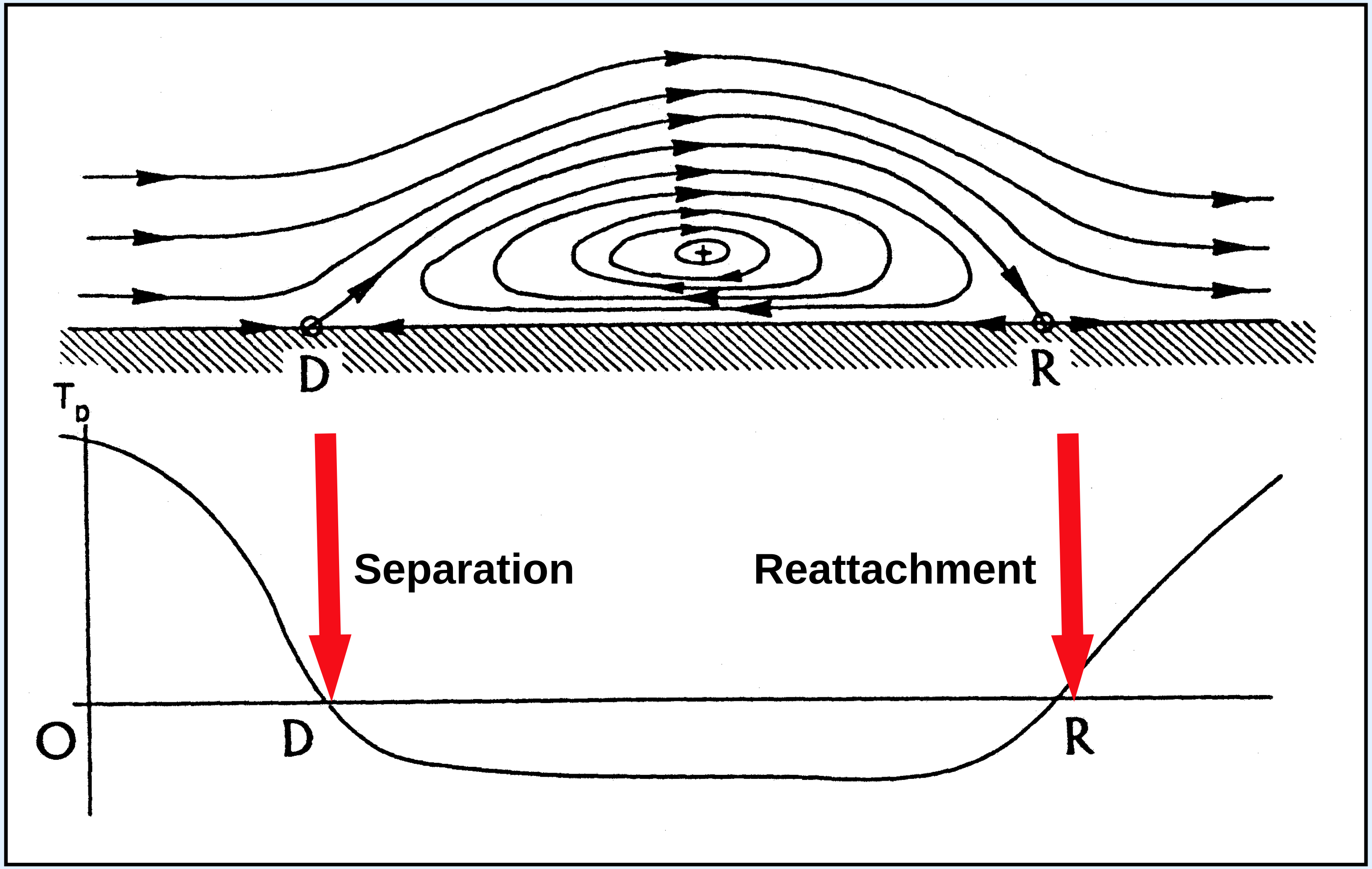
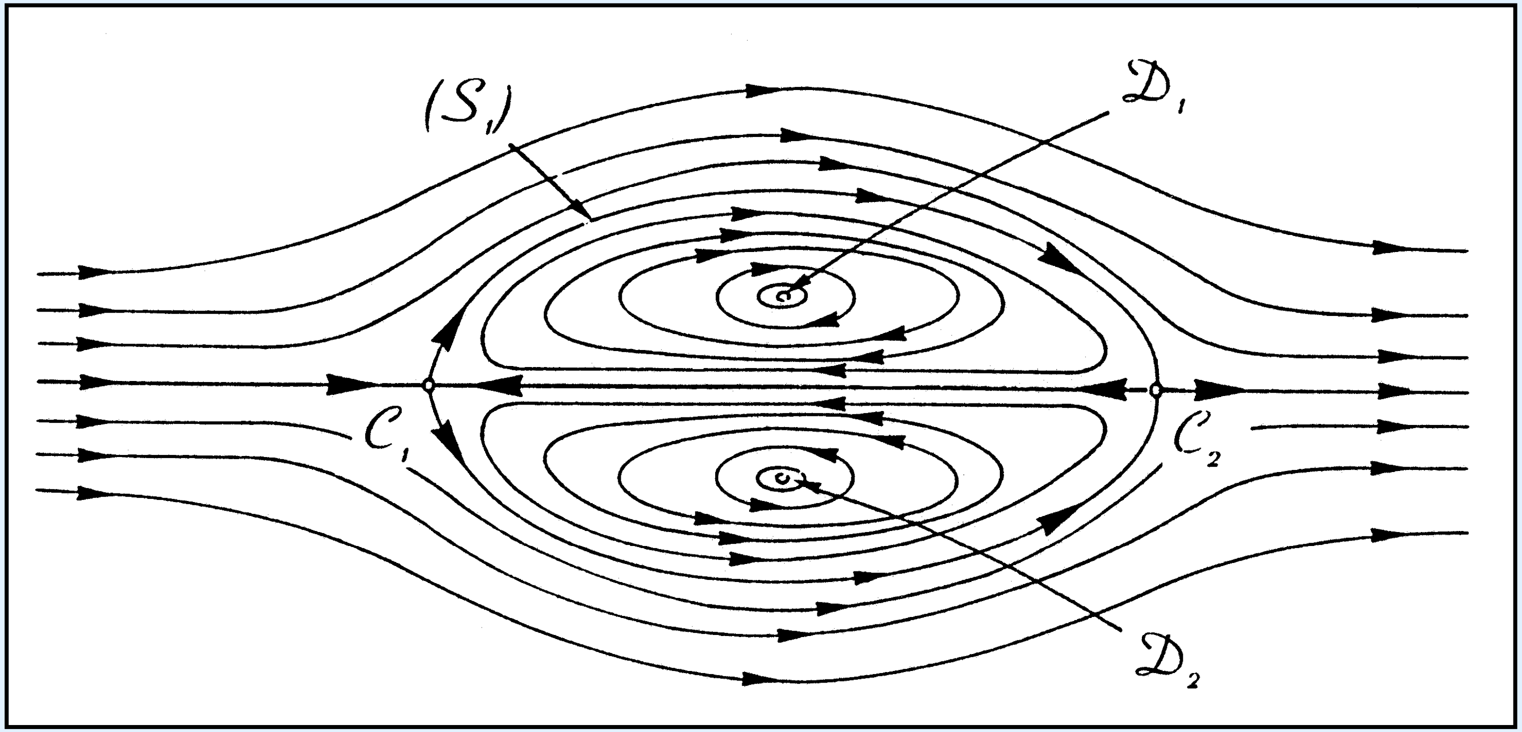
Separation in two-dimensional flow
Classical definition



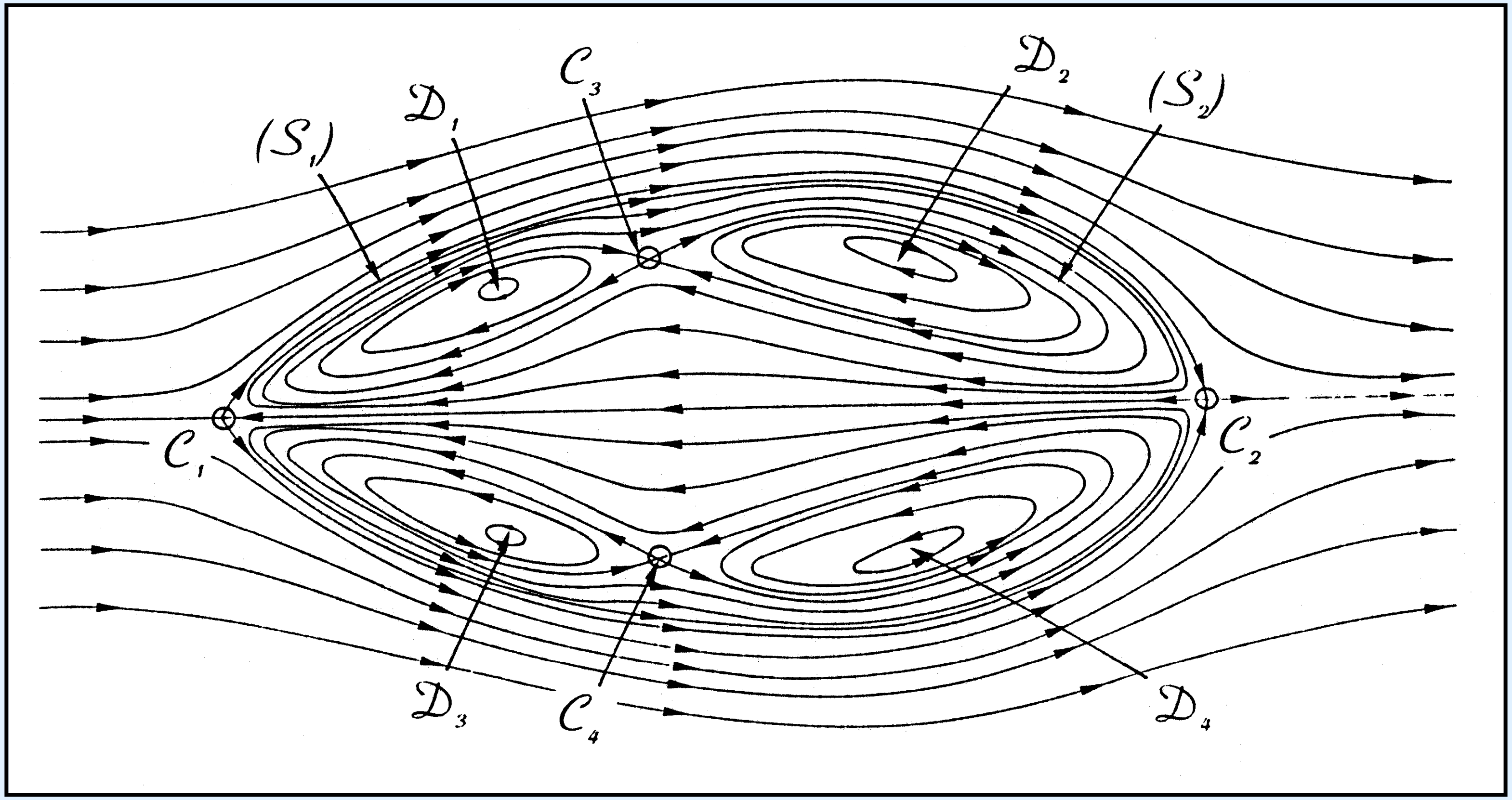
Skin friction distribution

Generalisation of the notion of two-dimensional separation



Bubble inside an axisymmetric wake:
the toroidal vortex is closed on itself

Generalisation of the notion of two-dimensional separation



Structure of a burst vortex. Meridian flow

Separation in two-dimensional flows

- There are many experimental evidences of the existence of three-dimensional perturbations in two-dimensional separated flows.

  Ginoux - 1960
  Roshko and Thomke - 1965
  Settles et al. - 1978
  others...

- Question: is the word "perturbation" appropriate as meaning a defect relatively to a real configuration?

- In reality, the so-called real configuration doest not exist, the perturbed case having only a true existence.

Separation in two-dimensional flows

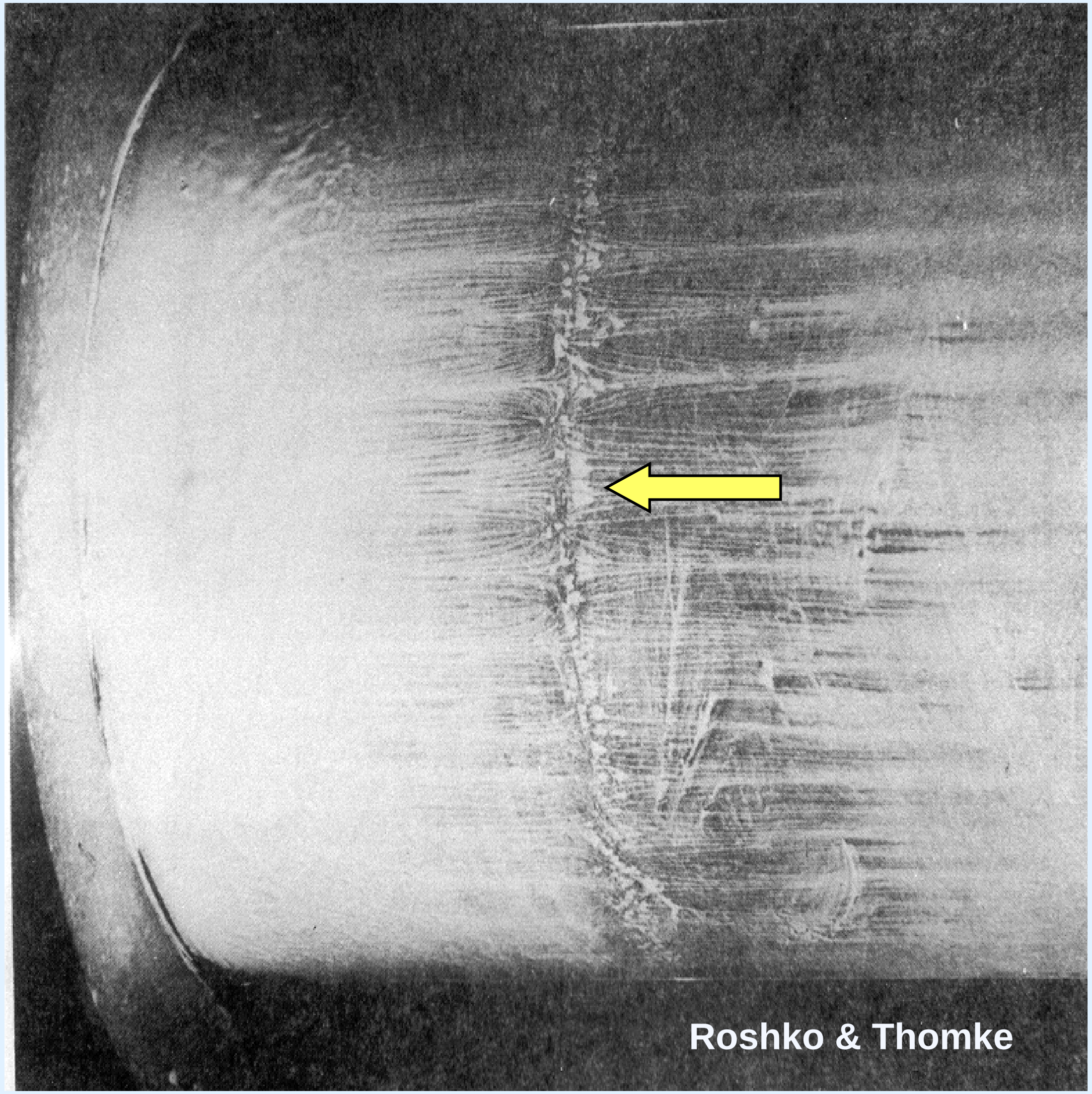
- In the framework of the critical point theory, in a two-dimensional flow a separation line– of detachment or attachment - bears an infinite string of saddle points.

- Such a circumstance is very unlikely in the real world where the three-dimensional character must manifest itself:

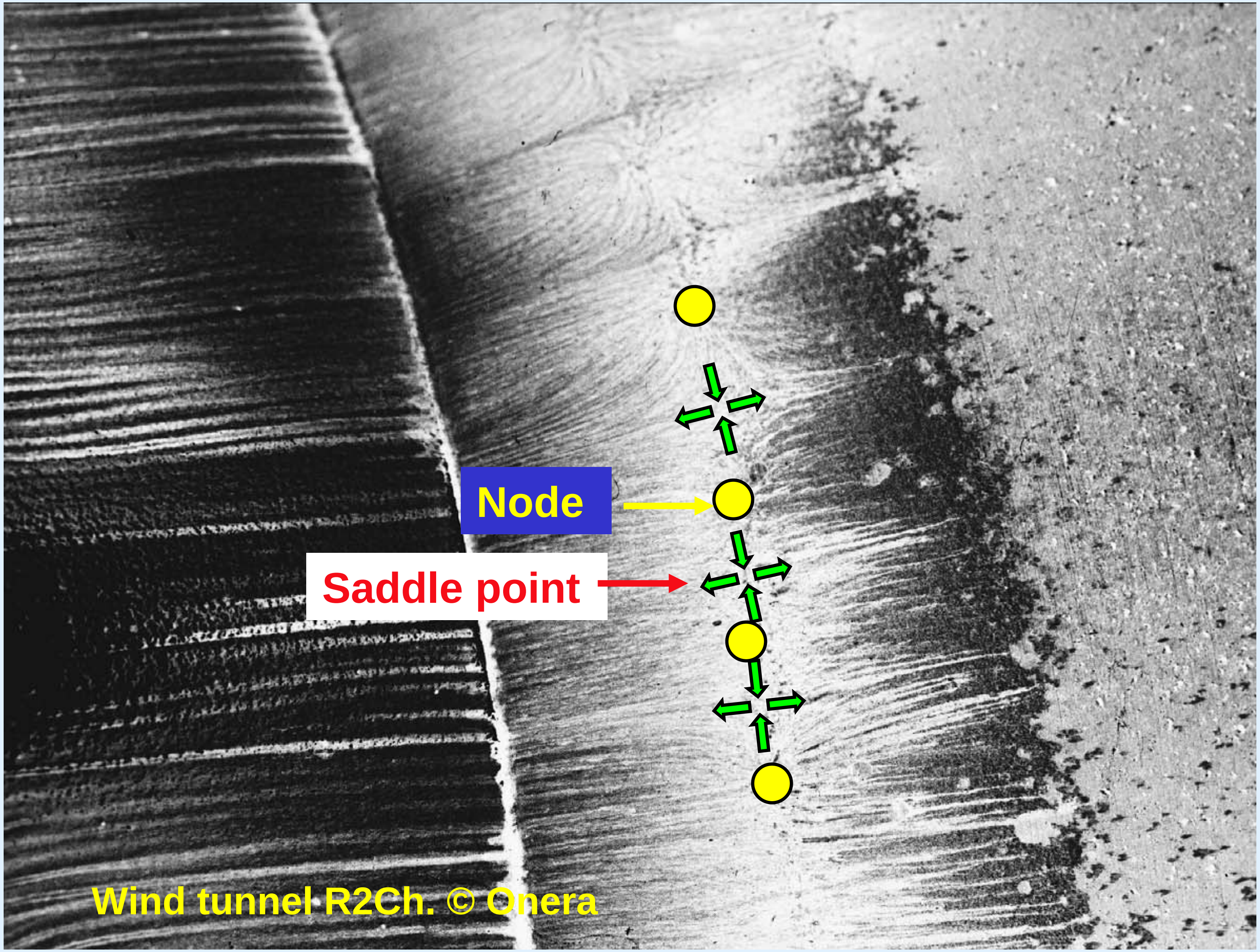
  - either a the microscopic scale by existence of sub-structures superimposed on an organisation globally two-dimensional,

  - or at the macroscopic scale by an overall organisation having lost any two-dimensional character.

Separation in two-dimensional flow
Reattachment behind an axisymmetric step



Separation in two-dimensional flow
Reattachment on an axisymmetric flare



The critical point theory and two-dimensional flow

Examination of the case $q = 0$

$$q = \left(\frac{\partial \tau_x}{\partial x} \frac{\partial \tau_z}{\partial z} - \frac{\partial \tau_z}{\partial x} \frac{\partial \tau_x}{\partial z} \right)$$

The eigenvalues are given by :

$$S^2 + pS = 0 \quad \text{ou} \quad S(S+p) = 0$$

Roots $\rightarrow S_1 = 0 , S_2 = -p$

Skin friction line equations :

$$x(t) = \frac{A_1\mu_2}{\lambda_1\mu_2 - \lambda_2\mu_1} - \frac{A_2\mu_1}{\lambda_1\mu_2 - \lambda_2\mu_1} \exp(pt)$$

$$z(t) = -\frac{A_1\lambda_2}{\lambda_1\mu_2 - \lambda_2\mu_1} + \frac{A_2\lambda_1}{\lambda_1\mu_2 - \lambda_2\mu_1} \exp(pt)$$

The critical point theory and two-dimensional flow

Let us write: $$B_1 = \frac{A_1}{\lambda_1\mu_2 - \lambda_2\mu_1}, \; B_2 = \frac{A_2}{\lambda_1\mu_2 - \lambda_2\mu_1}$$

$$x(t) = B_1\mu_2 - B_2\mu_1 \exp(pt)$$

$$z(t) = -B_1\lambda_2 + B_2\lambda_1 \exp(pt)$$

Skin friction lines ➡ straight lines of equation:

$$\lambda_1 x + \mu_1 z = B_1(\lambda_1\mu_1 - \lambda_2\mu_2)$$

with slope: ➡ $$\frac{dz}{dx} = -\frac{\lambda_1}{\mu_1}$$

The critical point theory and two-dimensional flow

$$\text{if } \lambda_1 > 0 \text{ and } \mu_1 > 0 \text{ and if } p > 0$$

When t varies from $+\infty$ to $-\infty$ the solution curve is run from infinity to the critical point of coordinates:

$$x(+\infty) = -\infty \quad \rightarrow \quad x(-\infty) = x^* = B_1\mu_2$$
$$z(+\infty) = +\infty \quad \rightarrow \quad z(-\infty) = z^* = -B_1\lambda_2$$

- Points x^* et z^* are on the straight line of equation:

$$\boxed{\lambda_2 x^* + \mu_2 z^* = 0}$$

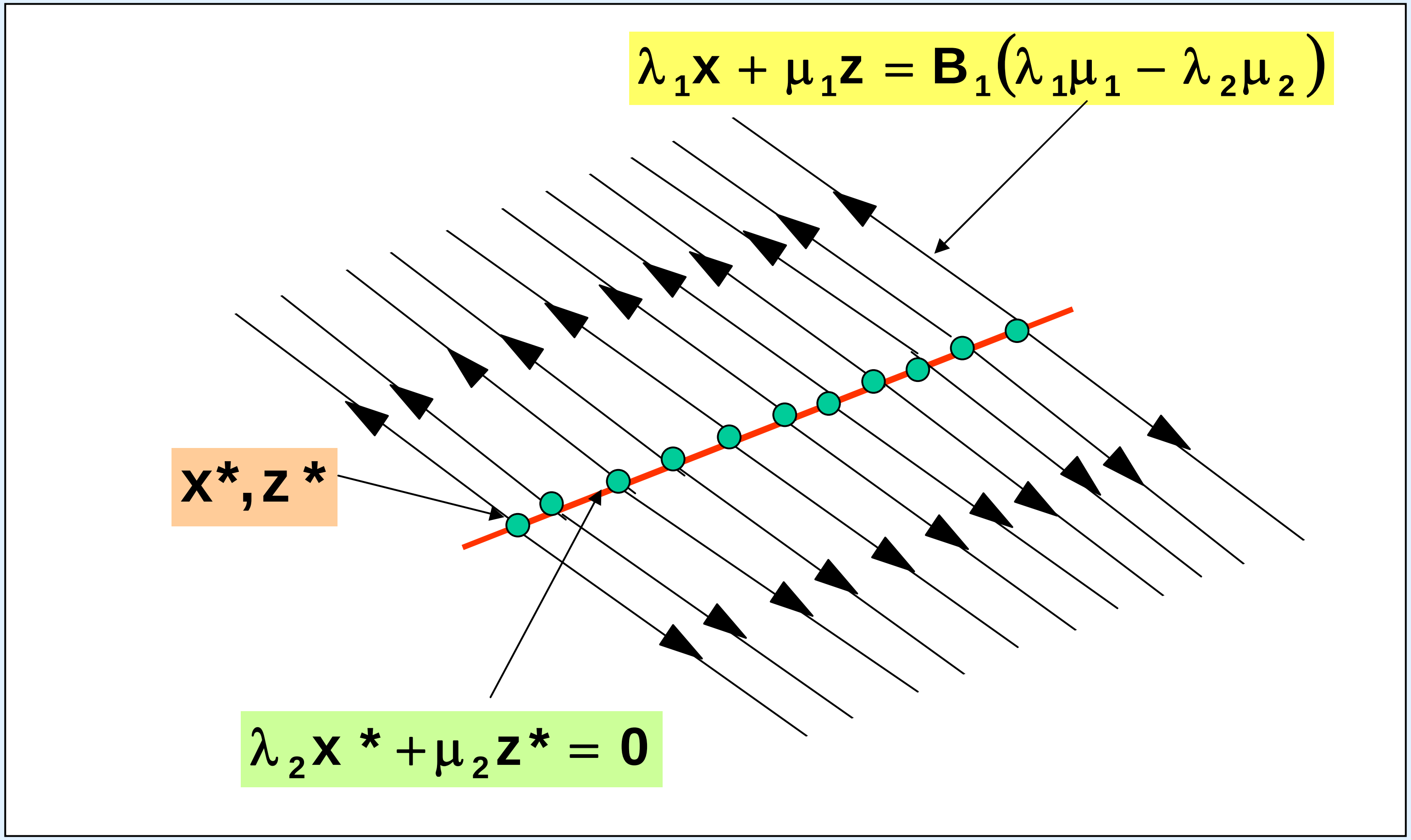
- This line bears an infinity of critical points obtained by varying B_1

- When t varies from $-\infty$ to $+\infty$ the skin friction lines are run according to a motion starting from the critical point

➡ attachment behaviour

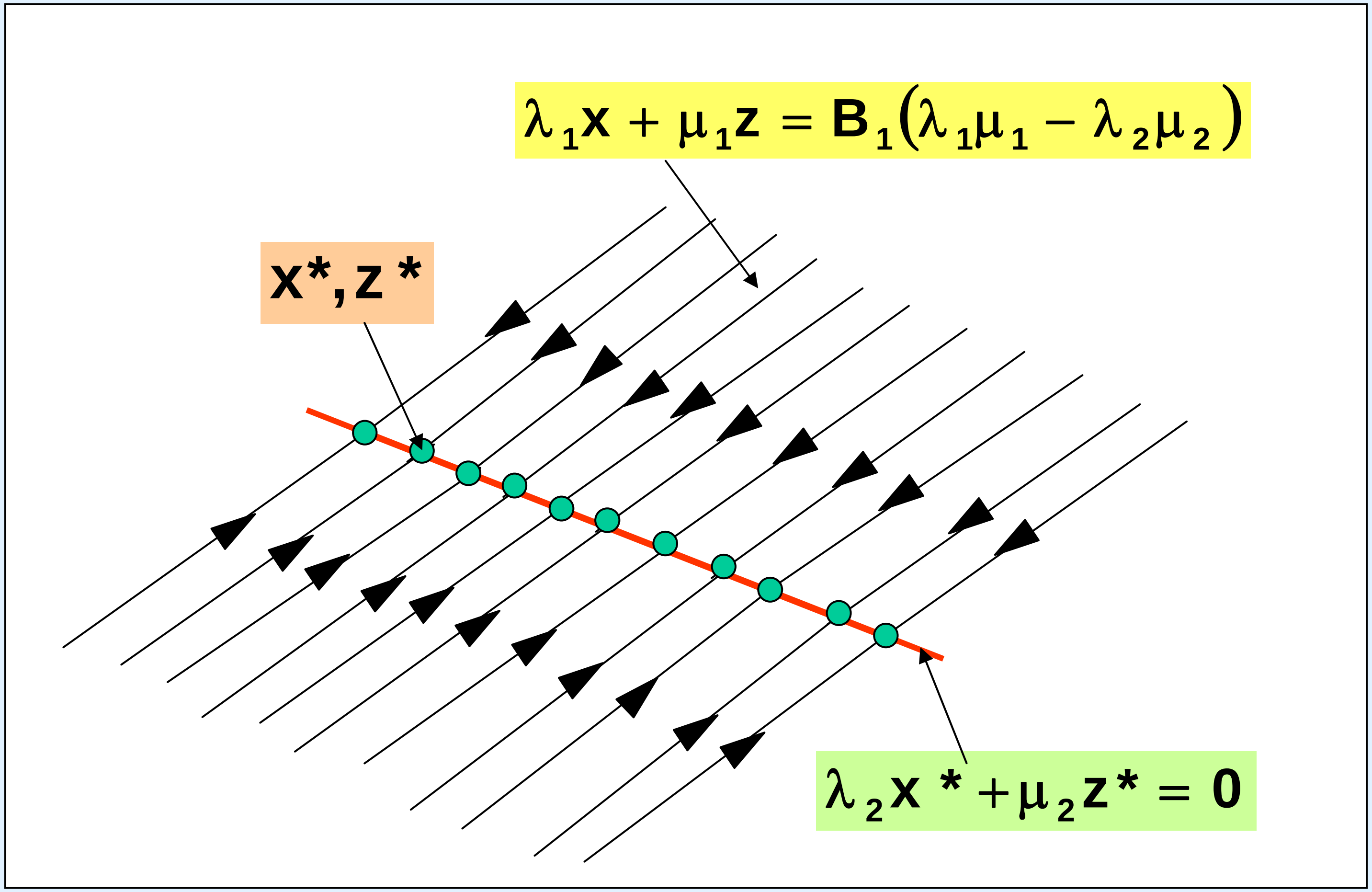
The critical point theory and two-dimensional flow

Case $p > 0$ **Motion away from the critical point (attachment)**

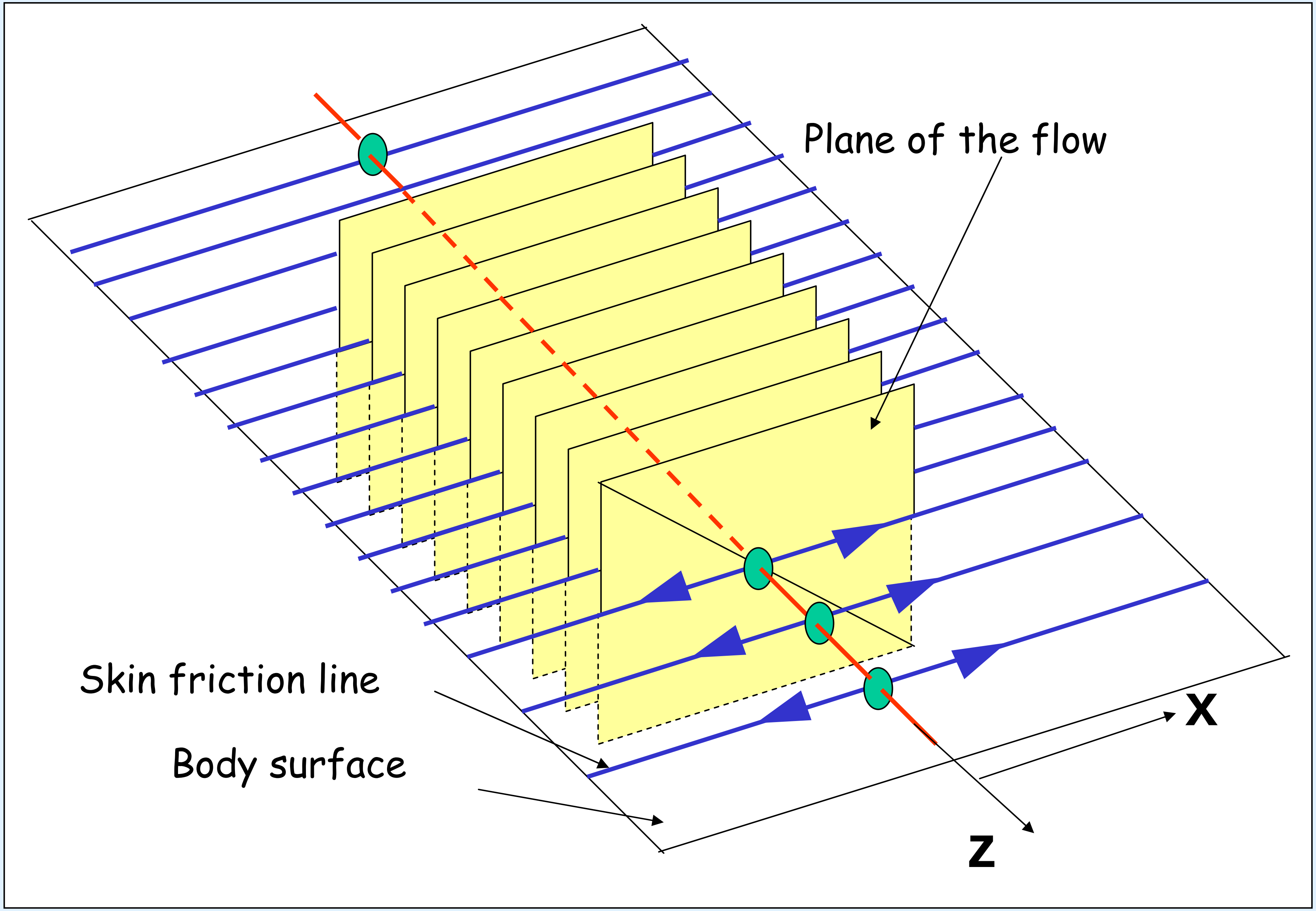


The critical point theory and two-dimensional flow

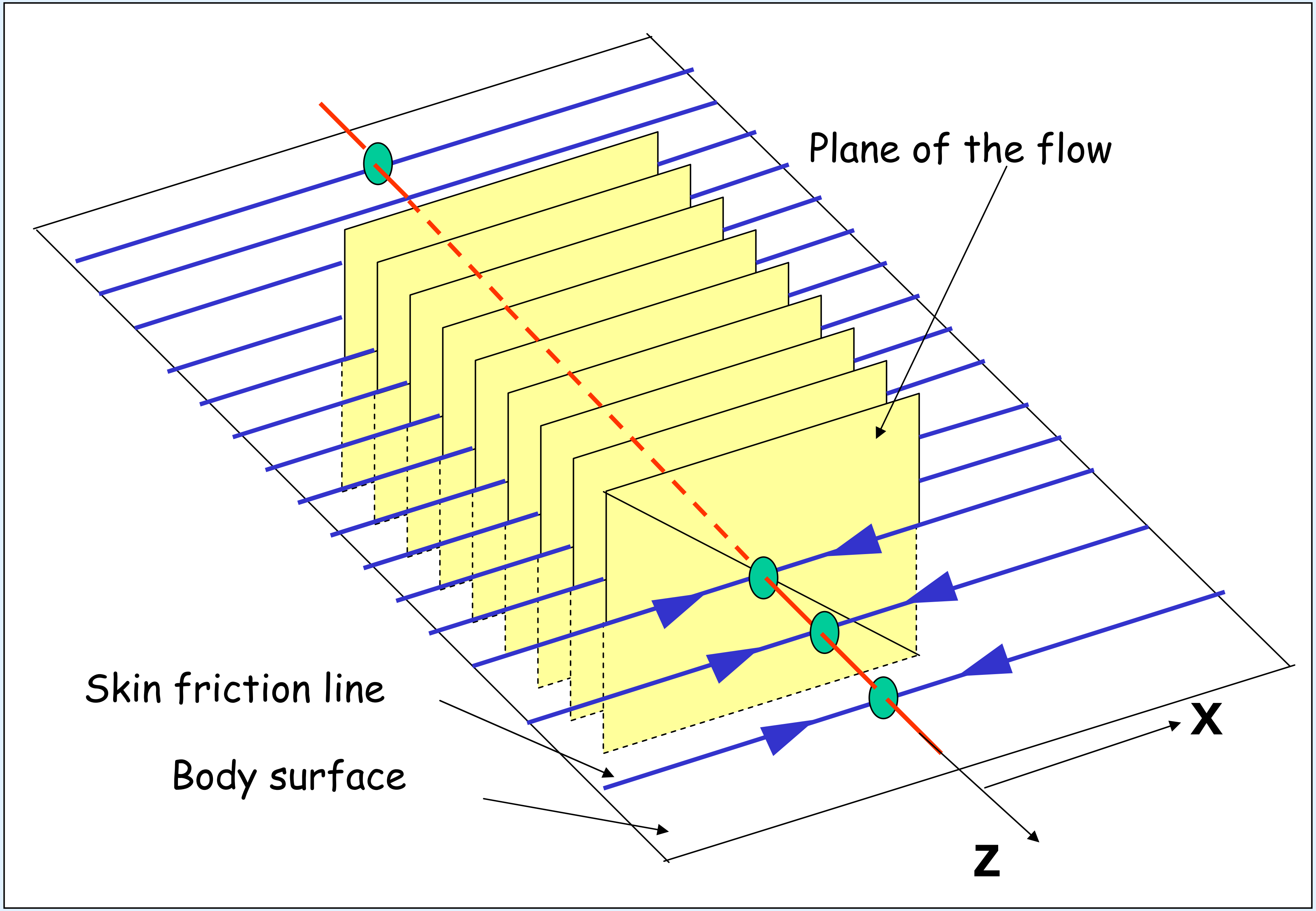
Case $p < 0$ Motion towards the critical point (detachment)



Topological structure of planar reattachment

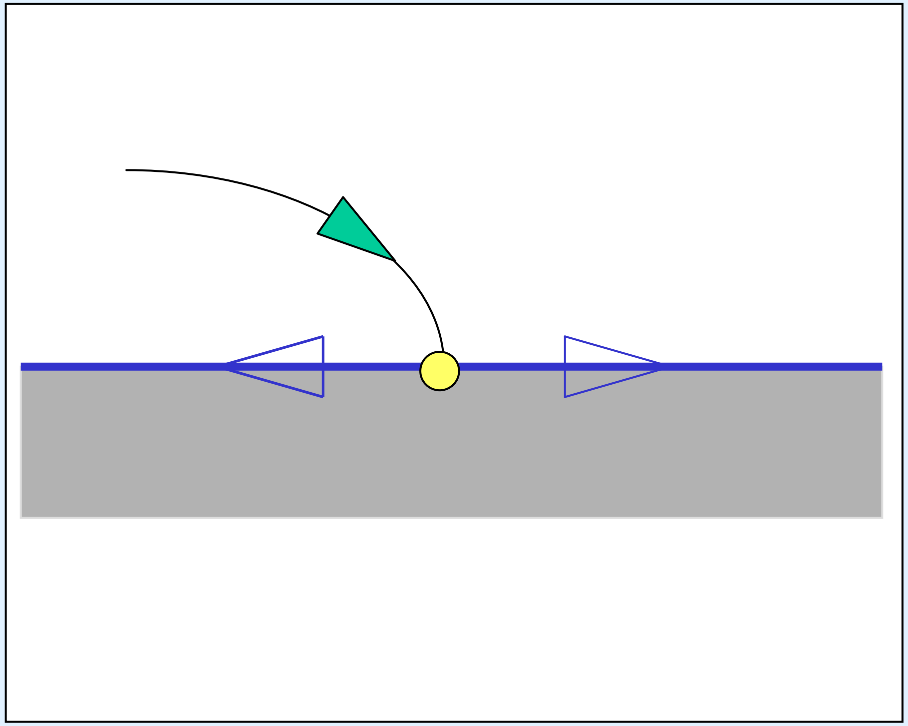


Topological structure of planar detachment (separation)

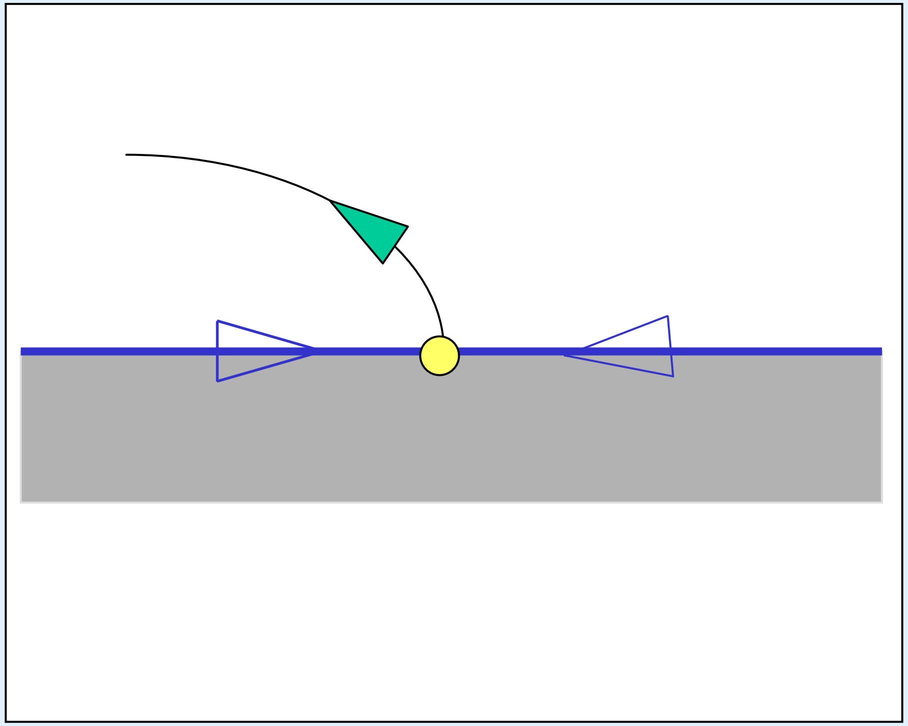


Topological structure of planar separation

Critical point in the plane of the flow

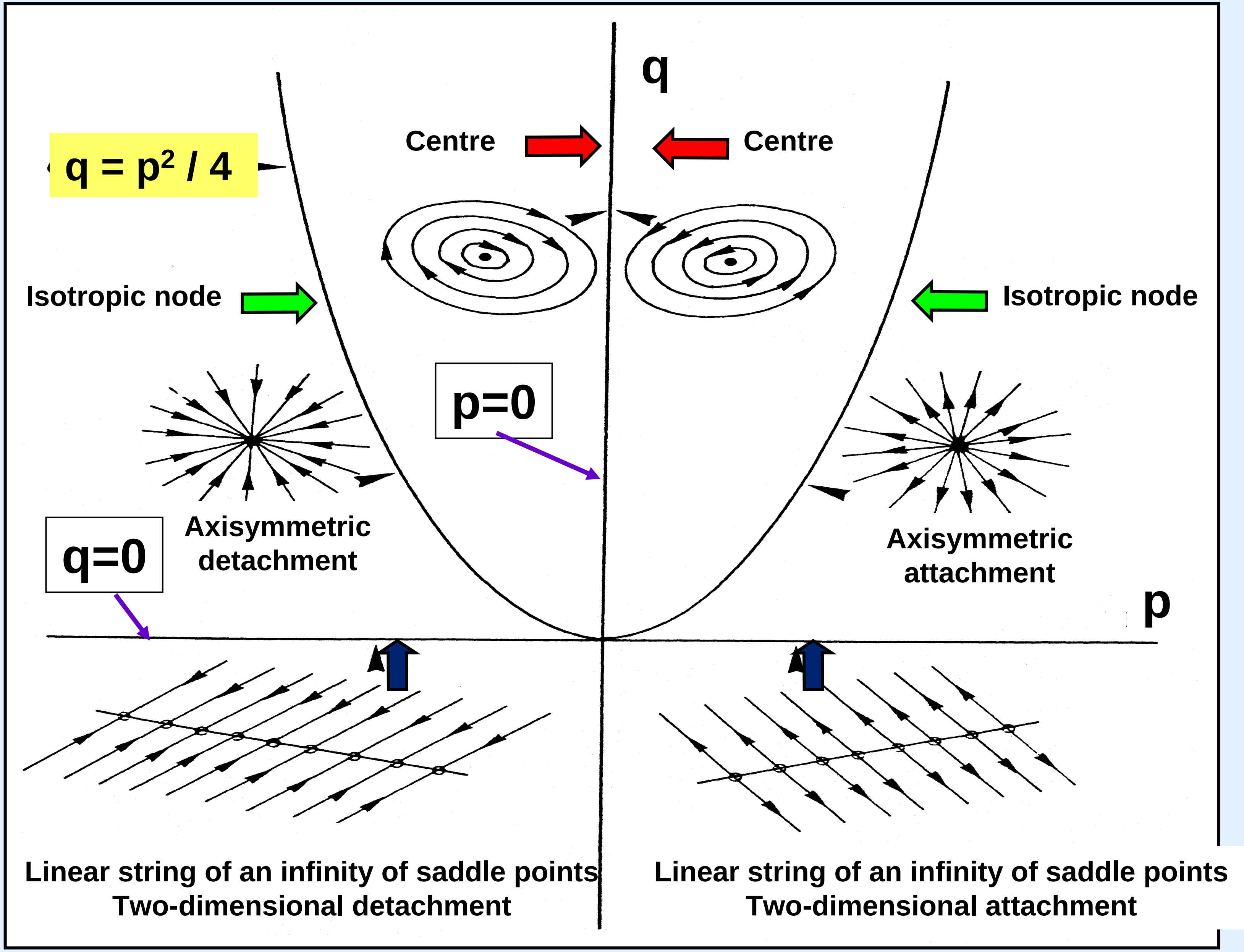


Attachment

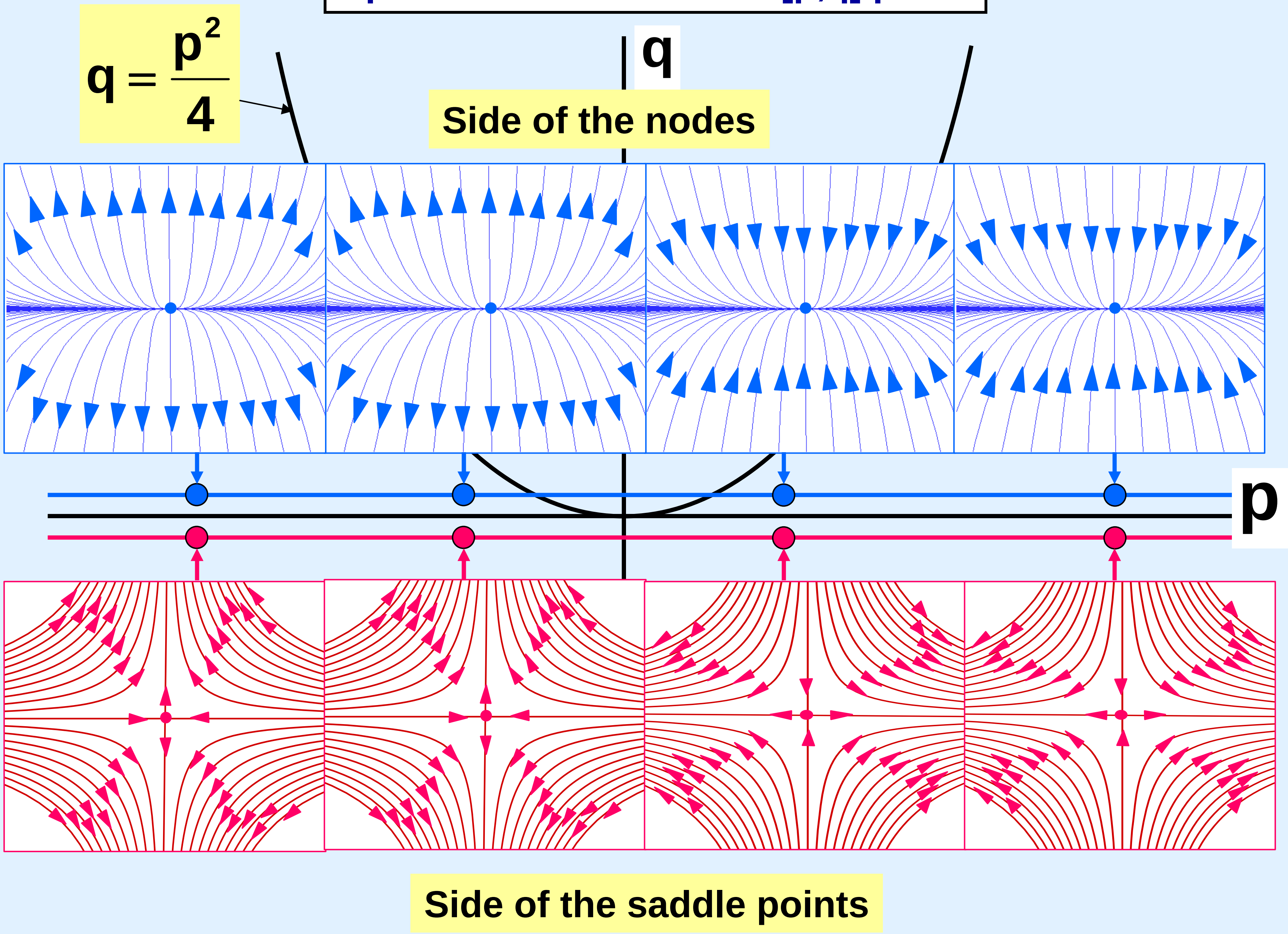


Detachment

Special situations in the [p,q] plane

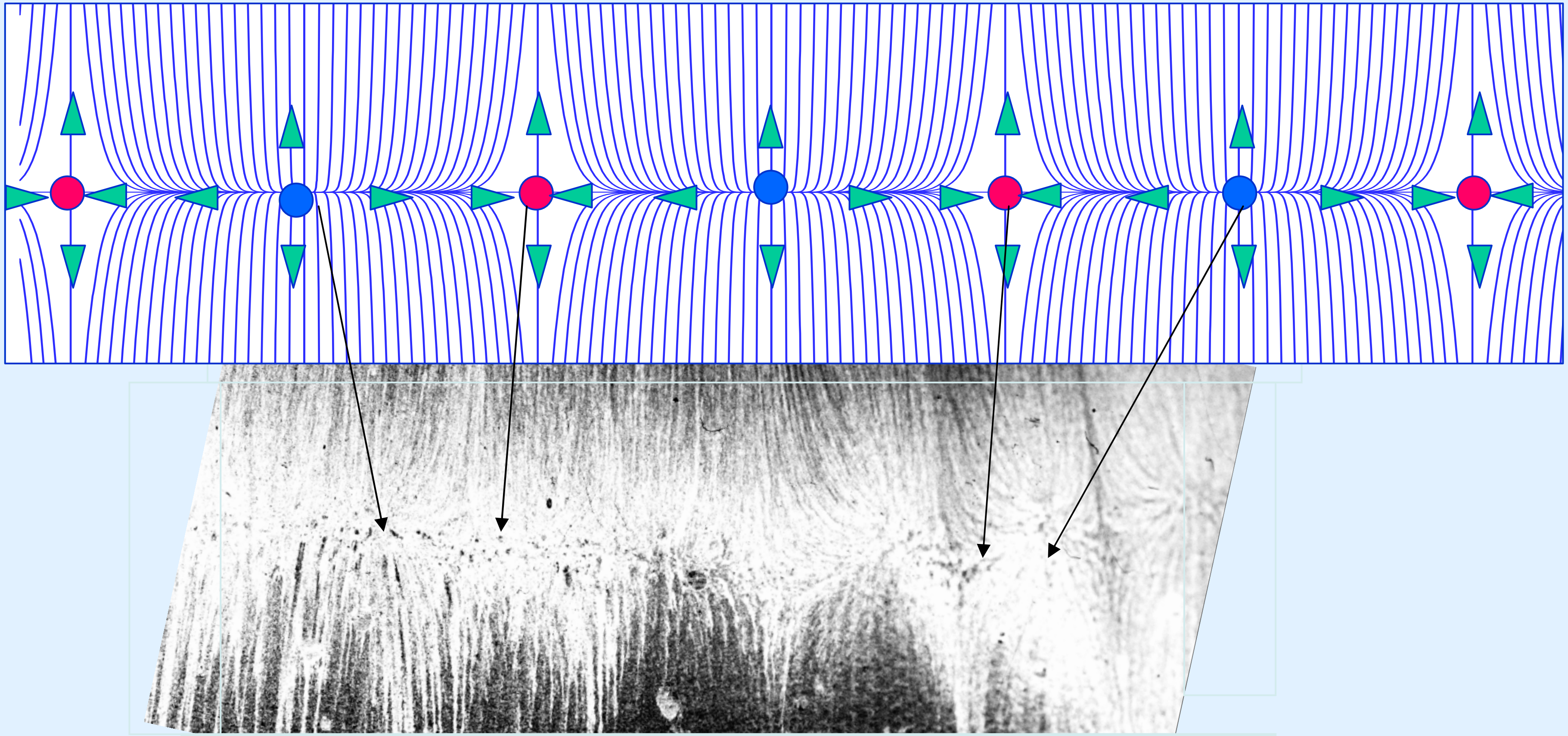


Special situations in the [p,q] plane



Special situations in the [p,q] plane

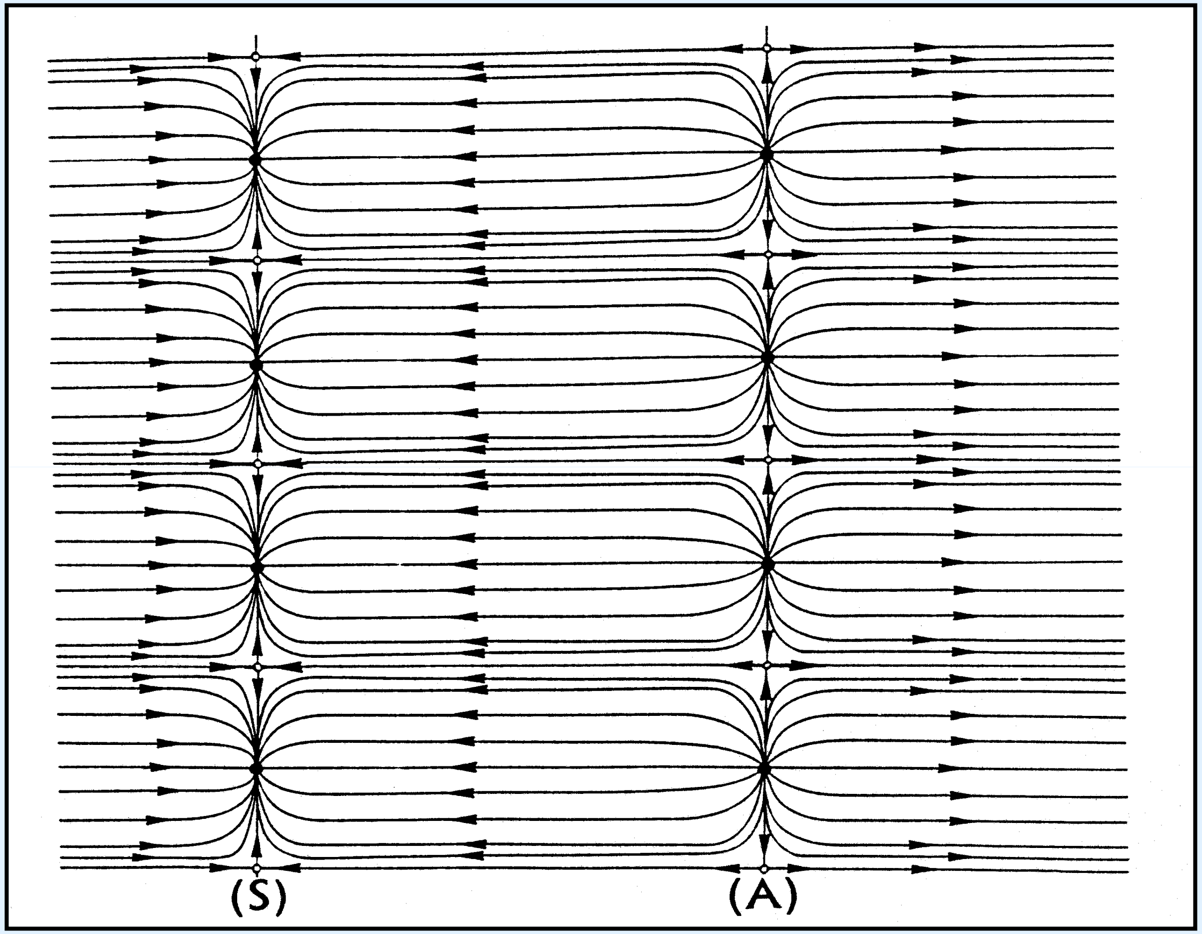
Tendency to axis $q = 0$ or when nodes and saddle points meet



Attachment in a axisymmetric flow

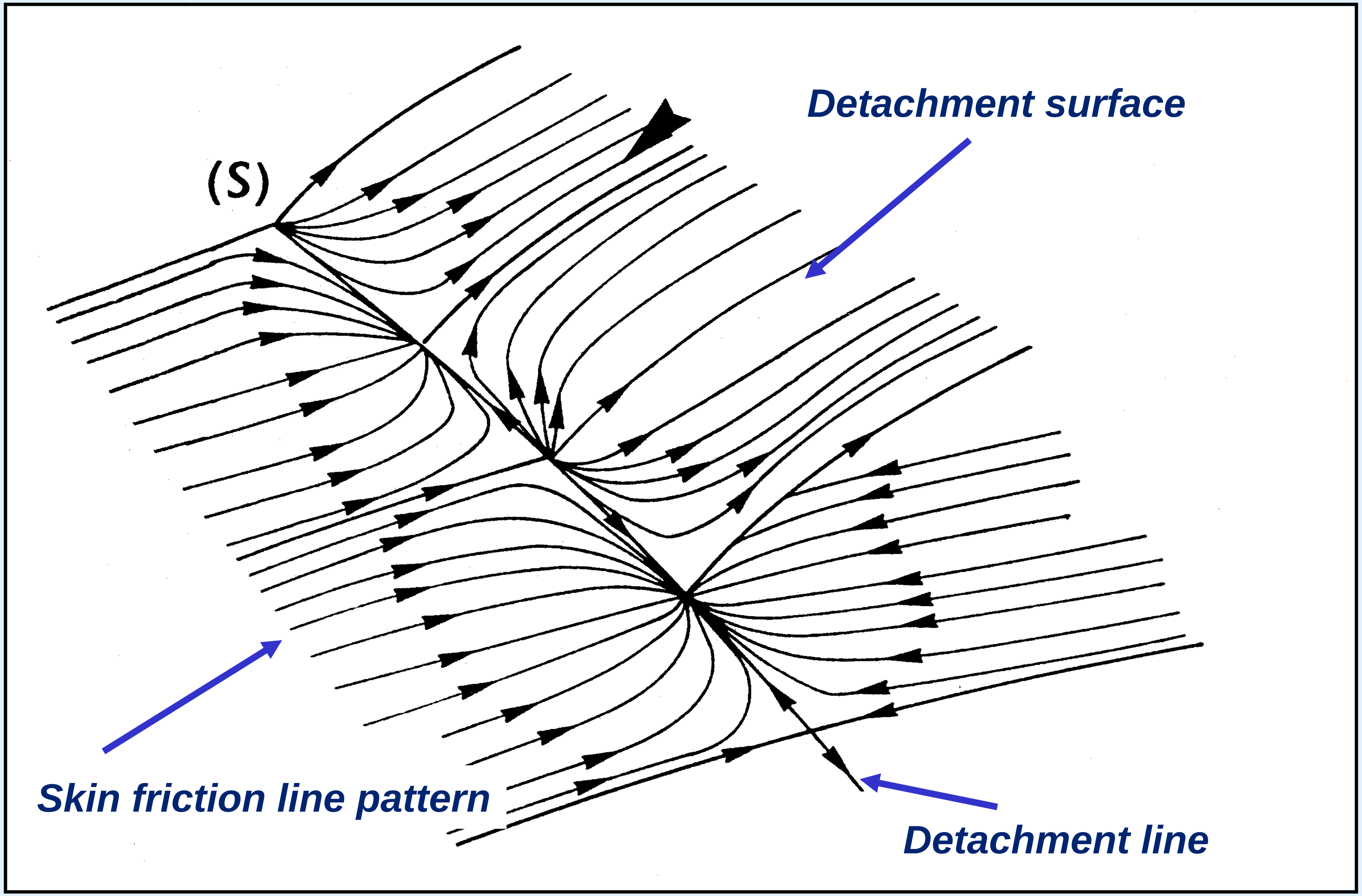
Separation in two-dimensional flow

Detachment **Reattachment**



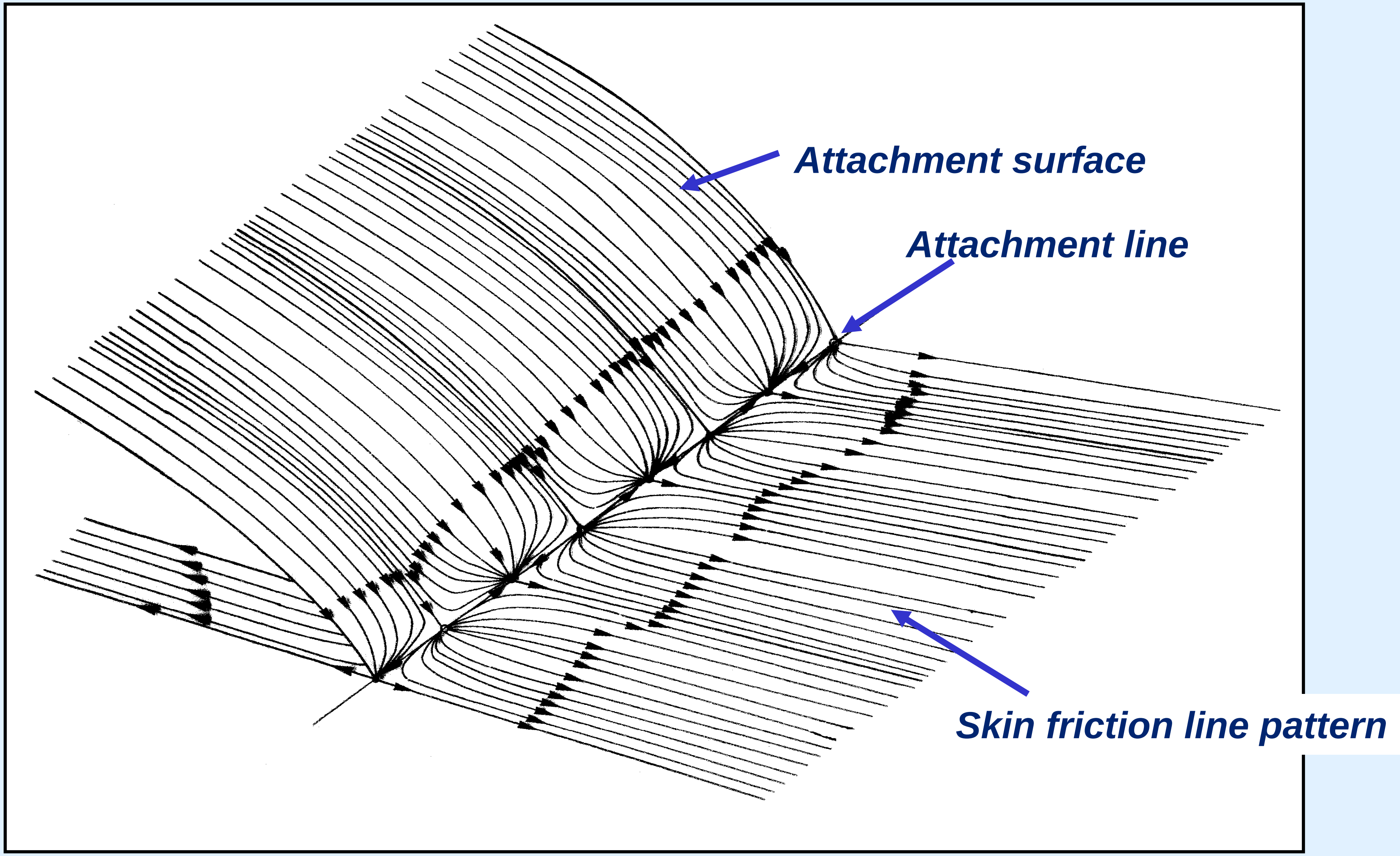
Infinite string of node-saddle point combinations in correspondence

Separation in two-dimensional flow



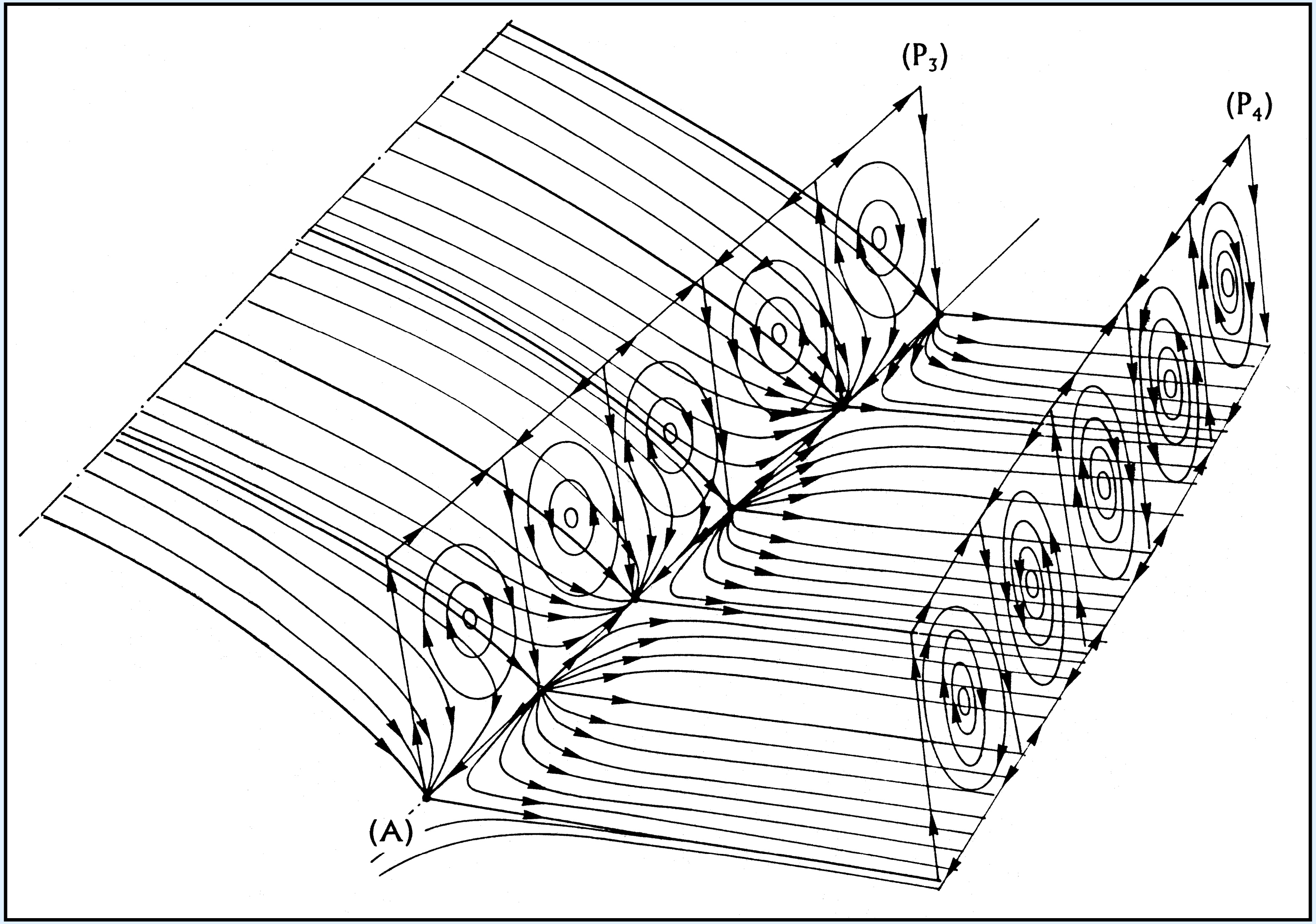
Detachment region

Separation in two-dimensional flow



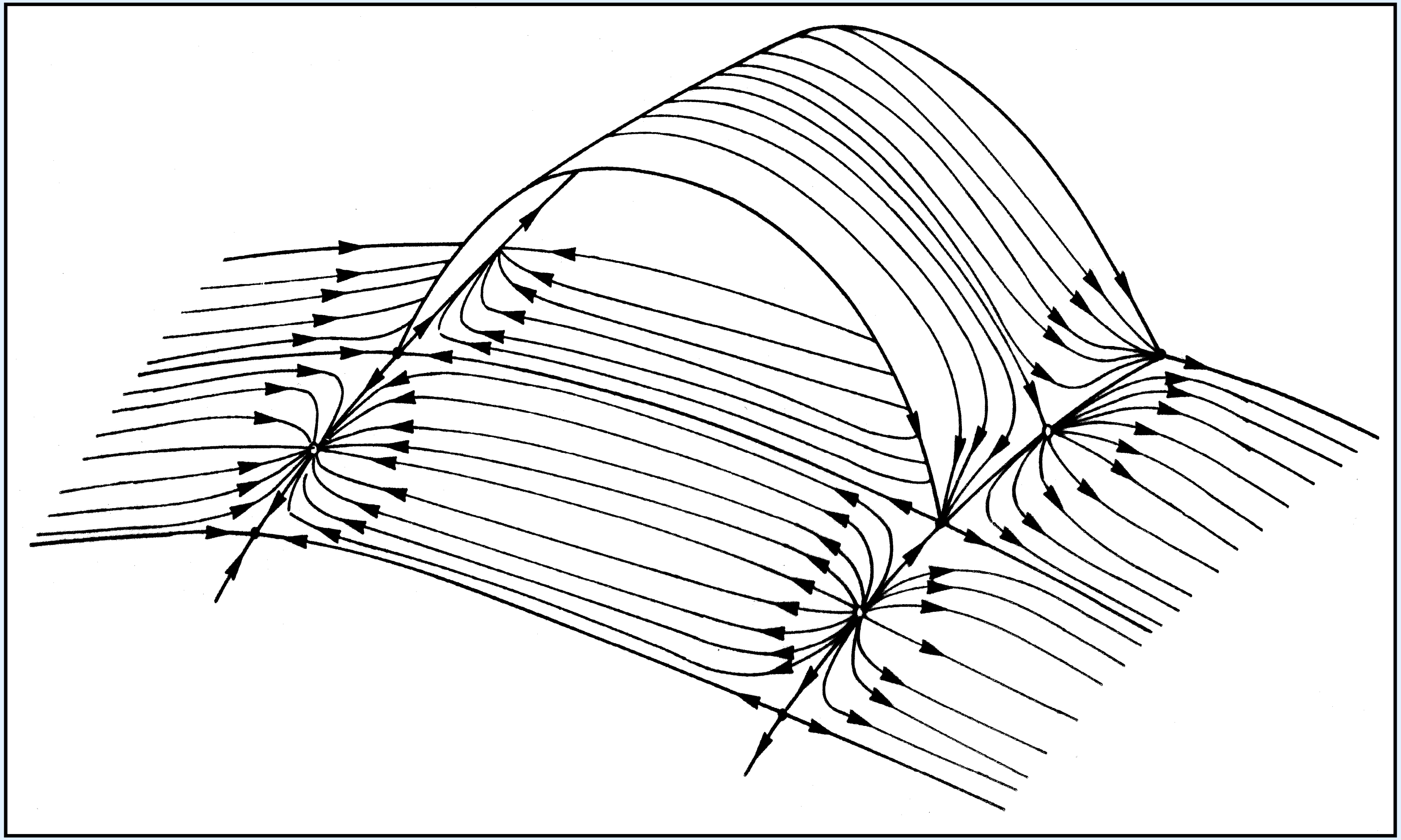
Attachment region

Separation in two-dimensional flow



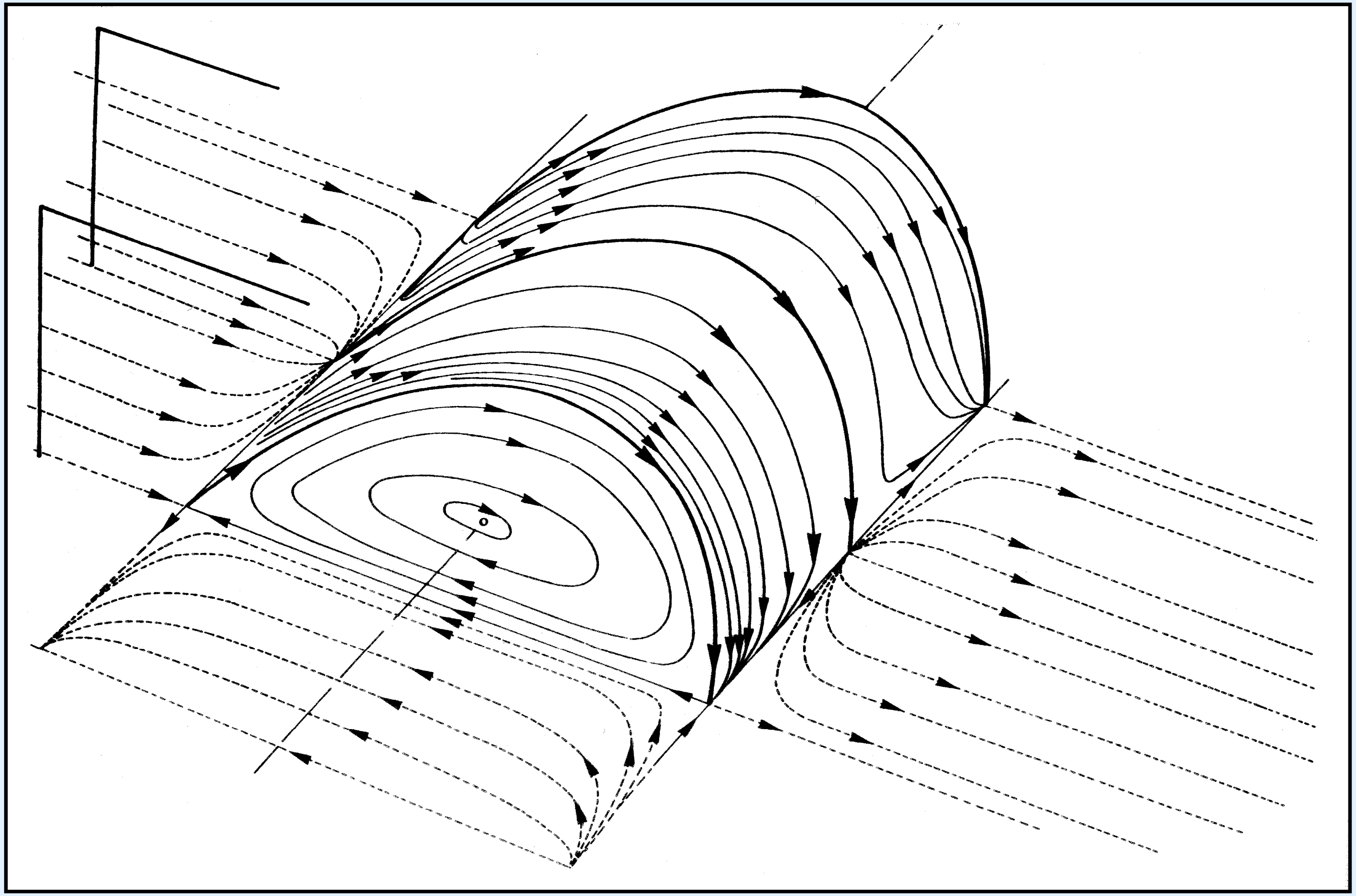
Flow topology and contra-rotating vortices

Detachment and reattachment in two-dimensional flow



Detachment-reattachment surface

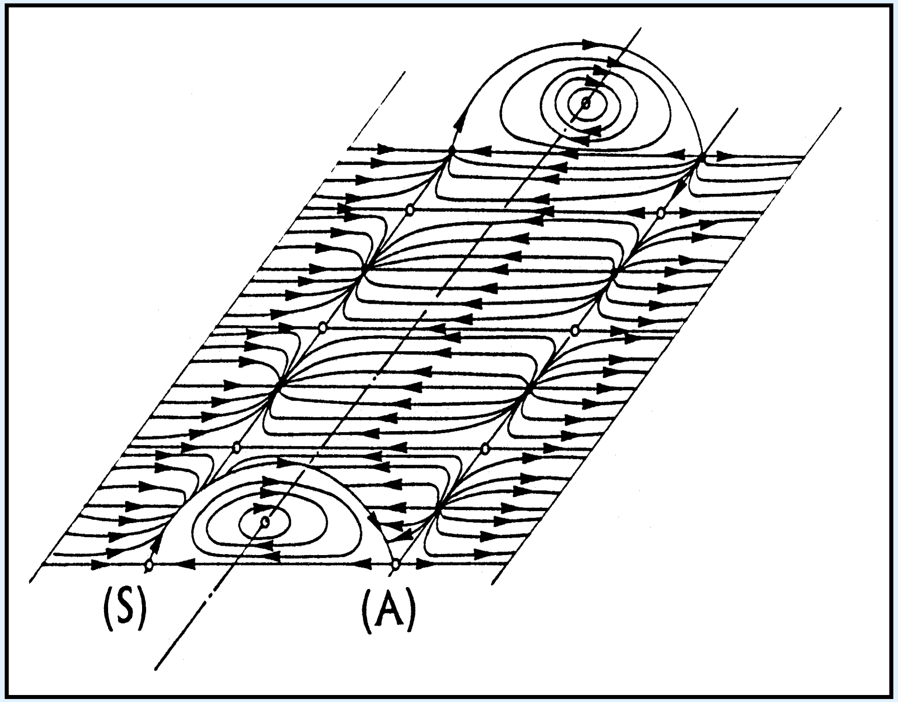
Detachment and reattachment in two-dimensional flow



Flow organisation in the separation bubble

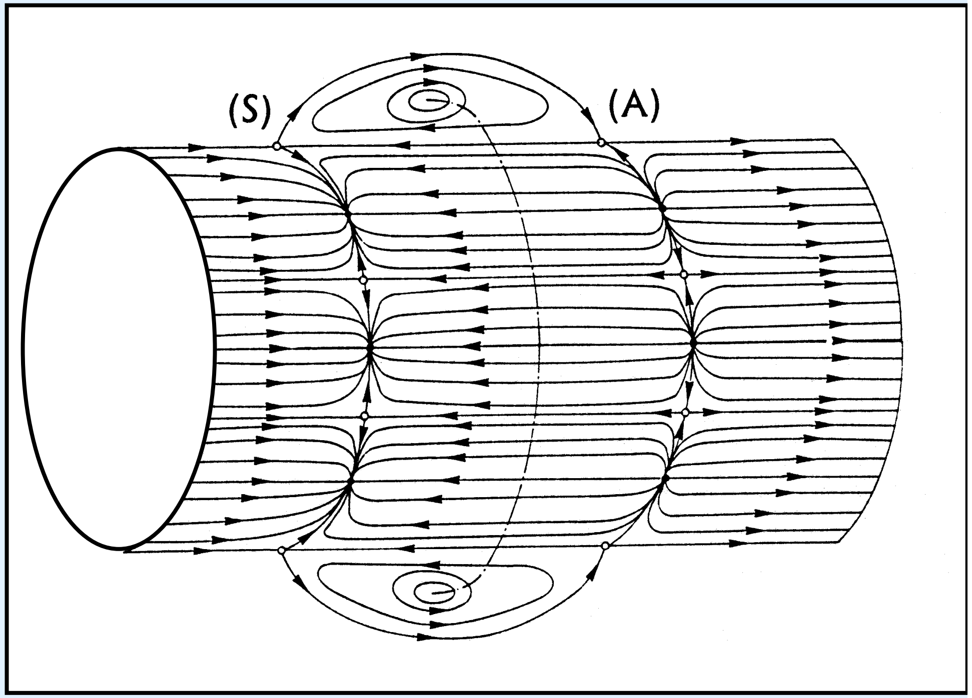
Detachment and reattachment in two-dimensional flow

Planar two-dimensional (improbable)



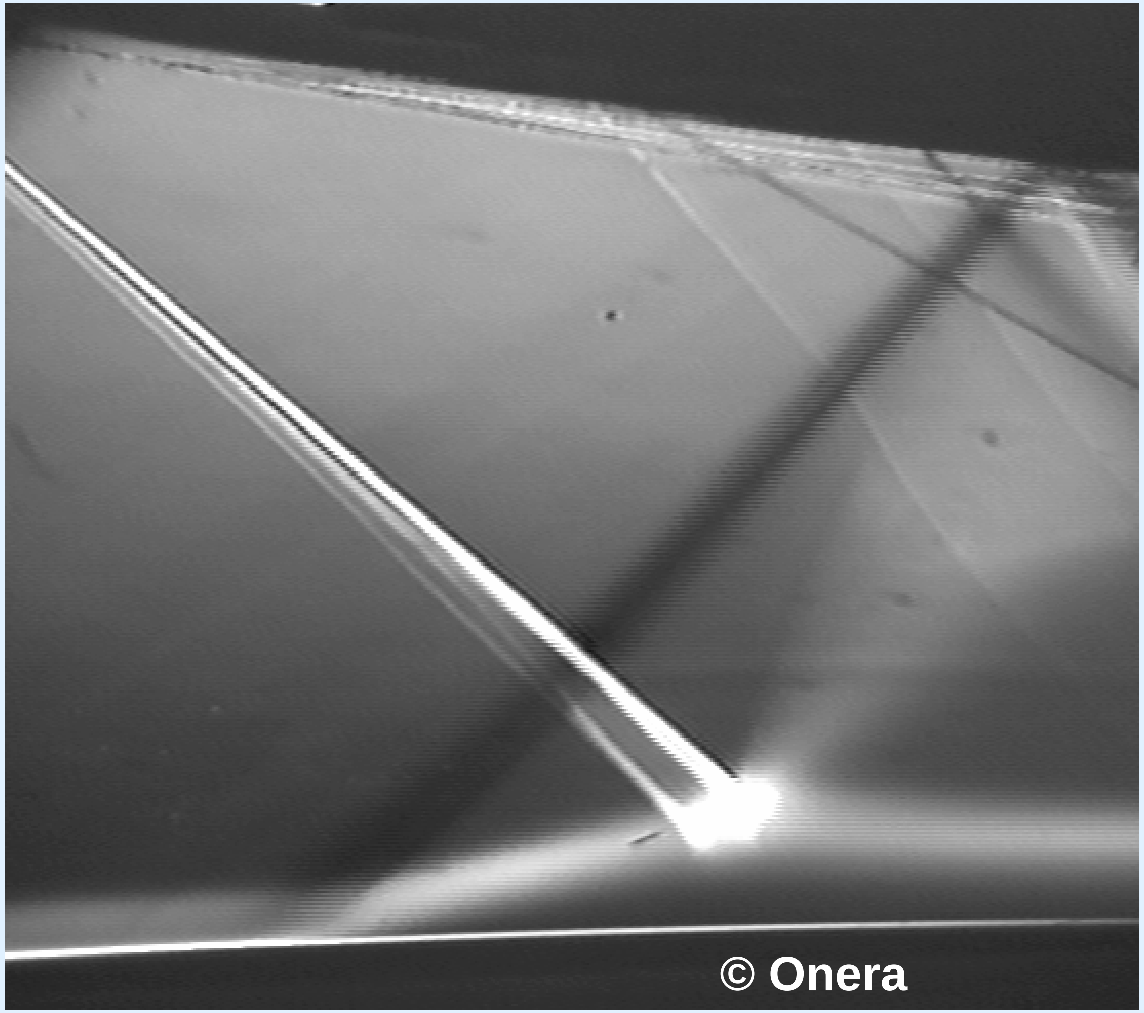
Configuration rarely observed. The spanwise limitation of the geometry imposes a three-dimensional large scale structure.

Axisymmetric two-dimensional



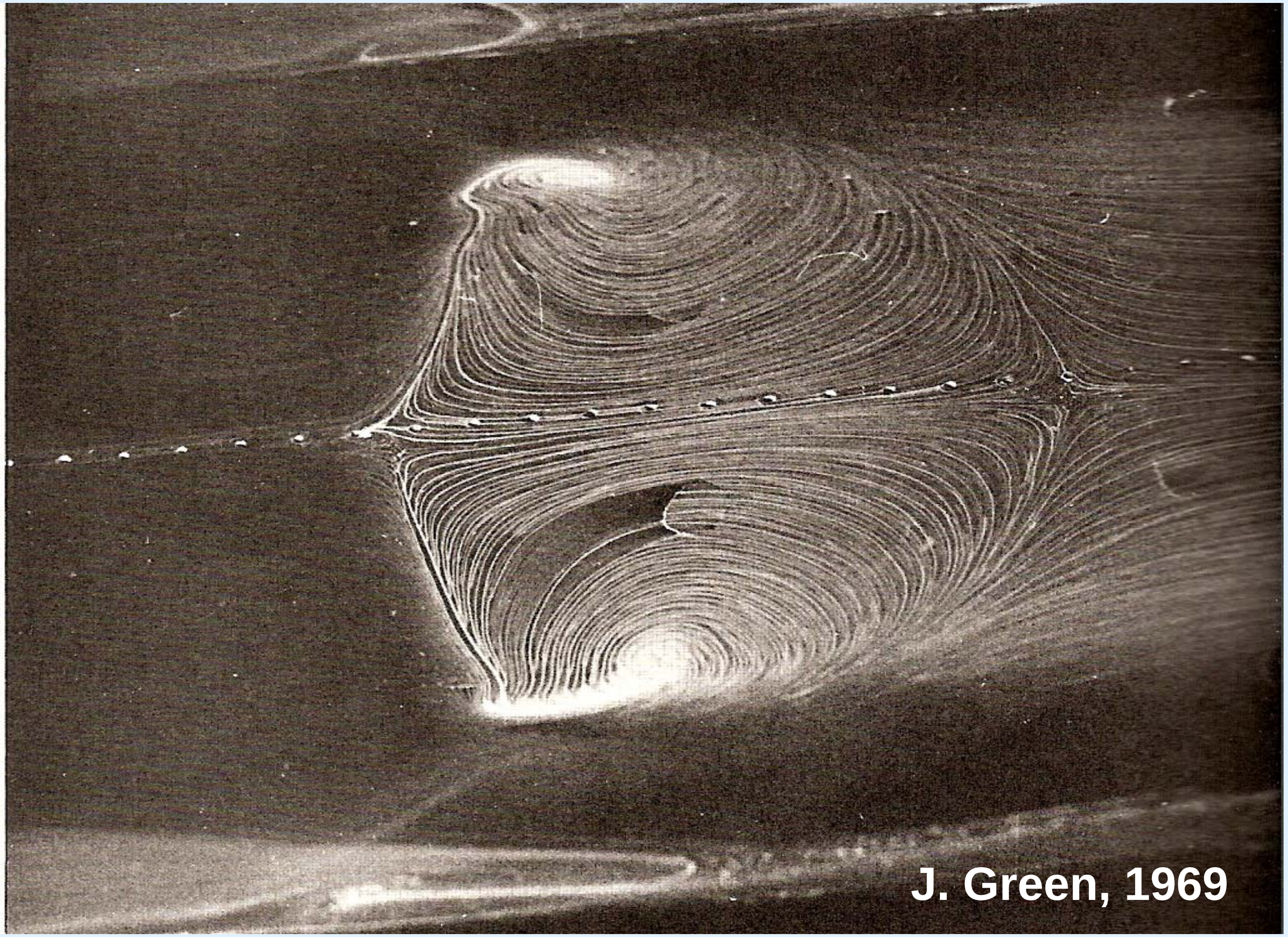
The axisymmetry allows a periodic organisation of this type.

Topology of flows in planar two-dimensional geometries



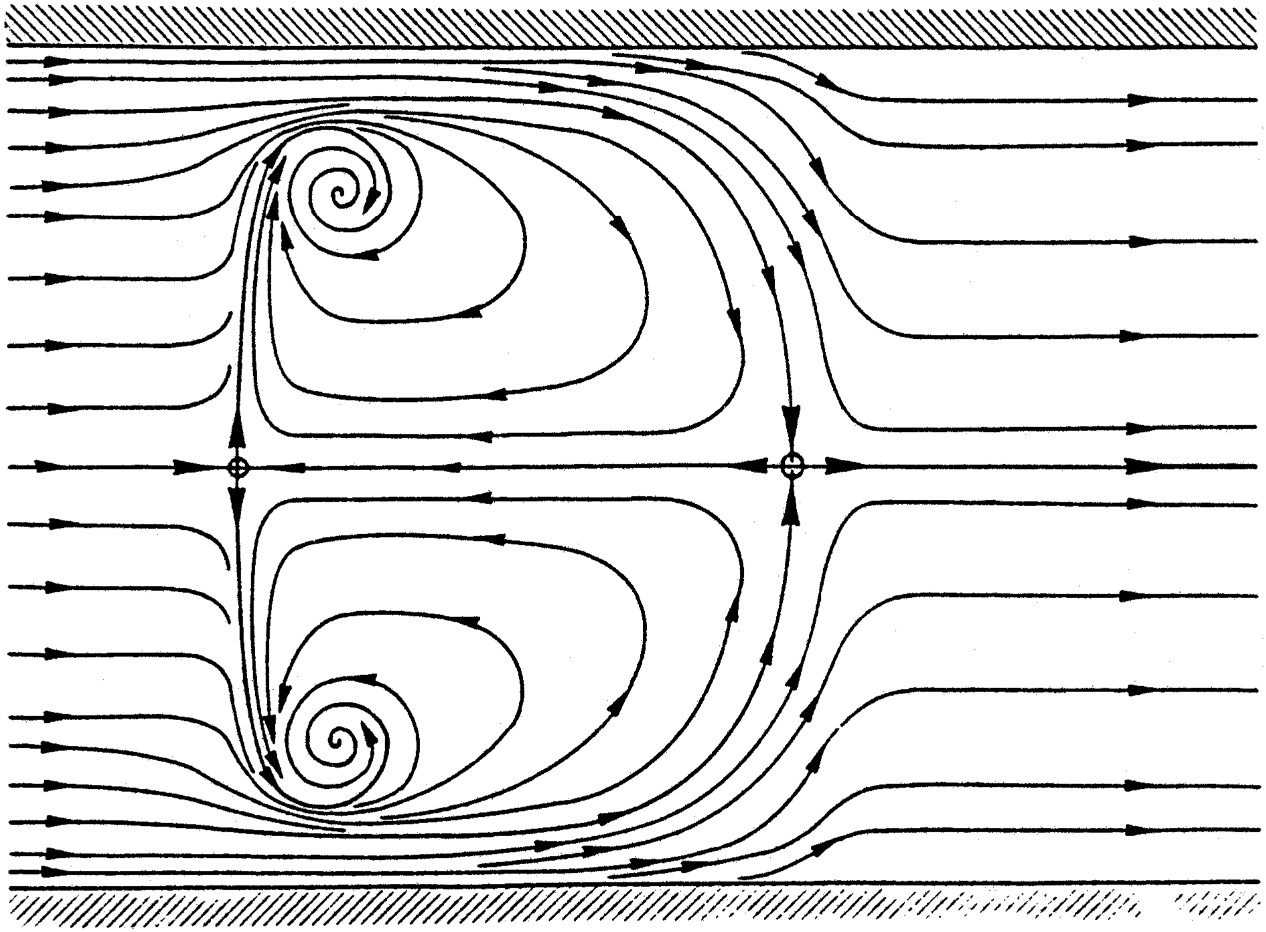
Shock wave reflection at Mach 2

Reflection of an oblique planar shock wave



Surface flow visualisation

Reflection of an oblique planar shock wave



Skin friction line pattern showing side effects

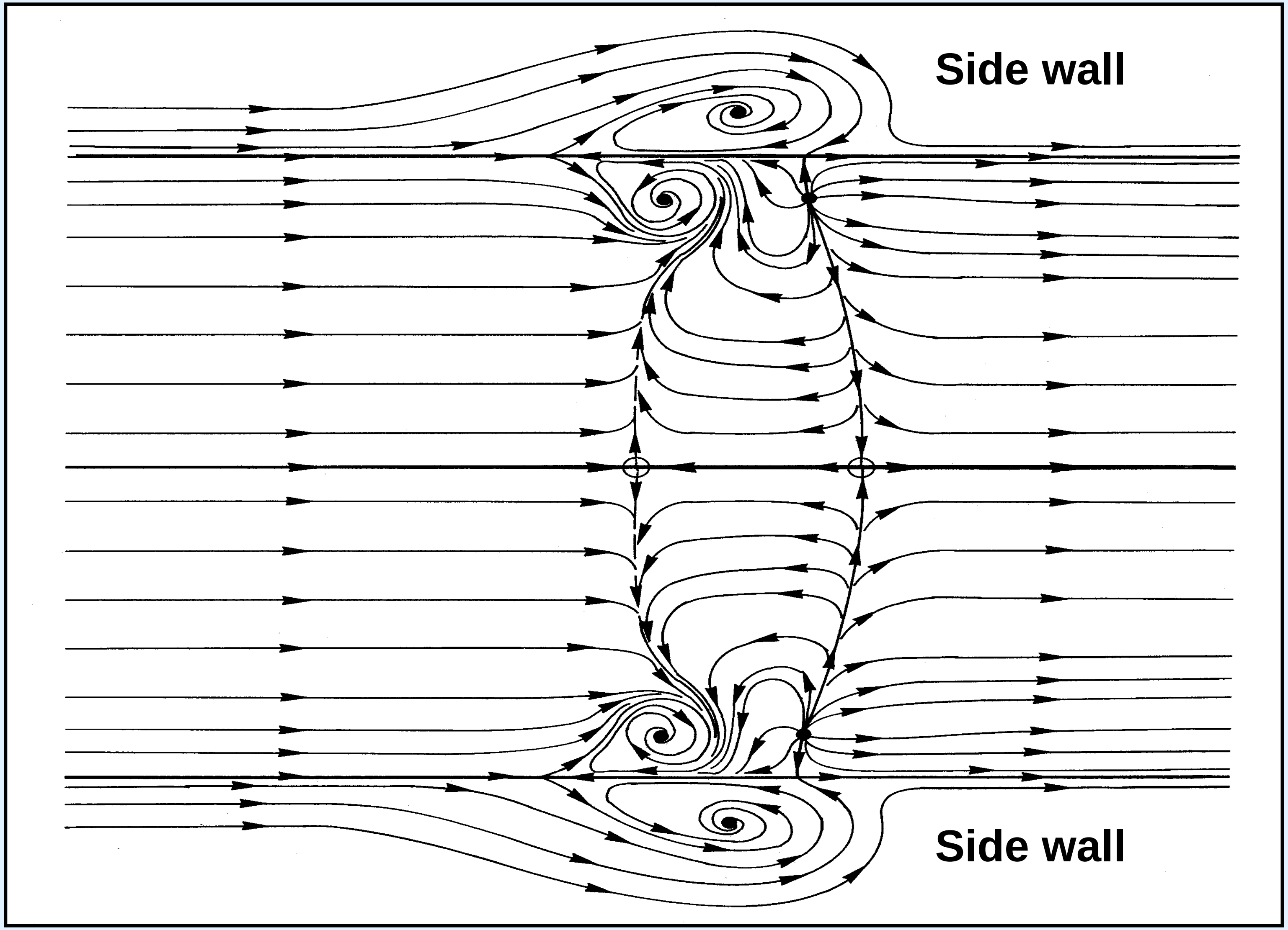
Topology of flows in planar two-dimensional geometries

Transonic channel in the Onera wind tunnel S8Ch

Detachment and attachment in a transonic channel

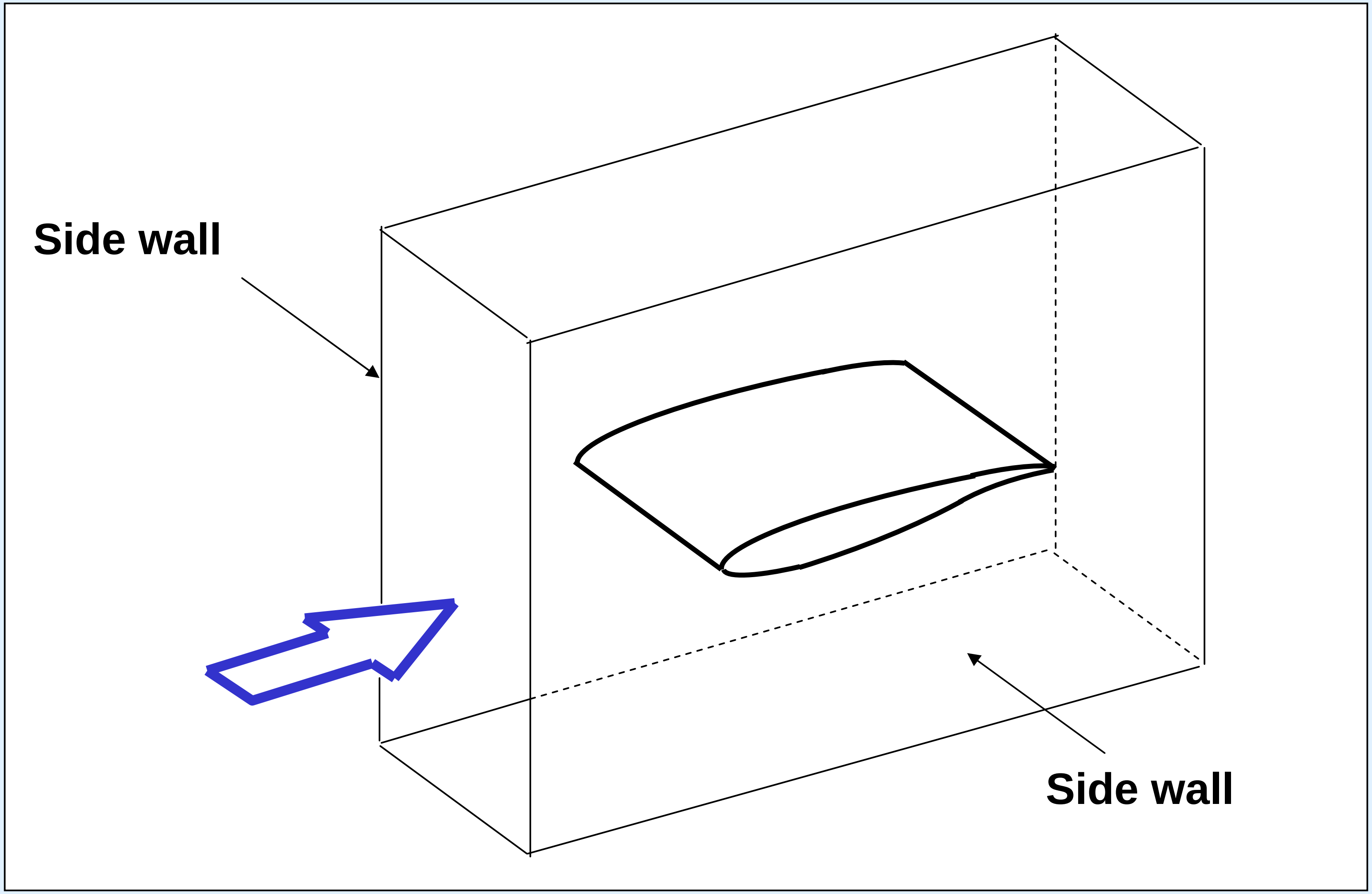
Surface flow visualisation

Detachment and attachment in a transonic channel



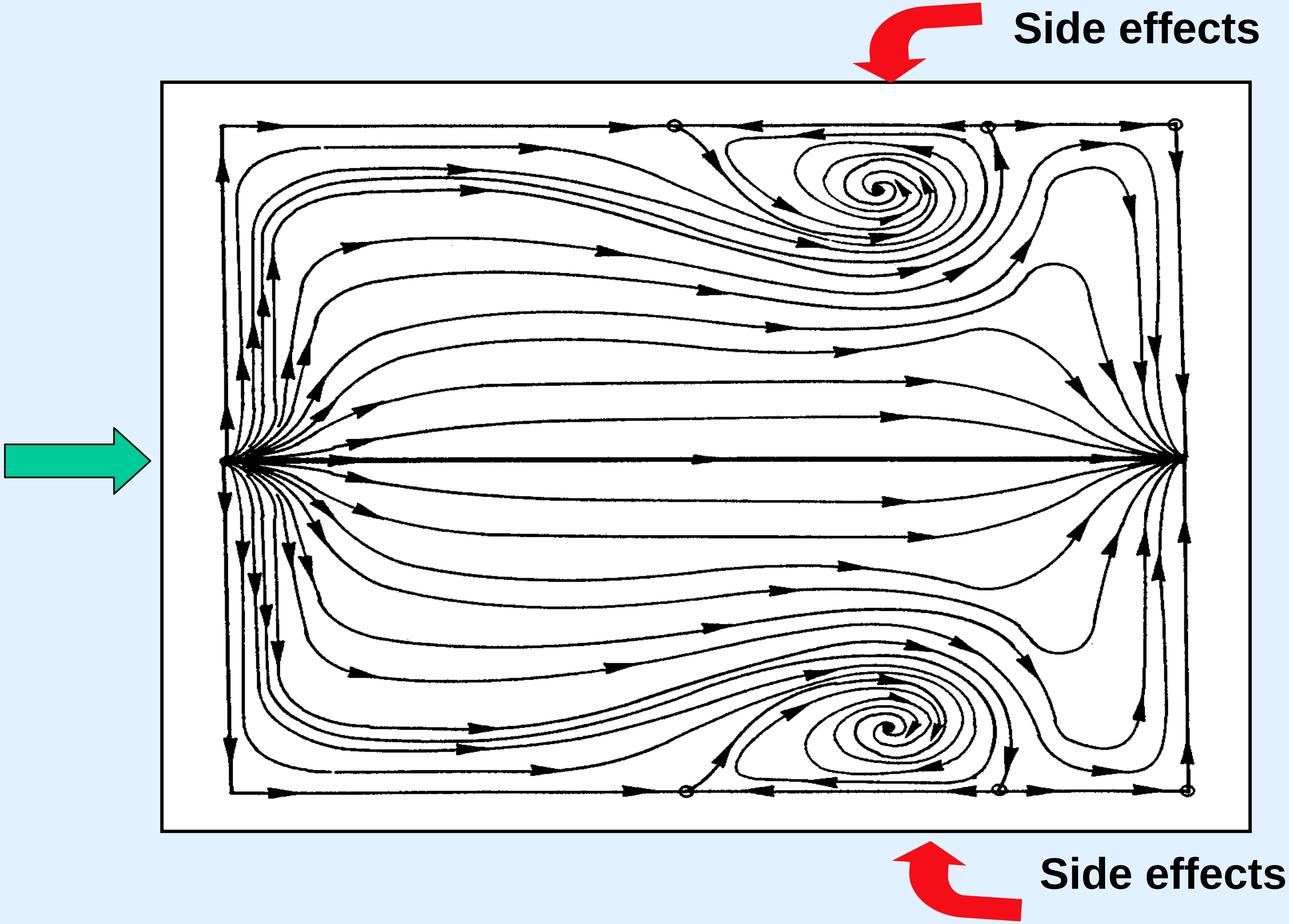
Skin friction line pattern topology

Flow past a two-dimensional profile in a transonic wind tunnel



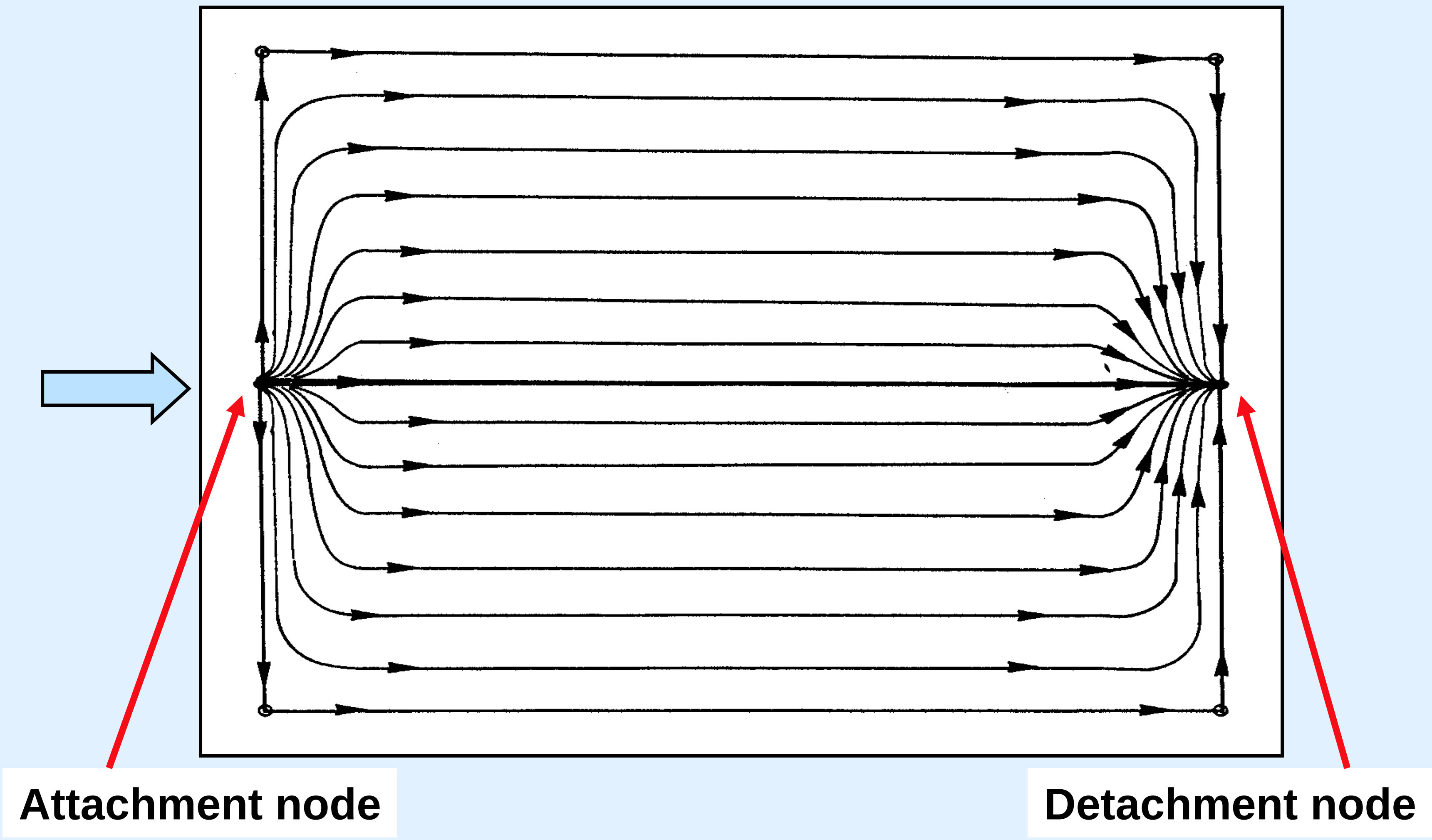
Two-dimensional profile in a transonic wind tunnel

Skin friction line pattern on the suction side

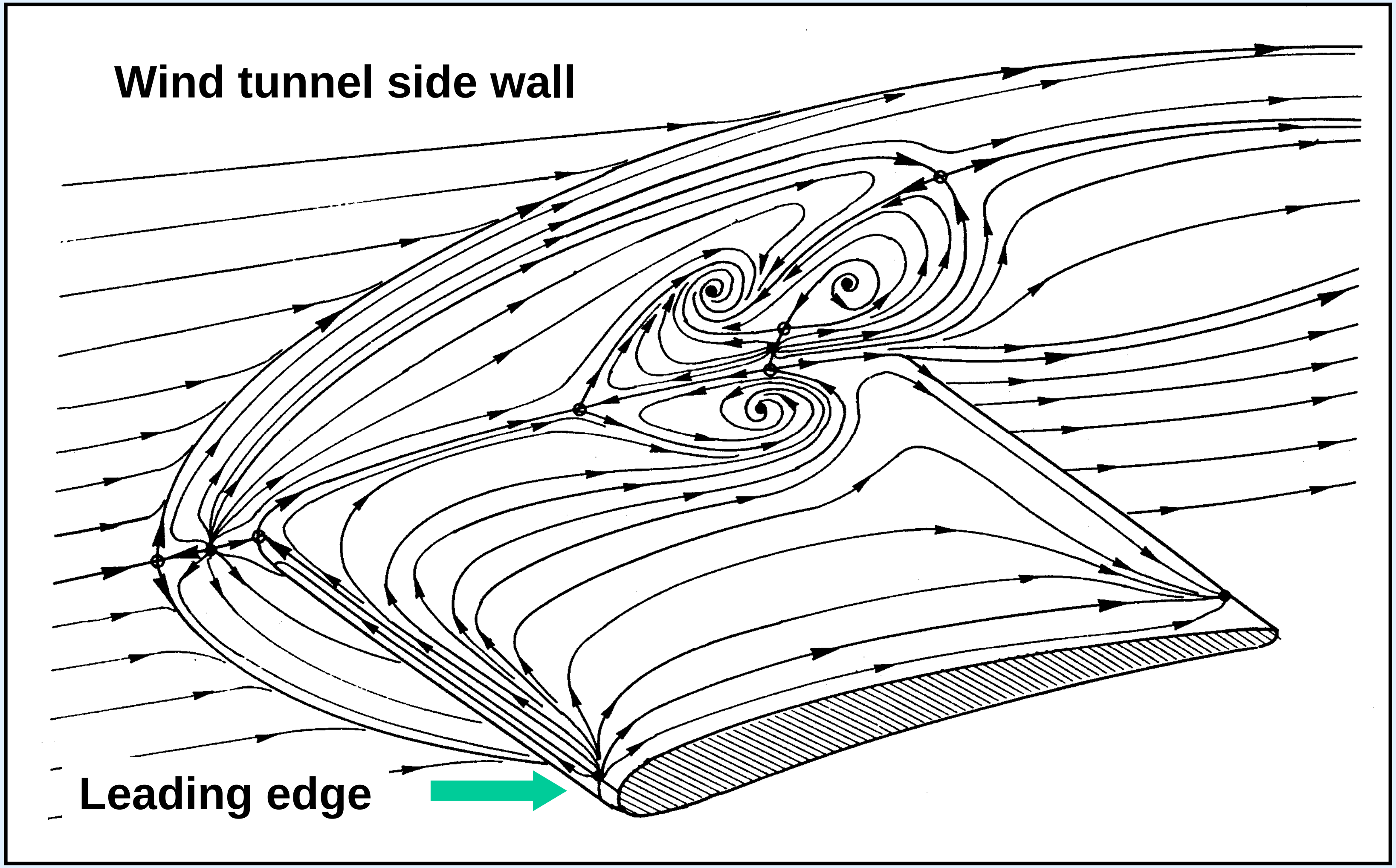


Two-dimensional profile in a transonic wind tunnel

Skin friction line pattern on the pressure side



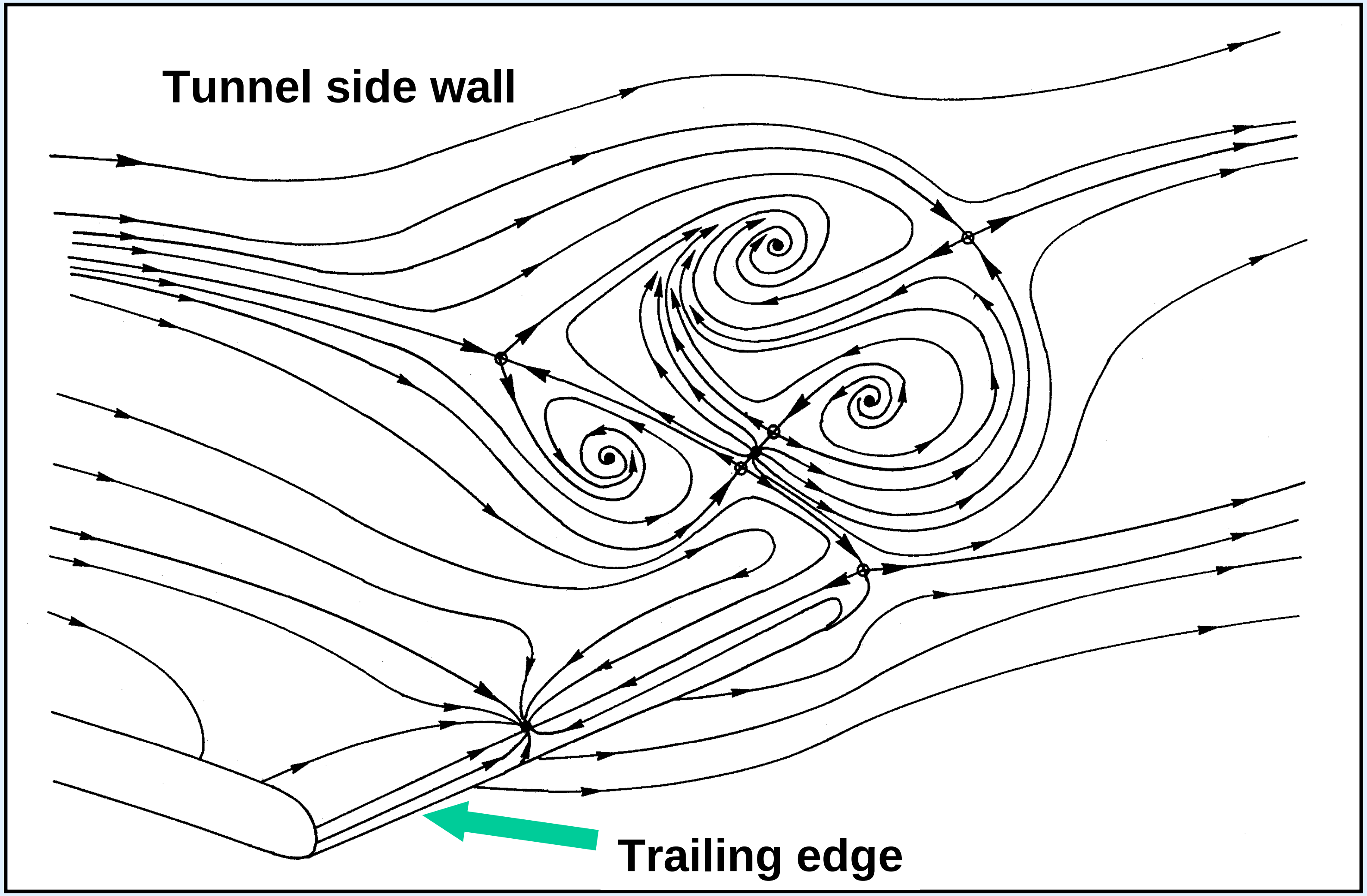
Two-dimensional profile in a transonic wind tunnel



Skin friction line pattern at the profile-side wall junction

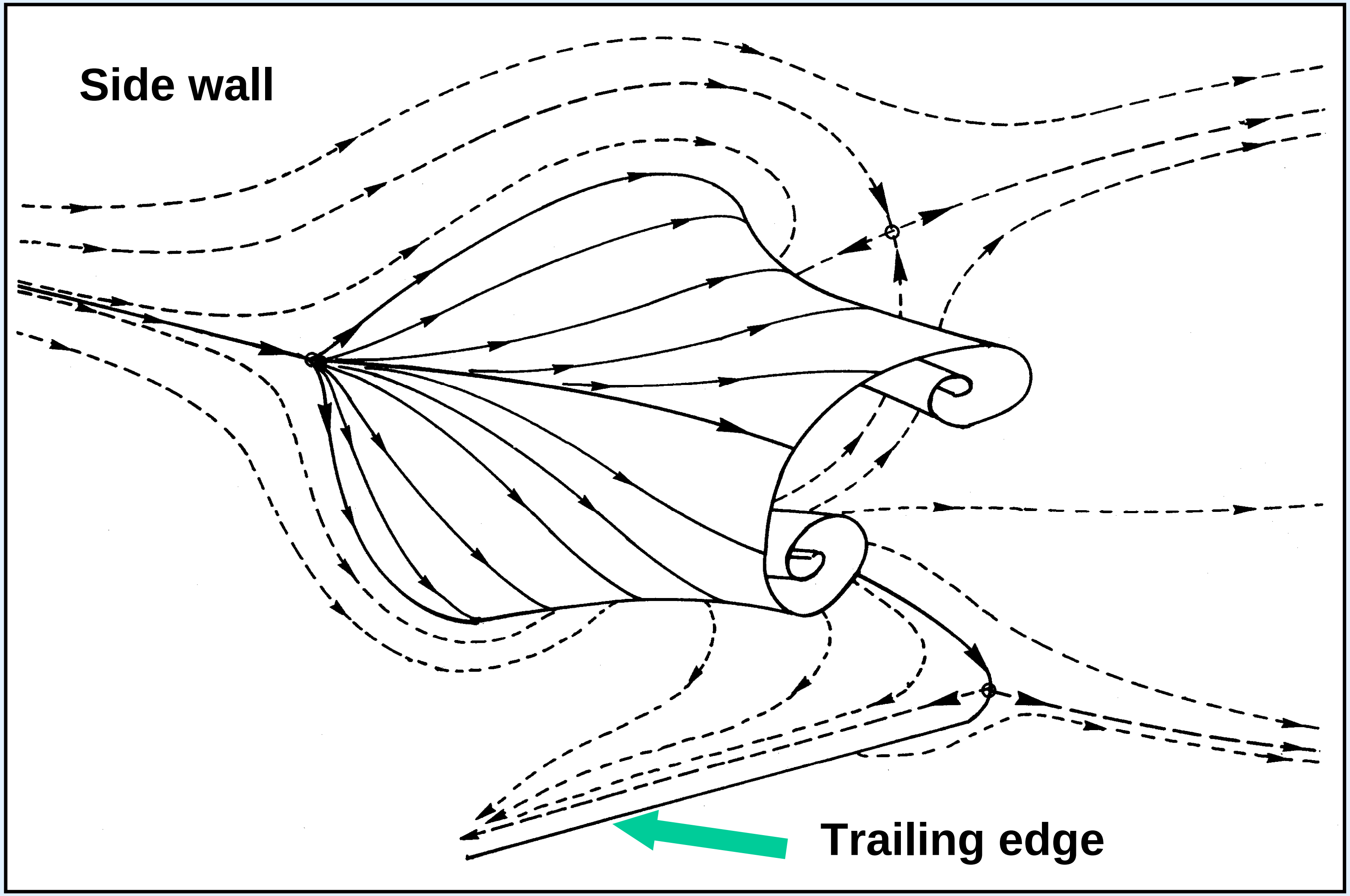
Two-dimensional profile in a transonic wind tunnel

Skin friction line pattern at the profile-side wall junction



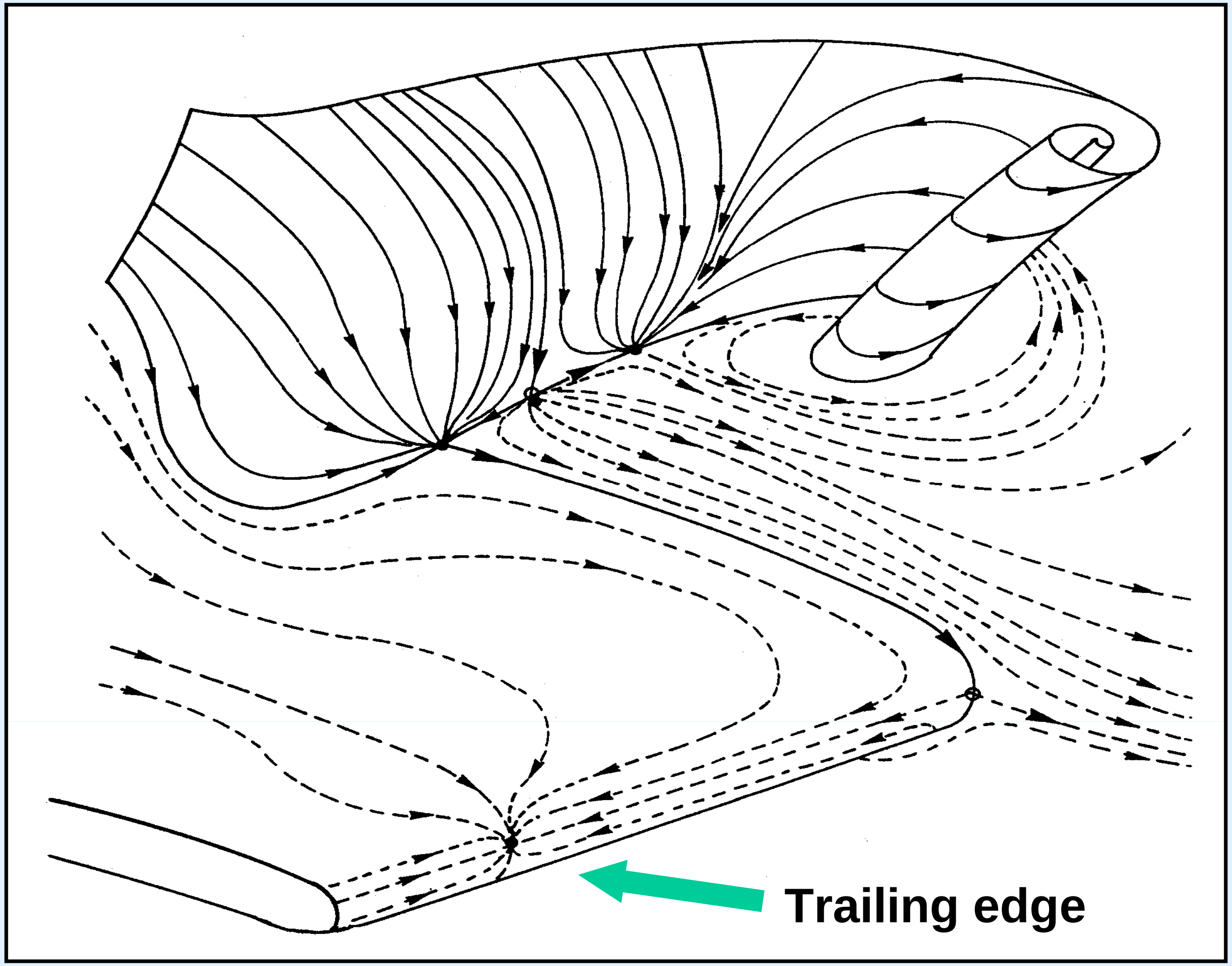
Two-dimensional profile in a transonic wind tunnel

Detachment surface Σ_1



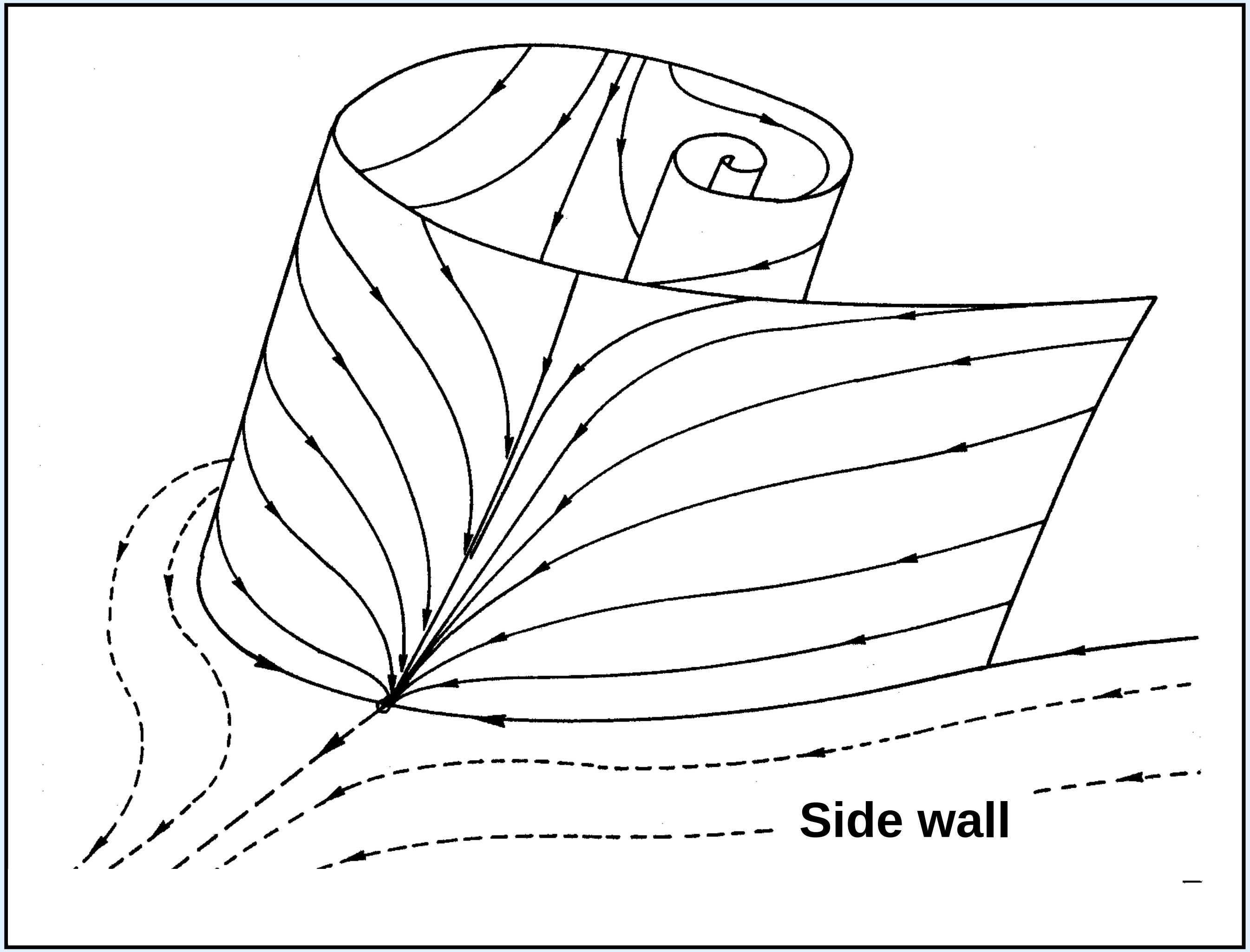
Two-dimensional profile in a transonic wind tunnel

Detachment surface Σ_2



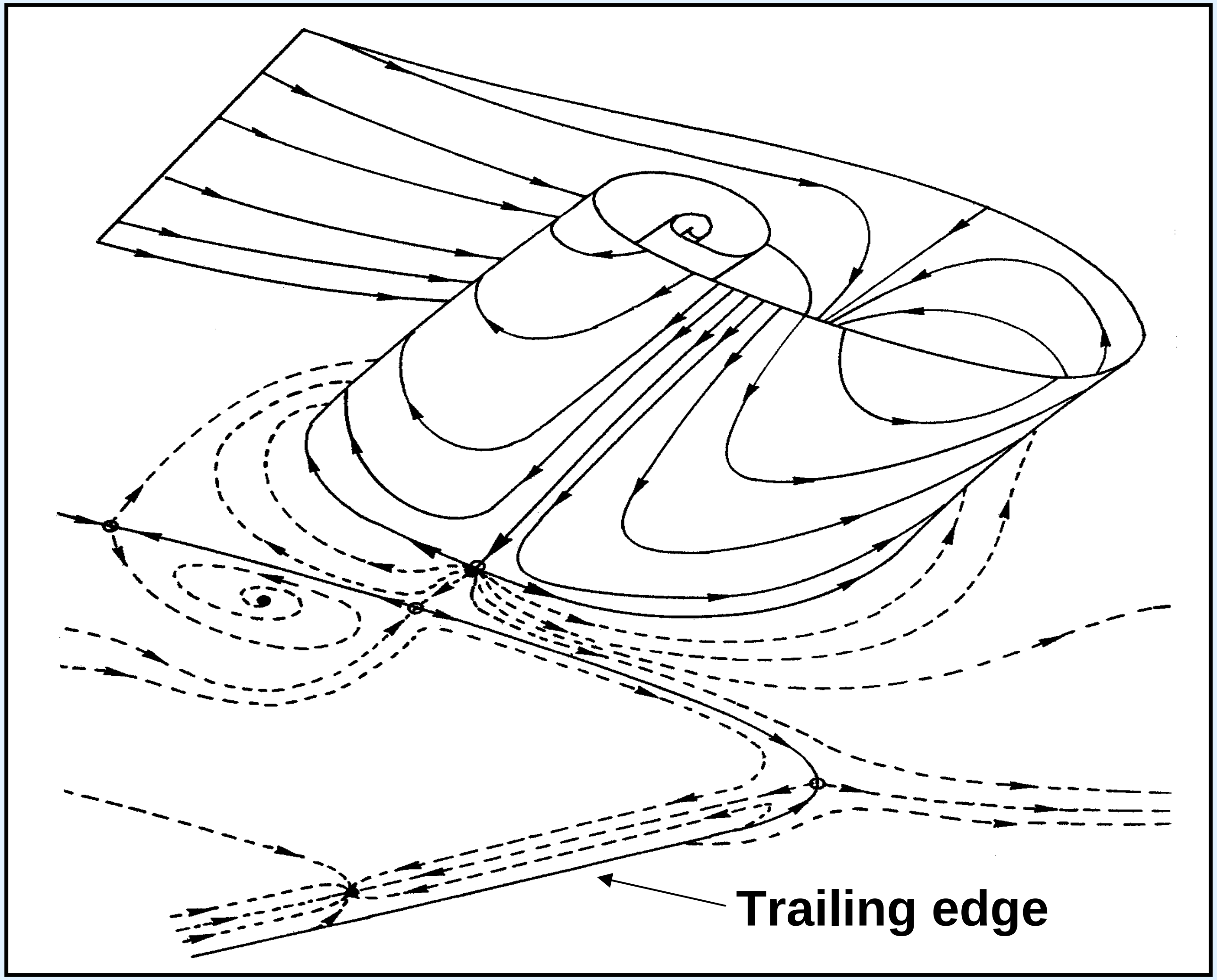
Two-dimensional profile in a transonic wind tunnel

Detachment surface Σ_3



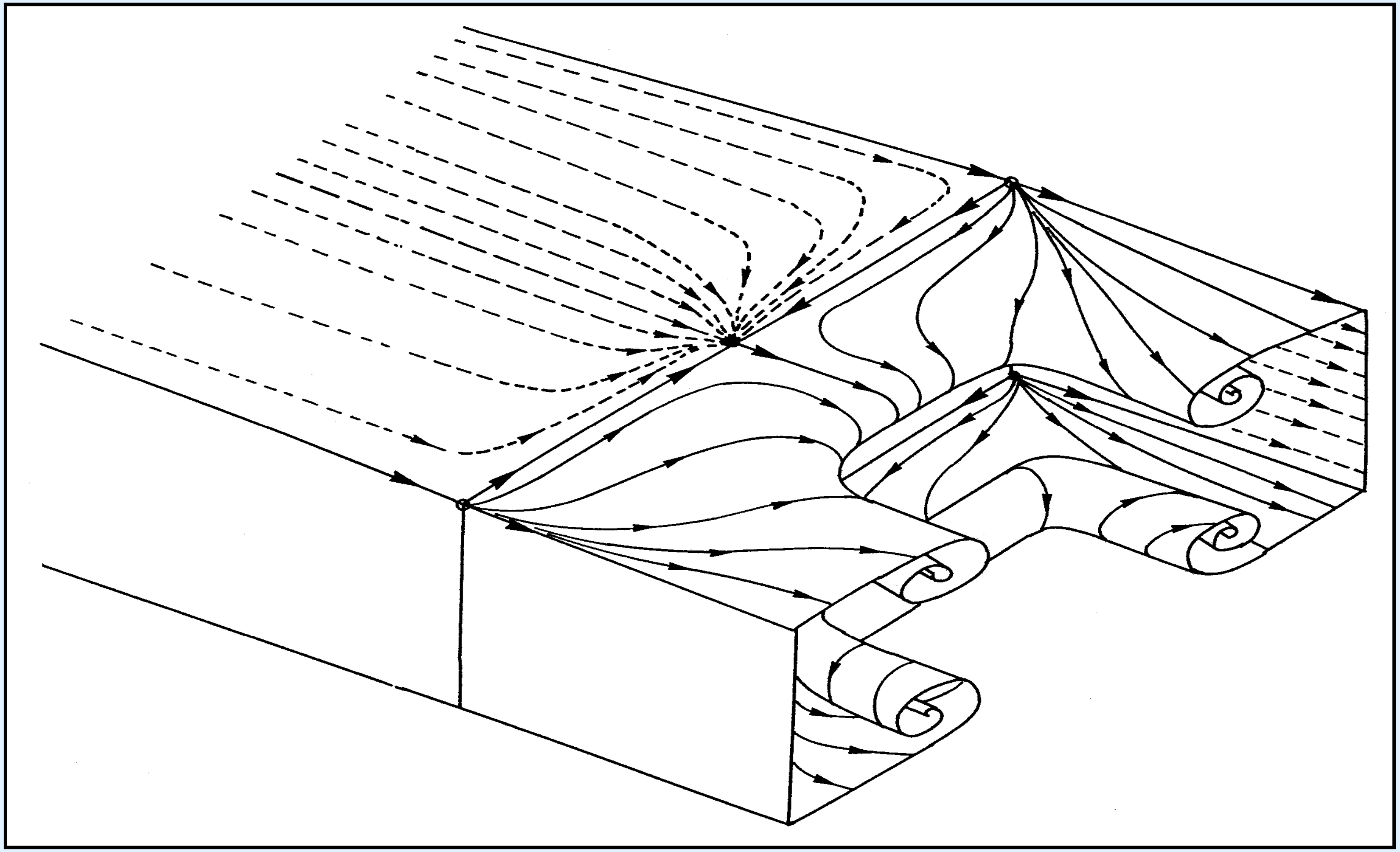
Two-dimensional profile in a transonic wind tunnel

Detachment surface Σ_3. Other view



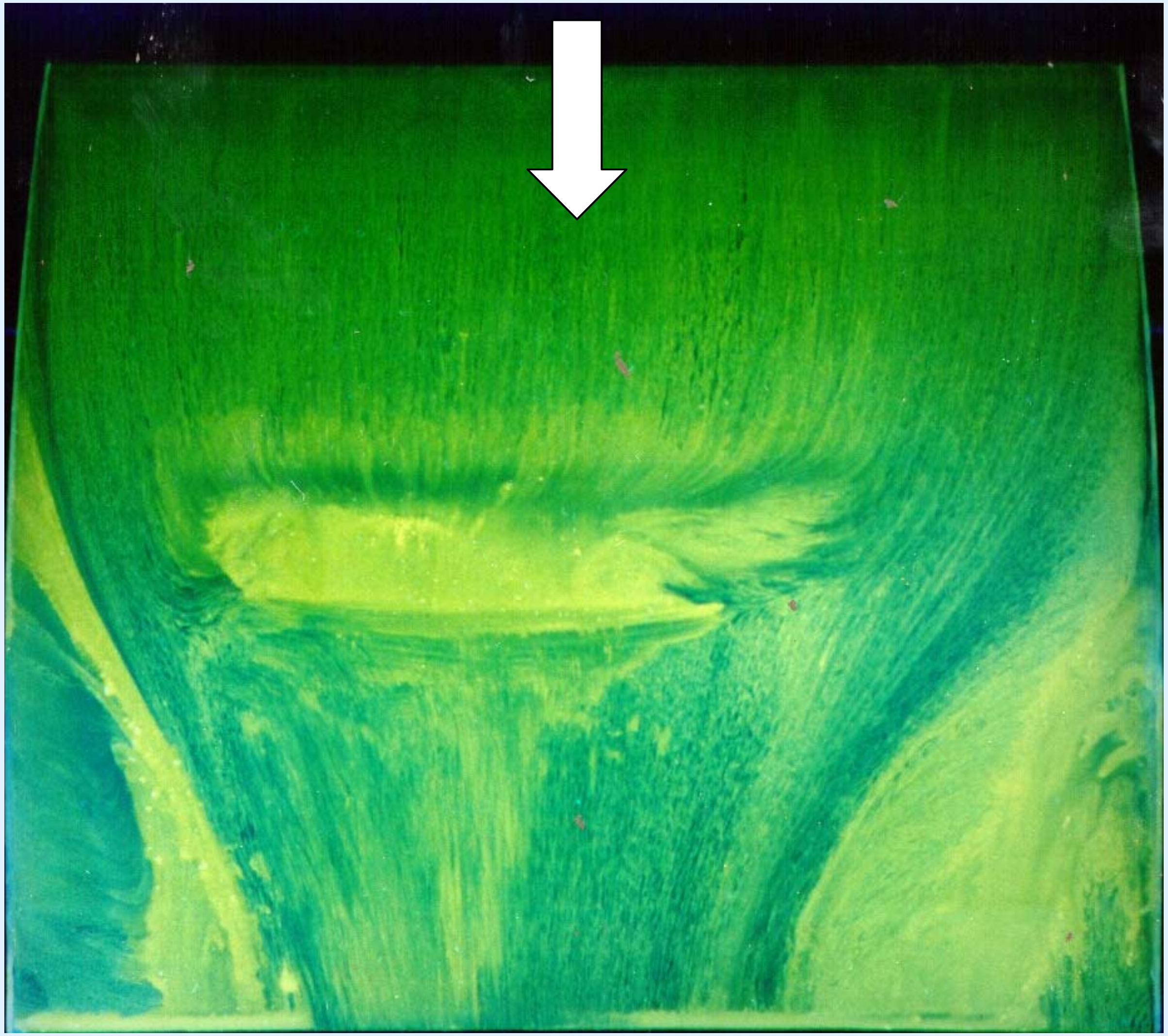
Two-dimensional profile in a transonic wind tunnel

Detachment surface starting from the truncated trailing edge



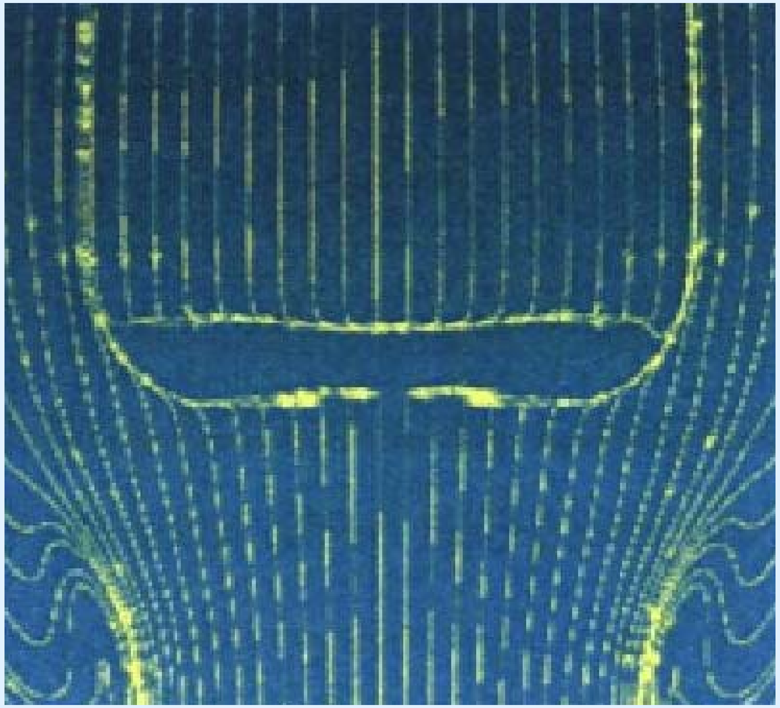
Flow in a schematic compressor cascade

Flow in a schematic compressor cascade

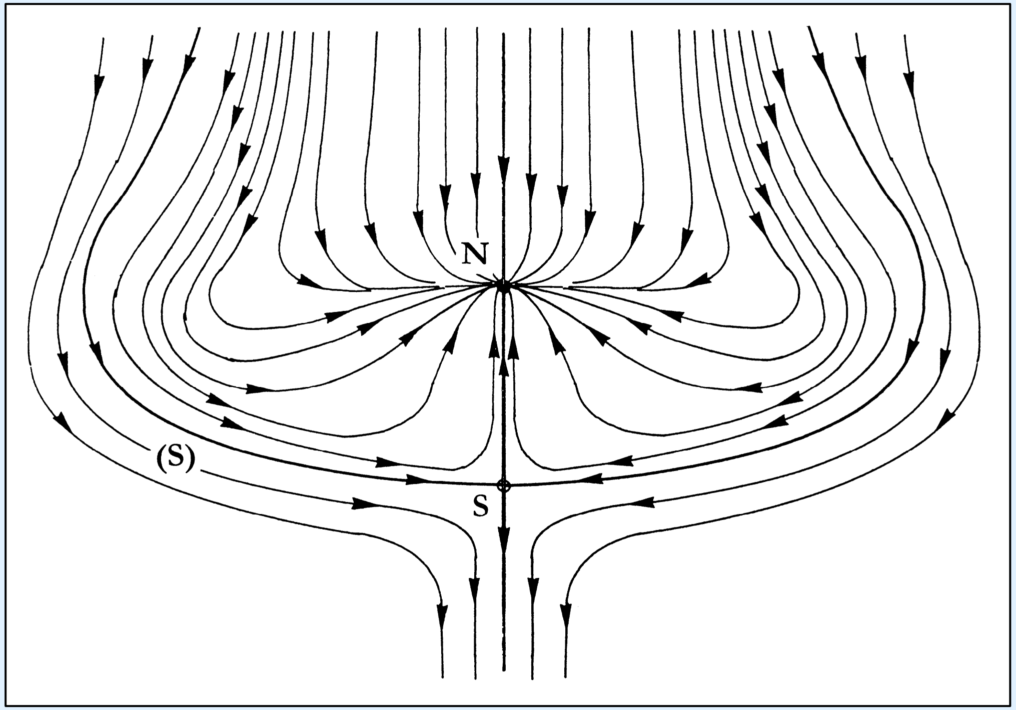


Skin friction line pattern on a blade suction side

Flow in a schematic compressor cascade



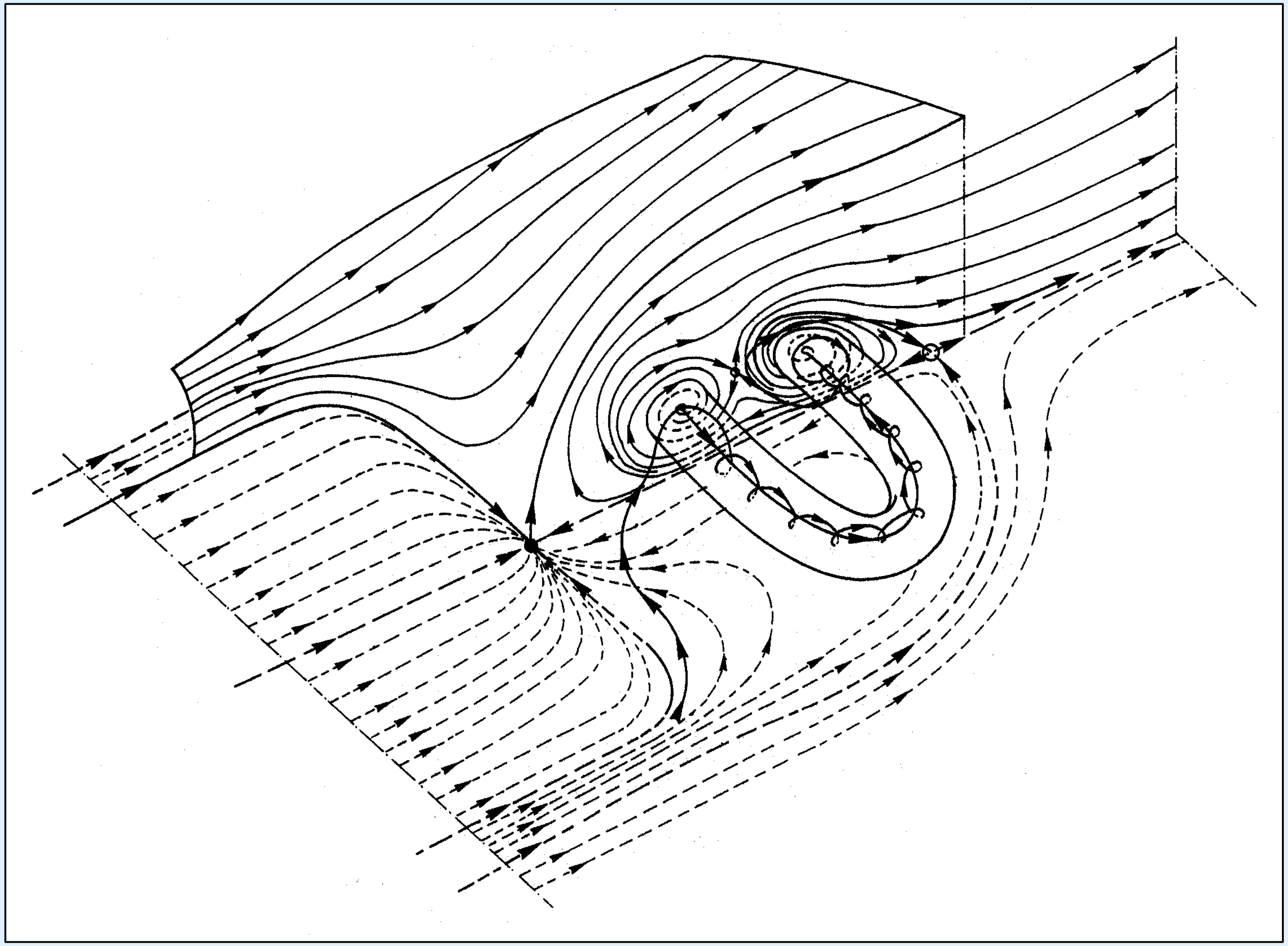
Navier-Stokes computation



Topological interpretation

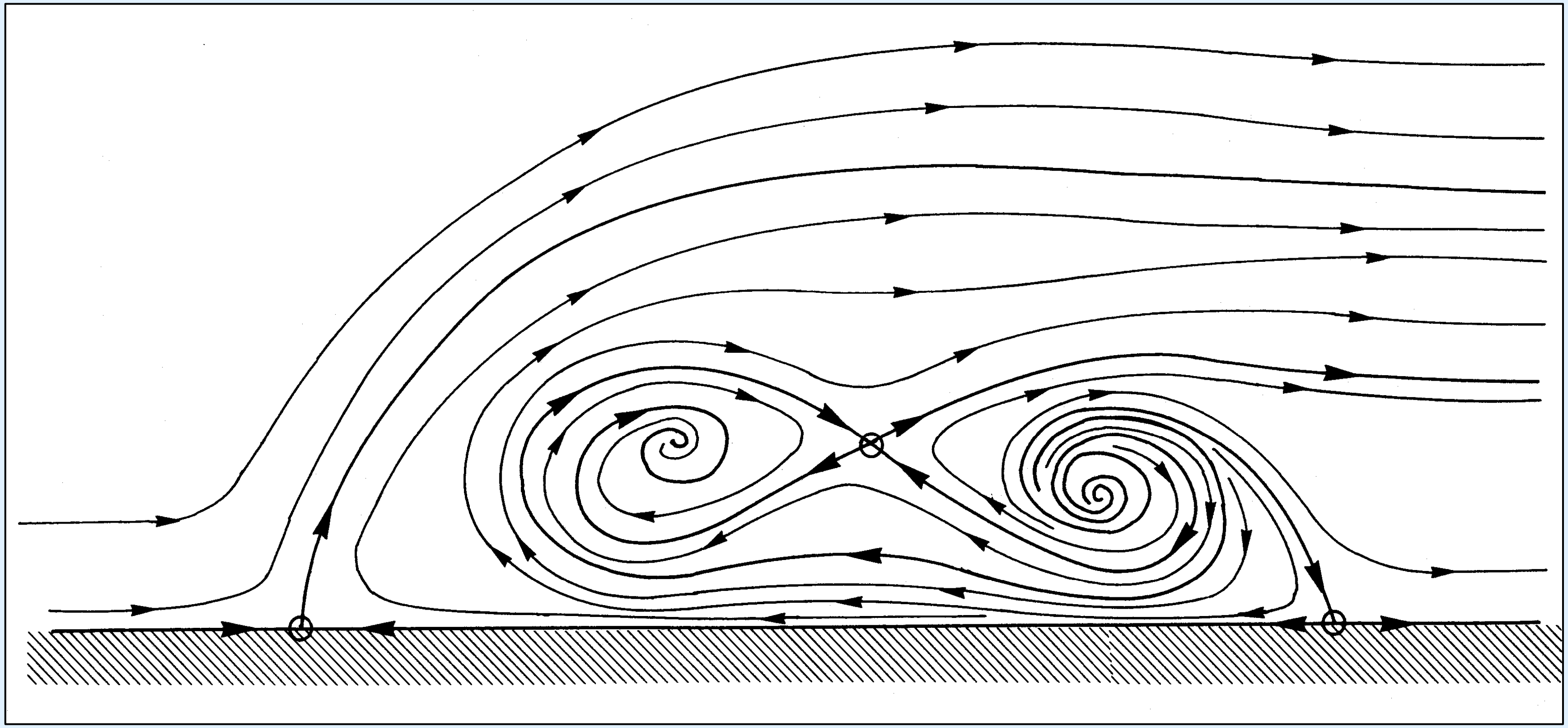
Skin friction line pattern on a blade suction side

Flow in a schematic compressor cascade



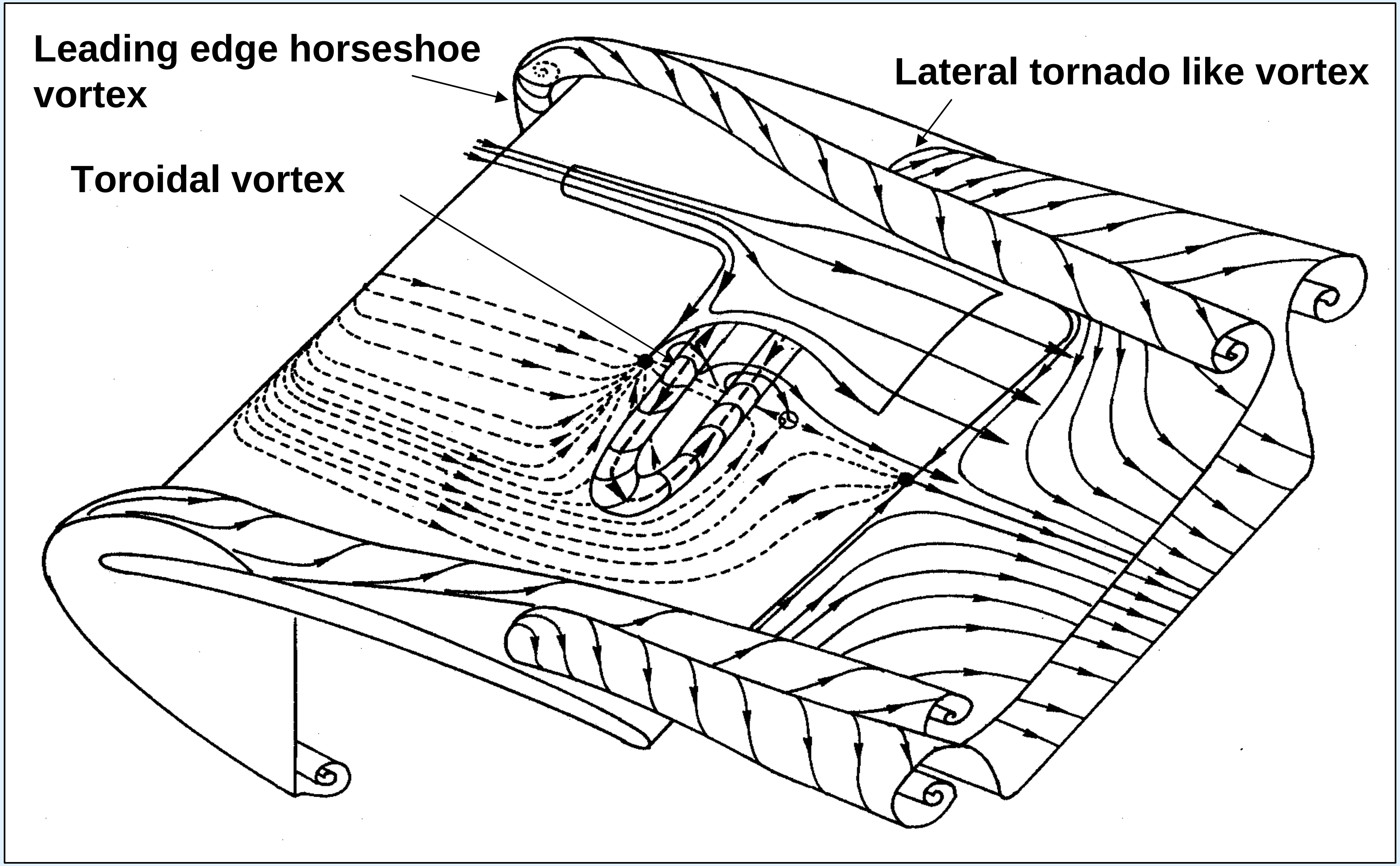
Reconstruction of the toroidal vortex

Flow in a schematic compressor cascade



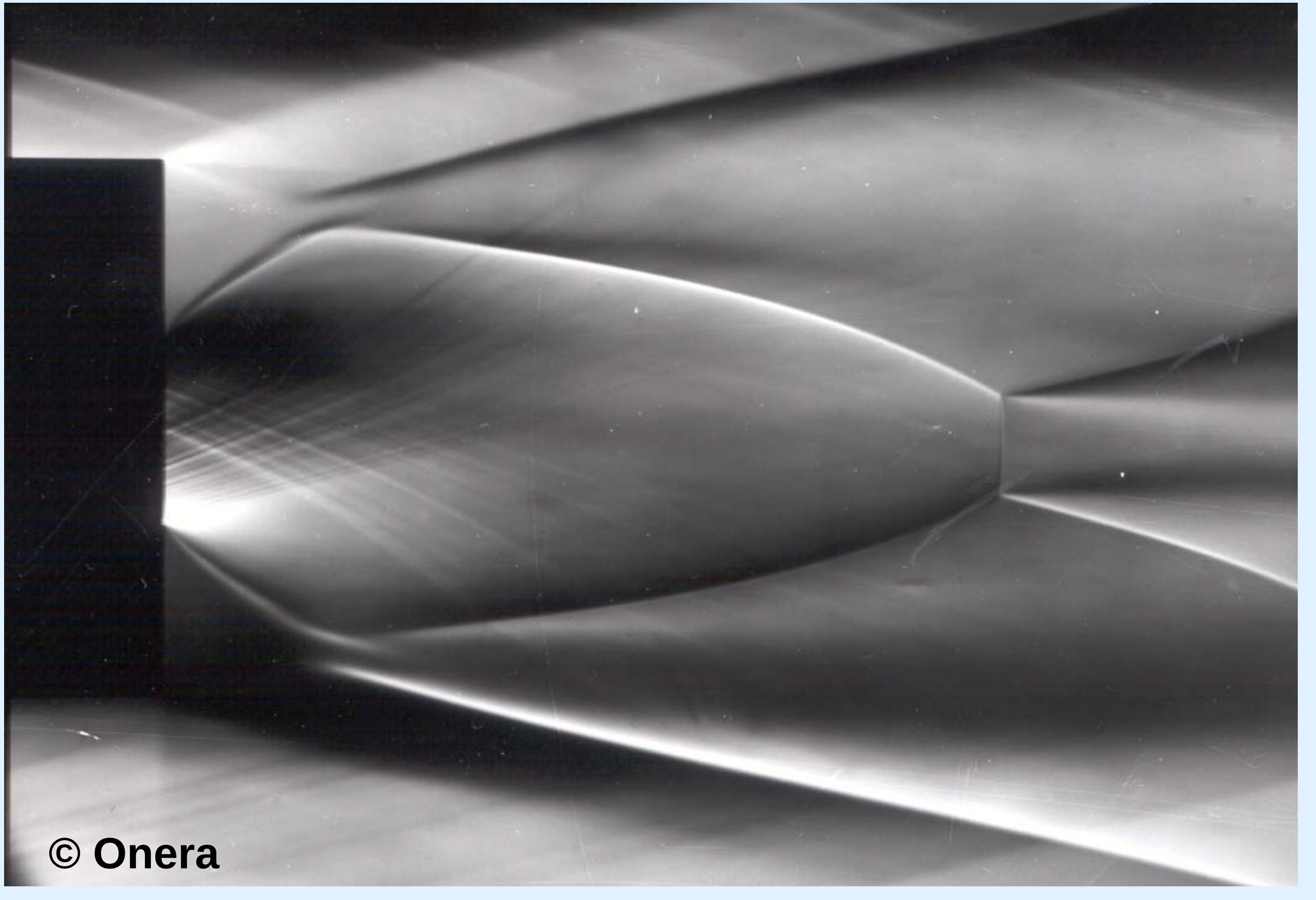
Cut of the vortex by a median plane

Flow in a schematic compressor cascade



Flow reconstruction past the blade

Axisymmetric flows

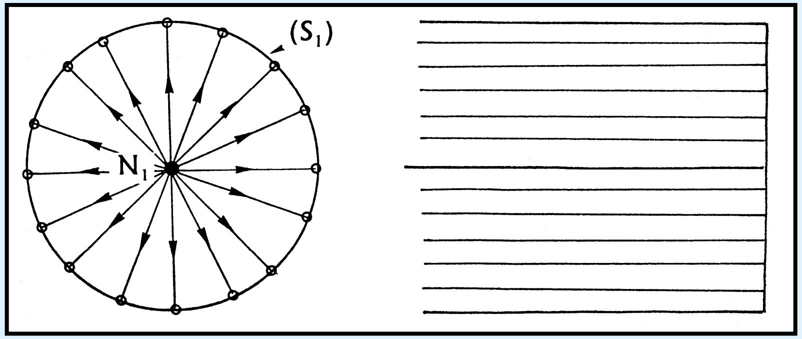


Propelled afterbody in the Onera-Meudon wind tunnel R1Ch

Axisymmetric afterbody at zero incidence

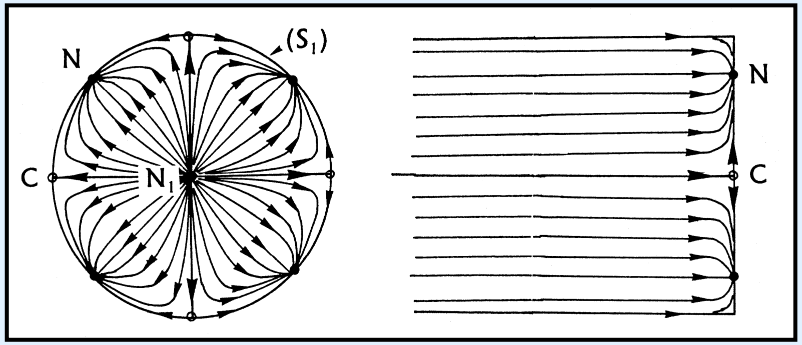
Ideal axisymmetric case (improbable)

The base sharp shoulder bears an infinite string of saddle points

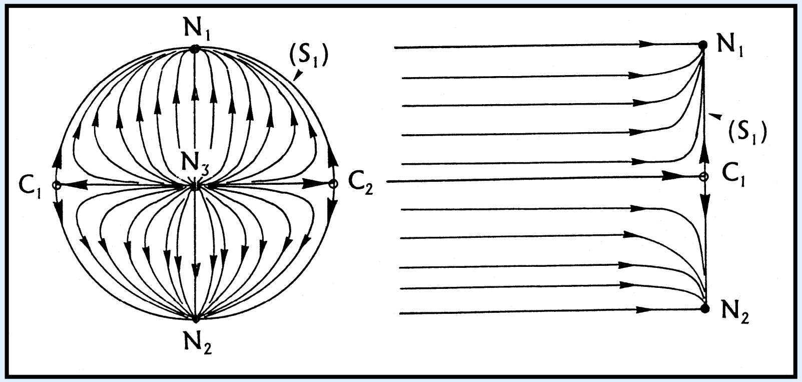


Cellular organisation

The base sharp shoulder bears a finite number of saddle points and nodes

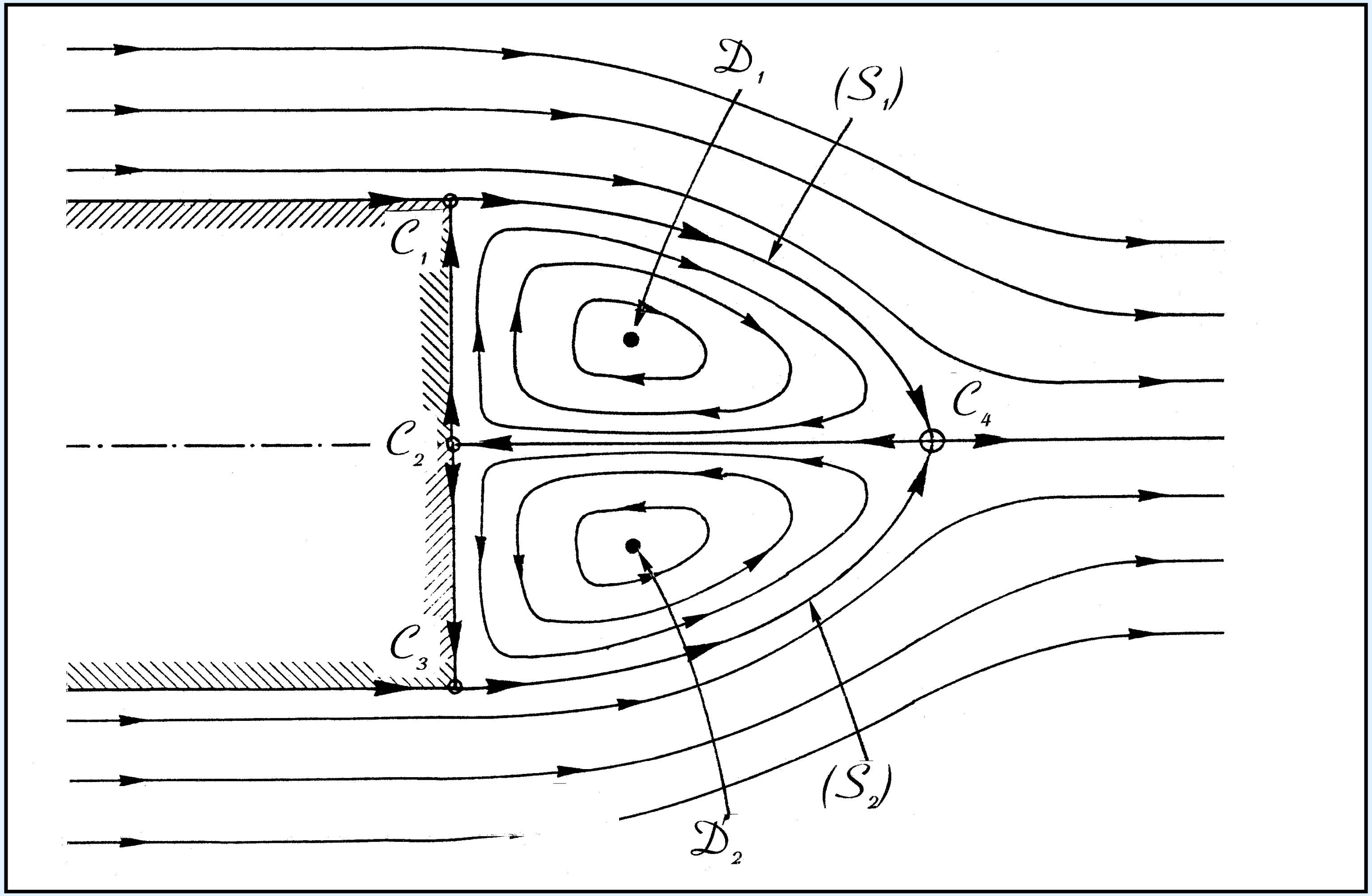


Two-vortex organisation



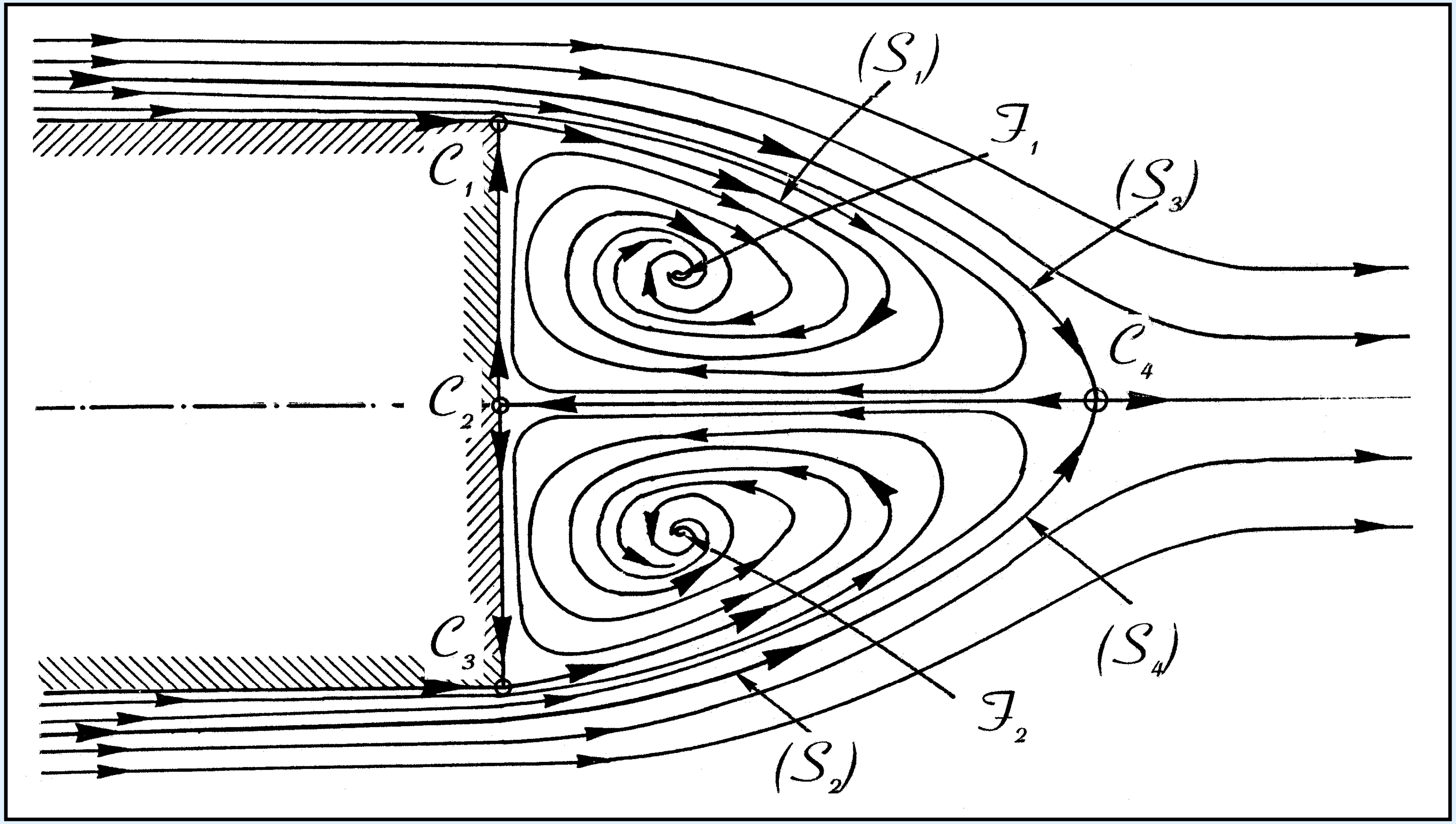
Possible skin friction line pattern

Non-propelled axisymmetric afterbody at zero incidence



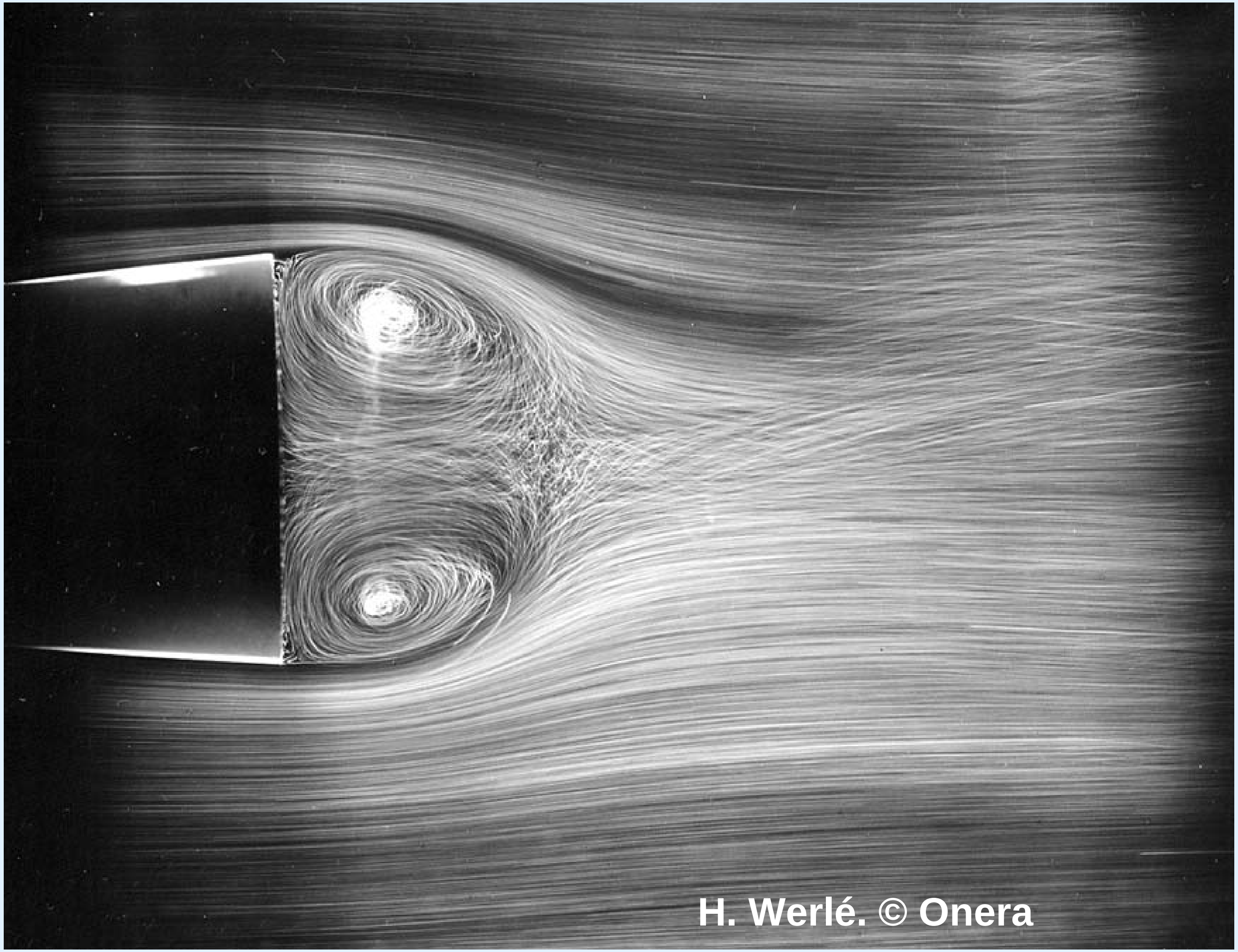
Flow in the meridian plane. Ideal axisymmetric flow

Non-propelled axisymmetric afterbody at zero incidence

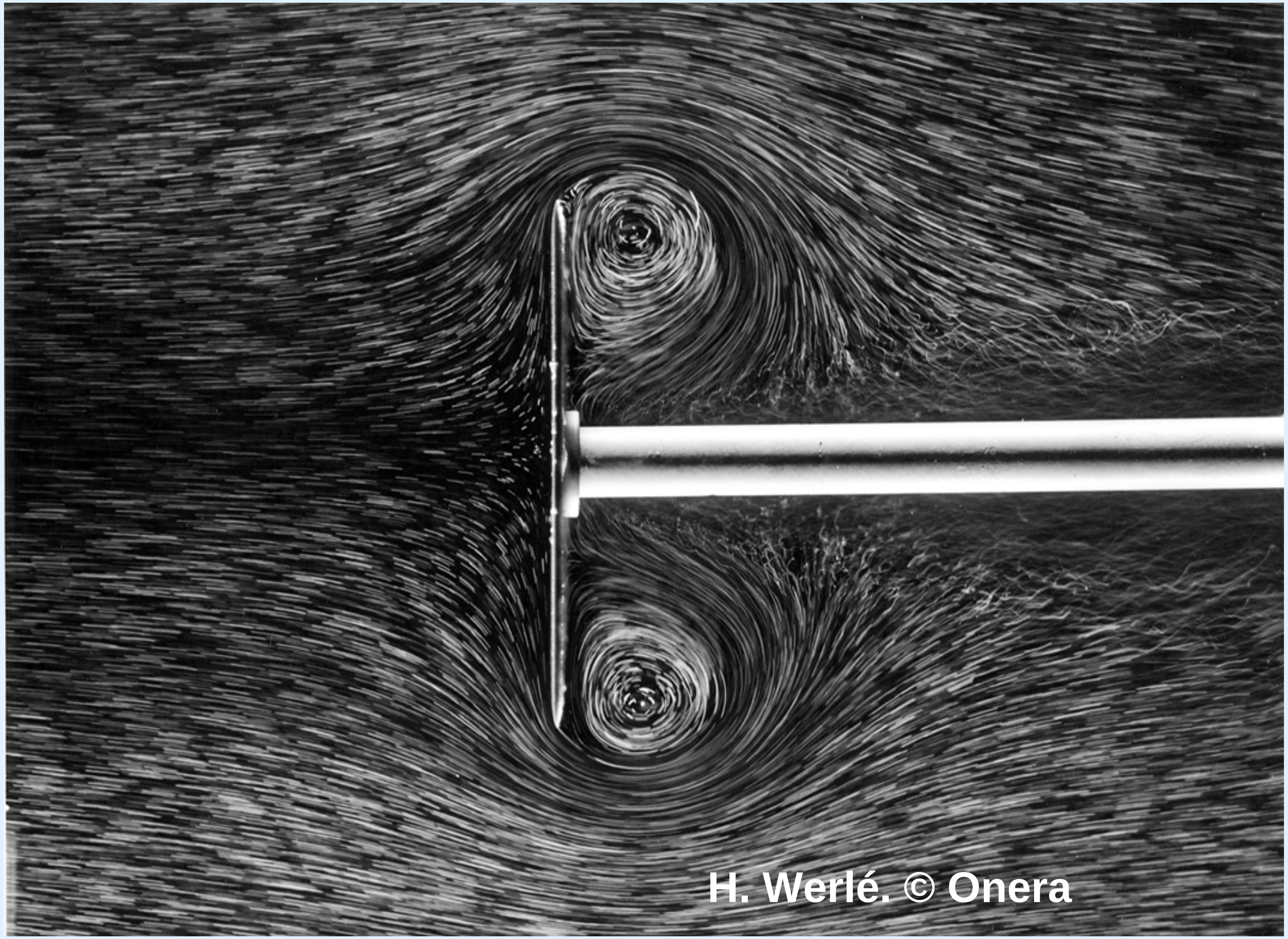


Flow in the meridian plane. Effective nearly axisymmetric flow

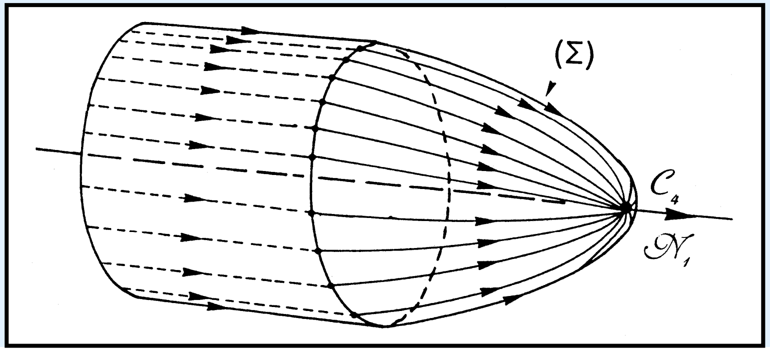
Non-propelled axisymmetric afterbody at zero incidence



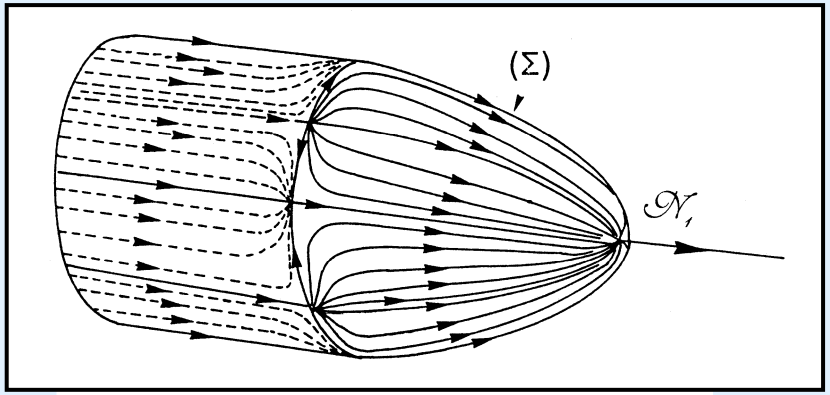
Flow behind a circular disk



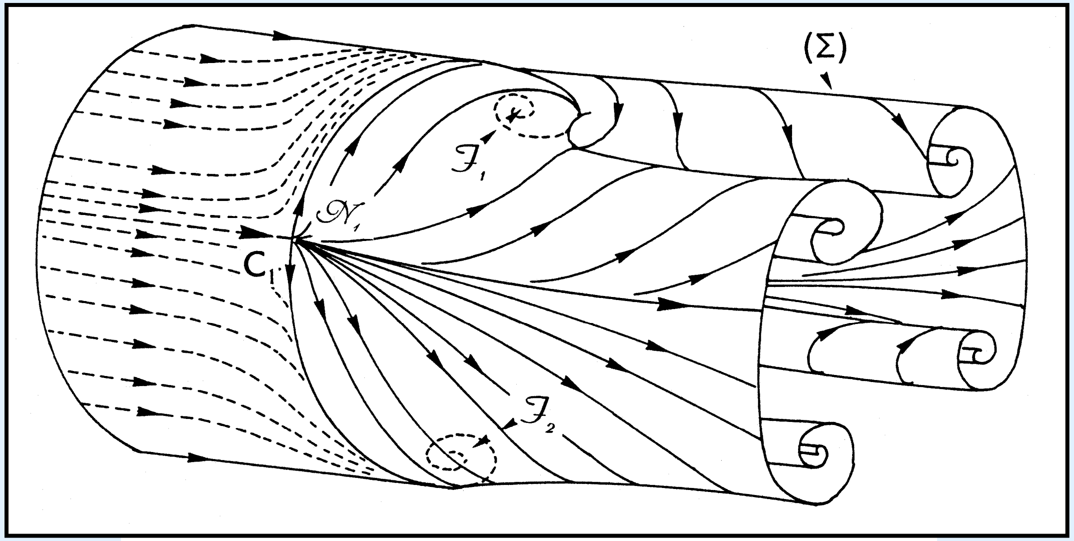
Non-propelled axisymmetric afterbody at zero incidence



Ideal axisymmetric case (improbable)



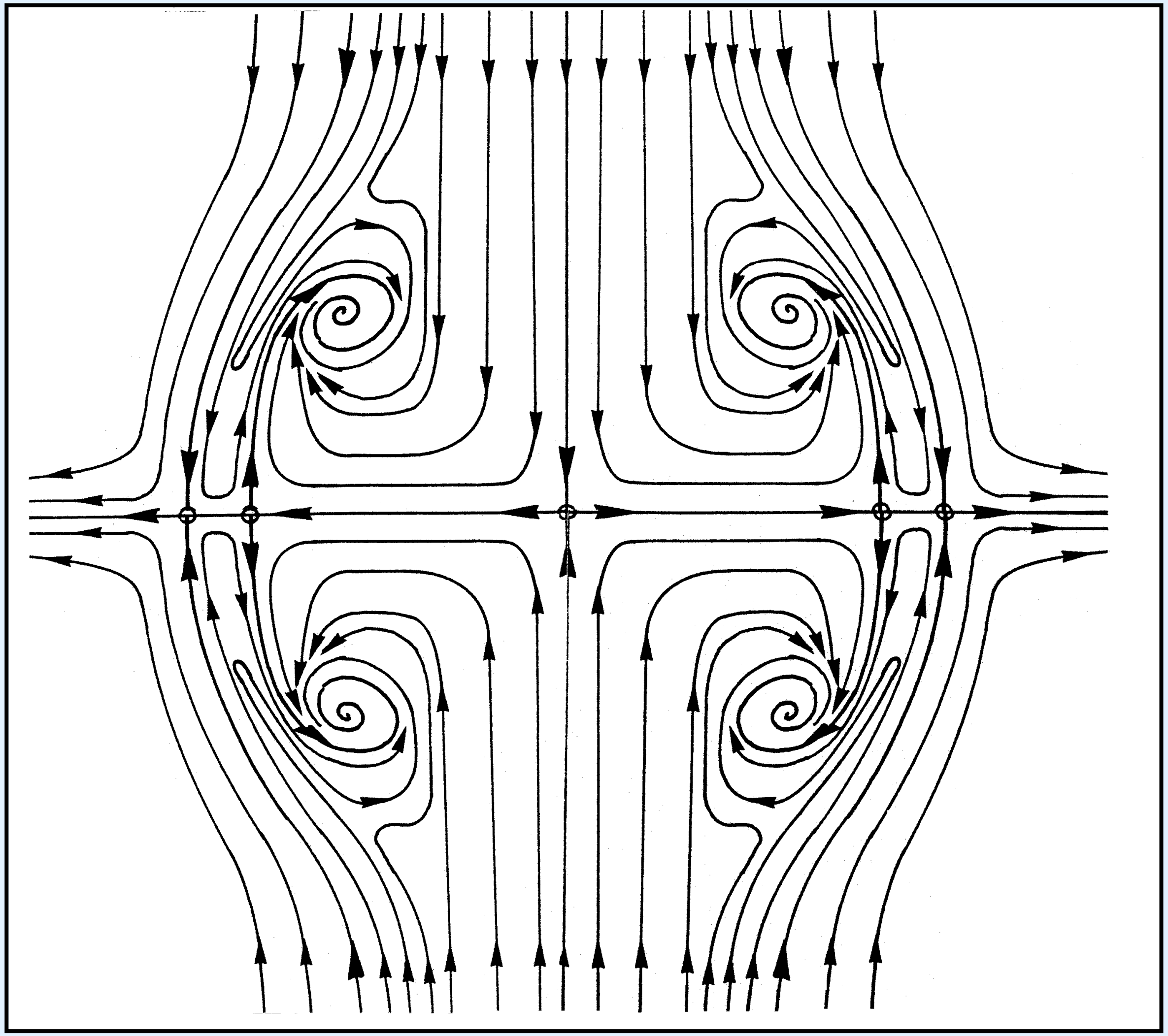
Cellular organisation



Two-vortex organisation

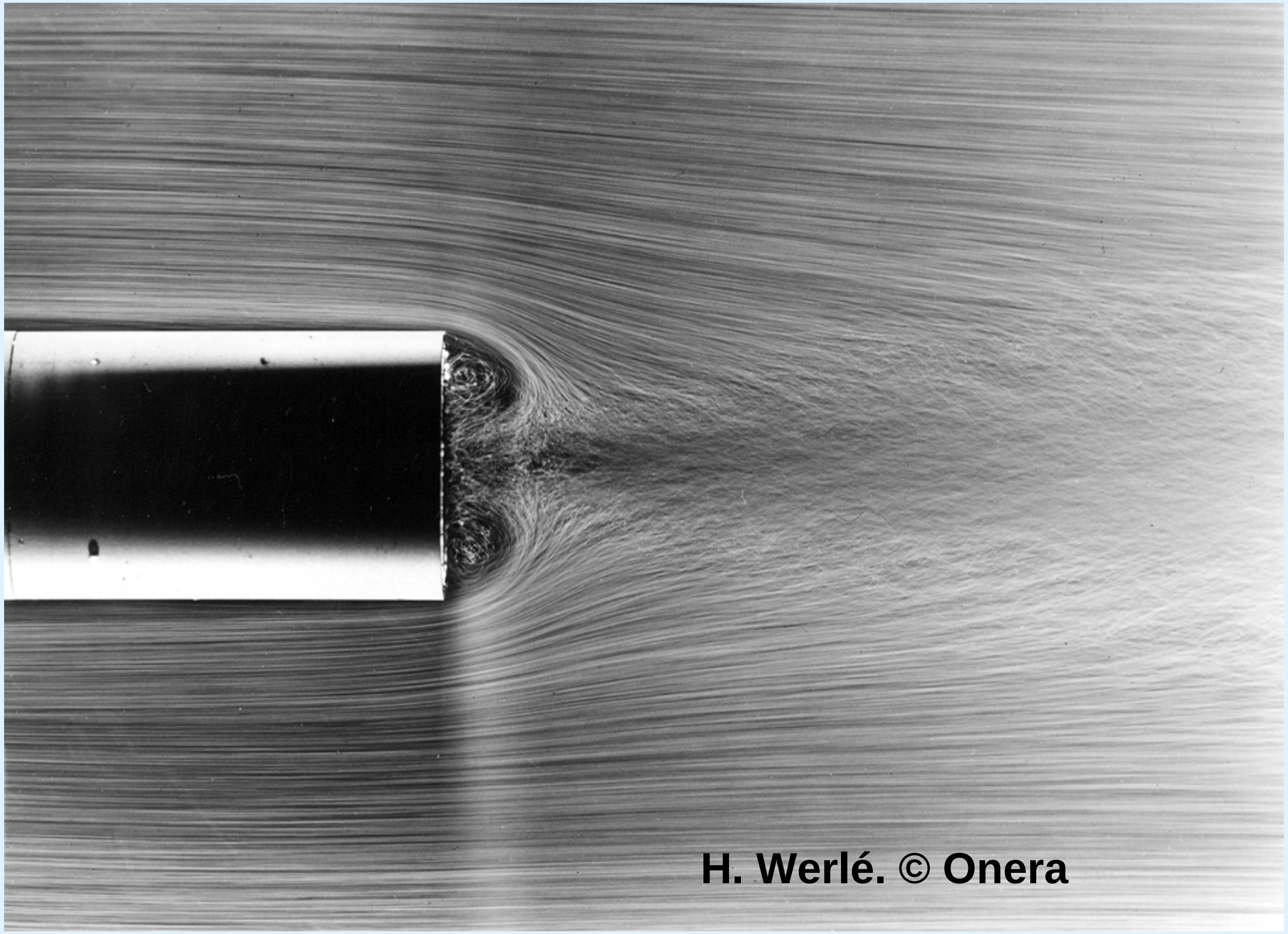
Skin friction lines and detachment surface at the base

Non-propelled axisymmetric afterbody at zero incidence

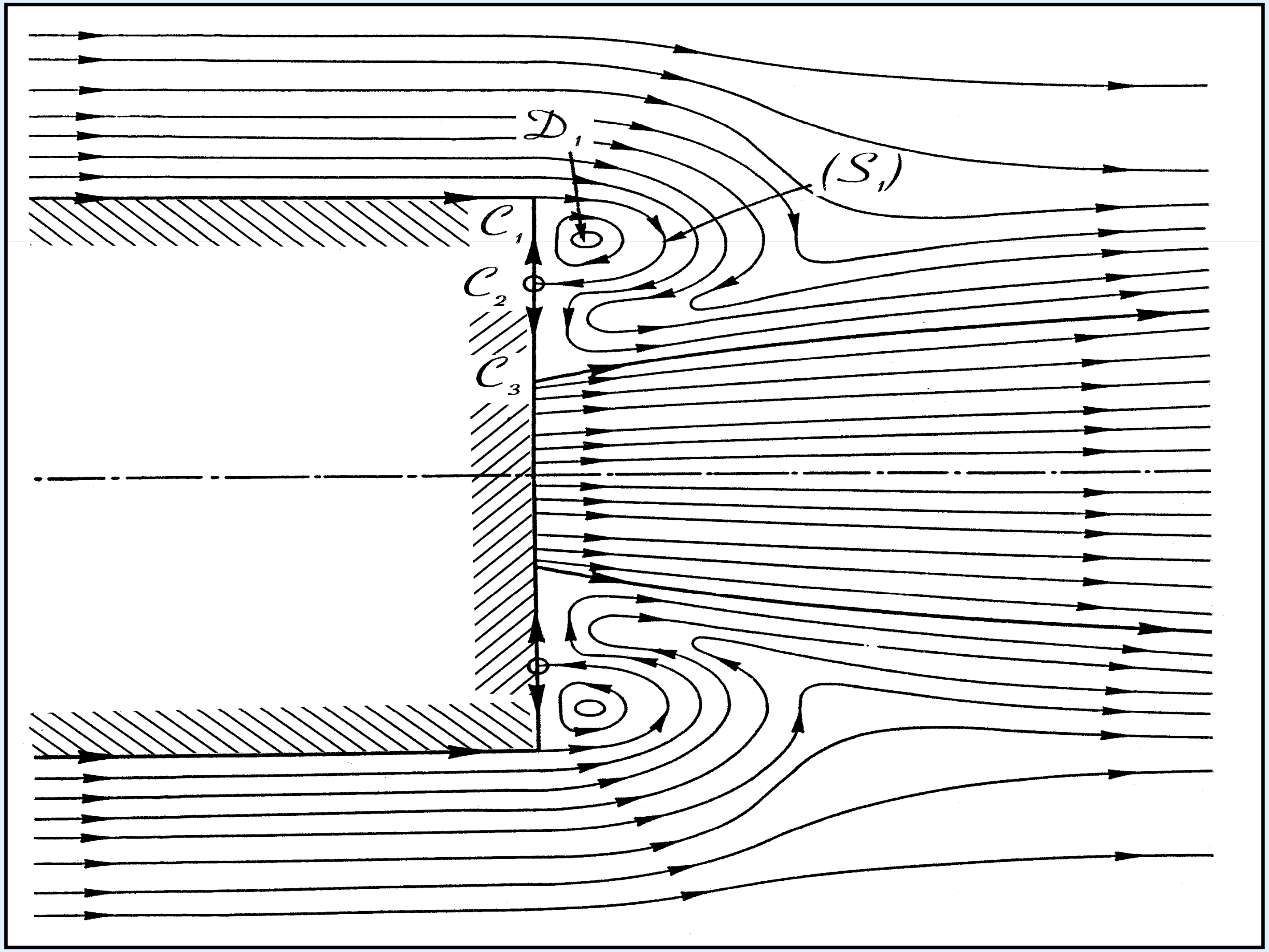


Two-vortex system. Field in a vertical downstream plane

Propelled axisymmetric afterbody at zero incidence

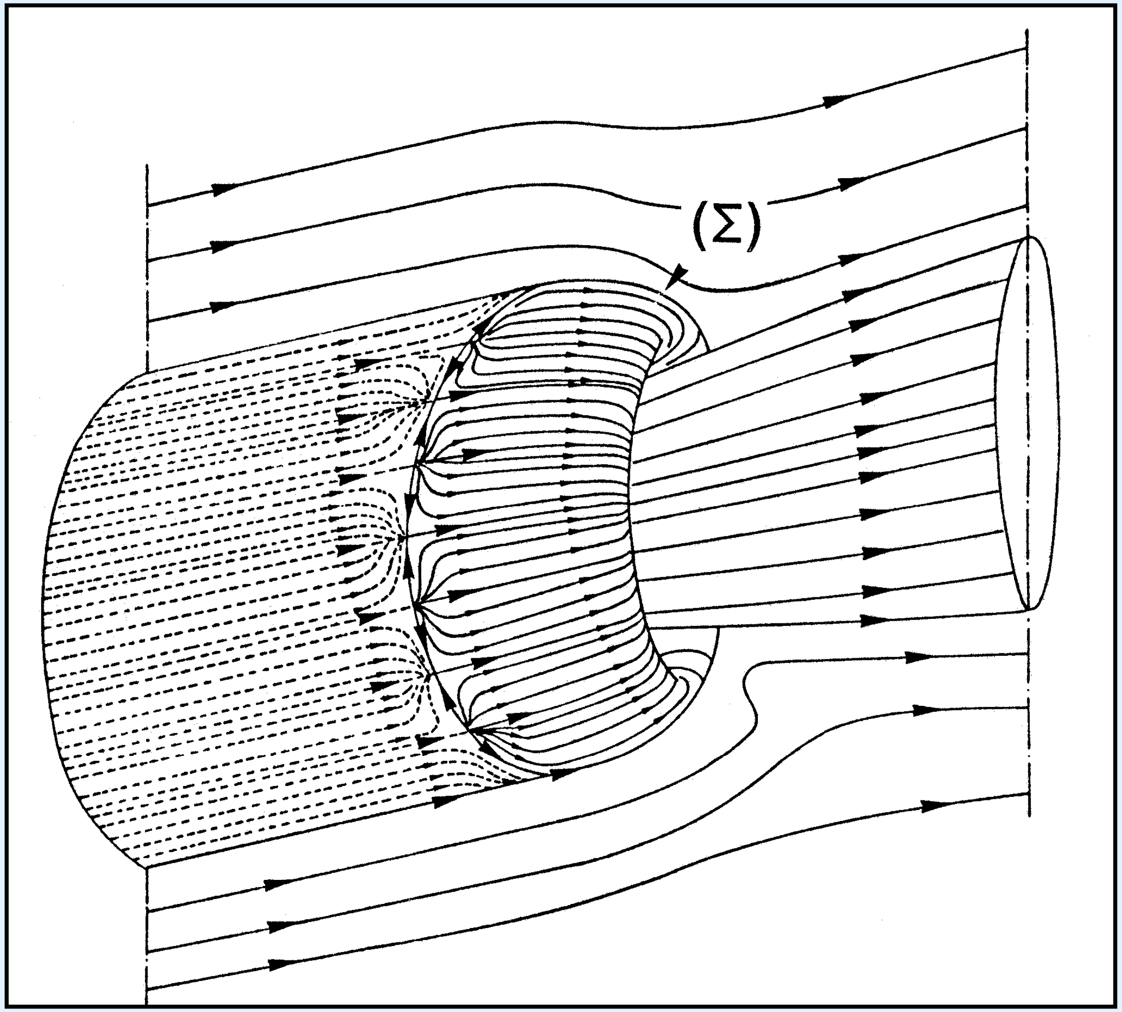


Propelled axisymmetric afterbody at zero incidence



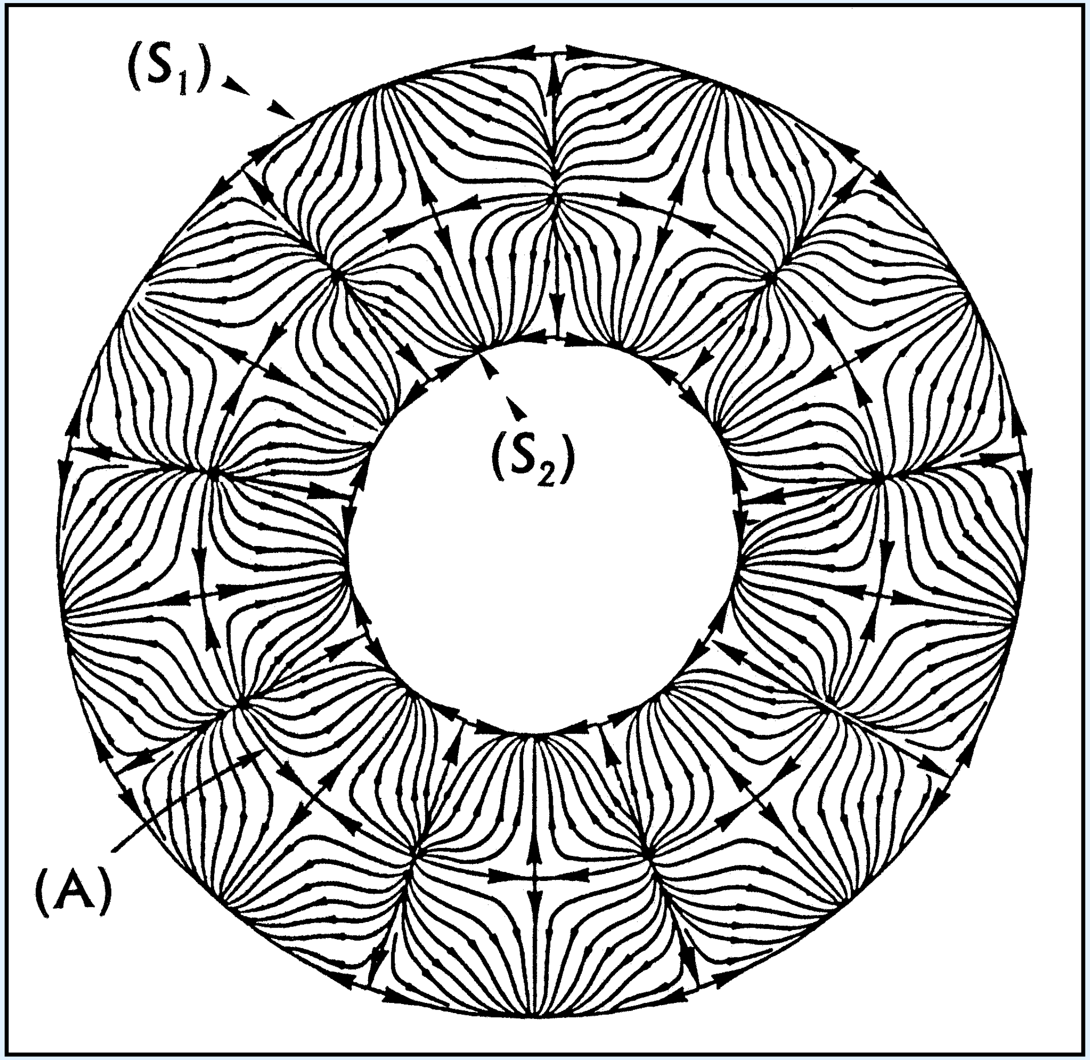
Meridian field. Ideal axisymmetric flow

Propelled axisymmetric afterbody at zero incidence



Cellular organisation. Separation surfaces

Propelled axisymmetric afterbody at zero incidence

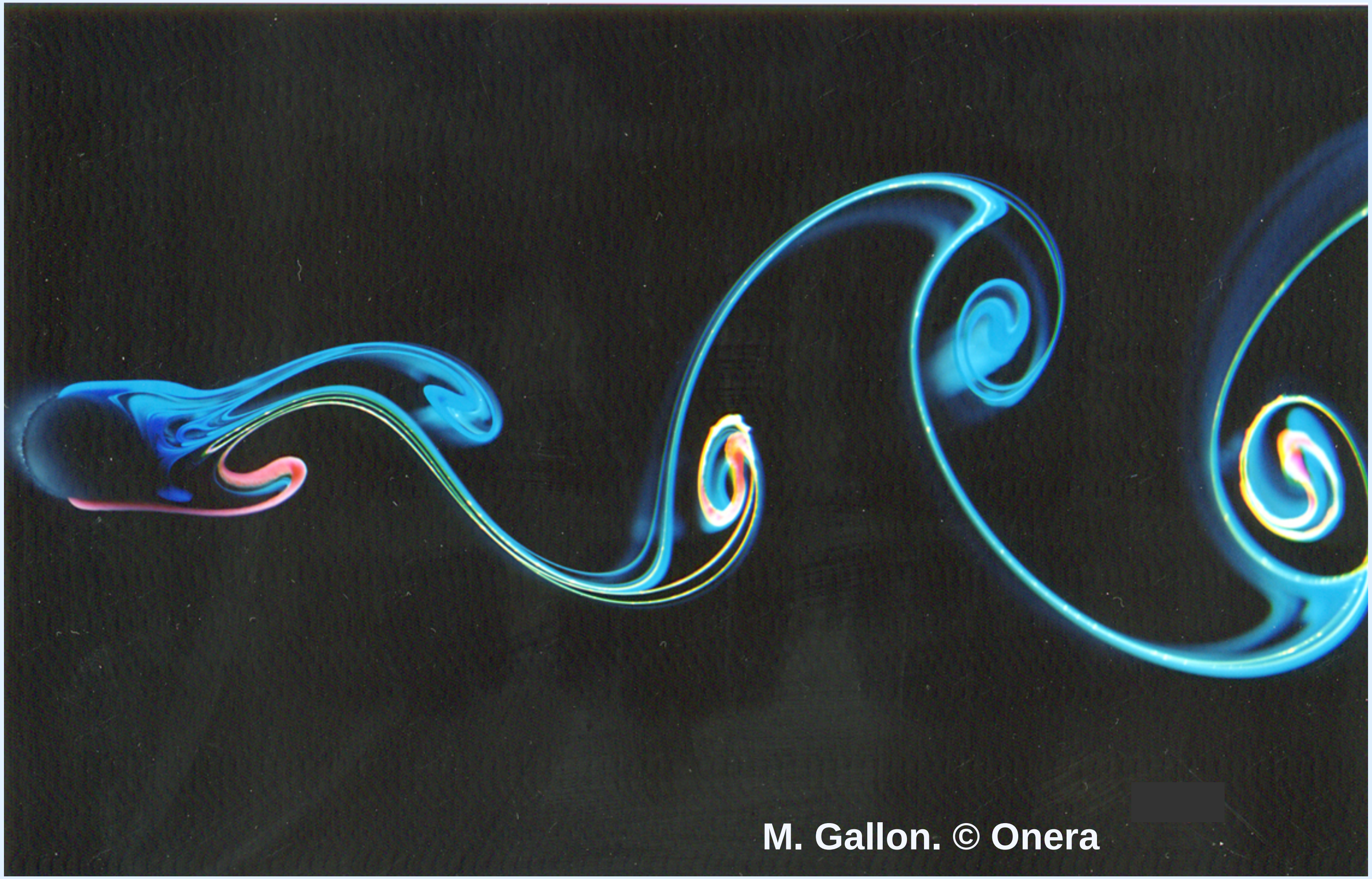


Cellular organisation. Skin friction line pattern on the base

Unsteady flow

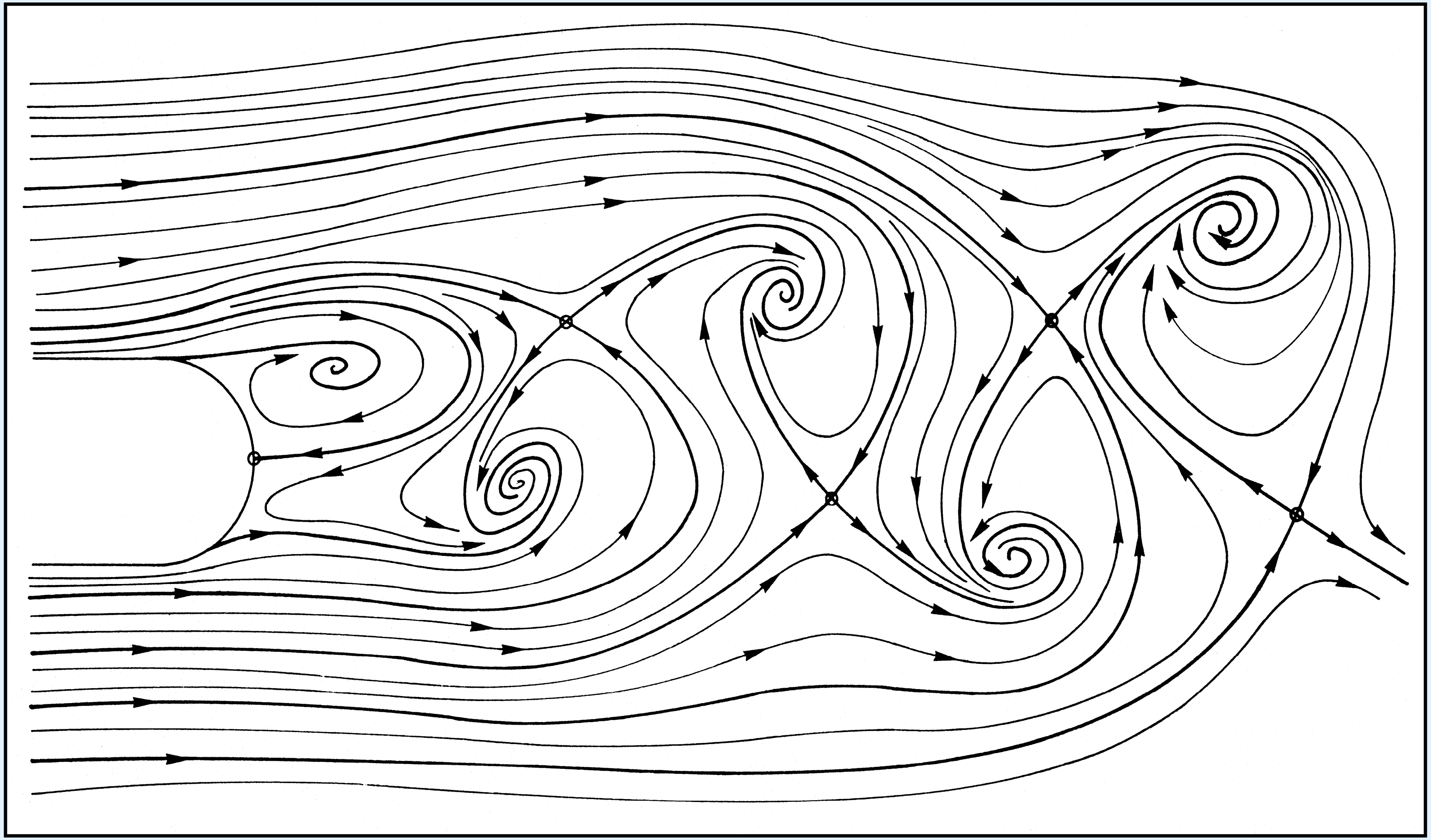
- The critical point theory and the resulting topological concepts can be applied to any vector field.
- If the flow is time dependant, the previous considerations are applied to the field at a given instant.
- Taking the time into consideration allows a still more faithful description of reality, the steady case being as inexistent as the two-dimensional case.
- The resulting analysis avoids the use of an average flow concept which is often acrobatic.

Karman vortex street behind a cylinder



Karman vortex street behind a cylinder

Instantaneous field topology



Concluding remarks (1)

➔ Application of two-dimensional concepts to three-dimensional flows can be highly misleading. In 3D it is necessary to introduce a new terminology more precise and more accurate.

➔ The critical point theory provides a tool – or grammar – allowing a rational description of three dimensional fields.

➔ The skin friction line patterns are the imprint on the surface of the outer flow. Their close examination and analysis are indispensable.

Concluding remarks (2)

➔ Modern investigation techniques – multi-hole pressure probes, LDV, PIV – coupled with powerful computing capacity may produce of a huge quantity of results.

➔ Construction of a topologically consistent picture of these results is a prerequisite to any attempt to understand the physics or separated thee-dimensional flows.

➔ The above remarks also apply to the results produced by computer codes solving the Navier-Stokes equations.