Fluid Kinematics

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Overview

- Fluid Kinematics deals with the motion of fluids without considering the forces and moments which create the motion.

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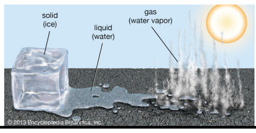
What is a fluid ?

Tension: Force per unit area
- Normal tension: perpendicular to the surface
- Shear tension: parallel to the surface

Materials respond differently to shear stresses:
- Solids deform non-permanently
- Plastics deform permanently
- Fluids do not resist: they flow

In a fluid at mechanical equilibrium the shear stresses are ZERO.

A fluid may be a gas or a liquid, characterized by: ρ, β, η



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Lagrangian Description

- Lagrangian description of fluid flow tracks the position and velocity of individual particles.
- Based upon Newton's laws of motion.
- Difficult to use for practical flow analysis.
  - Fluids are composed of *billions* of molecules.
  - Interaction between molecules hard to describe/model.
- However, useful for specialized applications
  - Sprays, particles, bubble dynamics, rarefied gases.
  - Coupled Eulerian-Lagrangian methods.
- Named after Italian mathematician Joseph Louis Lagrange (1736-1813).

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Eulerian Description

- Eulerian description of fluid flow: a **flow domain** or **control volume** is defined by which fluid flows in and out.
- We define **field variables** which are functions of space and time.
  - Pressure field, P=P(x,y,z,t)
  - Velocity field, $\vec{V} = \vec{V}(x, y, z, t)$

$$\vec{V} = u(x,y,z,t)\vec{i} + v(x,y,z,t)\vec{j} + w(x,y,z,t)\vec{k}$$

  - Acceleration field,

$$\vec{a} = \vec{a}(x, y, z, t)$$

$$\vec{a} = a_x(x,y,z,t)\vec{i} + a_y(x,y,z,t)\vec{j} + a_z(x,y,z,t)\vec{k}$$

  - These (and other) field variables define the **flow field**.
- Well suited for formulation of initial boundary-value problems (PDE's).
- Named after Swiss mathematician Leonhard Euler (1707-1783).

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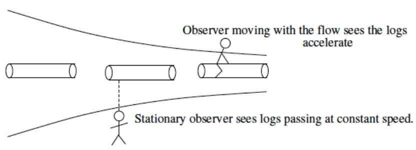
Example:Lagrange versus Euler



Rate of change of the velocity at a fixed point in the flow field versus the acceleration of a fluid particle, at that point.

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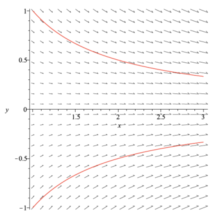
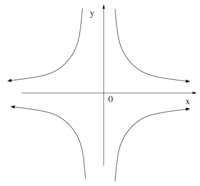
Hyperbolic 2d steady flow





$$u = kx, \quad v = -ky.$$

$$\frac{dx}{kx} = -\frac{dy}{kv}$$

$$|x||y| = e^C$$

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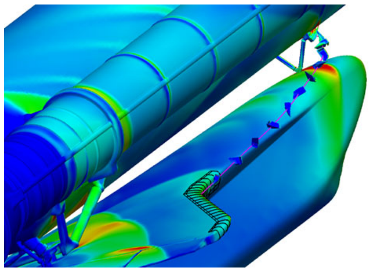
Example: Coupled Eulerian-Lagrangian Method



Forensic analysis of Columbia accident: simulation of shuttle debris trajectory using Eulerian CFD for flow field and Lagrangian method for the debris.

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Acceleration Field

- Consider a fluid particle and Newton's second law,

$$\vec{F}_{particle} = m_{particle}\vec{a}_{particle}$$

- The acceleration of the particle is the time derivative of the particle's velocity.

$$\vec{a}_{particle} = \frac{d\vec{V}_{particle}}{dt}$$

- However, particle velocity at a point is the same as the fluid velocity,

$$\vec{V}_{particle} = \vec{V}\left(x_{particle}(t), y_{particle}(t), z_{particle}(t)\right)$$

- To take the time derivative of $V_{particle}$ the chain rule must be used.

$$\vec{a}_{particle} = \frac{\partial \vec{V}}{\partial t}\frac{dt}{dt} + \frac{\partial \vec{V}}{\partial x}\frac{dx_{particle}}{dt} + \frac{\partial \vec{V}}{\partial y}\frac{dy_{particle}}{dt} + \frac{\partial \vec{V}}{\partial z}\frac{dz_{particle}}{dt}$$

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Acceleration Field

- Since $\frac{dx_{particle}}{dt} = u, \frac{dy_{particle}}{dt} = v, \frac{dz_{particle}}{dt} = w$

$$\vec{a}_{particle} = \frac{\partial \vec{V}}{\partial t} + u\frac{\partial \vec{V}}{\partial x} + v\frac{\partial \vec{V}}{\partial y} + w\frac{\partial \vec{V}}{\partial z}$$

- In vector form, the acceleration can be written as

$$\vec{a}(x,y,z,t) = \frac{d\vec{V}}{dt} = \frac{\partial \vec{V}}{\partial t} + \left(\vec{V} \cdot \vec{\nabla}\right)\vec{V}$$

- First term is called the **local acceleration** and is nonzero only for unsteady flows.
- Second term is called the **advective acceleration** and accounts for the effect of the fluid particle moving to a new location in the flow, where the velocity is different.

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Material Derivative

- The total derivative operator is called the **material derivative** and is often given special notation, D/Dt.

$$\frac{D\vec{V}}{Dt} = \frac{d\vec{V}}{dt} = \frac{\partial \vec{V}}{\partial t} + \left(\vec{V} \cdot \vec{\nabla}\right)\vec{V}$$

- Advective acceleration is nonlinear: source of many phenomena and primary challenge in solving fluid flow problems.
- Provides ``transformation'' between Lagrangian and Eulerian frames.
- Other names for the material derivative include: **total, particle,** and **substantial** derivative.

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Example (hyperbolic 2d steady flow)

- Consider an accelerating fluid flow, such as the logs flowing through a narrowing channel. Suppose,

$$\mathbf{u} = (U + kx, U - ky, 0).$$

- The advective term is

$$(\mathbf{u} \cdot \boldsymbol{\nabla})\mathbf{u} = \left((U + kx)\frac{\partial}{\partial x} + (U - ky)\frac{\partial}{\partial y}\right)(U + kx, U - ky, 0).$$

- Hence the acceleration of the log is

$$\frac{D\mathbf{u}}{Dt} = (k(U + kx), -k(U - ky), 0)$$

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Flow Visualization

- Flow visualization is the visual examination of flow-field features.
- Important for both physical experiments and numerical (CFD) solutions.
- Numerous methods
  - Streamlines and streamtubes
  - Pathlines
  - Streaklines
  - Timelines
  - Refractive techniques
  - Surface flow techniques

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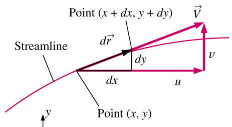
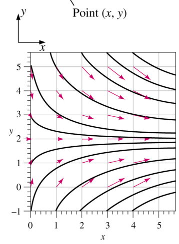
Streamlines





- A **Streamline** is a curve that is everywhere tangent to the *instantaneous* local velocity vector.
- Consider an arc length

$$d\vec{r} = dx\vec{i} + dy\vec{j} + dz\vec{k}$$

- $d\vec{r}$ must be parallel to the local velocity vector

$$\vec{V} = u\vec{i} + v\vec{j} + w\vec{k}$$

- Geometric arguments results in the equation for a streamline

$$\frac{dr}{V} = \frac{dx}{u} = \frac{dy}{v} = \frac{dz}{w}$$

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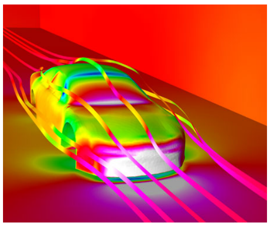
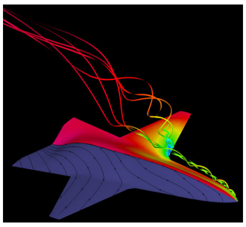
Streamlines

NASCAR surface pressure contours and streamlines



Airplane surface pressure contours, volume streamlines, and surface streamlines



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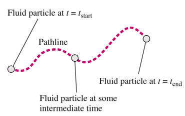
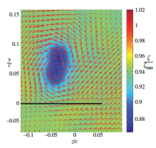
Pathlines





Stereo PIV measurements of the wing tip vortex in the wake of a NACA-66 airfoil at angle of attack.

- A **Pathline** is the actual path traveled by an individual fluid particle over some time period.
- Same as the fluid particle's material position vector

$$\left(x_{particle}(t), y_{particle}(t), z_{particle}(t)\right)$$

- Particle location at time t:

$$\vec{x} = \vec{x}_{start} + \int_{t_{start}}^{t} \vec{V} dt$$

- Particle Image Velocimetry (PIV) is a modern experimental technique to measure velocity field over a plane in the flow field.

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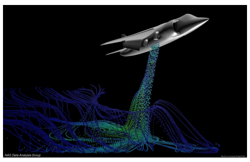
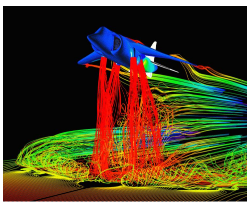
Streaklines





- A **Streakline** is the locus of fluid particles that have passed sequentially through a prescribed point in the flow.
- Easy to generate in experiments: dye in a water flow, or smoke in an airflow.

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Comparisons

- For steady flow, streamlines, pathlines, and streaklines are identical.
- For unsteady flow, they can be very different.
  - Streamlines are an instantaneous picture of the flow field.
  - Pathlines and Streaklines are flow patterns that have a time history associated with them.
  - Streakline: instantaneous snapshot of a time-integrated flow pattern.
  - Pathline: time-exposed flow path of an individual particle.

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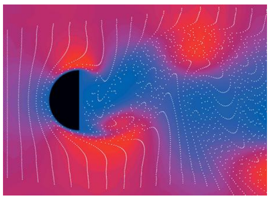
Timelines



- A **Timeline** is the locus of an array of fluid particles and it shows the position of the array at a given moment in time.
- If one point was taken on a timeline and traced with time, a pathline would be obtained.
- Timelines can be generated using a hydrogen bubble wire.

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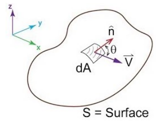
Flow rate

The **volumetric flow rate** is the volume of fluid which passes per unit time; usually it is represented by the symbol *Q*.

$$Q = \int \vec{V} \cdot \vec{n} dA$$



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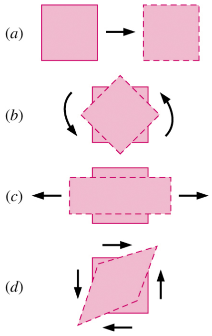
Kinematic Description



- In fluid mechanics, an element may undergo four fundamental types of motion.
  a) Translation
  b) Rotation
  c) Linear strain
  d) Shear strain
- Because fluids are in constant motion, motion and deformation is best described in terms of rates
  a) velocity: rate of translation
  b) angular velocity: rate of rotation
  c) linear strain rate: rate of linear strain
  d) shear strain rate: rate of shear strain

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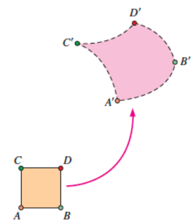
Example

A fluid element illustrating

- translation,
- rotation,
- linear strain,
- shear strain, and
- volumetric strain.



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Rate of Translation and Rotation

- To be useful, these rates must be expressed in terms of velocity and derivatives of velocity
- The **rate of translation vector** is described as the velocity vector. In Cartesian coordinates:

$$\vec{V} = u\vec{i} + v\vec{j} + w\vec{k}$$

- **Rate of rotation** at a point is defined as the average rotation rate of two initially perpendicular lines that intersect at that point. The rate of rotation vector in Cartesian coordinates:

$$\vec{\omega} = \frac{1}{2}\left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)\vec{i} + \frac{1}{2}\left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right)\vec{j} + \frac{1}{2}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\vec{k}$$

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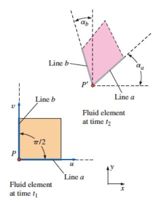
Rate of rotation (recap)



In 2d, $\omega = \frac{1}{2}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)$

In 3d, $\vec{\omega} = \frac{1}{2}\nabla \times \vec{V}$

Rate of rotation vector in Cartesian coordinates:

$$\vec{\omega} = \frac{1}{2}\left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)\vec{i} + \frac{1}{2}\left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right)\vec{j} + \frac{1}{2}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\vec{k}$$

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Linear Strain Rate

- **Linear Strain Rate** is defined as the rate of increase in length per unit length.
- In Cartesian coordinates

$$\varepsilon_{xx} = \frac{\partial u}{\partial x}, \varepsilon_{yy} = \frac{\partial v}{\partial y}, \varepsilon_{zz} = \frac{\partial w}{\partial z}$$

- Volumetric strain rate in Cartesian coordinates

$$\frac{1}{V}\frac{DV}{Dt} = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}$$

- Since the volume of a fluid element is constant for an incompressible flow, the volumetric strain rate must be zero.

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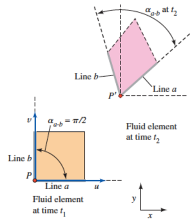
Shear Strain Rate



Shear Strain Rate at a point is defined as *half of the rate of decrease of the angle between two initially perpendicular lines that intersect at a point.*

$$\varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$$

Shear strain rate can be expressed in Cartesian coordinates as:

$$\varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right), \varepsilon_{zx} = \frac{1}{2}\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right), \varepsilon_{yz} = \frac{1}{2}\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)$$

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Shear Strain Rate

We can combine linear strain rate and shear strain rate into one symmetric second-order tensor called the **strain-rate tensor.**

$$\varepsilon_{ij} = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{pmatrix} = \begin{pmatrix} \frac{\partial u}{\partial x} & \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) & \frac{1}{2}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) \\ \frac{1}{2}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right) & \frac{\partial v}{\partial y} & \frac{1}{2}\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right) \\ \frac{1}{2}\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right) & \frac{1}{2}\left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right) & \frac{\partial w}{\partial z} \end{pmatrix}$$

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Shear Strain Rate

- Purpose of our discussion of fluid element kinematics:
  - Better appreciation of the inherent complexity of fluid dynamics
  - Mathematical sophistication required to fully describe fluid motion
- Strain-rate tensor is important for numerous reasons. For example,
  - Develop relationships between fluid stress and strain rate.
  - Feature extraction and flow visualization in CFD simulations.

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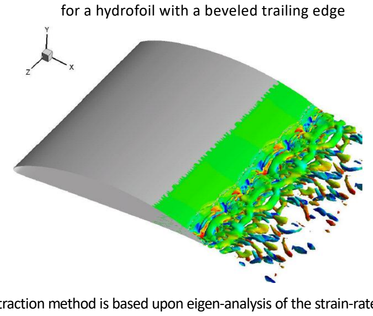
Shear Strain Rate

Example: Visualization of trailing-edge turbulent eddies for a hydrofoil with a beveled trailing edge



Feature extraction method is based upon eigen-analysis of the strain-rate tensor.

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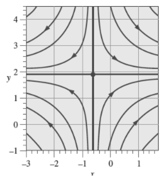
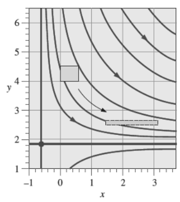
Example (hyperbolic 2d steady flow)

$$\vec{V} = (u, v) = (0.5 + 0.8\,x)\vec{i} + (1.5 - 0.8\,y)\vec{j}$$



Rate of translation: $u = 0.5 + 0.8x \quad v = 1.5 - 0.8y \quad w = 0$

Rate of rotation: $\vec{\omega} = \frac{1}{2}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\vec{k} = \frac{1}{2}(0 - 0)\vec{k} = 0$



$$\varepsilon_{xx} = \frac{\partial u}{\partial x} = 0.8\ \mathrm{s}^{-1} \quad \varepsilon_{yy} = \frac{\partial v}{\partial y} = -0.8\ \mathrm{s}^{-1} \quad \varepsilon_{zz} = 0$$

$$\varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) = \frac{1}{2}(0 + 0) = 0$$

$$\frac{1}{V}\frac{DV}{Dt} = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} = (0.8 - 0.8 + 0)\ \mathrm{s}^{-1} = 0$$

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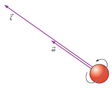
Vorticity and Rotationality

- The **vorticity vector** is defined as the curl of the velocity vector

$$\vec{\zeta} = \vec{\nabla} \times \vec{V}$$

- Vorticity is equal to twice the angular velocity of a fluid particle.



$$\vec{\zeta} = 2\vec{\omega}$$

Cartesian coordinates

$$\vec{\zeta} = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)\vec{i} + \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right)\vec{j} + \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\vec{k}$$

Cylindrical coordinates

$$\vec{\zeta} = \left(\frac{1}{r}\frac{\partial u_z}{\partial \theta} - \frac{\partial u_\theta}{\partial z}\right)\vec{e}_r + \left(\frac{\partial u_r}{\partial z} - \frac{\partial u_z}{\partial r}\right)\vec{e}_\theta + \left(\frac{\partial (r u_\theta)}{\partial r} - \frac{\partial u_r}{\partial \theta}\right)\vec{e}_z$$

- In regions where $\zeta = 0$, the flow is called **irrotational.**
- Elsewhere, the flow is called **rotational.**

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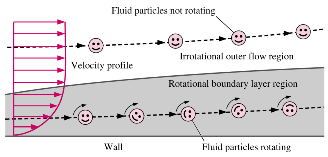
Vorticity and Rotationality



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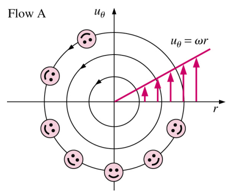
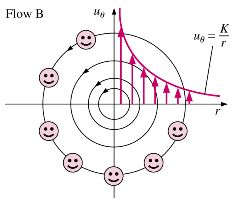
Comparison of Two Circular Flows

Special case: consider two flows with circular streamlines





(b)

$u_r = 0, u_\theta = \omega r$

$$\vec{\zeta} = \frac{1}{r}\left(\frac{\partial (r u_\theta)}{\partial r} - \frac{\partial u_r}{\partial \theta}\right)\vec{e}_z = \frac{1}{r}\left(\frac{\partial (\omega r^2)}{\partial r} - 0\right)\vec{e}_z = 2\omega\vec{e}_z$$

$u_r = 0, u_\theta = \frac{K}{r}$

$$\vec{\zeta} = \frac{1}{r}\left(\frac{\partial (r u_\theta)}{\partial r} - \frac{\partial u_r}{\partial \theta}\right)\vec{e}_z = \frac{1}{r}\left(\frac{\partial (K)}{\partial r} - 0\right)\vec{e}_z = 0\vec{e}_z$$

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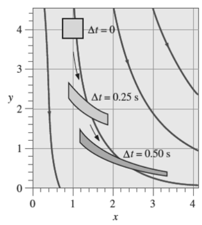
Example



$$\vec{V} = (u, v) = x^2\vec{i} + (-2xy - 1)\vec{j}$$

Vorticity: $\vec{\zeta} = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\vec{k} = (-2y - 0)\vec{k} = -2y\vec{k}$

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Reynolds—Transport Theorem (RTT)

- A **system** is a quantity of matter of fixed identity. *No mass can cross a system boundary.*
- A **control volume** is a region in space chosen for study. Mass can cross a control surface.
- The fundamental conservation laws (conservation of mass, energy, and momentum) apply directly to systems.
- However, in most fluid mechanics problems, control volume analysis is preferred over system analysis (for the same reason that the Eulerian description is usually preferred over the Lagrangian description).
- Therefore, we need to transform the conservation laws from a system to a control volume. This is accomplished with the Reynolds transport theorem (RTT).

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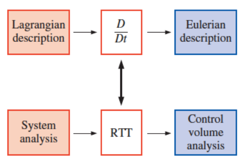
Reynolds—Transport Theorem (RTT)



There is an analogy between the transformation from Lagrangian to Eulerian descriptions (for differential analysis using infinitesimally small fluid elements) and that from systems to control volumes (for integral analysis using finite flow fields).

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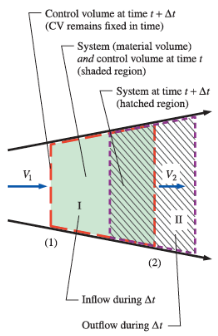
System and control volume (simple geometry)



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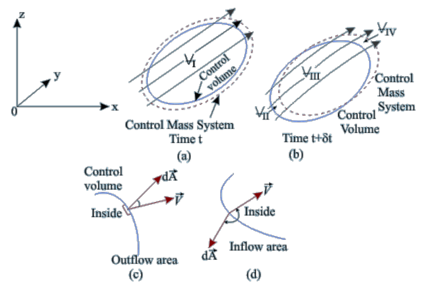
Control Volume (general)



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Reynolds—Transport Theorem (RTT)

- Material derivative (differential analysis):

$$\frac{Db}{Dt} = \frac{\partial b}{\partial t} + \left(\vec{V} \bullet \vec{\nabla}\right) b$$

- General RTT (integral analysis):

$$\frac{dB_{sys}}{dt} = \int_{CV} \frac{\partial}{\partial t}(\rho b)\, d\mathcal{V} + \int_{CS} \rho b \vec{V} \bullet \vec{n} dA$$

- Interpretation of the RTT:
  - Time rate of change of the property B of the system is equal to (Term 1) + (Term 2)
  - Term 1: the time rate of change of B of the control volume
  - Term 2: the net flux of B out of the control volume by mass crossing the control surface

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RTT Special Cases

For **moving** and/or **deforming** control volumes,

$$\frac{dB_{sys}}{dt} = \frac{d}{dt}\int_{CV} \rho b \, d\mathcal{V} + \int_{CS} \rho b \vec{V}_r \cdot \vec{n} \, dA$$

- Where the absolute velocity V in the second term is replaced by the **relative velocity** $V_r = V - V_{CS}$
- V_r is the fluid velocity expressed relative to a coordinate system moving **with** the control volume.
- This can also be written as (Leibnitz Theorem)

$$\frac{dB_{sys}}{dt} = \int_{CV} \frac{\partial}{\partial t}(\rho b)\, d\mathcal{V} + \int_{CS} \rho b \vec{V} \cdot \vec{n} \, dA$$

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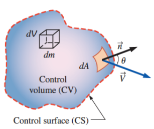
Conservation of mass (continuity equation)

- Integral form

$$\frac{\partial}{\partial t}\int_{CV} \rho \, d\mathcal{V} + \int_{CS} \rho \vec{V} \cdot d\vec{A} = 0$$

$$\frac{\partial}{\partial t}\int_{CV} \rho \, d\mathcal{V} \quad = \quad -\int_{CS} \rho \vec{V} \cdot d\vec{A}$$

Rate of increase of mass in CV = Net influx of mass



General conservation of mass: $\quad \frac{d}{dt}\int_{CV} \rho \, dV + \int_{CS} \rho(\vec{V} \cdot \vec{n})\, dA = 0$

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Conservation of mass (continuity equation)

Differential form

- Use Stokes Theorem to transform the surface integral into a volume integral and equate the integrands,

$$\nabla \cdot (\rho \vec{V}) = -\frac{\partial \rho}{\partial t}$$

- For an incompressible fluid (constant density) the continuity equation reduces to

$$\nabla \cdot \vec{V} = 0$$

and the velocity field has ZERO divergence.

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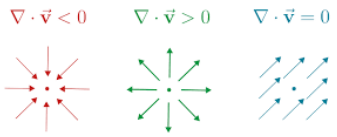
Simple examples of field divergence



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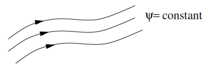
Streamfunction ψ

- If the fluid is incompressible $\boldsymbol{\nabla} \cdot \mathbf{u} = 0$
- Then the 2d flow field can be written as

$$\mathbf{u} = \boldsymbol{\nabla} \times \mathbf{A} = \left(\frac{\partial \psi}{\partial y}, -\frac{\partial \psi}{\partial x}, 0 \right)$$

with
$$u = \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial x}.$$

- The streamfunction is constant along a streamline
- For steady flows, the streamlines do not cro does not cross the streamlines.



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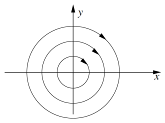
Example: Vortex

$$\mathbf{u} = \frac{a}{x^2 + y^2}(y, -x) \equiv (u, v).$$



$$\psi = \frac{a}{2} \ln \left(x^2 + y^2\right)$$

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