B22

Fluid Dynamics IB
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Example Sheet 1

1. A steady two-dimensional flow (pure straining) is given by $u = \alpha x$, $v = -\alpha y$ with α constant.
 (i) Find the equation for a general streamline of the flow, and sketch some of them.
 (ii) At $t = 0$ the fluid on the curve $x^2 + y^2 = a^2$ is marked (by an electro-chemical technique). Find the equation for this material fluid curve for $t > 0$.
 (iii) Does the area within the curve change in time, and why?

2. Repeat question 1 for the two-dimensional flow (simple shear) given by $u = \gamma y$, $v = 0$ with γ constant. Which of the two flows stretches the curve faster at long times?

3. A two-dimensional flow is represented by a streamfunction $\psi(x, y)$ with $u = \partial\psi/\partial y$ and $v = -\partial\psi/\partial x$. Show that
 (i) the streamlines are given by $\psi = \text{const}$,
 (ii) $|\mathbf{u}| = |\nabla\psi|$, so that the flow is faster where the streamlines are closer,
 (iii) the volume flux crossing any curve from $\mathbf{x}_0$ to $\mathbf{x}_1$ is given by $\psi(\mathbf{x}_1) - \psi(\mathbf{x}_0)$,
 (iv) $\psi = \text{const}$ on any *fixed* (i.e. stationary) boundary.
 [Hint for (iii): $\mathbf{n}\,ds = (dy, -dx)$.]

4. Verify that the two-dimensional flow given in Cartesian coordinates by

$$u = \frac{y - b}{(x-a)^2 + (y-b)^2}, \qquad v = \frac{a - x}{(x-a)^2 + (y-b)^2}$$

satisfies $\nabla\cdot\mathbf{u} = 0$, and then find the streamfunction $\psi(x, y)$ such that $u = \partial\psi/\partial y$ and $v = -\partial\psi/\partial x$. Sketch the streamlines.

5. Verify that the two-dimensional flow given in polar coordinates by

$$u_r = U\left(1 - \frac{a^2}{r^2}\right)\cos\theta, \qquad u_\theta = -U\left(1 + \frac{a^2}{r^2}\right)\sin\theta$$

satisfies $\nabla\cdot\mathbf{u} = 0$, and find the streamfunction $\psi(r, \theta)$. Sketch the streamlines.

$$\left[\text{Take:} \quad \nabla\cdot\mathbf{u} = \frac{1}{r}\frac{\partial}{\partial r}(r u_r) + \frac{1}{r}\frac{\partial}{\partial\theta}(u_\theta) \quad \text{and} \quad u_r = \frac{1}{r}\frac{\partial\psi}{\partial\theta}, \quad u_\theta = -\frac{\partial\psi}{\partial r}\right]$$

6. Verify that the axisymmetric flow (uniaxial straining) given in cylindrical polar coordinates by $u_r = -\frac{1}{2}\alpha r$, $u_z = \alpha z$ satisfies $\nabla\cdot\mathbf{u} = 0$, and find the Stokes streamfunction $\Psi(r, z)$. Sketch the streamlines.

$$\left[\text{Take:} \quad \nabla\cdot\mathbf{u} = \frac{1}{r}\frac{\partial}{\partial r}(r u_r) + \frac{\partial u_z}{\partial z} \quad \text{and} \quad u_r = -\frac{1}{r}\frac{\partial\Psi}{\partial z}, \quad u_z = \frac{1}{r}\frac{\partial\Psi}{\partial r}\right]$$

7. Consider the two-dimensional flow $u = 1/(1+t)$, $v = 1$ in $t > -1$. Find and sketch
(i) the streamline at $t = 0$ which passes through the point $(1, 1)$,
(ii) the path of a fluid particle which is released from $(1, 1)$ at $t = 0$,
(iii) the position at $t = 0$ of a streak of dye released from $(1, 1)$ during the time interval $-1 < t \leq 0$.

8. An axisymmetric jet of water of speed $1\,\mathrm{m\,s^{-1}}$ and cross-section $6\times10^{-4}\,\mathrm{m}^2$ strikes a wall at right angles and spreads out over it. By using the momentum integral equation, calculate the force on the wall due to the jet. [Neglect gravity.]

9. Starting from the Euler momentum equation for a fluid of constant density with a potential force $-\nabla\chi$, show that for a fixed volume V enclosed by surface A

$$\frac{d}{dt}\int_V \tfrac{1}{2}\rho u^2\, dV \;+\; \int_A H\mathbf{u}\cdot\mathbf{n}\, dA \;=\; 0$$

where $H = \frac{1}{2}\rho u^2 + p + \chi$ is the Bernoulli quantity, so concluding that H is the transportable energy.

10. How high can water rise up one's arm hanging in the river from a lazy $(1\,\mathrm{m\,s^{-1}})$ punt? [Use Bernoulli on surface streamline, where $p = 1$ atmosphere.]

11. A rotating circular tank of radius a is filled with a volume V of fluid of density ρ. The tank is allowed to rotate for a long time, until the flow is a two-dimensional rigid-body motion with constant angular velocity ω around the axis (so that $u = -\omega y$, $v = \omega x$, $w = 0$, $\rho = $ const). Derive the equation for the pressure, p, at any point in the rotating fluid. What is the equation for the height $h(r)$ of the free surface? (Hint: Integrate the Euler equation to find the pressure and determine the constant of integration from the volume conservation).

12. Waste water flows into a tank at $10^{-4}\,\mathrm{m^3\,s^{-1}}$ and out of a short exit pipe of cross-section $4 \times 10^{-5}\,\mathrm{m}^2$ into the air. In steady state, estimate how high above the pipe is the water in the tank?

13. A water clock is an axisymmetric vessel with a small exit pipe in the bottom. Find the shape for which the water level falls equal heights in equal intervals of time.

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