

SOE3152

UNIVERSITY OF EXETER

**SCHOOL OF ENGINEERING AND
COMPUTER SCIENCE**

DEPARTMENT OF ENGINEERING

Fluid Dynamics A

Time allowed : TWO HOURS

September 2002

Full marks may be obtained from full answers to three questions. Candidates have a free choice of questions.

For **DEFERRED** candidates, the marks for this module are calculated from the better of : 70% of the percentage mark for this paper plus 30% of the percentage mark for associated coursework, or 100% of the percentage mark for this paper.

For **REFERRED** candidates, the marks for this module are calculated from 100% of the mark for this paper. The maximum mark that can be achieved is 40%.

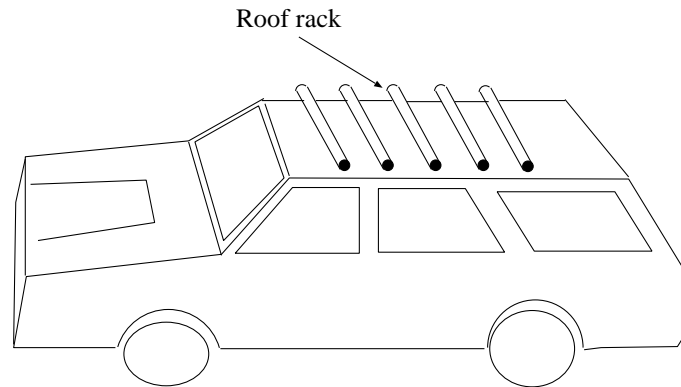
This is a **closed book** examination. Candidates are permitted to use approved portable calculators. A separate formula and data sheet has been provided. Graph paper will be provided on request.

SECTION A

Question 1 (20 marks)

1(a) (5 marks) Sketch the different flow patterns you would expect to see behind a cylinder oriented with its axis normal to the flow at Re between 0.1 and 50,000.

1(b) (3 marks) A car roof rack consists of 5 cylindrical bars 1.8m in length and 1.4cm in diameter across the roof of the car, as shown in the figure below :



The roof is 2m in length. If the car is driven at 80km/hr, what is the drag force exerted on each bar?

1(c) (5 marks) What is the ratio of the the drag on the roofrack to the drag on the roof?

1(d) (2 marks) At what frequency do the bars vibrate?

1(e) (5 marks) How can drag be reduced on a moving body?

Question 2 (20 marks)

2(a) (8 marks) The torque developed by a water turbine depends on the volumetric discharge Q , head H , density ρ , angular velocity ω and efficiency η . Use dimensional analysis to find an expression for the torque.

2(b) (4 marks) A centrifugal fan delivering $2.5 \text{ m}^3/\text{s}$ of air at 20° C runs at 900 RPM. The impeller outer diameter is 80 cm and the inner diameter is 50 cm. The impeller blade width at inlet is 18 cm, and the blades are set at 20.6° . Is the no-shock condition fulfilled? Assume zero whirl at the inlet.

2(c) (4 marks) In part b. the blades are shaped so that the flow velocity is independent of radius. The blades are set at an angle of 50° at the outlet. Draw the outlet velocity triangle. What is the blade width at the outlet?

2(d) (4 marks) Calculate the theoretical head developed by the fan. What might account for the difference between the theoretical and actual heads developed?

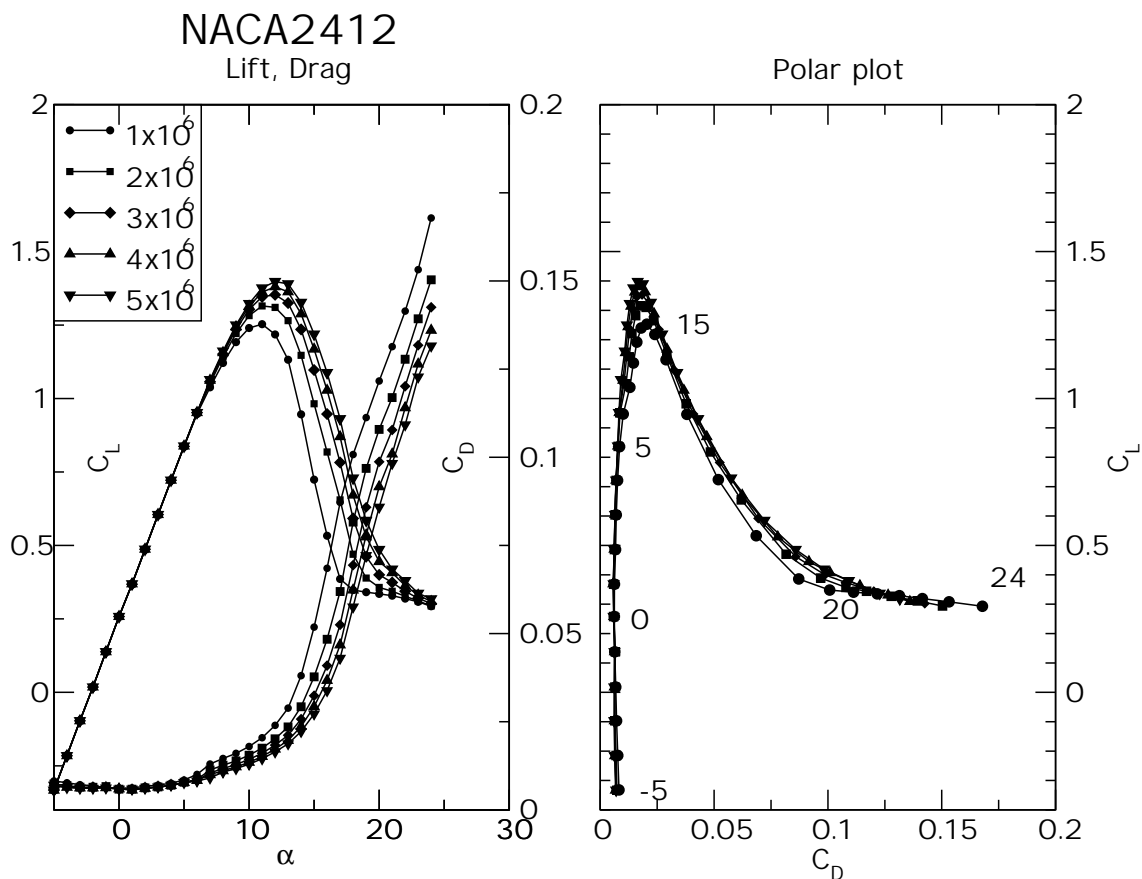
Question 3 (20 marks)

3(a) (8 marks) How does an aerofoil generate lift? Contrast the designs of wing for **i.** a human powered aircraft and **ii.** a jet fighter.

3(b) (6 marks) A light aircraft has two wings each of span 5 m and constant chord 0.8 m, designed using the NACA2412 airfoil (plots appended). The wings are set at an angle of 3° to the horizontal. If the aircraft is flying at 3000 m at 252 km/hr, calculate its total mass and the drag on the wings.

3(c) (4 marks) The wings of the aircraft in the preceeding section are equipped with flaps which can be lowered during takeoff and landing. Explain how these operate. If the flaps increase the lift coefficient C_L by 0.5 and the drag by 0.2, calculate the minimum speed that the aircraft must achieve to take off.

3(d) (2 marks) Estimate the maximum power that the engines must produce. What other effects are likely to contribute to this?



SECTION B

Question 4 (20 marks)

4(a) (5 marks) Define the following terms :

- i. Kolmogorov length scale
- ii. The time average of a fluctuating quantity $a(t)$.
- iii. The “Law of the Wall”

4(b) (5 marks) Describe the structure of a turbulent boundary layer. Your answer should include a sketch.

4(c) (4 marks) Air at $T = 20^\circ \text{C}$ and atmospheric pressure flows with a free stream velocity of 20 m/s over a flat plate. Calculate the boundary layer thickness at a point 2 m from the leading edge of the plate, given that the empirical expression

$$\frac{\delta}{x} = \frac{0.376}{\text{Re}_x^{0.2}}$$

holds, and assuming that the boundary layer is turbulent. Justify this last assumption.

4(d) (6 marks) The wall shear stress at this point in the flow is $\tau_0 = 0.71 \text{ kg m}^{-1} \text{ s}^{-2}$. Calculate the Prandtl mixing length 1 cm from the wall, assuming that the wall shear stress is a constant through the boundary layer, and that the flow profile obeys the log law.

Question 5 (20 marks)

5(a) (8 marks) A decaying flow is described by the vector formula

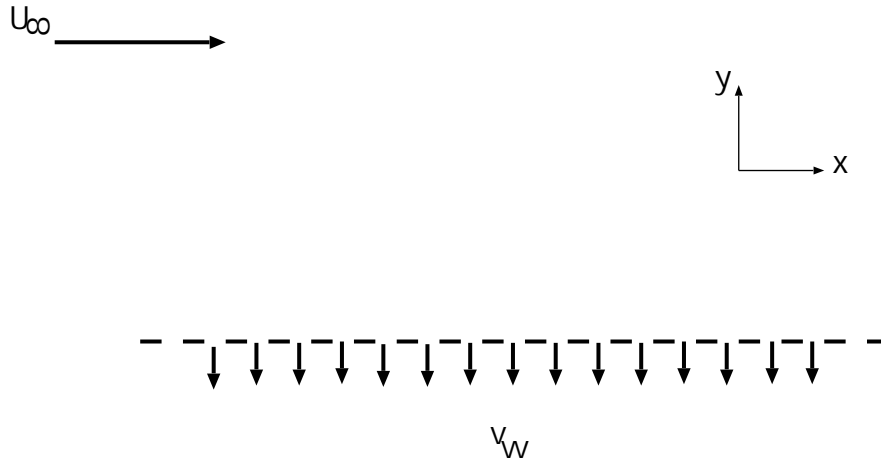
$$\underline{u} = \underline{i}xe^{-t} - \underline{j}ye^{-t}$$

Evaluate

i. $\nabla \cdot \underline{u}$ ii. $\frac{D\underline{u}}{Dt}$

Is the flow incompressible?

5(b) (4 marks) An incompressible fluid is flowing past a flat plate, forming a boundary layer. However the plate is slightly porous, and fluid is being sucked away at a constant speed v_w , as shown in the diagram :



The fluid removal rate is adjusted so that the boundary layer is of a constant thickness, and so the flow is steady and uniform in the x direction.

What is the value of u_x as $y \rightarrow \infty$ (i.e. a long way away from the plate)? Use the continuity equation to show that the y component of the velocity, u_y is uniform throughout the boundary layer and find its value.

5(c) (8 marks) For this case the Navier-Stokes equation for u_x reduces to

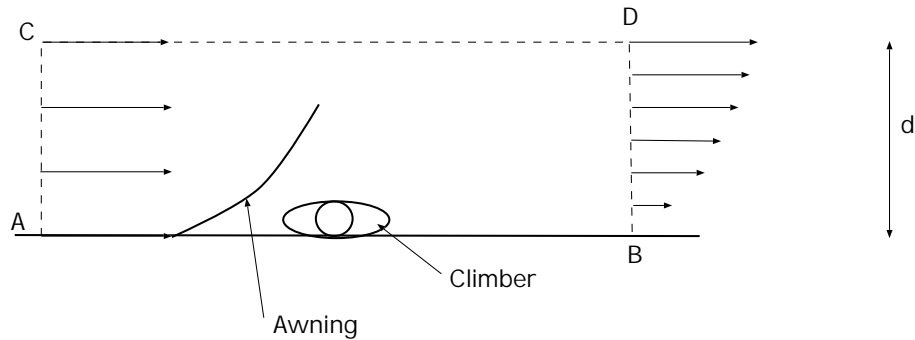
$$u_y \frac{\partial u_x}{\partial y} = \nu \frac{\partial^2 u_x}{\partial y^2}$$

Justify this expression. Solve this equation to find an equation for $u_x(y)$.

Question 6 (20 marks)

A mountain climber has put up an awning as protection in a storm with air speed U_0 . The flow separates from the edge and forms a wake whose velocity profile at BD of the control volume (see figure below) is

$$u_x(y) = \begin{cases} \frac{U_0}{2} \left[1 - \cos\left(\frac{\pi y}{\delta}\right) \right] & 0 \leq y \leq \delta \\ U_0 & y > \delta \end{cases}$$



Assuming that the flow may be considered to be 2 dimensional and uniform across AC, and that the viscous stresses along AC, CD, DB may be neglected :

6(a) (6 marks) Evaluate the mass flux across CD.

6(b) (10 marks) Find the force in the x -direction on the awning

6(c) (4 marks) Compare the displacement and momentum thicknesses in the wake BD.

$$\left[\text{You may assume that} \quad \cos^2 \theta = \frac{1}{2} (1 + \cos 2\theta) \right]$$