Version CAH/3

EGT3
ENGINEERING TRIPOS PART IIB

Friday 25 April 2014 9.30 to 11

Module 4A3

TURBOMACHINERY I

Answer not more than ***two*** *questions.*

All questions carry the same number of marks.

The ***approximate*** *percentage of marks allocated to each part of a question is indicated in the right margin.*

Write your candidate number ***not*** *your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Attachment: Compressible Flow Data Book (38 pages).
Engineering Data Book

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

1 (a) A compressor cascade is tested with an inlet Mach number of 0.65 and an inlet flow angle of 47°. The exit flow angle is 18°. The inlet stagnation pressure is 1 bar and the inlet stagnation temperature is 300 K. The development of the sidewall boundary layers causes the mass flow rate per unit frontal area to increase by 10 percent from inlet to the exit of the cascade. The stagnation pressure loss coefficient is given by

$$Y_P = \frac{p_{01} - p_{02}}{p_{01} - p_1} = 0.035$$

where p_{01} is the inlet stagnation pressure, p_{02} is the exit stagnation pressure and p_1 is the inlet static pressure. Determine the mass flow rate per unit frontal area at cascade inlet, the stagnation pressure ratio across the cascade, the exit Mach number and the static pressure ratio across the cascade. Comment on the value of the ratio of the exit Mach number to the inlet Mach number. [40%]

(b) The blade profiles in the cascade of part (a) are to be used in the rotor of an axial compressor stage that has zero swirl at inlet. The rotational speed is set so that the relative inlet Mach number and the relative inlet flow angle are the same as the inlet Mach number and the inlet flow angle in the cascade test. The absolute inlet stagnation temperature is 300 K. Calculate the blade speed and the relative inlet stagnation temperature. [20%]

(c) The stagnation pressure loss coefficient of the rotor in part (b) also equals 0.035 when evaluated in the relative frame of reference. The mean radius is constant through the rotor and the mass flow rate per unit frontal area increases by 10 percent from inlet to exit. Determine the absolute flow angle at rotor exit. [20%]

(d) Sketch the rotor velocity triangles and calculate the stage loading coefficient. [20%]

Use $c_p = 1005\ \text{J kg}^{-1}\,\text{K}^{-1}$, $R = 287\ \text{J kg}^{-1}\,\text{K}^{-1}$ and $\gamma = 1.4$ for air.

2 (a) Describe the measurements that would be needed to determine the stagnation pressure loss coefficient and the exit flow angle of a turbine cascade. Explain the boundary condition adjustments required to study the effects of exit Mach number and Reynolds number on loss and exit flow angle. [20%]

(b) A turbine cascade operates with subsonic inlet flow and an exit Mach number of 1.3. The inlet flow angle is 40° from the axial direction. The mass averaged stagnation pressure loss coefficient based on exit dynamic head is 0.1, and the measured exit flow angle is −70° from the axial direction. Calculate the inlet Mach number. [20%]

(c) Two thirds of the stagnation pressure loss occurs downstream of the throat. Calculate the opening to pitch ratio o/s for the cascade. Explain why there is a discrepancy between the measured flow angle and the value given by the simple geometric expression $\cos^{-1}(o/s)$. [25%]

(d) The blade pitch is 50 mm and the inlet stagnation pressure is 1 bar. Calculate the force per unit span acting on each blade in the axial and tangential directions. [35%]

Assume air throughout this question with $\gamma = 1.4$.

3 A multistage air compressor has the characteristic shown in Fig. 1, where p_{01} is the inlet stagnation pressure, p_{02} is the exit stagnation pressure, T_{01} is the inlet stagnation temperature, Ω is the rotational speed, and $\dot{m}$ is the air mass flow rate. At the design point the compressor rotates at 100% speed and has a stagnation pressure ratio of 8.3. At this condition, the flow coefficient of the first compressor stage is 0.5 and there is zero incidence onto the first rotor. The compressor has uniform, axial inflow with no inlet guide vanes and no variable stators. It is run in a static test rig with a choked nozzle downstream.

(a) Determine the compressor polytropic efficiency at the design point. [15%]

(b) Assuming that the polytropic efficiency remains constant show that the equation of a working line of the compressor can be written as

$$\left(\frac{p_{02}}{p_{01}}\right) = C\left(\frac{\dot{m}\sqrt{T_{01}}}{p_{01}}\right)^{\frac{2\gamma\eta_p}{(2\gamma\eta_p-\gamma+1)}}$$

where C is a constant and η_p is the compressor polytropic efficiency. [20%]

(c) The compressor is rotated at 80% speed, whilst operating on the working line that passes through the design point. Using the characteristic, estimate the compressor stagnation pressure ratio. If the inlet axial velocity is proportional to the mass flow find the flow coefficient of the first stage and the incidence angle onto the first rotor. [30%]

(d) Explain, with the aid of sketches of stage characteristics, how the operation of the front and rear stages of the compressor will be different at 80% speed compared to 100% speed on the design point working line. [20%]

(e) The compressor is operated continuously at 100% speed, starting at the design point, while the downstream exit nozzle area is slowly reduced until the flow becomes unstable. Describe the type and location of the stall that is likely to occur. [15%]

Use $\gamma = 1.4$ for air in this question.

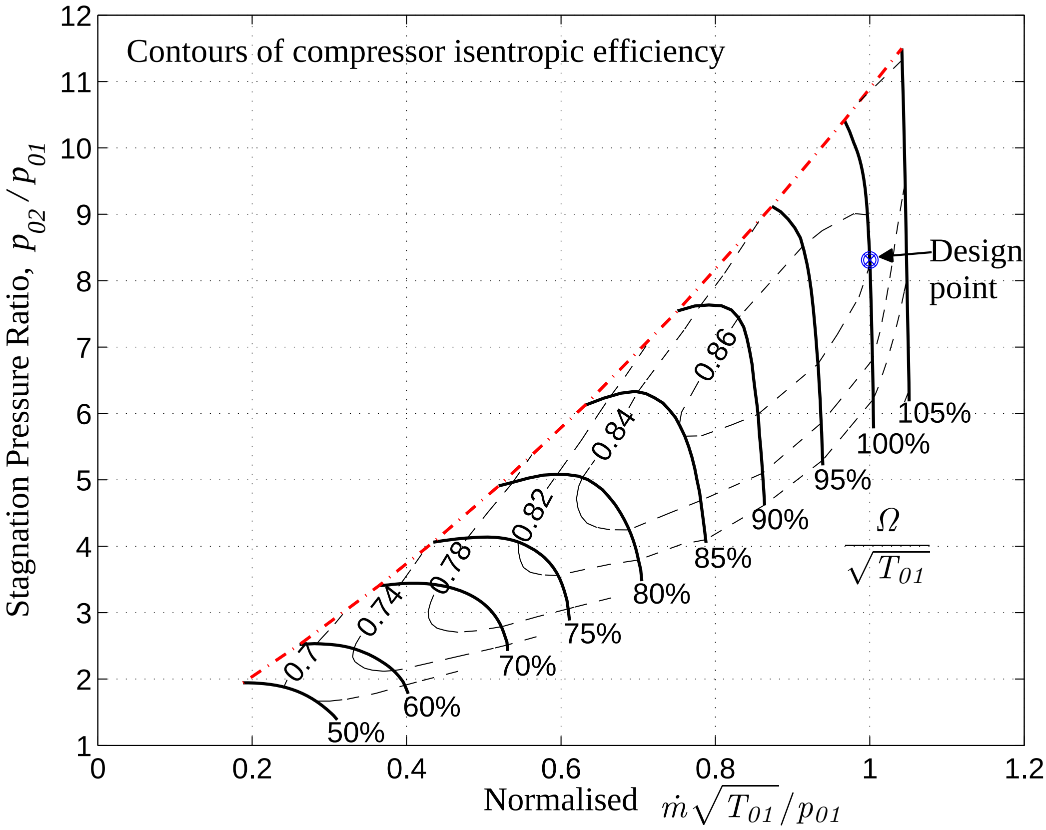

Fig. 1

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4A3 Exam Paper Answers 2014

Q1. (a) 140.1 kg s^{-1} m^{-2} , 0.9913, 0.46

(b) 161.9 m s^{-1}, 313 K

(c) 37.4^{0}

(d) 0.57

Q2. (b) 0.235

(c) 0.308

(d) -2864 N m^{-1}, 1473 N m^{-1}

Q3. (a) 89.5 %

(c) 4.93, 0.4, 4.8^{0}