EGT3
ENGINEERING TRIPOS PART IIB

Tuesday 2 May 2017 2 to 3.30

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: Excerpt from Compressible Flow Data Book (pages 1-16 of 38 pages).
Engineering Data Book

10 minutes reading time is allowed for this paper.

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

1 (a) An axial turbine stator operates with inlet stagnation pressure and temperature $p_{0,\mathrm{E}}$ and $T_{0,\mathrm{E}}$. The blade profile is tested in a linear cascade with geometric scale, SF, at matched Reynolds and Mach number. Assuming a flow at stagnation temperature $T_{0,\mathrm{C}}$, show that the cascade inlet stagnation pressure is

$$p_{0,\mathrm{C}} = p_{0,\mathrm{E}} \frac{1}{SF} \frac{\mu_\mathrm{C}}{\mu_\mathrm{E}} \sqrt{\frac{T_{0,\mathrm{C}}}{T_{0,\mathrm{E}}}}$$

where μ is the dynamic viscosity. [20%]

(b) A stator has axial inlet flow with a stagnation pressure and temperature of 35 bar and 1073 K, an inlet Mach number of 0.3, an exit Mach number of 0.9, an axial chord of 5 cm and a pitch to axial chord ratio of 0.8. It is tested in a 5 passage linear cascade with a geometric scale 50% greater than the real blade with a ratio of blade height to axial chord of 2.

(i) In general terms, what are the advantages and disadvantages of using a cascade with a greater number of passages and a large ratio of blade height to chord? [10%]

(ii) For an inlet stagnation temperature of 373 K, what is the inlet stagnation pressure and total mass flow rate through the cascade for Mach and Reynolds number matched conditions? [15%]

(c) The inlet flow to the cascade of part (b) is provided by a compressor.

(i) The compressor draws air at 1 bar, 300 K and has a total-to-total isentropic efficiency of 0.8. Assuming that the flow is cooled and delivered to the cascade without stagnation pressure loss, calculate the shaft power required by the compressor. [20%]

(ii) Considering a machine with a characteristic diameter of 1.2 m, find the specific speed, N_s, for this duty. With reference to the Cordier line of Fig. 1, suggest the most suitable type of turbomachine and briefly explain the general form of the graph. Calculate the rotational speed of the machine. [25%]

(iii) Explain the issues which would be encountered if this type of machine were to be run at lower exit pressure and higher flow rate conditions. [10%]

Assume air with specific heat capacity $c_p = 1005\ \mathrm{J\,kg^{-1}\,K^{-1}}$, a constant ratio of specific heats $\gamma = 1.40$, and transport properties which vary as a function of temperature only.

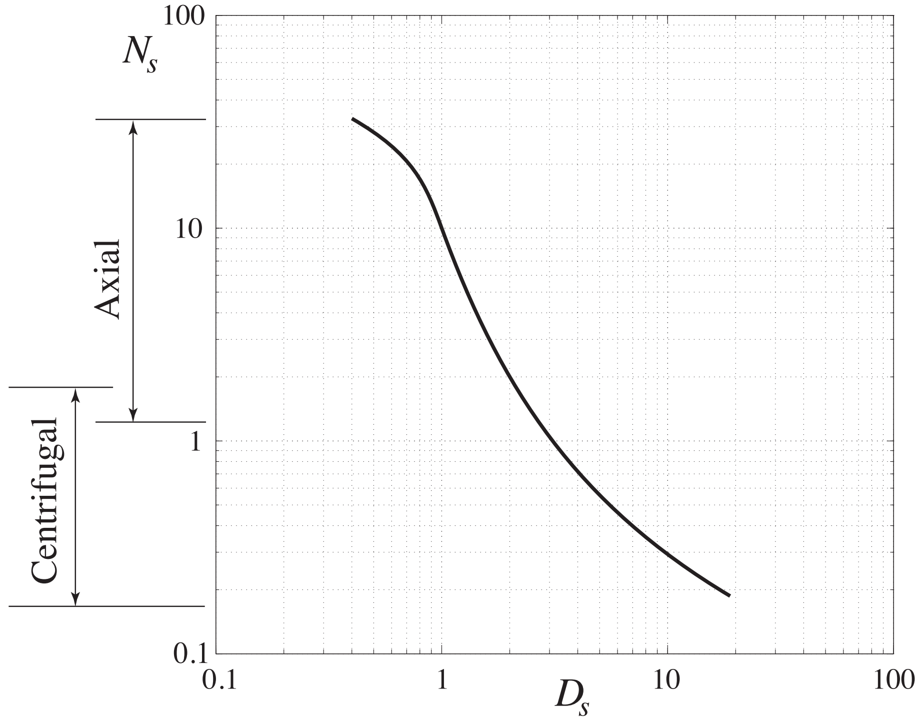

Fig. 1

$$N_s = (\dot{m}/\rho_{\text{exit}})^{1/2}\,\Omega\,(\Delta h_0)^{-3/4} \text{ and } D_s = (\Delta h_0)^{1/4}\,\rho_{\text{exit}} D/\dot{m}$$

D	characteristic diameter, [m]
$\dot{m}$	mass flow rate, [kg s^{-1}]
Ω	rotational speed, [rad s^{-1}]
ρ_{exit}	exit density [kg m^{-3}]
Δh_0	total enthalpy change, [J kg $^{-1}$]

(TURN OVER

2 (a) A compressor rotor is designed for operation with subsonic relative inlet flow.

(i) Explain how and why the stagnation pressure loss coefficient and relative exit flow angle would be expected to vary with rotational speed. Use simple sketches of the flow field and near-surface velocity distribution to illustrate your answer. [20%]

(ii) How would the operating range vary with inlet Mach number? [10%]

(iii) Noting any limitations, explain how a compressor rotor can be designed for use with supersonic relative inlet flow. [10%]

(b) The design operating point of a subsonic inlet compressor rotor corresponds to a speed of 4180 rpm and an inlet stagnation pressure and temperature of 1.0 bar and 300 K without inlet swirl. The mean radius of the rotor is 0.35 m. At the design operating point, the inlet relative flow angle is -45°, the relative inlet stagnation to exit static pressure ratio is 1.15 and the relative stagnation pressure loss coefficient is 0.04.

(i) Calculate the design condition inlet and exit relative Mach numbers. [20%]

(ii) Lieblein's correlation for diffusion factor, DF, has the form

$$DF \approx 1 - \frac{\cos\beta_1}{\cos\beta_2} + \frac{1}{2}\left(\frac{s}{c}\right)|\tan\beta_2 - \tan\beta_1|\cos\beta_1$$

where β_1 and β_2 are the relative inlet and exit flow angles. The pitch to chord ratio, s/c, of the rotor blade is 0.95. Estimate the diffusion factor at design conditions. Assuming that the exit flow angle remains constant, use an iterative approach to estimate the incidence at stall (relative to the design condition). [20%]

(c) Estimate the limiting value of negative incidence (relative to the design condition) if the inlet relative Mach number is held at the design condition, the flow upstream of the throat is isentropic and the throat opening to pitch is 0.68. [20%]

You may assume the working fluid is air with specific heat ratio $\gamma = 1.40$ and specific heat capacity $c_p = 1005\ \mathrm{J\,kg^{-1}K^{-1}}$ for all parts of this question.

3 (a) Show that a change in inlet mass flow rate of an axial compressor stage results in a change in $\dot{m}\sqrt{T_{02}}/p_{02}$, the exit flow function from the stage, which is larger than the change in the inlet flow function $\dot{m}\sqrt{T_{01}}/p_{01}$, where p_0 and T_0 represent the stagnation pressure and temperature and $\dot{m}$ the mass flow rate. [30%]

(b) Explain how, at the compressor design speed, the front and rear stages of a high speed multistage compressor respond to small changes in the inlet mass flow to the compressor. Illustrate your explanation with sketches of the front and rear stage characteristics. [20%]

(c) Explain why, at part speed operation, the stage responsible for stall of the compressor is likely to be different to that at the compressor design speed. [20%]

(d) Describe how, in practice, designers ensure stable and efficient part speed performance of high speed multistage compressors and discuss the compromises that these design decisions entail. [30%]

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1 (a) -

(b) -

(i) -

(ii) 6.88 bar, 31.83 $\mathrm{kg\,s^{-1}}$

(c) (i) 8.82 MW

(ii) $N_s = 0.8$, centrifugal machine would be best. $3.49 \times 10^3 \mathrm{rad\ s^{-1}}$

2 (a) (i) -

(ii) -

(iii) -

(b) (i) $M_{1,\mathrm{rel}} = 0.636$, $M_{2,\mathrm{rel}} = 0.435$

(ii) $DF_{\mathrm{design}} \approx 0.45$, $i_{\mathrm{stall}} \approx +5^\circ$ relative to the design condition.

(c) $i_{\mathrm{choke}} \approx -6.4^\circ$ relative to the design condition.

3 (a) -

END OF PAPER