Version MPFS/2

EGT3
ENGINEERING TRIPOS PART IIB

Tuesday 29 April 2014 2 to 3:30

Module 4C16

ADVANCED MACHINE DESIGN

*Answer **all** 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: Module 4C16 Data Sheet (3 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 Table 1 gives the operating data for a 360° 'square' journal bearing, i.e. one whose diameter $2R$ equals its axial length L. The radial load is W and M is the torque required to maintain the steady rotational speed ω. The radial clearance is c and η is the viscosity of the lubricant.

(a) Establish that if the clearance c is reduced while load, speed, viscosity and dimensions remain unchanged then the shaft moves towards the concentric position. [15%]

(b) Explain how Petrov's law for the frictional torque, i.e. $M^* = 2\pi$, is derived and why it gives quite good answers even when the eccentricity e is not small. [15%]

(c) The oil in such a bearing will become heated as a result of internal shearing. For the purposes of analysis, the shaft can be considered to be at a uniform temperature and the bearing can be treated as a thin annulus of thickness d whose outer surface is at ambient temperature θ_a, as illustrated in Fig. 1. If there are no temperature variations along or around the bearing then, by equating the energy dissipated in the oil film to the rate of heat transfer through the bearing, which has thermal conductivity K, show that the increase in the oil film temperature above θ_a is approximately

$$\frac{M^*}{2\pi}\frac{\eta U^2}{K}\frac{d}{c}$$

where U is the surface speed of the shaft and M^* is the non-dimensional torque given in Table 1. [30%]

(d) The radii of both shaft and bearing increase due to thermal expansion, the increase being $\beta R\bar{\theta}$ where β is the coefficient of thermal expansion, R is the shaft radius and $\bar{\theta}$ is the *average* temperature of either the shaft or the bearing. Derive an expression for the clearance ratio c/R under operating conditions and hence show that the bearing will seize if the initial clearance ratio at ambient temperature is less than about

$$1.27\left\{\beta\left(\frac{\eta U^2}{K}\right)\left(\frac{d}{R}\right)\right\}^{1/2},$$

using the data in Table 1, recalling the answer to part (a) and ignoring any variation of viscosity with temperature. [30%]

(e) For the case $\beta = 3\times10^{-5}$, $\eta = 0.1$ Pa s, $U = 5$ m s^{-1}, $K = 50$ W m^{-1} K^{-1}, $d = 0.02$ m, and R = 0.2 m calculate the critical clearance ratio and the associated temperature rise. Comment on the assumption of constant viscosity. [10%]

$$\varepsilon = e/c\,,\ \ W^* = \frac{Wc^2}{\eta\omega LR^3}\,,\ \ M^* = \frac{Mc}{\eta\omega LR^3}$$

$\varepsilon = e/c$	0	.05	.1	.2	.3	.4	.5	.6	.7	.8	.9
$W^* = \frac{Wc^2}{\eta\omega LR^3}$	0.000	.112	.227	.474	.768	1.15	1.68	2.50	3.91	6.89	16.5
$M^* = \frac{Mc}{\eta\omega LR^3}$	5.10	5.09	5.08	5.03	5.19	5.38	5.77	6.32	7.29	9.11	13.4

Table 1

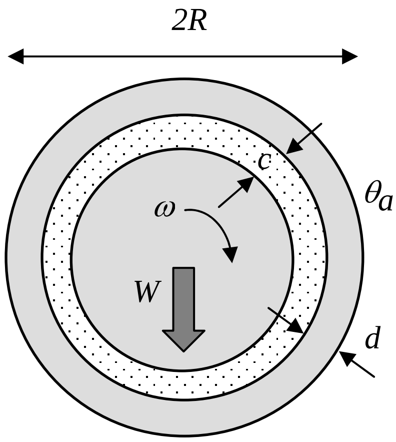

Fig. 1

2 Figure 2 shows a cam which operates a reciprocating follower of tip circle radius r. The cam has a base circle radius of $3r$ and a tip circle radius $2r$. The line of action of the follower passes through the axis of rotation of the cam. The centres of the base circle, tip circle and follower are O, A and B respectively. The cam rotates anti-clockwise at a steady angular velocity ω. Both cam and follower are prismatic bodies with the cross-sections shown in Fig. 2 and with a width L (out of the plane of the figure).

(a) (i) Find the follower accelerations at minimum and maximum lift. [15%]

(ii) Derive an expression for the follower acceleration when contact is along the straight flank, as a function of the angle of inclination θ of the flank relative to the horizontal. [30%]

(iii) The follower has a mass of 0.1 kg and is maintained in contact by a spring which provides a constant downward force P. Determine the magnitude of spring force necessary to keep the follower in contact with the cam when it is rotating at $\omega = 200$ rad/s with $r = 10$ mm. [35%]

(b) (i) Determine the minimum width L of contact between cam and follower necessary to ensure that the lubrication film thickness is sufficient to avoid significant metal-to-metal contact when the follower is in contact with the cam base circle. Use the design data given in Table 2 and the Dowson and Higginson formula for film thickness given below. [10%]

(ii) Discuss whether this design is adequate for all points of contact. No further calculations are necessary. [10%]

Viscosity η_0	0.1 Pa s
Pressure viscosity coefficient α	2×10^{-8} Pa^{-1}
Effective Young's Modulus E*	115 GPa
Surface roughness	1 μm
Dimension r	10 mm

Table 2

Dowson and Higginson :
$$\frac{h_{\min}}{R} = 2.65\left(2\alpha E^*\right)^{0.54}\left(\frac{\bar{U}\eta_0}{2E^*R}\right)^{0.7}\left(\frac{W}{2E^*RL}\right)^{-0.13}$$

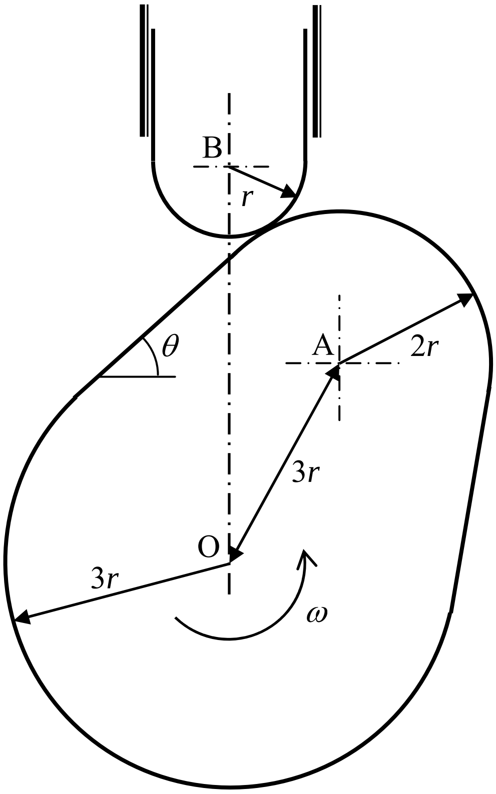

Fig. 2

(TURN OVER

3 Figure 3 illustrates schematically an 'infinitely variable transmission' (IVT) made up of a toroidal continuously variable transmission (CVT) drive coupled to an epicyclic gear box. The input shaft is connected to the input of the CVT and also, directly, to the sun gear S of the epicyclic. The output of the CVT is connected to the annulus A and the output of the transmission system is taken from the planet carrier C.

(a) If V, equal to $-\omega_A/\omega_{in}$, is the speed ratio through the CVT, show that the system output velocity ω_{out} is related to the input velocity by the expression

$$\frac{\omega_{out}}{\omega_{in}} = \frac{1 - BV}{1 + B}$$

where B is the ratio of the number of teeth on the annulus A to that on the sun gear S. [10%]

(b) Sketch a graph of $-\omega_{out}/\omega_{in}$ against V for the case $B = 2$ and where the CVT has a ratio range of $1/3 \le V \le 3$. [10%]

(c) Explain the concept of 'geared neutral' in the context of this transmission. [10%]

(d) The transmission (with $B = 2$) is used in a vehicle operating on a constant gradient such that the output torque has constant value $T_{out} = -1$ N m. The efficiency of the CVT is $\eta = 0.8$ and losses in the epicyclic may be neglected. If the input shaft is driven at a constant speed of $\omega_{in} = 1$ rad s^{-1} find expressions in terms of ω_{out} for:

(i) the output power P_{out};

(ii) the power P_{CVT} passing from the input shaft through the CVT;

(iii) the total input power P_{in}. [55%]

(e) Sketch a graph of P_{out}, P_{CVT} and P_{in} against ω_{out} and comment on any regimes of behaviour observed. [15%]

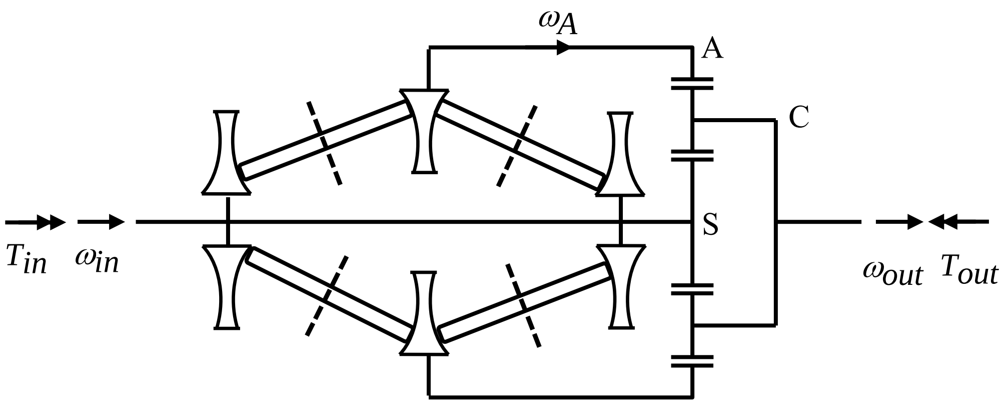

Fig. 3

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Engineering Tripos Part IIB: Module 4C16
Advanced Machine Design

Numerical answers - 2013/14

1. (e) 8 °C
2. (a) (iii) 240 N, (b) (i) 2.65 mm