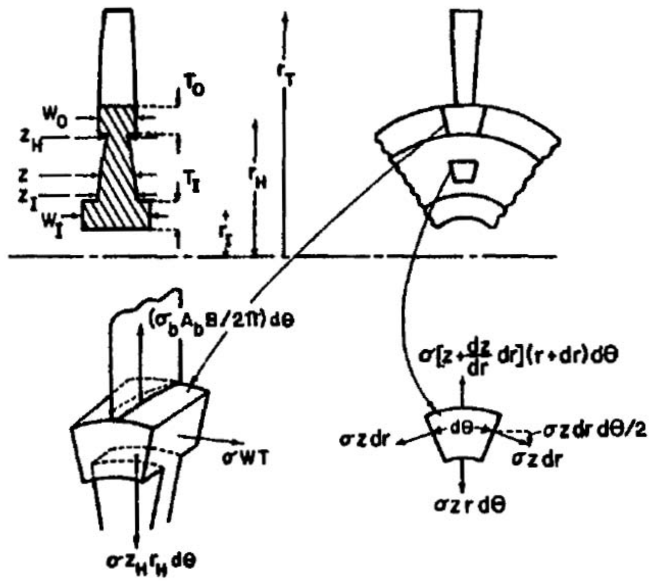
16.50 Lecture 32

Subjects discussed: Engine structures; Centrifugal stresses; Engine arrangements

Centrifugal stresses and design of discs

By disc we refer to the rotating structural members that carry the rotating blades in the turbomachine. They are unusual as structural members in that they must withstand very large tensile stresses generated by centrifugal forces. Their mass is a large part of the total mass of an engine, and they set the limit on blade speed, so an understanding of their characteristics is essential to appreciating the performance limits of modern aircraft engines.



We begin by describing the state of stress of a small volume element of a disc. The net outwards elastic force on the element is

$$\frac{d}{dr}(\sigma zrd\theta)dr - \sigma z\,dr\,d\theta = \sigma r\frac{dz}{dr}dr\,d\theta$$

and, by design, in order to utilize the material most efficiently, we wish to keep the stress level σ constant throughout the disc. The force balance is then

$$\rho z\omega^2 r^2 d\theta dr = -\sigma r(\frac{dz}{dr})drd\theta$$

$$\frac{1}{z}\frac{dz}{dr} = -\frac{\rho(\omega^2 r)}{\sigma}$$

$$z = \text{ct. x}\exp(-\frac{\rho\omega^2 r^2}{2\sigma})$$

Add a rim and consider the radial force balance on a slice of this rim, as in the bottom left sketch. There are B blades, not necessarily at the same stress as the disc, and their centrifugal pull is smoothly distributed around the periphery:

$$\rho_o W_o T_o (r_H d\theta)\omega^2 r_H + \frac{\sigma_{bH} A_b B}{2\pi} d\theta = \sigma z_H r_H d\theta + \sigma W_o T_o d\theta$$

Rim centrifugal force	Centrifugal pull from blades	Support from rim stress	Radial force from hoop stress

$$\sigma = \frac{\rho_0 \omega^2 r_H^2 + (\frac{B}{2\pi})\sigma_{bH}(A_b / W_o T_o)}{1 + \frac{z_H r_H}{W_o T_o}} \qquad (2)$$

So the disc supports the rim, and reduces its stress. Now we add an inner rim; it supports the disc and there are no blade loads, so in this case

$$\rho_I W_I T_I (r_I d\theta)\omega^2 r_I = -\sigma z_I r_I d\theta + \sigma W_I T_I d\theta$$

$$\sigma = \frac{\rho \omega^2 r_I^2}{1 - \frac{z_I r_I}{W_I T_I}} \qquad (3)$$

For the blades themselves, the full blade mass is supported by the root stress:

$$\sigma_{bH} = \frac{\rho_b \omega^2}{A_{bH}} \int_{r_H}^{r_T} A_b(r)\, dr \qquad (4)$$

So how do we design a disc

a) From aerodynamics, choose ωr_T, r_H / r_T, B, $A_b(r)$ W_o

b) Set permissible stresses σ and σ_{bH} (ωr_T may then be limited by (4))

c) Choose a T_o and get Z_H from (2)

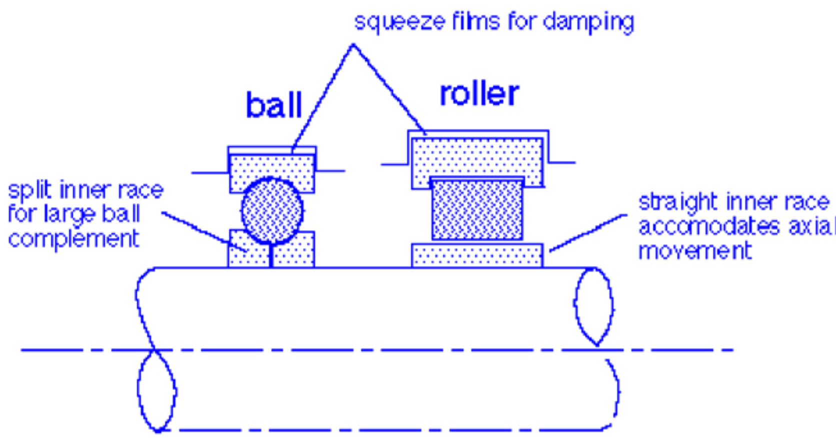
d) Choose an r_I and get Z_I from (1)

e) Get $W_I T_I$ from (3)

Engine arrangements

As noted, engines are unusual amongst engineering structures in that such a large fraction of their total mass is rotating at high speeds. This large rotating mass must be supported on bearings so as to maintain quite close clearances between the blade tips and the stationary casings, on the order of 1 mm on a rotor of 1 m diameter, or one part in 10^3. At the same time of course the stationary structure must be as light as possible.

All existing engines use ball and roller bearings to support the rotating assemblies, called "spools". These are shown schematically in the figure:



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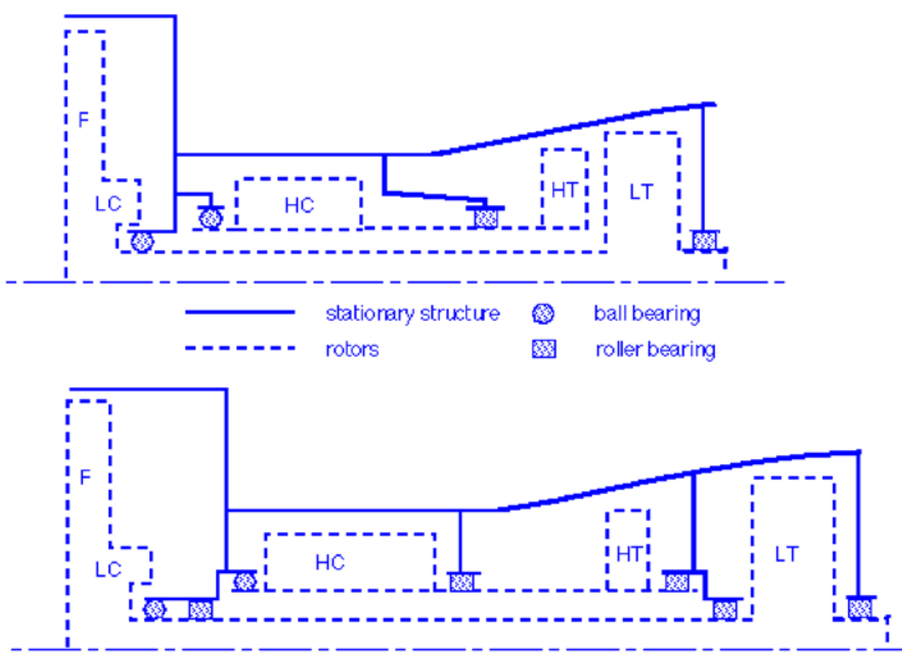
The function of the squeeze films will be discussed in the next lecture.

Ordinarily each rotating spool is supported by one ball bearing that positions it axially and also absorbs radial loads, and one or more roller bearings that accept radial loads but allow axial movement to accommodate thermal expansion and structural deformations.

Two-spool support arrangements are shown schematically in the figure:



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The top arrangement uses just two bearings, one ball and the other roller, to support each of the two spools. It is compact and at least in principle relatively light. The lower arrangement uses three bearings on the inner spool, one ball and two roller, and four bearings on the outer (low speed) spool, one ball and three roller. Both of these arrangements have advantages and both have been used successfully in high-bypass commercial transport engines. This is just one more illustration of the fact that design solutions are not unique.