ON THE LOAD OF BEARINGS WITH NON-NEWTONIAN LUBRICANTS

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Received April 10, 1987
Presented by Dr. L. Láng

Abstract

We determine the load carrying capacity of bearings with different type of non-Newtonian lubricants as a function of the number of revolution. We call attention to a danger of some kind of poor bearing operations in case of suspension-type lubricants.

Introduction

In a previous paper we showed that the differential equations derived for long journal bearings with non-Newtonian lubricants and with small loads are in formal analogy to those with Newtonian lubricants [1]. In the classical equations joining load and eccentricity, the viscosity is to be substituted by the derivative of the shear stress function with respect to shear rate [2,3]. The loss is taken the same as in the case of the unloaded bearing. Simply speaking, the shear rate in the narrow clearance deviates only slightly from a mean value, hence the linear approximation of the shear stress function leads to appropriate results. This way, we are able to determine the derivative of the load with respect to the eccentricity at zero load, from which a useful approximation for moderate loads is got, and a base for further estimations, which we do not analyse in this paper because of the departure from Reynolds' equations. It is worth mentioning here that the derivative of a non-Newtonian shear stress function does depend on shear rate, hence the value substituting viscosity varies with sliding speed. A steep starting section of the shear stress function is favorable at the start of running, as it causes good load-carrying capacity at slow runs. On the other hand, it is very convenient from the view point of the loss that the starting steepness of the shear stress function breaks down and a more moderate increasing follows. When designing the rheological properties of a lubricant it must be kept in mind that a too sudden break down involves the danger of severe wear at high sliding speeds, as it will be shown later. We mention, that the ratio of the shear stress to the shear rate is usually referred to as viscosity which can differ markedly from the derivative. Applying the former, when calculating the load-carrying capacity may lead to severe errors. In the same special case, the load-carrying capacity may reduce to zero without the above mentioned ratio called viscosity giving any information on it.

Non-Newtonian lubricants

Analysing the load-carrying capacity of a long bearing the Sommerfeld variable is used:

$$\Delta = \frac{wc^2}{l\eta U R^2} \tag{1}$$

where

w = total load
c = radial clearance in the unloaded bearing
l = bearing length
η = viscosity
U = sliding speed
R = radius of the shaft.

In small loaded bearings Δ is proportional to the eccentricity:

$$\Delta = 6\pi\varepsilon, \tag{2}$$

which is explained by the formula of the gap width.

$$d = c(1 + \varepsilon \cos\theta) \tag{3}$$

where the angle θ is measured from the position of the maximal gap width.

To avoid wear it is required that the Sommerfeld variable does not exceed a critial value. At a given load (w) and for a bearing (c,R,l), a minimal value for the product $\eta \,.\, u$ is required.

In the following we change to the average shear rate instead of the sliding velocity by

$$U = \varkappa \,.\, c \tag{4}$$

Moreover the differential viscosity of the non-Newtonian fluids will replace η:

$$\eta = \frac{d\tau}{d\varkappa} \tag{5}$$

So we get the next expression for Sommerfeld's variable:

$$\Delta = \frac{wc}{l\,\dfrac{d\tau}{d\varkappa}\,\varkappa R^2} \tag{6}$$

From here we conclude that within the demanded operating conditions, the product $\varkappa \frac{d\tau}{d\varkappa}$ has not to exceed a given value. Estimating applicability of the different type lubricants, we have to study the values of this product as a function of the mean shear rate. If the viscometric function of the lubricant, the function $\tau(\varkappa)$, is known in an explicite way there is nothing to prevent calculations. Unfortunately, there is no general viscometric function, we have often to use approximations based on a few data available. In the next sections we present calculations for suspension-type lubricants and for oils with polymeric additives.

Suspensions

The rheological properties of the suspension-type lubricants are generated by elastic colloid particles. Oldroyd [6] and recently Verhás [7,8,9] studied the rheological behaviour of colloids. Based on their results, the shearing stress function is given in the form:

$$\tau(\varkappa)=\eta_f+\frac{\eta_s-\eta_f}{1+\left(\frac{\varkappa}{\varkappa_*}\right)^2} \tag{7}$$

where η_s and η_f are the limiting viscosity for slow and fast shear, respectively, and $\varkappa_*$ is a characteristic shear rate.

From Oldroyd's formulae [6] we can determine those values which are given by Verhás [8] in explicite forms:

$$\varkappa_*=\frac{2(1-\varphi)\mu}{(3+2\varphi)\eta_0}, \qquad \eta_s=\eta_0\frac{2+3\varphi}{2(1-\varphi)}, \qquad \eta_f=\eta_0\frac{3(1-\varphi)}{3+2\varphi} \tag{8}$$

Here φ means the volume fraction of the dispersed elastic material, μ is their shear modulus, and η_0 is the viscosity of the continuous phase without additives. The quantity $\varkappa \cdot - \frac{d\tau}{d\varkappa}$ characteristic for the load-carrying capacity of the journal bearing is obtained by differentiating the function (7):

$$\varkappa\frac{d\tau}{d\varkappa}=\eta_f\varkappa+(\eta_s-\eta_f)\frac{\left[1-\left(\frac{\varkappa}{\varkappa_*}\right)^2\right]\varkappa}{\left[1+\left(\frac{\varkappa}{\varkappa_*}\right)^2\right]^2} \tag{9}$$

The function

$$f(x)=\frac{1}{\varkappa_*(\eta_s-\eta_f)}\varkappa\frac{d\tau}{d\varkappa}=\frac{\eta_f}{\eta_s-\eta_f}x+\frac{(1-x^2)x}{(1+x^2)^2} \tag{10}$$

is plotted in Fig. 1 for several ratios η_f/η_s. Here the notation: $x=\frac{\varkappa}{\varkappa_*}$ has been introduced.

As it seems also in the figure, in the case of too small values η_f/η_s, the load-carrying capacity of a bearing is not a monotonously increasing function of the peripheral velocity but significant drops are also possible. This sympton is rather striking for those having a good practice with Newtonian lubricants, consequently, it is also rather dangerous.

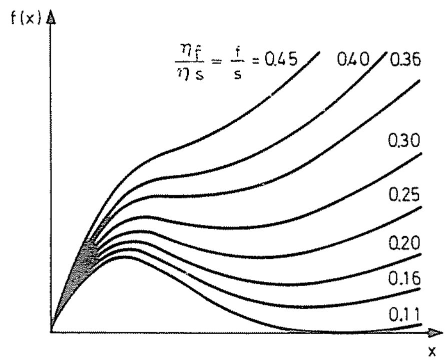

Fig. 1

The critical value for η_f/η_s is about 0.36. The exact value is

$$\left(\frac{\eta_f}{\eta_s}\right)_{crit}=\frac{351+135\sqrt{10}}{2187}$$

From formulae (8) we determine the volume fraction at which the mentioned danger may occur. Substituting into (8),

$$\left(\frac{\eta_f}{\eta_s}\right)_{crit}=\frac{6(1-\varphi)^2}{(2+3\varphi)(3+2\varphi)}=0.36$$

we get $\varphi_{crit}=0.2467$ which has to be taken as an approximate value because the accuracy of formulae (8) over the limit $\varphi=0.1$ is doubtful.

The too high volume fraction is dangerous, of course, even if it is formed inside the bearing when it runs. However, this question is too difficult for the methods used here.

Lubricants with polymeric additives

The material of chain molecules has proved to be very good additives. Following Rouse [10], Bueche [11] and Zimm [12] we use the viscometric function

$$\tau(\varkappa)=\eta_f\varkappa+\frac{1}{4}kTL\pi\sqrt{2\tau_1\varkappa}\,\frac{\sinh\pi\sqrt{2\tau_1\varkappa}-\sin\pi\sqrt{2\tau_1\varkappa}}{\cosh\pi\sqrt{2\tau_1\varkappa}-\cos\pi\sqrt{2\tau_1\varkappa}} \tag{11}$$

for lubricants with polymeric additives.

Here
η_f means the oil viscosity without additive (solvent).
k Boltzman's constant.
T absolute temperature
L number of polymer chains in unit volume
τ_1 the longest relaxation time.
At small shear rates the function (11) is approximated as:

$$\tau(\varkappa)=\eta_f\varkappa+\frac{1}{6}kTL\pi^2\tau_1\varkappa$$

from which the viscosity at slow shear rate is

$$\eta_s=\eta_f+\frac{1}{6}\pi^2kTL\tau_1$$

Using this and introducing the notation:

$$x=\pi^2 2\tau_1\varkappa,$$

function (11) is reformulated as

$$\tau(x)=\frac{\eta_f}{2\pi^2\tau_1}x+\frac{3(\eta_s-\eta_f)}{2\pi^2\tau_1}x\,\frac{\sinh\sqrt{x}-\sin\sqrt{x}}{\cosh\sqrt{x}-\cos\sqrt{x}} \tag{12}$$

From here we get:

$$\varkappa\frac{d\tau}{d\varkappa}=x\frac{d\tau}{d\varkappa}=\frac{\eta_f}{2\pi^2\tau_1}x+$$

$$+\frac{3(\eta_s-\eta_f)}{2\pi^2\tau_1}\left\{\frac{\sqrt{x}}{2}\,\frac{\sinh\sqrt{x}-\sin\sqrt{x}}{\cosh\sqrt{x}-\cos\sqrt{x}}+\frac{1-\cosh\sqrt{x}\cos\sqrt{x}}{(\cosh\sqrt{x}-\cos\sqrt{x})^2}\right\} \tag{13}$$

The function

$$f(x) = \frac{2\pi^2\tau_1}{3(\eta_s - \eta_f)} \varkappa \frac{d\tau}{d\varkappa} = \frac{\eta_f}{3(\eta_s - \eta_f)} x + \tag{14}$$
$$+ \frac{\sqrt{x}}{2} \frac{\sinh\sqrt{x} - \sin\sqrt{x}}{\cosh\sqrt{x} - \cos\sqrt{x}} + x \frac{1 - \cosh\sqrt{x}\cos\sqrt{x}}{(\cosh\sqrt{x} - \cos\sqrt{x})^2}$$

for $\eta_f = 0$ is plotted in Fig. 2.

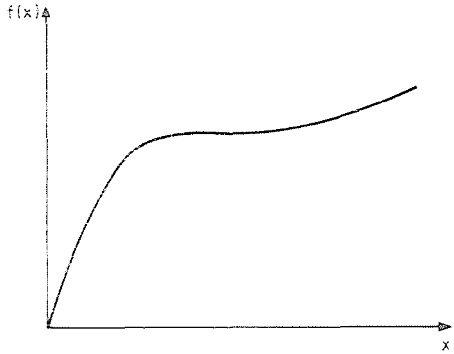

Fig. 2

Even in the extreme case, when the viscosity of the solvent is negligible there is no decreasing section of the function. The plateau of the graph in Figure 2 offers very convenient work points for different operating conditions.

The polymeric additives do not expose the danger of decreasing load-carrying capacity.

Summary

For moderately loaded long bearing we presented a calculation method for the load-carrying capacity of lubricants with suspension type and polymeric additives. Hopefully, the reported formulae are helpful not only when doing the choice of a suitable lubricant but also while designing new lubricants.

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