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Squeeze Film Lubrication between Rough Annular Plates with Rabinowitsch Fluid Model

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Abstract: *The purpose of this paper is to analyse the behaviour of squeeze film lubrication between rough annular plates based on the Rabinowitsch fluid model. Utilizing a small perturbation method, a closed–form solution is obtained and for several values of different operating parameters, the results are found. Accordingly, two sorts of one-dimensional surface roughness (radial and azimuthal) patterns are considered in setting of Christensen stochastic theory. Expressions for non-dimensional pressure, non-dimensional load carrying capacity and squeeze film time are obtained. Further it is seen that the effect of radial (azimuthal) surface roughness pattern on the squeeze film lubrication between rough annular plates with Rabinowitsch fluid model is to decrease (increase) the non-dimensional pressure, non-dimensional load carrying capacity and squeeze film time.*

Keywords: *Surface roughness, Rough Annular plates, Squeeze film, Rabinowitsch fluid.*

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I. INTRODUCTION

In recent years, the study of non-Newtonian Fluids has attracted much attention, because of their applications in industrial practices and engineering sciences. In earlier days, the analysis of squeeze film performances for circular and annular plates were focused upon the use of Newtonian fluids as the lubricants. Contribution of this work can be found in the works done by Lin[1], Usha and Vimala[2], Allen and Mclillop[3],Wu[4] and Singh et al.[5]. Due to the requirement of squeeze film systems operating under different conditions, the increasing use of oils mixed with high molecular-weight polymers as lubricants has received importance. So to stimulate the behaviour of the flow of these types of non-Newtonian fluid models, researchers have applied several non-Newtonian fluid models to examine the squeeze film characteristics of thin film bearings. To study the non-Newtonian effects of lubricants on the squeeze film characteristics between annular or circular disks, the power law fluid model has been applied by Usha and Vimala[6], Shukla[7], Elkouh[8], Elkouh et al.[9] and to stimulate the effects of non-Newtonian lubricants on the squeeze film characteristics between circular disks, the couple stress fluid model is used by Bujurke and Kudenatti[10], Ramanaiah[11] and Lin and Hung[12] in their works. The combined effects of surface roughness and couple stresses on squeeze film lubrication between porous circular stepped plates is analysed by Naduvinmani et al.[13]. In recent years, a non-Newtonian fluid model-Rabinowitsch fluid model is used to explore the non-linear behaviour of non-Newtonian lubricants. In this model, the relationship between the shearing stress and shearing strain rate is as follows

$$\tau_{xy} + k\tau^3{}_{xy} = \mu\frac{\partial u}{\partial y} \quad (1)$$

Where μ denotes the initial viscosity of the fluid and k is the non-linear factor determined from the experiments. By using this cubic equation model, the analysis can be carried for the dilatant fluids when $k < 0$, Newtonian fluids when $k = 0$ and pseudo-plastic fluids when $k > 0$. By considering this Rabinowitsch fluid model, many researchers have examined the effects of non-Newtonian lubricants on the performance characteristics of hydrodynamic thin film bearings. The present analysis is on the squeeze film lubrication between rough annular plates with Rabinowitsch fluid model. Utilizing a small perturbation method, a non-linear modified Reynolds equation is derived and a closed form solution for the non-dimensional film pressure, the non-dimensional load-carrying capacity and the squeeze film time are obtained.

II. MATHEMATICAL FORMULATION

The geometry of the bearing is as shown in the Fig-1. Let us assume a squeezing flow between two rough annular plates moving towards each other with velocity: $v=\left(-\frac{\partial H}{\partial t}\right)$.In the present study, Rabinowitsch fluid is considered to be a non-Newtonian lubricant. The equations of continuity and motion of an incompressible fluid from Lin[1] and Hashimoto[14] for axial-symmetry cylindrical coordinates reduce to the following:

$$\frac{1}{r}\frac{\partial(ru)}{\partial r}+\frac{\partial v}{\partial y}=0 \tag{2}$$

$$\frac{\partial p}{\partial r}=\frac{\partial \tau_{xy}}{\partial y} \tag{3}$$

$$\frac{\partial p}{\partial y}=0 \tag{4}$$

The used boundary conditions for the velocity components are

$$u=0,\ v=0 \text{ at } y=0 \tag{5a}$$

$$u=0, v=-V=\frac{\partial H}{\partial t} \text{ at } y=H \tag{5b}$$

Integrating the momentum Eq. (3) with respect to y yields the shear stress:

$$\tau_{xy}=\frac{\partial p}{\partial r}y+I_1 \tag{6}$$

Denoting the pressure gradient as $f=\frac{\partial p}{\partial r}$ and substituting Eq.(6) into the Eq.(1) and integrating with respect to y, the velocity component is given by

$$u=\frac{1}{\mu}\left\{f\frac{y^2}{2}+I_1y+k\left(f^3\frac{y^4}{4}+f^2y^3I_1+\frac{3}{2}fy^2I_1^2+yI_1^3\right)\right\}+I_2 \tag{7}$$

And using the boundary conditions (5a) and (5b), we get $I_1=-\frac{1}{2}fH$ and $I_2=0$.

And Eq. (7) becomes

$$u=\frac{1}{\mu}\left\{\frac{1}{2}fF_1+kf^3F_2\right\} \tag{8}$$

Where $F_1=y(y-H)$, $F_2=\frac{y^4}{4}-\frac{y^3H}{2}+\frac{3}{8}y^2H^2-\frac{yH^3}{8}$

Using equation (8) in continuity equation and integrating with respect to y between the limits 0 to H, the modified Reynolds equation for Rabinowitsch fluid is got in the form

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\left\{H^3\left(\frac{\partial p}{\partial r}\right)+\frac{3k}{20}H^5\left(\frac{\partial p}{\partial r}\right)^3\right\}\right]=12\mu\frac{\partial H}{\partial t} \tag{9}$$

Let us assume $f(h_s)$ as the probability density function of the stochastic film thickness h_s. Considering the stochastic average of equation (9) with respect to $f(h_s)$ the averaged modified Reynolds type equation is obtained in the form

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\left\{E(H^3)\left(\frac{\partial E(p)}{\partial r}\right)+\frac{3k}{20}E(H^5)\left(\frac{\partial E(p)}{\partial r}\right)^3\right\}\right]=12\mu\frac{\partial H}{\partial t} \tag{10}$$

where the expectancy operator is denoted as $E(*)$ and defined by

$$E(*)=\int_{-\infty}^{\infty}(*)f(h_s)\,dh_s \tag{11}$$

Following Christensen [15], we assume that

$$f\left(h_s\right)=\begin{cases}\dfrac{35}{32c^7}\left(c^2-h_s^2\right)^3 & -c<h_s<c\\ 0 & \text{elsewhere}\end{cases} \tag{12}$$

where $\bar{\sigma}=c/3$ is the standard deviation.

Using the Christensen's stochastic theory, the analysis is done for two kinds of one dimensional surface roughness patterns namely, radial roughness pattern and azimuthal roughness pattern.

One-dimensional radial roughness

For the one dimensional radial roughness pattern, the roughness striation are in the form of long narrow ridges and valleys running through *r*-direction (i.e. they are straight ridges and valley passing through y = 0, r = 0 to form star pattern), in this case the non-dimensional stochastic film thickness assumes the form $H_i=h_i+h_s\left(\theta,\xi\right)$ for $i=1,2$ and the stochastic modified Reynolds equation (10) takes the form

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\left\{E\left(H^3\right)\left(\frac{\partial E\left(p\right)}{\partial r}\right)+\frac{3k}{20}E\left(H^5\right)\left(\frac{\partial E\left(p\right)}{\partial r}\right)^3\right\}\right]=-12\mu\frac{dH}{dt} \tag{13}$$

One-dimensional azimuthal roughness

For the one dimensional azimuthal roughness pattern, the roughness striation are in the form of long narrow ridges and valleys running through θ-direction (i.e. they are circular ridges and valleys on the flat plate that are concentric on z = 0, r = 0), in this case the non-dimensional stochastic film thickness assumes the form $H_i=h_i+h_s\left(r,\xi\right)$ for $i=1,2$ and the stochastic modified Reynolds equation (10) takes the form

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\left\{\frac{1}{E\left(\frac{1}{H^3}\right)}\left(\frac{\partial E\left(p\right)}{\partial r}\right)+\frac{3k}{20}\frac{1}{E\left(\frac{1}{H^5}\right)}\left(\frac{\partial E\left(p\right)}{\partial r}\right)^3\right\}\right]=-12\mu\frac{dH}{dt} \tag{14}$$

For an axisymmetric case, equation (13) and equation (14) together can be written as

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\left\{G_1\left(H,c\right)\left(\frac{\partial E\left(p\right)}{\partial r}\right)+\frac{3k}{20}G_2\left(H,c\right)\left(\frac{\partial E\left(p\right)}{\partial r}\right)^3\right\}\right]=-12\mu\frac{dH}{dt} \tag{15}$$

where $$G_1\left(H,c\right)=\begin{cases}E\left(H^3\right) & \textit{for radial roughness}\\ \left\{E\left(\dfrac{1}{H^3}\right)\right\}^{-1} & \textit{for azimuthal roughness}\end{cases} \tag{16a}$$

$$E\left(H^3\right)=\frac{35}{32c^7}\int_{-c}^{c}H^3\left(c^2-h_s^2\right)^3dh_s \tag{16b}$$

$$E\left(\frac{1}{H^3}\right)=\frac{35}{32c^7}\int_{-c}^{c}\frac{\left(c^2-h_s^2\right)^3}{H^3}dh_s \tag{16c}$$

and $$G_2\left(H,c\right)=\begin{cases}E\left(H^5\right) & \textit{for radial roughness}\\ \left\{E\left(\dfrac{1}{H^5}\right)\right\}^{-1} & \textit{for azimuthal roughness}\end{cases} \tag{17a}$$

$$E\left(H^5\right)=\frac{35}{32c^7}\int_{-c}^{c}H^5\left(c^2-h_s^2\right)^3dh_s \tag{17b}$$

$$E\left(\frac{1}{H^5}\right)=\frac{35}{32c^7}\int_{-c}^{c}\frac{\left(c^2-h_s^2\right)^3}{H^5}dh_s \tag{17c}$$

Introducing the dimensionless quantities

$$r^* = \frac{r}{b},\ p^* = \frac{E(p)h_0^2}{\mu b\left(-\frac{dh^*}{dt}\right)},\ a^* = \frac{a}{b},\ \beta = k\frac{\mu^2}{h_0^2\left(-\frac{dh^*}{dt}\right)^2},\ H^* = \frac{H}{h_0},\ C = \frac{c}{h_0}$$

Eq. (15) becomes

$$\frac{\partial}{\partial r^*}\left[r^*\left\{G_1^*\left(H^*,C\right)\left(\frac{\partial p^*}{\partial r^*}\right)+\frac{3}{20}\beta G_2^*\left(H^*,C\right)\left(\frac{\partial p^*}{\partial r^*}\right)^3\right\}\right] = -12r^*$$

The squeeze film pressure can be perturbed as

$$p^* = p_0^* + \beta p_1^* \tag{18}$$

Substituting into equation (15) and leaving the second and higher order terms of β, the two separate equations governing the squeeze film pressure p_0^* and p_1^* are obtained respectively

$$\frac{\partial}{\partial r^*}\left[r^*\left\{G_1^*(H^*,C)\frac{\partial p_0^*}{\partial r^*}\right\}\right] = -12r^* \tag{19}$$

$$\frac{\partial}{\partial r^*}\left[r^*\left\{G_1^*(H^*,C)\frac{\partial p_1^*}{\partial r^*}+\frac{3}{20}G_2^*(H^*,C)\left(\frac{\partial p_0^*}{\partial r^*}\right)^3\right\}\right] = 0 \tag{20}$$

Integrating equation (19) and equation (20) with respect to r^* and using boundary condition

$$p^* = 0 \text{ at } r^* = a^* \tag{21a}$$

$$p^* = 0 \text{ at } r^* = 1 \tag{21b}$$

we get

$$p_0^* = \frac{3\left(a^{*2}-1\right)}{G_1^*\left(H^*,C\right)}\left\{\frac{\left(r^{*2}-1\right)}{\left(a^{*2}-1\right)}\frac{\log r^*}{\log a^*}\right\} \tag{22}$$

$$p_1^* = \frac{81G_2^*\left(H^*,C\right)}{10G_1^{*4}\left(H^*,C\right)}\left[\left\{\left(r^{*2}+1\right)-3\frac{\left(a^{*2}-1\right)}{\log a^*}-\frac{\left(a^{*2}-1\right)^3}{4r^{*2}\left(\log a^*\right)^3}\right\}\left(r^{*2}-1\right)\right.$$
$$\left.-\left\{\left(a^{*2}+1\right)-3\frac{\left(a^{*2}-1\right)}{\log a^*}-\frac{\left(a^{*2}-1\right)^3}{4a^{*2}\left(\log a^*\right)^3}\right\}\frac{\left(a^{*2}-1\right)\log r^*}{\log a^*}\right] \tag{23}$$

and using in equation (18), we get

$$p^* = -\frac{3\left(a^{*2}-1\right)}{G_1^*\left(H^*,C\right)}\left\{\frac{\left(r^{*2}-1\right)\log r^*}{\left(a^{*2}-1\right)\log a^*}\right\}$$
$$+\frac{81\beta}{10}\frac{G_2^*\left(H^*,C\right)}{G_1^{*4}\left(H^*,C\right)}\left[\left\{\left(r^{*2}+1\right)-3\frac{\left(a^{*2}-1\right)}{\log a^*}-\frac{\left(a^{*2}-1\right)^3}{4r^{*2}\left(\log a^*\right)^3}\right\}\left(r^{*2}-1\right)\right.$$
$$\left.-\left\{\left(a^{*2}+1\right)-3\frac{\left(a^{*2}-1\right)}{\log a^*}-\frac{\left(a^{*2}-1\right)^3}{4a^{*2}\left(\log a^*\right)^3}\right\}\frac{\left(a^{*2}-1\right)\log r^*}{\log a^*}\right] \tag{24}$$

The load carrying capacity is considered in the form

$$E(W) = 2\pi\int_a^b rE(p)\,dr \tag{25}$$

which takes the non-dimensional form as

$$W^* = 2\pi\int_{a^*}^1 r^* p^* dr^* \tag{26}$$

Substituting the expression of the film pressure and integrating the equation (26), we can obtain the non-dimensional load carrying capacity W^* in the form

$$W^* = -\frac{3\pi\left(a^{*2}-1\right)^2}{2G_1^*\left(H^*,C\right)}\left\{\frac{\left(a^{*2}+1\right)}{\left(a^2-1\right)}-\frac{1}{\log a^*}\right\} + \frac{81\pi\beta}{5}\frac{G_2^*\left(H^*,C\right)}{G_1^{*4}\left(H^*,C\right)}\left\{\frac{1}{3}\left(a^{*6}-1\right)-\frac{\left(a^{*2}-1\right)^2\left(a^{*2}+1\right)}{\log a^*} - \frac{\left(a^{*2}-1\right)^3\left(a^{*2}-3\right)}{4\left(\log a^*\right)^2}+\frac{\left(a^{*2}-1\right)^5}{16a^{*2}\left(\log a^*\right)^4}\right\} \tag{27}$$

Where $W^* = \dfrac{E\left(p\right)h_0^2}{\mu b\left(-\dfrac{dH^*}{dt}\right)}$

The squeezing film time can be calculated by integrating (27) with respect to h^* as follows

$$t^* = \int_{h_m=h_f}^{1}\left[-\frac{3\pi\left(a^{*2}-1\right)^2}{2G_1^*\left(H^*,C\right)}\left\{\frac{\left(a^{*2}+1\right)}{\left(a^2-1\right)}-\frac{1}{\log a^*}\right\} + \frac{81\pi\beta}{5}\frac{G_2^*\left(H^*,C\right)}{G_1^{*4}\left(H^*,C\right)}\left\{\frac{1}{3}\left(a^{*6}-1\right)-\frac{\left(a^{*2}-1\right)^2\left(a^{*2}+1\right)}{\log a^*} - \frac{\left(a^{*2}-1\right)^3\left(a^{*2}-3\right)}{4\left(\log a^*\right)^2}+\frac{\left(a^{*2}-1\right)^5}{16a^{*2}\left(\log a^*\right)^4}\right\}\right]dh^* \tag{28}$$

where $t^* = \dfrac{E(W)h_0^2}{\mu b^4}t$

III. RESULTS AND DISCUSSIONS

In the present paper, utilizing the Christensen Stochastic theory for the study of rough surfaces, the effect of surface roughness on the squeeze film lubrication between rough annular plates with Rabinowitch fluid has been analysed by considering two kinds of one dimensional roughness pattern viz. radial roughness pattern and azimuthal roughness pattern. The effect of surface roughness is characterised by roughness parameter *C*. The limiting case of $C \to 0$ corresponds to smooth case studied by Jaw-Ren Lin [16].

Squeeze Film Pressure

The variation of non-dimensional pressure P^* with r^* for different values of β with $a^* = 0.3$, $h^* = 0.4$ and $C = 0.3$ is shown in figure 2, for both the radial and azimuthal roughness patterns. It is observed that, the squeeze pressure P^* decreases for increasing value of β for both radial and azimuthal roughness patterns. The variation of non-dimensional pressure $P^*$with $r^*$for different values of C with $a^* = 0.3$, $h^* = 0.4$and $\beta = 0.001$ is shown in figure 3, for both type of roughness patterns. It is observed that increasing values of roughness parameter *C*, the squeeze film pressure P^* increases for azimuthal roughness pattern and decreases for the radial roughness pattern.

Load carrying capacity

The variation of non-dimensional load carrying capacity $W^*$with $h^*$for different values of β with $a^* = 0.3$ and $C = 0.3$ is shown in figure 4, for both the radial and azimuthal roughness patterns. It is observed that, the load carrying capacity W^* decreases for increasing value of β for both radial and azimuthal roughness patterns. The variation of non-dimensional load carrying capacity W^* with $h^*$for different values of C with $a^* = 0.3$ and β =0.001 is shown in figure 3, for both type of roughness patterns. It is observed that increasing values of roughness parameter *C*, the load carrying capacity W^*decreases for both azimuthal roughness pattern and radial roughness pattern.

Squeeze Film Time

The variation of non-dimensional squeeze film time t^* with h_f^* for different values of β, $a^* = 0.3$ and C = 0.3 is shown in the figure 5, for both type of roughness patterns. It is observed that as the values of β increases, the squeeze film time decreases in both radial and azimuthal roughness patterns. Figure 6 depicts the variation of non- dimensional squeeze film time t^* with h_f^* for different values of C with $a^* = 0.3$ and β =0.001. It is observed that as the values of C increases the squeeze film increase (decrease) in t^* is more for azimuthal (radial) roughness pattern.

IV. CONCLUSIONS

The squeeze film lubrication between rough annular plates with Rabinowitsch fluid is presented in this paper.According to the analysis and the result discussed, conclusions can be drawn as follows.

- It is found that for the rough annular plates, the non-dimensional pressure, non-dimensional load carrying capacity and squeeze film time decreases with increasing value of β.
- In the presence of a Rabinowitsch fluid, one-dimensional radial (azimuthal) roughness pattern on the rough annular plates decreases (increases) the pressure, load carrying capacity and the squeeze film time.
- Hence the results so obtained are more useful for better performance and stability. So the present results are excepted to be closer to the physical situation.

Nomenclature

a inner radius of the annular plates
a^* non-dimensional inner radius
b outer radius of the annular plates
β non-dimensional non-linear factor of lubricants
C non-dimensional roughness parameter
E expectancy operator
h_s stochastic film thickness
H_i film thickness
H non-dimensional film thickness
P pressure in the film region
P^* non-dimensional pressure
r, θ radial and axial coordinates, respectively
t time of approach
t^* non-dimensional time of approach
V squeezing velocity
u, w velocity components of lubricant in the x- and y- directions, respectively
W load carrying capacity
W^* non-dimensional load carrying capacity
μ initial viscosity
k non-linear factor of lubricants
τ_{xy} shear stress component

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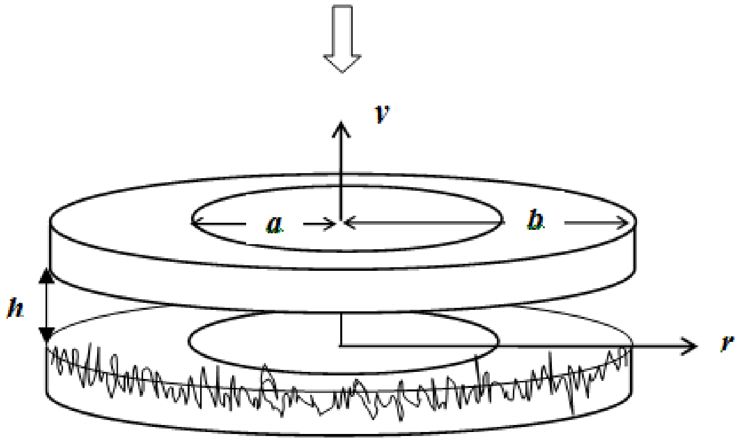

Figure 1. Schematic diagram of the problem

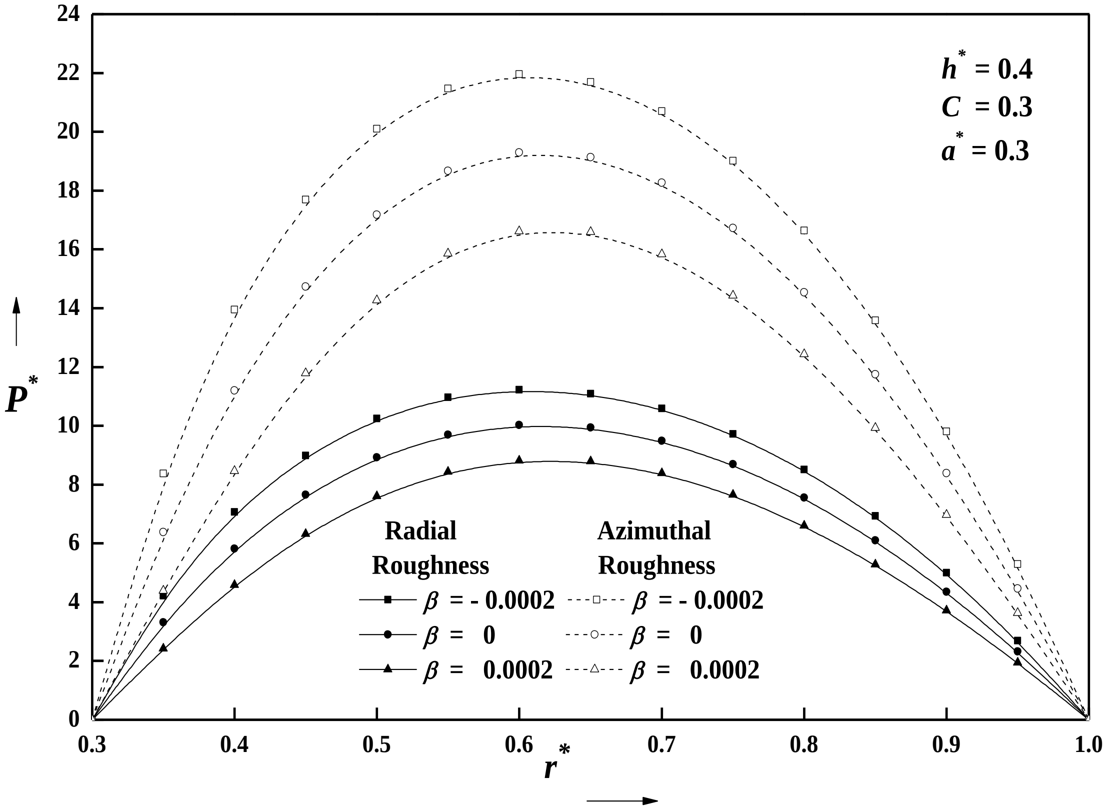

Figure 2. Variation of non-dimensional pressure P^* with r^* for different values of □ with $h^*= 0.4$, $a^*= 0.3$ and $C = 0.3$

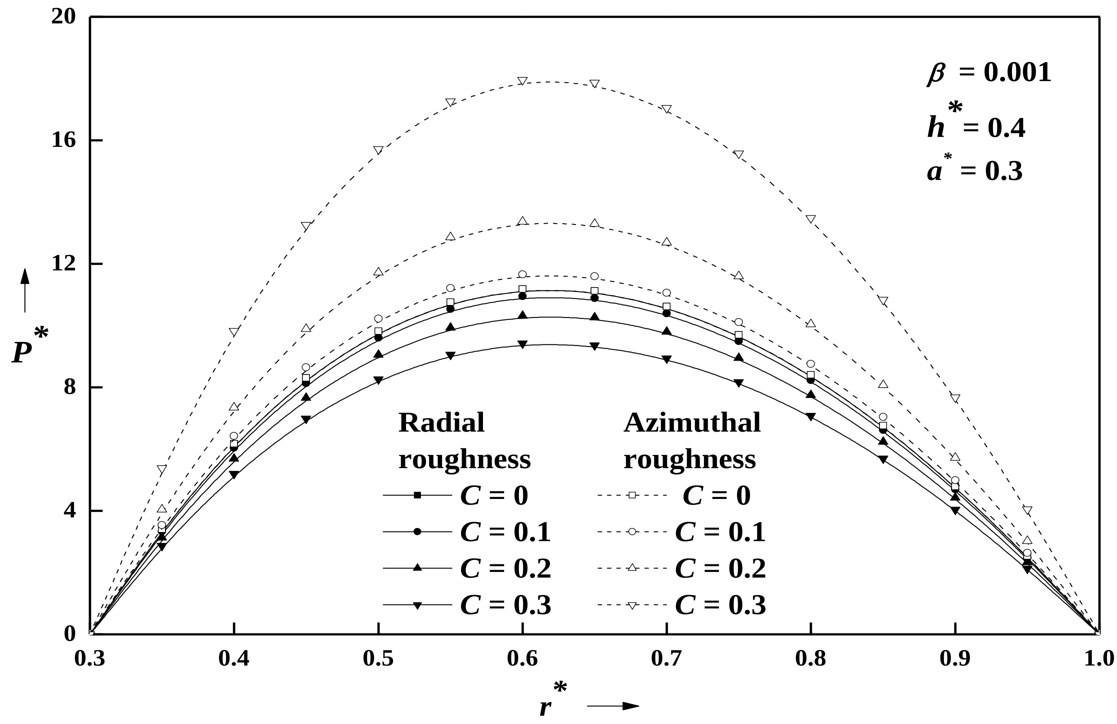

Figure 3. Variation of non-dimensional pressure P^* with r^* for different values of C with $\beta = 0.001$, $a^* = 0.3$ and $h^* = 0.4$

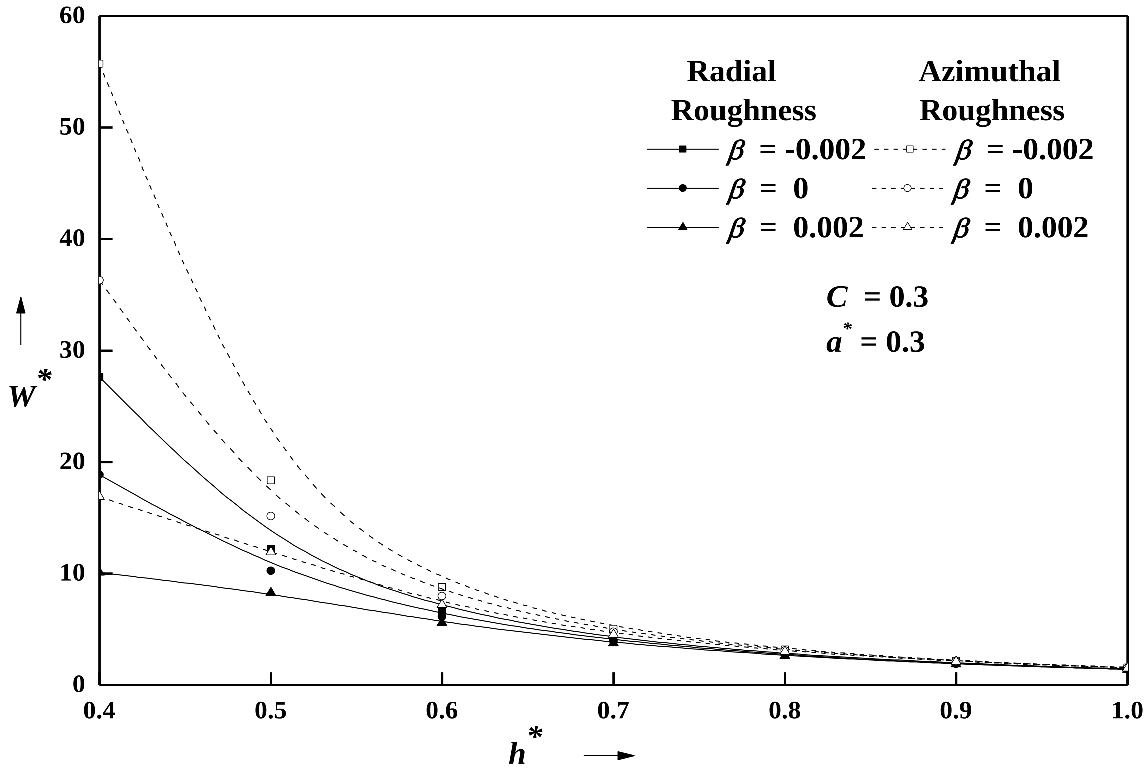

Figure 4. Variation of non-dimensional load carrying capacity w^* with film thickness h^* for different values of β with $a^* = 0.3$ and $C = 0.3$

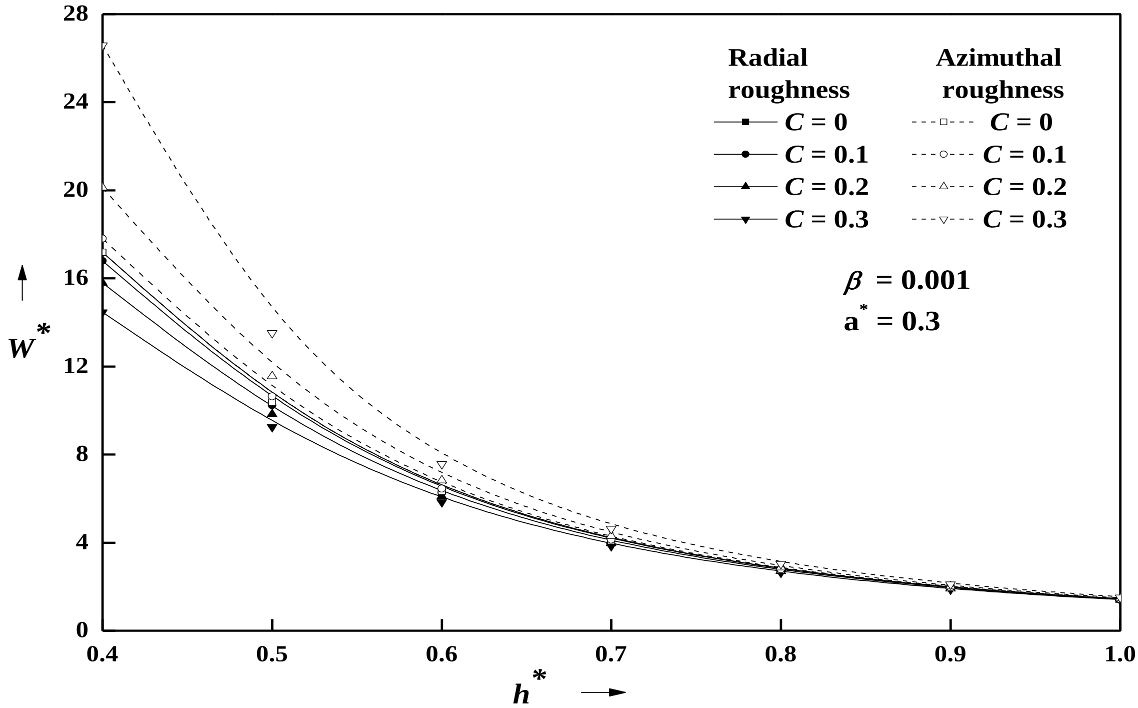

Figure 5. Variation of non-dimensional load carrying capacity w^* with h^* for different values of C with a^*= 0.3 and β = 0.001.

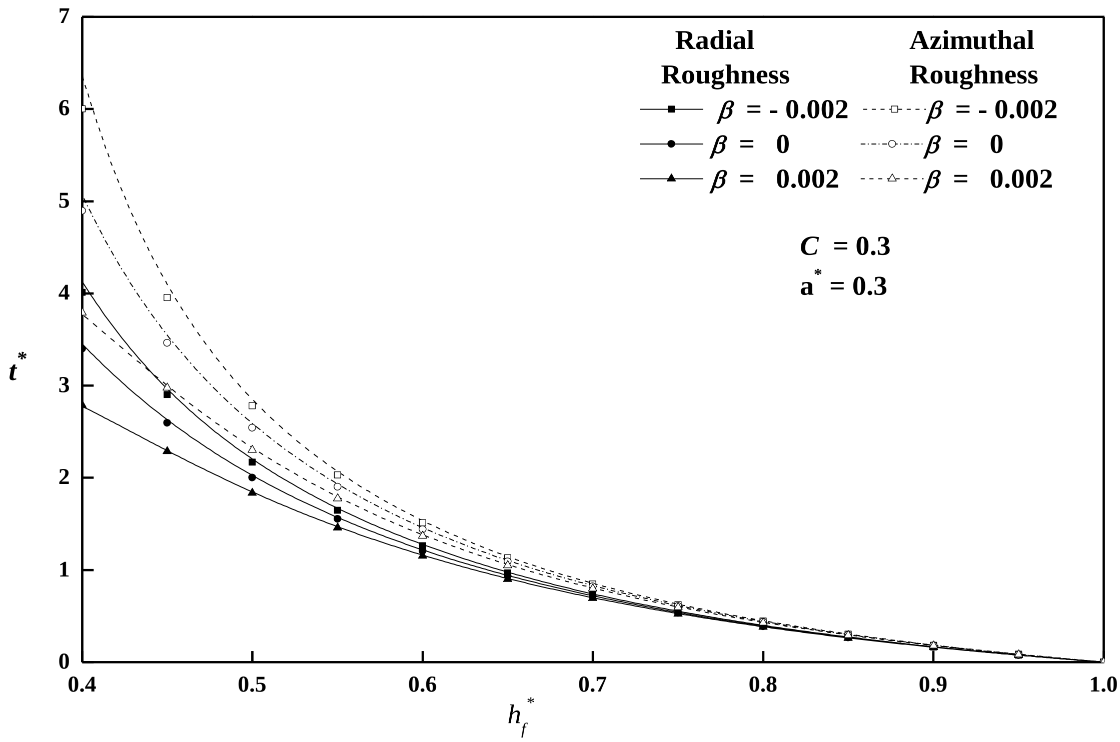

Figure 6. Variation of squeeze film time t^* with film thickness h^* for different values of β with a^*= 0.3 and C = 0.3

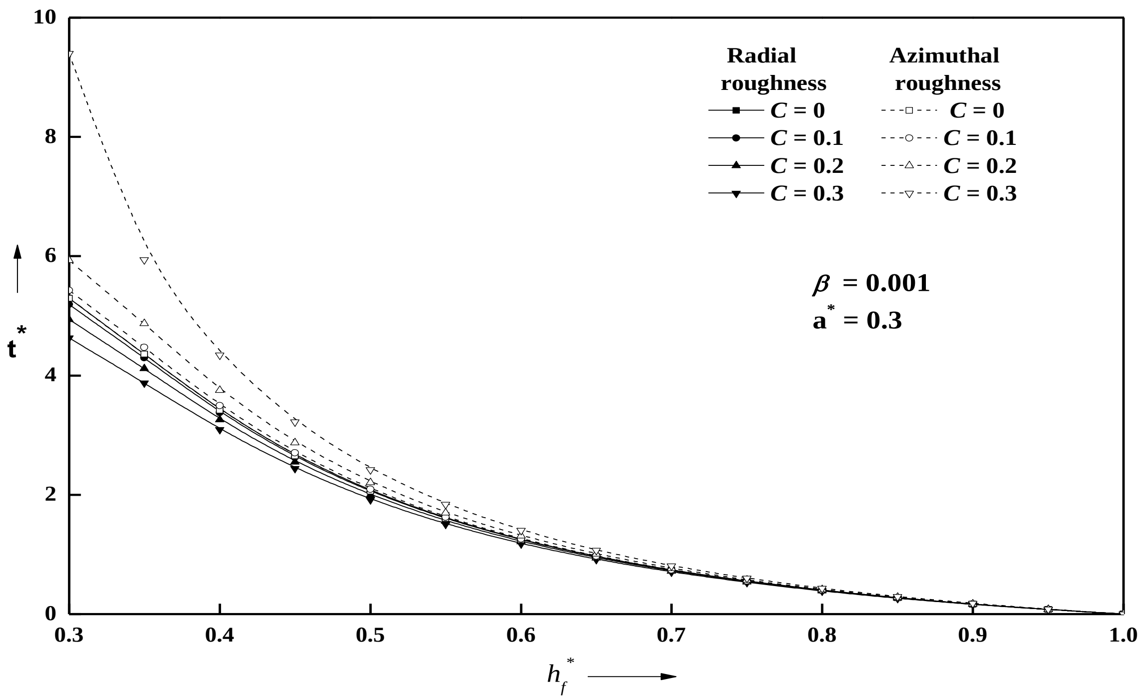

Figure 7. Variation of squeeze film time t^* with film thickness h^* for different values of C with a^*= 0.3 and β = 0.001

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