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Clearance and lubricant selection for avoiding seizure in a circumferential groove journal bearing based on a lumped model analysis

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Abstract – This study presents a new simple lumped model for analyzing the thermally induced seizure of fully lubricated eccentric circumferential groove journal bearings (CGJB). The model represents a significant upgrade of a previous seizure lumped model developed by Pascovici & Kucinschi, in 2002. Main upgrades consist of: eccentric operation, introduction of hydrodynamic lubricant flow rate component, and evaluation of friction power losses based on the short bearing theory with Barwell's hypothesis on the divergent zone. The viscosity–temperature variation is replaced with Tipei's viscosity-clearance relationship, as in the previous model. The decrease of viscosity, as a consequence of temperature increase, does not always limit clearance loss, and the seizure process ends with a concentric journal-bushing merged system. Although CGJB's are less sensitive to this seizure mechanism, the threat still exists and must be avoided. As a result, bearing designers and users should check whether if several safe-operation criteria are met. A recent Institute Pprime experiment on CGJB's provided a base set of operating parameters, from which numerical simulations have been performed to determine in what conditions the CGJB fails, under thermally induced seizure.

Key words: Fluid film / journal bearing / circumferential groove / seizure / analytical model

Résumé – Choix du jeu et du lubrifiant pour éviter le serrage d'un palier hydrodynamique à rainure circonférentielle basé sur un modèle d'analyse globale. Cette étude présente un nouveau modèle simple conçu pour analyser le serrage d'origine thermique d'un palier avec une rainure circonférentielle (CGJB), un film complet et une excentricité non nulle. Le modèle présenté ici est une mise à niveau d'une analyse antérieure développée par Pascovici & Kucinschi, en 2002. Ce modèle considère un fonctionnement excentré, introduit le débit de lubrifiant hydrodynamique et les calculs de pertes de puissance par frottement sont effectués avec la théorie du palier court et l'approximation de Barwell pour la zone divergente. La variation de la viscosité en fonction du jeu du palier est approchée en utilisant la relation de Tipei, comme dans le modèle original. La diminution de la viscosité, due à l'augmentation de la température, ne réduit pas toujours la perte de jeu, et le processus de serrage se termine par un système concentrique fusionné coussinet-arbre. Bien que les paliers à rainure circonférentielle soient moins sensibles à ce mécanisme de serrage, la menace existe toujours et elle doit être évitée. En conséquence, les concepteurs et les utilisateurs de paliers doivent vérifier si plusieurs critères pour une exploitation sans danger sont respectés. Des essais récents sur le CGJB à l'Institut Pprime ont fourni une base de données de paramètres de fonctionnement. À partir de celle-ci, des simulations ont été effectuées pour déterminer dans quelles conditions le CGJB est détruit en raison d'un serrage d'origine thermique.

Mots clés : Film fluide / palier / rainure circonférentielle / serrage / modèle analytique

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Nomenclature

b_g	width of the bearing lubricant supply groove	[mm]
B	width of one bearing land	[mm]
B_e	total width of the bearing	[mm]
c_b	specific heat capacity of the bushing	[J/(kg.K)]
c_c	specific heat capacity of the bearing	[J/(kg.K)]
c_l	specific heat capacity of the lubricant	[J/(kg.K)]
c_s	specific heat capacity of the shaft	[J/(kg.K)]
C	radial clearance	[μm]
C_p	dimensionless coefficient of performance (or load capacity)	[–]
d_s	diameter of the shaft	[mm]
D	inner diameter of the bushing	[mm]
D_e	outer diameter of the bushing	[mm]
h_{min}	minimum film thickness	[μm]
l_s	relevant width of the shaft (for thermal calculations)	[mm]
M	weighted (or equivalent) mass of the bearing	[kg]
n	rotational speed of the shaft	[rpm]
p_s	supply pressure of the lubricant (relative to the atmosphere)	[MPa]
p_m	mean pressure on the bearing	
P_f	friction power loss	[W]
Q	volumetric flow rate of the lubricant	[m^3.s^{-1}]
Q_{HD}	hydrodynamic component of the lubricant flow rate (volumetric)	[m^3.s^{-1}]
Q_{HS}	hydrostatic (supply) component of the lubricant flow rate (volumetric)	[m^3.s^{-1}]
t	time	[s]
T	temperature (average or lumped) of the entire system	[°C]
T_0	initial temperature (average or lumped) of the entire system	[°C]
T_s	supply temperature of the lubricant	[°C]
V	volume	[mm^3]
V_b	volume of the bushing	[mm^3]
V_s	volume of the shaft	[mm^3]
W	applied load on the bearing	[N]
	Greek	
α	linear thermal expansion coefficient of the shaft	[mm/(m.K)]
δ	dimensionless loss of clearance	[–]
$\varDelta$	radial thermal expansion of the shaft	[μm]
$\varGamma$	coefficient related to hydrodynamic flow rate clearance losses	[–]
ε	eccentricity ratio	[–]
$\varLambda$	coefficient related to friction power clearance losses	[–]
μ	dynamic viscosity of the lubricant	[Pa.s]
ρ	density	[kg.m^3]
ρ_b	density of the bushing	[kg.m^{-3}]
ρ_l	density of the lubricant	[kg.m^{-3}]
ρ_s	density of the shaft	[kg.m^{-3}]
τ	dimensionless time	[–]
ψ	relative clearance	[–]
	Subscripts	
0	initial	
b	bushing	
c	system (combined)	
co	concentric	
f	friction	
l	lubricant	
s	shaft	
	Abbreviations	
CGJB	circumferential grove journal bearing	
DS	data set	
HD	hydrodynamic	
HS	hydrostatic	
SDS	standard data set	

1 Introduction

The journal bearings undergoing thermal seizure are rapidly damaged within the first minutes of adverse operation, due to clearance loss. As the demand for more compact and higher performance machinery translates into more severe operating regimes, engineers require tools to identify dangerous configurations and safe operating regimes.

Conway-Jones and Leopard [1] acknowledged this problem and pursued an experimental study of tilting-pad journal bearings for accelerated start-up regimes. Their work revealed that seizure may be avoided by a better selection of the lubricant supply temperature and shaft rotational speeds.

Available theoretical studies, on thermally induced seizure, predict two major outcomes: either a safe steady-state operation or an adverse operation prone to rapid thermal seizure.

Bishop and Ettles [2] developed two models for predicting seizure in bearings with thermoplastic liners. Their research revealed that the time for seizure development is relatively short and is further reduced with the square root of the shaft's size decrease. They proposed a limiting factor, based on the mean bearing pressure, sliding velocity and clearance ratio, that if exceeded leads to unsteady (seizure) operations.

Analysis of thermal seizure using lumped models was firstly proposed by Pascovici et al. [3] for fully submerged journal bearings. Although the model was considered rough, it provided a fast criterion for avoiding seizure, and enabled plotting a safe operations map.

Research on seizure for tilting-pad journal bearings has been continued by Monmousseau et al. [4]. Theoretical analyses in transient thermal regimes were conducted for bearings subjected to various accelerations and operating in safe conditions. The results were compared to experimental data. For bearings under severe operating conditions, the main cause of seizure was the loss of clearance due to the thermal expansion of the shaft. In a second study [5], the model was upgraded introducing the thermoelastohydrodynamic behavior, and bearing seizure was assessed by taking into account the influence of several operating parameters (rotational speed, radial bearing clearance and supply temperature). Among the solutions [6] to reduce the risk of seizure are included: milder acceleration regimes, increase of lubricant supply temperature, and use of greater initial clearances.

A fast tool in assessing the seizure risk for circumferential groove journal bearings (CGJB's) has been forwarded by Pascovici and Kucinschi [7]. The theoretical analysis considered a simple lumped model of a fully lubricated concentric CGJB. The axial lubricant supply flow (hydrostatic) removed part of the heat produced through viscous dissipation, while the remaining heat was stored in the bearing leading to clearance losses. The model considered only the thermal expansion of shaft, and its development was based on Tipei's viscosity-clearance relationship [8].

To end with, both engineers and researchers may refer to a state of art on thermally induced seizure published by Wang [9]. The paper reviews research on the conformal contacts failure, but also introduces several results of non-conformal contacts, for thermal seizure comparisons.

The goal of the study presented herein is to upgrade the previous CGJB lumped model [7], and assess thermal seizure for different operating scenarios.

2 The lumped model

The new lumped model represents a significant upgrade of Pascovici & Kucinschi's previous model [7]. The new model is built within the boundaries of short journal bearing theory [3, 7, 10]. Main upgrades consist of: eccentric operation, introduction of the lubricant hydrodynamic flow rate component, and evaluation of friction power losses based on short bearing theory with Barwell's [10] divergent zone hypothesis. To ease the mathematical reasoning, the model assumes a direct acceleration process. Nevertheless it is suitable for assessing rapid thermal seizure risks, associated to the first couple of minutes of functioning.

A recent Institute Pprime experiment on lightly loaded CGJB's [11], running in safe steady-state conditions, provided a base set of operating parameters. From this basic set of parameters, new severe operating scenarios have been generated and evaluated for seizure risks with the new lumped model.

2.1 Assumptions

The seizure analysis is based on a lumped thermohydrodynamic model in which part of the heat produced by viscous friction is rejected by the Newtonian lubricant flow. The amount of heat remaining in the system is responsible for the bearing's loss of clearance. Assuming a high thermal inertia, environment interactions are not considered for modeling rapid seizure phenomena, this will be explained later on.

Lumped models imply an average temperature for the entire system (i.e. shaft, bearing and lubricant). If one considers that the shaft rotates with a high speed, and that a virtual line on its surface, from one end to another, would travel the entire circumferential domain, then the assumption is not unreasonable. However, this is not the case for the lubricant or bushing where the temperature varies in all directions, however any thermal gradients rest outside the lumped model.

Film separation occurs downstream the minimum film thickness regardless the operating conditions. Therefore, the lubricant does not spread across the entire width in the divergent zone, but flows through numerous thin streamlets. Barwell's [10] hypothesis on the divergent zone consists of replacing the thin streamlets with an equivalent film breadth. Hence, the viscous power losses are determined analytically through the short journal bearing theory, but augmented with a modifying factor, allowing for film rupture.

Short journal bearing theory allows for an eccentric operation modeling, hence both hydrodynamic and hydrostatic lubricant flow components are considered. The previous model considered only the hydrostatic flow component at concentric operations, responsible for lubricant supply.

To further simplify the model, allowing for fast results, the relationship between viscosity and temperature is replaced by a dependency of the viscosity on the clearance, Tipei [8]. As the relationship has previously been used with good agreement [8] in steady-state hydrodynamic lubrification regimes, the authors have extrapolated for this transient seizure model.

Evolution of the system temperature in time, results from simultaneously solving the power balance and dimensionless coefficient of performance (load capacity) equations. The solution is obtained by considering a warm start-up temperature (i.e. the lubricant supply temperature is the initial system temperature), and the acceleration process is very fast (i.e. the shaft starts rotating with the nominal speed).

Although the system is constrained by many assumptions, it is important to emphasize that it is best used in conjunction with rapid thermal seizure phenomena, which occur in the first couple of minutes of adverse operation.

For rapid thermomechanical seizure, one may consider that the thermal inertia of the bearing and its enclosure is very high, and the (bushing) thermal expansion may be delayed or even prohibited by the enclosure.

One may reason that until some heat is rejected to environment, the bushing expands inwards, leading to further clearance loss. After a certain time period, heat reaches the environment and the enclosure starts expanding outwards, also allowing the bushing to expand outwards. In reality, the bushing always expands both inwards and outwards simultaneously, but after several minutes, the overall effect represents an increase of clearance. Note, unlike the rotating shaft, the bushing is stationary and thus most thermal effects are local.

This constrain of rigid bushing simultaneously raises and lowers the risk of seizure, as a thermal expansion of the bushing would ultimately increase the operating clearance after a sharp decrease. These aspects are not studied in the current paper, as the bushing thermal deformation not considered, and the heat generated through viscous friction is either stored in the system or eliminated through the lubricant side leakages (there is no heat transfer with the environment).

2.2 Geometry of the bearing

The CGJB consists of two load-carrying lands placed symmetrically with respect to a supply groove, Figure 1.

2.3 Mathematical description

In this section are presented the main equations shaping the seizure simple lumped model. Note that unless otherwise specified, units are in SI.

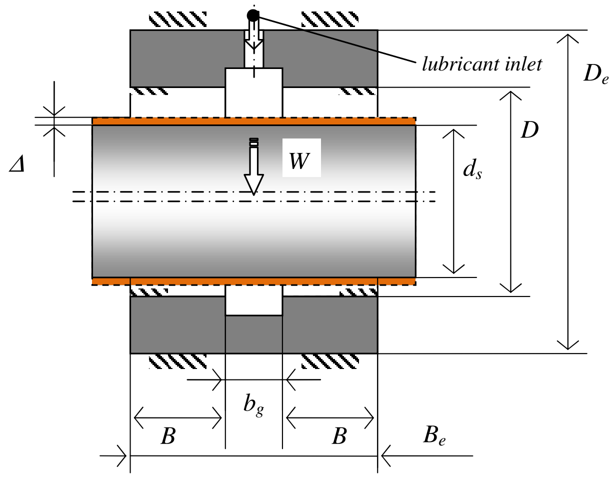


Fig. 1. Geometry of the bearing.

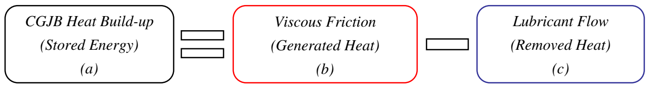


Fig. 2. Energy balance of the system.

The mathematical modeling's keystone represents the relationship between the dynamic viscosity (μ), and the radial clearance (C) proposed by Tipei [8]:

$$\mu = \mu_0 \frac{C}{C_0} = \mu_0 \frac{C_0 - \Delta}{C_0} \tag{1}$$

where subscript (0) denotes initial, and (Δ) is the radial thermal expansion of the shaft.

For the first minutes of operation, high thermal inertia assumption prohibits bushing expansion. Therefore, evolution of bearing clearance in time is modeled only considering the shaft's linear thermal expansion:

$$C = C_0 - \frac{D}{2}\alpha\left(T - T_0\right) = C_0\left(1 - \delta\right) \tag{2}$$

where (α) is the shaft linear thermal expansion coefficient, (T) the average temperature of the system, and (δ) the dimensionless loss of clearance.

Mathematically, the lumped seizure model can be completely described by a coupled system of Equations (3): the power balance equation (or transient energy equation), overview in Figure 2, and the bearing coefficient of performance (or load capacity), characterizing one-land of the CGJB. The latter is obtained from short journal bearing theory, Equation (5.1).

$$\begin{cases} c_{\mathrm{c}} M \frac{\mathrm{d}T}{\mathrm{d}t} = P_{\mathrm{f,co}} f_{P_{\mathrm{f}}}\left(\varepsilon\right) - \rho_{\mathrm{l}} c_{\mathrm{l}} Q\left(T - T_0\right) \\ C_{\mathrm{p}} = \left(1 - \delta\right) f_{C_{\mathrm{p}}}\left(\varepsilon\right) \end{cases} \tag{3}$$

Considering the first equation of system (3), i.e. power balance equation, then the left side corresponds to the total power accumulated in the bearing (shaft and bushing):

$$c_{\mathrm{c}} M \frac{\mathrm{d}T}{\mathrm{d}t} \tag{4a}$$

with $(M = (\rho_b c_b V_b + \rho_s c_s V_s)/(c_c))$ a weighted (or equivalent) total bearing mass (bushing + shaft) with respect to thermal effects, and $(c_c = (c_b + c_s))$ the specific heat capacity of total bearing. This is in accordance with the lumped model assumption, i.e. the entire system is considered as a single black box that accumulates energy in time.

The first group of terms on the right hand side corresponds to the viscous friction generation. These power losses are approximated with short journal bearing theory and a reduced film breadth in the divergent zone, according to Barwell's hypothesis:

$$P_{f,co} f_{P_f}(\varepsilon) = \left(2\pi DB\mu \frac{(\pi Dn)^2}{C}\right) \times \left(\frac{2+\varepsilon}{(1+\varepsilon)\sqrt{1-\varepsilon^2}}\right) \quad (4b)$$

The eccentric operation introduces the hydrodynamic (HD) component, and also influences the hydrostatic (HS) component. The latter corresponds to the lubricant supply, and is characterized by axial flow:

$$\rho_l c_l Q (T - T_0) = \rho_l c_l (Q_{HS} + Q_{HD})(T - T_0) \quad (4c.1)$$

where (ρ_l) and (c_l) are the lubricant density, and specific heat capacity, respectively.

The expressions are in accordance with short journal bearing theory:

$$\begin{cases} Q_{HS} = \left(\frac{2\pi DC^3}{12\mu}\frac{p_s}{B}\right)(1 + 1.5\varepsilon^2) = Q_{HS,co} f_{Q_{HS}}(\varepsilon) \\ Q_{HD} = (\pi BDnC)\varepsilon = (\pi BDnC) f_{Q_{HD}}(\varepsilon) \end{cases} \quad (4c.2)$$

with (p_s) (relative) lubricant supply pressure, and (n) shaft's rotational speed (in rps – revolutions per second).

The dimensionless coefficient of performance (or load capacity), C_p, results from short journal bearings theory, Equation (5.1):

$$\frac{\mu n}{p_m \psi^2} = \frac{1}{(B/D)^2} f_{C_p}(\varepsilon) \quad (5.1)$$

with $f_{C_P}(\varepsilon)$, evaluating the eccentricity's influence on load capacity:

$$f_{C_p}(\varepsilon) = \frac{(1-\varepsilon^2)^2}{\pi\varepsilon\sqrt{\pi^2(1-\varepsilon^2) + 16\varepsilon^2}}$$

Introducing the expressions of relative clearance $(\psi = 2C/D)$, mean bearing pressure $(p_m = W/(2BD))$, dynamic viscosity $(\mu = \mu_0(1-\delta))$ and radial clearance $(C = C_0(1-\delta))$ into (5.1), and afterwards regrouping the dimensional terms, one obtains the second part of the system (3), revealing:

$$C_p = \frac{B^3 D\mu_0 n}{2WC_0^2} \quad (5.2)$$

Hence, one gets the correlation between the dimensionless bearing coefficient of performance (or load capacity) (C_p), and the other dimensionless terms:

$$C_p = (1-\delta) f_{C_p}(\varepsilon) \quad (5.3)$$

A less complicated form of Equations (3) represents its dimensionless form, Equations (6), that could be easier implemented in numerical algorithms:

$$\begin{cases} \frac{d\delta}{d\tau} = \Lambda f_{Pf}(\varepsilon) - \delta\left((1-\delta)^2 f_{Q_{HS}}(\varepsilon) \right. \\ \qquad\qquad \left. + \Gamma(1-\delta) f_{Q_{HD}}(\varepsilon)\right) \\ C_p = (1-\delta) f_{C_p}(\varepsilon) \end{cases} \quad (6)$$

The dimensionless form (6) results by considering some algebra and the replacements given in Equations (7).

$$\begin{cases} d\delta = \frac{\alpha D}{2C_0} dT \\ \Lambda = \frac{6\pi^2 \alpha D^3 B^2 n^2 \mu_0^2}{\rho_l c_l C_0^5 p_s} \end{cases} \begin{cases} \Gamma = \frac{12nB^2\mu_0}{C_0^2 p_s} \\ \tau = \frac{\pi C_0^3 p_s \rho_l c_l D}{6c_c MB\mu_0} t \end{cases} \quad (7)$$

The final mathematical form characterizing the lumped seizure model represents the dimensionless form, Equations (6).

3 The standard parameters and the range of simulations

The model presented in the previous section has been translated into a numerical code that enabled studying various operating scenarios. The basic set of parameters (standard data set or SDS), described in Table 1, are correlated to a recent Institute Pprime experiment on lightly loaded CGJB's [11].

Fast thermally induced seizure has been assessed through extensive simulations covering a broad range of operating conditions. The influence of four parameters has been studied: type of lubricant (ISO VG 32 and ISO VG 46), shaft rotational speed (500–20 000 rpm), applied load (1000, 5000 and 10 000 N) and initial radial clearance (5–225 μm).

Several data sets of parameters (DS), summarized in Table 2, provide support for discussing the results.

4 Results and discussion

The numerical algorithm used for obtaining the results is presented in Figure 3. Although the acceleration effects have not been accounted, the algorithm can be adapted to include these effects.

The standard data set (SDS) yielded a seizure-free operation, as seen in Figure 4. Within the first couple minutes of operation, the clearance loss is about 10 percent of the original clearance. Afterwards, the lumped model predicts stabilization, this has been also observed experimentally as the SDS was a seizure-free operation. The

Table 1. Standard data set (SDS) of operating parameters.

Applied load on the bearing	W	1000 N	Inner diameter of the bushing	$D_b = D$	100 mm
Rotational speed of the shaft	n	1000 rpm	Width of one bearing land	B	20 mm
Initial radial clearance	C_0	75 μm	Number of bearing lands	–	2
Lubricant type	–	ISO VG 32	Relevant width of the shaft (for thermal calculations)	l_s	140 mm
Supply pressure of the lubricant (relative to the atmosphere)	p_s	0.2 MPa	Material of the bushing	–	bronze
Dynamic viscosity of the lubricant	$\mu_{40\ ^\circ\mathrm{C}}$	0.0293 Pa.s	Material of the shaft	-	steel
Supply temperature of the lubricant	$T_s = T_0$	40 °C	Initial temperature (average or lumped) of the entire system temperature	T_0	40 °C

Table 2. Additional data sets (DS) of operating parameters

		Data Set 2 (DS-2)	Data Set 3 (DS-3)	Data Set 4 (DS-4)
Applied load on the bearing	W	5000 N	10 000 N	10 000 N
Rotational speed of the shaft	n	5000 rpm	10 000 rpm	10 000 rpm
Lubricant type	–	ISO VG 32	ISO VG 32	ISO VG 46
Dynamic viscosity of the lubricant	$\mu_{40\ ^\circ\mathrm{C}}$	0.0293 Pa.s	0.0293 Pa.s	0.0430 Pa.s

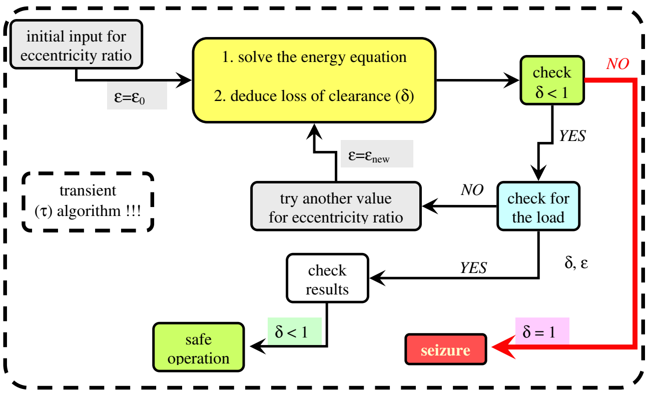


Fig. 3. Simple CGJB seizure – solve algorithm.

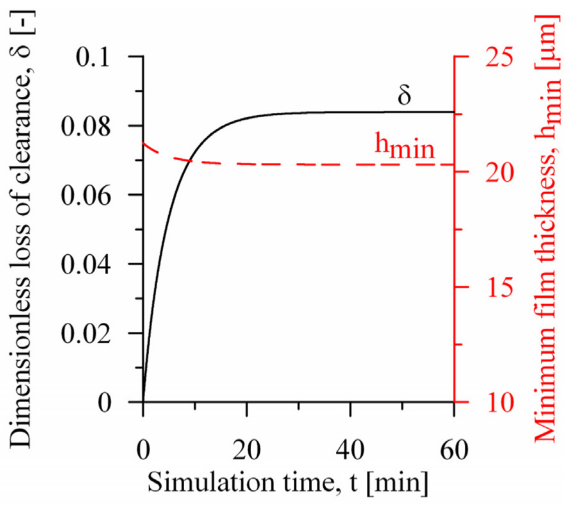


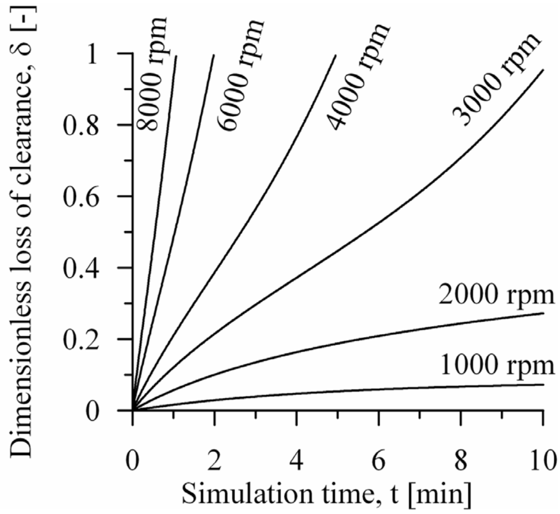
Fig. 4. SDS simulations.

time frame for presenting the results is long, compared to the time period that characterizes the loss of clearance.

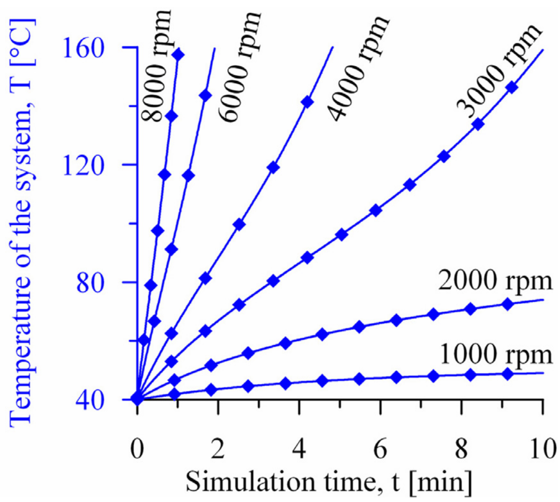
Safe operations correspond to curves of dimensionless loss of clearance, and/or minimum film thickness, tending to constant values. Thermomechanical seizure is considered to occur when the clearance is completely lost, i.e. dimensionless loss of clearance equals 1, and minimum film thickness equals 0.

The effect of speed, lubricant type, load and initial clearance has been pursued also for the SDS, Figures 5–8. The increase of the shaft speed has been plotted in Figures 5a–c for dimensionless clearance loss, average system temperature and minimum film thickness. Doubling the rotational speed may not lead to seizure, however values of 6000 or 8000 rpm predict a rapid seizure well-within the limits of the model. For the 3000 and 4000 rpm results, in reality and given enough time, the system may adapt and the thermal expansion of the bushing can limit the clearance loss. However, as only the shaft's expansion was considered here, the output is a slow seizure within 5 to 10 min.

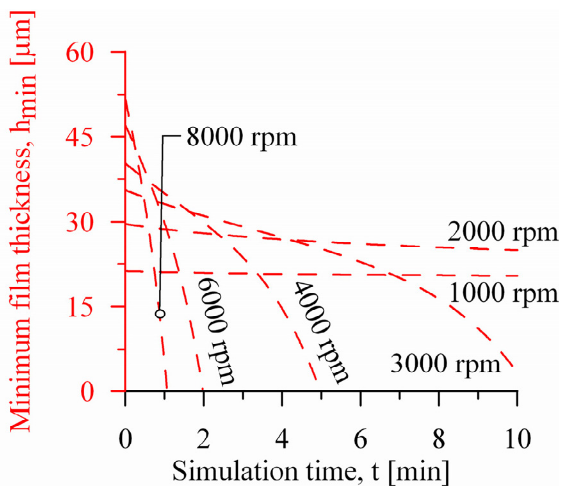
For the SDS operating parameters, choosing a more viscous lubricant, Figure 6, or increasing load up to 10 times, Figure 7, the model still predicted a safe operation regime. The increase of load leads to a decrease in minimum film thickness or a local temperature increase



(a)



(b)



(c)

Fig. 5. (a) SDS simulations with speed-sweep (δ-view). (b) SDS simulations with speed-sweep (T-view). (c) SDS simulations with speed-sweep ($h_{\min}$-view).

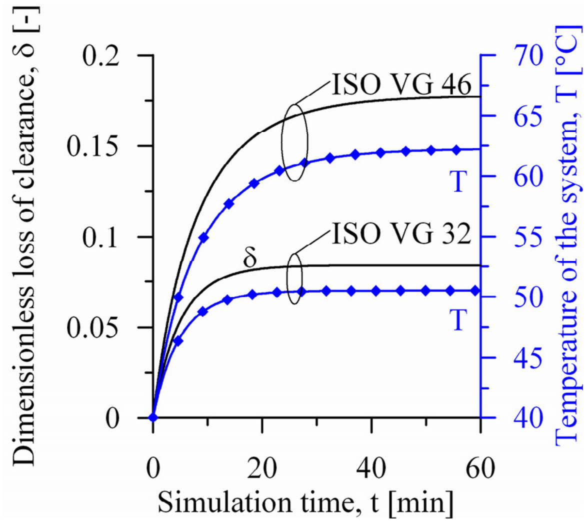


Fig. 6. SDS simulations with lubricant-sweep.

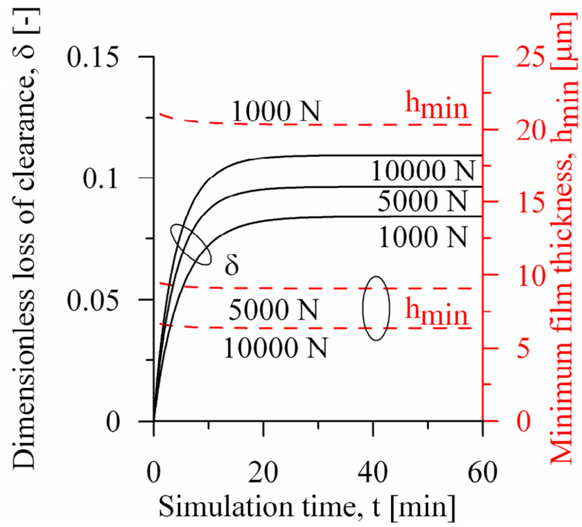


Fig. 7. SDS simulations with load-sweep.

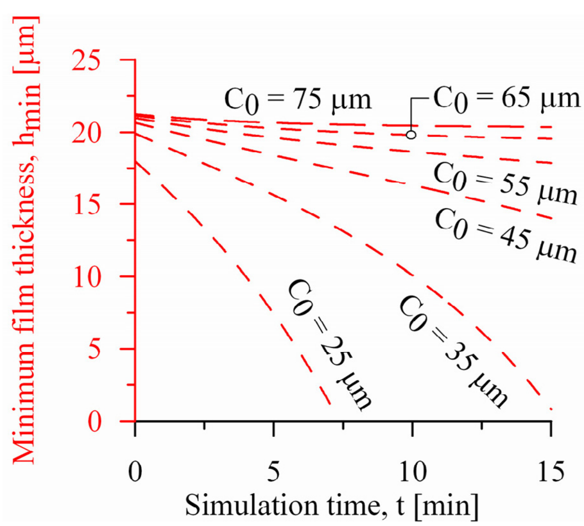


Fig. 8. SDS simulations with initial radial clearance-sweep.

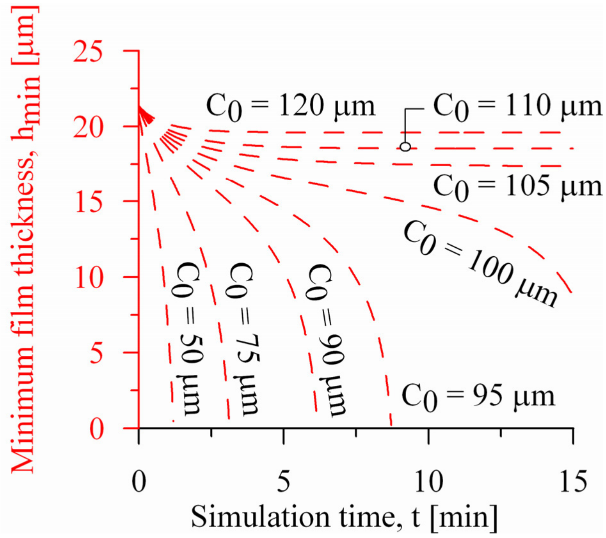


Fig. 9. DS-2 simulations with initial radial clearance-sweep.

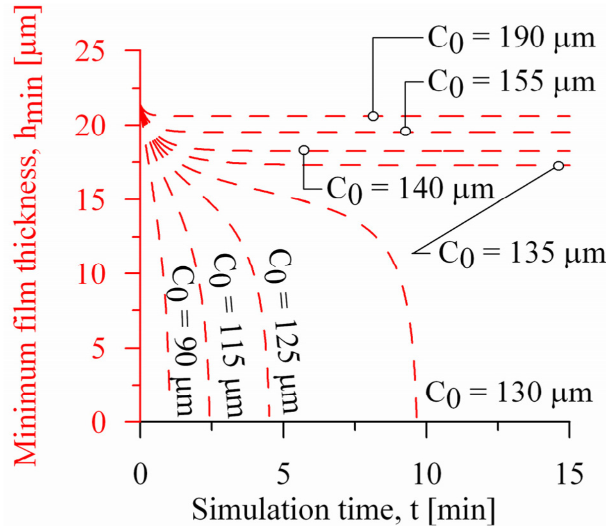


Fig. 10. DS-3 simulations with initial radial clearance-sweep.

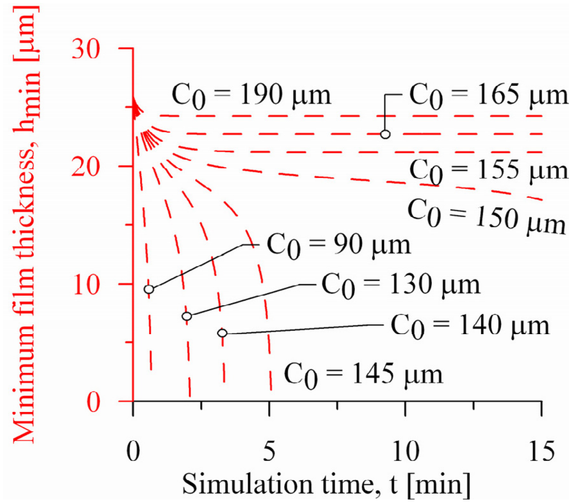


Fig. 11. DS-4 simulations with initial radial clearance-sweep.

in that region, however a higher eccentricity increases side leakages, and consequently the lubricant in-flow. Overall, load does not influence the temperature regime to a great extent. The results are valid, as the thermal regime in a bearing is characterized by the operating speed and/or initial clearance, as it will reveal in the following paragraphs. Seizure can trigger also by using thick lubricants at high rotational speeds.

Along with the rotational speed, the initial clearance influences the CGJB operation to a great extent, as previously stated. This can be easily proven simply by referring to friction power losses term in Equations (6), one sees that the initial clearance term is at the fifth power. Figure 8 shows the increase of the risk of seizure, following the decrease in initial radial clearance.

The effect of initial radial clearance has been pursued also for DS-2 to DS-4 operating parameters, and the results (Figs. 9–12) reveal that as operating conditions become more severe, it is required to adjust the clearance for seizure-free operations. Although this can be straightforward, it is necessary to evaluate clearance adjustments for safe operations.

Comparing Figures 5–12, some remarks can be made. Speed and initial radial clearance have the most influence on the seizure risk. The type of lubricant is also important, but applied load has a small influence, as seen directly in Figures 6 and 13, or by comparing Figures 10 and 11. The results are in accordance with the physics, as the heat produced in the bearing due to the viscous shear of the fluid layers. For Newtonian fluids, such as mineral oils, shearing depends mostly on: relative speed, clearance and viscosity.

Performing a very rough comparison between the current model results and those presented by Monmousseau et al. [5], it can be concluded that for a tilting pad journal bearing with the same overall dimensions, and with similar operating parameters, the time of seizure is comparable (within the first minutes), even though the lumped model is significantly a less complicated analysis. As in the references [5, 6] the plot is constructed with the actual radial bearing clearance and minimum film thickness variations in time.

A comparison with an existing speed-clearance map [12] is illustrated in Figure 13 for two lubricants: ISO VG 32 and ISO VG 46, for a 10 000 N applied load. The relative clearance, ($\psi = 2C/D$), is similar to reference [12].

In addition to the original plots [12], are represented curves of: initial safe radial clearance (safe value plus additional 10 μm to reduce the mathematical uncertainties), final safe radial clearance (corresponding to the initial safe values previously described, but allowing for thermal expansion) and curves of unsafe initial clearances (which lead to thermal seizure in about 1 min of operation). The final (operating) clearances are a good estimate for the reference curve and rest generally within the recommended boundaries. Higher lubricant viscosity requires an increase of initial clearance for safe operation, i.e. to

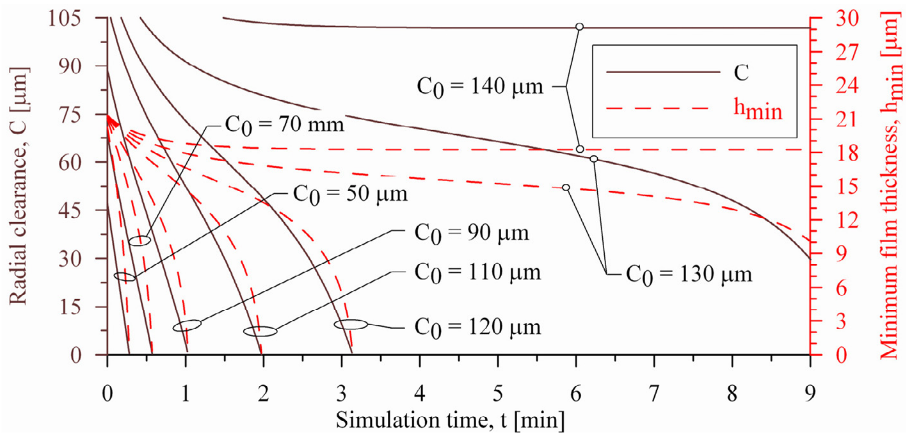


Fig. 12. DS-3 simulations with initial radial clearance-sweep (alternate view).

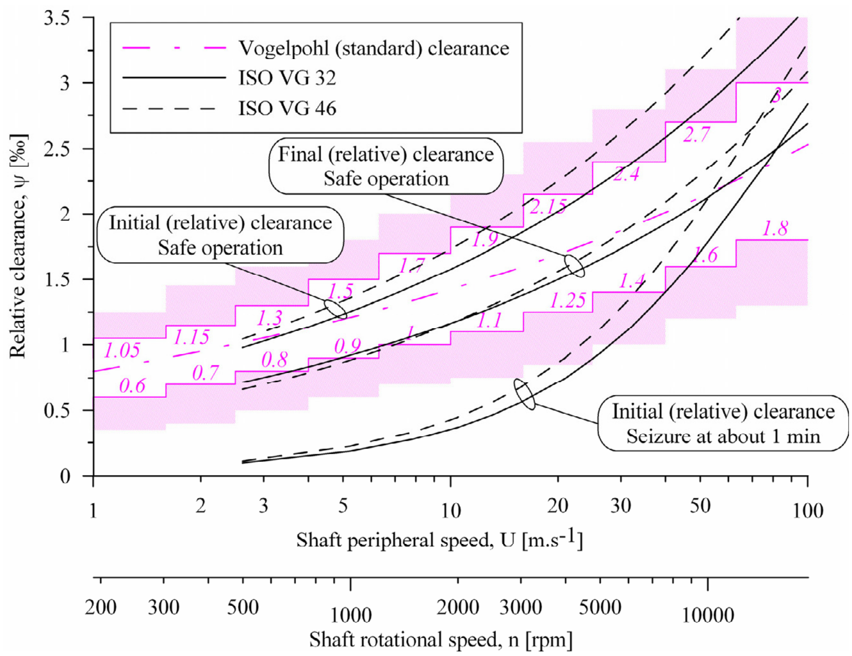


Fig. 13. 10 000 N with ISO VG 32 and ISO VG 46 clearance vs. speed map (Vogelpohl [12]) comparison view.

lower viscous friction losses. However, a too high clearance may not lead to a proper hydrodynamic operation, and a more powerful model should be used for addressing the cases close to the boundaries.

5 Conclusions

The study herein presents a simple and easy to implement lumped model for assessing seizure in circumferential groove journal bearings (CGJB's).

The results obtained with the lumped model can be considered for characterizing rapid seizure phenomena, which occurs within the first couple of minutes of adverse operation. If the time frame is extended, results obtained considering only a linear expansion of the shaft are unreliable, as the thermal expansion of the bushing increases operating clearances, or respectively decreases the risk of seizure.

The lumped model allowed for identifying the key parameters that influence the risk of seizure: initial bearing clearance and rotational speed. The type of lubricant is also important, and further studies will consider a broader range of lubricants.

Comparing the results to an existing well-known Vogelpohl chart used by bearing manufacturers reveals that the operating clearances for seizure-free regimes are within the recommended values. Hence, the model enabled drawing a chart for selecting the type of lubricant and initial bearing clearance for avoiding seizure in CGJB's.

Future upgrades of the model can consist of the introduction of acceleration regimes, but in order to extend the realistic time-frame for seizure estimations one has to take into account bushing thermal expansion.

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References

[1] J.M. Conway-Jones, A.J. Leopard, Plain bearing damage, In Proc. Fourth Turbomachinery Symposium, Gas Turbines Laboratories, Texas A&M University, College Station, Texas, USA 14-16 (1976) 55–63

[2] J.L. Bishop, C.M.McC. Ettles, The seizure of journal bearings by thermoelastic mechanisms, in Elsevier Wear 79 (1982) 37–52

[3] M.D. Pascovici, M.M. Khonsari, J.Y. Jang, On the modeling of a thermomechanical seizure, (Technical Brief), in ASME J. Tribol. 117 (1995) 744–747

[4] P. Monmousseau, M. Fillon, J. Frene, Transient thermoelastohydrodynamic study of tilting-pad journal bearings – comparison between experimental data and theoretical results, in ASME J. Tribol. 119 (1997) 401–407

[5] P. Monmousseau, M. Fillon, J. Frene, Transient thermoelastohydrodynamic study of tilting-pad journal bearings – application to bearing seizure, in ASME J. Tribol. 120 (1998) 319–324

[6] P. Monmousseau, M. Fillon, Transient thermohydrodynamic analysis for safe operating conditions of a tilting-pad journal bearing during start-up, in Elsevier Trib. Int. 33 (2000) 225–231

[7] M.D. Pascovici, B.R. Kucinschi, Seizure of a concentric circumferential-groove journal bearing, in 1st EDF-LMS Workshop, Bearings Under Severe Operating Conditions, Futuroscope, France, 19 (2002) F1–F8

[8] N. Tipei, W.A. Gross, Theory of lubrication: with applications to liquid- and gas-film lubrication, C.A. Stanford University Press, 506 pp., ISBN 978-0196902159, 1962

[9] Q. Wang, Seizure failure of journal-bearing conformal contacts, in Elsevier Wear 210 (1997) 8–16

[10] F.T. Barwell, S. Lingard, The thermal equilibrium of plain journal bearings, In Proc. 6th Leeds-Lyon Symposium on Tribology, Thermal Effects in Tribology, Lyon, France, 18–21, 1979, pp. 24–32

[11] A.F. Cristea, J. Bouyer, M. Fillon, M.D. Pascovici, Pressure and temperature field measurements of a lightly leaded circumferential groove journal bearing, Trib. Trans. 54 (2011) 806–823

[12] G. Vogelpohl, Betriebssichere Gleitlager. Berechnungsverfahren für Konstruktion und Betrieb, Springer-Verlag, Berlin, 315 pp. (in German)