A009

THE WORK ON HYDRODYNAMIC JOURNAL BEARINGS CARRIED OUT AT MINHO UNIVERSITY IN THE LAST 30 YEARS

Claro, J C P [1 (*)]; Miranda, A S [2]; Costa, L [3]; Brito, F P [4,5]; Fillon, M [6]
[1], [2], [4] Mechanical and Materials Technologies Centre (CT2M), University of Minho, Guimarães, Portugal
[3] Ministry of Energy and Water/DNAAS, Luanda, Angola
[5] ISEP, Porto, Portugal
[6] Institut Pprime, CNRS - Université de Poitiers-ENSMA, Dpt GMSC, Futuroscope Chasseneuil, France
[(*)]email: *jcpclaro@dem.uminho.pt*

ABSTRACT

The hydrodynamic journal bearing is still one of the most geometrically simple mechanical components, yet highly reliable and efficient and, above all, unique in what concerns to heavy duty – high load, high speed – support of rotating shafts.
Analytical studies, not only to understand the physical basis of its performance, but also to develop practical tools for an expedite design, as well as to assure its reliability and improved efficiency, were object of the early developments in fluids' hydrodynamic sciences, since the late XIX century, and are still been refined and improved on the XXI century.
Historical marks can be flagged as (i) simplified analytical resolutions of the hydrodynamic pressure distribution; (ii) computerized iterative resolution of the full pressure development equations; (iii) introduction of the lubricant feeding conditions; (iv) analysis of the thermal aspects and its influence on viscosity; (v) localized aspects of fluid flow, due to thermal/viscous phenomena and geometrical particularities.
This evolution led to increased accuracy on the performance predictions and to safer and higher efficiency of the designed components. On the other hand, analysis became more specific in use and, particularly with the introduction of the thermo-hydrodynamic analysis, led to the need of 'tailored' solutions to a given set of specific conditions. As a consequence, methods lost much of their 'universality' and ease of use to the common and sporadic designer.
This work intents to make a first evaluation of the response of three prediction methods – a commercial and widely used isothermal approach and an isothermal and a thermo-hydrodynamic procedures, these former developed at UMinho over the last years – in an attempt to highlight the variability of the predictions of the main performance parameters by the use of simpler and rapid methods, when compared with those based on more complex and accurate analysis, and their eventual influence on an efficient and reliable design solution.

1. A brief look at the advances on the analysis and design of hydrodynamic journal bearings

Fundamental principles of bearing's performance analysis are based on Osborne Reynolds' work (1886) which, in turn, relies on incompressible Newtonian fluid's flow Navier-Stokes formulation.
From these early works up to the 1st half of the XX century, the assumption of a proper analytical definition of the cavitation phenomena, as a basic principle of fluid's hydrodynamic pressure generation (and, consequently, of bearing's load carrying capacity) lead to an intensive research on the influence of the working parameters on the overall performance predictions. A special focus was put on the influence of feeding conditions on cavitation and

reformation boundaries location and geometry. Also pioneer studies on heat generation and flow were carried on.
First design methods resulted from Sommerfeld contribution (1904), eventually refined through the incorporation of the 'half-Sommerfeld' and the 'Reynolds' cavitation boundary conditions. This, the so called 'long bearing' solution, as well as the later 'short bearing solution', due to the works of Ocvirk (1952) and Dubois & Ocvirk (1957), were in fact simplified solutions relaying on 2D simplified approaches, scarcely reflecting the real geometrical and working conditions and, so, with limited advantage for the designer.
Nevertheless, remarkable works such as those due to Burke & Neale (1957) and Raimondi & Boyd (1958) must be highlighted by their major role on behalf of engineering bearing design.

However, in the 2nd half of the XX century, advances in iterative mathematical and computational methods made possible the solution of the full Reynolds equation, as well as the introduction of 'mass conservative' solutions in the analytical definition of the circumferential fluid pressure profile – Jakobson & Floberg (1957).
Simultaneously, increasing experimental research highlighted the relevance of the exact definition of the fluid film extent and shape, showing that it was dictated by various factors but above all by the feeding conditions – Clayton (1946), McKee (1952), Cole & Hughes (1956), Dowson (1957).
As a consequence, a step forward in the theoretical analysis was taken, from the 'fully flooded' bearing concept to the most common circumferential and axial feeding groove arrangements, taking into account the influence of their dimensions, locus and intake pressure to the overall induced film geometry.
This brought to a 'second generation' of calculating methods, taking into consideration the influence of different feeding arrangements, quantifying lubricant flow entering, leaving and recirculated within the bearing and establishing a heat balance, based on temperature rise generated by viscous drag and on feeding fluid refreshment phenomena. Backed up on a hybrid (analytical and semi-empiric) approach – a drawback due to the simplicity of the original analytical simulation – this also implied the introduction of an 'effective temperature' concept, as a key part of an iterative process, to access the performance conditions of the bearing based on an isothermal approach, such as ESDU item no. 66023 (1966).
Later on, with the advent of implicit methods mainly based on the work of Elrod (1981), it has been possible to deal with the cavitation/regeneration phenomena, allowing a much more reliable prediction of film's geometry, to whatever feeding and/or other geometric conditions.

On the other hand, the unification of the thermal and the hydrodynamic theoretical approaches accomplished by Dowson (1962) allowed the solution of flow and energy equations, with its boundary conditions – the so-called thermohydrodynamic or "Local Thermal Model", in opposition to the "Global Thermal Model" which only considered a constant 'effective temperature'.
Experimental findings by Dowson et al (1966) justified the wide use of a 2-D thermal analysis of the journal bearings restricted to the bearing midplane – Boncompain et al (1986), Khonsari & Beaman (1986), Ma and Taylor (1992). Subsequently, the solutions evolved to consider the conductive heat transfer across the bush and free convection with the ambient, thus estimating a non uniform bush surface temperature (Boncompain et al, 1986; Tucker and Keogh, 1995). On the other hand, the effect of lubricant feeding was also on focus, in order to estimate inlet groove mixing temperature, based on the degree of oil recirculation and fresh oil fed – Mitsui et al (1983), Kosasih & Tieu (2004).
Nevertheless, the thermal treatment of the ruptured film region was one of the fields that received more attention, due to its importance on bearing's thermal behavior, as shown by

Knight & Niewiarowski (1990), and several models were developed, from that one of Knight & Barret (1983) to the work of Nassab & Maneshian (2007), among others.

A further step was the incorporation of thermal expansion and elastic deformation predictions, in the thermohydrodynamic model, in order to access the bearing's gap variation due to temperature and pressure fields. From the simplified differential thermal expansion concept of Medwell & Gethin (1984), to the full FEA solution of the elastic problem, Bouyer & Fillon (2004) shown that these effects are not despicable when high load and high speed are involved.

2. Performance prediction methods at design level

To the sporadic design of a plain journal bearing, the choice can be put in terms of a simple and quick commercial method or a full, dedicated and specifically developed analysis.
In the first alternative, there is still the option for a rough approach, with little or none demands on pre-specifications, or for a more complete configuration, namely taking into consideration different geometries and arrangements, feeding conditions, etc.
In what concerns to a more specific analysis, there is also a possible choice between a 'lighter' isothermal solution and a higher computer demanding thermo-hydrodynamic method.
In this second alternative, the question relies on the choice of an approach that allows a dimensionless treatment of the data, with a restrict number of generalized parameters to be adjusted or, on the other hand, in a problem that must be tailored according to a reasonable number of parameters, constants and even unknowns, at the design stage.
In the designer point of view, this means to manage a graphically based method (nowadays also possible in terms of an electronic spreadsheet, not to refer the built-in 'black box' tools offered in broad design packages) or manipulate and run a specialized, and usually rather 'user-unfriendly', computer code.

3. Development of the plain hydrodynamic bearing analysis at UMinho

The implementation of Elrod's algorithm to the isothermal analysis of the plain journal bearing with a finite axial groove at (h_{max}), made by Miranda, A S (1983), brought a new highlight on the importance of feeding conditions, namely the strong influence of groove's geometry on film extent and shape, in what concerns to bearing's performance prediction.

Additionally, the exploration of the 'starvation' concept – lubricant flow supply below its 'theoretical' value, with the consequent drop in viscous power loss – showed the potential benefits in efficiency of this technique, as well as the possibility of its quantification at a design level.

Subsequent extension of the isothermal analysis to different, and most common, feeding conditions by Claro, J C P (1994) – namely one or two axial grooves at right angle to the load line and the 'crown' bearing – also conveyed the attention to new problems, such as (i) the hydrostatic effect of the feeding pressure, on a single groove at +90º arrangement under lightly load, and its influence on the overall working conditions, and (ii) the possible existence of a back flow at the 'downstream' groove on a +/-90º arrangement, actually promoting a negative feeding effect.

Later on, the introduction of the thermal analysis, applied to the bearing with one axial groove (at +90º to the load line and to the 'crown' bearing) by Costa, L (2000) promoted a detailed analysis of the recirculating flow phenomena (reverse and back flow) on groove's up and downstream edges, and its influence on an effective prediction of lubricant feeding flow and overall bearing temperature conditions.

Finally, with the extension of the thermal analysis to the bearing with two axial grooves at +/-90º to the load line, by Brito, FP (2009), a model for the lubricant mixing at the groove, coupling recirculation, reverse and backflow phenomena, was incorporated in the global heat exchange analysis. The conditions for a back flow phenomena – the concept of a groove acting as a 'sink', by opposition to a 'feeding' one – was expanded and detailed, leading to some unexpected (and not, till that moment, reported) working conditions. Also a ruptured film model incorporating the effect of a shaft-adhered layer of lubricant, as well as an averaged clearance gap correction, due to shaft and bush mean thermal expansion, were introduced.

4. Comparison of results, with different analytical approaches

4.1 Objectives

In this work, a study was carried out comparing the performance predictions of the isothermal (**IsoT**) and the thermohydrodynamic (**THD**) analytical methods, developed at UMinho since 1983 till 2009. Additionally, the predictions of **ESDU** 84031, Amendment A (1991) were also used, in order to evaluate the response of a (yet) widely used commercial design method.

This exercise had as a prime objective to look for and analyze the possible, and expected, differences obtained in the prediction of the main performance parameters, using methods with different levels of sophistication.
Additionally, it also intends to be a first approach on the identification of possible conditions where a lighter approach – being either a quick and straightforward commercial calculation method or a simpler and less computational demanding procedure – may be able to get reasonable solutions for engineering design or, on the other hand, when a specifically developed analysis and 'heavy' demanding – in processing time and skills of the designer – has to be used, in order to ensure the reliability and the efficiency of the resulting component.

4.2 The generic case selected

A basic geometry with a nominal diameter (d) of 100 mm and a length (b) of 80 mm, with axial feed groove dimensions of 80 mm length (a) and 18 mm width (w), was arbitrarily chosen.
A mineral oil (with 29.3/5.5 mPa.s at 40º/100ºC), fed at 40ºC and a pressure (p_f) of 0.1 MPa and two alternative axial groove feeding arrangements (one groove at +90º and two grooves at +/-90º to the load line) were considered.
In what concerns to working conditions, a fixed shaft rotating speed (N) of 3000 rpm was selected and, in order to cover a reasonable spectrum of conditions, eccentricity ratio (ε) was varied from 0.3 to 0.9, corresponding to expected load carrying capacities ranging from over 1 kN to around 7 kN.

4.3 Some particularities of the implementation

i) The ESDU design method relies on an iterative process ([1]) to adjust the value of an 'effective temperature' (Te), required to achieve convergence of the relevant performance parameters.

([1]) It is worth noting that this procedure is completely exogenous to the isothermal resolution of the basic equations of flow, being the result of a thorough compilation and treatment of empirical, experimental and practical data, which assures a remarkably simple and quick convergence of the calculation process for the determination of the 'effective temperature', which rules the all solution.

Already present in item no. 66023 (1966), and refined in item no. 84031 (1984), an additional iteration was added in item no.84031 Amendment A (1991) to take into account the mixing of fed and recirculated flows effect at groove's level temperature (T_{groove}).

Furthermore, as an additional help in design, a 'post-processing' procedure is offered, to calculate the expected maximum temperature (T_{max}) within the bearing – not despicable if low melting point lining materials are used in the bush – and also the average temperature of lubricant leaving the bearing (T_{out}), as a measure and prevention of oil degradation by oxidation.

ii) As the IsoT is not meant to be a complete design procedure, it has no intrinsic means to evaluate beforehand a lubricant relevant viscosity value (or the equivalent lubricant temperature) to be used in the subsequent calculations, which determines the results achieved.

In this study, the 'effective temperature' (Te) data obtained by ESDU method were primarily used as a reasonable approach. However, the development of the comparisons led to an alternative option, as detailed ahead.

iii) The THD analysis performs an iterative process, balancing heat generated internally by viscous drag and that one transferred to the environment, in the determination of the fluid's temperature distribution.

This means that not only specific data – such as the thermal characteristics of the bush, ambient temperature, etc. – must be selected beforehand, but also that are exclusively used by this method, with no link with ESDU or IsoT calculations.

4.4 Comparisons of bearing performance predictions

4.4.1 Temperature

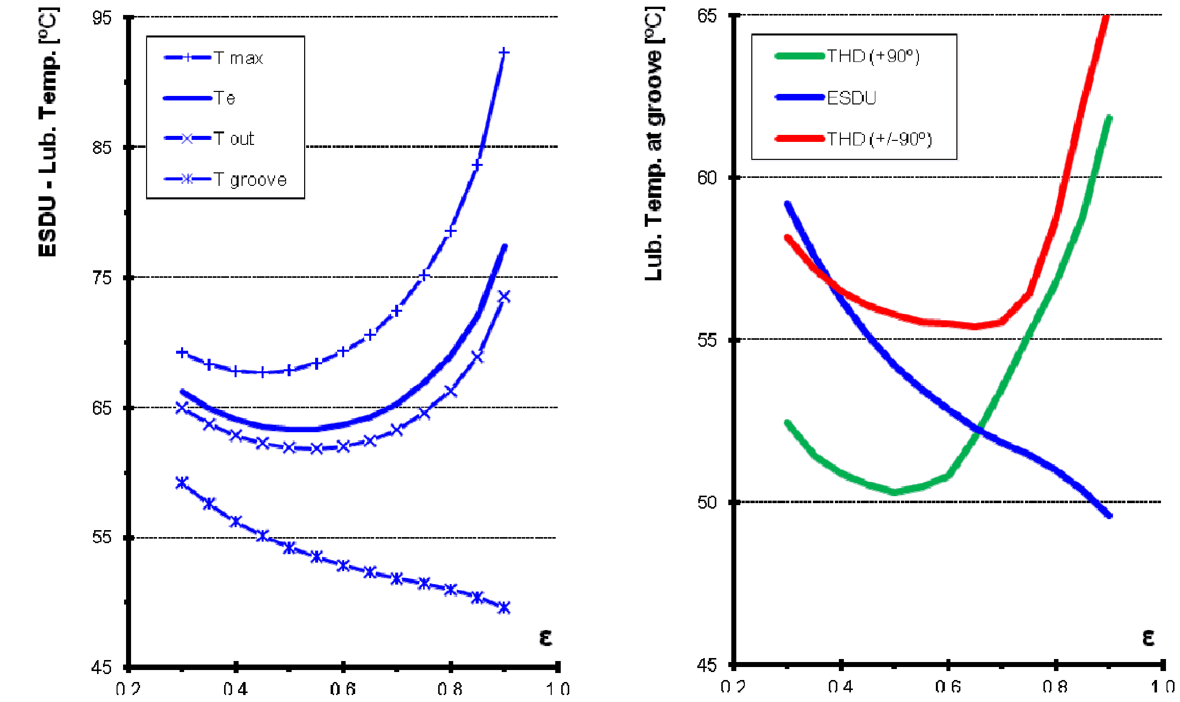
Due to its key role in the theoretical determination of the overall performance of the bearing, (besides the problems detailed above, in what concern to the differences in the analytical methods used) first considerations must be based on temperature predictions, which directly relate to the lubricant viscosity values employed in the calculation process.

In Fig.1(a) a plot of all the various temperatures predicted by ESDU, against eccentricity ratio (ε), is shown.

A fact that must be highlighted is that ESDU method, in its later version, doesn't make any distinction for the existence of one or two grooves, in the calculation of all performance parameters including temperature. So these curves are similar to the two geometries considered here.

Besides that, the most remarkable is the prediction of the temperature at the groove(s). Although the 'effective temperature' (Te), which is the main parameter for the calculation procedure, presents a strong increase for values of (ε) above ~0.5 – with the maximum temperature (T_{max}) and the average lubricant outlet temperature (T_{out}) following the same trend – on the other hand (T_{groove}), which theoretically reflects the mixing effect of the recirculated lubricant with that one fed through the groove, presents a continuous drop.

This can be interpreted as an increasing capability of locally refreshing the bearing, well over passing the effect of the heat internally generated, in spite of the heavier loading conditions. With an entry temperature kept constant, the only explanation relies on an increasing preponderance of feeding over recirculated flow, as eccentricity rises.



(a) ESDU predictions (b) T_{groove} (ESDU *versus* THD)

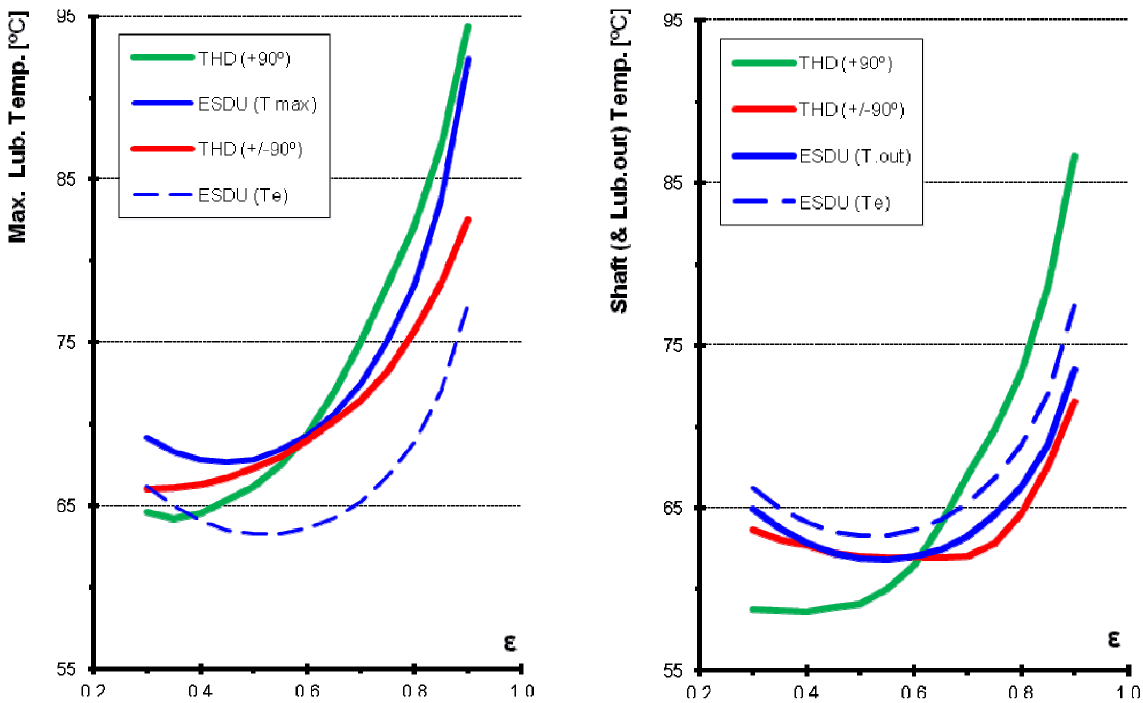
Fig.1 – Comparison of ESDU temperature predictions

Detailed discussion of this particularity is beyond the scope of this work, but a simple comparison with the results of THD analysis – Fig.1(b) – hardly sustain this hypothesis.
Nevertheless, (T_{groove}) can be looked as a secondary parameter – directly related to the native ESDU mixing phenomena modeling – and attention may be focused on the temperature parameters that can closely be associated with the heat flow along the bearing.

Fig.2 shows the predictions for (a) the maximum temperature within the bearing and (b) the side flow mean lubricant temperature ([2]). In both graphs, (Te) was also added as a dashed line.
As can easily be seen, in spite of the simplicity of the calculating process, the trend of ESDU temperatures' predictions stays fairly close to that of the THD analysis.
However it is worth noting that, taken into consideration that the net temperature values have a significant influence on the resulting lubricant viscosity, tolerance for those predictions is usually constrained to a ±2º window.

In a closer view it can be observed that, curiously, there is a reasonable proximity of the maximum temperature (T_{max}) curves, for the geometry with one groove at +90º to the load line – green and blue lines, on Fig.2(a) – except for very low eccentricities.
On the other hand, a good correlation is obtained for the side flow mean temperature (T_{out}), for the two grooves at +/-90º arrangement – red and blue lines, on Fig.2(b) – which, in this particular case, is also closely followed by the (Te) curve.

([2]) Due to differences inherent to the procedures, and for simplicity of the calculations, the mean shaft temperature (T_{shaft}) predicted by THD analysis is used here, for comparison with (T_{out}) of ESDU method.



(a) T_{Max} (b) T_{Shaft}/T_{Out}

Fig.2 – Maximum and side flow temperatures (ESDU *versus* THD)

4.4.2 Load capacity and Power loss

For a given application, and in a first approach, load capacity is the key working parameter, as it is for supporting it that the bearing is intended to. Simultaneously, in a designer point of view, the main objective is to achieve a set of conditions that ensures a resulting eccentricity within an acceptable range of values, to guarantee a safe operation ([3]).

As the hydrodynamic pressure development – which generates de load carrying capacity – directly depends on fluid's viscosity, and so on its temperature, heat produced by viscous drag – mainly translated in power loss within the bearing – makes the balance of these two parameters the basic challenge for the all performance prediction.

Fig.3 shows load carrying capacity curves, for the three analyses.
First remarks are that IsoT predictions are almost indistinguishable, for the one and two grooves arrangements, and that they display insignificant differences to those of ESDU.
On the other hand, THD analyses give values that differ for the different groove arrangements, always lower than all the others and clearly divergent with increasing eccentricity.
Though, it is worth noting that while for one groove at +90º the differences range from -30% to -40%, for ε=0.6 to 0.9, this is certainly not the case for two grooves at +/-90º, where discrepancies don't overpass the -15% along the all range (although, in net values of load capacity, that mean differences from around -2 to -10 kN).

([3]) As it was not intention of this work to analyze or discuss additional problems arising from extremely high or low eccentricity ratio regimes, (ε) was restricted to a conservative [0.3, 0.9] interval, usually considered as within the 'normal' operating ranges.

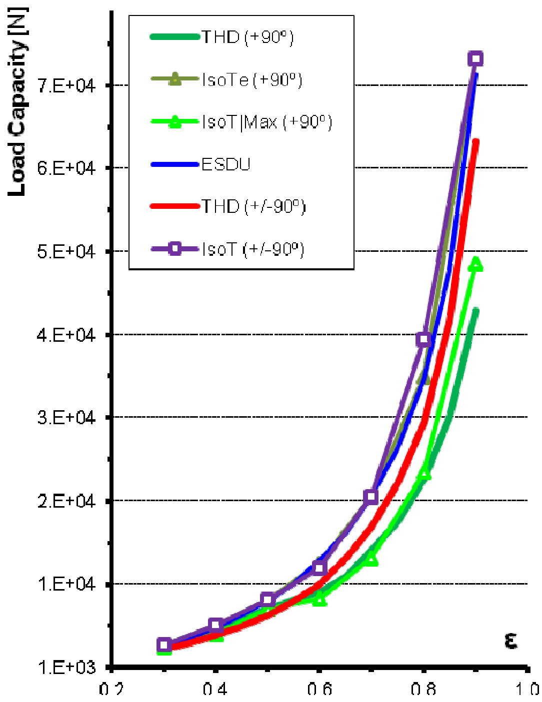


Fig.3 – Load capacity

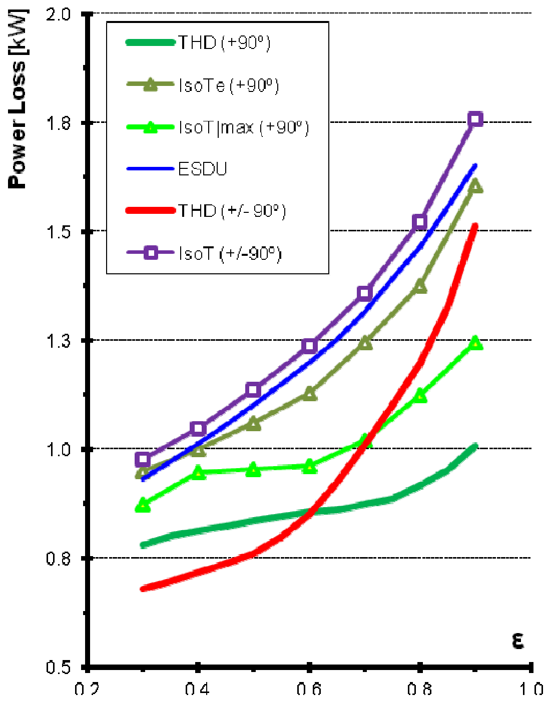


Fig.4 – Power loss

However the most noticeable is that, recalling the behavior of ESDU maximum temperature predictions for one groove at +90º, when compared with those of (Te), as discussed previously – Fig.2 – the fact is that if IsoT load capacity is calculated based on (T_{max}) and not on (Te) values, the discrepancies drop to a maximum of -12% (as displayed by the light green line, plotted in Fig.3).

In what concerns to power loss – Fig.4 – once again ESDU and IsoT show very close net predictions and overall trends, although the last one clearly differentiates the influence of the groove arrangements.

The noticeable convergence with increasing eccentricity, for the two grooves case – red line, in Fig.4 – is however the most unexpected result, taking into account the behavior observed by all the other relevant parameters ([4]).

Nevertheless, as well as for the load capacity, the use of (T_{max}) instead of (Te) in the IsoT calculation process for the one groove arrangement, leads not only to closer predictions but also to a significant change in the trend of the curve, getting it to a closer path of the THD one.

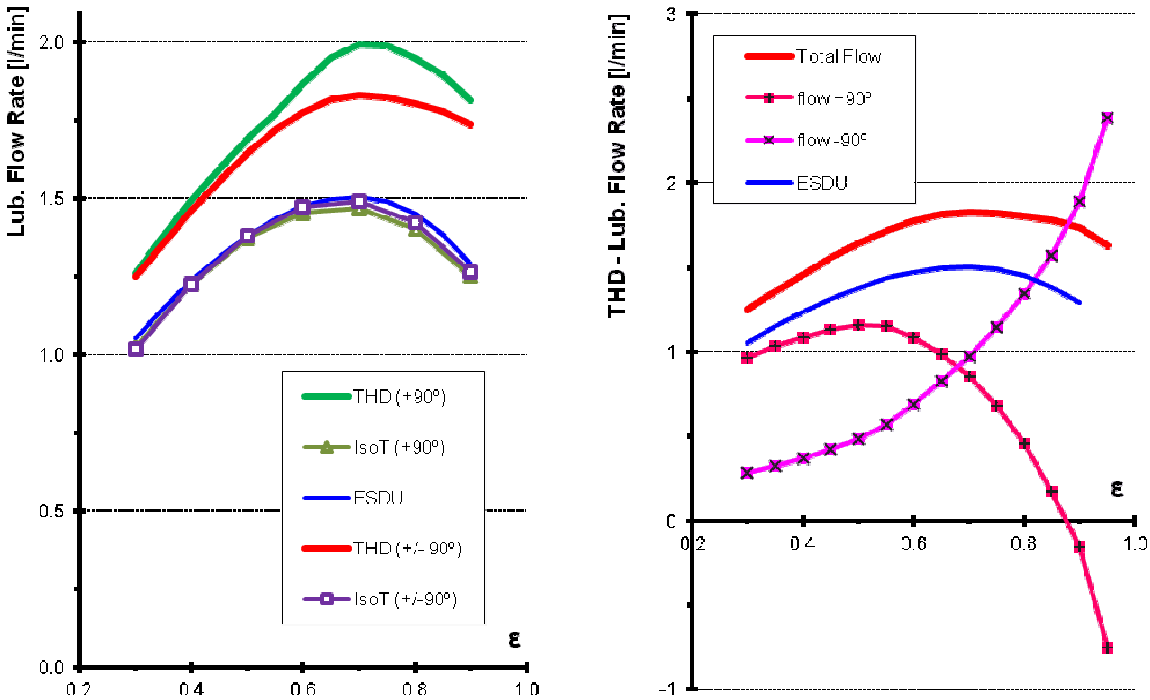
4.4.3 Lubricant flow rate

Flow rate is the most sensitive parameter to the features that may, or may not, be incorporated in a theoretical analysis, as it is directly influenced by the pressure development within the

([4]) Recalling the general idea that postulates a two groove arrangement as an usual way of increasing refreshment of the bearing – and consequently to lower temperature and higher viscosity levels – that means that, for similar conditions, an higher power loss of this arrangement could reasonably be expected.
However, Fig.4 shows that this effect only happens for eccentricity ratios above ~0.6, which may indicate that this can be an exceptional conjugation of working conditions (to which, apparently, only the THD analysis has enough sensitivity) but conclusions cannot be driven in a simple and straightforward way.

bearing, film shape and extent, lubricant temperature and consequent viscosity distribution and, eventually, by the overall feeding conditions, such as lubricant inlet pressure and temperature, shape, position and number of the grooves, etc.

Fig.5(a) shows the predictions obtained by each one of the methodologies.
In spite of the differences previously noticed between ESDU and IsoT analysis, in load capacity, power loss and working temperature – either using of (Te) or (T_{max}) – the curves on flow rate are noticeably close together. And not even the consideration of the two different feeding arrangements, made by IsoT, seems to add any perceptible difference to its results.



(a) Total flow rate (b) Feed rate (2 grooves +/-90º)

Fig.5 – Lubricant flow rate

But the most remarkable is the discrepancy between these two and the THD analysis. When comparing with ESDU predictions, differences rise from -16% at ε=0.3 to -29% and -26% at ε=0.9, for the one and two grooves arrangements, respectively. Differences to IsoT are even marginally higher, as its curves remain always under those of ESDU.
One reason for the discrepancies might be the clearance correction adopted by the THD method when accounting for average thermal expansion. Furthermore, taking into consideration that both ESDU and IsoT analyses predict substantially higher power losses – Fig.4 – and working temperatures that, at least for (Te) and one groove at +90º, can be substantially lower – Fig.2 – a considerably lower flow rate (also diverting with eccentricity) could reasonably be expected as a result of the overall calculation. This could be interpreted as a 'deficient' account, by these simpler analyses, for the refreshing action of feeding lubricant via a single groove at +90º.

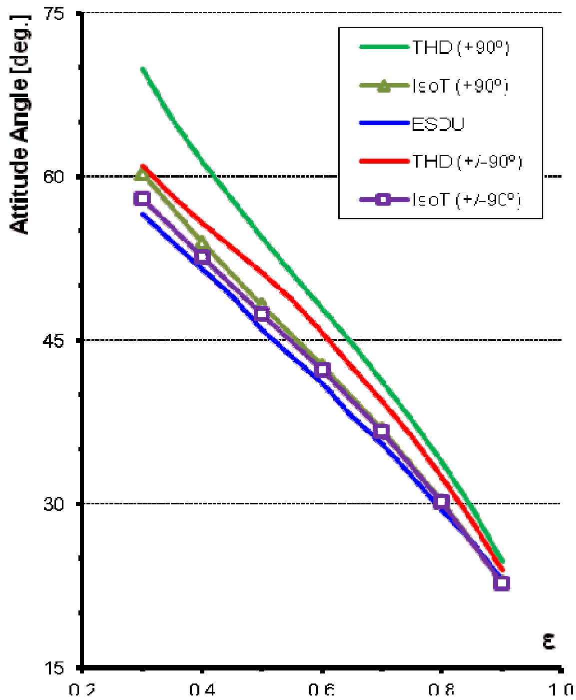
In what concerns to the two grooves arrangement, while ESDU and IsoT temperatures shown to be within a reasonable tolerance to those of the THD, the behavior of power loss predictions – as pointed out previously – do not help to understand the differences on flow rate (in spite of a closer overall trend, in this case, by comparison to that obtained for one

groove).
The explanation to this oddity can rely on a closer look to the contribution of each specific groove. Fig.5(b) displays not only ESDU and THD global flow rate predictions, but also the flow rate entering through each groove, individually, as calculated by the second analysis.
As can easily be seen, the flow through the groove at +90º suffers a drastic drop around ε=0.5, which goes below that one of the groove at -90º for ε>0.7, and not only vanishes but starts acting like a 'sink' (negative flow) for ε>0.85.
This is something that a method such as ESDU cannot accommodate but that, theoretically, the IsoT analysis could predict and deal with. Although, apparently the thermal phenomena can play a decisive role on its development, as THD results show.

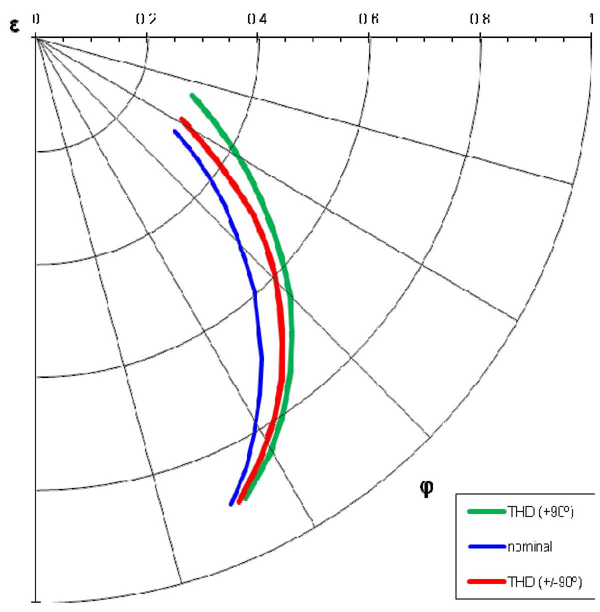
Nevertheless is yet to be understood how, when comparing THD predictions with the others, a drop/negative flow on one of the grooves is compensated by the flow on the other groove – as the total net flow keeps higher – and how that conjugates with a simultaneously strong increase in power loss, with a shallower (or, at least, 'delayed') rise in working temperature and no evidences of influence on the total load capacity.

4.4.4 Attitude angle and Center locus

Not being a decisive design parameter, the behavior of the attitude angle with eccentricity ratio – Fig.7(a) – can be relevant in reasoning the evolution of the clearance/entry gap – i.e., in the region of the groove(s) – due to its direct influence on feed flow rate.



(a) Attitude angle (φ)



(b) Center locus

(ESDU and IsoT center locus are coincident)

Fig.7 – Attitude angle versus Eccentricity ratio

In Fig.7(b) the same results are plotted in a polar form which, allowing to visualize the shaft center locus path, highlights not only the different results between a simpler and a more detailed analysis, but also the remarkable differences that can be observed for the two feeding groove arrangements considered.
Here the hydrostatic effect of feed pressure, found in the single groove but absent in twin

groove configuration (as the effect on one groove is cancelled by the opposite one) is apparent for low eccentricities, where the bearing is looser.

5. Conclusions

5.1 Prologue

A comparison of results from different methods is never a straightforward task.

In this work, and although with similar origin, using the same basic fluid's flow hydrodynamic methodology, the fact is that one (ESDU) is a complete design method, incorporating a pre and a post-processing process that allows the user to have a complete definition of the bearing starting from scratch, at expenses of a mixed empirical and experimental set of relations exogenous to the analytical procedure.

On the other hand, isothermal approaches (like IsoT) perform a throughout modeling of the geometric characteristics of the bearing – namely the feeding conditions – treating the whole set of parameters in a dimensionless manner. This allows for an 'universal' and very convenient process of analysis, but the translation to 'real' parameters must be based on the knowledge (or arbitrary evaluation) of a 'mean' lubricant temperature and/or viscosity.

In what concerns to the thermo-hydrodynamic analysis (THD), besides its own set of restrictions and simplifications – specially the inherent impossibility of a dimensionless treatment and processing, for direct comparison with IsoT – can/must take into consideration and *a priori* several 'surrounding conditions' such as ambient temperature, the thermal conductivity of the materials, etc. which cannot be avoided or even standardized.

Besides, when comparing isothermal with thermo-hydrodynamic analyses, a strong influence of eccentricity may be anticipated, as for low values of (ε) a more homogeneous temperature can be expected, and so an average temperature lead to a fair solution, while higher values produce large temperature gradients, and the constant value of the "effective temperature" can represent a very rough approach for the determination of the overall performance.

5.2 Analysis of results

In spite of the 'narrow' vision of the study, using only one set of conditions (bearing and groove dimensions, rotating speed, feed pressure, lubricant, etc.) although for a reasonable range of eccentricity ratios – translating a realistic set of operating conditions, within the most common working regimes expected in general mechanics – some earlier, but interesting, conclusions can be driven from this study, namely:

- in what concerns to the one groove arrangement, results indicate that a 'temperature 'correction can lead to closer prediction on both load capacity and power loss of the IsoT approach which, in turn, if integrated in the calculation process, can be expected to correct flow calculation;
- for the two grooves arrangement, the same challenge seems to be possible, as long as the conditions of occurrence of certain 'oddities' (such as a negative flow) are previously defined and avoided as, at least for the moment, there is no evidence that the IsoT model can cope properly with that phenomena.

5.3 Future developments

As previously referred, this work is only an early approach to a broader task of trying to delineate application boundaries of the different levels of analysis, for the plain journal bearing.

Only extending it, in terms of a considerable range of geometries and working conditions, but above all to compare the various predictions with experimental results, can highlight the real trends of the different working parameters and allow the discussion on accuracy, reliability and limitations of each type of analytical approach.

Nevertheless, and according to the points listed above,

- it is possible to devise a longer range task, in order to built up a 'heat balance' capable of, within limits to be well defined, make possible the use of a (much lighter and even reduced to a simple iterative automatic calculation method) isothermal analysis, capable of a reliability closer that one of a heavy and specifically design thermo-hydrodynamic procedure;
- The negative flow situation, on a two grooves arrangement, as indubitably seems to be a phenomenon that can arise on very particular circumstances, only with further investigation these can be characterized and deeply analyzed, in order to evaluate how reasonably an IsoT approach can deal with, and reflect their effect on the results.

As a final point, it is worth stating that a simpler method can be fair enough to evaluate a restrict set of operating conditions, eventually in a reasonable range, but will never be applicable for all possible situations – mainly for high design standards, when looking for optimal efficiency level for designing and/or maximizing the potentialities of the bearing.

ACKNOWLEDGMENTS

The members of the Tribology Group of the University of Minho would like to express their gratitude to C M Taylor (The Institute of Tribology, University of Leeds, UK) and M Fillon (Laboratoire de Mécanique des Solides, Université de Poitiers, France) for their invaluable support in the last 30 years.

Also a reference couldn't be forgotten to the indispensable financial support, which always made possible this team's work:

- Project grant 87.70/MATR, 1987 – JNICT, Portugal, 1987
- PhD grant BD/13922/97 – FCT/PRAXIS XXI, Portugal/EC, 1997
- Fundação Luso-Americana para o Desenvolvimento – financial support for participation in STLE/ASME International Tribology Conference, Kissimmee, Florida, USA, 1999
- Project grant POCTI/39202/EME/2001 – FCT/FEDER, Portugal/EC, 2001
- Programa ICCTI/Embaixada de França, "Acções Integradas Luso-Francesas" – financial support on scientific exchange LMS, Poitires – UMinho, 2002
- PhD grant SFRH/BD/22278/2005 – MCTES-FCT/POPH-QREN, Portugal/EC, 2005
- Fundação Luso-Americana para o Desenvolvimento – financial support for participation in ASME/STLE Joint Tribology Congress, San Antonio TX, USA, 2006

REFERENCES

- Brito, F C P – Thermohydrodynamic Performance of Twin Groove Journal Bearings Considering Realistic Lubricant Supply Conditions: a Theoretical and Experimental Study. Ph.D. Thesis, Departamento de Engenharia Mecânica, Universidade do Minho, Portugal, 2009

- Boncompain R; Fillon M; Frêne J - Analysis of thermal effects in hydrodynamic bearings, 'Journal of Tribology', American Society of Mechanical Engineers, vol.108, pp.219-224, 1986
- Burke, A.E.; Neale, M.J. - A Method of Designing Plain Journal Bearings for Steady Loads. 'Proceedings of the Conference on Lubrication and Wear', Inst. Mech. Engrs., 1957
- Bouyer J; Fillon M - Relevance of the Thermoelastohydrodynamic model in the analysis of a plain journal bearing subjected to severe operating conditions, 'Proceedings', Inst. Mech. Engrs., vol.218, Part J, Journal of Engineering Tribology, pp. 365-377, 2004
- Clayton, D. - An Exploratory Study of Oil Groove in Plain Bearings. 'Proceedings', Inst. Mech. Engrs., vol.155, 1946
- Claro, J C P – Reformulação do Método de Cálculo de Chumaceiras Radiais Hidrodinâmicas. Ph.D. Thesis, Departamento de Engenharia Mecânica, Universidade do Minho, Portugal, 1994
- Cole, J.A.; Hughes, C.J. - Oil Flow and Film Extent in Complete Journal Bearings. 'Proceedings', Inst. Mech. Engrs., vol.170, 1956
- Costa, L A M – Análise do Desempenho de Chumaceiras Radiais Hidrodinâmicas Considerando Efeitos Térmicos. Ph.D. Thesis, Departamento de Engenharia Mecânica, Universidade do Minho, Portugal, 2000
- Dowson, D. - Investigation of Cavitation in Lubricating Films Supporting Small Loads. 'Proceedings of the Conference on Lubrication and Wear', Inst. Mech. Engrs., 1957
- Dowson, D - A generalized Reynolds equation for fluid film lubrication, 'International Journal Mech. Science', Pergamon Press Ltd., 4, 159-170, 1962
- Dowson et al - An experimental investigation of the thermal equilibrium of steadily loaded journal bearings, 'Proceedings', Inst. Mech. Engrs., Pt 3B, 101, 70-80, 1966
- Dubois, G.B.; Ocvirk, F.W. - Analytical Derivation and Experimental Evaluation of Short Bearing Approximation for Full Journal Bearings. 'NACA Tech.Note', n.1157, 1957
- Elrod, H.J. - A Cavitation Algorithm. 'Journal of Lubrication Technology', Transactions of the American Society of Mechanical Engineers, vol.103, n.3, 350-354, 1981
- ESDU 66023 – Engineering Science Data Unit, ESDU International PLC, UK, 1966
- ESDU 84031 – Engineering Science Data Unit, ESDU International PLC, UK, 1984
- ESDU 84031, Amendment A – ESDU-IHS Inc. (http://www.ihsesdu.com), Denver, USA [ISBN 978 0 85679 495 7]
- Jakobson, B.; Floberg, L. - The Finite Journal Bearing Considering Vaporization. 'Transactions', Chalmers University of Technology, n.190, 1957
- Khonsari, M; Beaman J - Thermohydrodynamic analysis of laminar incompressible journal bearings, 'ASLE Transactions', vol.35, pp.141-150, 1986
- Knight J D; Niewiarowski A J - Effect of Two Film Rupture Models on the Thermal Analysis of a Journal Bearing, 'Journal of Tribology', American Society of Mechanical Engineers, 112, pp. 183-188, 1990
- Knight J D; Barret L - An approximate solution technique for multilobe journal bearings including thermal effects with comparison to experiment, 'ASLE Transactions', vol.26,

pp.501-508, 1983

- Kosasih P B; Tieu A K - An investigation into the thermal mixing in journal bearings, ‘Proceedings’, Inst. Mech. Engrs.’, vol.218, Part J: Journal of Engineering Tribology, pp. 379-389, 2004
- Ma, M T; Taylor C M - A theoretical and experimental study of thermal effects in a plain circular steadily loaded journal bearing, ‘IMechE Seminar: Plain Bearings - Energy Efficiency and Design’, Inst. Mech. Engrs., 1992
- McKee, S.A. - Oil Flow in Plain Journal Bearings. 'Transactions', American Society of Mechanical Engineers, vol.74, 1952
- Medwell, J D; Gethin, D T - Differential Expansion Problem in Journal Bearings, ‘Proc. 10th Leeds-Lyon Symposium on Tribology’, Butterworths Guildford, pp.297-301, 1984
- Miranda, A S – Oil Flow, Cavitation and Film Reformation in Journal Bearings, Including an Interactive Computer-Aided Design Study. Ph.D. Thesis, Dep. Mechanical Engineering, University of Leeds, UK, 1983
- Mitsui J; Hori Y; Tanaka, M - Thermohydrodynamic analysis of cooling effect of supply oil in circular journal bearings, ‘Journal of Tribology’, American Society of Mechanical Engineers, 105, pp.414–421, 1983
- Nassab S A G; Maneshian, B - Thermohydrodynamic analysis of cavitating journal bearings using three different cavitation models, ‘Proceedings’, Inst. Mech. Engrs.’, vol.221, Part J: Journal of Engineering Tribology, pp.501-513, 2007
- Ocvirck, F.W. - Short Bearing Approximation for Full Journal Bearings. 'NACA Report', Tech Note 2808, 1952
- Reynolds, O. - On the Theory of Lubrication and its Application to Mr.Beauchamp Tower's Experiments, Including an Experimental Determination of the Viscosity of Olive Oil. 'Philosophical Transactions', Royal Society, vol.177, 1886
- Raimondi, A.A.; Boyd, J. - A Solution for the Finite Journal Bearing and its Application to Analysis and Design: part III. 'Lubrication and Science Technology', Transactions of the American Society of Lubrication Engineers, vol.1, n.1, 1958
- Sommerfeld, A. - Zur Hydrodynamiscien Theorie der Schmierittehreibung. 'Z.Maths.Phis.', vol.50, pp. 97-155, 1904
- Tucker, P G; Keogh, P S - A generalized computational fluid dynamics approach for journal bearing performance prediction, ‘Proceedings’, Inst. Mech. Engrs., vol.209, Part J: Journal of Engineering Tribology, pp. 99-108, 1995