CABARET - A NEW SOFTWARE TOOL FOR ANALYSIS OF SOLID-LUBRICATED BALL BEARINGS IN SPACE APPLICATIONS

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ABSTRACT

CABARET is a new bearing analysis code, originally developed to predict performance of ball bearings in cryogenic rocket engine turbopumps, but increasingly being used to simulate bearing performance in low-speed mechanism applications too. This paper describes the main phenomena modelled within CABARET and gives examples of how the code can be used to assist in optimising the bearing design/selection process. A "sensitivity analysis" feature is shown to be especially useful. Finally we demonstrate that CABARET predictions agree closely both with those of other state-of-the-art bearing analysis codes (such as SHABERTH and ADORE) and with experimental data both for typical turbopump operating conditions and at lower speed.

Keywords: *Ball bearing, turbopump, analysis, modelling, simulation, validation*

1. INTRODUCTION

Designers of mechanisms incorporating ball bearings face conflicting requirements -on the one hand to optimise designs and on the other to minimise often expensive testing. Software simulation of bearing performance at the design stage can assist both in bearing selection and mechanism design and thus contribute to more efficient mechanism testing as well as trap problems which may otherwise be discovered only at the prototype testing stage - or worse, during qualification tests.

A number of software tools already exist, which permit modelling of various phenomena related to ball bearing performance. So-called "Fully Dynamic" codes such as ADORE (Ref. 1) and PADRE (Ref. 2) solve a set of equations of motion for each component of the bearing. In contrast so-called "Quasistatic" codes carry out a force and moment balance for the bearing as a whole, assuming the balls are in equilibrium under the action of both externally imposed loads (and moments) and forces generated as a result of the bearing operating conditions (e.g. centrifugal forces or gyroscopic moments in high-speed bearings) . Examples of such codes include BAPTISM (Ref. 3) and SHABERTH (Ref. 4). The quasistatic method is described in detail in Ref. 5.

CABARET (**C**ode for **A**nalysis of **BeA**rings in **R**ocket **E**ngine **T**urbopumps) is Quasistatic bearing analysis code, developed originally for analysis of rocket engine turbopump bearings, which operate at high speed, under cryogenic conditions with solid lubrication and high loads. These bearings are cooled by a flow of cryogen directly through the rotating bearing.

Though CABARET runs on a PC , it integrates within a single code simulations for all of the major tribo-mechanical features relevant to high-speed bearings; frictional heat dissipation (and bearing torque), deflections and contact stresses, thermal strain effects, cage stability, fatigue and vibration effects (Ref. 6). Whilst these analyses are generalised, and not confined to high-speed applications, each takes no more than a few seconds to run. Therefore CABARET is now increasingly being used as a design tool to predict solid-lubricated bearing performance in other, low-speed space mechanism applications.

2. FEATURES OF CABARET

a) Coulombic Torque Model

ESTL's previously reported torque models, known as NIM and SIM (Ref. 7) cannot be used at high-speed, due primarily to their deliberate neglect of the influence of centrifugal forces and gyroscopic moments. CABARET incorporates a new torque model, known as GENSIM (Ref. 8), which is generally applicable across all bearing operating speeds. This provides a Coulombic (load dependent) mean torque estimate based on an assumed sliding friction coefficient

Proc. Sixth European Space Mechanisms & Tribology Symposium, Technopark, Zürich, Switzerland, 4-6 October 1995 (ESA SP-374, August 1995)

between ball and raceway.

As bearing speed is increased, inner and outer contact angles become dissimilar . Figure 1 shows, for a given geometry (Table 1) CABARET's predicted contact angle divergence with increasing speed. In this particular case, above around 5000rpm there is a significant difference between inner and outer contact angles and this also reflects in the ball-race contact slip patterns. Under these conditions it is necessary to iteratively calculate and balance the spin and roll moments and corresponding lateral traction forces at inner and outer ball-race contacts for each ball within the bearing in order to predict the torque (in tractive rolling, when the ball is either being accelerated or retarded by collision with the cage for example, a further parameter, the longitudinal creep parameter is also required). The spin moments and traction forces are the frictional components resulting from Heathcote (conformity) slip and microslip due to ball spin and can be derived by integration of elemental forces and moments over the entire Hertzian contact ellipse (neglecting regions of stick ensures the resulting estimate is a "worst case" value). In GENSIM the need for repeated numerical integration to evaluate the spin and roll moments and traction forces (both lateral and longitudinal) is removed by use of regression curves fitted to non-dimensional parameters. This permits the fast and efficient calculation of these parameters and so of bearing torque. CABARET's generalised torque model (GENSIM) is believed to offer improved accuracy compared to previous models (NIM and SIM, see Ref. 8) which do not adequately model high-speed effects or lateral tractions.

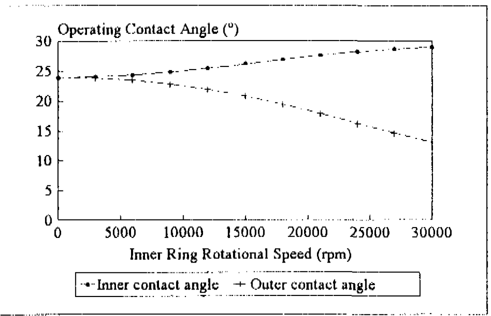

Figure 1 *CABARET predicted operating contact angle versus operational speed for bearing geometry as shown in Table 1 below.*

b) Thermal and Centrifugal Strain Effects

Clearly for turbopump bearings, both thermal and centrifugal effects can have significant influence on bearing performance. CABARET analyses permit balls, rings, cage, shaft and housing to be assumed at different temperatures, and also permits the changes in inner and outer ring fits, bearing preload, torque and heat generation due to thermal and centrifugal strain effects to be examined.

c) Cage Motion Simulation

A 3-degree-of-freedom cage motion simulation, which assumes that the significant cage motion occurs mainly in the plane of the bearing (Ref. 9) is implemented in CABARET. This model is an adaptation of that published by Kannel & Bupara (Ref. 10). Cage motion is simulated in free flight by repeated solution of the equations of motion at discrete time steps (from assumed initial conditions). Cage/ball or cage/land collisions are treated as impulses (with fixed duration depending on the tribo-mechanical properties of the materials used). Following each collision, the free-flight simulation continues with revised initial conditions dependent on the momentum of the cage prior to collision and the tribo-mechanical properties of cage and counterface (ball or land).

The cage simulation permits motion during several revolutions of the bearing to be modelled. Based on this predicted motion, an estimate of the cage-pocket and cage-land wear rates is produced using the simple Archard wear model (Ref. 11).

Since absolute numerical validation of the cage simulation model is impractical, it is proposed that this model is most usefully employed in parametric design analyses. Such use permits design trade-offs to be carried out using CABARET's estimates of cage position, velocity, wear rate, cage collision forces, or a subjective assessment of cage stability as parameters prior to a programme of experimental confirmation tests.

Typical results from the cage simulation are intuitively correct. As ball/cage friction is increased for example (alone) cage/ball speed ratio undergoes a transition from stable to unstable with large forces as a result of high impact velocities (see later Figure 6).

d) Fatigue Life Estimation

Fatigue Life estimation is also provided in CABARET. This calculates the L_{10} fatigue life of either bearing of a pair based on two different methods. Either the classical Lundberg Palmgren method (Ref. 12) can be used, or as an alternative, a fatigue model based on estimation of the sub-surface stress distribution can also be used (Ref. 13). The alternative, more refined method offers the possibility of accounting for both material property changes at cryogenic temperatures and the effects of the ball-race surface shear stress distribution arising from the interface frictional conditions.

e) Flash Temperature Estimation

Localised "flash temperatures" are generated at asperity contacts within the Hertzian ball-race contact zone both due to microslip (during normal operation) and due to skidding (which may briefly occur when bearings are subjected to high acceleration rates and varying axial loads) during turbopump start-up. These "flash temperatures" are the maximum temperatures occurring in the bearing.

CABARET has a facility, based on the use of the Archard (Ref. 14) flash temperature method for estimating maximum contact flash temperatures, both during normal operation and during start-up (assuming that the load and skid velocity profiles are known from suitable experimental observations).

This analysis permits turbopump designers to confirm that the predicted flash temperatures remain well below an explosive oxidation (or flash temperature) limit for the materials in use, operating environment and for the start-up load profile applied to the bearing.

f) Fluid Power Losses

Accurate estimation of the energy dissipated within the cryogenic coolant flowing through turbopump bearings is not straightforward. This is especially true if there is a possibility of two phase flow within the bearings (likely in extreme low-flow rate operating conditions due to the low heat of evaporation of cryogens). However, simple empirical models for fluid drag and churning losses have been incorporated within CABARET which give a first approximation to the fluid power dissipations (assuming single phase flow) based on classical methods.

g) Vibration Analysis

CABARET has the ability to estimate the vibration frequency and forces generated by assumed sinusoidal variations in inner or outer race form (known as lobing), together with the effects of variable compliance vibration.

h) Sensitivity Analysis

CABARET features a Sensitivity Analysis option which permits the effects of variations in input data to be observed for any of the above analyses. This option automates running of the code so that repeated manual running is not required in order to quantify parameter variations. Sensitivity Analyses can be used for example to examine the predicted effects of variations in friction coefficient, ball complement or bearing PCD on bearing torque, maximum contact stress or bearing stiffness. Any one of a number of input variables can be defined as the dependent variable for use in the Sensitivity Analysis, and the output quantities can be defined on completion of the runs.

3. CABARET AS A DESIGN TOOL

From the point of view of the mechanism, the critical bearing parameters are usually **mean bearing torque (or heat generation) and bearing stiffness.** However because of fatigue and lubricant selection/durability considerations it is also necessary for designers to be aware of the **maximum ball-race contact stress**. For maximum benefit of designers, bearing analysis codes must therefore allow Users the flexibility to explore not only single predictions for these parameters, but also to easily carry out sensitivity analyses which show how these outputs vary with key inputs (bearing structure, preloading materials and thermal effects). The following examples will show how CABARET fulfils this prime requirement of the designer both for single bearings and for analysis of a preloaded duplex pair. Using CABARET's Sensitivity Analysis option, data for each example below has been generated using a **single** CABARET run.

4. EXAMPLES OF CABARET USE

In this and all the following examples we assume a bearing geometry as shown in Table 1.

Ball Dia (mm)	12.7
Ball Complement	13
PCD (mm)	80.518
Free Contact Angle (°)	20.5
I.R. Conformity No.	1.06
O.R. Conformity No.	1.06
Preload (N)	5000
Op. Speed (rpm)	30000
Configuration for Pair	Back-Back
Nom Op. Temp. (K)	77
Assy Temp (K)	293
Ball/Ring Material	440C
Shaft Material	Inco 718
Housing Material	Ti-SAE-2.5Sn

Table 1 *Basic dimensions of bearings used in Examples below. These dimensions and operating conditions are approximately those used in the NASA HPOTP LOX Turbine Bearings (Ref. 15)*

In Figure 2 we show how the effective axial stiffness of a single bearing increases with operational speed due to the changing contact angles (shown in Figure 1)

Figure 3 shows how the Hertzian stresses at inner and outer contacts increase with preload (stress is non-zero at zero preload due to thermal strains).

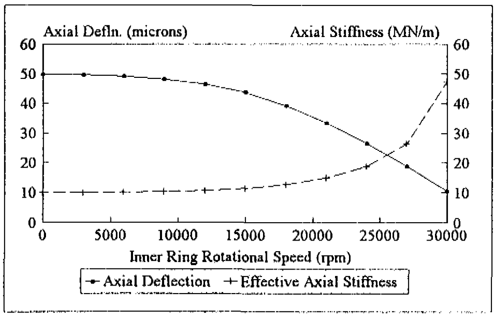

Figure 2 *CABARET predicted axial deflection and effective axial stiffness versus operational speed for single bearing (bearing geometry as given in Table 1).*

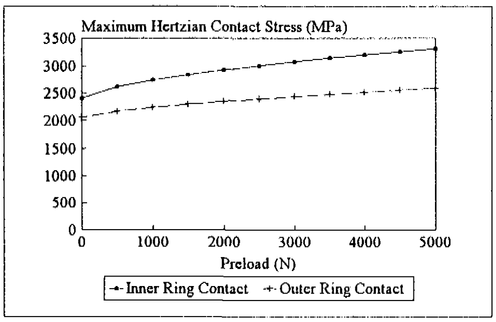

Figure 3 *CABARET predictions for maximum Hertzian contact stress versus preload for a bearing pair (operating conditions and bearing geometry as shown in Table 1).*

An alternative use is to observe the effects of changing bearing design parameters on specific characteristics. In Figures 4 & 5 we demonstrate that increasing contact angle and decreasing conformity number (i.e. increasing conformance of ball and race) both increase predicted mean torque for a given bearing.

Parametric design studies can also be carried out. Figure 6 shows the predicted cage/ball velocity ratio over up to 25 revolutions of a given bearing. Each curve is for a different assumed ball-cage friction coefficient (μbc). At low ball-cage friction values the cage is stable (cage/ball velocity ratio close to unity), but as μbc is increased, the cage quickly becomes unstable and the analysis terminates. Such analyses can be used to evaluate the effects of different tribological and geometrical conditions on performance.

Finally, CABARET can be used to simulate the performance of bearing pairs under defined thermal operating conditions. For example, in Figure 7 , the variation in predicted mean torque is shown with assumed inner ring/shaft and outer ring/housing interface temperatures. The torque drops to zero in one corner of the plot where thermal conditions lead to balls becoming off-loaded and increases to a maximum where conditions result in increasing effective preload.

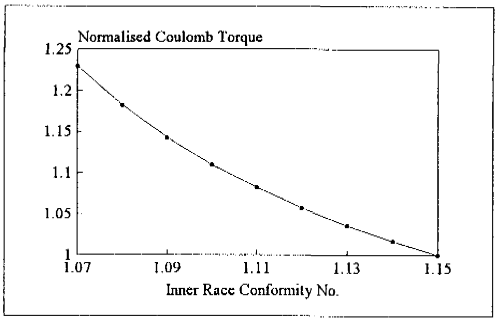

Figure 4 *CABARET predicted Coulomb torque variation with inner race conformity number. Torque is normalised relative to the standard conformity number of 1.15 (bearing geometry as shown in Table 1).*

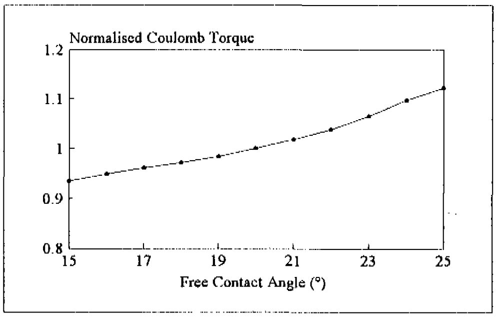

Figure 5 *CABARET predicted operating Coulomb torque variation with free contact angle. Torque is normalised relative to the standard contact angle of 20.5° (bearing geometry as shown in Table 10).*

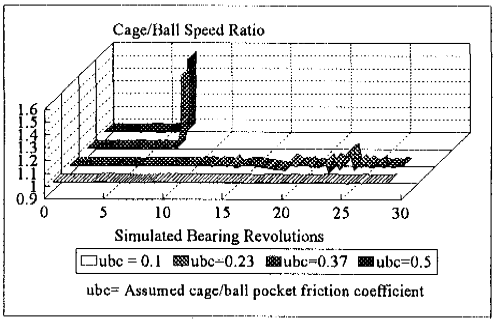

Figure 6 *CABARET predicted cage/ball speed ratio versus bearing revolutions for different assumed ball-cage friction coefficients (cage geometry unchanged). As friction coefficient rises, cage motion becomes unstable.*

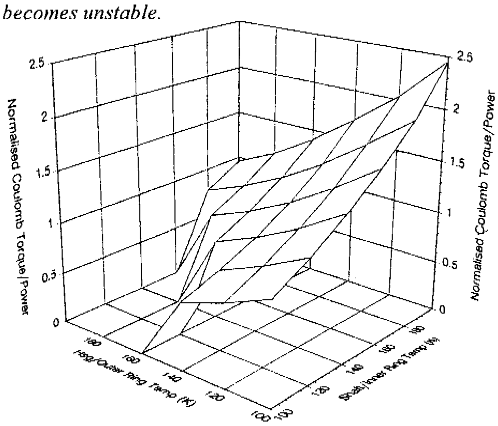

Figure 7 *CABARET predicted Coulomb torque versus shaft/inner ring and housing/outer ring interface temperatures. Torque is normalised relative to operation with both interfaces at 100K (bearing geometry as given in Table 1).*

Results from this type of simulation can be fed back to other analyses to permit assessment of critical parameters such as maximum Hertzian contact stresses as a function of applied loads.

5. VALIDATION DATA

Numerical codes are only valuable if their predictions are physically meaningful and accurate. CABARET has so far been subjected to a number of validation tests. In the first instance these tests took the form of inter-code benchmarking, where CABARET predictions were compared directly with those of other codes including SHABERTH and ADORE. Secondly, comparisons were made between CABARET predictions and experimental observations, though due to a scarcity of data these cover a more limited range of geometry and operating conditions. Both types of comparison show acceptably close agreement (Ref. 16) as demonstrated in Figures 8 to 10 for various bearing configurations. Figure 8 compares predicted contact angles for a number of codes against experimentally measured contact angles for a high speed hybrid ceramic ball bearing (Ref. 17).

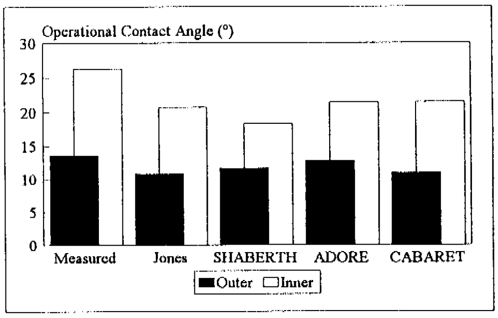

Figure 8 *Comparison of predicted contact angles for CABARET and 3 other software models versus experimental measurements (Ref 17) made after testing a hybrid ceramic bearing (type 101) at 103000rpm with applied axial load of 200N.*

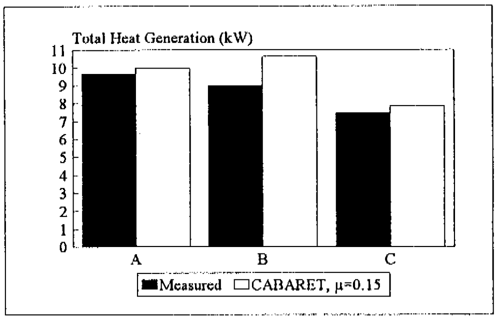

Figure 9 *Comparison of CABARET predictions and experimentally measured total heat generation for 3 different turbopump operating conditions. Total heat comprises both Coulombic frictional heating and viscous energy dissipation in the LOX flow through the bearing. A typical PTFE friction coefficient of μ=0.15 was used in the CABARET analysis.*

Figure 9 shows CABARET predicted total heat generation (including both heat dissipated in Coulombic torque and in viscous dissipation within the LOX coolant) compared to experimental measurements under 3 different load/speed combinations. Finally Figure 10 shows a comparison of predicted and experimentally measured mean torque for a low-speed bearing pair versus axial load.

In all cases above, CABARET predictions agree closely with those of other models. Experimental agreement is also very close.

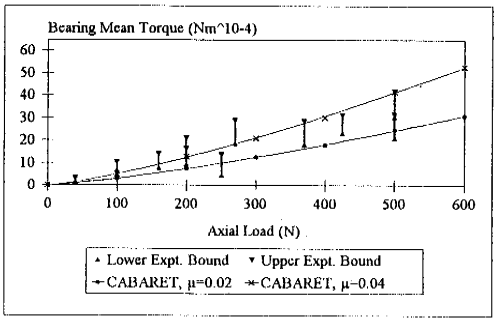

Figure 10 *Comparison of predicted and experimental mean bearing torque versus axial preload. Data relates to ED20 type bearing operating at 100 rpm with MoS_2 applied to raceways and steel cage.*

6. CONCLUSION

Bearing analysis software has been developed which offers designers an integrated series of analysis options and a broad range of analysis types for both turbopump and other bearing applications. The software incorporates a generalised Coulomb torque model which is applicable at all speeds. A powerful sensitivity analysis capability is also useful for design engineers. Examples of the predictions of this software have been presented. Validations suggest that, though the code runs on a PC, its predictions are no-less accurate than other state of the art bearing analysis codes. Agreement with experimental data is also shown to be very close.

7. ACKNOWLEDGEMENTS

This work was carried out under ESTEC Contract 8280/89/NL/FG under the technical management of H. J. Luhmann, and C. Garcia Marirrodriga. ESTL would like to thank M.J. Todd, F Golding & FiatAvio SpA for their cooperation in this programme.

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