Dinon to the successful formulation of this program are greatly appreciated.

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DISCUSSION

J. D. Robinson[1] and M. J. Carrano[1]

The authors have extended the work of Harris[2], Rumbarger[3], et al, by developing a quasidynamic analysis with several unique features. The analysis considers the influence of shaft misalignment, geometry-induced roller preload, roller skew, and resulting guide flange forces. In addition, the effects of either transient or steady state thermal response on operating internal clearance are included.

This program could be used as a design tool to predict bearing operating fits, internal operating clearance, race temperatures, heat generation, and fatigue life. Also, steadystate cage speed can be studied as a function of bearing outer ring geometry.

The quasi-dynamic method adopted by the authors makes use of the requirement that each of the rolling elements and the cage be in static equilibrium assuming a steady state has been reached. Once this approach is taken, the accuracy of the solution depends on describing the force and moment system in sufficient detail.

For example, as the roller skews, a restoring moment acting about the bearing radial axis is developed as a result of the interaction between the roller cylindrical surface and the outer race curvature. This moment occurs whether or not the roller is crowned. An additional gyroscopic moment is imposed on the roller whenever skewing occurs since the roller spin axis is no longer parallel with the orbital axis. Furthermore, hydrodynamic shear force at the roller/guide flange interface appears to have been neglected. These forces and moments will influence the magnitude of the reaction loads at the guide flanges. Perhaps the authors would care to comment on why they chose to omit these forces.

It appears to us that the effect of incorporating the roller "tilt" degree of freedom will be insignificant for high DN roller bearings due to the magnitude of the centrifugal force field present. The authors comments are solicited on this point.

Although this program will be useful in the early stages of roller bearing design, some words of caution are in order regarding the ability of a quasi-dynamic analysis to predict actual bearing performance at higher DN levels. Results obtained from high DN roller bearing tests reveal that dynamic interaction loads on bearing components can be many times higher than the "steady-state" loads. Synchronous skew vibration caused by roller unbalance can induce eccentric roller end wear which can result in premature bearing failure. This failure mode cannot be predicted by either a static or quasi-dynamic analysis. In addition, dynamic loads produced by cage unbalance can lead to severe wear on the land riding surfaces of the cage.

It is our opinion that understanding these dynamic phenomena is of great importance to successful high DN roller bearing design and underscores the need for continued development of complete dynamic analyses. Do the authors share this opinion and do they have any immediate plans to extend their analysis in this direction?

H. H. Coe[4] and F. T. Schuller[4]

The authors are to be complimented for their achievement of CY-

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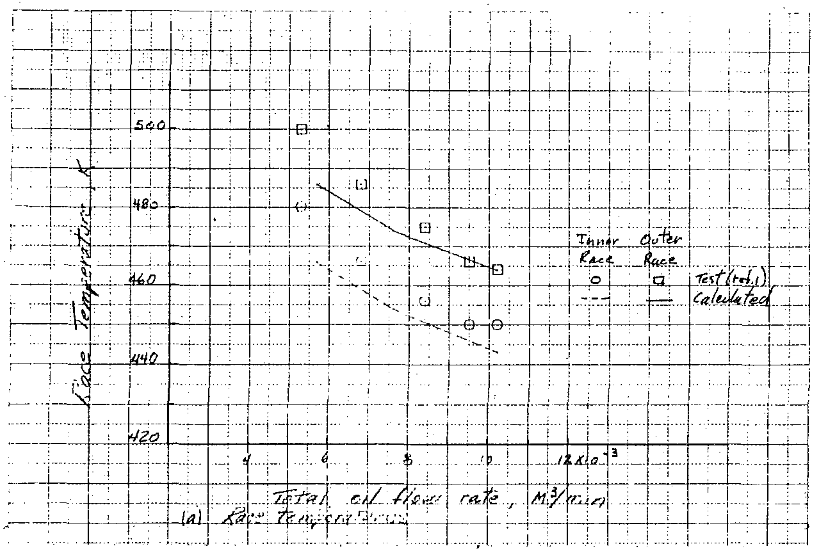

Fig. 9 Comparison of calculated and experimental bearing data using a diametial clearance of −.02 mm. Shaft speed, 22,500 rpm; radial load, 8900N (2000 (6)) lub volume, 2 percent

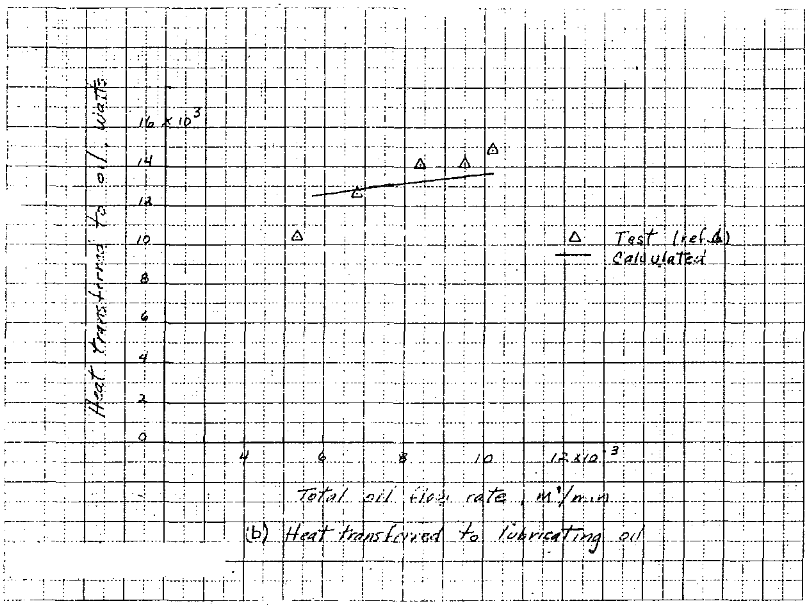

Fig. 9 (concluded)

BEAN, a viable, practical, useful, operating computer program for high speed cylindrical roller bearings. As a user of this program, our first step was to obtain predicted values of certain bearing operating characteristics and then to compare these values with corresponding experimental data. The results of this comparison were interesting.

CYBEAN was used to calculate the inner- and outer-race temperatures, the heat generated by the bearing, the amount of heat transferred to the lubricant, and the cage speed, for comparison purposes. Calculations were done for several loads, speeds and lubricant flow rates, for the 118-mm bore bearing tested in reference [25]. *One of the comparisons at 3.0 million DN* is shown in Fig. 9. The radial load was 8900 N (2000 lb), the *lubricant volume was two percent* and the *diametral clearance was set at a minus .02 mm.* The race temperatures are close and have *the correct trend with flow rate.* The calculated values of the heat transferred to the lubricating oil are also reasonably close and seem to have the correct trend with flow rate.

Generally, the calculated values of inner race temperature at the higher speeds were much lower than the corresponding experimental data, unless the bearing clearance was set negative. This is not an unreasonable assumption as reference [25] suggests that a negative clearance existed at 25,500 rpm. Also the experimental data showed virtually zero cage slip at this condition, which would further indicate a very small clearance.

Nevertheless, on the basis of absolute temperature, all calculated values were within 10 percent of the experimental data and most were within five percent.

The computation time ranged from 2 to 8 minutes for the nonmisaligned cases, using the thermal analysis. It may be concluded that this large program operates efficiently, provides reasonable answers for quasidynamic bearing simulation, and thus provides a tool for comparison of bearing designs.

W. J. Crecelius[5]

The authors have developed an analytical tool having capabilities unavailable in existing codes. Most important among these are:

1. The depth and breadth of the elastic interaction analysis
2. Roller skew capability
3. Flexible outer ring and outer ring support analysis

The completeness of the interaction analysis permits the inclusion of even the smallest component of force. For instance; under an applied radial load the inner and outer ring axes are not coincident and thus the outer and inner raceway/roller load vectors are not colinear. A small component of force acts tangent to the pitch circle tending to decelerate and accelerate the roller as it enters and exits the load zone.

A second example of the thoroughness of the interaction analysis becomes apparent as the roller skews. The outer raceway/roller contract changes from a line to two truncated points. The restoring moment generated is included in the roller equilibrium equations.

The above affects are considered only when the influence of friction upon kinematics is being sought, and thus have been omitted in most analyses. With friction effects and additional degrees of freedom convergence difficulties are usually encountered. The authors may want to comment on their experience with CYBEAN convergence as friction is considered.

An item requiring clarification is how the roller load dependent, flexible ring, analysis is embodied within the solution loop. The sophistication of the other aspects of the analysis are insignificant if the load distribution is inaccurately predicted.

Two minor points deserve comment. The authors have omitted an important reference wherein the lubrication, friction and cage models used in CYBEAN are documented, namely, SKF Report No. AL76P003 "Improved Flexible Shaft Bearing Thermal Analysis With NASA Friction Models and Cage Effects."

The second item is the authors implication that bearing temperatures increase as cage slip is encountered. Generally, system temperatures decrease.

The authors' choice of analytical results is surprising. With the new elements of the analysis being the flexible outer ring and housing plus roller skew these items should have been emphasized. The sample problem does not even address a flexible outer ring and roller skew receives only a cursury treatment. A detailing of all forces and moments affecting skew of the most heavily loaded roller would be most interesting, especially with the large skew angle predicted. If the principle cause of skew is the roller end-flange friction force resulting from the ring alignment forcing the roller against the flange, the roller end friction coefficient would have to be in excess of 0.35 to generate the predicted skew angle. This value is high and suggests additional skew generating factors which are not apparent.

CYBEAN could become a useful design tool. This will largely be dependent upon convergence reliability, the accuracy of the roller-raceway load distribution prediction, the cage slip and the roller skew predictions.

Hopefully the authors will have the opportunity to exercise the code and demonstrate more thoroughly its predictive accuracy.

Authors' Closure

The authors wish to thank the discussers for their thoughtful comments.

Messrs. Robinson and Carrano have indicated that certain forces and moments may have been omitted. Hydrodynamic shear at the roller end-flange contact (REFC) was not considered in this first version of CYBEAN. Program users have been executing the code with constant coefficients of friction at the REFC. A second generation version of CYBEAN, currently under development, will model this effect in greater detail.

Since roller skew angles are typically small (5–10 μ rad), the resulting gyroscopic moment is small and can be neglected. The restoring moment acting about the roller radial axis, as pointed out by Mr. Crecelius, has been included in this analysis [18].

The authors agree that in some high speed applications the effect of roller tilt can be neglected, although identification of cases where the approximation is valid requires execution of the code. Generally, since the centrifugal force field is strongly dependent on material density (among other things), the failure to include the assessment of "tilt" will produce large errors in the analysis of bearings manufactured from low density materials, such as silicon nitride. Therefore, this degree of freedom has been included in the CYBEAN formulation.

Regarding Messrs. Robinson and Carrano's comments on the ability of quasi-dynamic codes to predict "actual" bearing performance, the authors must point out that "actual" bearing performance is described by a very broad set of parameters. Heat generation, system temperatures, thermal growth, roller skid, misalignment and geometry induced preload are within this set of parameters, and their crosscoupled interactions must be accurately assessed to assure successful bearing performance. CYBEAN was developed for this purpose, and its accuracy in predicting a subset of "actual" performance parameters has been verified by correlation with high DN bearing tests.

The authors are pleased to see the degree of correlation between CYBEAN predicted temperature data and the experimentally measured data presented by Messrs. Coe and Schuller. As code users, their comments regarding program performance add credibility to the analysis for the representation of "actual" bearing behavior.

In light of the current high cost of dynamic simulations, it is the authors' opinion that the complete dynamic analysis of a rolling element bearing system (i.e. a thermo-mechanical dynamic simulation), although conceptually feasible, would result in a code which is far too costly to execute for practical design requirements. Additionally, as a minimum practical step, the complete dynamic simulation will still require execution of a quasi-dynamic code, such as CYBEAN, to provide reliable system initial conditions.

The convergence difficulties which are usually encountered when friction is considered have been controlled in CYBEAN by using the two numerical techniques described in Appendix C: equation partitioning and kinematic replacements. The authors are aware of some 80 CYBEAN executions since its development, and satisfactory convergence was achieved in each.

Because of space limitations, the authors could not include a detailed flowchart of CYBEAN architecture. This may be found in [18], and shows how the roller load dependent, flexible ring analysis is embodied within the solution loop.

The authors thank Mr. Crecelius for reminding them of SKF Report No. AL76P003, a very important reference and agree with his comment regarding system temperature relationships with cage slip. This effect is illustrated in [25].

The authors choice of analytic results reflects the submission deadline for this material. A more detailed demonstration of CYBEAN performance is expected to be published shortly by Mr. H. Coe [7].

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[5] SKF Industries, Inc., Philadelphia, Pa.