DISCUSSION

J. Pirvics[1]

The motivation for the construction of dynamic analysis software resides in the need to examine effects which have emerged from secondary to primary significance as applications require advanced performance from rolling element bearings. Secondary effects emerging to primary significance in one area of simulation require a parallel upgrade in the detail level in all others. Failure to adhere to this principle makes the credibility of obtained numerical results suspect. Furthermore, the practical utility of advanced, complex software, resides in its ability to address the pressing practical design information questions raised by advanced system design demands.

In the light of the above statements, the following comments and questions are raised for consideration by the author:

1. The cage-rolling element interaction simulation model does not enable a physically realistic, smooth transition from a hydrodynamic to an elastic interaction mode. The spurious, numerical time step dependent, contact force spikes represent fictitious forcing functions which drive the response dynamics of the system simulated. The inference may therefore be made that the credibility for the cage as well as roller dynamics representation and therefore bearing performance is in error.

2. The flange-roller interaction model does not contain hydrodynamic effects. Therefore, roller force and moment balance and therefore resulting displacements/orientations are inaccurate. Small inaccuracies in displacement result in large elastic interaction driving forces and therefore create misleading performance assessment.

3. High speed rolling element engine bearing applications rely on accurate preload design. The latter is accomplished by interference fits as well as in and out of phase eccentric lobing of inner and outer raceways. In addition, flexible outer ring, variable stiffness housing support simulation capability are prerequisite for meaningful design analysis. Also, inner and outer ring cross section profiles need to be variable as software input to examine alternate means for skew control. The absence of such assets in a dynamic analysis program places the latter out of position as a natural extension of contemporary quasidynamic bearing analysis tools, e.g. SKF/NASA program CYBEAN (CYlindrical BEaring ANalysis).

4. The validity of the initial conditions selected in any time transient analysis is vital for subsequent solution significance. Given this requirement for good initial starting values, which software, having skew analysis capability, was used to obtain them? Also, how much system time was needed for the 32 roller case cited by the author in this series of papers to obtain these starting values?

5. A dependence on a quasi-static starting state requires the tracking of the emerging solution for more than a single shaft revolution to detect the presence or absence of cyclic synchronous or asynchronous behavior. This implies computation times which are more than those cited for the 100 deg maximum rotor rotation by the author. Using the characteristic case data presented by the author, it appears that a minimum of 3.4 hours of CDC 6600 system time are needed for two revolutions of the shaft (720 deg/100 deg $\times$ 30 min.).

6. DREB has been compiled and executed on CDC hardware in which single precision exceeds the double precision of typical IBM and Univac counterparts. In the light of the numerical accuracy sensitivity of the formulation, is this a machine restriction for the software to remain in the computation time and core requirements noted? Given the slower speeds of these machines and the slower convergence to starting values would the author indicate total IBM computation times required for the orbit case cited in item 5 above?

7. Integration in time marches a solution to points in a numerical solution hyperspace which can be time step size dependent. Step size control mechanisms and stability considerations for single, carry over to the multiple equation case. However, high order Runge Kutta algorithms, applied to systems of equations customarily are time consuming computations and defy absolute definition of error. Therefore, the demonstration of convergence and stability is usually made by comparison of executions with different time step sizes. It would be very useful for the user, in his assessment of the numerical self-consistency as well as practical utility of the software to have the author comment on his experience with the noted, standard numerical program self-consistency check.

8. The numerical round-off and truncation accuracy of the mathematics employed can be readily checked by executing a symmetric case (thrust loaded ball or cylindrical rolling element case with no misalignment). The evolution in time of deviations from constant values of performance parameters would indicate numerical noise solutions. Retention of constant values would enhance the credibility for adequate control of the numerical mathematics. Would the author comment on his experience (especially with the simpler ball bearing case in his companion paper) in the execution of this customary numerical solution self consistency check?

9. Has experimental evidence been correlated with numerical prediction? Specifically, L. J. Nypan's 1978 NASA Contractor Report 3048, "Roller to Separator Contact Forces and Cage to Shaft Speed Ratios in Roller Bearings" as well as Nypan's results in the paper he presents at this meeting, "Measurement of Separator Contact Forces in Ball Bearings Using a Derotation Prism"[2].

[1] Technology Services, SKF Industries, Inc., King of Prussia, Pa. 19406.

Author's Closure

The author welcomes the various questions and comments presented by Dr. Pirvics. The need for a truly dynamic simulation, such as DREB, has been obvious over the last many years. In fact, it has been well established that dynamic problems such as roller skew, skidding and cage instabilities can only be modelled by dynamic analysis where the differential equations of motion form the primarily foundation. The results obtained with any simplified static or quasi-static type of equilibrium analysis will only further emphasize the need for a dynamic treatment as considered in the present investigation. With such a significant practical relevance of the dynamic model considered in the paper and the DREB computer program, the specific questions can be answered as follows:

1. Elastohydrodynamic effects for the rolling element/cage interactions have not been considered in the present model and hence a fictious spike in the rolling element/cage contact force does appear when the time-step size is small enough to detect the noted transition. However, by making the step size somewhat larger, it has been confirmed that such a rough transition disappears. In any case, this transition has little or no effect on the general motion after the collision (perhaps due to very small transition times) and hence the results presented are sound. The improvement in the model will certainly help understand the mechanics of collision between the rolling element and the cage and will eliminate some of the numerical problems associated with the simulation of the rolling element/cage collision.

2. Roller/flange interactions are only moderate in the present investigation with cylindrical roller bearings. Under large misalignments or with tapered roller bearings these interactions do become important and the author expects to present more sophisticated models in the near future.

3. The present model and the computer program DREB does provide extensive capability in modelling radial preload. Any of the races may be out of round and the out of roundness can, in fact, be time dependent. Hence truly dynamic simulations for radially preloaded bearings can be readily obtained and such simulation will provide an order of magnitude deeper insight into the problem than that obtained by any quasi-static or quasi-dynamic equilibrium analysis.

4. In obtaining the initial conditions for roller bearing simulations, equilibrium analysis was performed only in the radial direction and the modeling for roller skew is only obtained by subsequent integration of the differential equations of motion. An equilibrium analysis for roller skew will not only be time consuming but it may also be very unrealistic.

5. The general nature of the differential equations has been found to be quite stiff and hence any explicit numerical method of integration results in a relatively small step size. This does lead to the problem of large computing time when large transients are to be investigated and the author expects to investigate some of the implicit methods and hopefully eliminate this problem in the near future. In the absence of any significant transients, however, the present program has provided solutions for over a shaft revolution in less than half an hour of computing time. In fact, since the shaft speed does not enter in the time scale, in the present formulation, more of the shaft rotation is accomplished in a given amount of computer time at higher bearing speeds.

6. DREB does operate on the IBM, Univac and some of the other computing systems. This has been demonstrated by a number of commercial users of the DREB program. The author has only used the CDC 6600 system and hence a reasonable value for computing time of an IBM or other systems is unknown to him at this time.

7. Any solutions which are step-size dependent will be inaccurate and perhaps unstable. The truncation error at each step is therefore checked in DREB and accuracy of all solutions is guaranteed. No solutions are step-size dependent within a specified limit on truncation error. It is true that it is difficult to determine the absolute truncation errors in Runga-Kutta methods; however, as shown in the paper there are certain modifications which do provide a reasonable estimate. Such estimates are used to optimize the step size in DREB. Of course, the validity of such a scheme has been checked by comparing solutions obtained with different step-sizes.

8. The numerical checks on either truncation or round off errors cannot be performed by executing a thrust ball bearing case on DREB. Even with a thrust bearing if the cage is eccentric it will result in nonuniform loads on the balls and in the event the cage is removed, a major part of DREB will be bypassed and hence any conclusions derived from such a test will hardly be sufficient. The problem of a cageless thrust ball bearing has been studied by the author earlier [7] and the present DREB solutions do complement the simplified simulations obtained in the past [7].

9. Comparison of DREB predictions with the available experimental observations has been difficult on two grounds. Firstly, the data available on cage motion has been generally inadequate; most of the time only the nominal cage speed is measured and although the measured values agree reasonably well with even some of the quasi-static equilibrium predictions, such comparisons are clearly inadequate for evaluating the strength of DREB. Secondly, in cases where ball/cage forces are measured the cage pockets have been greatly modified and hence the nature of interactions has been significantly altered. It is necessary that DREB be modified to simulate the actual stiffnesses involved in the modified cages before a reasonable comparison of the results can be made. Hopefully, this will be done in the near future. The author also has plans to carry out an experimental investigation in which the general cage motion will be measured and perhaps some meaningful comparisons with the DREB predictions will be possible.

In summary, the author does believe that realistic solutions to the time dependent propagation problem in rolling bearings is the key to the understanding of cage instabilities, roller skew, skidding and some of the other dynamic problems existing in the modern rolling bearing systems. Quasi-static or quasi-dynamic (as the discussor calls it) equilibrium solutions should only be used for fatigue life estimates, stiffness computations and perhaps for determining the initial conditions for integrating the various differential equations of motion. The dynamic analysis presented in the paper and the DREB computer program have yet to be studied further in a number of areas. Experimental validation of the DREB results and improvements in the integrating algorithms are two areas which should be immediately pursued and the author does expect to report progress on these subjects in the near future.