DISCUSSION

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The author has succeeded in making a difficult measurement; the ball/separator force in a high speed bearing. However, several details of the technique should be clarified.

(1) How does the derotation prism work (The reference quoted is not in the readily available literature)?

(2) Does the natural frequency of the beam influence the measurements? If the natural freq. were near the forcing frequency, large oscillations of the beam would occur.

(3) Extremely small deflections of the beam were measured; e.g., in Fig. 2A at 98 lb/in spring constant, a one lb. load would only deflect the beam .010 in.—what is the resolution?

(4) The relative softness (deflection) of the beam influence the motion of the balls. Can you be sure that the stiffness of the beams considered gives a good picture of the ball/cage forces with the stiff separator?

(5) How were the horizontal and vertical components of each force data point determined? What is vertical and horizontal, with respect to what?

(6) When radial load is about twice the thrust load, BSV should produce maximum cage load? Did you investigate this condition?

R. P. Shevchenko

This is an interesting and important piece of experimental work and the deductions from the data seem to me to be quite logical in the main. It is hoped that these beginning efforts will be continued to overcome the instrumentation difficulties and to verify or modify the present results.

The author, California State University (Northridge) and NASA-LRC should be commended for this work in ball bearing cage research, a very difficult undertaking.

The reasons for the paucity of knowledge about cage behavior and the forces that influence its behavior lie in the fact that both cage analysis and experimentation are necessarily quite complicated. Dr. Gupta will have convinced you of this as far as cage analysis is concerned in his preceding papers in this session. The DREB (Dynamic Rolling Element Bearing) deck is not only an awesome example of creative construction, its appetite for computer time in present form is voracious.

The experimental approach is handicapped by the requirement of data (strain, temperature, for example) that can be obtained accurately only from instrumentation that affects either the structure of the cage or its operation. Test technique(s) such as holding the cage stationary duplicates a normally unrealistic condition.

Our author-experimenter has now encountered some of these experimental difficulties in the effect on ball-cage load of varying dynamometer beam stiffness and the effect of beam centrifugal deflection into cage contact and probable reading error.

Whether the ball-cage force results can be back-calculated to match DREB "collision" values remains to be seen. Probably not.

Concerning one main purpose of the work: When does the ball drive the cage and vice versa?

For high thrust load and low radial load the cage drives the balls all the way around. Nypan and DREB agree on this. For low thrust and high radial load the balls drive the cage through the load zone or at least start driving the cage somewhere in the load zone. (The assumption is made that the load zone is at the bottom of bearing which is not clear in the paper). This appears to agree with recent, unpublished vendor roller bearing data in which rollers accelerate into the load zone and presumably drive the cage through. Some in-house work on a large high speed ball bearing using DREB gave contrary results that show the cage driving the balls through the radial load zone and the balls driving the cage opposite the radial load zone.

It would be interesting if Dr. Gupta could comment on this after he has had some opportunity to verify these observations.

The question also arises whether the ball contact force traces have been affected by the natural frequencies of the cantilevered beam?

The derivation of cage-race contact forces and angular location from the ball-cage force horizontal and vertical vector components could be very useful and it should be further investigated. Obviously, the variation of force observed as beam stiffness was varied raises questions about varying oil film stiffness all around the cage as well as variation from one cantilevered beam to another. Perhaps the load angular locations calculated could be checked against the individual photographs of the beam deflection to see where the cage approaches the race. I would imagine that the cage-race clearance would be of the same order as the beam deflection range or possibly greater.

It is bothersome to see the fluctuation in cage-race minimum clearance location in a ball bearing which is inherently quite consistent in its mechanical phenomenological trends. It is possible that the cage is so lightly loaded that it flops about from small changes in contact forces such as occurs with whirl instability phenomena. This could be shown by lack of angle repeatability in subsequent runs or in different bearings.

I am sorry to say that I ordered the reference papers too late and therefore missed the following items that would have been helpful:

A cross-section of the rig.

A sketch of the cantilever beam force transducer installation.

A photograph of the cage rail window (slot) with the cantilevered beam.

Further, it is recommended that oil flow and temperature be varied in future tests. (The test oil flow rate was not disclosed in paper.)

A last question! Was there evidence of cage or ball slippage at the lowest load conditions?

A last comment! The cantilevered beam centrifugal deflection is further aggravated by its having an inherently weakened rail for support.

I would like to extend my gratitude to my colleagues, especially Roger Barnsby and Paul Brown, for their helpful contributions to this discussion.

Author's Closure

The author wishes to thank Mr. Dow and Mr. Schevchenko for their interest and thoughtful comments.

As the Pechan prism used in this work is rotated about its optical axis, the image passing through rotates at twice the prism's angular rate. By rotating the prism in the same direction as the bearing separator, and synchronized at half the separator speed, a stationary image of the separator is produced. The principle is most easily understood by experimenting with an inexpensive Dove prism, which also functions as a derotation prism.

The natural frequency of the beams used is calculated to be about 1000 H_z while the maximum cage orbital speed was about 90 H_z. With photographs being taken every two to four shaft revolutions beam vibrations might introduce scatter in the data, but should not affect the average of data points.

Film negatives were measured in a film reader that produced a 10 times the original separator dimensions image on a ground glass screen. Measurements on this image could be repeated to 0.1 mm (0.004 in.). In an experiment where twenty photographs of the stationary apparatus were analyzed in the same manner as data photo-

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graphs, the standard deviation of indicated force was 1.3 N (0.3 lb).

The beam deflection surely affected the ball forces and their location. The two highest spring constant beams both indicated about the same force magnitudes. The maximum limit of ball traction may have been developed by these beams.

Vertical and horizontal force components are parallel and perpendicular to the radial load direction which was vertically down through the 0 (and 360) degree value of Figs. 2–5.

Fig. 8(*d*) of reference [6] shows ball contact forces for a radial load of 4450 N (1000 lb) and thrust load of 2220 N (500 lb). The result appears similar to a 4450 N (1000 lb) radial load case.

Positive forces in the plots of ball force versus location are forces tending to accelerate (drive) the cage. The negative forces indicated in the thrust loaded cases are resisting and retarding the cage against the journal bearing shaft-cage friction. Radial loads were applied so that the balls experienced increasing radial loads as they moved from 270 in to 360 degrees, with decreasing radial loads being experienced as the balls moved from 0 to 90 degrees.

Information on cage-shaft contact force and location and additional information on test conditions omitted from this paper in the interest of brevity is included in (6). The oil flow rate was 1.1 m^3/min (0.3 gpm) until a bearing seized at 12,000 rpm Jan. 6, 1977. The oil flow rate was 2.2 m^3/min. (0.6 gpm) for all figures after that date. Cage to shaft speed ratios were observed to range from 0.465 to 0.433.