disks. The ratio of these nonuseful tractive forces to the useful ones at a particular cage velocity and speed ratio increases directly as the ball diameter. Centrifugal forces exerted by the balls against their cage seats also increase directly with ball diameter. Equations (39) and (15), respectively, express these effects quantitatively and emphasize the importance of using a large number of small balls rather than vice versa.

A similar situation exists with regard to the radius of the cage. The same equations reveal that the balls should be clustered as closely as possible to the center of the cage, if maximum speeds are to be achieved. This fact also influences the design, in that it indicates that the cage should always be mounted peripherally as shown in Figs. 1 and 2. Although it is kinematically possible and in some ways mechanically attractive to mount the cage on a central shaft, which may be passed through a large enough hole in one of the disks to allow a reasonable amount of transverse shifting of the cage axis relative to the disk axes, such an arrangement results in a most unfavorably large radius for even the innermost ball orbits.

Fig. 12 summarizes the most important relations between the variables which affect the allowable operating speeds. It shows, for example, that, if balls of \( \frac{1}{8} \) to \( \frac{1}{4} \)-in. diameter are used in a cage of small radius, cage velocities may easily run into the range between 3000 and 5000 rpm, depending on the limiting speed ratio to be reached at these cage speeds. In this connection it may be observed that if these cage speeds are reached when the device is idling with no load on the output shaft, in any design in which there is a torque-proportional normal loading system, then a minimum normal loading of about one tenth the maximum loading must always be applied to the cage to prevent scuffing of the disks through excessive slip arising from ball inertia.

References


2 After the foregoing analysis was completed it came to the attention of the writer that a mathematical derivation encompassing the relations up to but not beyond Equation (13) was first accomplished in 1933 by Dr. Hans Schnabel of Germany. No publication was ever made.


DISCUSSION

T. Kusuda

Has the author formulated the useful tractive force on each ball at its specific orbit, as well as at a specific angular location relative to the center of the orbit? I believe that the net useful tractive force thus developed can be integrated over all the balls in the cage at a time instant. In the paper he has only treated absolute magnitude of the inertial tractive forces and stated that they will become serious at specific values of \( \alpha \). If the integrated net useful tractive force is compared with the theoretical tractive force without inertial effect, we could establish the transmission efficiency due to the inertial forces. In order to calculate actual efficiency, the slip factor must also be included, which is not included in the paper.

Author's Closure

I wish to thank Mr. Kusuda for his discussion and to make the following notes regarding his comments:

(1) There is no rigorous way to make a direct integration of the useful tractive forces, since the force system is redundant to the degree \( (n - 1) \), where \( n \) is the total number of balls. Some approximate values can be gained by considering rolling creep, lateral forces due to misalignment, and centrifugal effects, but it is probably more practical to seek empirical results.

(2) Inertial tractive forces are independent of \( \alpha \), as shown in Equation (36).

(3) Inertial effects have no influence on efficiency.

(4) The slip factor varies from one part in 10,000 to one part in 1000, depending on the load, so it is a negligible part of the losses.