Is There An Optimum Bearing Design?

c. P. J. Baum, July 2001.

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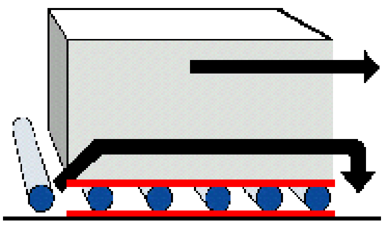
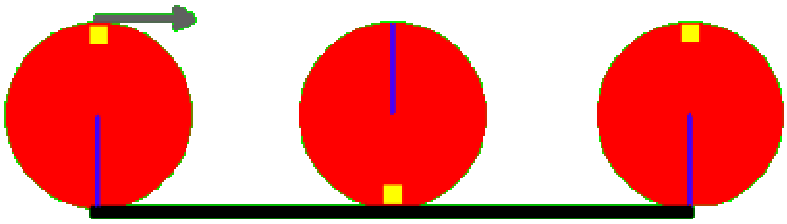
Introduction

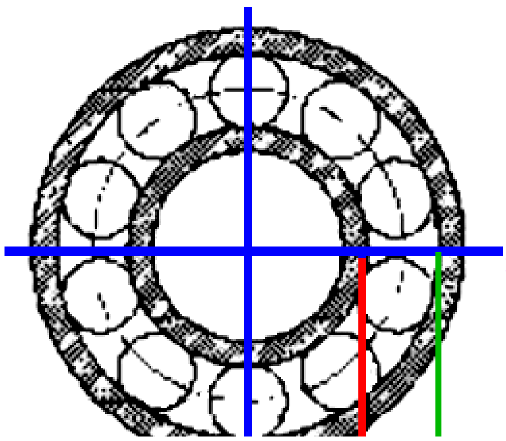
Recently I was asked what kind of bearing would be best for inline skating. Having thought about this question for a while I have come up with some fundamental properties of bearings that impact the optimum bearing design. In the figure below (left) I have sketched an early roller bearing design using cylindrical rollers as King Tut might have used to roll pyramid blocks into place. The drawing on the right hand side illustrates the fact that if the cylinder grips the base plate perfectly the cylinder moves one circumference to the right as it makes one revolution. The blue line and the yellow square return to their original places after exactly one revolution and they have interchanged positions at 1/2 revolution. Most importantly, If we place a plate or block on top of the cylinders and it grips the rollers perfectly, the top plate moves exactly one circumference forward as the cylinders rotate one revolution. So, if the cylinders are perfectly round, perfectly gripping, and very low weight, King Tut's linear bearing is nearly perfect in design.

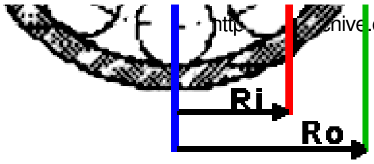



Now if we change the geometry of the bearing to make it accommodate a wheel, the modern design looks rather like the bearing on the left side below (the right hand drawing - a two-row bearing - is discussed later). As shown, the modern circular roller bearing has an inner race and an outer race which retain the rolling balls between the races. Call the inner race's outside radius Ri and call the outer race's inner radius Ro. Note that the inner and outer race's circumferences are not the same: Ci = 2*pi*Ri and Co = 2*pi*Ro so the difference in circumference is Ci -Co = 2*pi*(Ro-Ri). Normally, the bearing is tight-fitting so that Ro-Ri=Db where Db is the diameter of the rolling balls. Finally, the circumference difference is:

Co - Ci = 2*pi*Db

Now consider that if the rolling balls firmly grip both the inner and outer races the balls roll a different distance on each race as the bearing completes one revolution but the performance is like the linear bearing otherwise.



The ball bearing in practice is partly rolling and partly sliding. The lubrication reduces the coefficient of friction between the balls and the races which drops the power loss but probably also weakens the grip between the balls and the races. The question of interest for performance is how to quantify the power loss from sliding.

Modelling The Dual Constraints: Friction and Temperature

Bearing Frictional Power Loss

The bearing frictional power loss (Pf) is calculated from the friction force (F) and the slip velocity (vs) as: Pf = F.vs
And we use F = mu*M*g where mu is the appropriate coefficient of friction, M is the mass loading and g is the local accereration of gravity. M will be approximately the skater's total mass divided by the number of bearings (2 per wheel, 5 wheels per skate or 10 total) if only one skate is on the ground at a time. The slip velocity will be the slip distance per revolution (S) divided by the revolution period (tau). So vs = S/tau. Putting what we have so far together:

$$Pf = mu*M*g*S/tau.$$

We find the revolution period, tau, from the wheel's circumference (2*pi*R) divided by the wheel's axle speed, v (which is also the skater's forward velocity). The final result for bearing frictional power loss is:

$$Pf = \frac{mu*M*g*v*S}{2*pi*R}$$

Neither the bearing race diameters nor the ball diameter enter this equation but the wheel diameter (D = 2*R) does. Interestingly the wheel diameter is intertwined with the bearing properties and the wheel should not be considered separately from the bearing. Now we find that large diameter wheels not only have smaller rolling resistance, they also have smaller bearing frictional resistance.

Bearing Heating

Assume that the bearing friction force leads to heating. Then energy conservation yields:

$$mb*Nb*Nr*cp*DelT = Pf*tau = mu*M*g*2*pi*Db$$

where the new terms are mb = mass of one ball, Nb = number of balls in one row, Nr is the number of rows (normally one but a picture above shows a case where Nr =2), cp = specific heat, and DelT is the temperature rise per wheel revolution. We can express the mass of a ball as mb = (rho*pi*Db^3)/6 where rho is the mass density of a ball. Solving for the temperture rise:

$$DelT = mu*M*g*2*pi*Db/(mb*Nb*Nr*cp) = mu*M*g*12/(rho*Db^{2}*Nb*Nr*cp)$$

So small ball diameter, Db, leads to a large temperature rise and there will be some minimum diameter which is usable depending on the ball material properties.

Bearing Combined Constraint

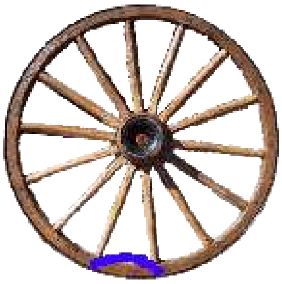
The two equations for power loss and heating can be combined to yield one equation for the ball diameter (squared) :

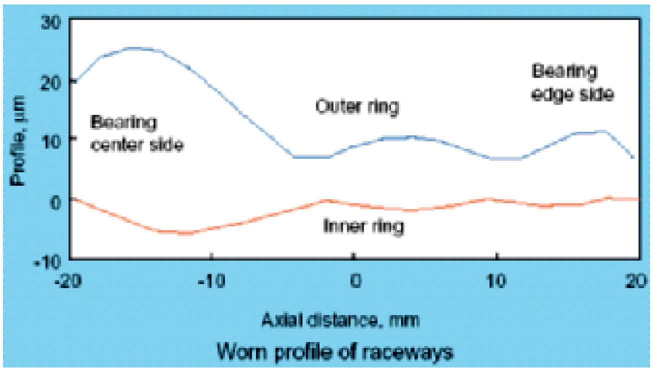
$$Db^2 = \frac{24*pi*Pf*R}{v*DelT*rho*Nb*Nr*cp*S}$$

To use this equation one would choose the maximum bearing power loss, Pf, which is acceptable and also specify the maximum temperature rise per revolution, DelT, which can be tolerated. Together with the wheel diameter, the skater's speed (v) the sliding distance (S) and the material properties this determines the minimum ball diameter.

Factors In Bearing Sliding

Like the spokes of a wagon wheel (left below) the balls in the bearing support the outer and inner circular members and keep the members at a constant radial distance apart. The blue curve at the bottom of the wagon wheel shows a greatly exaggerated deformation of the outer circular member under gravity. Likewise, the balls prevent the outer raceway from deforming at the position of the balls but the strength of the raceway is all that prevents bending between the balls. Unlike the wagon wheel, the balls roll around the races so that any deformation of the races propagates around the outer member at the speed of the balls themselves. To get a clue to the distances that are important in a good bearing look at the figure on the right below. This shows that the outer raceway wear ranges between 10 and 25 microns (micron = meter/1,000,000).The inner raceway wears much more slowly. This sequence of figures is adapted from a paper by H. Aramaki "Roller Bearing Analysis Program Package (BRAIN)", 1997, which is on the net in .pdf format.



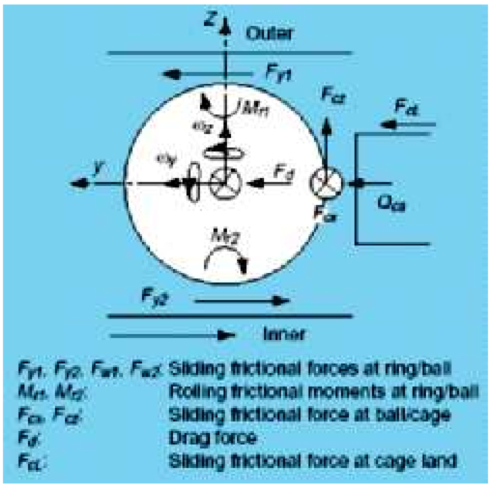


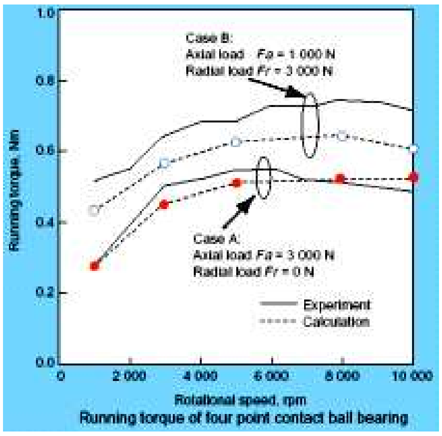
Worn profile of raceways

It is apparent that any deformation from perfect circles in any rolling member will show up as a drag force or power loss. Consequently there must be enough balls to support the outer raceway adequately and this depends on the thickness and materials properties of the outer raceway. The figure below (left) shows only a few of the forces considered in bearing computer programs: various sliding and rolling friction forces. Other forces which are accounted for in the BRAIN program include contact forces, centrifugal force, gyroscopic moments, and lubrication viscous drag. Much of the analysis of bearing performance builds on the work of A.B. Jones in the 1960's which was picked up and expanded on by NASA. Now it is apparent that finding an optimum bearing is a very much greater chore than I had imagined when I set out to write this page so I will narrow the scope to a description of the factors involved. Any final design will need computer analysis and lab or street testing.

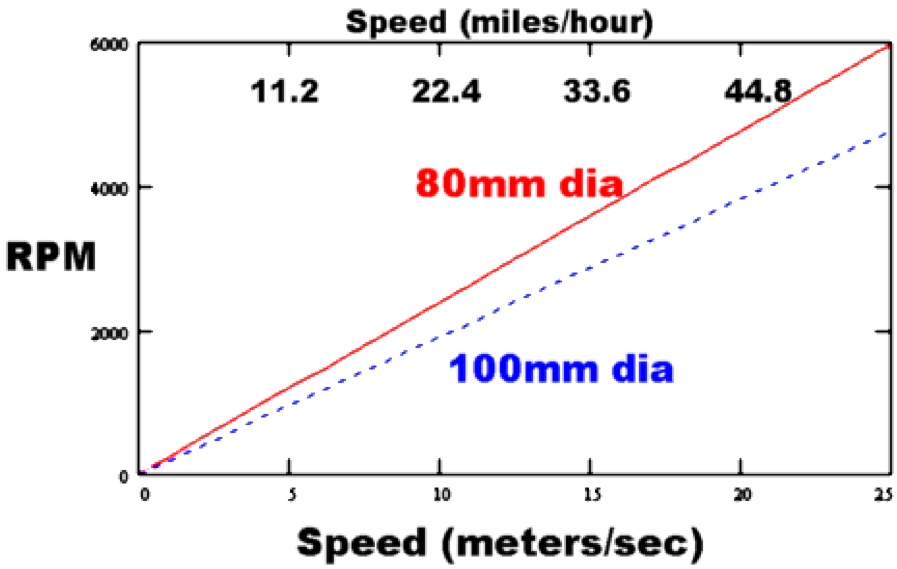
The figure on the lower right appears to show the importance of lubrication viscous drag. The torque required to spin up a bearing to speed increases at first, then levels off, and even drops at very high

speed. This is interpreted as a drop in lubricant viscosity at higher temperatures from the higher speed.





For comparison 80mm and 100mm diameter skate wheels are considered in the figure below. Typically the rpm will be in the 2000-3000 range except for downhill where the rpm is much higher.

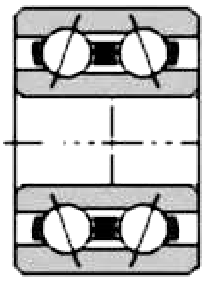


Some sliding friction results when the spacers between rolling elements contact the raceway. Friction also arises from slippage of the rolling elements. This mainly occurs in the unloaded region of a bearing where clearance between rolling elements and raceway is at a maximum (My interpretation is in an appendix at the bottom of this page). Slippage also increases with decreasing speed because the reduction of centrifugal force on the rolling elements results in greater clearance. Friction can also result from rusting or corrosion of metal surfaces which produces abrasive oxide particles. Needless to say, cleanliness is extremely important for fast bearings as is the requirement that they not be allowed to become wet (rust).

The temperture coefficient of expansion is important because changes in the dimension of any rolling element will result in vibration, slippage, or drag through a compressive contact force which retards rolling. The practical effect of these requirements will be discussed in the *Bearing Sizing and Material* section.

So far we have assumed that the only forces acting are perpendicular to the axis of the bearing as in an automobile which is gear-driven and

gravity loaded. In the skater's case there can be significant force along the bearing's axis when the skater strokes. This axial loading can wear an ordinary bearing out quickly leading to vibration and slippage. There are new bearing designs including the single-row and double-row angular contact bearings. In an ordinary bearing the balls contact the races in a plane perpendicular to the bearing axis whereas in an angular contact bearing the balls are at an angle other than 90 degrees with respect to the bearing axis. The angle is determined by the amount of axial offset in the grooves in the inner and outer races. A double row angular contact bearing has two rows of balls with opposite offset angles so that axial loading can be resisted from both sides. This kind of design extends the bearing lifetime significantly. Here is an example of a double-row angular contact bearing (left) and a single-row angular contact bearing (right):



You might think that a single row bearing with a deep groove would match the performance of a double row angular contact bearing. This seems to be true in terms of axial loading capability but the lower friction of the angular contact bearing seems to have the advantage over the deep groove single row bearing.

Bearing Sizing And Materials

Skate bearings usually are in a "608" size or a "688" minibearing or microbearing (note: minibearings like Baby Bonts <u>don't fit all frames</u> and may require an adapter to fit wheels designed for larger bearings). Traditionally they have used 7-10 balls with chrome-steel races. Recently the hybrid bearing made it's way into the skating scene. Beware that the term hybrid is used in two different senses which mix the traditional chrome-steel with the new ceramic materials (usually Silicon nitride).

1. **Metal raceways with all ceramic balls.**
2. **Metal raceways with half metal balls and half ceramic balls (alternating)**

One manufacturer states that using half ceramic balls is almost as good as using all ceramic balls but at a much lower cost.

Now as SINERAMICS indicates, the Silicon Nitride ("SiN") ceramic balls can be made in two different processes and come in three grades. Sineramics (the parent company of the apparently defunct SINSYSTEMS) also shows that SiN balls are available in three grades. Grade A was used in aerospace and Grade B was used in skate bearings. Grade C was even lower quality. So beware that not all SiN balls are equal.

Below are some figures (adapted from the Boca Bearings site) which show some common sizes of bearing balls and some advantages of ceramic balls. Older bearings used the 5/32 inch size with 7-8 balls while SinSystems went to a 1/8 inch size ball with 9 balls. Bont's minibearing uses 10 steel balls but I did not see the diameter listed.

INCH	MILLIMETER	FRACTION
.0312	.7937	1/32"
.0315	.8000	
.0394	1.0000	
.0469	1.1906	3/64"
.0472	1.2000	
.0625	1.5875	1/16"
.0781	1.9844	5/64"
.0787	2.0000	
.0937	2.3812	3/32"
.0984	2.5000	
.1094	2.7781	7/64"
.1181	3.0000	
.1250	3.1750	1/8"
.1406	3.5719	9/64"
.1562	3.9687	5/32"
.1575	4.0000	

ADVANTAGES OF SILICON BALLS COMPARED TO STEEL BALLS

PROPERTY	UNITS METRIC	Si_3N_4 CERAMIC	STEEL
DENSITY	g/cm	3.2	7.8
HARDNESS	H (LOAD: 20 kgf, 30 sec)	1500	700
STRENGTH	3 pt/Tensile: MPa	730-1000	800-2000
FRACTURE TOUGHNESS	Kg: MPa m2/2	7	30
ELASTIC MODULES	x102 MPa	3.0	2.0
POISSON'S RATIO		.27	.30
THERMAL EXPANSION	x10 / C (RT-800 C)	3.2	12.5
HEAT RESISTANCE	C	900	180

BENEFITS AND ADVANTAGES OF USING CERAMIC BALLS (SILICON NITRIDE)OVER STEEL BALLS

- Wear Resistance, longer life
- Lighter Weight, faster response to rotational speeds
- Increased stiffness
- Corrosion resistance
- High temperature capability
- Electrical non-conductivity
- Tolerance to poor lubricating environment
- Superior strength and durability
- Are 40% lighter weight then steel balls
- Are 1-1/2 times stiffer then steel balls
- Are 3 times stronger then steel balls
- Has 25% less thermal expansion than steel balls
- Has 50% less thermal conductivity then steel balls
- Has 2 to 5 times longer service then steel bearings

OTHER ADVANTAGES OF CERAMIC BALLS USED IN HYBRID BEARINGS

- Hybrid bearings run at least 5 times longer then the comparable steel bearings with lubrication
- Hybrid bearings can run at least 15 times longer then steel without lubrication
- Allows a greater accuracy in dynamic performance of the bearing at high speed

Table adapted from Boca Bearings.

Powell claims in advertising material that its Bones ceramics are 4mph faster than conventional bearings. But be aware that poor quality ceramic balls are subject to cracking and pitting so look into the source carefully when purchasing hybrid bearings. Below is a photo of one hybrid bearing:

Boss (BSB) sells bearings with titanium alloy races. Recently they started making titanium balls also. They claim titanium has advantages similar to

ceramics but would not seem so likely to crack.

Discussion and Conclusions

A lot of progress has been made in bearing design and fabrication in recent years. The older chrome-steel bearings work pretty well and are fairly cheap but they wear out quickly. So the hybrid bearing, using ceramic balls and chrome-steel raceways, was developed. This proved to be a great advantage but there remain a couple of problems: high quality ceramic balls are expensive, and the raceways still wear out quickly. Some bearing companies advertise that they will reclaim your old ceramic balls and install them in new raceways which helps, but raceway technology is still lagging. Now it is possible that the titanium raceway will be an advantage but I cannot find enough evidence yet to state that as likely. It seems certain that ceramic bearing are here to stay but whether they stay in skating seems to be a question of price vs. quality control.

One trend that can be discerned is the downsizing of skate bearings and the increase in number of balls. While 7-8 balls were standard, it is not unusual to find 9-10 now. It seems to me that this is a healthy trend. As the outer raceway diameter drops it becomes less likely to flex so one might expect less vibration and slippage. The old argument for large and heavy balls (large "m") came from the fact that they had more centrifugal force when spinning and so were more likely to make good rolling contact with the outer raceway whereas lighter ones might slip. This argument seems to have fallen away as a smaller diameter outer raceway (small "r") increases centrifugal force (F = mv*v/r) without the need for massive balls. And with the smaller mass comes less stress and longer wear. In addition, the bearing stiffness increases with an increasing number of balls as there are more support points for the raceways. Consequently, I expect this trend to continue toward smaller balls and more of them.

Now as regards the number of rows of balls per bearing, there has been very little exploration in skating. I came across one double-row bearing used in hockey but none for speed. It seems clear that the angular contact bearing has advantages over the old design. Most bearing companies advertise that they produce angular contact hybrid bearings so they are embracing this design. But I have not seen any mention in skate bearing ads that they use angular contact bearings. So either they don't use them or they don't think it's important enough to mention. It appears that the double-angular-contact bearing has advantages wherever sideways (axial) loading occurs. Since this looks very likely in skating it seems that they should be employed. Of course they are wider than ordinary bearings, but since the outer diameter and ball diameter can be reduced it does not look too hard to modify the wheel slightly or come up with an adapter to fit them into existing wheels. In the hockey case the wider double-row bearing meant that the bearing spacer could be eliminated altogether.

Appendix: Ball Speed And Slippage

Consider that the balls in a bearing travel slower than the outer raceway. You can convince yourself of this by measuring the "King Tut" bearing: Get two flat rulers (or yardsticks, meter sticks etc) and a cylinder , perhaps a pill bottle. Lay the first ruler on the ground and place the cylinder on top of it. Finally, the second ruler goes on top of the cylinder. Now as you push the cylinder with the top ruler the top ruler moves twice as far as the center of the cylinder. Consequently, the center of mass of the cylinder moves only half as fast as the top ruler. For our bearing this means that the center of mass of a ball moves at half the speed of the outer raceway when it is firmly gripping the raceway. It is only the outer edge of the ball which moves at the speed of the raceway by virtue of the ball's rotation.

Normally the balls are kept spinning by the motion of the outer raceway.

But, if the ball separates from the outer raceway the ball's spin rate will slow down due to air drag, lubricant viscous drag, and friction with the ball spacer material between the outer and inner raceways. Consequently, the next time the ball makes contact with the outer raceway its edge must be accelerated back up to the speed of the raceway or there will be slippage and friction between the ball and the raceway. In order to minimize the energy needed to spin the balls back up to speed the balls should have low rotational inertia. That is, the balls should be low mass and small size. I find this a convincing argument against large diameter heavy (steel) balls.

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