Low technology rolling-element bearings for animal-powered transport and equipment

by

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Abstract

Conventional bearings used in animal-powered machinery have been of two types: either plain boundary-lubricated bearings made of wood or brass running on steel shafts, or high technology rolling-element bearings made from vacuum degassed steel and imported from the industrialised nations of the "north". Both types have been found to be wanting in ease of manufacture and use, availability and cost, or longevity and maintenance.

Work carried out in the past 10 years at the University of Warwick suggests that cheap and relatively easily manufactured rolling-element (anti-friction) bearings can be made from common materials such as cold-rolled steel bar, malleable-iron water pipe and plywood. Present indications are that these bearings can have lives well in excess of those required for typical animal carts and indeed for many other applications as well.

One advantage of such bearings is that, apart from some raw material, all manufacturing could take place in the country and, in many cases, the locality of use. In most countries of the "south" today, difficulties with foreign exchange are crucial to the success of new technologies, and retaining labour costs in the locality of use can be highly beneficial. In many situations the costs of moving parts, and in particular the costs of obtaining and fitting bearings, are a major component of the final cost of the product. In some cases as much as 40% of the net price to the manufacturer can be attributed to bearings. Clearly the profitability of manufacturing and operating carts, implements and machinery will be influenced by these high costs. Re-inventing the wheel, or at least the rolling-element wheel bearing, promises to result in substantial reductions in net vehicle or implement operating costs. This paper outlines some of the thinking behind the University of Warwick Development Technology Unit's work in this area and some of the tests and experiments that have been conducted by it.

Introduction

The history of the animal cart is an old one and today a very large number are in use worldwide. The largest concentrations are found in the Indian subcontinent and efforts are being made to spread the extensive use of animal traction to most African countries as well.

An historical problem for all carts has been the provision of bearings and, to a lesser extent, the wheels for them. In the industrialised north a tradition of integrated wheel and bearing systems was built up based on tapered wrought iron (and later steel) stub axles together with brass or bronze bushes mounted in wooden wheels (Sturt, 1943). These tapered bearings allowed the running clearance to be adjusted by varying the wheels' axial positions on the axles using washers and wedges. Although these systems were quite successful there was interest in reducing both the wear and the friction of the bearings of animal-drawn vehicles, both from the point of view of reductions in maintenance and from considerations of the fatigue of the animals used. The advent of commercial rolling-element bearings in the early part of this century (such bearings were developed and introduced primarily for factory use) eclipsed plain bearing systems and replaced them within only a few years. The advantages of the new rolling bearings were their low friction, particularly on starting, and their low wear and long life. These bearings made it possible, for the first time, to "fit and forget".

In the intermediate technologies intended for Third World countries, problems with the provision, installation and maintenance of conventional rolling-element bearings are well known. While the costs of deep-groove ball races of the sizes fitted to, say, the Land Rover, are tolerable in Nigeria or Kenya, in many other countries even these sizes are expensive and difficult to obtain.

Use of conventional rolling-element bearings in Third World applications generates further problems during design and manufacture. Careful design may be required to avoid early bearing failure through misalignment and bearing fight. Another problem concerns the accuracy with which the bearing seats and housings can be made in a workshop of limited capacity and operator skill level. Conventional bearings are lifed on the basis that they are mounted on shafts and in housings that control their running clearances. For example, a 50 mm shaft should be finished to an accuracy of perhaps 0.05 mm. This is on the limit of what can be achieved by a good operator with a single point tool in a good lathe. The author has personal experience, in one African country, of 115 mm shafts, made from galvanised water pipe, which were not only not round but which were tapered and in error by about 0.35 mm on diameter after being worked on by a good operator on a good lathe.

What is required is a bearing that is not much more difficult to manufacture than a wooden bearing installation and yet can function for long periods when badly misaligned and poorly lubricated. Animal cart bearings do have some easy features: loads are reasonably modest, and speeds are slow by comparison with many other bearing applications. Also, much higher wear can be tolerated than is commonly possible in conventional applications, so the criterion of bearing failure can be relaxed. (In the present work "failure" means jamming that cannot be rectified by cleaning and relubrication.)

The issue of the place of manufacture is important and has implications for the effective cost of many animal-based technologies. Many authors (Starkey (1988), for example) have detailed the difficulties experienced by emergent farmers with inappropriately designed equipment manufactured overseas, or in some distant location. These authors make clear the point that local design and manufacture enable more effective communication between manufacturer and customer and more ready modification of poor design and repair of existing equipment.

The author became aware of the difficulties in using conventional rolling bearing while working in Botswana in 1982. He carried out a short research project (Oram, 1983) based on the idea that rolling-element bearings made of less than ideal materials might be adequate in some circumstances. He had made pantograph bearings from mild steel in the 1970s and there were other precedents for alternative materials. Some industrial castors and wheelbarrow wheels have rolling-element bearings of low-carbon steel, and the UK company Bearings Non Lube Ltd has been making rolling-element bearings from thermoplastics for some years for many industries including food and photographic process applications. Races of these bearings are made of polyacetyl, and balls of stainless steel, glass or nylon. The races are often moulded to include some other component, for example, a wheel or roller, with the bearing. The author's tests were made on bearings of black mild steel plate and bright drawn round bar. Bearings were of 160 mm inner race diameter with 20 mm diameter rollers 19 mm or so long; loads were up to 7 kN; and speeds were about 150 rpm. The test was terminated after about two million revolutions by jamming caused by conflict between axially and radially disposed rollers, a crossed roller format of orthogonal rollers and races having been erroneously used.

Since that time a number of other students (Godden, 1986; Austin, 1987; Mascia, 1989) have worked on alternative rolling-element bearings, including crossed roller bearings, needle roller bearings, a cylindrical roller thrust bearing, bearings consisting of steel strip tyres on wooden backings and bearings with wooden races only. Results of tests on such bearings have been encouraging. Even at high loadings on the edge of plasticity, bearings have survived for periods adequate for animal-power applications and in most cases tests have been suspended because of the time taken for testing, rather than because the bearing failed. The author thus believes that these bearings merit further attention and may offer the solution to some bearing problems.

The present approach marks a change from a conventional approach to bearing provision, namely using highly selected materials, to one of using only those materials that are more readily available and to accepting that performance will be adversely affected. Although it would be possible to investigate and promote the use of modest hardening processes, for example, case hardening of the bearing components, pressure for this has been resisted because it is felt that problems will arise with quality control during such processes; and in any case additional work such as this is unlikely to be cost-effective in terms of the potential material saving.

Conventional bearing approaches

Conventional bearings used for vehicle wheels reflect the choice open to designers of most machinery: use either plain bearings or anti-friction or rolling-element bearings.

Plain bearings are used in two operating modes: either as directly rubbing bearings where intimate contact is made between the bush and the shaft throughout operation or, with higher speeds and in the presence of a suitable lubricant, the load may be carried by a viscous film which completely separates shaft and bush. Under the latter conditions no wear takes place. This latter mode of operation is called hydrodynamic and unfortunately usually requires conditions which cannot be met in animal transport applications. At intermediate speeds contact may exist and thus wear can occur.

Plain bearings exhibit high friction at start and at low speed but may have effective friction coefficients lower than those of anti-friction bearings at high speeds when operating in the hydrodynamic mode. They are capable of accepting a small amount of permanent misalignment and inaccuracy in manufacture and assembly by both plastic deformation and wearing in or "running in". They are not good at tolerating loss of lubricant but may have lubricant supplied fairly reliably over a long period by porous bushes or other absorbent material in the vicinity. Careful choice of materials for the shaft and bush is necessary to ensure that operation in the rubbing mode does not result in "pick up" of one surface by the other, ie, localised welding of one surface to the other which can cause very rapid wear. It is usual to make shafts of a hardish material such as steel and bushes of softer material such as white metal (an alloy of lead and tin) or brass. Because of the generous area of contact between shaft and bush they are tolerant of shock and abuse, even with modest material quality.

Wooden bearings have a special place in animal transport bearing technology and have been, and are being, investigated for this application. Intermediate Technology Transport Ltd and the Technology Development Advisory Unit in Zambia have carried out investigations into timber selection and oil impregnation. Difficulties have been expressed regarding timber selection, wear and dirt and lubricant sealing, but some organisations are happy with their performance. Conventional rolling-element bearings have characteristics complementary to those of plain bearings. They are tolerant of interruption in lubricant supply and have low friction throughout the speed range. They are not good in situations of shock and misalignment and never "wear in" so that a misalignment set during manufacture or assembly is present throughout the life of the bearing. As stated above they depend for their running clearances on their fit onto the shaft and into the housing and are especially vulnerable to tight fits in conjunction with misalignment and axial loads. A notable trend in the automotive area is the adoption of "integrated hub bearing" configurations such as those used on the Fiat Panda and the Saab 9000 series passenger cars where, under particular space pressure, both outer and inner bearing races have been extended to provide bolted fixing points to the suspension system and to the wheel hub. These integrated systems reduce assembly costs and the dangers of bearing fitting. One company has introduced the Fiat Panda bearing for animal-drawn carts with mixed success.

Stress analysis of rolling-element bearings

Hertz was the first mathematician to devise an analytical basis for determining stresses in the contact areas of "higher pairs" or nonconformal surfaces. He developed expressions for both compressive stress and shear stress which show that shear stress reaches a maximum of 0.304 of the maximum compressive stresses at a depth of 0.78 times the contact strip half width (for parallel cylindrical bodies). Maximum compressive stress is given by:

$$\sigma = \left(\frac{F}{\pi L} \times \frac{\frac{1}{r_1} + \frac{1}{r_2}}{\frac{(1-\nu_1^2)}{E_1} + \frac{(1-\nu_2^2)}{E_2}} \right)^{\frac{1}{2}}$$

Transforming this equation to show the maximum roller load when yield stress is reached gives:

$$F = \pi L \sigma_y^2 \left(\frac{\frac{(1-\nu_1^2)}{E_1} + \frac{(1-\nu_2^2)}{E_2}}{\frac{1}{r_1} + \frac{1}{r_2}} \right)$$

The half width b of the contact strip is given by:

$$b = \left(\frac{4F}{\pi L} \left[\frac{\frac{(1-\nu_1^2)}{E_1} + \frac{(1-\nu_2^2)}{E_2}}{\frac{1}{r_1} + \frac{1}{r_2}} \right] \right)^{\frac{1}{2}}$$

where:

σ is compressive stress

σ_y is compressive stress at yield

ν is Poisson's ratio

F is roller load

L is roller length

r is roller radius

E is Young's modulus or material stiffness

The subscripts denote the two materials.

Examination of these equations shows that roller load at the point of plasticity rises with the square of material hardness (or yield stress) and inversely as material stiffness. Table 1 shows the load to just produce plasticity and the contact strip half width for a range of candidate bearing materials. The effect of Young's modulus is striking in the case of polyacetyl bearings where the low stiffness allows relatively large contact areas and low stresses. Clearly, permissible loads on intermediate technology roller bearings are very modest by

Table 1: Alternative bearing materials and bearing loads

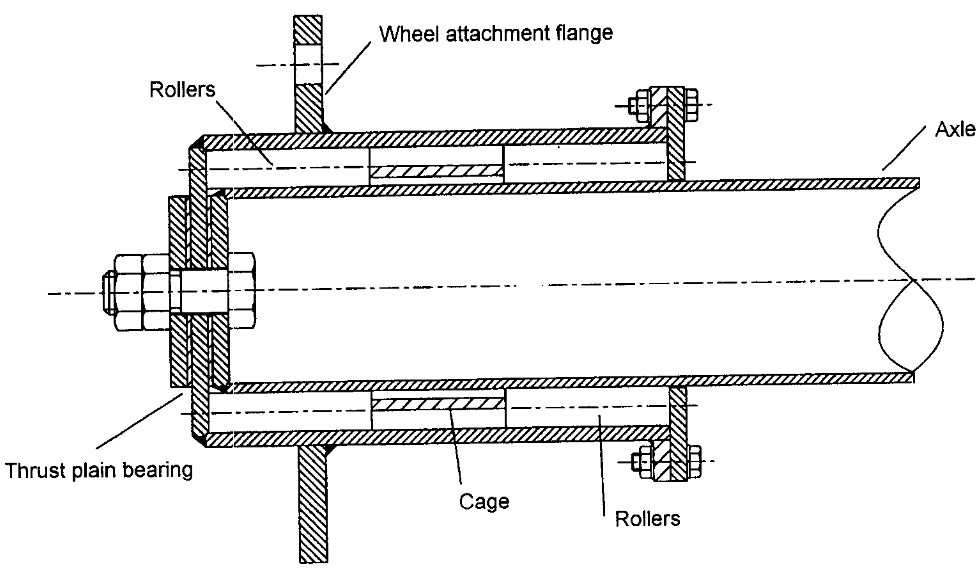
Material	*Young's modulus (MPa)*	*Compressive yield stress (MPa)*	*Poisson's ratio*[1]	*Roller load*[2] *at three times yield stress (N)*	*Contact strip half width at yield (mm)*
Bearing steel	210 000	1 850	0.29	10 049	0.10
Mild steel	210 000	350	0.29	360	0.02
Galvanised water pipe	210 000	195	0.28	112	0.01
Aluminium	70 000	200	0.36	335	0.03
Brass	100 000	400	0.33	960	0.04
Wood	20 000	50	0.45	67	0.02
Polyacetyl	3 000	65	0.35	832	0.24

[1] *For wood this is heavily dependent on orientation: average figure taken from Beaver (1986)*
[2] *For 25 mm diameter shaft and 10 mm diameter rollers each 10 mm long*

comparison with those that may be applied to bearings made of conventional bearing steel. As a comparison, conventional roller bearings for 25 mm shafts have static ratings of about 10 000 N, and ball bearings a static rating of about 4000 N. Notwithstanding the greatly reduced potential loading, reasonable loads can be carried provided enough race area is available. This may not be too difficult (see the bearings shown in Figures 1 and 2). In essence we are replacing small bearings of good material with larger ones of poorer material.

No discussion has so far been made of multiple roller contact. Manufacturing accuracy in conventional ball and roller bearings allows loads, both radial and axial, to be carried by more than one rolling element. Stribeck, in the middle of this century, and those after him, assumed that all rolling elements in a thrust bearing, or half of them in a radially loaded bearing, carried load (Allan, 1945; Barwell, 1979). This situation is not likely with intermediate technology rolling-element bearings where manufacturing accuracy is low. A roller would be completely unloaded by making it smaller than the others in the set by a small fraction of the dimensions shown in the last column of Table 1. Nevertheless it is probable that more than one element is under load at any instant, simply from considerations of kinematic stability. Observations of test bearings at Warwick indicate that three rollers normally support the load. There is an argument that in intermediate technology bearings a certain amount of "running in" or plastic deformation could take place so that the outer race might become a

Figure 1: Proposed low technology rolling-element bearing hub for carts using old rims of the Land Rover type



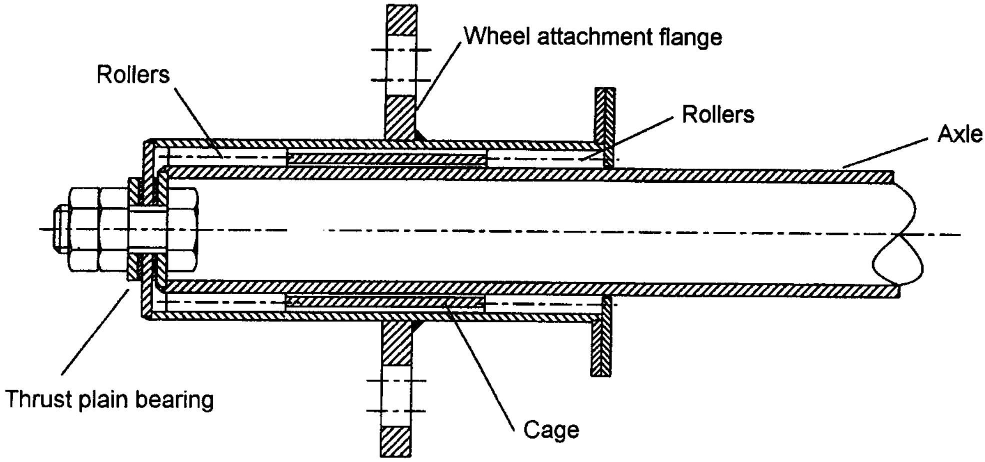


Figure 2: Proposed low technology rolling-element bearing for passenger car rims

better fit to the roller profile. This effect might well improve misaligned operation also.

All work in the present programme has centred on the use of cylindrical roller bearings because of both ease of manufacture and the low potential load carrying capacity of intermediate technology ball bearings.

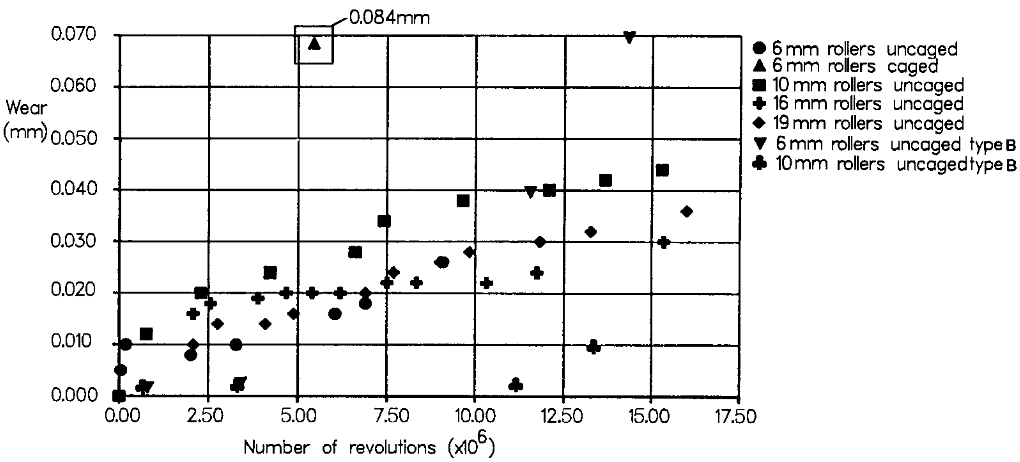
Intermediate technology rolling-element bearings

Experimental work at Warwick

Figure 3 shows data from a series of tests by Mascia (1989). Experiments were conducted on bearings with 26 mm diameter shafts and with nominally 10 mm long rollers. The imposed load was obtained by spring balance and was maintained at 500 N throughout all tests except those with a caged bearing on which the load was 400 N because the caged rollers were only 8 mm long. Rotational frequency was maintained at 500 rpm in nearly all tests. Wear in these tests, in which race stresses probably approached yield for most of the time, was about 2 microns/million revolutions when using free machining mild steel obtained in the UK, except for the anomalous test with the full cage, when the rate of wear was very high. No pursuit of this anomaly was made because it was thought that little use would be made of cages in low technology anti-friction bearings.

In some early tests in this series, pick-up between locating components in the test bearings and loss of

Figure 3: Wear of experimental low-carbon steel rolling element bearings (Source: Mascia, 1989)



lubricant resulted in the races being polluted with large amounts of steel swarf. The "Type B" bearing cited in Figure 3 contained brass washers to prevent this pick-up.

A figure of 15 million revolutions required for bearing life was arrived at by assuming that a cart travels 20 km daily for 200 days per year over a 10 year life.

Other work has included tests on naked wooden outer races and outer races of wood with 1.6 mm and 3 mm steel surfaces. In one such test an outer race of 200 mm diameter carried a load of 40 kN for 1000 revolutions and although it sustained some damage this was essentially exaggerated by flaws existing before tests started.

A bearing made of parallel discs of 18 mm birch plywood, to a total axial length of about 110 mm, successfully carried a load of about 3.5 kN for many hours as part of an animal-powered gear experiment. Its use illustrates the ease with which a solution can be obtained with intermediate technology bearings. No other solution was readily possible using conventional bearings.

Provisional designs

Figures 1 and 2 show cross-sections of provisional designs of wheel hub for carts using wheels from passenger cars or four-wheel drive vehicles such as Land Rovers. Radial load is carried by small diameter rollers of almost needle-roller proportions, disposed in two separated bearings to cater for the out-of-plane moments arising from cornering or running on cambered roads. Plain bearings cater for axial loads in both cases for simplicity. A small volume of oil should be able to lodge in the hubs to provide long-term lubrication. Not shown in either Figure 1 or 2 is any form of dirt or oil seal. Leather will probably be used in proposed tests in Nigeria.

A major constraint, especially with the hub intended for use with the car rims, was the overall diameter of the hub. Passenger car rims have only a small hole about 60 mm in diameter in their middle to accept the hub and it is preferable to position the rim in the middle of the hub axially in order to equalise load on the two bearings. Alternative configurations, able to cope with small wheel holes, are possible but are a little more complicated to construct and will not be investigated in the present programme until proven necessary. To date all designs have used steel components throughout. Testing of these hubs has already started.

Other uses of low technology rolling-element bearings

Other applications include hand carts and pedal-powered farm and urban vehicles for transporting passengers and goods on farms or in towns. Such bearings could also be used in crop processing machinery, wind turbines, water pumping turbines and hydropower plants. Another application that the author has been working on is stationary animal-powered gears for water pumping, crop processing and the like. This requires large torques.

Further work

Much further work is required. All designs to date have been in steel and have involved machining of either races or rollers or both. A suggestion by Hawkins (1992) is to fabricate the outer race from strip or wire around a former and freeze the final assembly by welding or other means. This might allow serious production of bearings for slow speed use without any machining and would thus enlarge substantially the number of potential manufacturers. It is envisaged that one major advantage of such bearings would be the possibility of local manufacture so that repair of hardware would be more readily achievable and better contact and feedback between manufacturer and customer possible.

Table 1 suggests that materials other than steel, in particular components of brass, wood and possibly aluminium, might make good candidates for further work. A second material to avoid steel-on-steel contact would be beneficial, since this contact causes friction and wear in existing designs. Some slip is inevitable in all rolling contacts under load and there are many points where incidental and irregular contact takes place and pick-up is potentially possible.

Work is necessary to carry further the investigation of steel tyres or races mounted in wooden backings or structures. Work completed so far suggests that this approach may be successful; it would certainly save substantial amounts of steel. Again races of plywood have performed satisfactorily in some light duties on animal engine pulleys; this could be taken further.

Work is also required on dirt/abrasive material tolerance and wear. To date all bearings have been fairly clean and have run with oil or grease most of the time. Some use of vegetable or cooking oil has been made but this and anti-oxidant additives could be investigated.

In some countries large numbers of scrap motorcycle wheels are used. These wheels have bearings which may well be damaged during removal from the machine or during use on the cart. Light motorcycle (eg, Honda 200 cc) wheels usually have integral brake drums of steel cast into the aluminium hub. These brake surfaces may make adequate bearing surfaces.

Research is under way at Warwick on a number of these issues and some results are published in the MSc thesis of Umara (1992).

Conclusions

Present bearing technologies using either locally made wooden bearings or rolling-element bearings imported from industrialised countries have shortcomings: in the case of the former, bearing life may be short; and in the latter case foreign exchange and skilled labour supply may be a problem. Rolling-element bearings made from materials usually fairly readily available may be able to fill the price/performance gap between these two bearing choices. Preliminary work undertaken over the past 10 years in the Development Technology Unit in the UK suggests that this technology deserves further investigation.

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Photograph opposite
Logging with oxen in a forestry plantation in Malawi