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History of Ball Bearings

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The precision rolling-element bearing of the twentieth century is a product of exacting technology and sophisticated science. It is simple in form and concept, yet so effective in reducing friction and wear in a wide range of machinery. The spectacular development of numerous forms of rolling-element bearings in the twentieth century is well known and documented, but it is possible to trace the origins and development of these vital machine elements to periods long before there was a large industrial demand for such devices and certainly long before there were adequate machine tools for their effective manufacture in large quantities. Much of the present chapter will therefore be devoted to the early history of ball bearings and, of course, the closely related and apparently longer history of roller bearings.

The influence of general technological progress on the development of ball bearings, particularly those concerned with the movement of heavy stone building blocks and carvings, road vehicles, precision instruments, water-raising equipment, and windmills is discussed, together with scientific studies of the nature and magnitude of rolling friction. The essential features of most forms of modern rolling-element bearings were established by the latter half of the nineteenth century, but it was the

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formation of specialist, precision-manufacturing companies in the early years of the twentieth century that finally established the ball bearing as a most valuable, quality, readily available machine component. The availability of ball and roller bearings in standard sizes has had a tremendous impact on machine design throughout the present century. Such bearings still provide a challenging field for further research and development, and many engineers and scientists are currently engaged in exciting and demanding research projects in this area. In many cases new and improved materials or enlightened design concepts have extended the life and range of application of ball bearings, yet in other respects much remains to be done in explaining the extraordinary operating characteristics of bearings that have served our technological age so very well for almost a century. Indeed, this book records recent developments in the understanding and analysis of one important aspect of ball bearing performance - the lubrication mechanism in the small, highly stressed conjunctions between the balls and the rings or races.

The basic form and concept of the ball bearing is simple. If loads are to be transmitted between surfaces in relative motion in a machine, the action can be facilitated in a most effective manner if rolling elements are interposed between the sliding members. The frictional resistance encountered in sliding is then largely replaced by the much smaller resistance associated with rolling, although the arrangement is inevitably afflicted with high stresses in the restricted regions of effective load transmission.

The history of ideas that led to the now familiar arrangement of ball bearings is intimately linked with the development of an appreciation of the advantages of rolling over sliding motion. This includes the early use of rollers in transporting heavy loads and the development of the wheel. Such developments took place in the earliest civilizations, and it is here that our story begins.

1.1 Rollers and the Wheel in the Early Civilizations

There is no evidence from prehistoric times to suggest that early man used rollers to move heavy objects, although this does not prove that wooden sticks, logs, or stones were never used for this purpose. No cave drawings, carvings, or artifacts have emerged to illustrate such progress in prehistoric times.

In the early civilizations the position was quite different, and there are abundant indications that the advantages of rolling over sliding motion had been recognized. The earliest civilization arose in Mesopotamia in the region of Sumer adjacent to the Persian Gulf, probably about 3200 B.C., and it is interesting that writing and the wheel emerged at about the same time in this society. The later developments in Egypt, the Indus Valley, and China all provided further evidence of the development of the wheel, but this progress was not reflected in Central and

South America. This anomalous situation in America between about 430 and 2480 years ago is both curious and interesting.

1.1.1 Rollers

The bas reliefs discovered by Sir A. H. Layard (1849, 1853) at Nineveh have been said by some, including Layard, to represent the first recorded use of rollers for transporting building blocks and stone carvings. However, the evidence from the picture of Assyrians moving a human-headed bull some 2680 years ago shown in Figure 1.1 is ambiguous because of the orientation of the "rollers" beneath the sledge. At the rear of the sledge, and perhaps at the front also, the logs are clearly arranged in a manner that indicates that they could indeed have been used as rollers, but in the load-bearing region beneath the sledge they are incorrectly aligned. Were they really being used as rollers or merely as hard surfaces on which the sledge could slide when moving over soft ground?

Man has used sledges for transporting heavy objects for almost 9000 years, but if Layard's interpretation of the Nineveh evidence is correct, it appears that man also recognized the merits of rolling over sliding motion in Assyria some 2700 years ago.

1.1.2 The Wheel

The transition from sliding sledges to rolling, wheeled vehicles is recorded in the delightful Uruk pictographs shown in Figure 1.2. This record dates back almost 5000 years. A later Chinese pictograph from about 3480 years ago shows that the spoked wheel had developed in the East by that time. In the Middle East it took a full millenium for the relatively sophisticated structure of the spoked wheel to replace the solid or tripartite wheel. In spite of the fact that, from an archaeological point of view, wood is a miserable material that decays all too quickly, about 50 wheels or wheeled vehicles have been found in Europe and Western Asia that can be dated to 4000 to 5000 years ago. It is fortunate that the wheel was so highly prized in the early civilizations that it was frequently buried in tombs, since this aided preservation.

The early wheels in the Middle East were solid and of tripartite structure, as shown in Figure 1.3. Three planks were dowelled and mortised together, and wooden or even copper battens were used to hold the fabricated structure together. The rims were often heavily studded with copper nails. Most of the early evidence suggests that the wheels rotated on stationary axles, and this arrangement has persisted throughout the ages for road but not for rail vehicles. Piggott (1968) has recorded the distribution of finds of wheels and early vehicles on maps as part of his investigation of the spread of the invention of the wheel to North Western Europe. The center of the invention does indeed appear to be located in the region between the Tigris and Euphrates, but there is interesting and more recent evidence of early developments near the Caspian Sea between the Kura and Araxes rivers.

1.2 The Development of Early Forms of Rolling-Element Bearings in the Classical Civilizations (ca. 900 B.C. - A.D. 400)

There is clear evidence of the development of early forms of both ball and roller bearings in the classical civilizations from 900 B.C. to A.D. 400. The Romans provided the most impressive and interesting examples, but intriguing evidence of the possible use of rolling bearings was also furnished by the Greeks, Celts, and Chinese.

1.2.1 The Greeks

Aristotle, who was one of Plato's most famous pupils, made reference to the force of friction and observed that it was lowest for round objects. It cannot be claimed that this marked the birth of the ball bearing industry, since Aristotle was more concerned with celestial mechanics and the motions of heavenly objects than with the problems of Greek artisans and engineers. The Mechanicians in Alexandria certainly used and probably developed pivot bearings and plain bearings made of metal, but there is no evidence of the use or study of rolling bearings in Alexandria.

A number of important military machines were developed by engineers for Alexander the Great. One of these, a movable tower containing a battering ram, was created by Diades about 330 B.C. The battering ram was mounted on an early form of linear roller bearing containing wooden rollers turned on a lathe.

1.2.2 The Romans

Some of the richest records of the development of bearings in the period of the classical civilizations are found in the writings of that famous Roman engineer and architect Marcus Vitruvius Pollio (see Morgan and Warren, 1960). His accounts of the movement of stone columns of both square and circular cross sections by building them into wooden wheels, or by using gudgeons and a garden-roller arrangement, are well-known illustrations of the way in which builders took advantage of rolling motion in the construction industry. Vitruvius also included in his writings a detailed account of the work of the Greek engineer Diades.

Perhaps the most spectacular archaeological evidence of the development of rolling bearings in this era came from Lake Nemi, some 18 miles southeast of Rome. The Romans were given to worshipping Diana, the moon goddess of virginity and hunting, in the groves surrounding Lake Nemi, which lies in the basin of an extinct volcano. They also constructed at least two ships on this inland lake for the pleasure of the ruling class.

On the 3rd of October 1895 divers found one of these ships, together with a number of interesting bronze and wooden objects. The second ship was found on November 18th of the same year, together with further interesting objects, on the bed of the lake. Interest in these reports grew until 1927, when Benito Mussolini announced an archaeological undertaking to recover the sunken ships in Lake Nemi. The procedure adopted was to lower the level of the lake by pumping and cutting passages through the mountains. As the work progressed, a bronze from the first ship was exposed in June 1929, and the second ship was revealed in 1930. It was ascertained that both ships had been built between A.D. 44 and 54. The numerous finds were housed in a fine, purpose-built museum completed on the side of the lake in 1933.

Among the Lake Nemi finds were forerunners of three of the most common forms of current rolling-element bearings. The most interesting mechanical device found on the ships was a platform designed to revolve on trunnion-mounted bronze balls. It was, in fact, a ball thrust bearing, although this was only recognized after the salvage operation in the 1930's and careful reconstruction of the finds. A number of the bronze balls had been salvaged from the first ship by divers in 1895, and 16 are now preserved in the Museo Nazionale Romano. More loose balls, together with two secured by iron straps to a fragment of wood, as shown in Figure 1.4, were located in the 1930's.

A reconstruction of the thrust-bearing arrangement is shown in Figure 1.5, and the superficial similarity between this device and modern thrust bearings is quite remarkable. There is, however, one important structural difference, since the balls were restrained from moving freely between the wooden tables by the trunnions and iron straps. Furthermore the loads were not transmitted across diametrically opposite points on the balls, but rather between the lower point on the balls and the flat wooden base on the one hand and the upper generators of the trunnions and the turntable on the other. The balls sat in relatively deep recesses in the turntable, as shown in the insert in the top corner of Figure 1.5. In a remarkable passage in his account of the material found in Lake Nemi, Ucelli (1940) confirmed this geometrical feature by noting that the machining marks left on the bronze balls after turning on a lathe were visible everywhere except in a narrow band corresponding to the region of contact between the ball and the flat wooden table.

A number of cylindrical bronze rollers were also found on the bed of Lake Nemi, but their purpose remains a mystery. A third and most remarkable find consisted of a number of trunnion-mounted wooden rollers within wooden rings. Ucelli formed the view that they represented an early taper-roller thrust bearing.

The ships of Lake Nemi must surely represent one of the outstanding features of rolling bearing history. The sudden appearance of such remarkable embryonic forms of ball, cylindrical, and taper roller bearings employing both bronze and wood, not only in the same century but in the same decade and even in the same location is truly outstanding. The purpose of these bearing elements can be debated, but Ucelli wrote:

> But even if the function cannot be ascertained, the evidence of the ingenious contrivance is undoubtedly of interest in the history of technology.

The story of these ancient Roman ships is remarkable enough, but there is an almost unbelievable final twist. On the 31st of May 1944, during the culmination of the Battle of Rome, the museum was destroyed, the ships burnt, and most of the valuable remains lost. Ucelli's well-illustrated and beautifully presented book thus forms a most valuable and sole record of an amazing event in the history of ball bearings.

1.2.3 The Celts

The Celts had a reputation for building fine carts and wagons. Dowson (1979) has discussed the evidence for their development of roller bearings almost 2000 years ago. The oak hubs on a fine four-wheeled cart found in Western Jutland, Denmark, in 1881 contained some remarkable bronze collars and bearings. There were 32 axial grooves in each collar, and wooden sticks or rollers were found in some of these grooves. It appears that the Celts were trying to replace conventional, plain hub bearings by a form of bronze roller bearing fitted with wooden rollers. There is no evidence that the Celts used early forms of ball bearings, but it seems clear that other forms of rolling-element bearings were developing in European countries about 2000 years ago.

1.2.4 The Chinese

The rival claim of China to an early place in the history of rolling bearings has been noted by Needham (1965). Some remarkable annular bronze objects containing four or eight internal compartments and dating back over 2100 years were found in a village in Shansi. A sketch of one of these objects is shown in Figure 1.6. The suggestion that the Chinese were actively involved in the early development of rolling-element bearings is strengthened by the records of granular iron dust in each internal cell.

The real purpose of these objects is unknown, but it is interesting to speculate on the possibility that a rotating shaft might have been supported on balls or rollers constrained to rotate within the internal compartments or cells.

1.3 The Middle Ages (ca. A.D. 400 - 1450)

It is both curious and interesting to find that practically nothing emerged during this dark and empty period in the western world to further the stirring developments of rolling-element bearings evident in the classical civilizations. There was undoubtedly interest in other facets of tribology toward the end of the dark millenium, but not in rolling-element bearings. Furthermore neither the well-established Chinese civilizations nor the Central or South American societies appear to have moved forward in this sphere of technology. One of the curious features of the otherwise highly advanced early American cultures is that neither the wheel nor the rolling-element bearing was in evidence.

1.4 The Renaissance (ca. A.D. 1450 - 1600)

Practically all the evidence discussed so far has been based on archaeological finds, but for the period of greatly enhanced interest in both culture and machinery known as the Renaissance, manuscripts and even printed books provide an increasing and vital store of knowledge.

We are only now learning to appreciate fully the work of that great genius Leonardo da Vinci (1452 - 1519) in the field of tribology. It is true that most of his writings on the subject were included in the Codex Atlanticus published at the end of the nineteenth century, but more recent records were found in the manuscripts revealed in Madrid in 1967.

Leonardo introduced a scientific approach to subjects and he wrote:

> Those who are enamoured by practice without science are like a pilot who goes into a ship without rudder or compass and never has any certainty where he is going...

Also,

> Practice should always be based upon a sound knowledge of theory.

Leonardo studied friction and appeared to carry out experiments that revealed the basic laws attributed at a later stage to Amontons (1699). He concluded that the coefficient of friction in sliding was constant and equal to 1/4 for all materials.

The advantages of rolling over sliding motion in low-friction supports for machinery were clearly recognized in early Renaissance industry. One idea, adopted for lightly loaded shafts, was to mount a gudgeon on two wooden discs supplied with their own axles. Leonardo was clearly fascinated by this "roller-disc" bearing, which can be viewed as a forerunner of the free rolling-element bearing, since he sketched a number of possible arrangements as illustrated in Figure 1.7. Indeed, the idea was for a long time attributed to Leonardo, but when the Codex Madrid I was located in Madrid in 1967, it became clear that he was made aware of the use of this novel form of shaft support system in Germany by a German mechanic named Giulio, who acted as his assistant. However, according to Reti (1971), Leonardo was responsible for the suggestion of a three-disc support, shown to the center-right in Figure 1.7.

Illustrations of the use of roller-disc bearings in Renaissance industry can be found in texts by Agricola (1556) and Ramelli (1588). A number of examples have been collected and reproduced by Dowson (1979). A fine illustration of roller-disc bearings supporting the shafts in a treadmill-operated chain of dippers that appeared in Ramelli's text is shown in Figure 1.8.

The potential of true rolling motion for low-friction supports was fully recognized by Leonardo, for he wrote in the Codex Madrid I:

> I affirm, that if a weight of flat surface moves on a similar plane their movement will be facilitated by inter-posing between them balls or rollers; and I do not see any difference between balls and rollers save the fact that balls have universal motion while rollers can move in one direction alone. But if balls or rollers touch

> each other in their motion, they will make the movement move difficult than if there were no contact between them, because their touching is by contrary motions and this friction causes contrariwise movements.
>
> But if the balls or the rollers are kept at a distance from each other, they will touch at one point only between the load and its resistance...and consequently it will be easy to generate this movement.

Leonardo saw little advantage of balls over rollers, save for the universal motion of the former, but his views on the advantages of rolling-element bearings represented a considerable advance on the Greek, Roman, Celtic, and Chinese arrangements discussed in Section 1.2.

The insight signified by the recognition of the need to separate rolling elements is remarkable. It is a point that can be made with merit in the introduction to any text dealing with the mechanics of rolling-element bearings, and it readily leads to the concept of the separator, retainer, or cage described in Chapter 2. These essential components of modern ball bearings were anticipated by Leonardo when he sketched his own form of ball thrust bearing complete with separator, as shown in Figure 1.9.

Leonardo's sketches of several forms of rolling-element pivot bearings were truly phenomenal. The designs shown in Figure 1.10

clearly represent outstanding advances in bearing arrangements. Commenting on the ball pivot bearing in the Codex Madrid I, Leonardo wrote:

> three balls under the spindle are better than four, because three balls are by necessity certainly always touched, while using four there would be a danger that one of them is left untouched.

Leonardo's studies of rolling-element bearings and the introduction of the roller-disc bearing into industry dominate the history of our subject in Renaissance times, but there were other indications of the growing interest in the use of rolling motion to reduce friction and wear.

Early in the sixteenth century cast-iron balls were manufactured, and Allan (1945) has drawn attention to the fact that they were used as low-friction supports in maneuvering heavy objects like gun carriages. Another interesting reference to the use of ball thrust bearings was recorded in the autobiography of a Florentine goldsmith named Benvenuto Cellini.

In 1534 The King of France commissioned Cellini to produce a statue of Jupiter about 1.4 meters (4 1/2 ft) high. The translation of Cellini's description reads:

> Having with the utmost diligence finished the beautiful statue of Jupiter, I placed it upon a wooden socle, and within that socle I fixed four little globes of wood which were more than half hidden in their sockets and so admirably contrived that a little child could with the utmost ease move this statue backwards and forwards, and turn it about.

Cellini was clearly pleased with the performance of his thrust bearing, which contained four free-rolling, wooden balls.

A further indication of interest in rolling-element bearings in Renaissance times is found in the history of horology. An astronomical clock of great complexity constructed in 1561 by Eberhardt Baldewin, clockmaker to William IV of Hesse, clearly contained simple roller bearings in the gear train that operated the dial of mercury.

By the end of the sixteenth century the concept of rolling-element bearings was established in industry. However, for all but the lightest loads, the elements rotated about a fixed axis and were not free rolling as in modern bearings. The transition from fixed-axes to free-rolling arrangements was one of the most important developments in bearing technology in later times.

1.5 The Development of Bearings and Early Concepts of Rolling Friction in the 17th and Early 18th Centuries (A.D. 1600 - 1750)

Most of the references to bearings in this 150-year period were concerned with plain bearings. Those that discussed rolling-element bearings were almost exclusively restricted to roller-disc or roller bearings. The literature nevertheless presents a record of growing interest in the development of rolling-element bearings for an increasing range of applications and is therefore worthy of note.

Perhaps the most significant feature of the period is that scientists like Robert Hooke started to express views on the nature of rolling friction.

1.5.1 Roller Bearing Applications

Most of the interest in roller bearings centered on their application to wagons and carriages, but there was an interesting application in a chronometer used for navigation.

One of the prize winners in an open competition instituted by the Board of Longitude, London, in 1714 for the determination of longitude at sea to within 0.5° to 1° was an English watchmaker by the name of Henry Sully. Sully, who resided in Paris for many years and who wrote in French, fitted a form of roller bearing in his highly accurate chronometer in 1716 and won the prize.

Roller bearings were used in windmills in Europe in the period under review, and a fine example of a large bearing in a Dutch sawmill, or paltrok, is included in books by van Natrus, et al. (1734, 1736). A large roller thrust ring containing wooden rollers having lengths and diameters of about 180 mm (7 in.) is clearly shown above the base of the mill in Figure 1.11. Wailes (1957) has noted that smaller cast-iron rollers were used in English windmills at a later date.

The introduction of roller bearings into the developing forms of horse-drawn road vehicles during this period is worthy of special mention. Carriage bearings were to provide important indications of improvements in roller bearings until the special requirements of the railways accelerated the development in the nineteenth century. Since our history is concerned mainly with ball bearing development, the present account of roller bearings in carriages will be restricted to the contributions by Hooke, de Mondran, and Rowe.

Hooke was Robert Boyle's assistant and lifelong friend, and in 1662 he became Curator of Experiments to the recently formed Royal Society. In his discourse on carriages to the Royal Society on February 25, 1685 (Gunther, 1930), Hooke discussed various aspects of wheel design for vehicles constructed for celerity. In a paragraph devoted largely to plain bearings, he included the telling words:

> but the best way of all is, to make the gudgeons run on large truckles, which wholly prevents gnawing, rubbing and fretting.

This interesting reference to the roller-disc bearing developed in Renaissance times and applied to static machinery in the sixteenth and seventeenth centuries is a clear indication of the application of such bearings to wheeled vehicles.

In 1710 the Academy of Science in Paris approved a design for a carriage submitted by de Mondran. The journals were supported on discs or rollers and, apart from Robert Hooke's reference to the advantages of mounting the gudgeons of carriages on truckles, this is probably the earliest reference to the use of roller-disc bearings on vehicles. It was said that:

> because of the rolling contact friction, one horse could easily do the work which could hardly be accomplished by two.

Alan (1945) also mentioned that another early eighteenth century document refers to a gun carriage invented by Fahy that had a bearing arrangement similar to de Mondran's.

The last and perhaps most colorful entry in this history of roller bearings in the early eighteenth century was provided by Jacob Rowe (1734). Rowe was awarded Patent Specification No. 543 by His Majesty King George II, and in a small booklet printed under Tom's Coffee House in Russell Street, Covent Garden, London, he explained in delightful detail how his "friction-wheels" could be applied to carts, wagons, coaches, watermills, windmills, and horse-operated mills.

Rowe referred to the practice of using rollers in the weighing of anchors at sea and claimed great advantages for his wheel supports in terms of costs and labor. The 50 percent improvement claimed by de Mondran for these early forms of rolling bearings was supported by Rowe's comments on his friction wheels:

> great advantage it may be to farmers, carriers, masons, miners, etc. . . . and to the publick in general, by saving them one half of the expenses they are now at in the draught of these vehicles, according to the common method.

One of Rowe's illustrations showing the application of friction-wheels to a fine coach is presented in Figure 1.12. The wheels "A" and "B" had diameters of about 0.61 m (24 in.) and 0.46 m (18 in.), respectively. Such friction-wheels were invariably made of wood, sometimes hooped with iron, and they rotated on iron axles mounted in iron or bell-metal bearings.

Jacob Rowe was also one of the first men to quantify the economic aspects of tribology, as least as far as friction in bearings was concerned. He argued that if all wagons and carriages were fitted with friction-wheels, they could be drawn by half the 40,000 horses then employed in the United Kingdom. Since the labor of the horse was valued at 1s. 6d. per day, this represented a direct saving of £1500 per day, or £547,500 per annum. Furthermore the cost of keeping a horse was estimated to be £10 per annum, and the savings on this account thus equalled £200,000 per annum. Rowe's estimate of the total potential savings on the operation of wheeled vehicles was thus £747,500 per annum, but he also considered that one-third of the power required to operate "Forcible Engines" employing wheels could be saved by the introduction of friction-wheels. This amounted to a further £200,000 per annum, giving a grand total of potential savings of £947,500. There is no evidence that this improvement in the accounts of the early eighteenth century exchequer was achieved, but Jacob Rowe's treatise is a fascinating document.

This brief account of the development of roller-disc bearings and free roller bearings in the seventeenth and early eighteenth centuries is important, since it provides the background to the next stage, which was the use of individual, free-rolling ball bearings during the early stages of the Industrial Revolution.

1.5.2 Early Concepts of Rolling Friction

Western Europe was the center of seventeenth-century interest in mechanical devices, and it was in this region, mainly in France and England, that the impressive early scientific studies of friction originated. Amontons' (1699) classical study of sliding friction was followed by notable contributions by Philippe de la Hire, Leibnitz, Francois Joseph de Camus, the Reverend John Theophilus Desaguliers, Bernard Forrest de Belidor, and Leonhard Euler. Rolling friction was discussed by Robert Hooke and mentioned briefly by Leibnitz and Desaguliers.

Some of the earliest and most interesting observations on the nature of rolling friction are to be found in the writings of Robert Hooke. In his 1685 discourse on carriages he recognized two components of rolling friction:

> The first and chiefest, is the yielding, or opening of the floor, by the weight of the wheel so rolling and pressing; and the second, is the sticking and adhering of the parts of it to the wheel.

His comments were, of course, related to the resistance to motion of a wheel, but the two familiar aspects of frictional resistance associated with material deformation and adhesion entered his appraisal of the problem.

In relation to the deformation loss Hooke noted that the overall resistance was small, even for undulating surfaces, if both the wheel and the ground were hard:

> yet is there little or no loss, or considerable impediment to be accounted for; for whatever force

> is lost, in raising or making a wheel pass over a rub, is gain'd again by the wheel's descending from the rub.

A distinction was drawn between the role of recoverable and nonrecoverable deformation in the important passage:

> Nor is the yielding of the floor any impediment, if it returns and rises against the wheel, for the same reason; but the yielding, or sinking of the floor, and its not returning again, is the great impediment from the floor; for so much of motion is lost thereby, as there is no force requisite to sink such a rut into the said floor by any other means; whether by weight, or pressure or thrusting directly down, or any ways obliquely.

On the question of sticking and adhesion Hooke wrote:

> The second impediment it receives from the floor, or way, is the sticking and adhering of the parts of the way to it; for by that means, there is a new force requisite to pull it off, or raise the hinder part of the wheel from the floor, or way,

> to which it sticks, which is most considerably in
> moist clayie ways, and in a broad rimm'd wheel.

A diagrammatic representation of Hooke's observations on rolling friction is reproduced in Figure 1.13 from Dowson's (1979) "History of Tribology," by permission of the Longman Group.

Leibnitz (1706) was careful to distinguish between sliding and rolling friction. Desaguliers (1734) saw lubricants as materials that would fill up the holes or surface imperfections on surfaces to facilitate movement and minimize wear by acting as rollers. A mechanistic view dominated eighteenth century thinking on the subject of dry, sliding friction, and resistance to motion was attributed to the action of one surface sliding over another composed of a myriad of tiny inclined planes formed by the surface asperities. It was therefore natural to believe that a lubricant successfully reduced friction by filling the depressions and effectively smoothing the surface, but Desaguliers introduced the possibility of a lubricant forming tiny rollers interposed between the surfaces.

1.6 The Industrial Revolution (ca. A.D. 1750 - 1850)

Important developments in the history of both ball and roller bearings undoubtedly took place during the Industrial Revolution, although the bearings themselves were but primitive versions of their twentieth century offspring. Mass production and precision manufacture came with grinding, which was itself a product of the development of machine tools during the Industrial Revolution. The decisive steps in rolling-element bearing development had, in fact, been taken before the end of the eighteenth century with free-rolling ball and roller bearings being used in road carriages and industrial machinery. Since ball and roller bearings had achieved their separate identities and references to each were increasingly numerous and significant during the Industrial Revolution, the present section is restricted almost entirely to ball bearings. Wider accounts of rolling-element bearing history during this period have been presented by Allan (1945) and Dowson (1976, 1979).

1.6.1 Carriage Bearings

A small book printed in London for C. Varlo (1772) is a most interesting contribution to the late eighteenth century literature on carriage bearings. Varlo proclaimed the merits of rolling motion over sliding motion and then described one of the earliest practical ball bearings for use on carriage axles. His claim that the bearing would operate without either friction or the need for grease led him to predict that it would

> doubtless in time...become general, as in every mechanical power it will save at least one third the strength, but in heavy weights much more...

His words are a fine example of accurate technological forecasting and a sound prediction of the future of the ball bearing industry.

Varlo's own drawing of the ball bearing fitted to his postchaise is shown in Figure 1.14. The inner bush, marked B, was located on the nonrotating axle (A) by means of an octagonal mounting. When the bush was fixed in one orientation relative to the load, Varlo recorded excessive wear of about 3 mm (1/8 in.) after a mere 800 km (500 miles) of running in his postchaise. He therefore distributed the wear and extended the life of the bearing by occasionally rotating the inner bush and realigning it on the stationary axle.

The balls or globes (G) rolled freely between inner and outer bushes (B) and (F) in grooves formed by the sideplates (C) and (E). The outer bush (F) was made in two parts joined by a square bolt (I), rotation within the nave being prevented by the three projections (H). He recommended bearings containing balls of diameters 25.4 mm (1 in.), 31.6 mm (1 1/4 in.), and 38.1 mm (1 1/2 in.) for differing duties in ships and carriages. He stressed that the hardest cast or case-hardened metal with the finest grain should be used for both the globes and the bushes. He also recommended that the side plates should form a channel such that the lateral clearance with the globes was a minimum and that the number of balls or globes should be the maximum that could be accommodated with freedom. It is interesting that Varlo attributed such friction as did exist in his bearing to the rubbing of adjacent balls, rather than to rolling friction at the contacts with the bushes. He dismissed anxiety over excessive heating in rolling bearings by the simple, but enlightened, statement that "where there is no friction, there can be no heat."

Field trials involved journeys from York with the postchaise fitted with Varlo's ball bearings. After a journey from York to Liverpool on roundabout roads and a return route through Derbyshire, he set off for Edinburgh. After a total journey of over 1100 km (700 miles) in 1772, he wrote about the bearings:

> They are not yet wore much above the sixteenth of an inch deep; and the balls are very little smaller, and keep globular.

An iron-founder from Carmarthen by the name of Philip Vaughan deserves a special reference in this history, since he was the first person to patent a ball bearing of great merit for carrying the loads on

> certain axle trees, axle arms, and boxes for light and heavy wheel carriages.

The drawing of Vaughan's (1794) ball bearing, complete with axle, reproduced in Figure 1.15 shows that the balls ran in deep grooves. The balls were inserted into the bearing at point A, and after packing, the section of the outer race labeled "4th" was inserted to complete the bearing assembly. Like Varlo's earlier invention the bearing was devoid of a separator or cage for the balls.

Joseph Resel of Austria was granted a patent in 1829 for both roller and ball bearings for carriages and machinery, and it is interesting that he claimed for his bearings both a reduction in friction and the possibility of running without lubricant.

1.6.2 Weather Vanes and Cranes

An early contribution to the history of rolling bearings, and indeed tribology, was provided by weather vanes on old Trinity Church, Lancaster, Pa., and Independence Hall, Philadelphia, Pa. The former is believed to have been built about 1794 and the later about 1770. Both weather vanes were supported on roller thrust bearings consisting of copper rollers running on bronze rings. The rollers were pierced to enable them to rotate on brass spindles in a copper cage. The bearing found on Independence Hall is shown in Figure 1.16. Eaton (1969) has presented an account of this interesting extension of rolling-element bearing applications in the United States late in the eighteenth century.

The Scottish civil engineer R. Stevenson, father of the novelist Robert Louis Stevenson, used roller bearings in the lantern of the Bell Rock Lighthouse and ball bearings in the cranes used for the lighthouse construction in 1805.

1.6.3 The Equestrian Monument to Peter the Great - St. Petersburg (ca. A.D. 1769)

Count Marin Carburi (1777) demonstrated great ingenuity when he had the granite pedestal for the statue to Peter the Great moved across the marshes and along the rivers of Finland to St. Petersburg (Leningrad). Carburi had argued that the sculptor Etienne-Maurice Falconet should be provided with a single, large block of granite for the pedestal, rather than a number of separate blocks that would have to be joined. He found such a block some 12.8 m (42 ft) long, 8.2 m (27 ft) wide, and 6.4 m (21 ft) high in marshy ground, surrounded by birch and pine trees, near a bay in the Gulf of Finland. The block, of mass 13.3 million kg (3 million lb), was moved on a remarkable linear ball bearing consisting of some 30 or 32 balls running in copper-lined troughs in heavy wooden rails. The 127-mm (5-in.) diameter balls were made of an alloy of brass to which tin and pewter were added.

An illustration of the granite block on its linear ball bearing and a section of the remarkable bearing itself are shown in Figure 1.17. The disadvantages of rollers compared with balls were fully outlined by Carburi, and it is interesting that he selected an alloy of brass for his large-scale, linear bearing elements. He had earlier ascertained that iron balls broke or were flattened and that cast-iron balls splintered into several pieces under the heavy load.

The use of rollers to assist the transportation of heavy blocks of stone in Assyria some 2680 years ago may be open to debate, but the impressive use of linear ball bearings for a similar purpose in Russia 200 years ago is impressive in both nature and scale and well documented.

1.6.4 Sprowston Postmill (ca. A.D. 1780)

Windmills have contributed substantially to the development of plain and rolling-element bearings, as outlined by Dowson (1979), but one particular mill holds a special significance in the history of ball bearings. Sprowston postmill, built in a small village outside Norwich about 1730, attracted the attention of the artist John Crome and established a reputation as a fine example of the millwright's craft during its 200-year life.

The owners of the mill agreed that it should be transferred to the care of the Norfolk Archaeological Trust on March 25, 1933, but on March 24 showers of sparks from a nearby gorse brushwood fire settled on the stationary sails and the entire wooden structure was destroyed. In the wreckage were found the millstones, some gears, and large cast-iron rings that proved to be part of the steady bearing from the shear beams beneath the lower floor of the postmill superstructure.

The cast-iron rings were large, with inner and outer diameters of 0.61 m (24 in.) and 0.86 m (34 in.), respectively. They contained some 40 cast-iron balls 57 mm (2 1/4 in.) in diameter, as shown in Figure 1.18. The complete assembly, which represents one of the earliest known applications of metal ball bearings in industrial machinery, is fortunately still preserved in the Bridewell Museum, Norwich. The diameter of the deep grooves in which the balls ran was 70 mm (2 3/4 in.), giving a ratio of groove to ball radius of 1.22. This ratio is somewhat larger than that encountered in many modern ball bearings, but quite remarkable in concept and execution for the late eighteenth century.

Clark (1938) has presented a detailed account of this historic ball bearing, and further descriptions can be found in books by Harrison (1949) and Wailes (1954). The bearing certainly dates back to about 1780 and might even be 50 years older, since the mill was constructed in 1730.

1.6.5 Studies of Rolling Friction by Coulomb, Morin, and Dupuit

The most comprehensive study of friction in the eighteenth century was undertaken by Charles Augustin Coulomb (1785). His memoir entitled "Théorie des Machines Simples" was submitted in 1780 and judged to be the winner of a prize of 2000 louis d'or offered by l'Académie des Sciences. Coulomb was mainly concerned with sliding, but he also considered rolling friction. The force required to sustain the steady motion of rollers made of lignum vitae or elm over oak boards was recorded, and Coulomb found that the force of rolling friction was directly proportional to load and much smaller than the force encountered in sliding friction. He also concluded that the resistance to rolling was inversely proportional to the radius of the roller.

Arthur Jules Morin, who became a professor at, and later the Director of, the Conservatoire des Arts et Métiers at Paris and a General in the French Army, later played a dominant role in the study of rolling friction. Indeed, the laws of friction exposed by earlier workers were widely known as Morin's laws until the end of the nineteenth century.

Morin's (1835) reports were widely accepted, but his views on rolling friction were challenged by a young French engineer named Arsene Dupuit. The subject of rolling friction was important because it governed the effort required to move freight wagons, passenger coaches, and cannons. Morin agreed with Coulomb's findings that the resistance to rolling was proportional to the applied load and inversely proportional to the radius of the roller. Dupuit agreed with the load relationship but found after a careful study that the rolling resistance was inversely proportional to the square root of the roller radius. Dupuit's (1839) theory of rolling friction was remarkably simple, yet farsighted, and in retrospect it can be seen that his concepts were remarkably close to present-day understanding of the subject. The full story of this little known yet heated debate on rolling friction has been told by Tabor (1962).

1.7 The Emergence of the Precision Ball Bearing (ca. A.D. 1850 - 1925)

The modern forms of rolling-element bearings finally emerged during the period 1850 to 1925 although many refinements in design, manufacture, and analysis were to occupy the central period of the twentieth century. Patent applications form a valuable record of rolling-element bearing development in the period under review, and Allan (1945) has presented a valuable listing of relevant patents. General industrial applications included capstans, turntables, axles and railway rolling-stock axle-boxes, mills and millstones, lifting tackle, footstep bearings, marine propeller shafts, and big-ends and gudgeon pins in reciprocating engines. However, it was the humble bicycle that provided the real spur to ball bearing development.

1.7.1 The Bicycle Bearing

The history of the bicycle stretches back well beyond the nineteenth century, but in due course attention was focused on the limited performance of such machines because of excessive friction in the plain bearings. The first patent for ball bearings in bicycles was issued to A. L. Thirion on May 16, 1862, and a great deal of experimental work on ball bearings for wheel hubs, crank spindles, and steering sockets took place in England and France during the next half century. The count of British patent applications for ball bearings for bicycles shown in Figure 1.19 clearly indicates a peak of activity in the last decade of the nineteenth century.

These efforts to develop ball bearings for bicycles were well worthwhile, for the bearing friction was reduced to one-fifth or even one-tenth of its former value. As a result maximum speeds were increased, and bicycles fitted with ball bearings started to win road races in Europe.

The demand for large numbers of steel balls of adequate quality and reliability for this important mode of transportation provided the ideal commercial conditions and technological challenge to encourage the formation of specialist precision-bearing manufacturing companies.

1.7.2 Materials and the Manufacture of Steel Balls

An industry grew up in England for the manufacture of steel balls for bicycles for both the home and European markets. Geometric accuracy of the balls was important, since a ball that was larger than the others in a bearing carried a disproportionate amount of the load and inevitably suffered premature failure, but the lack of suitable materials also hindered the development of ball bearings toward the end of the nineteenth century.

In former times the balls were made of cast iron, as in the Sprowston windmill bearing described in Section 1.6.4, but the brittleness of this material caused manufacturers to seek alternative materials. It was soon recognized that it was not just the crushing strength of the balls, but also their ability to resist plastic flow and fatigue that governed the material requirements. With contact stresses in excess of 1.4 GN/m^2 (200,000 lbf/in^2) the requirements placed upon ball bearing materials soon became more exacting than in almost any other engineering activity. The requirements for special steels and precision manufacturing processes in the ball bearing industry were undoubtedly important contributory factors in the development of materials science early in the twentieth century.

It is necessary to harden ball bearing steels to enable them to withstand the severe contact conditions mentioned earlier. The advent of case-hardening, in which steel containing about 0.15 percent of carbon was heated in a carbonaceous environment to enable additional carbon to be absorbed in a thin skin or case, at the turn of the century considerably enhanced the range of bearing materials. However, extreme care had to be exercised to ensure homogeneity, and in due course most manufacturers turned to a through-hardened steel of fine grain containing about 1 percent carbon and 1 1/2 percent chromium. The introduction of stainless steels containing high proportions of chromium, typically 12 to 15 percent, just before World War I, encouraged the adoption of such materials to combat hostile environments. A more complete account of ball bearing materials is presented in Section 2.4.

Balls were initially produced by casting or by turning from a rod or bar, and great ingenuity was exercised in lathe work, in which balls of remarkable accuracy were turned and parted off with barely a vestige of a machining pip. However, the demand for greater output inevitably caused turning to be superseded by grinding. In the smaller size ranges rough balls were first produced from steel wire or bar in automatic cold-heading processes; larger balls were made by hot pressing. The thin flash of metal that remained on the equator of the balls was then removed by tumbling or rough grinding. Further grinding between cast-iron discs and flat grinding wheels arranged such that the axes of rotation of the balls were continuously varying, together with long periods in rotary tumblers and a strict inspection procedure, eventually yielded the precision steel balls required by industry.

By 1890, steel balls could be made to within ±25 m (0.001 in.) of a nominal size, and this limit was halved by 1892. Finer tolerances could be achieved, but only at prohibitive cost. The scene was now set for the emergence of specialist ball bearing companies to meet the demands of the manufacturing industry early in the twentieth century.

1.7.3 The Birth of Precision Ball Bearing Companies

Throughout the later half of the nineteenth century most engineering companies tended to make complete machines, even to the extent of making their own bearings. Some small firms concentrated on the manufacture of steel balls, but they rarely achieved a dominant position as bearing manufacturers. It was the companies involved in the manufacture of bearings in large numbers for their own products that provided the springboard for the formation of the large twentieth century rolling-element bearing industry.

Dowson (1979) has published an account of the early history of both ball and roller bearing companies, and a brief review of some of the landmarks in ball bearing development is presented here.

An entrepreneur by the name of Charles Arthur Barrett, who was a partner in a family business of iron and brass founders in London, recognized the growing demand for ball bearings for bicycles early in the 1890's. He formed the Preston Davis Ball Bearing Co. but soon encountered great difficulty in manufacturing steel balls of adequate quality. Barrett heard of the reputation of the Hoffmann Machine Co., New York, and the skill of E. G. Hoffmann in devising equipment for the manufacture of steel balls of high accuracy. He therefore traveled to New York, bought the English and European rights for the process, and persuaded

Hoffmann to come to England to establish the Hoffmann Manufacturing Co., Ltd., in Chelmsford, in January 1898.

The new company started in a small way with 20 employees, but within 10 years it was making over 1 million steel balls a day. The initial process involved the use of a fine lathe like that shown in Figure 1.20, that had two chucks revolving together. This lathe turned steel balls from bar with an insignificant parting blemish. However, the company was plagued with technical problems that were relieved only when a grinding process for steel spheres developed by C. C. Hill in the United States was adopted. The company rapidly developed a fine reputation for the manufacture of ball bearings of high precision early in the twentieth century. British patent 15131 for a single-row ball bearing was awarded to E. G. Hoffmann in 1902.

In Sweden a plant engineer with the Göteborg textile company Gamlestadens Fabriker, by the name of Sven Wingquist, became concerned about the large number of bearing failures attributable to the misalignment and deflection of line shafting. He considered alternative bearing arrangements that might accommodate misalignment, including deep-groove ball bearings. However, late in 1906 and early in 1907, he developed the concept of a self-aligning, double-row ball bearing, and a new bearing company, A. B. Svenska Kullagerfabriken (SKF), was established in Göteborg in February 1907. Wingquist's first sketch of his self-aligning ball bearing, drawn on Easter Day, March 31, 1907, is shown in Figure 1.21. The company expanded rapidly, and overseas factories were established in England in 1911, Germany in 1914, the United States in 1916, and France in 1917.

Other important ball and roller bearing companies were established in Europe and the United States at the end of the nineteenth century and early in the twentieth century. The Timken Roller Bearing Axle Co. was established in St. Louis, Missouri, in 1898. The company moved to Canton, Ohio, to be near the developing automobile industry in 1902, and in 1909 the Bearing and Axle Divisions separated. Timken bearings were manufactured in Great Britain from 1909. A company that manufactured woodworking machinery in the United Kingdom, and that had always made its own bearings, found that the latter products were much in demand by other companies. This commercial pressure, together with a shortage of bearings from overseas during World War I, led to the creation of the Ransome and Marles Bearing Co., Ltd. In Germany the Deutsche Waffen- und Munitionsfabriken played an important role in the development and manufacture of rolling bearings. In the United States the expanding automobile and precision-manufacturing industries encouraged the formation of specialist bearing companies. One such firm was the Fafnir Bearing Co., established in Connecticut in 1911.

The worldwide adoption of ball and roller bearings, manufactured by the specialist bearing companies created early in the twentieth century, was rapid and impressive. Kakuta (1979) has told how the first rolling bearings were imported into Japan from SKF in 1910 and how the first ball bearings were partially manufactured in Japan by Nippon Seiko K.K. in 1916. Full manufacture of ball bearings, including the production of bearing steels, commenced in Japan in 1926.

1.8 Scientific Studies of Contact Mechanics, Ball Bearings, and Rolling Friction (ca. A.D. 1870 - 1925)

1.8.1 Contact Mechanics

Heinrich Rudolph Hertz was studying electrical phenomena with Helmholtz in Berlin when he attended a meeting of the Physical Society of Berlin at which Newton's rings were discussed. He began to wonder how changes in geometric form of the glasses that were pressed together to demonstrate the phenomenon might influence the observations and proceeded to solve the complex problem of contact stresses between elastic solids during the Christmas vacation of 1880. Hertz (1881) presented his classical paper to the Physical Society of Berlin on January 31, 1881, when he was 23 year old.

The mathematical expressions developed by Hertz for the deformations and contact stresses within the elliptical regions of intimate contact between arbitrarily shaped elastic solids when loaded together, subsequently provided the basis for contact stress analysis in ball bearings.

1.8.2 Studies of Ball Bearings

Two names dominate the history of scientific studies of ball bearings at the time that specialist bearing companies were being formed: Richard Stribeck and John Goodman.

Professor Richard Stribeck undertook most of his basic studies of bearings in Berlin between 1898 and 1902. He was commissioned by Deutsche Waffen- und Munitionsfabriken to carry out experiments to determine the safe load on balls and complete bearings and soon found that very small loads could lead to plastic deformation. He found that the limiting safe load that would avoid permanent deformation between static balls was proportional to the square of the ball diameter (F_{max} d_c). Stribeck (1901) also considered load sharing in complete bearings and concluded that the load on the most heavily loaded ball F_{max} was related approximately to the bearing load F and the number of balls n by the relationship $F = nF_{max}/4.37$. From this result the celebrated and more conservative Stribeck equation for the static-load-carrying capacity of a ball bearing emerged in the form $F = nF_{max}/5 = C_1nd_c/5$, where C_1 is a constant.

Stribeck not only confirmed the essential features of Hertzian contact theory, he also provided a simple guide for the selection of basic ball bearing configurations for particular applications.

John Goodman developed an interest in ball bearings as early as 1887 and subsequently studied their performance over many years

in the University of Leeds, where he held the Chair in Engineering. Professor Goodman's (1912) paper on ball bearings concentrated on the factors affecting their endurance. He noted that the balls sometimes developed specks and flakes that rapidly led to failure of the complete bearing. He also noted that the safe load-carrying capacity of ball bearings was reduced as speed increased and suggested that the effect was probably related to the well-known effect of very rapid reversals of stress. He thus focused attention on the phenomenon of fatigue and found that it led to a considerable reduction in the safe load carried by bearings, compared with the predictions of the Stribeck equation. He expressed the load-carrying capacity F in terms of the ball diameter d_c, the race diameter d, and the rotational speed N as $F = C_2 d_c/(Nd + C_3 d_c)$, where C_2 and C_3 are constants.
This well-known Goodman equation proved to be exceedingly useful in predicting the load-carrying capacity of bearings at various speeds, and it has been perpetuated to the present day with little modification.

Few would disagree with Allan's (1945) assessment of contributions to the science of ball bearings that:

> the contributions of Heinrich Hertz, Professor Stribeck, and Professor Goodman were doubtless the most outstanding in the early days of the industry.

1.8.3 Rolling Friction

Although rolling friction is generally much less than sliding friction, it is nevertheless finite, and the nature of the resistance to rolling motion has attracted considerable effort. It was Osborne Reynolds, the hydrodynamicist and father of fluid-film lubrication theory, who extended the studies reported in Section 1.6.5 in the period under review.

Reynolds (1875) considered the rolling of a cylinder over a plane and concluded that local slipping between the contacting solids contributed to the rolling resistance. He demonstrated the effect by rolling an iron cylinder over a rubber surface and noting that the translation of the cylinder was appreciably less than expected for contact between rigid solids.

This differential or microslip is, however, quite small and incapable of accounting for the resistance to rolling experienced by steel components.

Heathcote (1921) extended the work of Reynolds on microslip to the action of a ball rolling in a groove. He recognized that within the Hertzian contact zone there would be two lines of zero slip, with relative sliding taking place in opposing directions on each side of these lines.

By 1925 the concepts of microslip established by Reynolds and Heathcote were widely acceptable, but in recent years refinements to the analysis and further elegant experimental work has suggested that other actions, such as hysteresis, might be of even greater significance in pure rolling under dry conditions. Further, in real bearings, the conjunctions are normally lubricated by elastohydrodynamic action, and viscous dissipation within the lubricant then dominates rolling resistance.

1.9 The Past 50 Years

The major part of this history of ball bearings is concerned with the period before 1925, but it is necessary to say something about more recent devlopments of these essential machine elements.

Since 1925 our knowledge of the factors influencing the performance and life of ball bearings has increased considerably. The question of bearing life or endurance has been a dominant problem, and the manufacturers of ball bearings have accumulated vast experience and long hours of laboratory testing of complete bearing assemblies. This experience has been incorporated into extensive statistical analysis of bearing life, which is largely governed by fatigue. With the probability of survival of a particular bearing ranging from 100 percent to zero, corresponding to numbers of rotations ranging from zero to infinity, it has been useful to provide estimates of the fatigue life that 90 percent of a given population of bearings can be expected to achieve and the median life that 50 percent of the bearings should endure. These estimates are known as the L_{10} and L_{50} figures for particular bearing groups, and information contained within manufacturers' catalogs enables the designer to select suitable bearings for a particular application. This dominant feature of ball bearing characteristics is discussed in some detail in Chapter 3, Section 3.5.

Arvid Palmgren (1945) made a major contribution to studies of ball bearing endurance. His extensive work is well summarized in his book. Other valuable accounts of the more recent development of ball bearings have been published by Allan (1945), Jones (1946), Shaw and Macks (1949), Wilcock and Booser (1957), Hall (1957), Bisson and Anderson (1964), Harris (1966), Hersey (1966), Tallian (1969), and Houghton (1976). The American Society of Mechanical Engineers also published a useful booklet of life adjustment factors for bearings by Bamberger, et al. (1971).

The period since 1925 has also witnessed a tremendous extension of analytical studies of bearings. This has covered such topics as bearing kinematics, stresses, deformations, load-carrying predictions, mechanics of rolling contact, friction, and lubrication. The publications mentioned above provide good summaries of these developments.

The improvement of bearing materials has also attracted considerable attention since 1925. The use of vacuum-melted steels with fewer inclusions and material defects has greatly extended the fatigue life of ball bearings. Special materials such as high-temperature tool steels, martensitic stainless steels, stellites, molybdenum bearing steels, and even ceramics have extended the range of applications of ball bearings to very high and cryogenic temperatures and other hostile environments.

Bearing materials and manufacturing processes are discussed further in Section 2.4.

Finally, our understanding of the remarkable mechanism of ball bearing lubrication has greatly increased during the past half century, and particularly during the last 25 years. Studies of gear lubrication revealed that a special form of fluid-film lubrication, which was in due course termed elastohydrodynamic, accounted for the remarkable performance of many highly stressed, lubricated machine elements that operated under the most arduous conditions with modest friction and little wear for very long periods of time. In this mode of lubrication either elastic deformation of the solids or the marked increase in viscosity of the lubricant under high pressure, or both, enhance the mechanism of fluid-film lubrication in a most spectacular manner. The first book on elastohydrodynamic lubrication was published by Dowson and Higginson in 1966. Their text was devoted almost exclusively to nominal line-contact situations. The present text extends such studies to the general case of nominal point contacts. In this book we draw together the current understanding of elastohydrodynamic lubrication of elliptical contacts, develop empirical relationships for the prediction of lubricant film thickness, and show how such equations can be used in the analysis of ball bearings. The importance of minimum film thickness is twofold. First, it must be significant in relation to the surface roughness of the bearing solids in order to avoid gross distress of the accurately produced components, and second, it has a pronounced and important effect on bearing fatigue life.

1.10 Closure

The ball bearing is a precision, yet essentially simple, machine element of great utility. It is widely regarded as a product of twentieth century technology, yet it developed from a firm base built up over hundreds and even thousands of years. The concept emerged in embryo form in Roman times, faded from the scene during the Middle Ages, was revived during the Renaissance, developed steadily in the seventeenth and eighteenth centuries for various applications and was firmly established for individual road carriage bearings during the Industrial Revolution.

Toward the end of the nineteenth century the great merit of ball bearings for bicycles promoted interest in the manufacture of accurate steel balls. Initially the balls were turned from bar on special lathes, with individual general machine manufacturing companies making their own bearings. Growing demand for both ball and roller bearings encouraged the formation of specialist bearing manufacturing companies at the turn of the century and thus laid the foundations of a great industry. The advent of precision grinding techniques and the availability of improved materials did much to confirm the future of the new industry.

Twentieth century development of the ball bearing has concentrated largely on the question of bearing endurance, associated with the introduction of improved materials and manufacture. Analysis of all aspects of bearing mechanics has moved forward rapidly in recent years. In one of the most important developments, studies of elastohydrodynamic lubrication of point contacts have been extended to the stage where theoretical results can be used directly in the analysis of ball bearing lubrication. It is this application that represents the main purpose of the present text, and one that represents an additional, small contribution to the justification of the confident prediction made by John Goodman for the future of ball bearings in 1912:

> there are very few instances in which roller or ball bearings might not be used to advantage,... the extra first cost is very soon repaid by the reduction of friction and the saving of oil. Such bearings require far less attention; they are more 'foolproof'; and the wear is extremely small and therefore does not upset the alignment of the shaft; but to ensure success ball bearings must not be greatly overloaded, and they must be carefully fixed in the first instance.

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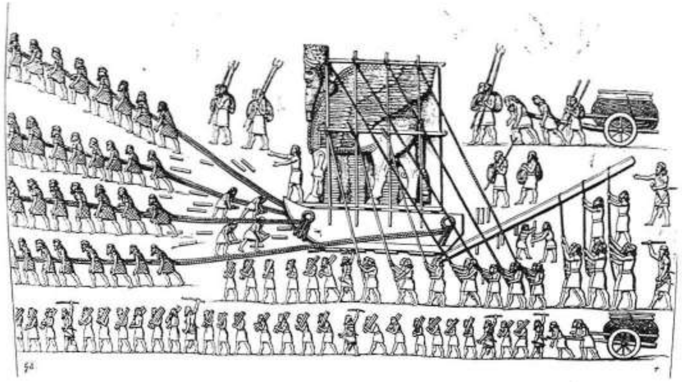


Figure 1. 1. - Assyrians using logs to position a human-headed bull (ca. 700 B. C.) - from a bas-relief at Kouyunjik.

Figure 1. 2. - Uruk pictographs for sledge and wheeled vehicle (ca. 3000 B. C.).

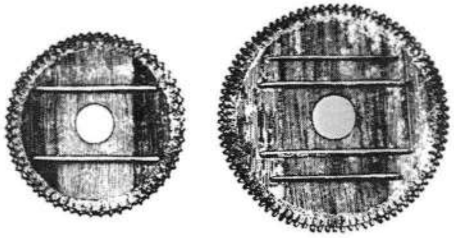


Figure 1. 3. - Nail-studded tripartite wheels with wooden felloes from Susa Apadana, tomb 280 (ca. 2500 B. C.).

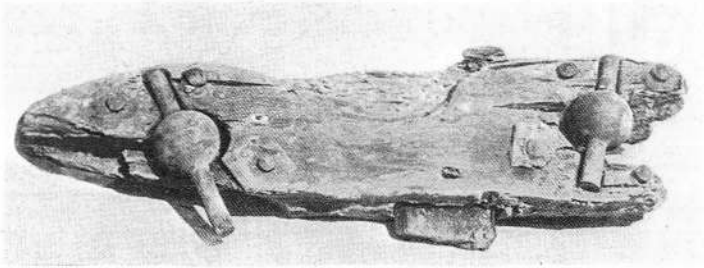


Figure 1. 4. - Fragment of revolving wooden platform with bronze balls and iron straps from the ships in Lake Nemi (ca. A. D. 50).

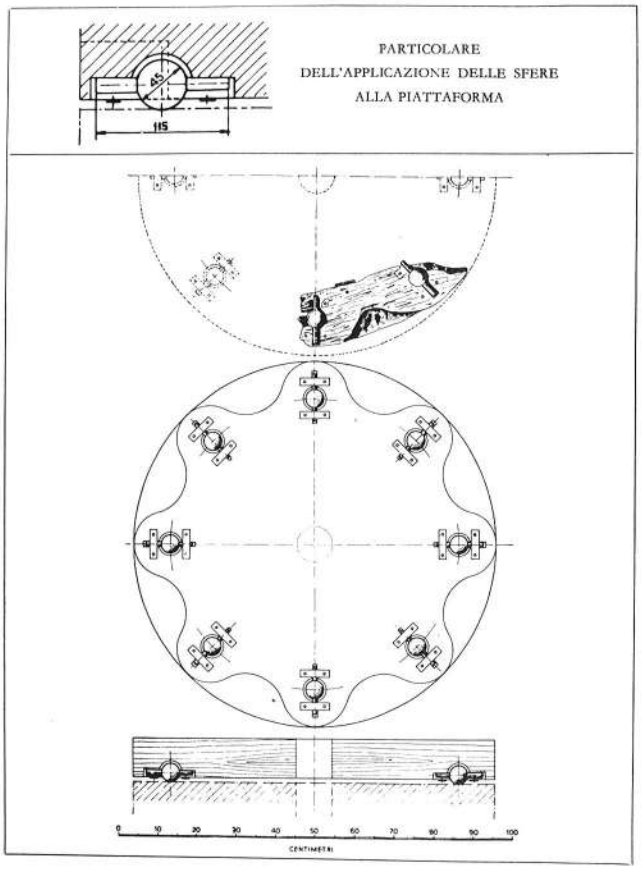


Figure 1.5. - Reconstruction of the revolving wooden platform on trunnion-mounted bronze balls from the ships in Lake Nemi (ca. A.D. 50).

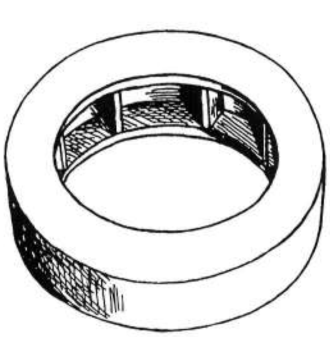


Figure 1.6. - Annular bronze object with internal compartments found in Hŝueh-chia-yai village, Shansi, China (2nd century B. C.).

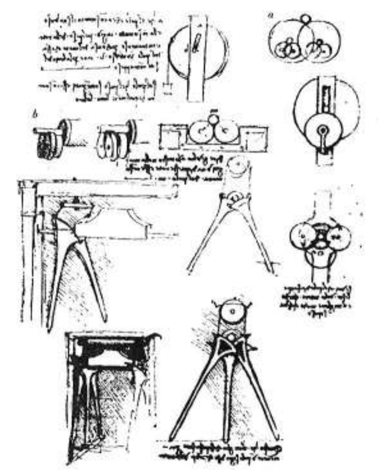


Figure 1.7. - Leonardo da Vinci's sketches in Codex Madrid I of roller-disc bearings for continuous and oscillatory motion.

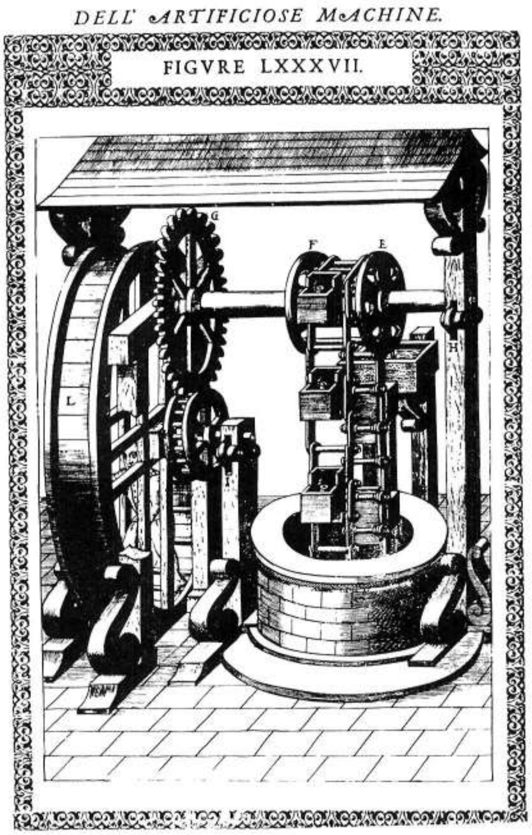


Figure 1.8. - Roller-disc bearings supporting main shafts (at H and I) on a treadmill-operated chain of dippers (after Ramelli 1588).

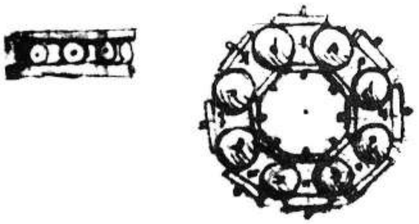


Figure 1.9. - Early form of ball thrust bearing complete with "separator" proposed by Leonardo da Vinci in Codex Madrid I.

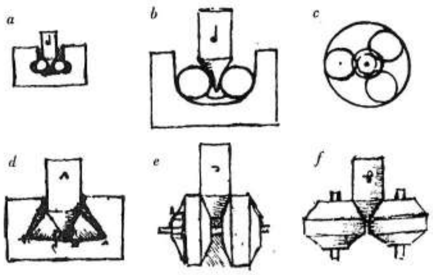


Figure 1.10. - Leonadro da Vinci's sketches of ball, cone, and roller pivot bearings in Codex Madrid I.

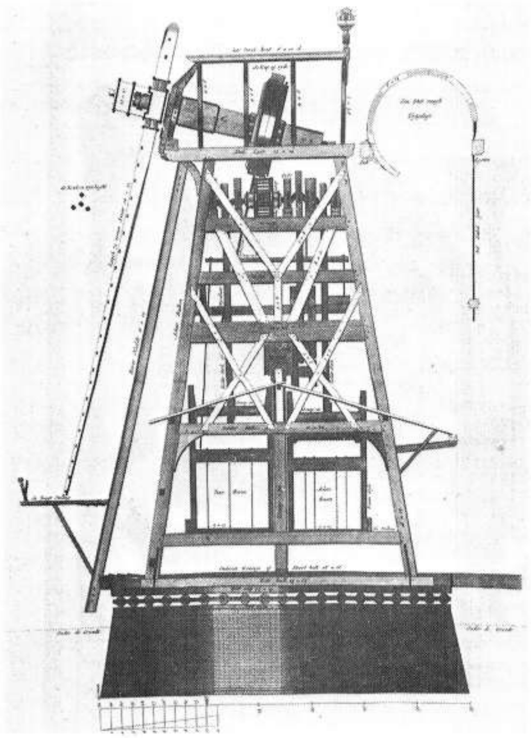


Figure 1.11. - Early eighteenth century Dutch sawmill, or paltrok, mounted on large roller thrust ring containing trunnion-mounted, wooden rollers having lengths and diameters of about 180 mm (7 in.).

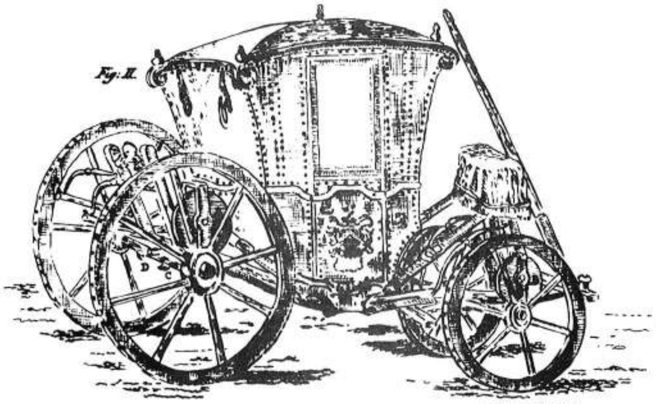
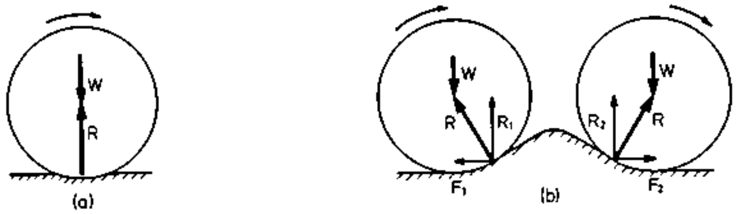


Figure 1.12. - Jacob Rowe's illustration of a coach fitted with friction-wheels (A and B), 1734.

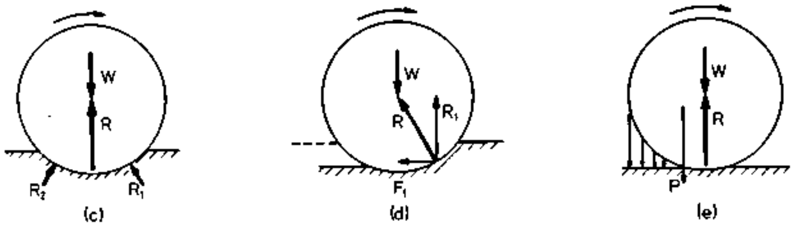


(a)

HARD WHEEL ON HARD, FLAT SURFACE
(LITTLE SURFACE PENETRATION. ROLLING RESISTANCE SMALL)

(b)

HARD WHEEL ON HARD, UNDULATING SURFACE
($F_1 = F_2$; $R_1 = R_2 = W$. OVERALL RESISTANCE TO ROLLING SMALL)



(c)

HARD WHEEL ON ELASTIC SURFACE
(REACTION ON FRONT OF WHEEL-R_1 BALANCED BY REACTION FROM ELASTIC RECOVERY R_2. ROLLING RESISTANCE SMALL)

(d)

HARD WHEEL ON DEFORMABLE SURFACE
(REACTION ON FRONT OF WHEEL NOT BALANCED BY ELASTIC RECOVERY. MAIN CAUSE OF ROLLING RESISTANCE)

(e)

ADHESION BETWEEN BACK OF WHEEL AND GROUND
(RESULTANT FORCE OF 'STICKING' OR 'ADHESION' (P) ON REAR OF WHEEL EXERTS RESISTING TORQUE)

Figure 1.13. - Representation of Robert Hooke's (1685) view of rolling friction.

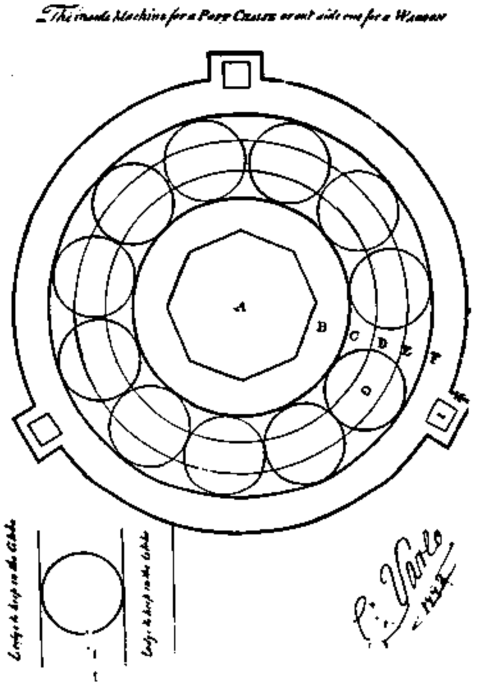


Figure 1.14. - C. Varlo's (1772) drawing of his new ball bearing for taking off friction in wheel carriages.

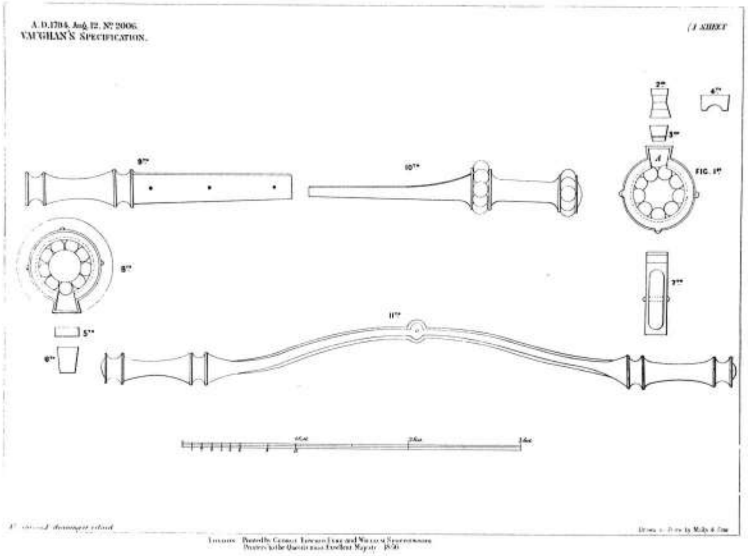


Figure 1.15. - Philip Vaughan's (1794) ball bearing for "certain axle-trees, axle-arms, and boxes for light and heavy wheel carriages."

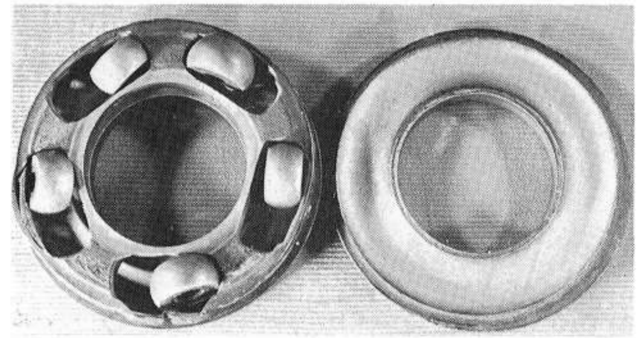


Figure 1.16. - Early roller bearing (ca. 1770) from Independence Hall, Philadelphia, Pa.

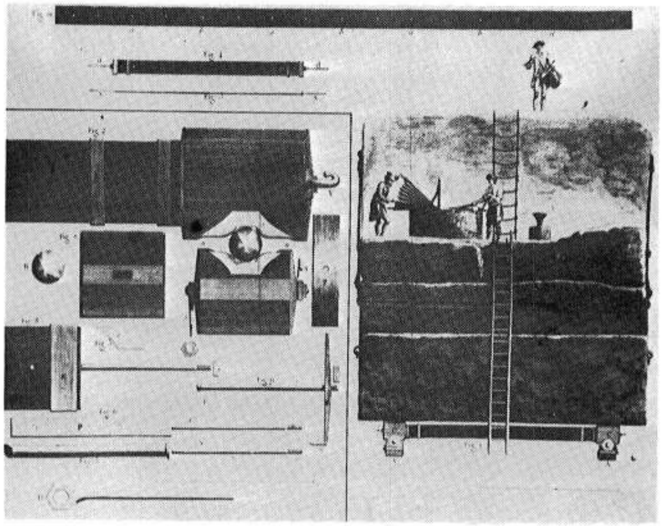


Figure 1.17. - Count Marin Carburi's system for transporting, on linear ball bearings, the granite block for the equestrian monument to Peter the Great (ca. 1770).

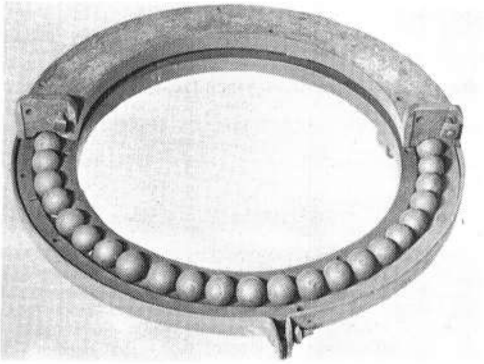


Figure 1.18. - Ball bearing from Sprowston postmill (ca. 1780), showing some of 40 cast-iron balls of 57 mm (2 1/4 in.) diameter.

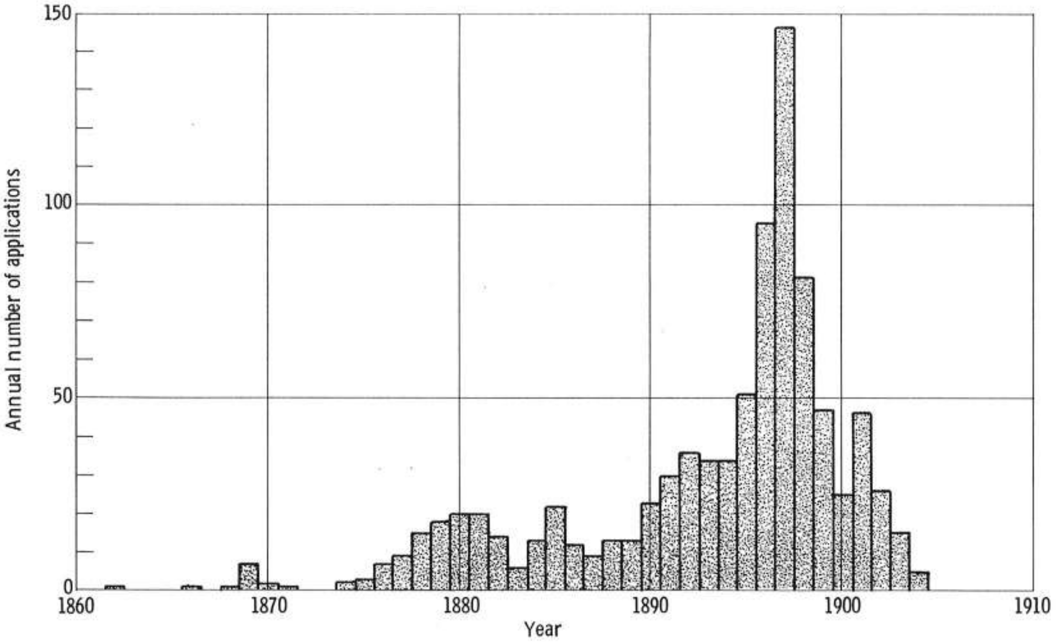
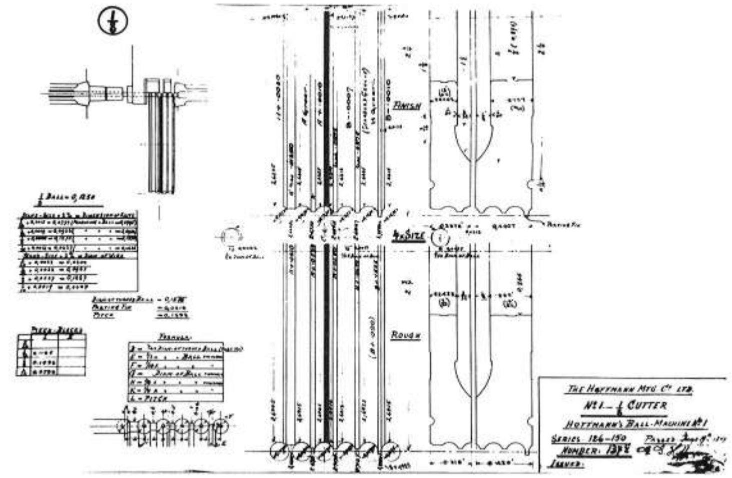
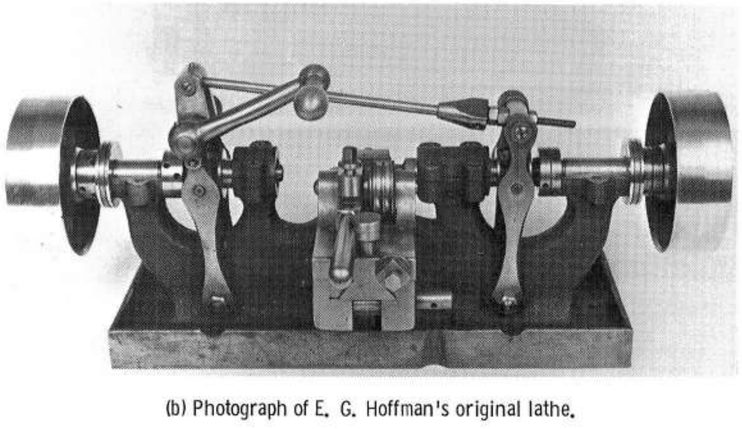


Figure 1.19. - British patent applications for bicycle ball bearings.



(a) Engineering drawing of Hoffman ball-turning machine with parting-off cutter (1899).



(b) Photograph of E. G. Hoffman's original lathe.

Figure 1.20. - Hoffman ball-turning machine and lathe.

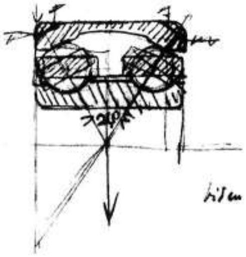


Figure 1.21. - Sven Wingquist's first sketch of his revolutionary self-aligning, double-row ball bearing (1907).

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16. Abstract
The familiar precision rolling-element bearings of the twentieth century are products of exacting technology and sophisticated science. Their very effectiveness and basic simplicity of form may discourage further interest in their history and development. Yet the full story covers a large portion of recorded history and surprising evidence of an early recognition of the advantages of rolling motion over sliding action and progress toward the development of rolling-element bearings. In the present paper the development of rolling-element bearings will be followed from the earliest civilizations to the end of the eighteenth century. The influence of general technological developments, particularly those concerned with the movement of large building blocks, road transportation, instruments, water-raising equipment, and windmills will be discussed, together with the emergence of studies of the nature of rolling friction and the impact of economic factors. By 1800 the essential features of ball and rolling-element bearings had emerged, and it only remained for precision manufacture and mass production to confirm the value of these fascinating machine elements.

17. Key Words (Suggested by Author(s))
Rolling-element bearings; Concentrated contacts; Nonconforming contacts; Elastohydrodynamic lubrication

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